



(43) International Publication Date  
18 December 2014 (18.12.2014)

(10) International Publication Number  
**WO 2014/200920 A2**

- (51) **International Patent Classification:**  
*G02F 1/025* (2006.01)
- (21) **International Application Number:**  
PCT/US2014/041550
- (22) **International Filing Date:**  
9 June 2014 (09.06.2014)
- (25) **Filing Language:** English
- (26) **Publication Language:** English
- (30) **Priority Data:**  
61/832,940 9 June 2013 (09.06.2013) US  
61/833,488 11 June 2013 (11.06.2013) US  
61/913,945 10 December 2013 (10.12.2013) US
- (72) **Inventor; and**
- (71) **Applicant :** HO, Seng-Tiong [US/US]; 120 Picardy Lane, Wheeling, IL 60090 (US).
- (72) **Inventor:** HUANG, Yingyan; 230 Locust Rd., Wilmette, IL 60091 (US).
- (74) **Agents:** SCHERER, Christopher, M. et al.; Andrus Intellectual Property Law, LLP, 100 East Wisconsin Avenue, Suite 1100, Milwaukee, WI 53202 (US).

(81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

**Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

(54) **Title:** ULTRA-LOW-VOLTAGE BROAD-MODULATION-BANDWIDTH LOW-OPTICAL-LOSS OPTICAL INTENSITY OR PHASE MODULATORS

(57) **Abstract:** Integrated optical intensity or phase modulators capable of very low modulation voltage, broad modulation bandwidth, low optical power loss for device insertion, and very small device size are of interest. Such modulators can be of electro-optic or electro-absorption type made of an appropriate electro-optic or electro-absorption material in particular or referred to as an active material in general. An efficient optical waveguide structure for achieving high overlapping between the optical beam mode and the active electro-active region leads to reduced modulation voltage. In an embodiment, ultra-low modulation voltage, high-frequency response, and very compact device size are enabled by a semiconductor modulator device structure, together with an active semiconductor material that is an electro-optic or electro-absorption material, that are appropriately doped with carriers to substantially lower the modulator voltage and still maintain the high frequency response. In another embodiment, an efficient optical coupling structure further enables low optical loss. Various embodiments combined enable the modulator to reach lower voltage, higher frequency, low optical loss, and more compact size than previously possible in the prior arts.



WO 2014/200920 A2

# ULTRA-LOW-VOLTAGE BROAD-MODULATION-BANDWIDTH LOW-OPTICAL-LOSS OPTICAL INTENSITY OR PHASE MODULATORS

## CROSS-REFERENCES TO RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Application No. 61/832,940, filed June 9, 2013; U.S. Provisional Application No. 61/833,488, filed June 11, 2013; and U.S. Provisional Application No. 61/913,945, filed December 10, 2013, the contents of which are incorporated herein by reference in their entireties.

## BACKGROUND

The present invention relates to semiconductor photonic, discrete optic, integrated optic, and opto-electronic devices. In particular, the present invention relates to integrated optical modulators capable of modulation of the light beam intensity or phase by an electrical signal. Such modulators are required for converting electrical signals into optical signals so that the light beam can be used to transmit information over an optical communication system. The light source in an optical communication system is typically a semiconductor laser and the transmission of light is typically via an optical fiber.

The typical optical modulators available currently such as modulators based on Lithium Niobate ( $\text{LiNbO}_3$ ) crystals, free-carriers in silicon, or semiconductor quantum wells in compound semiconductors typically have high modulation voltage of around 5 Volts with around 6dB (75%) device insertion loss (meaning only 25% of optical power will go through the device) with modulation frequency capable of going up to 40 Giga-Hertz (40GHz) in which 1 GHz is  $10^9$  Hz. The radio-frequency (RF) power required to power up an optical modulator with a modulation voltage of 5V is  $P=V^2/R$  in which R is typically the transmission-line impedance of 50 Ohms. Thus a 5V modulation voltage will correspond to a modulator RF power of 0.5 Watt ( $5^2/50$  Watt). This power is very high especially when the modulator is used in an electronic-photonic integrated circuit (EPIC) or photonic integrated circuit (PIC), as the total power consumption of a large electronic microprocessor chip with millions of transistor is only a few Watts. Viewing the modulator as just one active device, its power requirement is extremely high when compared to a single electronic transistor, considering the fact that the typical power consumption of an electronic transistor in a typical micro-processor-type electronic chip is in the 0.2 to 1 micro-Watt (200 to 1,000 nanoWatts) range per transistor at the operating speed of 1GHz. Also CMOS

voltage is rapidly going below 1 Volt. Thus, modulator capable of operating at below 1 Volt would be of great interest to make it compatible with CMOS circuits. While there have been efforts on reducing the modulation voltage, they are typically achieved by making the device length longer, which often leads to high optical loss (>75% loss). Beside the undesirable long device length, high loss and “low voltage” is not very useful as it would mean a higher power laser would be needed to gain back the same optical power modulation and higher power laser will consume high electrical power as well.

While there are various modulator devices with different functionalities, they can share the same general device structure that give high device operating efficiency or device performance (e.g. modulator capable of ultra-low voltage, broad modulation bandwidth, low optical loss). This general device structure capable of giving high device efficiency or high device performance is the focus of the present invention.

Another area of applications is called Radio-Frequency Photonics (RF Photonics). RF Photonics enables high frequency electrical signal to be transported via modulating an optical beam and transmit it through an optical fiber. The electrical signal is then recovered with a high-speed optical power detector. In RF photonics, it is also desirable to have modulator voltage going below 1 Volt (preferably below 0.5 Volt) with a low device throughput loss of <75% for the optical beam. In all these applications, high modulation bandwidth of exceeding 1 Giga-Hertz's (GHz) up to tens of GHz preferably reaching 100GHz is generally desirable as well. In many on-chip applications, it is desirable that the modulator's physical length be shorter than around 1mm. While the prior arts on optical intensity or phase modulators are able to either reach one or two of the desirable properties such as high modulation bandwidth (>1GHz) or low optical-power throughput loss (<75%), they are typically not able to reach all the desirable properties that include low modulation voltage, high modulation bandwidth, low optical throughput loss, and compact device size all in one optical intensity or phase modulator device.

### **Modulator Figure of Merits and the Advantages of the Present Invention**

As noted, achieving low modulator voltage  $V_{MOD}$  alone is not sufficient for these applications. The modulator must have low device insertion loss (i.e. high optical throughput power) or high optical power transmissivity  $T$  defined as the modulator's output optical power over input optical power  $T_{MOD} = (\text{optical power output})/(\text{optical power input})$ . Any loss in the modulator device's optical throughput power is equivalent to low electrical signal power to

optical signal power conversion, which is an important factor to be considered in the figure of merit for the desirable modulators. As the amount of optical power modulated is proportional to the modulator voltage, in terms of the signal to noise transmitted,  $1/T_{\text{MOD}}^2$  is equivalent to  $V_{\text{MOD}}^2$  (or  $1/T_{\text{MOD}}$  is equivalent to  $V_{\text{MOD}}$ ), which is also an important factor to be considered in the figure of merit for the desirable modulators. That is, a reduction in  $T_{\text{MOD}}$  by a factor of 2 is equivalent to an increase in  $V_{\text{MOD}}$  by a factor of 2, and is equally undesirable for achieving low signal to noise ratio in the signal modulation and transmission. Similar arguments go to the modulation depth (MD) of the modulators defined as the percentage of the optical power being changed by the modulator. In terms of the signal to noise transmitted,  $1/(\text{MD}^2)$  is equivalent to  $V_{\text{MOD}}^2$ , and shall be an important factor to be considered in the figure of merit for the desirable modulators.

Typically, the higher the modulator bandwidth BW (in GHz), the better the modulator, and is a factor to be considered in the figure of merit. Also, the shorter the modulator device length  $L_{\text{MOD}}$ , the better it is. There is typically a linear tradeoff between device length and modulator voltage so  $(L_{\text{MOD}}^2)$  is equivalent to  $V_{\text{MOD}}^2$  as a factor to be considered in the figure of merit. Finally, the maximum optical power MP (in milliWatt) that can be taken in by the modulator without losing modulation performance is also important, and is a factor to be considered in the figure of merit. This is some time called the modulator's optical saturation power and the modulation saturation can occur due to carrier excitation by the high optical power passing through the modulator material. In term of electrical signal to optical signal power transfer, the higher the optical power, the more the electrical signal can be converted back to RF voltage from the modulated optical beam at the photodetector end. Hence  $1/(\text{MP}^2)$  is equivalent to  $V_{\text{MOD}}^2$  as a factor to be considered in the modulator figure of merit. Bandwidth (BW) and modulation power (or energy per unit time) are inversely proportional in figure of merit. Note that 2x the modulation bandwidth means half RF energy per data transmitted as the time period is halved. Thus signal to noise is actually worse by 2x though data rate is 2 x faster—meaning the advantage of higher modulation is sort of cancelled off by the higher noise but we will not exactly account for the noise in the figure of merit. All faster pulses suffer the same low power and high noise trade off (i.e. it is not intrinsic to the modulator). We will still see larger BW as an advantage like smaller RF power ( $1/V_{\text{MOD}}^2$ ).

Combining all the above-mentioned factors, when comparing the modulator performances, it is useful to compare them in terms of the following “Modulator Figure of Merits” defined in terms of the quantities mentioned above as follows:

$$MFOM = T_{MOD}^2 \times MD^2 \times MP^2 \times BW / (V_{MOD}^2 \times L_{MOD}^2), \quad (1)$$

where “x” in the above equation means mathematical “multiplication” and “/” means mathematical “division”. For the discussion in this patent, we will ignore the MP factor for simplicity (i.e. we will set MP=1). The squaring in  $V_{MOD}$  is because of power consideration. The other factors are done in its equivalent to  $V_{MOD}$ . Defined this way, the higher the value of MFOM, the better the modulator for the purpose of achieving large frequency bandwidth, low device’s optical power throughput loss, small device size, low modulation voltage, high modulation depth, and high device’s optical power tolerance. This MFOM shall be compared with that of an “ideal optical intensity and phase modulator” defined below. For the purpose of applying to RF Photonics and EPICs, we define a reference “ideal optical modulator” to be one that has the following characteristics:  $T_{MOD}=0.25$ ,  $V_{MOD}=0.5$  (V),  $L_{MOD}=1$  (mm),  $BW=40$  (GHz),  $MD=0.9$ . The MFOM of such an ideal modulator denoted as “MIFOM” is then given by:

$$MIFOM = 0.25^2 \times 0.9^2 \times 40^2 / (0.5^2 \times 1^2) \text{ (mW}^2 \times \text{GHz} / (\text{V}^2 \times \text{mm}^2)) = 8 \text{ (GHz} / (\text{V}^2 \times \text{mm}^2)). \quad (2)$$

The ratio between the MFOM of an optical modulator and the MIFOM is of particular interest as it would be an indication of how close the modulator in question is to an “ideal modulator” or how much it surpasses the ideal modulator. This ratio may be referred to as the Modulator’s Relative to Ideal FOM or relative modulator figure of merit (RMFOM) defined as follows:

$$RMFOM = (MFOM / MIFOM). \quad (3)$$

When this value is close to 1 or higher than 1, the optical modulator is said to compare favorably with the target ideal modulator in terms of the modulator performances. On the other hand, when this value is much smaller than 1, the optical modulator is not good compared with the performances of the target ideal modulator.

A typical performance for a “compound semiconductor based” modulator of the prior arts has  $T_{MOD}=0.25$ ,  $V_{MOD}=5$  (V),  $L_{MOD}=2$  (mm),  $BW=40$  (GHz),  $MD=0.9$ . The MFOM of such a typical modulator of the prior art is given by:

$$MFOM = 0.25^2 \times 0.9^2 \times 40 / (5^2 \times 2^2) \text{ (GHz} / (\text{V}^2 \times \text{mm}^2)) = 0.02 \text{ (GHz} / (\text{V}^2 \times \text{mm}^2)). \quad (4)$$

Its RMFOM is then given by:

$$RMFOM = 0.02 / 8 = 0.0025 = (1/400). \quad (5)$$

This is 400 times worse than the targeted ideal optical modulator. The prior arts for realizing optical modulators are thus highly inadequate in terms of realizing the targeted performances of the ideal modulator.

A typical performance for a “silicon based” modulator of the prior arts has  $T_{MOD}=0.25$ ,  $V_{MOD}=2$  (V),  $L_{MOD}=5$  (mm),  $BW=10$  (GHz),  $MD=0.9$ . The MFOM of such a typical silicon modulator of the prior arts is then given by:

$$MFOM=0.25^2 \times 0.9^2 \times 10 / (2^2 \times 5^2) \text{ (mW}^2 \times \text{GHz} / (\text{V}^2 \times \text{mm}^2)) = 0.005 \text{ (mW}^2 \times \text{GHz} / (\text{V}^2 \times \text{mm}^2)).$$

(6)

Its RMFOM is then given by:

$$RMFOM=0.005/8 = 0.000625 = (1/1600). \text{ (7)}$$

This is 1600 times worse than the targeted ideal optical modulator. The prior arts for realizing silicon based optical modulators are thus highly inadequate in terms of realizing the targeted performances of the ideal modulator.

In the present invention, the major limitations of the prior arts are overcome, making it possible for the optical modulator of the present invention to have RMFOM ranging from 0.01 to over 2.5, which is generally over 10 to 1,000 times higher in term of figure of merit than the typical optical modulators based on the prior arts. This is a very significant advantage for the present invention over the optical intensity or phase modulators based on the prior arts.

### Exemplary Modulators in the Prior Art

An exemplary embodiment of the present invention for the modulation material is based on utilizing the near bandgap effect of refractive index change due to carrier band-filling and other electro-optic effects in compound semiconductor, resulting in electro-optic (EO) modulators. Another exemplary embodiment of the present invention for the modulation material is based on utilizing the electro-absorption effects in compound semiconductor, resulting in electro-absorption (EA) modulators.

Electro-absorption modulation of an optical beam is based on optical absorption change due to an applied voltage, which as is well known to those skilled in the art. Electro-absorption modulation can be induced by a shift in the semiconductor bandgap energy under an applied voltage or induced by carrier injection-depletion that can change the optical absorption or gain property of the semiconductor materials. These mechanisms for electro-absorption modulation are relatively straight-forward and well known in the prior art.

For electro-optic modulator, the mechanisms involved are more complex. It is thus of interest to review the physics of refractive index change in silicon-based modulators and compound semiconductor based modulators below.

### Physics of refractive index change in silicon based modulators

The main difference between compound semiconductor based modulators and silicon modulators for operations at the 1550nm wavelength range for fiber-optic communications is that while silicon has an absorption band gap, it is at 900nm, which is far away from the operating wavelength of 1550nm. Hence, the refractive index change in silicon is not due to effects related to the band-gap energy but due to free-carrier plasma effect. Free-carrier plasma can change the refractive index over a broad wavelength range but also will cause optical absorption. Hence, free-carrier plasma effect has a drawback in that when the refractive index change due to the free carriers is high, the amount of free-carrier absorption is also high so there is a significant amount of optical absorption that reduces the optical beam intensity when the phase shift induced by the free-carrier plasma is high. In silicon, the refractive index change due to the free-carrier plasma effect is known to those skilled in the art as given approximately by:

$$\Delta n_{\text{plasma}} = -(8.8 \times 10^{-22} \Delta N_e + 8.85 \times 10^{-18} \Delta N_h^{0.8}), \quad (8)$$

where  $\Delta N_e$  is electron carrier density in ( $1/\text{cm}^3$ ), and  $\Delta N_h$  is hole carrier density in ( $1/\text{cm}^3$ ). For example, with a carrier density of  $10^{18}/\text{cm}^3$ , the refractive index change of the active P-N junction region denoted by  $\Delta n_{\text{plasma}}$  can be around  $\Delta n_{\text{plasma}}=0.002$  for holes and  $\Delta n_{\text{plasma}}=0.0009$  for electrons. These are relatively low values that limit the low-voltage performances of silicon-based optical modulators.

### Physics of refractive index change in compound semiconductor based modulator

Below, a material is said to be an active modulator material or more precisely an active electro-optic (EO) material if the material's refractive index can be altered by an applied voltage, an electric current, or either injection or depletion of carriers. A material is said to be an active electro-absorption (EA) material if the material's optical absorption or optical gain can be altered by an applied voltage, an electric current, or either injection or depletion of carriers. The active EO or EA materials are more generally referred to as active modulator material or medium (ACM), or as active area, or simply as active medium. In an active EO material, the refractive index change can then be used to shift the optical phase of an optical beam or change the intensity of the optical beam (using for example a Mach Zehnder interferometer as is well known to those skilled in the art). The modulation is said to result from electro-optic modulation (as oppose to electro-absorption modulation for which the optical absorption of the modulator material is

altered). An advantage of EO modulator in general is that it can have intensity change that is somewhat linear as a function of the applied voltage, or can be corrected by an external electrical circuit to make the modulation linear. Such linear intensity modulation capability is important for applications to Radio-Frequency Photonics (RF Photonics) area.

In compound semiconductor, the energy bandgap of the compound semiconductor, whether it is bulk compound semiconductor or quantum wells, can be designed to be close to the wavelength of operation. For example, in some situation, such as electro-optic modulation, it is advantages to design the bandgap to be at 1350nm for operation at 1550nm wavelength range. In other situation, such as electro-absorption modulation, it is advantages to design the bandgap to be at 1450nm for operation at 1550nm wavelength range. The prominent refractive index change effect most frequently utilized by the prior art is quantum confined stark effect (QCSE), which changes the refractive index due to strong electric field applied across the quantum wells that shifts the transition energy of the quantum wells, which then leads to a change in the refractive index. It is purely an electric field effect and does not involve electron or hole carriers. The refractive index change due to QCSE is given as:

$$\Delta n_{QCSE} = (1/2) n^3 K_{QCSE} E^2, \quad (9)$$

where  $K_{QCSE} \sim 0.3 \times 10^{-18} \text{ m}^2/\text{V}^2$  for InGaAsP quantum wells,  $n$  is the refractive index of the quantum well material, and  $E$  is the applied electric field in Volt/meter. QCSE is a quadratic electro-optic (QEO) effect as it depends on the electric field square. Another refractive index shift effect is due to the intrinsic electro-optic coefficient of the compound semiconductor material called Pockels effect. This effect is also referred to as linear electro-optic effect (LEO) of the crystal. For InP, it is given by:

$$\Delta n_{Pockels} = (1/2) n^3 r_{41} E, \quad (10)$$

where  $r_{41} \sim 2 \times 10^{-12} \text{ m/V}$  for InP material. Assuming a 2V applied voltage across a 200nm thick active modulator material giving an electric-field strength  $E = 1\text{V}/(100\text{nm}) = 10^7 \text{ V/m}$ , then the above with  $n=3.4$  would give  $\Delta n_{QCSE} = 0.0005$  and  $\Delta n_{Pockels} = 0.00033$ . At a higher voltage of 4 V, QCSE would overtake Pockels effect substantially and becomes the dominant effect giving  $\Delta n_{QCSE} = 0.002$ . Thus in the typical compound semiconductor modulator design, QCSE is the main effect used for achieving refractive index shift. Both QCSE and Pockels effect just need an applied field (i.e. no carrier is needed), which is often seen as an advantage to achieve low optical loss (carrier can cause free-carrier optical absorption loss).

Other effects that are seldom used in compound semiconductor based modulators are

dependent on electron or hole carriers. One effect is the carrier plasma effect, which is also used by silicon modulators as discussed above. The refractive index change due to the carrier plasma (PL) effect is given by:

$$\Delta n_{\text{plasma}} = [(-e^2 \lambda_0^2) / (8 \pi_2 c_2 \epsilon_0 n)] * (\Delta N_d / m_e^*). \quad (11)$$

- 5 It has a value similar to Pockels effect under the same applied field if the quantum well (or bulk material) doping  $N_d$  is n-doped with an electron doping density of around  $N_d = N_e = 1 \times 10^{17} / \text{cm}^3$ . Another effect is due to carrier filling up the conduction bands (or valence bands). It is called the band filling (BF) effect. Fig. 1a illustrates the case for which the electron carriers fill up the conduction band, leading to a shift in the absorption energy from close to the bandgap energy  $E_g$  to larger than the bandgap energy  $E_g + \Delta E$  (or in wavelength  $\Delta g - \Delta \lambda$ ). As shown in Fig. 1b, this change in the “absorption energy edge” from absorption curve  $\alpha_{E_g}(\lambda)$  to  $\alpha_{E_g + \Delta E}(\lambda)$  leads to a change in the refractive index of the material  $\Delta n(\lambda)$  due to what is known to those skilled in the art as the Kramer’s Kroganig’s relation which says that a change in the absorption spectrum  $\Delta \alpha(\lambda) = \alpha_{E_g + \Delta E}(\lambda) - \alpha_{E_g}(\lambda)$  as a function of the wavelength ( $\lambda$ ) must lead to a change in the spectrum for the refractive index  $\Delta n(\lambda)$  as a function of the wavelength. This results in a change in the refractive index at the operating wavelength of the beam at  $\lambda_B$  (say at 1550nm) or its corresponding beam photon energy  $E_B$  due to the absorption edge change (say at  $\lambda_g = 1350\text{nm}$ ) because of carriers filling up the semiconductor energy bands (e.g. it can be electrons filling the conduction bands or holes filling the valence bands). The refractive index change at the operating wavelength can be expressed as:

$$\Delta n_{\text{BandFil}} = R_{\text{BandFil}}(\lambda) \times \Delta N_e, \quad (12)$$

- where the proportionality coefficient  $R_{\text{BandFil}}(\lambda)$  is dependent on the optical wavelength  $\lambda$  and its value would be high at close to the bandedge compared to its value at away from the bandedge. At a doping density of  $N_e = 10^{17} / \text{cm}^3$ ,  $\Delta n_{\text{BandFil}}$  can be 2-3 times higher than  $\Delta n_{\text{plasma}}$  or  $\Delta n_{\text{Pockels}}$  under the same applied voltage for the III-V (e.g. InP/InGaAsP) material system when the band-edge is at 1350nm or 200nm away from the operating wavelength of 1550nm but may be lower than  $n_{\text{QCSE}}$  at a high enough applied voltage  $V$  as QCSE scales as the square of the electric field and is proportional to  $V^2$ , whereas other changes in the refractive index including  $\Delta n_{\text{BandFil}}$  are only proportional to  $V$ . Normally  $\Delta n_{\text{BandFil}}$  cannot be too high in the optical modulator structures of the prior arts due to a few reasons.

First,  $\Delta n_{\text{QCSE}}$  can always be dominating at high enough voltage or high enough applied field as it is proportional to  $V^2$ .

Second, in the prior art, the quantum well (or bulk) active material (ACM) is either undoped or lowly doped with carriers having a doping density typically lower than about  $1 \times 10^{17}/\text{cm}^3$ . The no doping or low doping is due to the problem in the modulator designs of the prior art that high carrier doping density will substantially increase the optical absorption loss of a light beam going through the entire modulator. In the modulator design of the prior art, the optical loss would occur not only just at the active modulator section at which the refractive index or absorption is designed to change under an applied voltage but also in the rest of the connecting region such as in a Mach-Zehnder interferometer geometry. This results in a long waveguide section all doped with the high carrier doping density, which then results in high optical loss due to the high free-carrier density from the doping. For example, while the active modulator region may have a length of 0.5mm, the entire modulator with the Mach-Zehnder interferometer geometry may have a total physical beam propagation length of 2-5mm.

Third, a highly doped quantum well region will decrease what is known to those skilled in the art as the carrier depletion width  $d_{\text{PN}}$  of the P-N junction, a region between the P-doped region and N-doped region in which no or few carriers exist. The smaller the depletion width  $d_{\text{PN}}$ , the larger the device capacitance as the width defines the dielectric width of a capacitance in which one capacitor plate is the N-doped region and another capacitor plate is the P-doped region, and these two plates are separated by the depletion width  $d_{\text{PN}}$ . As is known to those skilled in the art, the smaller the "plate separation", the larger the capacitance  $C_{\text{PN}}$ . The large P-N junction capacitance  $C_{\text{PN}}$  will drastically reduce the modulation bandwidth of the optical modulator partly due to RC frequency cutoff, where R will be the effective series resistance of the device  $R_{\text{ser}}$  and the RC modulator frequency cutoff will be  $f_{\text{RC}} = 1/(2 \pi R_{\text{ser}} C_{\text{PN}})$ . Thus the quantum well in prior art is typically undoped and if it is doped, it is kept to a doping density of  $1 \times 10^{17}/\text{cm}^3$  or lower or it would be hard to achieve large modulation bandwidth for the modulator due to higher device capacitance  $C_{\text{MOD}}$  that would lead to low modulator RC cutoff frequency  $f_{\text{RC}}$ , given the typical device series resistance  $R_{\text{ser}}$  achievable in the prior art. The  $1 \times 10^{17}/\text{cm}^3$  doping level gives approximately a depletion width around 100-300nm under zero to a few volts of applied voltage, which is about the active region and waveguide core thickness of a conventional semiconductor based modulator. Going to higher doping than  $1 \times 10^{17}/\text{cm}^3$  will be regarded as inefficient design as the depletion width will be too small to cover the active region and waveguide core thickness, and also will unnecessarily lower the modulation bandwidth due to the higher junction capacitance. In the present invention, this limitation is overcome, resulting in substantially lower

modulation voltage while maintaining high modulation frequency cutoff.

### An Exemplary Modulator in Prior Art

Fig. 2 shows an electro-optic (EO) modulator of prior art. In particular a modulator made of III-V compound semiconductor material. An electro-absorption modulator in the prior art will have a similar optical and electrical structure except that the active material is replaced by a material that can cause electro-absorption (i.e. a material whose optical absorption can be altered under an applied voltage, an electric current, or either injection or depletion of carriers). For the purpose of illustration of a modulator of prior art, we will describe an EO modulator.

The EO modulator utilizes semiconductor quantum well's quantum-confined stark effect as the main electro-optic (EO) effect. Under an applied electric field, the quantum well's width effectively narrows and pushes the energy level higher, resulting in a decrease in the refractive index due to increase in the energy bandgap. The direction of the electric field does not matter so it is a quadratic electro-optic effect. For 1550nm operation, a typical modulator structure is shown in Figure 2 showing device 10000. In device 10000, the device is fabricated on a semiconductor substrate SUB 10010. In an exemplary device substrate SUB 10010 is N-doped InP with N-type doping density of  $N=3 \times 10^{18}/\text{cm}^3$ . Above the substrate is a lower electrical Ohmic contact layer LOHC 10020. In an exemplary device LOHC 10020 is N-doped InGaAs with N-type doping density of  $N=1 \times 10^{18}/\text{cm}^3$  and a thickness of  $0.1\mu\text{m}$ . Above the LOHC 10020 is a lower conducting waveguide cladding layer (LCWCd) 10030. In an exemplary device LCWCd 10030 is N-doped InGaAs with N-type doping density of  $N=1 \times 10^{18}/\text{cm}^3$  and a thickness of  $1.5\mu\text{m}$ . Above the LCWCd 10030 is a lower waveguide core separate confinement heterostructure (SCH) layer (LWCoSCH) 10040. In an exemplary device LWCoSCH 10040 is N-doped InGaAlAs with energy bandgap wavelength of  $1.3\mu\text{m}$  and N-type doping density of  $N=1 \times 10^{17}/\text{cm}^3$ , a thickness of  $0.1\mu\text{m}$ . Above the LWCoSCH 10040 is an active electro-optic and waveguide core layer (AEOWCo) 10050. In an exemplary device AEOWCo 10050 is comprising of 14 quantum wells (8nm thick) and 15 barrier layers (5nm thick) made of InGaAlAs material with no or low doping (called intrinsic semiconductor or I-type semiconductor), resulting in a total thickness of  $0.182\mu\text{m}$  for layer AEOWCo 10050. The quantum well layer has 35% compressive strain with respect to InP lattice and the barrier layer has 40% tensile strain with respect to InP lattice. Above the AEOWCo 10050 is an upper waveguide separate confinement heterostructure (SCH) layer (UWCoSCH) 10060. In an exemplary device UWCoSCH 10060 is P-doped InGaAlAs with

energy bandgap wavelength of  $1.3\mu\text{m}$  and P-type doping density of  $P=1 \times 10^{17}/\text{cm}^3$ , a thickness of  $0.1\mu\text{m}$ . Above the UWCoSCH 10060 is an upper conducting waveguide cladding layer (UCWCd) 10070. In an exemplary device UCWCd 10070 is P-doped InP with energy bandgap wavelength of  $0.9\mu\text{m}$  and P-type doping density of  $P=1 \times 10^{18}/\text{cm}^3$ , a thickness of  $1.5\mu\text{m}$ . Above the UCWCd 10070 is an upper electrical Ohmic contact layer UOHL 10080. In an exemplary device UOHC 10080 is P-doped InGaAs with P-type doping density of  $P=1 \times 10^{19}/\text{cm}^3$  and a thickness of  $0.1\mu\text{m}$ . Above the UOHC 10080 is an upper metal contact layer UMC 10090. In an exemplary device UMC 10090 is single or multi-layer metal denoted by layer UM1 10091, UM2 10092, UM3 10093, ... with UM1 layer directly on top of UOHC 10080. In one exemplary embodiment, UM1 is 20nm of Ti, UM2 is 50nm of Pt, UM3 is 1000nm of Au. On the lower side above the LOHC 10020 is a lower metal contact layer LMC 10100. LMC 10100 is single or multi-layer metal denoted by layer LM1 10101, LM2 10102, LM3 10103,... with LM1 layer directly on top of LOHC 10020. In one exemplary embodiment, LM1 is 17nm of Au, LM2 is 17nm of Ge, LM3 is 17nm of Au, LM 4 is 17nm of Ni, LM5 is 1000nm of Au.

### Summary of Limitations of Prior Arts in Intensity or Phase Modulators

Below, we summarize further the limitations of prior arts in modulators by using the example of a semiconductor based modulator. The typical semiconductor modulators have switching voltages of around 2-5V with a device length of a few millimeters. The optical mode is confined by weakly-guiding structure in the vertical direction with effective mode size of  $0.5-1\mu\text{m}$  and thick optical cladding of  $\sim 1.5\mu\text{m}$  to prevent the guided optical energy from reaching the top or bottom metal electrode with high metal optical absorption loss. The waveguide core usually has quantum wells (QWs) to enhance the refractive index modulation under an applied electric field. Based on such structure, compound semiconductor EO modulators with 40GHz modulation bandwidth have been achieved with use of QWs and a PIN (P-doped, Intrinsic (i.e. undoped or being an Intrinsic semiconductor material), N-doped) type structure, with  $V_{\pi}$  of 2-3V (voltage that gives a total relative phase shift of  $\pi$  in the modulator Mach Zehnder Interferometer (MZI)). **Fig. 3** shows the general cross-section of such a PIN modulator structure, which is a general schematic of the more detailed exemplary device structure shown in **Fig. 2**. The modulator performance gives a modulator voltage of 3V, a modulation bandwidth of 30GHz, and a modulator length of 1mm (see [REF 1]). All bandwidth noted here is analog 3dB optical power bandwidth (not in digital Gb/s that needs smaller analog bandwidth).

There are typically four contributions to electro-optic modulation for a semiconductor modulator: (1) Linear Electro-Optic effect (LEO); (2) Quadratic Electro-Optic effect (QEO) including quantum confined stark effect (QCSE) when quantum wells are used; (3) Band-Filling effect (BF); (4) Plasma Effect (PL). These are well described in the literature. Most modulators with QWs utilize LEO+QCSE as the main effects. Some may involve BF and PL as additional effects.

The voltage is usually high (2-5V) in prior arts partly because these conventional EO modulators used a weakly confined waveguide structure with thick cladding of typically 1.5 micrometer thickness to avoid metal optical absorption loss. This resulted in a vertical optical mode with width of approximately 0.5 to 1 micrometer at full-width-at-half-maximum (FWHM) power points but the full optical energy is extended to 2-3 micrometers in size vertically. If the entire optical mode region is filled with active EO materials such as quantum wells (utilizing the QCSE), then the electrode spacing will be about 2 to 3 micrometers (or 2,000nm to 3,000nm) in spacing, which is large. The use of PIN structure can reduce the electrode spacing to say to around 200-300nm, but then the percentage of the 200-300nm thick electro-optic medium overlapping with the 1,000nm large optical beam mode energy and the RF field (called the mode-medium overlapping factor) will be small (down to ~10%). The applied RF electric field is usually somewhat uniformly distributed in the active electro-optic medium. Thus, the advantage of 10 times higher electric field (due to electrode spacing reduced from 2,000nm to 3,000nm down to 200nm to 300nm) is cancelled by the proportionately reduced mode-medium overlapping factor (from near 100% down to ~10%). As a result, the modulation voltage is not changed much by the use of the PIN structure.

Due to one or more of the abovementioned reasons as illustrated via an EO modulator in the prior art, conventional semiconductor EO or EA modulators have high modulation voltages of 2-5V depending on its device length and the nonlinear electro-optic effects used among the four main effects (LEO, QCSE, BF, or PL effect). Typically 2V to 3V  $V\pi$  can be achieved with 2-3mm long device. If all four effects are used, it could be reduced to ~1mm long device with 2V to 3V  $V\pi$ . The modulator voltage cannot be much smaller and the length cannot be much shorter and still maintain the high modulation bandwidth of 10GHz or higher.

In the present invention, the above limitations of the prior arts are overcome, resulting in broadband low voltage modulators with small device size having a relative figure of merits, RMFOM, that are generally over 10 to 1,000 times higher than modulators in the prior arts.

## SUMMARY

It is an aim of the present invention to provide compact intensity or phase modulators with very low switching voltage, high modulation bandwidth, low optical loss, short modulator device  
5 length, high optical saturation intensity, resulting in intensity or phase modulators with exceedingly high modulator relative figure of merit that is generally over 10 times to 1,000 times higher than the modulators based on prior arts.

It is another aim of the invention to provide compact modulator devices that can be used as isolated optical modulators with integration possibility or as isolated optical components, using  
10 either integration technology or free-space and discrete optics.

The compact modulator devices can be constructed with discrete optical and mechanical components or can be integrated in a photonic integrated circuit or an electronic-photonic integrated circuit (EPIC).

The present invention discloses means to realize modulator devices that will have a wide  
15 range of utilities and can be used as devices on chips including but not limited to photonic integrated circuits (PICs) or EPICs and methods of making the same.

The present invention has overcome the aforementioned limitations of the prior arts on modulators. In one embodiment of the present invention involving semiconductor as the electro-active layer (ECL), the limitation is overcome by shifting away from the use of QCSE and instead  
20 utilizing structures that can greatly enhance the refractive index change based on the carrier band-filling effects by orders of magnitude larger, the present invention achieves this by employing substantially higher carrier doping density for the active material (ACM) made up of either quantum wells or bulk semiconductor materials.

Normally, in the prior arts, this high carrier doping density region, though may give  
25 higher modulation due to higher carrier induced refractive index change is intentionally avoided due to high free-carrier absorption loss and also due to higher PN junction capacitance  $C_{PN}$  that can reduce the frequency response.

The present invention overcomes the disadvantages and can achieve the high modulation frequency and low optical loss for the device insertion in spite of the high carrier doping (and  
30 hence low modulation voltage), resulting in ultra-low-voltage high-speed low-loss ultra-compact optical intensity and phase modulators.

For the purpose of illustrations and not limitation, these are for example firstly achieved

by utilizing “near-bandgap refractive index change structures” such as the band-edge band-filling effects that has high refractive index change (and hence lower modulation voltage) with use of mainly the n-type carriers (that has lower optical free-carrier absorption loss) and the use of device structure that enables only a short length of the device that is doped (e.g. via a multilayer passive-active device integration structure(ML-APDI)), resulting in low total optical loss;  
5 secondly achieved by the employment of high-speed electrical structures such as by lowering the resistance of the waveguide cladding layer in the modulator using much thinner cladding layer and by using mainly n-dopants for the electrical conduction in the cladding layer to lower the device series resistance  $R_{ser}$ . The lower  $R_{ser}$  will balance back the increased P-N or P-I-N junction  
10 capacitance  $C_{PN}$  due to the high carrier doping density, and hence maintain a high RC cutoff frequency  $f_{RC}$  that is depending on the product of the R and C:  $f_{RC} = 1/(2 \pi R_{ser} C_{PN})$ ; thirdly by using a much thinner vertical waveguiding structure with high waveguide core to cladding refractive index ratio (also called refractive-index contrast), giving a high optical mode energy overlapping with the refractive index change layers (i.e. modulator active layers) or also referred  
15 to as a high mode-medium overlapping factor, resulting in higher change in the optical phase shift per unit propagation distance for the optical beam and hence lower modulation voltage; and/or fourthly by eliminating the top and bottom metal contacts that can cause optical absorption loss. The percentage of optical mode energy overlapping with the modulator active layers (e.g. the active EO or EA material layer) and the applied RF field or electrical current is also called the  
20 “optical mode energy to active layer overlapping factor” or as “mode-medium overlapping factor”. The applied RF electric field or electrical current is usually somewhat uniformly distributed in the active material layer.

One or more of the advantaging factors above may be employed separately or jointly and when more than one of these factors are applied jointly, they could mutually enhance each other.  
25 For example, the higher change in optical phase per unit propagation distance means that the device length can be shorter, leading also to lower total optical free-carrier absorption loss that increases with propagating length, enabling the realization of ultra-low-voltage high-speed lowloss optical intensity and phase modulators that are also ultra-compact.

While electro-optic (EO) modulator is discussed above, several of the abovementioned  
30 advantages in the present invention can equally apply to an electro-absorption (EA) modulator by changing the active EO material to electro-absorption (EA) material, and can use non-semiconductor material as the EO or EA material (i.e. as the active material (ACM)).

The modulator resulted from the present invention is capable of achieving relative modulator figure of merits RMFOM that is 10 to 1,000 times better (i.e. higher) than that of the modulators based on the prior arts. Thus, the present invention has significant performance advantages for integrated optical modulators over the performances of integrated optical modulators based on the prior arts. The fact that no such high RMFOM has been reached largely by the modulators in the prior arts indicate that the present invention is not presently obvious to those skilled in the art, as in majority of the optical modulator applications, high RMFOM is always desirable.

An additional embodiment of the present invention is the compatibility of the modulators with electronic-photonic (EPIC) integrated circuit platform based on silicon-on-insulator (SOI) substrate. This embodiment is for the purpose of illustration and not limitation. For example, other types of substrate such as Gallium Arsenide (GaAs) and Indium Phosphide (InP) can be used as long as the general structural requirements of the modulator in the present invention are met.

In one aspect of the present invention, the low “mode energy to active EO material overlapping factor” or simply called the “mode-medium overlapping factor”, with the quantum wells in the prior art is overcome by employing substantially thinner waveguiding layer with substantially higher refractive-index contrast between the waveguide core and cladding in the vertical direction (direction perpendicular to the substrate). This is achieved, for example, by eliminating the top and bottom metal contact enabling the thicknesses of the top and bottom cladding layers to be reduced without causing optical loss due to metal by replacing the usual metal contact with a Low-Refractive-Index Ohmic transparent conducting (LRI-OTC) material that has low optical refractive index to serve as the low-resistance electrical contact to the P-doped or N-doped semiconductor.

Normally, such thin waveguiding layer can increase the device insertion loss as it is hard to couple light into the layer optically, especially from an optical fiber. The present invention overcomes the disadvantage and can achieve the high device efficiency (have low power consumption or small device size or low device optical insertion loss). The present invention achieves this by employing an efficient optical beam mode coupling structure to couple light between an input/output transparent waveguide to the waveguide containing the active gain/absorption medium (called up/down coupler).

In another aspect of the present invention, the up/down coupler is has low alignment

sensitivity.

In another aspect of the present invention, the low-refractive-index Ohmic transparent conducting (TCO) material is capable of achieving "Ohmic contact" by having an electron work function reasonably matched to a P-type or N-type semiconductor adjacent to the TCO material.

5 In another aspect of the present invention, the Low-Refractive-Index Ohmic transparent conducting material is a transparent conducting oxide (TCO) or large bandgap semiconductor with Fermi level reasonably matched to a P-type or N-type semiconductor next to it so that Ohmic contact can be achieved between the TCO and the P-type or N-type semiconductor layer.

10 In as yet another aspect of the present invention, the low-refractive-index Ohmic transparent conducting oxide for N-side Ohmic contact is Indium Oxide (InO), Indium Tin Oxide (ITO), Zinc Oxide (ZnO), Zinc Indium Tin Oxide (ZITO), Gallium Indium Oxide (GIO), Gallium Indium Tin Oxide (GITO), and Cadmium Oxide (CdO) or materials containing any one or more than one of these oxides.

15 In as yet another aspect of the present invention, the low-refractive-index Ohmic transparent conducting oxide for P-side Ohmic contact is Indium Oxide (InO), Indium Tin Oxide (ITO), Zinc Oxide (ZnO), Zinc Indium Tin Oxide (ZITO), Gallium Indium Oxide (GIO), Gallium Indium Tin Oxide (GITO), and Cadmium Oxide (CdO), or materials containing any one or more than one of these oxides.

20 In as yet another aspect of the present invention, the low mode-medium overlapping factor of the prior art with the quantum wells is overcome by using a side conduction structure for the top metal contact to the top P-doped or N-doped semiconductor.

25 In another aspect of the present invention, the difference between the refractive index in the waveguide cladding and refractive index in the waveguide core is in the very-strongly to medium-strongly waveguiding region for waveguide confinement in the direction perpendicular to the substrate.

In another aspect of the present invention, the difference between the refractive index in the waveguide cladding and refractive index in the waveguide core is in the weakly waveguiding region for waveguide confinement in the direction perpendicular to the substrate.

30 In another aspect of the present invention, the thickness of the central waveguide core in the active layer structure (ALS) called the electro-active waveguiding core is either in the ultra-thin or very-thin regime.

In another aspect of the present invention, the thickness of the central waveguide core in

the active layer structure (ALS) called the electro-active waveguiding core is either in the ultra-thin, very-thin, or medium-thin regime.

In another aspect of the present invention, the thickness of the central waveguide core in the active layer structure (ALS) called the electro-active waveguiding core is in the thin regime.

5 In another aspect of the present invention, the electro-active waveguiding structure shall be in the very-strongly guiding regime, and the thickness of the electro-active waveguiding core shall either be in the ultra-thin regime or very-thin regime.

10 In another aspect of the present invention, the electro-active waveguiding core structure shall be in the medium-strongly guiding or very-strongly guiding regime, and the thickness of the electro-active waveguiding core shall either be in the ultra-thin regime, very-thin regime, or medium-thin regime.

In another aspect of the present invention, the electro-active waveguiding core structure shall be in the weakly guiding regime, and the thickness of the electro-active waveguiding core shall either be in the ultra-thin, very-thin, medium-thin, or thin regime.

15 In as yet another aspect of the present invention, the contact made by the low-refractive-index Ohmic transparent conducting material is preferably to N-doped semiconductor at both top and bottom part of the device structure, as N-doped semiconductor has lower electrical resistance than P-doped semiconductor and also has low optical absorption loss than P-doped semiconductor.

20 In as yet another aspect of the present invention, only one of the top and bottom contacts employs contact via low-refractive-index Ohmic transparent conducting material.

In as yet another aspect of the present invention, a pair of doped thin P-N layers serves as a hole-to-electron PN-changing PN junction or PN tunnel junction so as to change the metal contact with P-doped semiconductor to a metal contact with N-doped semiconductor, which  
25 enables drastic reduction in the Ohmic contact resistance as N-doped semiconductor is easier to achieve low Ohmic contact resistance.

In as yet another aspect of the present invention, the low mode-medium overlapping factor of the prior art with the quantum wells is overcome by using a side conduction structure for the top metal contact to the top P-doped or N-doped semiconductor. The side conduction  
30 geometry enables the waveguiding layer to be thin giving high mode-medium overlapping factor and yet maintaining low optical loss as the optical beam energy will not touch the optically lossy metal that is already moved to the side. Often the top cladding in such thin waveguide structure

can be made to be either air or some low-refractive-index dielectric material. In as yet another aspect of the present invention, the metal is deposited on both sides of the contact with as large an area as possible to reduce the Ohmic contact resistance. The side conducting layer is highly doped to reduce side conduction resistance but not so highly doped as to cause excessive optical absorption loss due to free carriers.

In as yet another aspect of the present invention, the top side conduction structure is preferably N-doped semiconductor with lower electrical resistance than P-doped semiconductor and also has low optical absorption loss than P-doped semiconductor.

In as yet another aspect of the present invention, the low mode-medium overlapping factor of the prior art with the quantum wells is overcome by using a side conduction structure for the bottom metal contact to the bottom P-doped or N-doped semiconductor. The side conduction geometry enables the waveguiding layer to be thin giving high mode-medium overlapping factor and yet maintaining low optical loss as the optical beam energy will not touch the optically lossy metal that is already moved to the side. Often the bottom cladding in such thin waveguide structure can be made to be either air or some low-refractive-index dielectric material.

In as yet another aspect of the present invention, the bottom side conduction structure is preferably N-doped semiconductor with lower electrical resistance than P-doped semiconductor and also has low optical absorption loss than P-doped semiconductor.

In as yet another aspect of the present invention, both the top and bottom side conduction structure is preferably N-doped semiconductor with lower electrical resistance than P-doped semiconductor and also has low optical absorption loss than P-doped semiconductor.

In as yet another aspect of the present invention, only one of the top and bottom contacts employs side conduction structure.

In as yet another aspect of the present invention, the side conduction structure includes a top transparent dielectric region over which and on both sides are deposited with metal for mechanical robustness.

In as yet another aspect of the present invention, a top transparent dielectric region acts as a lateral confining rib waveguiding structure.

In as yet another aspect of the present invention, a bottom transparent dielectric region acts as a lateral confining rib waveguiding structure.

In as yet another aspect of the present invention, a center dielectric region acts as a lateral confining rib waveguiding structure.

In as yet another aspect of the present invention, a wide top contact region acts to reduce the device contact resistance and conduction resistance, and together with the top metal side contact structure, acts to increase the optical mode energy overlapping with the active medium.

5 In as yet another aspect of the present invention, a waveguiding structure acts to propagate the optical beam into the modulator structure and avoid the extension of the highly doped quantum wells or bulk material to the transparent waveguiding region, thereby reducing the beam propagation length through the quantum wells or bulk material region that has high optical absorption. This reduces the total optical beam absorption loss through the modulator device.

10 In as yet another aspect of the present invention, the waveguiding structure tapers down to a width smaller than a wavelength in the waveguiding material so as to strongly push the mode away from the lower transparent waveguiding structure towards the quantum wells or bulk material, thereby increasing the optical mode energy overlapping with the quantum wells or bulk material.

15 In another aspect of the present invention, the refractive index change in the beam area required to achieve optical modulation is altered by depleting carrier from or injecting carrier to the N-doped or P-doped active region and alter the optical transition energy edge. This leads to a change in the smallest energy in which optical transition can take place. This change in the smallest energy in which optical transition can take place alters the refractive index of the medium.

20 In one aspect of the present invention, this carrier depletion or injection is from or to one or more quantum wells in the waveguiding beam energy area.

In one aspect of the present invention, this carrier depletion or injection is from or to bulk semiconductor material in the waveguiding beam energy area.

25 In another aspect of the present invention, the active medium is made up of compound semiconductor in which the material composition is chosen to result in an energy bandgap reasonably close to the optical wavelength of operation to result in high enough refractive index change due to band filling.

30 In another aspect of the present invention, the energy bandgap of the active medium is less than 30% of the photon energy away from the photon energy of operation to result in high enough refractive index change.

In as yet another aspect of the present invention, the active modulator active material (ACM) can be formed by non III-V materials such as silicon-germanium (SiGe) quantum wells or

SiGe bulk materials.

In as yet another aspect of the present invention, the active medium (ACM) has high-level doped carrier density with P-type or N-type doping and a doping density higher than  $2 \times 10^{17}/\text{cm}^3$  and lower than  $5 \times 10^{17}/\text{cm}^3$  primarily but not exclusively for low modulation voltage  $V_{\text{MOD}}$  or low modulation RF power  $P_{\text{MOD}}$  (low means  $V_{\text{MOD}} < 1.75\text{V}$  or  $P_{\text{MOD}} < 60\text{mW}$ ), and low-loss high-frequency modulator applications. Typically  $V_{\text{MOD}}$  and  $P_{\text{MOD}}$  are approximately related by the  $R_{\text{LOAD}}$  transmission line resistance or load resistance:  $P_{\text{MOD}} = V_{\text{MOD}}^2 / R_{\text{LOAD}}$ . In an exemplary embodiment,  $R_{\text{LOAD}}$  is around 50 Ohms.

In as yet another aspect of the present invention, the quantum wells have medium-high-level doped carrier density with P-type or N-type doping and a doping density higher than or equal to  $5 \times 10^{17}/\text{cm}^3$  and lower than  $1.5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for medium-low modulation voltage  $V_{\text{MOD}}$  or medium-low modulation RF power  $P_{\text{MOD}}$  (medium-low means  $V_{\text{MOD}} < 1\text{V}$  or  $P_{\text{MOD}} < 20\text{mW}$ ), and low-loss high-frequency modulator applications.

In as yet another aspect of the present invention, the quantum wells have very-high-level doped carrier density with P-type or N-type doping and a doping density higher than or equal to  $1.5 \times 10^{18}/\text{cm}^3$  and lower than  $5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for very-low modulation voltage  $V_{\text{MOD}}$  or very-low modulation RF power  $P_{\text{MOD}}$  (low means  $V_{\text{MOD}} < 0.6\text{V}$  or  $P_{\text{RF}} < 7\text{mW}$ ), and low-loss high-frequency modulator applications.

In as yet another aspect of the present invention, the quantum wells have ultra-high-level doped carrier density with P-type or N-type doping and a doping density higher than or equal to  $5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for ultra-low modulation voltage  $V_{\text{MOD}}$  or ultra-low modulation RF power  $P_{\text{MOD}}$  (ultra-low means  $V_{\text{MOD}} < 0.3\text{V}$  or  $P_{\text{MOD}} < 2\text{mW}$ ), and low-loss high-frequency modulator applications.

In as yet another aspect of the present invention, the quantum wells can be strained, unstrained, double-well, or multi-well quantum wells.

As an exemplary embodiment, the low voltage/power case can achieve a  $\text{RMFOM} > 0.05$  and the ultra-low voltage/power case can achieve a  $\text{RMFOM} > 2.5$ , while the prior art can only achieve a  $\text{RMFOM} < 0.005$ .

## BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments of the invention will hereinafter be described in conjunction with the appended drawings provided to illustrate and not to limit the invention, wherein like designations denote like elements, and in which:

5 Fig. 1a is a diagram illustrating the case for which the electron carriers fill up the conduction band, leading to a shift in the absorption energy from close to the bandgap energy  $E_g$  to larger than the bandgap energy  $E_g + \Delta E$  (or in wavelength  $\lambda \rightarrow \Delta \lambda$ );

Fig. 1b is a diagram showing a change in the “absorption energy edge” from absorption curve  $\alpha_{E_g}(\lambda)$  to  $\alpha_{E_g + \Delta E}(\lambda)$  leads to a change in the refractive index of the material  $\Delta n(\lambda)$ .

10 FIG. 2 is a diagram showing an electro-optic (EO) modulator of prior art. In particular a modulator made of III-V compound semiconductor material.

FIG. 3 is a diagram illustrating the cross-section of the PIN modulator structure.

FIG. 4a is a diagram showing the location of the “modulator input beam coupler structure (IBCS)”, the “Active Layer structure (ALS)”, and the “modulator output beam coupler structure  
15 (OBCS)”

FIG. 4b is an exemplary schematic for a cross-section of the input waveguide region. The region occupied by the optical beam (OB) is shown as a shaded region.

Fig. 4c is an exemplary schematic for a cross-section of IBCS region or OBCS region. The region occupied by the optical beam (OB) is shown as a shaded region.

20 FIG. 4d is an exemplary schematic for a cross-section of ALS region showing the active material (ACM) layer, the electro-active layer (ECL), and the waveguiding layers. The region occupied by the optical beam (OB) is shown as a shaded region.

FIG. 5a is a diagram showing a pair of capacitively-loaded traveling wave electrodes.

25 FIG. 5b is a diagram showing the cross-section d—d' in Fig.5a, illustrating that the bottom parts of the two phase modulators are connected.

FIG. 6a is a diagram showing equivalent lumped-element circuit of a pair of capacitively-loaded traveling wave electrodes (CL-TWE) powering the two phase modulators along the two arm of the Mach Zehnder Interferometer.

30 FIG. 6b is a diagram showing the top view of the CL-TWE lines for the traveling wave electrodes.

FIG. 7a/b is a diagram illustrating how the beam from the SOI waveguide is coupled into the thin-film modulator structure using two tapers

FIG. 8a is a diagram showing the cross-section for the side-conduction-layer (SCL) case.

FIG. 8b is a diagram showing the cross-section for the Ohmic Transparent Conductor (OmTC) case.

FIG. 9 is a diagram showing the details structures for an exemplary NIN modulator.

5           FIG. 10 is a diagram showing the details structures for an exemplary NPNN modulator.

FIG. 11 is a diagram showing the modulation BW for the NIN case with 2- $\mu\text{m}$ -wide active region so  $w_{\text{CAP}}=2\mu\text{m}$ .

10           FIG. 12 shows the modulation bandwidth for the NPNN case with 2- $\mu\text{m}$ -wide active region so  $w_{\text{CAP}}=2\mu\text{m}$ .

FIG. 13 is a diagram illustrating a general geometry of the **EO Modulator** of the present invention. **Fig. 13b** is a semi-transparent illustration of **Fig. 13a**.

FIG. 14 shows a diagram illustrating that material surrounding the input connecting waveguide core.

15           FIG. 15 shows a diagram illustrating the input beam coupler structure (IBCS). **Figs. 15a** show the input beam coupler structure (IBCS) comprises at least a tapering waveguide section generally tapering from wide to narrow. Optionally, the active layer structure ALS on top of the input tapering waveguide section can also be tapering in the form of an up taper (tapering from narrow to wide in the direction toward the active layer structure ALS). See for example **Fig. 15b**.

20           FIG. 16 shows a diagram illustrating a few exemplary cases for the top metal contact pad placements.

FIG. 17 shows a diagram illustrating a particular exemplary embodiment of aelectro-active waveguiding core structure EWCoS 22600.

25           FIG. 18 shows a diagram illustrating the output connecting waveguide structure.

FIG. 19 shows a diagram illustrating the division of the output connecting waveguide cladding into four different regions.

FIG. 20 shows a diagram illustrating the output beam coupler structure (OBCS)

FIG. 21 shows a diagram illustrating the electro-active layer (ECL).

30           FIG. 22a shows a diagram illustrating the structure around the PqN, NqN, or PN junction.

FIG. 22b shows a diagram illustrating the structure around the PqN, NqN, or PN junction with PN changing PN junction.

FIG. 23 shows a diagram illustrating an alternative structure involved having the metal Ohmic contact on the side away from the center region of layer TVSCOC 21700.

FIG. 24 shows a diagram illustrating an alternative structure involved having the “top lateral conduction geometry with metal contact” but also a lowloss dielectric material as layer 21810.

FIG. 25 shows a diagram illustrating an alternative structure for which the metal can even go on top of the top lowloss dielectric material region TDMR 21810 to make this top lateral conduction structure mechanically robust.

FIG. 26 shows a diagram illustrating an alternative structure with low capacitance but also low optical loss for example by using the top vertical/side conduction and Ohmic contact layer TVSCOC 21700 to confine the mode laterally.

Skilled artisans will appreciate that the elements in the figures are illustrated for simplicity and clarity, and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated, relative to the other elements, to help in improving understanding of the embodiments of the present invention.

## DETAILED DESCRIPTION

### Motivations of the present invention

There are various needs for ultra-low-RF-power ultra-wide-RF-bandwidth low-optical-loss high-optical-power modulators for various applications. Certain exemplary modulators employing exemplary embodiments of the present invention are capable of either Ultra Low Voltage, Ultra-High Modulation Bandwidth, Low Optical Loss, or High Optical Power, or a plurality of the above. In addition, they are generally ultra-compact, can be integrated with semiconductor laser, and can be made based on mass-producible silicon-photonics platform with EPIC (electronic-photonics integrated circuit) capability enabling future expansions to integrate with RF circuits or other photonic devices on chip.

### Needs for Compact Wide-Bandwidth Low-Power Low-Loss Modulators

New applications in communications and sensing require transmission of high-frequency electronic signals. Transmission of ultra-fast digital data over optical fiber system is also

important for next generation data centers. In order to address such needs, optical phase or intensity modulators that are capable of low switching voltage (lower than 0.5 to 1V), broad RF bandwidth (BW) (higher than 20GHz; preferably over 100GHz), low device optical power loss (preferably <6dB), and capable of withstanding optical powers of a few hundred milliWatts would be desirable. Prior arts in EO modulators are not able to realize such modulators. For example, the commonly available Lithium Niobate modulators in the market can go up to 40-100GHz but cannot reach low enough modulation voltage of below 1V. Polymer modulators could give broader bandwidth of over 100GHz but still have high switching voltages. Also they cannot withstand high optical powers. Semiconductor based modulators have various advantages in terms of their smaller size and shorter physical length but they are not yet able to give modulation voltage lower than 1V, broad modulation bandwidth higher than 20GHz, and low device optical throughput loss smaller than 6dB concurrently.

Exemplary embodiments of the present invention described below will utilize a few key factors combined to fully address the abovementioned problems resulting in low modulation voltage and wide modulation bandwidth concurrently. In some preferred embodiments, the resulting modulator also has short physical device length and low optical loss.

### **Broad Overview of the Present Invention**

An optical modulator device can be divided into a few key components composing the modulator. An input optical beam must be channeled to the modulator's active material medium (ACM) efficiently without too much loss of the beam's optical power. In conventional EO modulator, this is just done by joining input waveguide to the modulator waveguide. In the EO modulator of the present invention, due to the small optical mode in the modulator, in one exemplary embodiment, this input structure is an integral part of the modulator of the present invention. We call this the "modulator input beam coupler structure (IBCS)". A diagram illustrating such IBCS is shown in Fig. 4. An exemplary schematic for a cross-section of the input waveguide region is shown by Fig. 4b. An exemplary schematic for a cross-section of such IBCS region is shown by Fig. 4c. The region occupied by the optical beam (OB) in Fig. 4b and Fig. 4c is shown as a shaded region.

The modulator input beam coupler structure brings the optical beam from a waveguide into the modulator's main waveguide that contains the active electro-optic (EO) material or electro-absorption (EA) material. An active EO (or EA) material is a material whose refractive index (or absorption or gain) can be altered by an applied electric field or an electrical current. Such EO or EA

material will be called collectively as active material or medium (ACM). The active medium is typically embedded as part of the active layer structure (ALS) of the modulator. An exemplary schematic for such ALS is shown by Fig. 4d. The active medium (ACM) plus the immediately connected structure next to it for applying the required electric field or introducing the required current is called the electro-active layer (ECL). An exemplary schematic for such ECL is shown by Fig. 4d.

In addition, a more extensive electrical conduction structure is integrated with the electro-active layer and a waveguiding structure so that an electric field or electrical current can be brought into the electro-active layer encompassing the active material, and at the same time the waveguiding structure will guide an optical beam so that part of its beam power overlaps with the EO/EA material. This enables the optical beam to experience the change in phase shift induced by a change in the refractive index in the EO material layer or a change in the optical absorption (or in some cases optical gain) in the EA material layer.

A most commonly used structure immediately connected to and next to the active material for applying the required electric field or introducing the required current is a PIN structure, meaning that the electrical conduction to the active material is with a P-doped semiconductor followed by an intrinsic ("I") semiconductor, and then followed by another N-doped semiconductor. An exemplary schematic for such PIN structure is shown by Fig. 4d. The active medium is typically in the I layer but can also be in any of the P or N layer, including the transition region between the I and any of the P and N layer, or in plurality of these layers. The active medium can be the layer itself, or a quantum-well structure, or other active-medium structure embedded in the layer. Most commonly, the active material is quantum wells in the intrinsic layer. Most EO and EA modulators with such PIN structure and quantum wells in the intrinsic layer as the electro-active layer operates under a reverse bias to such a PIN structure (with negative voltage applied to P side and positive voltage applied to the N side). Reverse bias will not bring in much current to the active material but will bring in a strong electric field to the active material. The electric field acting on the quantum well then changes its refractive index or absorption at the beam's optical wavelength. In some situation, a modulator can operate with gain and a forward bias can be applied to such PIN structure (with positive voltage applied to P side and negative voltage applied to the N side). Forward bias brings a strong injection current to the active material. The electrical current exciting the carriers in the quantum well then changes its refractive index or gain (or absorption) at the beam's optical wavelength. Typically, modulator based on forward bias

has a slow turning off characteristics due to the slow nanosecond decay of excited carriers in the active medium after the voltage is turned off. Hence, typically the reverse bias case will give rise to much faster modulation speed than the forward bias case.

For modulators with, for example PIN junction or the like, the Electro-Active layer (ECL) will be the EO/EA material and the immediate P and N doped regions or the like. An exemplary schematic for such ECL with a PIN structure and the EO/EA active material (ACM) layer is shown by Fig. 4d.

The entire larger structure is called the active layer structure (or ALS) below. In short, the entire structure comprising: (1) the waveguiding layers; (2) the electro-Active layers; and (3) the other electrical conduction layers, is called the active layer structure (ALS) of the modulator in the present invention. An exemplary schematic for such ALS is shown by Fig. 4d. In many situations, part of the Electro-Active layer or part of the other electrical conduction layers also serve the double function as part of the waveguiding layers. Thus, each these layers often by itself, serves as multiple-function layer.

The optical waveguide in the ALS is called active waveguide, so as to distinguish it from the input and output waveguides that have no active EO/EA material. In another exemplary embodiment, the present invention is concerning on the specific structure of the active layer structure independent of the input and output mode coupling structures. The location of such ALS layer is shown in Fig. 4.

At the output, we have a “modulator output beam coupler structure (OBCS)” that couples the optical beam efficiently from the modulator active layer structure into a primarily passive output optical waveguide. Passive in this context means the waveguide acts primarily to transmit the optical beam energy. Primarily passive means it can also be active (e.g. with optical gain, absorption, or modulation) but for the purpose of this invention, the passive beam transmission function is the function utilized. In as yet another exemplary embodiment, this output structure is an integral part of the modulator of the present invention. The location of such OBCS is shown in Fig. 4. The cross section of OBCS is similar to that of IBCS. An exemplary schematic for a cross-section of such OBCS region is shown by Fig. 4c. The region occupied by the optical beam (OB) is shown as a shaded region.

For the purpose of illustration but not limitation, it is useful to provide an overview of an exemplary modulator device employing the present invention. The Active-Layer Structure in an exemplary EO modulator of the present invention could make use of up to six main key elements,

namely: (1) The use of an efficient coupling waveguide platform (EC-WG); (2) Low-Optical-Loss Ohmic Contact (LOL-OC), such as the use of transparent conductor and side conduction geometry, (3) Low-Optical-Loss and High Electrical Conductivity Waveguide Structure (LOL-HEC-WS) such as the use of PN-changing PN junction or PN tunnel junction to reduce the region with P-doping, (4) High-Response Active Material, such as material that has high EO or EA response under applied voltage, an electric current, or either injection or depletion of carriers (HR-AM); in an exemplary embodiment of the present invention, this is achieved with appropriately high carrier doping in quantum wells, and (5) Highly-Confined Thin-Film Electro-Active Waveguide (TF-ECW), so as to increase the amount of overlapping between the optical mode energy and the active material.

To summarize these few advantages, the modulators of the present invention encompass one or more of the above five main key elements, including the advantages in Beam input/output Coupling Waveguide, Ohmic Contact, Waveguide Conductive Structure, Active Layer, and Strongly Confined Thin-Film Active Waveguide. For general references, optoelectronic or photonic device structures that take advantage of a few of the above five main factors will be generally referred to as **WOCAT** device structures. While the WOCAT structure here is applied to optical phase and intensity modulators, it has applications beyond optical modulators such as applications to optical amplifier, photodetector, laser, light-emitting device, optical switching and logic device, and optical signal processing device.

As an exemplary embodiment, for the purpose of illustration and not limitation, the EO Modulators of the present invention are capable of achieving the significant advantages of ultra-low-voltage (<0.5V typical), broad RF bandwidth (20-100GHz), low optical loss (<6dB), short device length (<1mm), or high optical power (>100mW), or a plurality of the above. As an exemplary illustration but not limitation, such a modulator could make use of one or more of the following few key factors in its structure.

#### **Key Factor I: Low Voltage via Strong Mode Confinement**

For the purpose of discussion and not limitation, for an operating optical wavelength of 1550nm, an exemplary approach will be based on InP/InAlGaAs material system (called simply as InP/III-V). When used as 1550nm EO modulation material, the InP/III-V material system will involve quantum wells (QWs) at 1300-1400nm wavelength range that is close enough to the 1550nm operation wavelength to give high EO phase shift, but is still far away from 1550nm so

that optical carrier excitation will be low enabling high optical power ( $>100\text{mW}$ ). This will result in a high maximum optical power or high MP value (used in the Modulator Figure of Merits: MFOM). When used as  $1550\text{nm}$  EA modulation material, the InP/III-V material system will involve quantum wells (QWs) at  $1400\text{-}1550\text{nm}$  wavelength range that is close enough to the  
5  $1550\text{nm}$  operation wavelength to give high electro-absorption, and in some cases, optical gain (both absorption and gain can be used to modulate the intensity of an optical beam). However in that case, the MP value will be smaller due to the optical beam energy being absorbed and saturating the absorbing quantum well, thereby reducing the amount of optical modulation due to electro-absorption, when the optical beam power is high.

10 In order to achieve very low modulation voltage, one way is to make the optical mode confinement a lot tighter so as to drastically reduce the effective distance between the voltage-applying electrodes. This will enable the same electric field strength to be achieved with proportionally lower applied voltage (assuming the mode-medium overlapping factor is near 100% and cannot be increased further). If the mode-medium overlapping factor is small, then a  
15 stronger mode confinement giving a small mode size will increase the overlapping, which will also increase the modulation phase shift or absorption even with the same electric field strength. In either case, the voltage is lower due either to higher electric field or higher mode-medium overlap.

For a conventional semiconductor EO or EA modulator, the vertical mode size (FWHM)  
20 is about  $0.5\mu\text{m}$  to  $1\mu\text{m}$ . With high-refractive-index-contrast material using semiconductor with high refractive index ( $n\sim 3$  to  $4$ ) as the waveguide core surrounded by air, dielectric material, or polymer with low refractive index of  $n\sim 1$  to  $2$  as waveguide cladding, it is possible to reduce the vertical mode size by about 2.5 times to 10 times to  $\sim 0.1\text{-}0.2\mu\text{m}$  (at  $\lambda=1550\text{nm}$ ). For example, using the high refractive index of III-V semiconductor with  $n\sim 3.5$  as the waveguide core and air  
25 as cladding will result in a single-mode strongly confined waveguide physical height of about  $0.2\mu\text{m}$ , given by  $d_{\text{SM}}\sim \lambda/(2n)=1500\text{nm}/(2*3.5)=0.214\mu\text{m}$ . This gives a vertical mode size of  $\sim 0.1\mu\text{m}$ , which is a 5 to 10 times reduction in mode size or 5 to 10 times increase in the mode-medium overlapping factor. Suppose other factors remain the same, the modulation voltage is inversely proportional to the mode-medium overlapping factor. Thus, the 5 to 10 times higher  
30 mode-medium overlapping factor will reduce the modulation voltage by 5 to 10 times, and the  $5\text{V}$  modulation voltage of a typical conventional modulator structure can be reduced to below  $1\text{ volt}$  with use of the modulator structure of the present invention that has a strong mode confinement.

For the purpose of illustrations and not limitations, unless otherwise stated, all the dimensional numbers such as mode size and structural sizes given in this invention assume that the operating optical wavelength is around the wavelength of 1550nm. As is well known to those skilled in the arts, all these dimensions will scale proportionally when operating at other  
5 wavelength so that if the operating wavelength is at around 750nm, all the physical dimensions will be about half of that given for the 1550nm wavelength case. This invention is applicable to all other wavelengths and is not limited to the exemplary operating wavelength of 1550nm.

### **Key Factor II: Efficient Coupling into Strongly-Confined Waveguide**

10 In the present invention, the vertical mode confinement is reduced to  $<0.2\text{-}0.3\mu\text{m}$ . A challenge is how to achieve efficient optical beam coupling to the sub-micrometer waveguide. We will solve this problem using tapered waveguide that can be fabricated on a substrate and the ALS thin film on top of it can be attached via wafer bonding method or other methods after the waveguide is fabricated. Such tapered waveguide coupling structure can achieve over 90-95%  
15 optical power coupling efficiency.

### **Key Factor III: High Modulation Bandwidth via Low Ohmic Contact Resistance & Low-Optical-Loss High-Conductivity Waveguide Structure; and High Modulation Bandwidth via Enhanced EO Response**

20 To enable electrical current injection and voltage conduction into the modulator device with strong optical mode confinement, as an exemplary embodiment in the present invention, a **transparent conducting (TC)** material that has low refractive index and yet can achieve excellent Ohmic contact with N-doped InP semiconductor material with very low contact resistance is used. We call these **Ohmic Transparent Conducting (OmTC)** materials. These TC  
25 materials are typically metal oxides ( $\text{In}_2\text{O}_3$ , ZnO, InSnO, CdO, ZnInSnO, InGaO, etc) or doped metal oxides (e.g, the above listed metal oxides doped with magnesium Mg or zinc Zn etc), the most familiar one is ITO (Indium Tin Oxide; InSnO) used widely in LCD display. They are called transparent conducting oxides (TCO). For example, with appropriate processes, it is possible to achieve good Ohmic contact between  $\text{In}_2\text{O}_3$  or CdO and N-doped InP. We will call  
30 these **Ohmic TCO (OmTCO)**. OmTCO will enable robust electrical structures to be realized that also has high mode confinement.

Alternatively, we can use a side conduction layer (SCL) to bring the voltage into the top

layer for the low voltage modulators. The side conduction geometry enables the waveguiding layer to be thin giving high mode-medium overlapping factor and yet maintaining low optical loss as the optical beam energy will not touch the optically lossy metal that is already moved to the side. Often the top cladding in such thin waveguide structure can be made to be either air or some low-refractive-index dielectric material.

Both OmTCO or SCL can be used for the top contact. When the structure is thin, comparing to SCL the use of OmTCO for top contact has an advantage in terms of ease in fabrication and also potentially better device performances as the metal contact area can be larger.

However, solving electrical conduction is only half of the matter. The modulation speed of a conventional semiconductor EO or EA modulator is about 20-40GHz. It is desirable to reach 100GHz with voltage <1V. How can one do so? It turns out that the high contact resistance for the p-doped material with metal, that is the high P-Ohmic contact resistance with metal, is a main problem that limits higher modulation frequency. P-Ohmic contact typically has 10 times higher resistance than N-Ohmic contact (with their respective appropriate Ohmic-contact metals that can give reasonably low contact resistance).

We note that at the same dopant density, the P-doped cladding layer typically also has about 10 times higher resistance than if it is N-doped. While the cladding resistance is typically smaller than the P-Ohmic contact resistance especially since the active-layer structure is thin, the P-doped cladding can cause radio-frequency (RF) loss when a high-frequency modulating voltage pulse (or electrical signal) propagates along the modulator structure. In terms of free-carrier optical absorption, at the same dopant density, the P-doped cladding layer is also about 10 times higher than N-doped. If one reduces the P-doped cladding resistance by increasing the carrier doping density, one will also increase the optical loss, making it hard to achieve the long modulator length needed for low voltage, giving a trade-off between low voltage (need low doping density) and high frequency (need high doping density).

To gain higher electrical modulating frequency response for the modulator, it is important to reduce the P-Ohmic contact and cladding resistance by changing them to N-contact and N-doped cladding instead. A few exemplary structures can do so. These structures are broadly classified as alternative Electro-Active Layer Structure A, B, C, and D discussed below.

#### **Alternative Electro-Active Layer Structure A: NIN Structure**

Besides the usual PIN structure noted above that can be used as the electro-active layer

structure in the ALS, there are other alternative electro-active layer in the ALS structures that may have certain advantages. First is the use of an NIN electro-active layer in the ALS structure, meaning that the electrical conduction to the active medium is with an N-doped semiconductor followed by an intrinsic ("I") semiconductor, and then followed by another N-doped semiconductor. The active medium is typically in the I layer but can also be in any of the two N layers, including the transition region between the I and any of the two N layers, or in plurality of these layers. The active medium can be the layer itself, or a quantum-well structure, or other active-medium structure embedded in the electro-active layer.

In the situation whereby the modulator devices in the present invention requires largely only electric field to be applied to the active medium to affect the refractive index or optical absorption (or optical gain) of the active medium, it is appropriate to use such a NIN structure as the active layer.

Comparing to the use of the conventional PIN structure, such NIN structure will reduce the Ohmic contact resistance by 10 times as both sides of the metal contacts will be contacting to N-doped layers only. Note that in NIN, sometime a thin P-doped layer is introduced so that it forms NPIN, where the P-layer helps to block the electric current. the "NIN" here broadly includes NPIN. For NPIN case, a positive voltage applied to the N layer of the NP side will cause reverse bias at the NP junction and hence cut off any current flow (PIN side becomes forward bias). A positive voltage applied to the N layer of the PIN side will cause reverse bias at the PIN junction and hence also cut off any current flow. This reverse bias to the PIN junction case is normally preferred as it will mimic the reversed bias to the conventional PIN structure case more closely with voltage drop mainly across the PIN part of the structure (instead of the NP part of the structure).

The NIN structure also reduces the RF-loss due to P-doped cladding by 5 to 10 times. This enables the maximum length of the modulator limited by RF-loss cutoff to reach a longer length of over 1cm (for 40GHz bandwidth). RF-loss is sensitive to the capacitance loading of the modulator. The capacitance is mainly determined by the lateral width of the "junction capacitance region", called modulator-capacitor lateral width (labeled as  $w_{CAP}$  or  $w_{EC}$ ) below. Lateral is in a direction perpendicular to the direction of optical beam propagation and parallel to the substrate surface.

For a modulator with a typical ~200nm thick active region that defines the "effective separation of the junction capacitor plates", the required modulator capacitor lateral width has to

be  $w_{EC} < 2\text{-}\mu\text{m}$  in order to reach  $\sim 40\text{GHz}$  BW for a 1cm-long modulator. At 100GHz, this RF-loss limited modulator length could be around 3-5mm (for the same 2- $\mu\text{m}$  modulator capacitor width).

The optical-absorption-loss limited length (at 2dB attenuation so as to keep the total loss less than 6dB) due to N-doped claddings in NIN can be made to reach longer than 0.5-1cm so that the length will not be limited by optical loss (because it has lower optical loss than P-doped). If we put in a QW structure that increases the nonlinear response by about 3 times from just the use of LEO, then the modulator length for such NIN structure can be  $\sim 1.5$  to 3mm for achieving 1V. If we then also reduce the modulator capacitor lateral width to 1 $\mu\text{m}$  or less (to increase the frequency response), combined with the shorter length for 1V, 100GHz and 1V can then be reached concurrently.

Both these alternative NIN and NPIN (and the conventional PIN) structures are good for modulator devices that operate under reverse bias, and are alternative exemplary embodiments for the modulators in the present invention. Other alternative variations include reverse biased NP'TN, N'P'IN, N'P'TN, NP'TN, P'TN, P'IN, P'TN, 'P'TN, or P'T'N structures; or PNIP, PN'TP, P'N'IP, P'N'TP, PN'TP or PIP, P'TP, 'P'TP, N'TN, 'N'TN structures; where quantum wells are placed in the 'P', 'N', and 'T' layers (those layers in inverted commas 'X').

#### **Alternative Electro-Active Layer Structure B: P'N'N Structure**

The PIN (or NIN, NPIN) structures, while attractive in some ways, are suffering from their relatively long device length of over 1mm, which will become challenging when one tries to reach very high frequency such as 100GHz as in that case the electrodes' RF velocity matching with the optical velocity will have to be good, which is potentially possible to engineer but will make manufacturing more complex and costly. It would be desirable to reduce the modulator length to a much shorter length. It is also desirable to achieve a lower voltage of  $< 0.5\text{V}$ . It turns out that it is possible to do so with use of the P'N'N structure described below.

Another exemplary embodiment of the active-layer structure in the modulator structure of the present invention makes use of a novel P'N'N structure with or without QWs. Again strongly confined waveguide is used to reduce the voltage by for example 5 times.

The use of P'N'N structure involves doped layers with or without QWs. Reverse bias is applied to the P'N'N junction (with positive voltage to the N side). The center 'N' layer is doped with or without QWs. The doping enables carrier band-filling and plasma effects to be used to increase the phase shift. It enables BF+PL and also QCSE effects to be used beside the LEO

effect. When properly designed, this enables the nonlinear EO response to be many times higher than that with the use of LEO plus the typical QW QCSE. For EA modulation, this enables the EA response to be many times higher than that with the use of the typical QW QCSE.

Basically as is known to those skilled in the art, there is a carrier depletion layer at the P<sup>+</sup>N<sup>-</sup> junction (the carrier depletion is in a direction perpendicular to the P<sup>+</sup>N<sup>-</sup> junction creating a small carrier-free region "D" resulting in PD<sup>+</sup>N<sup>-</sup> in terms of carrier density distribution where D is depleted of carriers). Under reverse bias, the width of the depletion region (D) will increase. This means the carrier band-filling in the D region is modified, resulting in a change in the refractive index (at long wavelength of 1550nm) due to BF effect. If quantum wells are placed in the D region, they will enhance the refractive index change due to BF. If quantum wells are used, there will be a change in the optical absorption also (at energy above the quantum wells' lowest energy level) due to band filling as well. When operating as EO modulator (i.e. based on the refractive index change), the operating wavelength will be at an energy way below the quantum wells' lowest energy level so the optical absorption or optical absorption modulation will be minimal, and the main optical modulation effect will be due to refractive index modulation.

Further optimizing the design of the QW structure and doping can push the electro-optic or electro-absorption response even higher, but a price to pay for the optimized P<sup>+</sup>N<sup>-</sup>N structure is higher optical loss, which restricts the length of the modulator to be shorter than 1.0mm. The higher EO or EA response, however, more than made up for the shorter length. A good design we have computed for the P<sup>+</sup>N<sup>-</sup>N+QW structure for EO response gives 1 Volt at 0.2 nm length and 50GHz bandwidth (at modulator-capacitor width of  $w_{EC}=0.7\mu m$ ). The length is shorter than the 50GHz RF wavelength, which is around 2mm. As a result, it reduces the RF-optical velocity matching requirement and makes it easier to fabricate and easier to reach 50GHz. It also opens up various exciting possibilities. For example, 0.25V is also achievable when a longer device length of less than 1.0mm is used.

This P<sup>+</sup>N<sup>-</sup>N modulator will be another exemplary embodiment of the active-layer structure for the modulators of the present invention. Other alternative variations include reverse biased P<sup>+</sup>P<sup>+</sup>N<sup>-</sup> structure (typically N doped is preferred for the middle layer for achieving lower optical loss but P doped is also possible). Other variations include 'P<sup>+</sup>'N<sup>-</sup>N or P<sup>+</sup>P<sup>+</sup>'N<sup>-</sup> in which quantum wells are placed in both the 'P<sup>+</sup>' and 'N<sup>-</sup>' layers.

**Alternative Electro-Active Layer Structure C: NP'N'N Structure**

The short device length advantage of the P'N'N structures can be combined with the lower optical loss and lower electrical contact resistance advantage of NPIN (or NIN) structures to give both low optical loss and high modulation, by utilizing a NP'N'N structure described below. The NPIN (or NIN) structure only requires N Ohmic contacts as the two other layers contacting the metal contacts are both N-doped. As no P Ohmic contact is needed, it will reduce the total electrical series resistance of the modulator structure substantially, leading to higher frequency response. The material layers with P-dopant will also be thinner or fewer, which will also reduce the free-carrier induced optical absorption loss and further reduce the electrical series resistance as well (P-doped layer typically has 10 times higher optical absorption and 10 times higher electrical resistance than N-doped layer with the same carrier doping density).

Another exemplary embodiment of the active-layer structure in the modulator structure of the present invention makes use of a novel NP'N'N structure with or without QWs. Again strongly confined waveguide is used to reduce the voltage by for example 5 times.

The quantum wells, if used, are typically in the 'N' layer but can also be in any of the N or P layers, including the transition region between the 'N' and any of the two P or N layer, or in plurality of these layers. The active medium can be one or more of the layers (N, or P, or 'N' layer), or the quantum-well structure, or other active-medium structure embedded in the electro-active layer, or a combination of effects from the quantum wells and one or more of the layers (N, or P, or 'N' layer).

The use of NP'N'N structure involves doped layers with or without QWs. Reverse bias is normally applied to the P'N' junction but with both sides being N contacts (with positive voltage on the N side of the P'N' junction). Thus the NP junction is forward biased. The center 'N' layer has doped layers with or without QWs. The doping enables carrier band-filling and plasma effects to be used to increase the phase shift. It enables BF+PL and also QCSE effects to be used beside the LEO effect. When properly designed, this enables the nonlinear EO response to be many times higher than that with the use of LEO plus the typical QW QCSE. For EA modulation, this enables the EA response to be many times higher than that with the use of the typical QW QCSE.

Further optimizing the design of the QW structure and doping can push the electro-optic or electro-absorption response even higher, but a price to pay for the optimized NP'N'N structure is higher optical loss, which restricts the length of the modulator to be shorter than 1.0mm. The higher EO or EA response, however, more than made up for the shorter length. A good design we

have computed for the NP'N'N +QW structure for EO response gives 1 Volt at 0.2 mm length and 100GHz bandwidth (at modulator-capacitor lateral width of  $w_{EC}=0.7\mu m$ ). The length is shorter than the 100GHz RF wavelength, which is around 1mm. As a result, it reduces the RF-optical velocity matching requirement and makes it easier to fabricate and easier to reach  
 5 100GHz. It also opens up various exciting possibilities. For example, 0.25V is also achievable when a longer device length of less than 1.0mm is used. In addition, it can achieve lower optical loss and lower electrical contact resistance than the P'N'N structure.

This NP'N'N modulator will be another exemplary embodiment of the active-layer structure for the modulators of the present invention. The NIN is simpler but the NP'N'N has  
 10 better low-voltage and high-frequency performances and also almost as low an optical loss and as low the electrical contact resistance as the NIN structure. Other alternative variations include reverse biased NP'P'N, structure (typically N doped for the 'X' layer is preferred for achieving lower optical loss but P doped is also possible).

Still other alternative variations include N'P'N'N, N'P'NN for which if QWs are used,  
 15 they will be in both the 'P' and 'N' layers. For N'P'N'N case, under reverse bias, the depletion width between the 'P'N' junction will widen and will sweep out carriers from the quantum wells in both the 'P' side and the 'N' side, resulting in twice the refractive index change than if the quantum wells are only in the 'N' layer such as in a NP'N'N structure.

Other alternative variations include reverse biased NP'P'N; or PNIP, PN'P'P, P'N'PP,  
 20 P'N'P'P, or PN'N'P structures; where quantum wells are placed in the 'P', 'N', and 'I' layers (those layers in inverted commas 'X').

#### **Alternative Electro-Active Layer Structure D: Forward biased NN(+P(+))PIN Structure**

In the forward biased case, the low-optical-loss and low-electrical-resistance advantages  
 25 of NIN structure may be achieved, by utilizing a NN(+P(+))PIN structure described below.

Another exemplary embodiment of the active-layer structure in the modulator structure of the present invention makes use of a novel NN(+P(+))PIN structure. Again strongly confined waveguide is used to reduce the voltage by for example 5 times.

The active medium is typically in the I layer but can also be in any of the N or P layer,  
 30 including the transition region between the I and any of the N or P layer, in the other doped N(+) or P(+) or N or P layer, or in plurality of these layers. The active medium can be the layer itself, or a quantum-well structure, or other active-medium structure embedded in the electro-active

layer.

Forward bias is normally applied to the PIN junction (with positive voltage on the P side of the PIN junction). In that case, the N(+)P(+) junction is formally under reverse biased, which normally would not have much current flow. However, as is known to those skilled in the art, when the N(+) and the P(+) layers are highly doped (typically at a doping density of higher than about  $1 \times 10^{18}/\text{cm}^3$  and preferably higher than  $1 \times 10^{19}/\text{cm}^3$  for both the N and P material, the carrier can actually tunnel through under the reverse bias, resulting in current flow through the N(+)P(+) junction, into the PIN junction area that is forward biased. In that case, the N(+)P(+) junction is normally referred to as a carrier tunneling junction (or simply as tunnel junction). Such tunnel junction can be very thin with the N(+) and P(+) layer only tens of nanometers in thickness each. The net result is the changing of the P Ohmic contact at layer P to N Ohmic contact at layer N of the NN(+) side. As noted above, N Ohmic contact generally has a much lower (10 times lower) contact resistance than P Ohmic contact. The use of such pair of N(+)P(+) tunnel junction layers thus enables one to have N Ohmic contacts on both sides of the device. This structure also works if only electric field is wanted at the active medium (i.e. with PIN junction under reverse bias).

This NN(+)P(+)PIN structure will be another exemplary embodiment of the active-layer structure for the devices of the present invention. Other alternative variations include NN(+)P(+)IN, N(+)P(+)PIN, N(+)P(+)IN structures and the likes or with some doping in the active-medium layer typically in the intrinsic layer resulting in NN(+)P(+)P'N'N, NN(+)P(+)P'N'N, NN(+)P(+)N'N, N(+)P(+)P'N'N, N(+)P(+)P'N'N, N(+)P(+)N'N, NN(+)P(+)P'P'N, NN(+)P(+)P'N, N(+)P(+)P'P'N, or N(+)P(+)P'N structures; or PIN, PP(+)N(+)NIP, PP(+)N(+)N'P'P, PP(+)N(+)N'P'P, PP(+)N(+)P'P, P(+)N(+)N'P'P, P(+)N(+)N'P'P, P(+)N(+)P'P, PP(+)N(+)N'N'P, PP(+)N(+)N'P, P(+)N(+)N'N'P, or P(+)N(+)N'P structures; where quantum wells are placed in the 'P', 'N', and 'I' layers (those layers in inverted commas 'X'). They are good for devices that operate under forward bias for the PIN (or P(+)IN or PIN(+) or P(+)IN(+)) junction. They are also good for devices that operate under reverse bias for the PIN (or P(+)IN or PIN(+) or P(+)IN(+)) junction, and are alternative exemplary embodiments for the active photonic devices in the present invention.

When the context is clear below, we will drop the inverted commas in 'N' or 'P' designations in the electro-active layer structures above. The above examples are for the purpose of illustrations and not limitations. For example, the various doped structures may also be joint one on top of another forming a cascaded structure. Those skilled in the art will know other obvious

variations that are variations of the above examples of the various doped structures with or without the use of quantum wells.

### **Slow-Wave Electrode Structure for Velocity+Impedance Matching**

5 In certain applications such as traveling-wave modulator, a travelling-wave RF transmission line electrode structure should be fabricated along the device waveguide. Such traveling-wave RF transmission line electrode structure is often needed in order to achieve high-frequency response of 10-100Gb/s or higher for the modulator. Below describe such a travelling wave electrode and their optimization to match the velocity of propagation of the optical beam  
10 and the RF wave. In such travelling wave electrode, it is often advantages to engineer the electrode impedance to be around the standard impedance of  $50\Omega$  or some other preferred value depending on the application.

As the RF dielectric constant in III-V semiconductors is close to their dielectric constant at optical frequency, and the RF wave in the case of semiconductor modulators tends to have  
15 electric field fringing to the surrounding materials with lower dielectric constant, the RF wave tends to propagate at a faster velocity than the optical wave. This can be managed by using an adjustable slow-wave capacitively-loaded traveling wave (CL-TWE) RF transmission-line structure as shown in **Fig. 5a**. The price to pay is a longer length, trading off mainly optical loss (not much of RF loss) but it allows impedance matching.

20 It turns out that the slow-wave structure also enables freedom to engineer concurrent impedance matching to  $50\Omega$  as there is freedom to choose its filling factor "F" that will change its effective inductance-length product L and capacitance per unit length C. It usually ended up with slightly larger voltage-length product than if the impedance is allowed to be lower than  $50\Omega$ , resulting in longer length for the same modulation voltage. Most of the structures above have  
25 plenty of rooms to absorb the longer length. Hence, velocity matching and  $50\Omega$  can be engineered. However, velocity matching is less important when the modulator is shorter than 0.2mm as the RF wavelength at 100GHz is about 1mm.

### **Exemplary Device for the Modulators of the Present Invention**

30 The exemplary device below illustrates a particular exemplary embodiment of the EO modulator of the present invention, including the travelling-wave electrode, the Mach Zehnder Interferometer, and push pull geometry. The general scheme for the modulator is illustrated in

**Fig. 4.** In one particular exemplary embodiment and realization of such modulator, the said modulator can be fabricated on a “silicon photonics” platform for operation at the fiber-optic communication wavelength of around 1550nm. The modulator is fabricated on a silicon-on-insulator (SOI) wafer for which a thin layer (about 300nm thick) of silicon is pre-bonded onto a thermal silicon oxide layer with a thickness of 1-2 micrometers grown on top of a bottom silicon substrate. The 300nm thick top-layer silicon on SOI wafer serves as an on-chip optical waveguide, which can be fabricated into the channel waveguide shown in **Fig. 4b**, for which the optical beam is propagated in the channel waveguide as shown in **Fig. 4b**. In this particular embodiment, the channel waveguide core is made of high-refractive-index silicon (with a refractive index  $n_{\text{core}} \sim 3.6$ ). The waveguide core is surrounded by silicon dioxide or air with much lower refractive index of  $n_{\text{clad}} \sim 1$  to 1.5, that act as waveguide cladding. The use of silicon as waveguide enables electronic integrated circuits to be fabricated on the same chip. Such waveguides are well known to those skilled in the art and are often referred to as “silicon photonics” platform. If active photonic devices such as modulators are then fabricated, the entire platform is some time referred to as Electronic-Photonic Integrated Circuits (EPICs).

For the modulator shown in **Fig.5a**, a pair of travelling-wave RF transmission line electrodes is used to propagate the RF electrical signal along the EO modulator. These electrodes are designed so that the RF wave propagates at a velocity close to the optical wave velocity in the modulator’s optical waveguide. This is referred to as velocity matched transmission line. As is known to those skilled in the art, velocity matching is desirable when the modulator length is long comparing to the RF wavelength so that maximum modulation can be achieved in the optical beam.

In this example for the case of an EO modulator geometry, an optical beam is further split into two propagating arm forming a Mach Zehnder Optical Interferometer (MZI). Each arm has an EO phase modulator. As is known to those skilled in the art, it is typically arranged so that the RF wave will cause positive phase shift in one of the arm and negative phase shift in the other arm, resulting in what is known as “push-pull” configuration for the modulator. As is known to those skilled in the art, a number of configurations can be used beside the push pull configuration. Thus such RF electrode and MZI geometry are shown only for the purpose of illustration and not limitation.

An embodiment of the present invention is focused on the realization of an EO phase modulator that can be used as shown in a MZI geometry or as an isolated phase modulator for

various applications as is well known to those skilled in the art. The RF electrodes illustrate an exemplary embodiment in a particular application of the modulators of the present invention.

For this particular exemplary embodiment, the RF electrodes are a pair of capacitively-loaded traveling wave electrodes (CL-TWE). Each arm of the CL-TWE is electrically in contact with electrode traveling along an optical waveguide based EO optical phase modulator. The EO optical phase modulator is reverse biased by a DC applied voltage. Thus there are two phase modulators, one power by each arm. The two optical waveguiding arms then form a Mach Zehnder optical Interferometer (MZI) geometry for an input optical beam. The input optical beam is split with half the power going to each arm. At the output, the phase modulated beams from the two phase modulator outputs are then combined again giving the optical output for the MZI. As is well known to those skilled on the art, the MZI enables the phase modulation to be converted to optical intensity modulation at the beam combined optical output of the MZI. In the case of a push-pull geometry, as is known to those skilled in the arm, the two arms will receive opposite optical phase shift, enabling double the intensity modulation under the same applied voltage to the two phase modulators, one on on each arm of the MZI.

In order to realize a push-pull geometry, in terms of powering the two arms of the Mach Zehnder Interferometer (MZI), the illustrated scheme follows that of the PIN modulator. As shown in **Fig. 5a**, RF wave is launched into the CL-TWE from one end of the CL-TWE. The segmented periodic pairs of T-shaped electrodes bring the voltage from the main slotted electrodes to the modulator device. Each pair is separated by a periodic length  $l_p = l_m + l_g$  and each of the T-shape segment has a length  $l_m$ . The fill factor  $F$  is defined as  $F = l_m / l_p$  (see **Fig. 5a**), where "A/B" denotes division of A "over" B. Typically  $l_p = 50\text{-}100\mu\text{m}$ . Along the gap  $l_g = l_p - l_m$ , the modulator section has no applied voltage.

In this particular exemplary embodiment, the bottom parts of the two phase modulators are connected. This is shown in **Fig.5b** showing the cross-section f-f' in **Fig.5a**. Thus, any voltage  $V_s$  applied is split  $+V_s/2$ , and  $-V_s/2$  on the two arms forming a push-pull pair of phase modulators. Unlike the conventional push-pull modulators, there is no net voltage reduction by half as the line voltage  $V_s$  is twice the voltage applied to each modulator  $V_s/2$ . However the junction capacitances ( $C_j$  in **Fig.5a**) of the two phase modulators are connected in series, reducing the total capacitance or increasing the frequency, so there is a gain over the conventional push-pull EO modulator in broader frequency response (at the expense of higher voltage).

The equivalent lumped-element circuit of such a CL-TWE powering the two phase

modulators is shown in **Fig.6a**, in which the dotted line labeled as “Transmission Line” represents the basic unloaded transmission line model for the CL-TWE. The solid line part labeled as “Device Load” takes into account RF propagation loss of all the modulator structural elements including: (1) Metal Ohmic Contact Resistance and Capacitance  $Z_m$ ; (2) Resistance and  
 5 Capacitance  $Z_d$  of the Doped Waveguide Layers including those in the TCO materials (if TCO is used); (3) Modulator active-region Capacitance  $C_j$ ; (4) Both Transverse and Longitudinal Current losses in the Semiconductor Structure are included. The model gives us the frequency bandwidth limited by the RF losses (for long modulator) or by the RC time constant (for short modulator), and the transmission line impedance. It also gives us the CL-TWE filling factor  $F$  needed to  
 10 achieve velocity matching.

**Fig. 6b** shows the top view of the CL-TWE lines for the traveling wave electrodes. The voltage  $V_b$  in **Fig.6b** connecting between the bottom common contact and the top of one of the modulators giving  $V_{b1}=V_{b2}=V_b$  (when  $V_s=0$ ) is used to reverse bias the modulators. DC offset in  $V_s$  gives differential biasing that can be used to tune the operating point of the Mach Zehnder  
 15 optical interferometer by tuning the differential phase shift imposed by the two phase modulators along its two arms.

As is known to those skilled in the art, there are many other electrode structures that can be used. The above illustrates one embodiment of a traveling wave structure that can slow down the propagation velocity of the RF wave so as to achieve better velocity matching with the optical  
 20 beam in the modulator (it is some time referred to as slow-wave RF traveling-wave structure). Such velocity matching will help to achieve higher frequency response as is known to those skilled in the art. The above exemplary embodiment on the traveling-wave electrodes is shown for the purpose of illustrations and not limitation.

In terms of the optical beam, it enters the silicon waveguide from an optical fiber. There are many ways to couple optical beam from an optical fiber to silicon waveguide as is known to those skilled in the art such as via an integrated mode size transformer on silicon called Super-High-Numerical Aperture Graded Refractive Index (SuperGRIN) lens, which will efficiently couple the beam power from the optical fiber to the 300nm thick silicon waveguide on a SOI substrate (SOI waveguide). Alternative fiber to silicon waveguide couplers such as tapering down  
 30 waveguide or surface grating can also be used as is well known to those skilled in the art.

The beam from the SOI waveguide is then coupled into the thin-film modulator structure as shown by **Fig.7a/b** using two tapers (one on the active material layer (e.g. InP/III-V), one on

the primarily passive waveguide layer (e.g. Si)—see the top view). Due to the thin-thickness of the InP/III-V modulator's active layer structure (only 300-400nm thick) for operation at 1550nm wavelength range, this taper section can be very short (like 5-30 $\mu$ m depending on the thickness) and over 95% of the energy can be transferred into the thin film modulator device. The output  
 5 back into the optical fiber goes through a reverse process via two output tapers (one on the active material layer (e.g. InP/III-V), one on the primarily passive waveguide layer (e.g. Si)—see the top view) to bring the optical beam to the primarily passive waveguide layer (e.g. Si) and then to an output fiber-coupling lens.

The general structure for the NIN and NPNN modulators are also similar. What  
 10 differentiate them are the detailed layer structures. There are two versions of the general structure, one uses side-conduction layer (SCL), another Ohmic Transparent Conductor (OmTC).

**SCL Case.** In a particular exemplary embodiment for application to 1550nm wavelength range, the cross-section for the SCL case is shown in **Fig.8a**. At the bottom, the modulator has a highly doped lower layer that is about 100nm thick for this particular exemplary embodiment.  
 15 This layer is used to conduct the voltage side way and is called "bottom side conduction layer" (BSCL). As noted above, in the push-pull modulator circuit scheme for the particular exemplary embodiment, this layer is connected to the phase modulator at the other arm of the MZI.

Above this BSCL is an active EC layer structure that will be different for NIN and NPNN. It is then followed by a 100nm thick top layer. This top layer is largely N-doped and is used to  
 20 conduct voltage side way and is called the "top side conduction layer or TSCL". On top of this at the middle is deposited with 300nm-thick low-refractive-index SiO<sub>2</sub>. Both sides of TSCL are deposited with metal. The center SiO<sub>2</sub> layer prevents optical energy in the waveguide from touching the optically lossy metal.

The center active EC layer has to be narrow in width to make the device capacitance small  
 25 as its width  $w_{EC}$  will define the modulator-capacitor width  $w_{CAP} = w_{EC}$ . To enable fabrication, one way is to use a material for this active EC layer that can be chemically selectively etched sideway without etching the material that formed the BSCL or the TSCL layers. Other fabrication schemes may be used as long as the small width for  $w_{EC}$  is achieved (e.g. by etching the required width for  $w_{EC}$ , then depositing the material required for forming the TSCL layer). In order to achieve high  
 30 frequency response, an exemplary modulator structure requires  $w_{EC}$  to be around  $2\mu m = 2000nm$  or as narrow as  $0.7\mu m = 700nm$ . While it may seem to be small (making it challenging to fabricate), it is still larger than the typical thickness of this thin-film modulator structure with a

thickness of 300-400nm. Thus, the width  $w_{EC}$  still has a low aspect ratios ( $<1:3$ ) with the other nearby structural parameters. Low aspect ratios make it not too difficult to fabricate. It can be done by careful control of the etching. Both sides of the metal contact will be around  $2\mu m=2000nm$  in order to have a large enough Ohmic contact area with metal so as to have small enough metal contact resistance.

**OmTC Case.** In a particular exemplary embodiment for application to 1550nm wavelength range, the cross-section for the OmTC case is shown in **Fig.8b**. In the case of a OmTC based structure, there will be no TSCL. Thus, in this particular exemplary embodiment, the top layer thickness can be reduced by about 60nm, leaving 40nm for Ohmic contact with TC (Transparent Conductor) material in general or TCO (Transparent Conducting Oxide) material in particular. This 60nm thickness can be added to the bottom BSCL making it 160nm thick resulting in lower resistance and more robust structure. The top layer contacting the TC is N-doped for achieving good Ohmic contact. In this particular exemplary embodiment, the TC is  $In_2O_3$ . As the TC generally has low refractive index (e.g.  $n\sim 1.7$ ), the optical field energy will decay rapidly in the TC and will not touch the metal much. As TC can be deposited after the dry etching to form the width  $w_{EC}$  needed for the electro-active (EC) layer, no side etching of the center electro-active layer (ECL) is needed. We just need to etch vertically for the require thickness and then planarize with polymer, then deposit with TC. Hence, this OmTC case will enable a structure that is more robust, with lower resistance, and easier to fabricate than the SCL case.

#### Detailed Structures for NIN and NPNN Modulators

**NIN Structures.** In a particular exemplary embodiment for application to 1550nm wavelength range, the detail structures for a NIN modulators are shown in **Fig.9**. In this particular exemplary embodiment, the structure has a highly-doped bottom InP N-layer about 120nm thick (this becomes the BSCL) followed by a 195nm thick intrinsic layer made of AlGaInAs QW structure (with  $\lambda_{QW}\sim 1350nm$ ), and then by another highly-doped top InP N-layer about 125nm thick for side contact with metal. This gives a total thickness of 440nm. For this structure, the active EO region width  $w_{EC}$  or the modulator-capacitor width  $w_{CAP}$  defined by it ( $w_{CAP}=w_{EC}$ ) is chosen to be 2,000nm ( $2\mu m$ ). This width also gives the lateral optical mode confinement as shown by Fig.10b. In Fig.10a, we show the mode of a conventional modulator in comparison. The NIN mode in Fig.10b is 4 times smaller in the vertical direction, giving around 4 times larger

mode-medium overlapping factor.

The computed modulator length for  $V\pi=1V$  and  $F=1$  is  $L_{MOD}=2mm$ .

Table 1 show the material layer structure for this NIN structure based modulators with side metal contact for its top contact, spelling out the thicknesses and bandgap energies of the compound semiconductor material in each layer with the various doping density and strain (with InP as the substrate).

Table 1

| Layer Number | Layer Thickness          | NIN CASE Metal                              | Doping               |
|--------------|--------------------------|---------------------------------------------|----------------------|
| 1            | 120nm                    | InP (Bottom Layer-just above the substrate) | $n=1 \times 10^{19}$ |
| 2            | 5nm                      | AlGaInAs 1.3um                              | I                    |
| 3            | 5nm barrier              | AlGaInAs/1.1um/-0.8% tensile strained       | I                    |
| 4            | 2x7nm barrier inside     | AlGaInAs/1.1um/-0.8% tensile strained       | I                    |
| 5            | 3x6.5nm Well (PL=1350nm) | AlGaInAs/1.55um/0.9% compressive strained   | I                    |
| 6            | 5nm barrier              | AlGaInAs/1.1um/-0.8% tensile strained       | I                    |
| 7            | 60nm                     | AlGaInAs 1.3um                              | I                    |
| 8            | 125nm                    | InP (Top Layer)                             | $n=1 \times 10^{19}$ |
| Total        | 440nm                    |                                             |                      |

**NPNN structure.** In a particular exemplary embodiment for application to 1550nm wavelength range, as shown in **Fig.10.**, a NPNN structure has a highly-doped bottom InP N-layer about 160nm thick, followed by a 115nm thick active Electro-Active layer (ECL) made of AlGaInAs QW structure, then by a thin layer of InP P-doped layer (around 25nm), then by a highly-doped top InP N-layer about 80nm thick for top contact to Om-TCO. This gives a total thickness of 380nm. The Electro-Active region width  $w_{EC}$  is chosen to be 2,000nm (2 $\mu$ m).

Table 2

| Layer Number | Layer Thickness          | NPNN TCO CASE                               | Doping               |
|--------------|--------------------------|---------------------------------------------|----------------------|
| 1            | 160nm                    | InP (Bottom layer-just above the substrate) | $n=1 \times 10^{19}$ |
| 2            | 10nm                     | AlGaInAs 1.3um                              | $n=4 \times 10^{17}$ |
| 3            | 4nm barrier              | AlGaInAs/1.1um/-0.8% tensile strained       | $n=4 \times 10^{17}$ |
| 4            | 2x7nm barrier inside     | AlGaInAs/1.1um/-0.8% tensile strained       | $n=4 \times 10^{17}$ |
| 5            | 3x6.5nm Well (PL=1350nm) | AlGaInAs/1.55um/0.9% compressive strained   | $n=4 \times 10^{17}$ |

|       |             |                                       |                      |
|-------|-------------|---------------------------------------|----------------------|
| 6     | 4nm barrier | AlGaInAs/1.1um/-0.8% tensile strained | $n=4 \times 10^{17}$ |
| 7     | 63nm        | AlGaInAs 1.3um                        | $n=4 \times 10^{17}$ |
| 8     | 25nm        | InP                                   | $p=1 \times 10^{18}$ |
| 9     | 80nm        | InP (Top layer)                       | $n=1 \times 10^{19}$ |
| Total | 380nm       |                                       |                      |

As shown in **Fig.10**, comparing to NIN case, the main difference for this particular exemplary embodiment of a NPNN case is that the active EC layer has QWs that are also doped with N-type carriers and it is next to a bottom p-doped layer. Under a reverse bias, the depletion width between the p-doped layer and the N-doped QW region is enlarged with voltage. The voltage drop across this depletion region then imposes a constant electric field on the QW. The increase in phase shift is because more QWs are applied with the electric field when the voltage increases. The doped carriers also cause phase shift due to band-filling (BF) and Plasma (PL) effects. When optimized, the BF+PL+LEO+QCSE can lead to 3-5 times larger phase shift than LEO+QCSE. The thinner structure of 380nm comparing to NIN of 440nm also reduces the modulator length by another 20%. The computed modulator length for  $V_{\pi}=1V$  is  $L_{MOD}=0.4mm$ .

Table 2 shows the material layer structure for the NPNN structure based modulators with Om-TCO contact for its top contact, spelling out the thicknesses and bandgap energies of the compound semiconductor material in each layer with the various doping density and strain (with InP as the substrate).

### The Role of F for Velocity & Impedance Matching

In a particular exemplary embodiment for application to 1550nm wavelength range, the lumped-element model shown in **Fig.6a** is used to estimate the modulator device performances. We use a Table to summarize the different cases. We will illustrate some plots using a NIN case with SCL, and NPNN case with OmTC.

**NIN CASE with SCL.** In a particular exemplary embodiment, the modulation BW for the NIN case with 2- $\mu m$ -wide active region so  $w_{CAP}=2\mu m$  is shown in **Fig.11**.

A calculation shows that for the NIN structure, in order to reach 1V modulation voltage, the modulator length shall be 2mm. **Fig.11a** shows the net frequency response limited by RF loss (in dB/mm). Taking the 3.24dB/mm loss line in **Fig.11a**, one finds a frequency response bandwidth of 60GHz for the NIN structure with side metal conduction. These are for  $w_{CAP}=2\mu m$ .

**Fig.11b** shows the impedance for different  $F$  values as a function of the frequency. **Fig.11c** shows the propagating refractive index of the RF wave along the RF transmission line for different  $F$  values as a function of the frequency illustrating  $F \sim 0$  makes the RF refractive index close to 3.5, which is nearly matching the propagating refractive index of the optical beam in the modulator (typically around  $n \sim 3$  to 3.5), which is required for velocity matching.

**NPNN CASE with OmTC.** In a particular exemplary embodiment, the modulation bandwidth for the NPNN case with 2- $\mu\text{m}$ -wide active region so  $w_{\text{CAP}} = 2\mu\text{m}$  (this width determines the Modulator Capacitance  $C_j$ ) is shown in **Fig.12**.

A calculation shows that for the NPNN structure, in order to reach 1V modulation voltage, the modulator length shall be 0.4mm. **Fig.12a** shows the net frequency response limited by RF loss (in dB/mm). Taking the 34.2dB/mm loss line in **Fig.12a**, one finds a frequency response bandwidth of 100GHz for the NPNN structure with Ohmic TCO as top contact. These are for active-region width of 2 $\mu\text{m}$ . **Fig.12b** shows the impedance for different  $F$  values as a function of the frequency. **Fig.12c** shows the propagating refractive index of the RF wave along the RF transmission line for different  $F$  values as a function of the frequency illustrating  $F \sim 0.4$  makes the RF refractive index close to 3.5, which is nearly matching the propagating refractive index of the optical beam in the modulator (typically around  $n \sim 3$  to 3.5), which is required for velocity matching.

### More Detailed Descriptions of the Various Embodiments of the Present Invention

A schematics showing the general geometry of the **Active Photonic Devices** of the present invention is shown in **Fig. 13**. Figures **13a** and **13b** show a Active Photonic Device 20000 with a modulating section or referred to below as “Active-Layer Structure ALS 22500” section, coupled to an input connecting waveguide core ICWCo 22200. **Fig. 13b** is a semi-transparent illustration of **Fig. 13a**. The input connecting waveguide core ICWCo 22200 is fabricated on an input connecting-waveguide bottom cladding material ICWBCd 22200B disposed on a substrate SUB 21100.

In one exemplary embodiment shown in **Fig. 14**, illustrating an exemplary embodiment of the cross section at location A-A' of **Fig. 13**, to the top of the input connecting waveguide core is further deposited with input connecting waveguide top cladding material ICWTCd 22200T. Bottom refers to direction closer to the substrate and top refers to direction away from the

substrate. In **Fig. 14**, to the left of the input connecting waveguide core is also deposited with input connecting waveguide left cladding material ICWLCd 22200L and to the right of the waveguide core is disposed with input connecting waveguide right cladding material ICWRCd 22200R. Right or left is defined by taking the direction of beam propagation as the front direction and right or left means relative to this front direction. The division of the cladding into four different material regions is for the purpose of discussion and not limitation as these can be all the same materials or there can be more than 4 regions forming plurality of different regions as long as these regions act as waveguide cladding materials with effective refractive indices smaller than the effective refractive index of the waveguide core ICWCo 22200 so that the light beam power is confined mainly in the region of the waveguide core ICWCo 22200, as is well known to those skilled in the art. The cladding material is a general designation that can include "air" or "vacuum" or any transparent dielectric material as the material.

#### **Input Connecting Waveguide Region**

The input connecting waveguide core ICWCo 22200 is made up of a material or mixture of materials with an averaged material refractive index  $n_{ICWCo}$  22200n, has a thickness  $d_{ICWCo}$  22200d, and width  $W_{ICWCo}$  22200w. Let the refractive index of the bottom input connecting-waveguide bottom cladding material be  $n_{ICWBCd}$  22200Bn. Let the refractive index of the top cladding material ICWTCd 22200T be  $n_{ICWTCd}$  22200Tn, the refractive index of the left cladding material ICWLCd 22200L be  $n_{ICWLCd}$  22200Ln, and the refractive index of the right cladding material ICWRCd 22200R be  $n_{ICWRCd}$  22200Rn. The waveguide core 22200 and the claddings 22200T, 22200B, 22200R, 22200L, together forms input connecting waveguide ICWG 22200WG.

The vertical confinement of the optical beam is due to the refractive-index difference between the top and bottom waveguide claddings and the waveguide core and the claddings generally have lower refractive indices than that of the waveguide core so that  $n_{ICWTCd} < n_{ICWCo}$  and  $n_{ICWBCd} < n_{ICWCo}$ . The horizontal confinement of the optical beam is due to the refractive-index difference between the left and right waveguide claddings and the waveguide core and the claddings generally have lower refractive indices than that of the waveguide core so that  $n_{ICWRCd} < n_{ICWCo}$  and  $n_{ICWLCd} < n_{ICWCo}$ . The vertical direction is the direction perpendicular to the substrate plane and the horizontal direction is the direction parallel to the substrate plane.

The above illustration of an exemplary embodiment of input connecting waveguide

ICWG 22200WG, showing the waveguide cladding can be divided into different material regions (in the above case with four main material regions), is for the purpose of illustration and not limitation. As is known to those skilled in the art, the waveguide cladding can be made up of one single material or plurality of material regions, as long as the refractive indices of most of the  
 5 cladding material regions is lower than the refractive index  $n_{ICWC_0}$  of the waveguide core. This is also generally applicable to the other waveguide cladding situations below for other optical waveguides described in the present invention.

### Definition of Refractive index Contrast and Cladding Refractive Index Averaging

10 An important quantity in terms of waveguide mode confinement is the refractive index contrast between the averaged refractive index of the waveguide core and its immediate surrounding cladding materials called the refractive-index difference  $n_{Rd}$  defined by  $n_{Rd}^2 = n_{C_0}^2 - n_{Cd}^2$ , where  $n_{C_0}$  is the refractive index of the waveguide core (e.g.  $n_{C_0} = n_{ICWC_0}$ ) and  $n_{Cd}$  is the refractive index of the waveguide cladding (e.g.  $n_{Cd} = n_{ICWBCd}$  or  $n_{ICWTCd}$  or  $n_{ICWRCd}$  or  $n_{ICWLcd}$ ) or  
 15 an averaged of them thereof given by  $n_{aICWCd}$  22200aCdn.

The refractive-index averaging is more accurately done as averaged of its square values which are their dielectric constant  $\epsilon = n^2$ . This is because dielectric constants which describe the dipole strengths add linearly with each other as is known to those skilled in the art. Thus  $n_{aICWCd}^2$  for example can be computed by weighting the refractive index square in each of the different  
 20 cladding regions by the fraction of beam energy in each of the cladding regions. Hence:

$$n_{aICWCd}^2 = (n_{ICWBCd}^2 \times A_{ICWBCd} + n_{ICWTCd}^2 \times A_{ICWTCd} + n_{ICWRCd}^2 \times A_{ICWRCd} + n_{ICWLcd}^2 \times A_{ICWLcd}) / (A_{ICWBCd} + A_{ICWTCd} + A_{ICWRCd} + A_{ICWLcd}), \quad (13)$$

where in Eq. (13),  $A_{ICWBCd}$  is some effective cross-sectional weighting for the optical power in the bottom cladding material (e.g. given by the percentage of the total beam power),  
 25  $A_{ICWTCd}$  is some effective cross-sectional weighting for the optical power in the top cladding material,  $A_{ICWRCd}$  is some effective cross-sectional weighting for the optical power in the right cladding material,  $A_{ICWLcd}$  is some effective cross-sectional weighting for the optical power in the left cladding material.  $A_{ICWBCd}$ ,  $A_{ICWTCd}$ ,  $A_{ICWRCd}$ , and  $A_{ICWLcd}$  are called the effective beam power distribution areas in the respective regions of the waveguide cladding materials. Each of  
 30 these cross-sectional weighting has a value proportional to the fractional optical power (beam power integrated over the beam cross-sectional area of that region) in that region of the material for the guided optical beam or is given by the integration over the beam energy density (energy

per unit volume) over the volume of that region of the material assuming the volume is taken over a short propagation length. These are some definitions of the effective cross-sectional weighting labeled with prescript "A". Many other equivalent but approximate definitions of the effective cross-sectional weighting "A" can be used. Note  $n_{aICWCd}^2 \sim (n_{ICWBCd}^2 + n_{ICWTCd}^2 + n_{ICWRcd}^2 + n_{ICWLcd}^2)/4$ , if these weightings are about equal.

Likewise the waveguide core can also generally be made up of one or plurality of materials, and  $n_{aICWCo} = n_{aICWCo}$  can also be an averaged refractive index of the "m" number of materials with slightly different refractive indices  $n_{ICWCo1}$ ,  $n_{ICWCo2}$ ,  $n_{ICWCo3}$  ...  $n_{ICWCom}$ , that made up the waveguide core materials where

$$n_{aICWCo}^2 = (n_{ICWCo1}^2 \times A_{ICWCo1} + n_{ICWCo2}^2 \times A_{ICWCo2} + n_{ICWCo3}^2 \times A_{ICWCo3} + \dots + n_{ICWCom}^2 \times A_{ICWCom}) / (A_{ICWCo1} + A_{ICWCo2} + A_{ICWCo3} + \dots + A_{ICWCom}), \quad (14)$$

In Eq.(14), each of the  $A_{ICWCo1}, \dots, A_{ICWCom}$  is some effective cross-sectional weighting  $A_{ICWCoj}$  for the optical power in core material with refractive index  $n_{ICWCoj}$ , where j is one of 1, ..., m.  $A_{ICWCo1} + A_{ICWCo2} + A_{ICWCo3} + \dots + A_{ICWCom}$  are called the effective beam power distribution areas in the respective regions of the waveguide core materials.

### Input Optical Beam

As shown in Fig. 13, an input optical beam IBM 22140 is launched into input connecting waveguide core ICWCo 22200. As the cladding regions of input connecting waveguide ICWG 22200WG or in fact of any waveguide are typically ill-defined (the beam power can go into various depths and directions into the cladding) as is known to those skilled in the art, an input optical beam IBM 22140 launched into waveguide ICWG 22200WG is taken to mean it is launched with its power centered essentially at the waveguide core ICWCo 22200, so the reference to the beam being in waveguide 22200WG or waveguide core 22200 will generally be used interchangeably below. As is known to those skilled in the art, the input optical beam IBM 22140 will propagate in waveguide 22200 with a "propagating refractive index"  $n_{IBM\ 22140n}$ . This propagating refractive index  $n_{IBM\ 22140n}$  generally has a value smaller than the material refractive index  $n_{ICWCo\ 22200n}$  of the waveguide core ICWCo 22200 so that  $n_{IBM} < n_{ICWCo}$  as is known to those skilled in the art. Also, the propagating refractive index  $n_{IBM\ 22140n}$  generally has a value larger than the material refractive index  $n_{ICWQcd\ 22200Qn}$  of the waveguide cladding ICWQcd 22200Q where Q=T,B,L, or R, so that for most of the Q,  $n_{IBM} > n_{ICWQcd}$  to enable waveguiding, as is known to those skilled in the art. The optical beam has an optical power given

by  $P_{IBM}$  22140P, electric field polarization given by  $E_{IBM}$  22140E, and beam effective area given by  $A_{IBM}$  22140A.

In this invention, the propagating optical beam is generally assumed to have a spread of optical wavelength centered at an operating wavelength  $\lambda_{IBM}$  22140L. For illustration and not  
 5 limitation, the optical beam may be in the form of a train of optical pulses to transmit digital information. The optical beam may also be made up of light wave of one or plurality of (N) different frequency channels ( $\lambda_{IBM1}$ ,  $\lambda_{IBM2}$ ,  $\lambda_{IBM3}$ , ...,  $\lambda_{IBM N}$ ) where N is an integer. When the optical beam is made up of plurality of frequency channels, the optical transmission system or device is generally known as a wavelength division multiplexing (WDM) optical system or  
 10 device. Generally, the optical beam is made up of beam of light with a spectral width around the center operating wavelength  $\lambda_{IBM}$ .

### Input Beam Coupler Structure (IBCS) Region

**Figs. 15a** show the input beam coupler structure (IBCS) comprises at least a tapering  
 15 waveguide section (preferably tapering from wide to narrow but can also maintain the same width or taper from narrow to wide as will be elaborated below) connected to the input waveguide. Optionally, the active layer structure ALS on top of the input tapering waveguide section can also be tapering in the form of an up taper (preferably tapering from narrow to wide in the direction toward the active layer structure ALS, but can also maintain the same width or taper from wide to  
 20 narrow). See for example **Fig. 15b**.

Specifically, the input optical beam IBM 22140 enters from input connecting waveguide core ICWCo 22200 into an input connecting-waveguide taper section with an input tapering waveguide core ITWCo 22300 parameterized by a location  $z1$  (Fig. 15a), ITWCo- $z1$  22300 $z1$ , in which the width of a tapering waveguide core  $w_{ITWCo-z1}$  22300 $w-z1$  at distance  $z1$ , measured from  
 25 the beginning point of the taper, is changed from its input value at  $z1=0$   $w_{ITWCo-z1=0}$  22300 $w-z1=0$  of  $w_{ITWCo-z1=0}=w_{ICWCo}$  22200 to another width (that can be the same width) at  $z1>0$   $w_{ITWCo-z1>0}$  22300 $w-z1>0$ . The thickness of the tapering waveguide core is  $d_{ITWCo-z1}$  22300 $d-z1$  and its refractive index is  $n_{ITWCo-z1}$  22300 $n-z1$ . Typically, though not always,  $d_{ITWCo-z1}$  22300 $d-z1$  and  $n_{ITWCo-z1}$  22300 $n-z1$  are constant value in  $z1$  so we can drop the  $z1$  designation with  $d_{ITWCo-z1}=d_{ITWCo}$  22300 $d$  and  $n_{ITWCo-z1}=n_{ITWCo}$  22300 $n$ . In a preferred embodiment,  $d_{ITWCo-z1}$  is about the  
 30 same value as  $d_{ICWCo}$ . The tapering may be such that  $w_{ITWCo-z1}$  is a linear function of  $z1$  or quadratic function of  $z1$  (i.e. depending on  $z1^2$ ), but can also be of any curvilinear function of  $z1$ .

Let  $g_{ITWC_0}$  22300g denotes the total length of this tapering waveguide.

The end of the taper at  $z1=g_{ITWC_0}$  22300g at which the width of the waveguide core is  $w_{ITWC_0-g}$  22300w-g is connected to an input supporting structure ISTR 21200. While illustrated as a line that is continuation of the connecting waveguide material with a narrow width and air or other low refractive index materials surrounding its side, the supporting structure can be random dots or any shape of small amount of any materials that have an “effective refractive index” or small “averaged refractive index” (e.g. as defined by Eq. (13)) within the layer extended in the horizontal direction, given by an effective layer averaged refractive index  $n_{laISTR}$  21200nla. In the case it acts as the bottom waveguide cladding,  $n_{laISTR}$  has a value lower than the refractive index of the waveguide core  $n_{WC_0}$  22600Con in the electro-active waveguiding core structure EWCoS 22600 defined below. The input supporting structure ISTR 21200 may continue to guide wave or just acts as a supporting structure, depending on application scenarios.

In an exemplary embodiment, the input supporting structure ISTR 21200 is a narrow line. In that particular case, we can describe it as having a width  $w_{ISTR}$  21200w, thickness  $d_{ISTR}$  21200d, and length  $g_{ISTR}$  21200g. The length  $g_{ISTR}$  21200g may be zero. In that case, input supporting structure ISTR 21200 does not exist (the thin ALS film can still be supported in some way such as by its corners or sides, but not directly below). In a preferred embodiment,  $d_{ISTR}$  is about the same value as  $d_{ICWC_0}$ .

Along the taper in region outside the ALS region, the vertical confinement of the optical beam is due to the refractive-index difference between the waveguide core and top and bottom tapering waveguide claddings at the location  $z1$  defined above: ITWTCd- $z1$  22300T- $z1$  (refractive index  $n_{ITWTCd-z1}$  22300Tn- $z1$ ) and ITWBCd- $z1$  22300B- $z1$  (refractive index  $n_{ITWBCd-z1}$  22300Bn- $z1$ ) and the waveguide core and the claddings have lower refractive indices than that of the waveguide core so that the refractive index  $n_{ITWTCd-z1} < n_{ITWC_0-z1}$  and  $n_{ITWBCd-z1} < n_{ITWC_0-z1}$ . The horizontal confinement of the optical beam is due to the refractive-index difference between the left and right waveguide claddings at  $z1$ : ITWLCd- $z1$  22300L- $z1$  (refractive index  $n_{ITWLCd-z1}$  22300Ln- $z1$ ) and ITWRCd- $z1$  22300R- $z1$  (refractive index  $n_{ITWRCd-z1}$  22300Rn- $z1$ ), and the waveguide claddings have lower refractive indices than that of the waveguide core so that  $n_{ITWRCd-z1} < n_{ICWC_0-z1}$  and  $n_{ITWLCd-z1} < n_{ICWC_0-z1}$ . The vertical direction is the direction perpendicular to the substrate plane and the horizontal direction is the direction parallel to the substrate plane. Again, there can be one or plurality of cladding material regions, and the four cladding regions are mentioned for the purpose of illustration and not limitation.

In an exemplary embodiment,  $n_{ITWTCd-z1} = n_{ITWBCd-z1} = n_{ITWLCd-z1} = n_{ITWRCd-z1} = n_{ICWTCd}$ , and  $n_{ICWTCd} = n_{ICWBCd} = n_{ICWLCd} = n_{ICWRCd}$  so all the cladding indices in the tapering regions and the input connecting waveguide regions are all approximately equal. For example, these cladding regions can be filled with silicon dioxide materials with refractive index of  $n \sim 1.45$ . The refractive index of the waveguide core  $n_{ITWCo-z1}$  22300n-z1 can be silicon so that  $n_{ITWCo} = n_{ICWCo} \sim 3.6$ , where  $n_{ICWCo}$  22200n is the refractive index of the waveguide core for the input connecting waveguide.

On top of the input tapering waveguide core ITWCo 22300 starting at  $z1 = z1ALS$  22300z1ALS, is laid with an active layer structure ALS 22500. Typically  $z1ALS$  is before  $g_{ITWCo}$  22300g so that  $0 < z1ALS < g_{ITWCo}$ . The active layer structure starting at  $z1ALS$  can also have an up-taper with width tapering from narrow to wide in the direction toward the ALS structure. The various embodiments of this active layer structure ALS 22500 will be described in more detail below.

#### Alignment Insensitive Input Beam Coupler Structure (AI-IBCS)

- (1) Broadened input region, preferably narrower than mode 3.
- (2) Top taper first
- (3) Close to equal width
- (4) Narrow the lower one down
- (5) Narrow the top one down
- (6) Zigzag situation

#### Active Layer Structure-Beam Transport into the Structure

##### Bottom Side Conduction and Ohmic Contact Layer

Figs. 16a, 16b, and 16c show exemplary embodiments of the Active Layer Structure ALS 22500, which are exemplary cross-sections at location B-B' of Fig. 15a or Fig. 15b. In ALS 22500, at least a bottom side conduction and Ohmic contact layer BSCOC 21300 is disposed somewhere above part of input supporting structure ISTR 21200. The layer BSCOC 21300 with thickness  $d_{BSC}$  21300d, refractive index  $n_{BSC}$  21300n, a total width  $w_{BSC}$  21300w serves to conduct electrical current and voltage from a contact region to an electro-active layer (ECL).

##### Bottom Interspaced Material Layer

There can be other bottom interspaced material layer BIM 21250 between layer BSCOC

21300 and ISTR 21200, with thickness  $d_{\text{BIM}}$  21250d, a total width  $w_{\text{BIM}}$  21250w, and refractive index  $n_{\text{BIM}}$  21250n. This layer may be electrically conducting or electrical insulating. The value of  $d_{\text{BIM}}$  may take on zero thickness, in that case the bottom interspaced material layer BIM 21250 does not exist. The existence of a bottom interspaced material layer BIM 21250 is thus optional.

5

#### **Bottom Metal Contact Pads**

On top and to the left side of the bottom side conduction and Ohmic contact layer BSCOC 21300 is deposited of at least a first bottom left metal contact pad FBLM 21900L with thickness  $d_{\text{FBLM}}$  21900Ld, width  $w_{\text{FBLM}}$  21900Lw, and length  $g_{\text{FBLM}}$  21900Lg.

10

On top and to the right side of the bottom side conduction and Ohmic contact layer BSCOC 21300 is deposited of at least a first bottom right metal contact pad FBRM 21900R with thickness  $d_{\text{FBRM}}$  21900Rd, width  $w_{\text{FBRM}}$  21900Rw, and length  $g_{\text{FBRM}}$  21900Rw. In an exemplary embodiment, only either the first bottom left or the first bottom right metal contact pad is present. In another exemplary embodiment, plurality of such bottom metal contact pads is present. The exact location of these metal contact pads can be in many other locations beside the left or right location shown as long as the metal contact pads are in electrical contact with the bottom side conduction and Ohmic contact layer BSCOC 21300.

15

#### **Bottom Metal Electrodes**

On top of the first bottom left metal contact pad FBLM 21900L is a first bottom left metal electrode FBLME 21120L. On top of the first bottom right metal contact pad FBRM 21900R is a first bottom right metal electrode FBRME 21120R. In an exemplary embodiment, only either the first bottom left or the first bottom right metal electrode is present. In another exemplary embodiment, plurality of such bottom metal electrodes is present. The exact location of these bottom metal electrodes can be in many other locations beside the left or right location shown as long as the bottom metal electrodes are in electrical contact with the respective bottom metal contact pads.

25

#### **Bottom Interspaced Dielectric Current Conduction Layer**

On top of the center region of the layer BSCOC 21300 (i.e. region above or near supporting structure 21200) is deposited of a bottom interspaced dielectric current conduction layer BIDC 21350 with thickness  $d_{\text{BIDC}}$  21350d, layer width  $w_{\text{BIDC}}$  21350w, and an averaged refractive index  $n_{\text{BIDC}}$

30

21350n. The layer width  $w_{BDC}$  is the dimension of that layer in a horizontal direction perpendicular to the direction of the optical beam propagation. This layer is optional in that when thickness  $d_{BDC}$  21350d is zero, this layer does not exist.

## 5 Bottom Vertical Current Conduction Layer

On top of the bottom interspaced dielectric current conduction layer BDC 21350 is deposited of a bottom vertical current conduction layer BVC 21400 with thickness  $d_{BVC}$  21400d, layer width  $w_{BVC}$  21400w, and an averaged refractive index  $n_{BVC}$  21400n. The layer width  $w_{BVC}$  is the dimension of that layer in a horizontal direction perpendicular to the direction of the optical beam propagation.

## Electro-Active Layer

On top of the bottom vertical current conduction layer BVC 21400 is deposited of an electro-active layer EC 21500 with thickness  $d_{EC}$  21500d, width  $w_{EC}$  21500w, an averaged refractive index of the entire layer given by  $n_{EC}$  21500n, and an averaged absorption coefficient of the entire layer given by  $\alpha_{EC}$  21500a. The refractive index averaging is given in a similar way as illustrated by Eq. (13). The refractive index  $n_{EC}$  or the optical absorption coefficient  $\alpha_{EC}$  ( $\alpha_{EC} > 0$  means optical absorption and  $\alpha_{EC} < 0$  means optical gain) describing the fraction of energy absorbed per unit beam propagation length of the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The guided optical beam in the electro-active layer BEC 21140 in this electro-active waveguiding core structure EWCoS 22600 has a propagating refractive index  $n_{BEC}$  21140n. While in a preferred embodiment described below, the EC layer is made of semiconductor, it can also be any other active material according to various embodiments of the current invention. For example, it can be ferroelectric electro-optic material (e.g.  $\text{LiNbO}_3$  or  $\text{BaTiO}_3$ ) or organic electro-optic or electro-absorption material, whose refractive index or optical intensity gain and absorption coefficient  $\alpha_{EC}$  ( $\alpha_{EC} < 0$  means optical gain and  $\alpha_{EC} > 0$  means optical absorption) can be altered under an applied electric field or electric current or optical excitation beam as is well known to those skilled in the art.

In the case of an electro-optic modulator, a small averaged increment or decrement in the averaged refractive index of the electro-active layer EC 21500 is denoted as  $dn_{EC}$  21500dn so that its new average refractive index becomes  $n_{EC}(\text{new}) = n_{EC} + dn_{EC}$  will cause a change in the

propagating refractive index  $n_{BEC}$  21140n by  $dn_{BEC}$  21140dn from  $n_{BEC}$  to  $n_{BEC}(new)=n_{BEC} + dn_{BEC}$  due to the overlapping of the optical beam energy with the material regions in which  $dn$  is non-zero.

In the case of an optical amplifier or an electro-absorption modulator, a small averaged  
 5 increment or decrement in the averaged optical intensity absorption/gain coefficient of the electro-active layer EC 21500 is denoted as  $d\alpha_{EC}$  21500da so that its new average optical intensity loss/gain coefficient becomes  $\alpha_{EC}(new) = \alpha_{EC} + d\alpha_{EC}$  will cause a change in the absorption/gain coefficient  $\alpha_{BEC}$  21140a of the optical beam by  $d\alpha_{BEC}$  21140da from  $\alpha_{BEC}$  to  $\alpha_{BEC}(new)=\alpha_{BEC} + d\alpha_{BEC}$  due to the overlapping of the optical beam energy with the material  
 10 regions in which  $d\alpha$  is non-zero.

### Top Vertical Current Conduction Layer

On top of the electro-active layer EC 21500 is deposited of a top vertical current conduction layer TVC 21600 with thickness  $d_{TVC}$  21600d, width  $W_{TVC}$  21600w, and an averaged refractive  
 15 index  $n_{TVC}$  21600n

### Top Interspaced Dielectric Current Conduction Layer

On top of the top vertical current conduction layer TVC 21600 is deposited of a top interspaced dielectric conduction layer TIDC 21650 with thickness  $d_{TIDC}$  21650d, width  $w_{TIDC}$   
 20 21650w, and an averaged refractive index  $n_{TIDC}$  21650n. This layer is optional in that when thickness  $d_{TIDC}$  21650d is zero, this layer does not exist.

### Top Vertical/Side Conduction and Ohmic Contact Layer

On top of the top interspaced dielectric conduction layer TIDC 21650 is deposited of a top  
 25 vertical/side conduction and Ohmic contact layer TVSCOC 21700 with thickness  $d_{TVSC}$  21700d, width  $w_{TVSC}$  21700w, and an averaged refractive index  $n_{TVSC}$  21700n.

### Top Metal Contact Pads

In one embodiment (**Fig. 16a**), on top of the top vertical/side conduction and Ohmic contact  
 30 layer TVSCOC 21700 is deposited of a first top right metal contact pad FTRM 21800R with thickness  $d_{FTRM}$  21800Rd, width  $w_{FTRM}$  21800Rw, and length  $g_{FTRM}$  21800Rg. FTRM 21800R is typically to the right end on the top of TVSCOC 21700. In another embodiment (**Fig. 16b**), On top of the top

vertical/side conduction and Ohmic contact layer TVSCOC 21700 is deposited of a first top left metal contact pad FTLM 21800L with thickness  $d_{FTLM}$  21800Ld, width  $w_{FTLM}$  21800Lw, and length  $g_{FTLM}$  21800Lg. FTLM 21800L is typically to the left end on the top of TVSCOC 21700. In as yet another embodiment (**Fig. 16C**), on top of the top vertical/side conduction and Ohmic contact layer TVSCOC 21700 is deposited of a first top middle metal contact pad FTMM 21800M with thickness  $d_{FTMM}$  21800Md, width  $w_{FTMM}$  21800Mw, and length  $g_{FTMM}$  21800Mg. FTMM 21800M is typically at the middle part on the top of TVSCOC 21700. Middle part is the portion closest to the beam BEC 21140. This case shown by FIG. 16C is particularly applicable when the top vertical/side conduction and Ohmic contact layer TVSCOC 21700 is an Ohmic Transparent Conductor (OTC) or Low-Refractive-Index Ohmic Transparent Conductor (LRI-OTC).

In an exemplary embodiment, only either the first top left, first top middle, or the first top right metal contact pad is present. In another exemplary embodiment, plurality of such top metal contact pads are present. The exact location of these top metal contact pads can be in many other locations beside the left or right location shown as long as the top metal contact pads are in electrical contact with the top vertical/side conduction and Ohmic contact layer TVSCOC 21700.

### **Top Metal Electrodes**

On top of the first top left metal contact pad FTLM 21800L is a first top left metal electrode FTLME 21130L. On top of the first top middle metal contact pad FTMM 21800M is a first top middle metal electrode FTMME 21130M. On top of the first top right metal contact pad FTRM 21800R is a first top right metal electrode FTRME 21130R. In an exemplary embodiment, only either the first top left, first top middle, or the first top right metal electrode are present. In another exemplary embodiment, plurality of such top metal electrodes is present. The exact locations of these top metal electrodes can be in many other locations beside the left or right location shown as long as the top metal electrodes are in electrical contact with the respective top metal contact pads.

### **Electro-Active Waveguiding Core Structure and Central Waveguide Core Layer**

A layer or several layers that are in spatial proximity to the electro-active layer EC 21500 form an electro-active waveguiding core structure EWCoS 22600 at least a portion of it contains a central waveguide core layer WCo 22600Co. For the purpose of illustration and not limitation, a particular exemplary embodiment of an electro-active waveguiding core structure EWCoS 22600

is formed by the bottom vertical current conduction layer BVC 21400, the top vertical current conduction layer TVC 21600, and the electro-active layer EC 21500 as shown by Fig. 17. However, this electro-active waveguiding core structure can also be formed by any other layer or collection of layers as long as it is in spatial proximity to the electro-active layer so that the optical beam guided by it will have a reasonable amount of optical energy in the electro-active layer. The central waveguide core layer WCo 22600Co has an averaged refractive index  $n_{WCo}$  22600Con higher than the refractive index of most of the materials surrounding it. As is known to those skilled in the art, a waveguide core only needs its refractive index to be generally higher than the refractive indices of most of its surrounding materials in order to confine and guide optical beam (e.g. one example of such waveguides is commonly known as “rib waveguide” or “ridge waveguide”). For illustration and not limitation, in an exemplary embodiment, the central waveguide core layer WCo 22600Co is the electro-active layer EC 21500. As is known to those skilled in the art, the central waveguide core layer WCo 22600Co can also be in part of layer 21400 or layer 21600.

The central waveguide core layer WCo 22600Co has an averaged refractive index  $n_{WCo}$  22600Con higher than the refractive indices of most its surrounding and confines optical beam energy of beam BEC 21140, called the beam electro-active or beam EC, in the vertical and horizontal directions so that the peak of the beam intensity is within or near the central waveguide core layer 22600Co, and the optical beam is said to be a guided optical beam. The guided optical beam BEC 21140 in this electro-active waveguiding core structure EWCoS 22600 has a propagating refractive index  $n_{BEC}$  21140n that is smaller than the material refractive index of the central waveguide core layer  $n_{WCo}$  22600Con so that  $n_{BEC} < n_{WCo}$ . This criterion can be taken as the definition of the material region that made up the waveguide core (i.e. it is the region in which the material refractive index is higher than the beam propagating refractive index  $n_{BEC}$ ).

#### **Electro-Active Waveguide Core and Cladding Regions for Beam EC**

As is known to those skilled in the art, the entire electro-active waveguide core region for beam EC is the material region occupied by the beam EC, BEC 21140, in which the refractive index of the material is generally higher than  $n_{BEC}$  21140n. As is also known to those skilled in the art, the electro-active waveguide cladding regions for beam EC are the material regions occupied by the beam in which the refractive index of the material is generally lower than  $n_{BEC}$ .

For the purpose of discussion, one may take the electro-active waveguiding core structure EWCoS 22600 mentioned above as defined by this electro-optic waveguide core region.

Thus, the electro-active layer 22500 may be or may not be part of the waveguide core region for beam guided in the EC-layer BEC 21140 as long as the electro-active layer 22500 is in spatial proximity to the waveguide core region for EC-layer beam BEC 21140 so that a reasonable amount of the beam's optical energy is in the electro-active layer. Even if the electro-active layer 22500 is part of the waveguide core region, it is not necessarily the entire waveguide core region for EC-layer beam BEC 21140.

## 10 Beam Transport to Electro-Active Waveguide Core Structure

Most of the input optical beam energy of input beam IBM 22140 is transported from input tapering waveguide core ITWCo 22300 to the electro-active waveguide core structure EWCoS 22600, through the input tapering waveguide region between  $z_1 = z_{1ALS}$  22300 $z_{1ALS}$  and  $z_1 = g_{ITWCo}$  22300g, where the tapering waveguide core width  $w_{ITWCo-z_1}$  22300w- $z_1$  varies to a value of  $w_{ITWCo-g}$  at  $z_1 = g_{ITWCo}$  22300g from its value at  $z_1 = z_{1ALS}$  22300 $z_{1ALS}$  (it can be the same value as, smaller than, or larger than its value at  $z_1 = z_{1ALS}$  22300 $z_{1ALS}$ ). In a preferred embodiment, for the purpose of illustration and not limitation, this is enabled by reducing the tapering waveguide core width from a value approximately equal to or larger than half the optical wavelength in the waveguide core given by  $\lambda_{bm}/(2 * n_{ITWCo})$ , to well below half the optical wavelength in the waveguide core given by  $\lambda_{bm}/(2 * n_{ITWCo})$  so that  $W_{ITWCo-g} \ll \lambda_{bm}/(2 * n_{ITWCo})$ , where \* is numerical multiplication. More exactly, it is reduced from a width that is a width that enables the optical energy to be well confined in the waveguide core ITWCo 22300 just before it enters the ALS 22500 to a width (after it enter the ALS 22500) such that the optical energy is no longer well confined in the waveguide core ITWCo 22300 after it enters the ALS 22500 (the width for no longer well-confined is defined by the beam confinement after the taper waveguide core enters ALS 22500). Well confined means over 50% of the beam energy is in the waveguide core ITWCo 22300. Depending on the application situation, this can mean a smaller width (e.g. if the refractive index of the EC layer is approximately equal to or lower than the refractive index of the input tapering waveguide). It can also maintain the same width or even go to a larger width (e.g. if the refractive index of the EC layer is higher than the refractive index of the input tapering waveguide).

After the energy is transported to electro-active waveguide core structure EWCoS 22600

that contains the electro-active layer EC 21500, the optical beam is denoted as optical beam in the electro-active region or EC layer beam, BEC 21140.

### Output Connecting Waveguide

Output connecting waveguide core OCWCo 28200. The output connecting waveguide core OCWCo 28200 is fabricated on an output connecting-waveguide bottom cladding material OCWBCd 28200B disposed on a substrate SUB 21100 (Fig. 18).

In one exemplary embodiment shown in Fig. 19, illustrating an exemplary embodiment of the cross section at location C-C' of Fig. 18, to the top of the output connecting waveguide core is further deposited with output connecting waveguide top cladding material OCWTCd 28200T (FIG. 19). Bottom refers to direction closer to the substrate and top refers to direction away from the substrate. To the left of the input connecting waveguide core is deposited with output connecting waveguide left cladding material OCWLCd 28200L and to the right of the waveguide core is disposed with output connecting waveguide right cladding material OCWRCd 28200R. Right or left is taking the direction of beam propagation as the front direction and right or left means relative to this front direction. The division of the cladding into four different material regions as illustrated by FIG. 19 is for the purpose of discussion and not limitation as these can be all the same materials or there can be more than 4 material regions forming plurality of different material regions as long as these regions act as waveguide cladding materials with effective refractive index generally smaller than the effective refractive index of the waveguide core OCWCo 28200 so that the light beam power is confined near the region of the waveguide core OCWCo 28200, as is well known to those skilled in the art. The cladding material is a general designation that can include "air" or "vacuum" or transparent dielectric material as the material.

### Output Connecting Waveguide Region

The output connecting waveguide core OCWCo 28200 is made up of a material or mixture of materials with an averaged material refractive index  $n_{OCWCo\ 28200n}$ , has a thickness  $d_{OCWCo\ 28200d}$ , and width  $W_{OCWCo\ 28200w}$ . Let the refractive index of the bottom input connecting-waveguide bottom cladding material be  $n_{OCWBCd\ 28200Bn}$ . Let the refractive index of the top cladding material OCWTCd 28200T be  $n_{OCWTCd\ 28200Tn}$ , the refractive index of the left cladding material OCWLCd 28200L be  $n_{OCWLCd\ 28200Ln}$ , and the refractive index of the right

cladding material OCWRCd 28200R be  $n_{OCWRCd\ 28200Rn}$ . The waveguide core 28200 and the claddings 28200T, 28200B, 28200R, 28200L, together forms output connecting waveguide OCWG 28200WG.

The vertical confinement of the optical beam, called output optical beam OBM 28140, in the output connecting waveguide is due to the refractive-index difference between the top and bottom waveguide claddings and the waveguide core and the claddings generally have lower refractive indices than that of the waveguide core so that  $n_{OCWTCd} < n_{OCWC0}$  and  $n_{OCWBCd} < n_{OCWC0}$ . The horizontal confinement of the optical beam is due to the refractive-index difference between the left and right waveguide claddings and the waveguide claddings generally have lower refractive indices than that of the waveguide core so that  $n_{OCWRCd} < n_{OCWC0}$  and  $n_{OCWLCd} < n_{OCWC0}$ . The vertical direction is the direction perpendicular to the substrate plane and the horizontal direction is the direction parallel to the substrate plane. The output beam has a propagating refractive index given by  $n_{OBM\ 28140n}$ .

An important quantity in terms of waveguide mode confinement is the refractive index contrast between the averaged refractive index of the waveguide core and its immediate surrounding cladding materials called the refractive-index difference  $n_{Rd}$  defined by  $n_{Rd}^2 = \square n_{Co}^2 - n_{Cd}^2$ , where  $n_{Co}$  is the refractive index of the waveguide core (e.g.  $n_{Co} = n_{OCWC0}$ ) and  $n_{Cd}$  is the refractive index of the waveguide cladding (e.g.  $n_{Cd} = n_{OCWBCd}$  or  $n_{OCWTCd}$  or  $n_{OCWRCd}$  or  $n_{OCWLCd}$ ) or an averaged of them thereof given by  $n_{aOCWCd\ 28200aCdn}$ . The refractive-index averaging is more accurately done as averaged of its square values which are their dielectric constant  $\square = n^2$ , as illustrated by Eq. (13).

Likewise the waveguide core can also be made up of one or plurality of materials, and  $n_{OCWC0} = n_{aOCWC0}$  can also be an averaged refractive index of the "m" materials with slightly different refractive indices  $n_{OCWC01}, n_{OCWC02}, n_{OCWC03} \dots n_{OCWC0m}$ , that made up of the waveguide core materials.

### Output Beam Coupler Structure (OBCS) Region

Fig. 20 shows the output beam coupler structure (OBCS) comprises at least a tapering waveguide section (preferably tapering from wide to narrow but can also maintain the same width or taper from narrow to wide as will be elaborated below) connected to the input waveguide. Optionally, the active layer structure ALS on top of the output tapering waveguide section can also be tapering in the form of an up taper (preferably tapering from narrow to wide in the

direction toward the active layer structure ALS, but can also maintain the same width or taper from wide to narrow). See for example **Fig. 20b**.

Specifically, the energy of the electro-active beam BEC 21140 in the electro-active waveguiding core structure EWCoS 22600 is coupled efficiently to the output optical beam IBM 28140 energy in the output connecting waveguide core OCWCo 28200 via propagating through an output connecting-waveguide taper region. The output connecting-waveguide taper region has a output tapering waveguide core OTWCo 28300. The output tapering waveguide core at a location  $z_2$  is denoted by OTWCo- $z_2$  28300 $z_2$  (Fig. 19a), at which the width of the tapering waveguide core is denoted by  $w_{\text{OTWCo-}z_2}$  28300 $w$ - $z_2$ . The distance or location parameter  $z_2$  is given by the distance measured from the beginning point of the taper that is at a point along the output connecting waveguide core OCWCo 28200, typically outside (or away from) the ALS region. It is changed from its input value at  $z_2=0$   $w_{\text{OTWCo-}z_2=0}$  28300 $w$ - $z_2=0$  of  $w_{\text{OTWCo-}z_2=0}=w_{\text{OCWCo}}$  28200 to another width (that can be the same width) at  $z_2>0$   $w_{\text{OTWCo-}z_2>0}$  28300 $w$ - $z_2>0$ . The thickness of the tapering waveguide core is  $d_{\text{OTWCo-}z_1}$  28300 $d$ - $z_2$  and its refractive index is  $n_{\text{OTWCo-}z_1}$  28300 $n$ - $z_2$ . Typically, though not always,  $d_{\text{OTWCo-}z_2}$  28300 $d$ - $z_2$  and  $n_{\text{OTWCo-}z_2}$  28300 $n$ - $z_2$  are constant value in  $z_2$  so we can drop the  $z_2$  designation with  $d_{\text{OTWCo-}z_2}=d_{\text{OTWCo}}$  28300 $d$  and  $n_{\text{OTWCo-}z_2}=n_{\text{OTWCo}}$  28300 $n$ . In a preferred embodiment,  $d_{\text{OTWCo-}z_2}$  is about the same value as  $d_{\text{OCWCo}}$ . The tapering may be such that  $w_{\text{OTWCo-}z_2}$  is a linear function of  $z_2$  or quadratic function of  $z_2$  (i.e. depending on  $z_2^2$ ), but can also be of any curvilinear function of  $z_2$ . Let  $g_{\text{OTWCo}}$  denote the total length of this tapering waveguide.

The end of the taper at  $z_2=g_{\text{OTWCo}}$  28300 $g$ , typically inside (or toward) the ALS region at which the width of the waveguide core is  $w_{\text{OTWCo-}g}$  28300 $w$ - $g$ , is connected to output supporting structure OSTR 29200 that may be a continuation from and in some way physically connected to the input supporting structure ISTR 21200 or may be independent of it. While illustrated as a line that is continuation of the connecting waveguide material with a narrow width and air or other low refractive index materials surrounding its side, the output supporting structure can be random dots or any shape of small amount of any materials that have a low “effective refractive index” or small “averaged refractive index” (e.g. as defined by Eq. (13)) as is known to those skilled in the art, comparing to the refractive index of the waveguide core  $n_{\text{WCo}}$  22600 $n$  in the electro-active waveguiding core structure EWCoS 22600, resulting in an effective averaged refractive index  $n_{\text{aOSTR}}$  29200 $n$ a for this entire layer of supporting structure. The output

supporting structure OSTR 29200 may continue to guide wave or just acts as a supporting structure, depending on application scenarios.

In an exemplary embodiment, the output supporting structure OSTR 29200 is a narrow line. In that particular case, we can describe it as having a width  $w_{OSTR\ 29200w}$ , thickness  $d_{OSTR\ 29200d}$ , and length  $g_{OSTR\ 29200g}$ . The length  $g_{OSTR\ 29200g}$  may be zero. In that case, output supporting structure OSTR 29200 does not exist (the thin ALS film can still be supported by its corners or sides, but not directly below). In a preferred embodiment,  $d_{OSTR}$  is about the same value as  $d_{OCWC_0}$ . At some point the output supporting structure OSTR 29200 merges with the input supporting structure ISTR 21200 and thus ISTR 21200 and OSTR 29200 may be used interchangeably.

In region outside the ALS region, the vertical confinement of the optical beam along the taper is due to the refractive-index difference between the tapering waveguide core and the top and bottom tapering waveguide claddings at the location  $z$  defined above: OTWTCd-z2 28300T-z2 (refractive index  $n_{OTWTCd-z1\ 28300Tn-z2}$ ) and OTWBCd-z1 28300B-z2 (refractive index  $n_{OTWBCd-z1\ 28300Bn-z2}$ ) and the waveguide core and the claddings generally have lower refractive indices than that of the waveguide core so that the refractive index  $n_{OTWTCd-z2} < n_{OTWC_0-z2}$  and  $n_{OTWBCd-z2} < n_{OTWC_0-z2}$ . The horizontal confinement of the optical beam is due to the refractive-index difference between the left and right waveguide claddings at  $z2$ : OTWLCd-z2 28300L-z2 (refractive index  $n_{OTWLCd-z2\ 28300Ln-z2}$ ) and OTWRCd-z2 28300R-z2 (refractive index  $n_{OTWRCd-z2\ 28300Rn-z2}$ ), and the waveguide claddings generally have lower refractive indices than that of the waveguide core so that  $n_{OCWRCd-z2} < n_{OCWC_0-z2}$  and  $n_{OCWLCd-z2} < n_{OCWC_0-z2}$ . The vertical direction is the direction perpendicular to the substrate plane and the horizontal direction is the direction parallel to the substrate plane. Again, there can be one or a plurality of cladding material regions and the four cladding material regions are mentioned for the purpose of illustration and not limitation.

In an exemplary embodiment,  $n_{OTWTCd-z2} = n_{OTWBCd-z2} = n_{OTWLCd-z2} = n_{OTWRCd-z2} = n_{OCWTCd}$ , and  $n_{OCWTCd} = n_{OCWBCd} = n_{OCWLCd} = n_{OCWRCd}$  so all the cladding indices in the tapering regions and the input connecting waveguide regions are all approximately equal. For example, these cladding regions can be filled with silicon dioxide materials with refractive index of  $n \sim 1.45$ . The refractive index of the waveguide core  $n_{OTWC_0-z2\ 28300n-z2}$  can be silicon so that  $n_{ITWC_0} = n_{OCWC_0} \sim 3.6$ , where  $n_{OCWC_0\ 28200n}$  is the refractive index of the waveguide core for the input connecting waveguide.

On top of the tapering waveguide core OTWCo 28300 starting at  $z_2=z_{2ALS}$  28300 $z_{2ALS}$ , is laid with an active layer structure ALS 22500. Typically  $z_{2ALS}$  is before  $g_{OTWCo}$  so that  $0 < z_{2ALS} < g_{OTWCo}$ . An "active layer" is a material layer that can give optical gain or optical absorption or change in the refractive index. The various embodiments of this active layer structure ALS 22500 have already been described above.

### Active Layer Structure-Beam Transport from the Structure to Output

Most of the output optical beam energy of beam OBM 28140 is transported to output tapering waveguide core OTWCo 28300 from the electro-active waveguiding core structure EWCoS 22600, through the output tapering waveguide region that typically lies inside the ALS region, between  $z_2 = g_{OTWCo}$  28300g and  $z_2 = z_{2ALS}$  28300 $z_{2ALS}$ , where the tapering waveguide core width  $w_{OTWCo-z_2}$  28300w- $z_2$  varies from a value of  $w_{OTWCo-g}$  at  $z_2 = g_{OTWCo}$  28300g to a value of  $w_{OTWCo-z_{2ALS}}$  at  $z_2 = z_{2ALS}$  28300 $z_{2ALS}$  (it can be the same value as, smaller than, or larger than its value at  $z_2 = z_{2ALS}$  28300 $z_{2ALS}$ ). In a preferred embodiment, for the purpose of illustration and not limitation, this is enabled by changing the tapering waveguide core width at  $z_2 = z_{2ALS}$  28300 $z_{2ALS}$  from a value approximately equal to or larger than half the optical wavelength in the waveguide core given by  $\lambda_{bm}/(2 * n_{OTWCo})$ , to well below half the optical wavelength in the waveguide core at  $z_2 = g_{OTWCo}$  28300g given by  $\lambda_{bm}/(2 * n_{OTWCo})$  so that  $w_{OTWCo-g} \ll \lambda_{bm}/(2 * n_{OTWCo})$ , where  $*$  is number multiplication. More exactly, it is increased from a narrow width (in a region inside the ALS 22500) for which the optical energy is not well confined in the waveguide core OTWCo 28300 (the width for not well-confined is defined by the beam confinement in the waveguide core OTWCo 28300) to a wider width that enables the optical energy to be well confined in the waveguide core OTWCo 28300 just around when it exits the ALS 22500 region.

Well confined means over 50% of the beam energy is in the waveguide core OTWCo 28300. Depending on the application situation, this can mean a smaller width (e.g. if the refractive index of the EC layer is approximately equal to or larger than the refractive index of the input tapering waveguide). It can also maintain the same width or even go to a larger width (e.g. if the refractive index of the EC layer is higher than the refractive index of the input tapering waveguide).

After the energy is transported from the electro-active waveguiding core structure EWCoS 22600 that contains the electro-active layer EC 21500 down to the output taper at  $z_2 = z_{2ALS}$  and

further propagated to the taper starting location at  $z_2=0$  where the taper core width is  $w_{OTWCo-z_2=0}$  28300  $w_{z_2=0}$  and  $w_{OTWCo-z_2=0}=w_{OCWCo}$  28200, the optical beam is denoted as output optical beam or beam OBM 28140. Note that at  $z_2=0$ , the output tapering waveguide core OTWCo- $z_2$  28300  $z_2$  is joined to output connecting waveguide core OCWCo 28200.

5

### Length of Active Layer Structure

The active layer structure ALS runs a length from the input tapering waveguide core ITWCo 22300 at  $z_1=z_{1ALS}$  to the output tapering waveguide core OTWCo 28300 at  $z_2=z_{2ALS}$ . Along the ALS structure, the distance from  $z_1=z_{1ALS}$  is parameterized as coordinate  $z$ . Location 10  $z$  thus measures a specific location along the length of the active layer structure ALS 22500. The total length of ALS 22500 from  $z_1=z_{1ALS}$  to  $z_2=z_{2ALS}$  is called the structure length of the modulator  $SL_{mod}$  22550. Coordinate  $z$  ends at  $z_2=z_{2ALS}$  at which  $z=SL_{mod}$ .

Along  $z$ , the various widths and thicknesses of each of the layers in the ALS may vary and do not necessarily have to stay constant. As is known to those skilled in the art, such variation in 15 widths and thicknesses will not affect the general performance of the modulator. In addition, there may be more or fewer layers in the ALS other than specified as long as the functionalities of those layers specified are equivalently performed by the additional or fewer layers. As is known to those skilled in the art, such variations will not affect the general performance of the modulator. Hence, the various ALS structural variations as described above are for the purpose of 20 illustration and not limitation.

### Active Layer Structure-Electro Active Layer

The active material ACM 21500M in EC layer 21500 can be any active material as is known to those skilled in the art in which an applied electric field will change its refractive index 25 or optical absorption or optical gain in at least a portion of the material. The entire structure described above can be used with any active material in layer 21500. While we illustrate a particular semiconductor active material below, it is only one of the many possibilities, and is to illustrate a particular preferred embodiment of the intensity or phase modulator in the present invention. They are not meant to limit the scope of the invention.

30

### Semiconductor EC Material Layer

As noted, the electro-active layer EC need not be made of semiconductor materials. As an

exemplary embodiment, in the case for which the electro-active layer is made of semiconductor based material as shown in **Fig. 21**, the structure in the electro-active layer could comprise a PN junction 21500PN in which a first P-layer 21500LP<sub>1</sub> with P-type carrier dopant or called P-dopant (i.e. the resulting carriers from the dopant atoms are holes) and dopant density given by P<sub>1</sub>, 21500P<sub>1</sub> is vertically physically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer 21500LN<sub>1</sub> with N-type carrier dopant or called N-dopant (i.e. the resulting carriers from the dopant atoms are electrons) and dopant density given by N<sub>1</sub> 21500N<sub>1</sub>. Depending on the application situations, the electro-active layer may be the entire PN structure itself or may be part of the PN structure or may be just electrically connected to the PN structure.

Alternatively, the electro-active layer structure could also comprise a PqN junction 21500PqN in which a first P-layer 21500LP<sub>1</sub> with P-dopant and dopant density given by P<sub>1</sub> 21500P<sub>1</sub> is connected to a middle q-layer with either N dopant, P dopant, or being intrinsic "I" (i.e. commonly means with very low dopant or no dopant or being an Intrinsic semiconductor material) labeled as 21500MLq<sub>m</sub> (e.g. it will be labeled as 21500MLI<sub>m</sub> if it is intrinsic (i.e. undoped or being an intrinsic semiconductor material), 21500MLN<sub>m</sub> if it is N doped, and 21500MLP<sub>m</sub> if it is P-doped; m is an integer to sub-label the layer number and dopant density given by Mq<sub>m</sub>, 21500Mq<sub>m</sub> (e.g. it will be labeled as 21500MI<sub>1</sub> if it is intrinsic I<sub>1</sub>, 21500MN<sub>1</sub> if it is N<sub>1</sub> doped, and 21500MP<sub>1</sub> if it is P<sub>1</sub>-doped), and the middle q-layer is further connected to a first N-layer 21500LN<sub>1</sub> with N<sub>1</sub>-dopant and dopant density given by N<sub>1</sub> 21500N<sub>1</sub>. This middle q-layer may be made up of plurality of one or more doped layers 21500MLq<sub>1</sub>, 21500MLq<sub>2</sub>, ... 21500MLq<sub>T</sub>, where T is an integer specifying the number of layers. Depending on the application situations, the electro-active layer may be the entire PqN structure itself or may be part of the PN structure or may be just electrically connected to the PqN structure.

Further alternatively, the electro-active layer structure could comprise a NqN junction 21500NqN in which a first N-layer 21500LN<sub>1</sub> with N-dopant and dopant density given by N<sub>1</sub> 21500N<sub>1</sub> is connected to a middle q-layer with either N dopant, P dopant, or being intrinsic "I" (i.e. commonly means with very low dopant or no dopant or being an intrinsic semiconductor material) labeled as 21500MLq<sub>m</sub> (e.g. it will be labeled as 21500MLI<sub>m</sub> if it is intrinsic (i.e. undoped or being an Intrinsic semiconductor material), 21500MLN<sub>m</sub> if it is N doped, and 21500MLP<sub>m</sub> if it is P-doped; m is an integer to sub-label the layer number) and dopant density given by Mq<sub>m</sub>, 21500Mq<sub>m</sub> (e.g. it will be labeled as 21500MI<sub>1</sub> if it is intrinsic I<sub>1</sub>, 21500MN<sub>1</sub> if it

is  $N_1$  doped, and 21500MP<sub>1</sub> if it is P<sub>1</sub>-doped), and the middle q-layer is further connected to a second N-layer 21500LN<sub>2</sub> with N<sub>2</sub>-dopant and dopant density given by N<sub>2</sub> 21500N<sub>2</sub>. This middle q-layer may be made up of plurality of one or more doped layers 21500MLq1, 21500MLq2, ... 21500MLqT, where T is an integer specifying the number of layers. Depending on the application situations, the electro-active layer may be the entire NqN structure itself or may be part of the NqN structure or may be just electrically connected to the NqN structure.

Further alternatively, the electro-active layer structure could comprise a XqY junction 21500NqN in which a first X-layer 21500LX<sub>1</sub> is connected to a middle q-layer with either N dopant, P dopant, or being intrinsic "I" (i.e. commonly means with very low dopant or no dopant or being an intrinsic semiconductor material) labeled as 21500MLq<sub>m</sub> (e.g. it will be labeled as 21500MLL<sub>m</sub> if it is intrinsic (i.e. undoped or being an Intrinsic semiconductor material), 21500MLN<sub>m</sub> if it is N doped, and 21500MLP<sub>m</sub> if it is P-doped; m is an integer to sub-label the layer number) and dopant density given by Mq<sub>m</sub>, 21500Mq<sub>m</sub> (e.g. it will be labeled as 21500MI<sub>1</sub> if it is intrinsic I<sub>1</sub>, 21500MN<sub>1</sub> if it is N<sub>1</sub> doped, and 21500MP<sub>1</sub> if it is P<sub>1</sub>-doped), and the middle q-layer is further connected to a second Y-layer 21500LY<sub>1</sub>. This middle q-layer may be made up of plurality of one or more doped layers 21500MLq1, 21500MLq2, ... 21500MLqT, where T is an integer specifying the number of layers. Depending on the application situations, the electro-active layer may be the entire XqY structure itself or may be part of the XqY structure or may be just electrically connected to the XqY structure. In the above, X<sub>1</sub> and Y<sub>1</sub>, each may either be N-doped, P-doped, or being an intrinsic "I" semiconductor, and X<sub>1</sub> and Y<sub>1</sub> can be doped differently with different dopant type.

The P and N dopants may have spatially varying profiles in terms of their doping density (number of dopant carriers per unit volume) and the profiles may vary from one application to another. While there are various mode of operation for the active material, a commonly used mode is to apply reverse bias voltage V<sub>R</sub> 21500VR across the abovementioned PN or PqN layers (with negative voltage on the P side and positive voltage on the N side), so that an electric field E<sub>EC</sub> is generated to go across part of the EC layer 21500.

Depending on the application, for the abovementioned PN or PqN or NqN or XqY structure, the N<sub>1</sub> doped layer may be above or below the P<sub>1</sub>-doped layer (above means further away from the substrate and below means closer to the substrate). The EC layer 21500 may have quantum wells in the structure, typically in the q layer or close to the PN junction. At least one of the first P-layer, first N-layer, or the middle q-layer contains at least one quantum well. One or

more quantum wells can also be in both the first P-layer and first N-layer or in all the three layers: first P-layer, first N-layer, and middle q-layer or just in the middle q-layer. The quantum wells can be strained, unstrained, or double-well or multiple-well quantum wells as is known to those skilled in the art. It can also have no quantum well.

5 As an exemplary illustration, without quantum wells and without carrier doping in the q layer, in the case of EO modulation, the main electro-optic phase shift will be due mainly to linear electro-optic (LEO) effect. If q has carrier doping (N or P) then it will add plasma (PL) and bandfilling (BF) effect. If q layer has quantum wells, then quantum-confined stark effect (QCSE) will be added to enhance the EO phase shift. If the PqN is forward bias, then a lot of carriers will  
10 be injected into the q layer, causing refractive index change due to carrier injections or depletions. This may give significant phase shifts in the electro active (EC) material layer just due to PL and BF effects. However such modulator will be slow as removing the carrier is a slow process, typically at nano second speed or slower (e.g. <1GHz). In order to go to high modulation frequency (e.g. >1GHz), typically reverse biased is applied. In that case the electric field in the q  
15 layer will cause carrier depletion which will also give rise to PL or BF effects, and the electric field will cause LEO effect (with or without quantum wells) and QCSE also (with use of quantum wells). The PL, BF, QCSE can also cause the absorption coefficient  $\alpha_{EC}$  to change ( $\alpha_{EC}>0$  gives optical absorption) resulting in electro-absorption modulation, depending on the operating wavelength. As is known to those skilled in the art, for electro-absorption modulation, the  
20 operating optical wavelength is typically at relatively close to the band edge (edge of the material or quantum-well bandgap). For electro-optic modulation, the operating optical wavelength is typically at relatively far from the band edge (edge of the material or quantum-well bandgap). With carrier injection, it may also give population inversion resulting in optical gain ( $\alpha_{EC}<0$  gives optical gain) and hence giving rise to optical gain induced optical intensity or phase modulation.  
25 These effects due to change in  $\alpha_{EC}$  will result in electro-absorption or gain based modulators, instead of electro-optic modulators, and are a particular embodiment of the present invention.

The averaged incremental change in the refractive index  $dn_{EC}$  21500dn or change in the optical intensity loss/gain coefficient  $d\alpha_{EC}$  21500da of at least part of the material in the semiconductor electro-active layer 21500 can be caused by an applied electric field  $E_{EC}$  21500E,  
30 an electric current  $C_{EC}$  21500C, or either injection or depletion of carriers in the electro-active layer 21500 (note  $dn_{EC}$  21500dn is not the same as  $n_{EC}$  21500n, which is the averaged refractive index of the entire EC layer 21500 when there is no field).

### **Voltage and Current conduction to the Electro-Active Layer**

As shown in **Fig. 21**, the semiconductor electro-active layer EC 21500 is electrically connected to the top vertical current conduction layer TVC21600 on the top side and is electrically connected to the bottom vertical current conduction layer BVC 21400 on the bottom side. Bottom side is the side nearer to the substrate 21100. Two materials are electrically connected if an electric current can be passed between the two materials with a total electrical resistance times area lower than about  $10 \Omega\text{-cm}^2$  so that for  $10,000\mu\text{m}^2$  area, the total contact resistance is less than about  $100,000 \Omega=100\text{k}\Omega$  ( $10,000\mu\text{m}^2$  area is the area for a relatively large 5mm-long,  $2 \mu\text{m}$ -wide modulator device).

### **The use of Forward-Biased PN Junction or Tunnel PN Junction to Reduce P-dopant Optical Loss**

As an illustration but not limitation, for the EC 21500 layer, if its N layer is below the P layer, then the bottom vertical current conduction layer BVC 21400 can be (not always) an N-doped semiconductor material and the top vertical current conduction layer TVC 21600 can be (not always) a P-doped semiconductor material to enable easy current conduction without significant voltage dropped. The problem is that P-doped material has much higher (typically 10 times) electrical resistance and optical absorption than that of N-doped material at the same dopant density.

As will be noted below, this can be addressed as with use of a “forward-bias PN junction”, it is possible to make electrical connection to region of opposite dopant type without significant voltage dropped and that could have certain advantages. We will refer to this as a “PN-changing PN junction” (labeled as PNCPN junction) to distinguish it from the PN junction inside EC layer 21500. Such PNCPN junction will conduct current or voltage when it is forward biased. Note that if such a PN-changing PN junction has highly doped P and N layers, it can also be conducting electricity even when it is under a reverse bias. In that case we called it a tunnel junction as the current conduction is depending of some type of carrier tunneling across the reverse-biased junction, as is well known to those skilled in the art. Then in that case, it can be used for when the PN junction inside EC layer 21500 PN junction is either reverse or forward biased. Thus, when we call it “PN-changing PN junction”, it will be generally referred to when

the PN layer involved is either forward bias and conducting current or when it is highly doped and reverse biased but acts as a current-conducting tunneling junction.

For example, as shown in **Fig. 22a**, suppose in the abovementioned PN or PqN or XqY structure, the N doped layer is below the P-doped layer, then in that case the top vertical current conduction layer TVC 21600 can also be an  $N_2$ -doped (subscript 2 is just to label doping in this layer) semiconductor material in contact with the top layer of EC layer 21500 that is  $P_1$  doped (called layer 21500LP<sub>1</sub>), resulting in a PNCPN junction between layer 21600 and 21500 labeled as 21600-21500PNCPN.

Alternatively, as shown in **Fig. 22b**, layer TVC 21600 may start with a P-doped layer (called layer 21600LP<sub>2</sub>) with a dopant density of  $P_2$ , 21600P<sub>2</sub>, connecting to the top P-doped layer of layer EC 21500 with dopant density  $P_1$ , and the P-doped layer 21600LP<sub>2</sub> is also connected to another layer that is N doped (called layer 21600LN<sub>2</sub>) with dopant density  $N_2$ , 21600N<sub>2</sub> resulting in a PNCPN junction in layer 21600 labeled as 21600PNCPN. Then an applied voltage with negative voltage applied to the  $N_2$ -doped layer TVC 21600 will give a forward bias across the  $N_2P_2$  junction and transmit the voltage to the top  $P_1$  doped layer of EC layer 21500 that forms part of the  $P_1qN_1$  structure, resulting in reverse bias across the  $P_1qN_1$  junction in EC layer 21500. In that case, the  $N_2P_2$  layers act as a PN-changing PN junction. Likewise if the  $P_1qN_1$  junction on EC 21500 layer has  $P_1$  at the bottom connecting to an  $N_2$ -doped layer BVC 21400, then one has a PNCPN junction between 21400 and 21500 labeled as 21500-21400PNCPN junction forming the structure  $N_2P_1qN_1$  (see Fig. 22a); or one can have a PNCPN junction inside 21400 labeled as 21400PNCPN junction forming the structure  $N_1P_2P_1qN_1$  (see Fig. 22b).

The reason to effectively change the P-doped to N-doped layer via such P-N changing PN junction is because an N-doped layer typically can be doped to have a much lower electrical resistance than P-doped semiconductor material for two reasons: (1) the dopant density for N dopant typically can be higher than that of P dopant; (2) even at the same dopant density, the electrical conductivity of N doped material can typically be higher than that of P doped material by about 10 times. Note that, as is also well known to those skilled in the art, N-doped semiconductor material also typically has a much lower optical absorption than P-doped semiconductor material even if the N-type material is doped to the same electrical resistance as a P-type material (typically can be about 10 times lower in optical absorption).

This enables the use of highly N-doped layer with low electrical resistance for layer 21300, 21350, and 21400 from the bottom half up and 21700, 21650, and 21600 from the top half

down, thereby substantially lowering the series electrical resistance of the modulator structure. Low series electrical resistance will give high modulation frequency.

The example above is for the purpose of illustration and not limitation. For example, the PqN or PN junction in the electro-active layer EC 21500 may have P-doped side at the top, instead of the bottom, and a PN-changing PN junction is used so that the top layers can become N-doped materials. There are thus various variations in the use of the PN-changing PN junction as shall be obvious to those skilled in the art.

### Top vertical/side conduction and Ohmic Contact Layer

The top vertical/side conduction and Ohmic contact layer TVSCOC 21700 with thickness  $d_{TVSC}$  21700d and width  $w_{TVSC}$  21700w is also electrically connected at its bottom to the top vertical current conduction layer TVC 21600 through the top interspaced dielectric conduction layer TIDC 21650, and at its top to the top left/middle/right metal contact pad FT(L/M/R)M 21800(L/M/R) or any top metal contact pad FTXM 21800X (X refers to any of the plurality of top metal contact pads).

### Upper and Lower Waveguide Claddings of Active-Layer Structure

In one embodiment, the top vertical/side conduction and Ohmic contact layer TVSCOC 21700, with an averaged refractive index  $n_{TVSC}$  21700n, forms part of an top electro-active waveguide cladding 22600TCd for which  $n_{TVSC}$  21700n is smaller than the refractive index  $n_{WCo}$  22600Con of the central waveguide core 22600Co. In one exemplary embodiment, TVSCOC 21700 is a low-refractive-index Ohmic transparent conductor (LRI-OTC) (see illustration in Fig. 16)

The top interspaced dielectric conduction layer TIDC 21650 with an averaged refractive index  $n_{TIDC}$  21650n, in another exemplary embodiment also forms part of a top electro-active waveguide cladding 22600TCd for which  $n_{TIDC}$  21650n is smaller than the refractive index  $n_{WCo}$  22600Con of the central waveguide core 22600Co.

In as yet another embodiment, the top electro-active waveguide cladding is formed by an air or dielectric region (e.g. the dielectric region TDMR 21810 in Fig. 24 described later below) above layer TVSCOC 21700.

In one embodiment, part of a bottom electro-active waveguide cladding 22600BCd, in the case where the width  $w_{ISTR}$  of the input support structure ISTR 21200 is narrow, may be made up

of the input support structure ISTR 21200 below the bottom vertical current conduction layer BVC 21400 plus the cladding materials to its left, and right as follows: The input support structure ISTR 21200 is made up of a material or mixture of materials with a material refractive index  $n_{\text{ISTR } 21200n}$ .

5 In a preferred embodiment, for the purpose of illustration and not limitation, typically the input connecting-waveguide core ICWCo 22200, the input tapering waveguide core ITWCo 22300, and the input support structure ISTR 21200 all have a similar bottom, left and right cladding materials, though they can also have different cladding materials. For the input supporting structure ISTR 21200, let the refractive index of the left cladding material ISTRLCd 21200L be  $n_{\text{ISTRLCd } 21200Ln}$ , and the refractive index of the right cladding material ISTRRCd 21200R be  $n_{\text{ISTRRCd } 21200Rn}$ . The supporting structure 21200, the left claddings 21200L, and right cladding 21200R, together forms a material region with an effective layer averaged refractive index  $n_{\text{laISTR } 21200nla}$  that is a weighted average of  $n_{\text{ISTR } 21200n}$ ,  $n_{\text{ISTRLCd } 21200Ln}$ , and  $n_{\text{ISTRRCd } 21200Rn}$ , similar to the computation of averaged refractive index given by equation  
10 Eq.(13). The weighting for the averaging is depending on the distribution of the beam energy for guided beam BEC 21140 inside these material regions similar to that given by Eq. (13). The layer averaged material refractive index  $n_{\text{laISTR } 21200nla}$  experienced by the guided beam BEC 21140 in regions 21200, 21200L, 21200R, is typically smaller than the refractive index  $n_{\text{WCo } 22600Con}$  of the central waveguide core 22600Co. In that case, they form part of the bottom electro-active  
15 waveguide cladding 22600BCd.

However, in the case where the width  $W_{\text{ISTR}}$  of the input supporting structure ISTR 21200 is relatively wide, part of a bottom electro-active waveguide cladding 22600BCd will be made up mainly of the bottom cladding ISTRBCd 21200B below the input support structure ISTR 21200 with an averaged refractive index  $n_{\text{ISTRBCd } 21200Bn}$ , which as part of the embodiment would be  
20 filled with materials with  $n_{\text{ISTRBCd}}$  smaller than the refractive index  $n_{\text{WCo } 22600Con}$  of the central waveguide core 22600Co. In that case, substantial optical energy can be in the input supporting structure STR 21200, and the input supporting structure STR 21200 may become part of the waveguide core for beam BEC 21140.

In another embodiment, part of a bottom electro-active waveguide cladding 22600BCd  
30 may also be made up of the bottom interspaced material layer BIM 21250 (if it exists) with refractive index  $n_{\text{BIM } 21250n}$ . In one exemplary embodiment, BIM 21250 is a low-refractive-index Ohmic transparent conductor (LRI-OTC).

In as yet another embodiment, part of a bottom electro-active waveguide cladding 22600BCd may also be made up of the bottom interspaced dielectric current conduction layer BIDC 21350 with refractive index  $n_{\text{BIDC}} 21350n$ .

5 In as yet another embodiment, part of a bottom electro-active waveguide cladding 22600BCd may also be made up of the bottom side conduction and Ohmic contact layer BSCOC 21300 with refractive index  $n_{\text{BSCOC}} 21300n$ .

In as yet another embodiment, part of a bottom electro-active waveguide cladding 22600BCd may also be made up of the bottom side conduction and Ohmic contact layer ISTRBCd 21200B with refractive index  $n_{\text{ISTRBCd}} 21200Bn$ .

10 As to which layer shall be considered as the waveguide cladding is that in the waveguide cladding material region (a material region that surround the waveguide core), the energy density of the guided mode shall decay largely exponentially in a direction away from the waveguide core, as is known to those skilled in the art. This “waveguide cladding region” may be made of a single layer or spot (i.e. small cluster) of material or a collection of multiple layers or spots (i.e.  
15 small clusters) of connected materials (including air as a material). A spot is a three-dimensional cluster of material volume. The waveguide cladding refractive index  $n_{\text{Cd}}$  (e.g. as use in the in the next section) shall be taken as the averaged refractive index of this collection of multiple layers/spots of cladding materials that can have one layer/spot or plurality of layer/spots. The waveguide core shall be taken as the material region close to the center energy portion of the  
20 optical beam in which the material refractive index  $n_{\text{MAT}}$  is larger than or equal to the beam propagating refractive index  $n_{\text{BEC}}$  and the waveguide core refractive index  $n_{\text{Co}}$  (e.g. as use in the in the next section) shall be taken as the averaged refractive index of the entire core material region (which again can be composed of layers or spots of materials). For the purpose of illustration and not limitation, it is useful to divide the cladding regions to be the top waveguide  
25 cladding situated above the waveguide core, the bottom waveguide cladding situated below the waveguide core, the left waveguide cladding situated to the left of the waveguide core, and the right waveguide cladding situated to the right of the waveguide core.

### High Refractive Index Contrast and Mode-Medium Overlap

For the purpose of definition, it is useful to define a refractive index contrast parameter as described below. If a waveguide core refractive index is  $n_{Co}$  and the waveguide cladding (as defined by the exponential energy decay above) immediately adjacent to the waveguide core has a refractive index  $n_{Cd}$ , then we can define a waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{Co}^2 - n_{Cd}^2)$  and a refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{Co}^2 + n_{Cd}^2)$ . For the purpose of definition and not limitation, we define very-strongly wave guiding regime to be when  $R_{cts} > 0.5$  or  $R_{cts} = 0.5$ . It is also useful to define the medium-strongly wave guiding regime to be when  $0.5 > R_{cts} > 0.2$  or  $R_{cts} = 0.2$ , weakly guiding regime to be when  $0.2 > R_{cts} > 0.02$  or  $R_{cts} = 0.02$  and the very-weakly guiding regime to be when  $0.02 > R_{cts}$ .

In a preferred embodiment, the electro-active waveguiding core structure EWCoS 22600 is in the very-strongly guiding or medium-strongly guiding regime at least in the vertical direction (direction perpendicular to the substrate) in which the refractive index contrast of the waveguide core layer with the top and bottom cladding immediately adjacent to the electro-active waveguide core given by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  is larger than or equal to about 0.2 or is larger than or equal to about 0.5, where  $n_{Cd}$  is the refractive index of the top or bottom cladding. In the case of waveguiding core structure EWCoS 22600,  $n_{Co} = n_{WCo}$  where  $n_{WCo}$  22600Con is the averaged refractive index of the central waveguide core layer WCo 22600Co, and  $n_{Cd}$  is either  $n_{BIM}$ ,  $n_{BEDC}$ ,  $n_{laISTR}$  or  $n_{ISTRBCd}$  depending on which one(s) is(are) the bottom cladding(s).

This strong waveguiding in the vertical direction will enable much higher mode confinement that will push higher fraction of the beam energy into the electro-active layer. As a result, the phase shift in the guided beam BEC 21140 given by a change in  $n_{BEC}$  21140n under an applied voltage will be larger. This will result in substantially lower switching voltage. In order to increase this mode-medium overlapping factor, it is useful to reduce the total thickness of the electro-active waveguide core.

More precisely, it is useful to define the thickness  $d_{CORE}$  of the electro-active waveguide core as the distance between a first top boundary and a first bottom boundary. The first top boundary is the boundary between the waveguide core and the top cladding immediately adjacent to the waveguide core, and the first bottom boundary is the boundary between the waveguide core and the bottom cladding immediately adjacent to the waveguide core. If  $d_{CORE}$  is smaller than  $(\lambda_{bm} / (2 * n_{Co}))$ , the waveguide core is said to be in ultra-thin regime. If  $d_{CORE}$  is smaller than or equal to  $(\lambda_{bm} / n_{Co})$  and larger  $(\lambda_{bm} / (2 * n_{Co}))$ , then the waveguide core is said to be in very-thin

regime. If  $d_{\text{CORE}}$  is smaller than or equal to  $(1.5 \cdot \lambda_{\text{bm}}/n_{\text{Co}})$  and larger than  $(\lambda_{\text{bm}}/n_{\text{Co}})$ , the waveguide core is said to be in medium-thin regime. If  $d_{\text{CORE}}$  is smaller than  $(3 \cdot \lambda_{\text{bm}}/n_{\text{Co}})$  and larger than  $(1.5 \cdot \lambda_{\text{bm}}/n_{\text{Co}})$ , the waveguide core is said to be in the thin regime. If  $d_{\text{CORE}}$  is larger than  $(3 \cdot \lambda_{\text{bm}}/n_{\text{Co}})$ , the waveguide core is said to be in the thick regime.

5 In a preferred embodiment for the modulator of the present invention, in order to achieve additional enhanced performances such as very low modulation voltage, the electro-active waveguiding core structure EWCoS 22600 shall be in the very-strongly guiding regime, and  $d_{\text{CORE}}$  shall either be in the ultra-thin regime or very-thin regime.

10 In a preferred embodiment for the modulator of the present invention, in order to achieve additional enhanced performances such as low modulation voltage, the electro-active waveguiding core structure EWCoS 22600 shall be in the medium-strongly guiding or very-strongly guiding regime, and  $d_{\text{CORE}}$  shall either be in the ultra-thin regime, very-thin regime, or medium-thin regime.

15 In another preferred embodiment for the modulator of the present invention, the electro-active waveguiding core structure EWCoS 22600 shall be in the weakly guiding regime, and  $d_{\text{CORE}}$  shall either be in the ultra-thin, very-thin, medium-thin, or thin regime.

20 For example, if  $\lambda_{\text{bm}}=1550\text{nm}$ ,  $n_{\text{EC}}=3.0$ , then if  $d_{\text{CORE}}$  is smaller than or equal to  $(\lambda_{\text{bm}}/n_{\text{Co}})=517\text{nm}$ , it is in the very-thin regime, and if  $n_{\text{Cd}}=1.5$ , it also has  $R_{\text{cts}} > 0.5$  and hence is in the very-strongly wave guiding regime as well, which will satisfy the co-requirements. Both requirements have to be satisfied in order to draw an exemplary benefit of the present invention such as to enhance the low voltage performance of the modulator.

25 It is useful to define the electro-active field overlapping factor more precisely. Let the electric field distribution of the guided mode of optical beam BEC 21140 be given by  $E_{\text{OPT}}(x,y)$  21140E, where  $E_{\text{OPT}}$  is the electric field strength, and  $x$  and  $y$  are the coordinates in the cross-sectional area of the beam. The mode  $m$  is typically the fundamental guided mode with a single intensity peak at the beam center region. Let  $\Delta n$  21140dn be the change in the optical propagating refractive index experienced by the beam under an applied electric field  $E_{\text{EC}}(x,y)$  21500E (for the case of constant field  $E_{\text{EC}}(x,y) \sim V_{\text{EC}}/D_{\text{EC}}$ , where  $V_{\text{EC}}$  21500VEC is the applied voltage and  $D_{\text{EC}}$  21500DEC is the effective physical distance for which the voltage  $V_{\text{EC}}$  is applied across) that  
30 again has a value profile depending on the  $x$ - $y$  cross-sectional coordinates. For the case of refractive index modulation, then the phase shift  $\Delta\phi$  21140Ph experienced by an optical beam

propagating through the modulator under an applied voltage  $V(z_0, t)$ , where  $z_0$  is the propagating distance along the modulation, is given by:

$$\Delta\phi = (2\pi/\lambda_0)\Delta n,$$

$$\Delta n = \int_0^L \Gamma V(z_0, t) dz_0,$$

$$\Gamma = \frac{1}{V_{EO}} \frac{\iint (1/2)n_{eff}^2 r_{EO}(x, y) E_{EO}(x, y) |E_{OPT}(x, y)|^2 dx dy}{\iint |E_{OPT}(x, y)|^2 dx dy},$$

where  $V_{EC}$  is the applied RF voltage that gives rise to  $E_{EC}(x, y)$ ,  $r_{EO}(x, y)$  is an effective electro-optic coefficient describing how much the material's refractive index is changed under an applied field,  $n_{eff}$  is the effective refractive index of the propagating optical mode (same as  $n_{BEC}$ ). The quantity  $\Gamma$  is thus called the RF-field, optical mode, and active medium overlapping factor (also simply called the mode-medium overlapping factor). It is independent on  $V_{EC}$  as  $E_{EC}(x, y)$  is proportional to  $V_{EC}$ . The voltage  $V(z, t)$  is the actual applied voltage that may change with propagation distance  $z$  and time  $t$ .

The voltage to the entire modulator  $V_{MOD}$  is approximately given by  $V_{EC}$  assuming the voltage drop between the electro-active layers and the top or bottom electrode is small compared to  $V_{EC}$ .

While the above mode-medium overlapping factor is illustrated for the case of an electro-optic (EO) modulator, there are various other definitions of mode-medium overlapping factor more suitable for other applications such as for the case of electro-absorption (EA) modulator or the case involving optical absorption and gain medium, as is well known skilled in the art. These other definitions of mode-medium overlapping factor shall be used when appropriate and the specific definition of mode-medium overlapping factor is not meant to limit the present invention.

### Low-Refractive-Index Ohmic-Transparent-Conductor & Metal Contact Case

The difficulty of obtaining high mode-medium overlapping or tight mode confinement is that the optical mode will inevitably touch the metal contact pad if the top vertical/side conduction and Ohmic contact layer TVSCOC is the usual doped semiconductor. One way to solve this problem in the present embodiment is to utilize Low-Refractive-Index Ohmic Transparent Conductor (LRI-OTC) that is electrically conductive but having a low refractive index (the low-refractive-index criterion is defined in the section on "High-refractive-index-contrast mode confining structure in electro-active region"). In that case, the mode can be strongly confined in the electro-active waveguide core structure EWCS region and will rapidly decay in the top

electro-active waveguide cladding 22600UC. Layer 22600UC is basically the top vertical/side conduction and Ohmic contact layer TVSCOC 21700. This would be possible only if  $n_{TVSC}$  is small compared to the refractive index  $n_{WCo}$  22600Con of the central waveguide core layer WCo 22600Co. However, it is important that layer TVSCOC 21700, now made of transparent  
5 conductor, shall have Ohmic-like contact with the top vertical conduction layer TVC 21600 that may be semiconductor.

As an embodiment, layer TVSCOC 21700 is a low-refractive-index transparent conductor with Ohmic contact capability with layer TVC 21600. In that case, the material for layer TVSCOC 21700 will be called "Low-Refractive-Index Ohmic Transparent Conductor" (LRI-  
10 OTC). Ohmic transparent conductor differs from just transparent conductor as they have to have "low electrical contact resistance" with the next conduction layer in contact with it to pass current down to the electro-active layer without causing high voltage across the contact surface. For the purpose of illustration and not limitation, the next conduction layer is typically N-doped or P-doped semiconductor. Preferably, it shall also have low "low electrical contact resistance" with  
15 appropriate metal electrode. Materials for LRI-OTC include but are not limited to transparent conducting oxide (TCO) materials such as  $In_2O_3$  (or various Indium Oxides), ZnO (Zinc Oxides), ITO (Indium Tin Oxides), GITO (Gallium Indium Tin Oxides), Gallium Indium Oxide (GIO), ZITO (Zinc Indium Tin Oxides), CdO (Cadmium Oxide), or materials containing any one or more than one of these oxides.

In as yet another embodiment, layer TVSCOC 21700 can also be a low-refractive-index transparent conductor. In that case, the material for layer TVSCOC 21700 will be called "Low-Refractive-Index Transparent Conductor" (LRI-TC). Transparent conductor (TC) differs from Ohmic transparent conductor (OTC) as they do not need to have "low electrical contact resistance" with the next conduction layer in contact with it. For example, one can have  
25 modulators in which layer TVSCOC 21700 directly applies the electric field to the active material without further conducting the voltage down to the next layer. In that case, the other layers such as layer TVC 21600 may be undoped or an intrinsic semiconductor that does not conduct electric voltage or current.

In another embodiment, in order to achieve high frequency response, it is also desirable  
30 that the Ohmic contact between layer TVC 21600 and TVSCOC 21700 has low Ohmic contact resistance. Ohmic-like contact means the relation between the voltage and the current is largely linear. For the purpose of illustration and not limitation, low Ohmic contact resistance between

any two materials A and B generally means the voltage-over-current ratio for a current going between material A and material B is not substantially worse than the total sum of other electrical resistances that will affect the frequency response of the modulator.

In one exemplary embodiment, on top of layer TVSCOC 21700 with LRI-OTC material is metal pad that gives good metal Ohmic contact with the LRI-OTC material used. In an embodiment, the metal pad is the first top middle metal contact pad FTMM 21800M with thickness  $d_{FTMM}$  21800Md, width  $w_{FTMM}$  21800Mw, and length  $g_{FTMM}$  21800Mg.

This case is referred to as “top LRI-OTC-metal contact case”.

## 10 Side-Conduction and Metal Contact Case

Other alternative contacts include having layer TVSCOC 21700 to extend side way and have metal Ohmic contact on the side away from the center region of layer TVSCOC 21700 as shown in Fig. 23. In that case, Ohmic contact can be achieved from the metal to layer TVSCOC 21700 and the optical mode will not touch the metal, which can keep the optical mode to be low loss. This is referred to as “top side-conduction-metal contact case”.

Still another alternative structure involved having the “top lateral conduction geometry with metal contact” but also a top lowloss dielectric material region TDMR 21810 as shown in Fig. 24. This dielectric material can be chosen to have low refractive index and hence acting as a top electro-active waveguide cladding. Alternatively, the metal can even go on top of TDMR 21810 to make this top lateral conduction structure mechanically robust as shown in Fig. 25. Thus, there are various ways to realize what we refer to as the “top lateral conduction geometry with metal contact”.

Still another alternative structure involved having the “bottom LRI-OTC” in that the bottom interspaced material layer BIM 21250 between bottom side-conduction and Ohmic-contact layer BSCOC 21300, and ISTR 21200, with thickness  $d_{BIM}$  21250d is made of LRI-OTC. This enables a thicker layer for conducting current and voltage from the bottom electrode(s) with electrode(s) either at the bottom of the LRI-TOC layer or on top of the LRI-TOC layer (e.g. using top via hole on one or both sides of the ALS to contact the LRI-TOC layer through layer 21300) or directly on top of the bottom side-conduction and Ohmic contact layer BSCOC 21300.

### Lateral Optical Mode Confinement

Note that in another embodiment, the width  $w_{TVSC}$  21700w of layer 21700 can act on the optical mode of guided beam BEC 21140 laterally so as to confine the optical mode. Such lateral mode confinement is called “rib waveguide” structure, which is known to have low optical loss.

5 Thus, in an embodiment, layer 21700 also forms a rib-waveguide structure.

It must be understood that there are various ways to confine the optical mode laterally, including a small lateral width  $w_{EC}$  21500w for a small vertical portion of the electro-active layer 21500, which can also confine the optical mode laterally, called “lateral mode confinement” structure. Thus, in another embodiment, the electro-active layer is a “lateral mode confinement”  
10 structure.

Similarly, a small lateral width  $w_{SVC}$  21600w or  $w_{FVC}$  21400w for a small vertical portion of layer 21600 or 21400 can also confine the optical mode laterally. Thus in another embodiment, the bottom vertical conduction layer BVC 21400 is a “lateral mode confinement” structure. In as yet another embodiment, the top vertical conduction layer TVC 21600 is a “lateral mode  
15 confinement” structure.

In as yet another embodiment, the bottom interspaced dielectric current conduction layer BIDC 21350 with thickness  $d_{BIDC}$  21350d, layer width  $w_{BIDC}$  21350w, and an averaged refractive index  $n_{BIDC}$  21350n is a “lateral mode confinement” structure.

In as yet another embodiment, the bottom interspaced dielectric current conduction layer  
20 BIM 21250 with thickness  $d_{BIM}$  21250d, layer width  $w_{BIM}$  21250w, and an averaged refractive index  $n_{BIM}$  21250n is a “lateral mode confinement” structure.

In as yet another embodiment, the input supporting structure ISTR 21200 with thickness  $d_{ISTR}$  21200d, layer width  $w_{ISTR}$  21200w, and a refractive index  $n_{ISTR}$  21200n is a “lateral mode confinement” structure.

25 In as yet another embodiment, the output supporting structure OSTR 29200 with thickness  $d_{OSTR}$  29200d, layer width  $w_{OSTR}$  29200w, and a refractive index  $n_{OSTR}$  29200n is a “lateral mode confinement” structure.

In as yet another embodiment, the top lowloss dielectric material region **TDMR 21810** with thickness  $d_{TDMR}$  21810d, layer width  $w_{TDMR}$  21810w, and an averaged refractive index  $n_{TDMR}$   
30 21810n is a “lateral mode confinement” structure.

In as yet another embodiment, the top interspaced dielectric conduction layer TIDC 21650 with thickness  $d_{TIDC}$  21650d, layer width  $w_{TIDC}$  21650w, and an averaged refractive index  $n_{TIDC}$  21650n is a “lateral mode confinement” structure.

## 5 **Reducing Modulator Junction Capacitance**

In a preferred embodiment, the small lateral width  $w_{EC}$  21500W for a small vertical portion of the electro-active layer EC 21500 acts as a “lateral mode confinement” structure, but at the same time also reduces the capacitance between the top and bottom electric-field applying junction in the modulator structure. This is because capacitance is proportional to the plate area and the lateral width  $w_{EC}$  21500W will define the effective capacitance plate area across the PN (or PqN) layer in layer 21500, with P side serving as one capacitance plate and N side serving as another capacitance plate, spaced by the carrier depletion width between the P and N doped material regions, as is known to those skilled in the art. Reducing the modulator junction capacitance can increase the modulator frequency response. This will be referred to as capacitance reduction via EC-layer width reduction. This can also be applied to either layer 21400 or layer 21600 if a PN junction responsible for part of the total device capacitance is in layer 21400 or 21600. In that case, the width of either layer 21400 or 21600 or both shall be carefully chosen to reduce the total device capacitance.

## 20 **Separate lateral Mode Confinement and Modulator Junction Capacitance Reduction**

Note that it is possible to implement this “capacitance reduction via EC-layer width reduction” and still use the narrowed width of other layers to confine the optical mode laterally if the narrowed width of other layers is comparable to or smaller than this EC-layer width. This may have certain advantage by having low capacitance but also by using the top vertical/side conduction and Ohmic contact layer TVSCOC 21700\*\* (or any other layer between this layer and the layer ISTR 21200 including layer ISTR 21200 itself, except the EC-layer) to confine the mode laterally. This case is shown in **Fig. 26**. (\*\*such as when layer 21700 is an Ohmic Transparent Conductor case; for side metal contact case, it will be difficult to use layer 21700 to confine the optical beam mode. In that case, one can alternatively use the top interspaced dielectric conduction layer TIDC 21650 to confine the optical mode laterally)

### The use of Highly Doped Quantum Wells for Lower Modulation Voltage

This structure enables the modulation voltage to be drastically reduced using high carrier doping. While both N and P doping can be used, for the purpose of illustration and not limitation, the preferred embodiment is the use of N-doping in the active electro-active region as P doping will cause higher optical absorption loss than N doping at the same dopant density. The higher the doping density, the smaller the carrier depletion width at the PN junction and the larger the PN-junction capacitance. For a conventional modulator, the doping density is limited to  $N=10^{17}/\text{cm}^3$  as otherwise the high junction capacitance will begin to severely limit the frequency bandwidth of the modulator. In the applications below, the doping is made into the EC layer that may or may not have quantum wells present. The presence of quantum wells may enhance the refractive index change due to change in carrier band-filling in the quantum wells under an applied voltage. However, the absence of quantum wells will also work in that refractive index will also be changed due to change in carrier band-filling under an applied voltage. Thus, when quantum wells are mentioned, it is for the purpose of illustration and not limitation. The presence of quantum wells also enables refractive index change due to quantum confined Stark effects as noted above, which can further increase the change in the refractive index under an applied voltage. The quantum wells can be strained, unstrained, double-well, or multi-well quantum wells as is known to those skilled in the art.

In the present invention, in one application area, the EC layer has region with high-level doped carrier density with P-type or N-type doping and a doping density at or higher than  $2 \times 10^{17}/\text{cm}^3$  and lower than  $5 \times 10^{17}/\text{cm}^3$  primarily but not exclusively for low modulation voltage  $V_{\text{MOD}}$  20000V or low modulation RF power  $P_{\text{MOD}}$  20000P, and low-loss high-frequency modulator applications. In an exemplary embodiment, for illustration and not limitation, low means  $V_{\text{MOD}} < 2\text{V}$  or  $P_{\text{MOD}} < 80\text{mW}$ . Typically  $V_{\text{MOD}}$  and  $P_{\text{MOD}}$  are approximately related by the  $R_{\text{LOAD}}$  20000R transmission line resistance or load resistance:  $P_{\text{MOD}} = V_{\text{MOD}}^2 / R_{\text{LOAD}}$ . In an exemplary embodiment,  $R_{\text{LOAD}} = 50$  Ohms. This is referred to as having the quantum wells in highly-doped regime.

In another application area, the EC layer has region with medium-high-level doped carrier density with P-type or N-type doping and a doping density at or higher than  $5 \times 10^{17}/\text{cm}^3$  and lower than  $1.5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for medium-low modulation voltage  $V_{\text{MOD}}$  or medium-low modulation RF power  $P_{\text{MOD}}$ , and low-loss high-frequency modulator applications. In an exemplary embodiment, for illustration and not limitation, medium-low means  $V_{\text{MOD}}$

<1Volt or  $P_{MOD} < 20\text{mW}$ . This is referred to as having the quantum wells in medium-highly-doped regime.

In as yet another application area, the EC layer has region with very-high-level doped carrier density with P-type or N-type doping and a doping density at or higher than  $1.5 \times 10^{18}/\text{cm}^3$  and lower than  $5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for very-low modulation voltage  $V_{MOD}$  or very-low modulation RF power  $P_{MOD}$ , and low-loss high-frequency modulator applications. In an exemplary embodiment, for illustration and not limitation, very-low means  $V_{MOD} < 0.6\text{V}$  or  $P_{RF} < 7\text{mW}$ . This is referred to as having the quantum wells in very-highly-doped regime.

In as yet another application area, the EC layer has region with ultra-high-level doped carrier density with P-type or N-type doping and a doping density at or higher than  $5 \times 10^{18}/\text{cm}^3$  primarily but not exclusively for ultra-low modulation voltage  $V_{MOD}$  or ultra-low modulation RF power  $P_{MOD}$ , and low-loss high-frequency modulator applications. In an exemplary embodiment, for illustration and not limitation, ultra-low means  $V_{MOD} < 0.2\text{V}$  or  $P_{MOD} < 0.8\text{mW}$ . This is referred to as having the quantum wells in ultra-highly-doped regime.

The quantum wells can be strained, unstrained, double-well quantum wells, or multi-well as is known to those skilled in the art.

While the preferred embodiments and advantages of the invention have been illustrated and described, it will be clear that the invention is not limited to these embodiments and advantages only. Numerous modifications, changes, variations, substitutions and equivalents will be apparent to those skilled in the art without departing from the spirit and scope of the invention as described.

To further illustrate the present invention, for the purpose of illustration and not limitation, we describe a few exemplary devices below.

## **A First Exemplary Device of Electro-Optic Modulator with Side Conduction Geometry**

A preferred embodiment of an exemplary device is Modulator Device 20000 with the following specifications referred to as a first exemplary device of electro-optic modulator with side-conduction geometry:

Substrate SUB 21100 is silicon wafer substrate with a thickness of about 0.3mm.

Input connecting waveguide core ICWCo 22200 is made of silicon for which its averaged material refractive index  $n_{ICWCo}$  22200n is around  $n_{ICWCo} = 3.6$ , thickness  $d_{ICWCo}$  22200d is  $d_{ICWCo} = 250\text{nm}$ , and width  $W_{ICWCo}$  22200w is  $W_{ICWCo} = 400\text{nm}$ .

Input connecting-waveguide bottom cladding material ICWBCd 22200Bn is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{\text{ICWBCd } 22200\text{Bn}}$  is  $n_{\text{ICWBCd}}=1.45$ .

Input connecting waveguide top cladding material ICWTCd 22200T is silicon dioxide ( $\text{SiO}_2$ ) for which its refractive Index  $n_{\text{ICWTCd } 22200\text{Tn}}$  is 1.45.

5 Input connecting waveguide left cladding material ICWLCd 22200L is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{\text{ICWLCd } 22200\text{Ln}}$  is 1.45

Input connecting waveguide right cladding material ICWRCd 22200R is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{\text{ICWRCd } 22200\text{Rn}}$  is 1.45

10 The above form an input connecting waveguide ICWG 22200WG . The core-cladding refractive-index difference  $n_{\text{Rd}}$  defined by  $n_{\text{Rd}}^2 = (n_{\text{Co}}^2 - n_{\text{Cd}}^2)$  for waveguide ICWG 22200WG is  $n_{\text{Rd}}^2 = (3.6^2 - 1.45^2) = 10.86$  with  $n_{\text{Co}} = 3.6$  and  $n_{\text{Cd}} = 1.45$ . Its averaged Cladding Refractive Index is given by  $n_{\text{aICWcd}} = (n_{\text{ICWBCd}}^2 \times A_{\text{ICWBCd}} + n_{\text{ICWTCd}}^2 \times A_{\text{ICWTCd}} + n_{\text{ICWRCd}}^2 \times A_{\text{ICWRCd}} + n_{\text{ICWLCd}}^2 \times A_{\text{ICWLCd}}) / (A_{\text{ICWBCd}} + A_{\text{ICWTCd}} + A_{\text{ICWRCd}} + A_{\text{ICWLCd}})^{0.5} = 1.45$ . Its averaged Core Refractive Index is given by  $n_{\text{aCo}} = (n_{\text{Co1}}^2 \times A_{\text{Co1}} + n_{\text{Co2}}^2 \times A_{\text{Co2}} + n_{\text{Co3}}^2 \times A_{\text{Co3}} + \dots + n_{\text{Com}}^2 \times A_{\text{Com}}) / (A_{\text{Co1}} + A_{\text{Co2}} + A_{\text{Co3}} + \dots + A_{\text{Com}})^{0.5} = 3.6$ .

The input optical beam IBM 22140 has propagating refractive index  $n_{\text{IBM } 22140\text{n}}$ , for which  $n_{\text{IBM}}$  is approximately 2.8 with optical power  $P_{\text{bm } 22140\text{P}}$  approximately 1mW, electric field polarization  $E_{\text{bm } 22140\text{E}}$  to be in the horizontal direction parallel to the substrate surface. It has a beam effective area  $A_{\text{bm } 22140\text{A}}$  of  $A_{\text{bm}} = 0.04 \mu\text{m}^2$  and an optical wavelength centered at  $\lambda_{\text{bm } 22140\text{L}}$  with  $\lambda_{\text{bm}} = 1550\text{nm}$  with plurality of (N) frequency channels  $\lambda_{\text{bm1}} = 1548\text{nm}$ ,  $\lambda_{\text{bm2}} = 1549\text{nm}$ ,  $\lambda_{\text{bm3}} = 1550\text{nm}$ ,  $\lambda_{\text{bm4}} = 1551\text{nm}$ , and  $\lambda_{\text{bm5}} = 1552\text{nm}$  centered at  $\lambda_{\text{bm}} = 1550\text{nm}$ .

### Input Beam Coupler Structure (IBCS) Region

25 The input tapering waveguide core ITWCo 223000 is made of silicon. Its width at a location  $z1$ , ITWCo- $z1$  22300 $z1$  is denoted as width  $w_{\text{ITWCo-}z1} 22300\text{w-}z1$ . This width is tapered from width at  $z1=0$   $w_{\text{ITWCo-}z1=0} 22300\text{w-}z1=0$  that has a value of  $w_{\text{ITWCo-}z1=0} = 400\text{nanometers (nm)}$  to a width at  $z1>0$   $w_{\text{ITWCo-}z1>0} 22300\text{w-}z1>0$  that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{\text{ITWCo-}z1} 22300\text{d-}z1$  made of silicon is 30  $d_{\text{ITWCo-}z1} = 250\text{nm}$  with a refractive index  $n_{\text{ITWCo-}z1} 22300\text{n-}z$  that is  $n_{\text{ITWCo-}z1} = 3.6$ .

The total length of tapering waveguide  $g_{ITWCo}$  22300g is  $g_{ITWCo} = 20$  micrometers ( $\mu m$ ). The width of the waveguide core at the end of the tapering at  $z1 = g_{ITWCo}$  is  $w_{ITWCo-g}$  22300w-g with  $w_{ITWCo-g} = 50nm$ .

Input supporting structure ISTR 21200 has width  $w_{ISTR}$  21200w with  $w_{ISTR} = 50nm$  and thickness  $d_{ISTR}$  21200d with  $d_{ISTR} = 250nm$  and length  $g_{ISTR}$  21200g with  $g_{ISTR} = 20$  micrometers. It has an effective layer averaged refractive index  $n_{laISTR}$  21200nla with  $n_{laISTR} < 2.5$ .

Left cladding material ISTRLCd 21200L is air and has a refractive index  $n_{ISTRLCd}$  21200Ln given by  $n_{ISTRLCd} = 1$ , and Right cladding material ISTRRCd 21200R is air and has a refractive index  $n_{ISTRRCd}$  21200Rn given by  $n_{ISTRRCd} = 1$ . Its bottom cladding ISTRBCd 21200B is silicon dioxide (this is part of a Buried-Oxide BOX layer in a typical Silicon-On-Insulator SOI wafer) with averaged refractive index  $n_{ISTRBCd}$  21200Bn of  $n_{ISTRBCd} = 1.45$ .

The top cladding ITWTCd-z1 22300T-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWTCd-z1}$  22300Tn-z1 with  $n_{ITWTCd-z1} = 1.45$ . The bottom cladding ITWBCd-z1 22300B-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWBCd-z1}$  22300Bn-z1 with  $n_{ITWBCd-z1} = 1.45$ .

The left cladding ITWLCd-z1 22300L-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWLCd-z1}$  22300Ln-z1 with  $n_{ITWLCd-z1} = 1.45$ . The right cladding ITWRCd-z1 22300R-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWRCd-z1}$  22300Rn-z1 with  $n_{ITWRCd-z1} = 1.45$ .

In this exemplary embodiment,  $n_{ITWTCd-z1} = n_{ITWBCd-z1} = n_{ITWLCd-z1} = n_{ITWRCd-z1} = n_{ICWTCd}$  and  $n_{ICWTCd} = n_{ICWBCd} = n_{ICWLCd} = n_{ICWRCd}$ . Input tapering waveguide core ITWCo 22300 starting at  $z1 = z1ALS$  22300z1ALS, where  $z1ALS = 10$  micrometers, is laid with an active layer structure ALS 22500.  $0 < z1ALS < g_{ITWCo}$ .

## 25 Active Layer Structure-Beam Transport into the Structure

The active layer structure ALS 22500 is shown by the Table 3-1 below:

Table 3-1

| ALS 22500 Layer Number | Layer Thickness | NPNN TCO CASE                    | Doping/( $1/cm^3$ )    |
|------------------------|-----------------|----------------------------------|------------------------|
| BIM (21250)            | 100nm           | $In_2O_3$                        |                        |
| BSCOC 1                | 100nm           | InGaAsP 1.3um (Bottom layer-just | $N = 1 \times 10^{19}$ |

|                                  |                             |                                              |                         |
|----------------------------------|-----------------------------|----------------------------------------------|-------------------------|
| (21300)                          |                             | above the substrate)                         |                         |
| BIDC 2<br>(21350LN)              | 40nm                        | InP                                          | $N=1 \times 10^{19}$    |
| BVC 3<br>(21400)                 | 20nm                        | InGaAsP 1.3um                                | $N=1 \times 10^{19}$    |
| EC 4<br>(21500LN <sub>1</sub> )  | 10nm                        | AlGaInAs 1.3um                               | $N_1=1 \times 10^{19}$  |
| EC 5<br>(21500MLN <sub>1</sub> ) | 4nm barrier                 | AlGaInAs/1.1um/-0.8% tensile strained        | $MN_1=4 \times 10^{17}$ |
| EC 6<br>(21500MLN <sub>2</sub> ) | 2x7nm barrier<br>inside     | AlGaInAs/1.1um/-0.8% tensile strained        | $MN_2=4 \times 10^{17}$ |
| EC 7<br>(21500MLN <sub>3</sub> ) | 3x6.5nm Well<br>(PL=1350nm) | AlGaInAs/1.55um/0.9% compressive<br>strained | $MN_3=4 \times 10^{17}$ |
| EC 8<br>(21500MLN <sub>4</sub> ) | 4nm barrier                 | AlGaInAs/1.1um/-0.8% tensile strained        | $MN_4=4 \times 10^{17}$ |
| EC 9<br>(21500MLN <sub>5</sub> ) | 43nm                        | AlGaInAs 1.3um                               | $MN_5=4 \times 10^{17}$ |
| EC 10<br>(21500LP <sub>1</sub> ) | 20nm                        | AlGaInAs 1.3um                               | $P_1=1 \times 10^{18}$  |
| TVC 11<br>(21600P <sub>2</sub> ) | 25nm                        | InGaAsP 1.3 um                               | $P_2=1 \times 10^{18}$  |
| TVC 12<br>(21600N <sub>2</sub> ) | 20nm                        | InGaAsP 1.3 um                               | $N_2=1 \times 10^{19}$  |
| TIDC 13<br>(21650)               | 20nm                        | InP                                          | $N=1 \times 10^{19}$    |
| TVSCOC 14<br>(21700)             | 40nm                        | InGaAsP (Top layer)                          | $N=1 \times 10^{19}$    |
| Total                            | 380nm                       |                                              |                         |

In the table, the materials are unstrained (with InP as the substrate) if not specified as strained. The wavelength specified will be the material bandgap wavelength of the quaternary material involved (proper choice of the material composition is needed to achieve the required material bandgap and strain when grown on InP substrate).

#### Bottom Side Conduction and Ohmic Contact Layer

The active layer structure ALS 22500 has a bottom side conduction and Ohmic contact layer BSCOC 21300 that is InGaAsP layer given by layer 1 in Table 3-1 with thickness  $d_{BSC}$

21300d, where  $d_{\text{BSC}}=100\text{nm}$  and width  $w_{\text{BSC}}$  21300w, where  $w_{\text{BSC}}$  is approximately 54 micrometers along most of the length of the ALS. Its refractive index  $n_{\text{BSC}}$  21300n is  $n_{\text{BSC}}=3.4$ .

#### Bottom Interspaced Material Layer

5 The bottom interspaced material layer BIM 21250 is made of a Low-Refractive-Index Ohmic Transparent Conducting (LRI-OTC) material composed of Indium oxide ( $\text{In}_2\text{O}_3$ ) with thickness  $d_{\text{BIM}}$  21250d equals to  $d_{\text{BIM}} = 100\text{nm}$ , width  $w_{\text{BIM}}$  21250w equals to  $w_{\text{BIM}}=54$  micrometers, and average refractive index  $n_{\text{BIM}}$  21250n equals to  $n_{\text{BIM}}=1.7$ .

#### 10 Bottom Metal Contact Pads

The first bottom left metal contact pad FBLM 21900L is a multi-layer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-1. The total thickness of the metal contact pad is  $d_{\text{FBLM}}$  21900Ld, with  $d_{\text{FBLM}}=1068\text{nm}$ , and width  $w_{\text{FBLM}}$  21900Lw, where  $w_{\text{FBLM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBLM}}$  21900Lg is approximately 500 micrometers.

The first bottom right metal contact pad FBRM 21900R is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-1. The total thickness of the metal contact pad is  $d_{\text{FBRM}}$  21900Rd, with  $d_{\text{FBRM}}=1068\text{nm}$ , and width  $w_{\text{FBRM}}$  21900Rw, where  $w_{\text{FBRM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBRM}}$  21900Rg is approximately 500 micrometers.

#### Bottom Metal Electrodes

25 On top of the first bottom left metal contact pad FBLM 21900L is deposited the first bottom left metal electrode FBLME 21120L which is gold of thickness of approximately 2 micrometer thick.

On top of the first bottom right metal contact pad FBRM 21900R is deposited the first bottom right metal electrode FBRME 21120R which is gold of thickness of approximately 2 micrometer thick.

### Bottom Interspaced Dielectric Current Conduction Layer

Bottom interspaced dielectric current conduction layer BDC 21350 is a n-doped InP given by layer 2 in Table 3-1 with thickness  $d_{BDC}$  21350d equals to  $d_{BDC}=40\text{nm}$ , width  $w_{BDC}$  21350w equals to  $w_{BDC}=54$  micrometers, and average refractive index  $n_{BDC}$  21350n equals to about  $n_{BDC}=3.0$ .

### Bottom Vertical Current Conduction Layer

Bottom vertical current conduction layer BVC 21400 is n-doped InGaAsP given by layer 3 in Table 3-1 with thickness  $d_{BVC}$  21400d equals to  $d_{BVC}=20\text{nm}$ , width  $w_{BVC}$  21400w equals to  $w_{BVC}=2$ micrometers, and an averaged refractive index  $n_{BVC}$  21400n equals to  $n_{BVC}=3.4$ .

### Electro-Active Layer

Electro-active layer EC 21500 is made up of layers 4,5,6,7,8,9,10 in Table 3-1 with an averaged refractive index of the entire layer given by  $n_{EC}$  21500n with  $n_{EC}$  equals to approximately  $n_{EC}=3.4$ . Under an applied electric field, there will be a change in averaged refractive index  $dn_{EC}$  21500dn. The average refractive index becomes  $n_{EC}(\text{new}) = n_{EC} + dn_{EC}$ .

The total thickness  $d_{EC}$  21500d of this Electro-active layer is  $d_{EC}=114.5\text{nm}$ . Its width  $w_{EC}$  21500w is equal to  $w_{EC}=2$  micrometers.

The electro-active layer has a PqN junction at layer 4 to 10 for which layer 4 is layer 21500LN<sub>1</sub> that is N-doped with a dopant density of  $21500N_1=1\times 10^{19}/\text{cm}^3$  and layer 10 is layer 21500LP<sub>1</sub> that is P-doped with a dopant density of  $21500P_1=1\times 10^{18}/\text{cm}^3$

The intermediate layers 21500MLN<sub>m</sub> are all N-doped with a dopant density of  $21500MN_m=4\times 10^{17}/\text{cm}^3$ .

The applied field  $E_{EC}$  21500E (which may cause a current  $C_{EC}$  21500C to flow) is across the entire electro-active layer with a negative voltage applied to the top and positive voltage applied to the bottom of this entire electro-active layer known to those skilled in the art as reversed bias (with respect to the PN junction in the electro-active layer) of voltage  $V_R$  21500VR so the applied electro-active  $V_{EC}$  21500VEC is  $V_R$ .

The voltage applied to the electrodes of the modulator  $V_{MOD}$  20000V is approximately given by  $V_{EC}$ .

### Top Vertical Current Conduction Layer

Top vertical current conduction layer TVC 21600 is given by layer 11 and 12 in Table 3-1 made up of InGaAsP layer that is composed of 25nm-thick layer 21600LP<sub>2</sub> that is P-doped with dopant density  $21600P_2=1 \times 10^{18}/\text{cm}^3$ , followed by 20nm-thick N-doped InGaAsP layer 21600LN<sub>2</sub> with dopant density  $21600N_2=1 \times 10^{19}/\text{cm}^3$ . The total thickness for TVC 21600 is  $d_{\text{TVC}} 21600d$  with  $d_{\text{TVC}}=45\text{nm}$ . Its width is  $W_{\text{TVC}} 21600w$  equals to  $W_{\text{TVC}}=2$  micrometers, and its averaged refractive index is  $n_{\text{TVC}} 21600n$  equals to  $n_{\text{TVC}}=3.4$ . This N<sub>2</sub>P<sub>2</sub> junction forms a forward-Biased PN Junction (or Tunnel PN Junction). It forms a PN-changing PN junction (called PNCPN junction) 21600PNCPN.

### Top Interspaced Dielectric Current Conduction Layer

Top interspaced dielectric conduction layer TIDC 21650 is N-doped InP layer given by layer 13 in Table 3-1 with thickness  $d_{\text{TIDC}} 21650d$  equals to  $d_{\text{TIDC}}=20\text{nm}$ , width  $w_{\text{TIDC}} 21650w$  equals to  $w_{\text{TIDC}}=8$  micrometers, and averaged refractive index  $n_{\text{TIDC}} 21650n$  equals to  $n_{\text{TIDC}}=3.0$ .

### Top Vertical/Side Conduction and Ohmic Contact Layer

Top vertical/side conduction and Ohmic contact layer TVSCOC 21700 is made up of InGaAsP given by layer 14 in Table 3-1 with thickness  $d_{\text{TVSC}} 21700d$  equals to  $d_{\text{TVSC}}=40\text{nm}$ , width  $w_{\text{TVSC}} 21700w$  equals to  $w_{\text{TVSC}}=8$  micrometers, and an averaged refractive index  $n_{\text{TVSC}} 21700n$  equals to  $n_{\text{TVSC}}=3.4$ .

### Top Metal Contact Pads

The first top left metal contact pad FTLM 21800L is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21700 given by layer 14 in Table 3-1. The total thickness of the metal contact pad is  $d_{\text{FTLM}} 21800Ld$ , with  $d_{\text{FTLM}}=1068\text{nm}$ , and width  $w_{\text{FTLM}} 21800Lw$ , where  $w_{\text{FTLM}}$  is approximately 3 micrometers. The length of the metal contact pad  $g_{\text{FTLM}} 21800Lg$  is approximately 500 micrometers.

The first top right metal contact pad FTRM 21800R is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21700 given by layer 14 in Table 3-1. The total thickness of the metal contact pad is  $d_{\text{FTRM}} 21800Rd$ , with  $d_{\text{FTRM}}=1068\text{nm}$ , and width  $w_{\text{FTRM}}$

21800Rw, where  $w_{FTRM}$  is approximately 3 micrometers. The length of the metal contact pad  $g_{FTRM}$  21800Rg is approximately 500 micrometers.

There is no top middle metal contact pad FTMM 21800M.

## 5 Top Metal Electrodes

On top of the first top left metal contact pad FTLM 21800L is deposited the first top left metal electrode FTLME 21130L which is gold of thickness of approximately 2 micrometer thick.

On top of the first top right metal contact pad FTRM 21800R is deposited the first top right metal electrode FTRME 21130R which is gold of thickness of approximately 2 micrometer thick.

10

## Beam Transport to Electro-Active Waveguiding Core Structure

Input tapering waveguide region between  $z_1=z_{1ALS}$  22300 $z_{1ALS}$  and  $z_1=g_{ITWCo}$  22300g, Tapering waveguide core width  $w_{ITWCo-z}$  22300w varies down to a smaller value of  $w_{ITWCo-g}=50nm$  at  $z_1=g_{ITWCo}$  22300g from its value at  $z_1=z_{1ALS}$  22300 $z_{1ALS}$ .

15 Clearly  $W_{ITWCo-g} \ll \lambda_{bm}/(2 * n_{ITWCo})$ , with  $\lambda_{bm}=1550nm$  and  $n_{ITWCo}=3.6$ , where \* is number multiplication.

## Output Connecting Waveguide

20 Output connecting waveguide core OCWCo 28200 has averaged Refractive Index  $n_{OCWCo}=n_{aOCWCo}=3.6$ , thickness  $d_{OCWCo}$  28200d is  $d_{OCWCo}=250nm$ , and width  $W_{OCWCo}$  28200w is  $W_{OCWCo}=400nm$ .

Output connecting waveguide OCWG 28200WG has Output connecting-waveguide bottom cladding material OCWBCd 28200B that is silicon dioxide ( $SiO_2$ ) for which the refractive index  $n_{OCWBCd}$  28200Bn is  $n_{OCWBCd}=1.45$ .

25 Output connecting waveguide top cladding material OCWTCd 28200T is silicon dioxide for which the refractive index  $n_{OCWTCd}$  28200Tn is  $n_{OCWTCd}=1.45$ .

Output connecting waveguide left cladding material OCWLCd 28200L is silicon dioxide for which the refractive index  $n_{OCWLCd}$  28200Ln is  $n_{OCWLCd}=1.45$ .

30 Output connecting waveguide right cladding material OCWRCd 28200R is silicon dioxide for which the refractive index  $n_{OCWRCd}$  28200Rn is  $n_{OCWRCd}=1.45$ .

The resulted averaged cladding refractive Index  $n_{aOCWcd}$  28200aCdn is  $n_{aOCWcd}=1.45$ .

Output optical beam OBM 28140

### Output Beam Coupler Structure (OBCS) Region

Output tapering waveguide core OTWCo 28300 is made of silicon. Its width at a location  $z2$  OTWCo- $z2$  is denoted as width  $w_{OTWCo-z2}$  28300w- $z2$ . This width is tapered from width at  $z2=0$   $w_{OTWCo-z2=0}$  28300w- $z2=0$  that has a value of  $w_{OTWCo-z2=0}=400\text{nm}$  to a width at  $z2>0$   $w_{OTWCo-z2>0}$  28300w- $z2>0$  that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{OTWCo-z2}$  28300d- $z2$  made of silicon is  $d_{OTWCo-z2}=250\text{nm}$  with a refractive index  $n_{OTWCo-z2}$  28300n- $z2$  that is  $n_{OTWCo-z2}=3.6$ .

The total length of tapering waveguide  $g_{OTWCo}$  28300g is  $g_{OTWCo}=20$  micrometers ( $\mu\text{m}$ ). The width of the waveguide core at the end of the tapering at  $z2=g_{OTWCo}$  is  $w_{OTWCo-g}$  28300w-g with  $w_{OTWCo-g}=50\text{nm}$ .

Output supporting structure OSTR 29200 has width  $w_{OSTR}$  29200w with  $w_{OSTR}=50\text{nm}$  and thickness  $d_{OSTR}$  29200d with  $d_{OSTR}=250\text{nm}$  and length  $g_{OSTR}$  29200g with  $g_{OSTR}=20$  micrometers. It has an effective layer averaged refractive index  $n_{laOSTR}$  29200nla with  $n_{laOSTR}<2.5$ .

The top cladding OTWTCd- $z2$  28300T- $z2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWTCd-z2}$  28300Tn- $z2$  with  $n_{OTWTCd-z2}=1.45$  before going into the ALS region.

The bottom cladding OTWBCd- $z2$  28300B- $z2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWBCd-z2}$  28300Bn- $z2$  with  $n_{OTWBCd-z2}=1.45$ .

The left cladding OTWLCd- $z2$  28300L- $z2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWLCd-z2}$  28300Ln- $z2$  with  $n_{OTWLCd-z2}=1.45$ .

The right cladding OTWRCd- $z2$  28300R- $z2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWRCd-z2}$  28300Rn- $z2$  with  $n_{OTWRCd-z2}=1.45$ .

In this exemplary embodiment,  $n_{OTWTCd-z2}=n_{OTWBCd-z2}=n_{OTWLCd-z2}=n_{OTWRCd-z2}=n_{OCWTCd}$  and  $n_{OCWTCd}=n_{OCWBCd}=n_{OCWLCd}=n_{OCWRCd}$ .

Output tapering waveguide core OTWCo 28300 starting at  $z2=z2\text{ALS}$  28300z2ALS, is laid with an active layer structure ALS 22500.  $0<z2\text{ALS}<g_{OTWCo}$ .

Most of the output optical beam energy of beam OBM 28140 is transported to output tapering waveguide core OTWCo 28300 from the electro-active waveguiding core structure EWCoS 22600, through the output tapering waveguide region between  $z2=z2\text{ALS}$  28300z2ALS and  $z2=g_{OTWCo}$  28300g, where the output tapering waveguide core width  $w_{OTWCo-z2}$  28300w- $z2$  varies down to a smaller value of  $w_{OTWCo-g}$  at  $z2=g_{OTWCo}$  28300g from its value at  $z2=z2\text{ALS}$ , 28300z2ALS. The tapering waveguide core width is reduced to well below half the optical

wavelength in the waveguide core given by  $\lambda_{bm}/(2\pi n_{OTWC0})$  so that  $w_{OTWC0-g} \ll \lambda_{bm}/(2\pi n_{OTWC0})$ . After the energy transported from the electro-active waveguiding core structure EWCoS 22600 that contains the electro-active layer EC 21500 down to the output taper at  $z=0$  where the taper core width is  $w_{OTWC0-z=0} = 28300w_0$  and  $w_{OTWC0-z=0} = w_{OCWC0}$  28200, the optical beam is denoted as output optical beam or beam OBM 28140.

### Length of Active Layer Structure

The length of the active layer structure  $SL_{mod}$  22550 is approximately 500 micrometers.

### 10 High Refractive Index Contrast and Mode Overlapping

For the bottom cladding:

Waveguide core refractive index is  $n_{co}=3.6$

Waveguide bottom cladding is  $n_{BCd}=1.45$  (given by layer ISTRBC with  $n_{ISTRBCd}=1.45$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{BCd}^2) = 10.86$ .

15 Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{BCd}^2) = 0.7$ , which is in the very-strongly guiding regime.

For the top cladding:

Waveguide core refractive index is  $n_{co}=3.6$

20 Waveguide bottom cladding is  $n_{TCd}=1$  (given by material above TVSCOC layer which is air with  $n=1$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{TCd}^2) = 11.96$ .

Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{TCd}^2) = 0.86$ , which is in the very-strongly guiding regime.

25

### A Second Exemplary Device of Electro-Absorption Modulator with Transparent Conductor Geometry

A preferred embodiment of an exemplary device is Modulator Device 20000 with the following specifications referred to as a second exemplary device of electro-absorption modulator with Ohmic transparent conductor geometry: The main difference between this and the First Exemplary Device is in Table 3-2, in which the active layer is designed for electro-absorption

30

modulation. Also, there are no left and right top metal contact pads, only middle metal contact pad.

Substrate SUB 21100 is silicon wafer substrate with a thickness of about 0.3mm.

Input connecting waveguide core ICWCo 22200 is made of silicon for which its averaged material refractive index  $n_{ICWCo}$  22200n is around  $n_{ICWCo} = 3.6$ , thickness  $d_{ICWCo}$  22200d is  $d_{ICWCo} = 250\text{nm}$ , and width  $W_{ICWCo}$  22200w is  $W_{ICWCo} = 400\text{nm}$ .

Input connecting-waveguide bottom cladding material ICWBCd 22200B is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWBCd}$  22200Bn is  $n_{ICWBCd} = 1.45$ .

Input connecting waveguide top cladding material ICWTCd 22200T is silicon dioxide ( $\text{SiO}_2$ ) for which its refractive Index  $n_{ICWTCd}$  22200Tn is 1.45.

Input connecting waveguide left cladding material ICWLCd 22200L is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWLCd}$  22200Ln is 1.45

Input connecting waveguide right cladding material ICWRCd 22200R is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWRCd}$  22200Rn is 1.45

The above form an input connecting waveguide ICWG 22200WG. The core-cladding refractive-index difference  $n_{Rd}$  defined by  $n_{Rd}^2 = (n_{Co}^2 - n_{Cd}^2)$  for waveguide ICWG 22200WG is  $n_{Rd}^2 = (3.6^2 - 1.45^2) = 10.86$  with  $n_{Co} = 3.6$  and  $n_{Cd} = 1.45$ . Its averaged Cladding Refractive Index is given by  $n_{aICWcd} = (n_{ICWBCd}^2 \times A_{ICWBCd} + n_{ICWTCd}^2 \times A_{ICWTCd} + n_{ICWRCd}^2 \times A_{ICWRCd} + n_{ICWLCd}^2 \times A_{ICWLCd}) / (A_{ICWBCd} + A_{ICWTCd} + A_{ICWRCd} + A_{ICWLCd})^{0.5} = 1.45$ . Its averaged Core Refractive Index is given by  $n_{aCo} = (n_{Co1}^2 \times A_{Co1} + n_{Co2}^2 \times A_{Co2} + n_{Co3}^2 \times A_{Co3} + \dots + n_{Com}^2 \times A_{Com}) / (A_{Co1} + A_{Co2} + A_{Co3} + \dots + A_{Com})^{0.5} = 3.6$ .

The input optical beam IBM 22140 has propagating refractive index  $n_{IBM}$  22140n, for which  $n_{IBM}$  is approximately 2.8 with optical power  $P_{bm}$  22140P approximately 1mW, electric field polarization  $E_{bm}$  22140E to be in the horizontal direction parallel to the substrate surface. It has a beam effective area  $A_{bm}$  22140A of  $A_{bm} = 0.04 \mu\text{m}^2$  and an optical wavelength centered at  $\lambda_{bm}$  22140L with  $\lambda_{bm} = 1550\text{nm}$  with plurality of (N) frequency channels  $\lambda_{bm1} = 1548\text{nm}$ ,  $\lambda_{bm2} = 1549\text{nm}$ ,  $\lambda_{bm3} = 1550\text{nm}$ ,  $\lambda_{bm4} = 1551\text{nm}$ , and  $\lambda_{bm5} = 1552\text{nm}$  centered at  $\lambda_{bm} = 1550\text{nm}$ .

### Input Beam Coupler Structure (IBCS) Region

The input tapering waveguide core ITWCo 223000 is made of silicon. Its width at a location  $z1$ , ITWCo- $z1$  22300z1 is denoted as width  $w_{ITWCo-z1}$  22300w-z1. This width is tapered

from width at  $z1=0$   $w_{ITWCo-z1=0}$  22300w-z1=0 that has a value of  $w_{ITWCo-z1=0}=400$ nanometers (nm) to a width at  $z1>0$   $w_{ITWCo-z1>0}$  22300w-z1>0 that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{ITWCo-z1}$  22300d-z1 made of silicon is  $d_{ITWCo-z1} = 250$ nm with a refractive index  $n_{ITWCo-z1}$  22300n-z that is  $n_{ITWCo-z1}=3.6$ .

- 5 The total length of tapering waveguide  $g_{ITWCo}$  22300g is  $g_{ITWCo} = 20$  micrometers ( $\mu$ m). The width of the waveguide core at the end of the tapering at  $z1 = g_{ITWCo}$  is  $w_{ITWCo-g}$  22300w-g with  $w_{ITWCo-g}=50$ nm.

- 10 Input supporting structure ISTR 21200 has width  $w_{ISTR}$  21200w with  $w_{ISTR}=50$ nm and thickness  $d_{ISTR}$  21200d with  $d_{ISTR}=250$ nm and length  $g_{ISTR}$  21200g with  $g_{ISTR}=20$  micrometers. It has an effective layer averaged refractive index  $n_{laISTR}$  21200nla with  $n_{laISTR}<2.5$ .

- Left cladding material ISTRLCd 21200L is air and has a refractive index  $n_{ISTRLCd}$  21200Ln given by  $n_{ISTRLCd}=1$ , and Right cladding material ISTRRCd 21200R is air and has a refractive index  $n_{ISTRRCd}$  21200Rn given by  $n_{ISTRRCd}=1$ . Its bottom cladding ISTRBCd 21200B is silicon dioxide (this is part of a Burried-Oxide BOX layer in a typical Silicon-On-Insulator SOI  
15 wafer) with averaged refractive index  $n_{ISTRBCd}$  21200Bn of  $n_{ISTRBCd}=1.45$ .

The top cladding ITWTCd-z1 22300T-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWTCd-z1}$  22300Tn-z1 with  $n_{ITWTCd-z1}=1.45$ .

The bottom cladding ITWBCd-z1 22300B-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWBCd-z1}$  22300Bn-z1 with  $n_{ITWBCd-z1}=1.45$ .

- 20 The left cladding ITWLCd-z1 22300L-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWLCd-z1}$  22300Ln-z1 with  $n_{ITWLCd-z1}=1.45$ .

The right cladding ITWRCd-z1 22300R-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWRCd-z1}$  22300Rn-z1 with  $n_{ITWRCd-z1}=1.45$ .

- In this exemplary embodiment,  $n_{ITWTCd-z1} = n_{ITWBCd-z1} = n_{ITWLCd-z1} = n_{ITWRCd-z1} = n_{ICWTCd}$ , and  
25  $n_{ICWTCd} = n_{ICWBCd} = n_{ICWLCd} = n_{ICWRCd}$ . Input tapering waveguide core ITWCo 22300 starting at  $z1=z1ALS$  22300z1ALS, where  $z1ALS=10$  micrometers, is laid with an active layer structure ALS 22500.  $0 < z1ALS < g_{ITWCo}$ .

### Active Layer Structure-Beam Transport into the Structure

- 30 The active layer structure ALS 22500 is shown by the Table 3-2 below:

Table 3-2

| ALS 22500<br>Layer<br>Number        | Layer Thickness             | NPNN TCO CASE                                            | Doping/(1/cm <sup>3</sup> )        |
|-------------------------------------|-----------------------------|----------------------------------------------------------|------------------------------------|
| BIM<br>(21250)                      | 100nm                       | In <sub>2</sub> O <sub>3</sub>                           |                                    |
| BSCOC 1<br>(21300)                  | 100nm                       | InGaAsP 1.3um (Bottom layer-just<br>above the substrate) | N=1x10 <sup>19</sup>               |
| BIDC 2<br>(21350LN)                 | 40nm                        | InP                                                      | N=1x10 <sup>19</sup>               |
| BVC 3<br>(21400)                    | 20nm                        | InGaAsP 1.3um                                            | N=1x10 <sup>19</sup>               |
| EC 4<br>(21500LN <sub>1</sub> )     | 10nm                        | AlGaInAs 1.3um                                           | N <sub>1</sub> =1x10 <sup>19</sup> |
| EC 5<br>(21500MLI <sub>1</sub><br>) | 11nm barrier                | AlGaInAs/1.19um/-0.3% tensile strained                   | ML <sub>1</sub>                    |
| EC 6<br>(21500MLI <sub>2</sub><br>) | 3x7nm barrier inside        | AlGaInAs/1.19um/-0.3% tensile strained                   | ML <sub>2</sub>                    |
| EC 7<br>(21500MLI <sub>3</sub><br>) | 4x11 nm Well<br>(PL=1500nm) | AlGaInAs/1.55um/0.31% compressive<br>strained            | ML <sub>3</sub>                    |
| EC 8<br>(21500MLI <sub>4</sub><br>) | 11nm barrier                | AlGaInAs/1.19um/-0.3% tensile strained                   | ML <sub>4</sub>                    |
| EC 9<br>(21500MLI <sub>5</sub><br>) | 43nm                        | AlGaInAs 1.3um                                           | ML <sub>5</sub>                    |
| EC 10<br>(21500LP <sub>1</sub> )    | 20nm                        | AlGaInAs 1.3um                                           | P <sub>1</sub> =1x10 <sup>18</sup> |
| TVC 11<br>(21600P <sub>2</sub> )    | 25nm                        | InGaAsP 1.3 um                                           | P <sub>2</sub> =1x10 <sup>18</sup> |
| TVC 12<br>(21600N <sub>2</sub> )    | 20nm                        | InGaAsP 1.3 um                                           | N <sub>2</sub> =1x10 <sup>19</sup> |
| TIDC 13<br>(21650)                  | 20nm                        | InP                                                      | N=1x10 <sup>19</sup>               |
| TVSCOC<br>14<br>(21700)             | 240nm                       | In <sub>2</sub> O <sub>3</sub> (Top layer)               |                                    |
| Total                               | 625nm                       |                                                          |                                    |

In the table, the materials are unstrained (with InP as the substrate) if not specified as strained. The wavelength specified will be the material bandgap wavelength of the quaternary

material involved (proper choice of the material composition is needed to achieve the required material bandgap and strain when grown on InP substrate).

#### Bottom Side Conduction and Ohmic Contact Layer

5 The active layer structure ALS 22500 has a bottom side conduction and Ohmic contact layer BSCOC 21300 that is InGaAsP layer given by layer 1 in Table 3-2 with thickness  $d_{\text{BSCOC}} 21300d$ , where  $d_{\text{BSCOC}}=100\text{nm}$  and width  $w_{\text{BSCOC}} 21300w$ , where  $w_{\text{BSCOC}}$  is approximately 54 micrometers along most of the length of the ALS. Its refractive index  $n_{\text{BSCOC}} 21300n$  is  $n_{\text{BSCOC}}=3.4$ .

#### 10 Bottom Interspaced Material Layer

The bottom interspaced material layer BIM 21250 is made of a Low-Refractive-Index Ohmic Transparent Conducting (LRI-OTC) material composed of Indium oxide ( $\text{In}_2\text{O}_3$ ) with thickness  $d_{\text{BIM}} 21250d$  equals to  $d_{\text{BIM}} = 100\text{nm}$ , width  $w_{\text{BIM}} 21250w$  equals to  $w_{\text{BIM}}=54$  micrometers, and average refractive index  $n_{\text{BIM}} 21250n$  equals to  $n_{\text{BIM}}=1.7$ .

15

#### Bottom Metal Contact Pads

The first bottom left metal contact pad FBLM 21900L is a multi-layer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-2. The  
20 total thickness of the metal contact pad is  $d_{\text{FBLM}} 21900Ld$ , with  $d_{\text{FBLM}}=1068\text{nm}$ , and width  $w_{\text{FBLM}} 21900Lw$ , where  $w_{\text{FBLM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBLM}} 21900Lg$  is approximately 500 micrometers.

The first bottom right metal contact pad FBRM 21900R is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm  
25 Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-2. The total thickness of the metal contact pad is  $d_{\text{FBRM}} 21900Rd$ , with  $d_{\text{FBRM}}=1068\text{nm}$ , and width  $w_{\text{FBRM}} 21900Rw$ , where  $w_{\text{FBRM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBRM}} 21900Rg$  is approximately 500 micrometers.

30

### Bottom Metal Electrodes

On top of the first bottom left metal contact pad FBLM 21900L is deposited the first bottom left metal electrode FBLME 21120L which is gold of thickness of approximately 2 micrometer thick.

- 5 On top of the first bottom right metal contact pad FBRM 21900R is deposited the first bottom right metal electrode FBRME 21120R which is gold of thickness of approximately 2 micrometer thick.

### Bottom Interspaced Dielectric Current Conduction Layer

- 10 Bottom interspaced dielectric current conduction layer BDC 21350 is a n-doped InP given by layer 2 in Table 3-2 with thickness  $d_{BDC}$  21350d equals to  $d_{BDC}=40\text{nm}$ , width  $w_{BDC}$  21350w equals to  $w_{BDC}=54$  micrometers, and average refractive index  $n_{BDC}$  21350n equals to about  $n_{BDC}=3.0$ .

### 15 Bottom Vertical Current Conduction Layer

Bottom vertical current conduction layer BVC 21400 is n-doped InGaAsP given by layer 3 in Table 3-2 with thickness  $d_{BVC}$  21400d equals to  $d_{BVC}=20\text{nm}$ , width  $w_{BVC}$  21400w equals to  $w_{BVC}=2\text{micrometers}$ , and an averaged refractive index  $n_{BVC}$  21400n equals to  $n_{BVC}=3.4$ .

### 20 Electro-Active Layer

Electro-active layer EC 21500 is made up of layers 4,5,6,7,8,9,10 in Table 3-1 with an averaged refractive index of the entire layer given by  $n_{EC}$  21500n with  $n_{EC}$  equals to approximately  $n_{EC}=3.4$ . Under an applied electric field, there will be a change in averaged refractive index  $dn_{EC}$  21500dn. The average refractive index becomes  $n_{EC}(\text{new}) = n_{EC} + dn_{EC}$ .

- 25 The total thickness  $d_{EC}$  21500d of this Electro-active layer is  $d_{EC}=160\text{nm}$ . Its width  $w_{EC}$  21500w is equal to  $w_{EC}=2$  micrometers.

The electro-active layer has a PqN junction at layer 4 to 10 for which layer 4 is layer 21500LN<sub>1</sub> that is N-doped with a dopant density of  $21500N_1=1 \times 10^{19}/\text{cm}^3$  and layer 10 is layer 21500LP<sub>1</sub> that is P-doped with a dopant density of  $21500P_1=1 \times 10^{18}/\text{cm}^3$

- 30 The intermediate layers 21500MLN<sub>m</sub> are all undoped (intrinsic).

The applied field  $E_{EC}$  21500E (which may cause a current  $C_{EC}$  21500C to flow) is across the entire electro-active layer with a negative voltage applied to the top and positive voltage applied to

the bottom of this entire electro-active layer known to those skilled in the art as reversed bias (with respect to the PN junction in the electro-active layer) of voltage  $V_R$  21500VR so the applied electro-active  $V_{EC}$  21500VEC is  $V_R$ .

The voltage applied to the electrodes of the modulator  $V_{MOD}$  20000V is approximately  
5 given by  $V_{EC}$ .

### Top Vertical Current Conduction Layer

Top vertical current conduction layer TVC 21600 is given by layer 11 and 12 in Table 3-2 made up of InGaAsP layer that is composed of 25nm-thick layer 21600LP<sub>2</sub> that is P-doped with  
10 dopant density 21600P<sub>2</sub>= $1 \times 10^{18}/\text{cm}^3$ , followed by 20nm-thick N-doped InGaAsP layer 21600LN<sub>2</sub> with dopant density 21600N<sub>2</sub>= $1 \times 10^{19}/\text{cm}^3$ . The total thickness for TVC 21600 is  $d_{TVC}$  21600d with  $d_{TVC}$ =45nm. Its width is  $W_{TVC}$  21600w equals to  $W_{TVC}$ = 2 micrometers, and its averaged refractive index is  $n_{TVC}$  21600n equals to  $n_{TVC}$ =3.4. This N<sub>2</sub>P<sub>2</sub> junction forms a forward-Biased PN Junction (or Tunnel PN Junction). It forms a PN-changing PN junction (called PNCPN junction)  
15 21600PNCPN.

### Top Interspaced Dielectric Current Conduction Layer

Top interspaced dielectric conduction layer TIDC 21650 is N-doped InP layer given by layer 13 in Table 3-2 with thickness  $d_{TIDC}$  21650d equals to  $d_{TIDC}$ = 20nm, width  $w_{TIDC}$  21650w equals to  
20  $w_{TIDC}$ =2 micrometers, and averaged refractive index  $n_{TIDC}$  21650n equals to  $n_{TIDC}$ =3.0.

### Top Vertical/Side Conduction and Ohmic Contact Layer

Top vertical/side conduction and Ohmic contact layer TVSCOC 21700 is made up of Low-Refractive-Index Ohmic Transparent Conductor (LRI-OTC) (In<sub>2</sub>O<sub>3</sub>) given by layer 14 in Table 3-2  
25 with thickness  $d_{TVSC}$  21700d equals to  $d_{TVSC}$ =240nm, width  $w_{TVSC}$  21700w equals to  $w_{TVSC}$ = 2 micrometers, and an averaged refractive index  $n_{TVSC}$  21700n equals to  $n_{TVSC}$ = 1.7.

### Top Metal Contact Pads

The first top middle metal contact pad FTMM 21800M is multilayer metal made up of  
30 (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21700 given by layer 14 in Table 3-2. The total thickness of the metal contact pad is  $d_{FTMM}$  21800Md, with  $d_{FTMM}$ =1068nm, and width  $w_{FTMM}$

21800Mw, where  $w_{FTMM}$  is approximately 2 micrometers. The length of the metal contact pad  $g_{FTMM}$  21800Mg is approximately 500 micrometers.

There is no top left or right metal contact pad FTLM 21800L or FTRM 21800R.

## 5 Top Metal Electrodes

On top of the first top middle metal contact pad FTMM 21800M is deposited the first top middle metal electrode FTMME 21130M which is gold of thickness of approximately 2 micrometer thick.

## 10 Beam Transport to Electro-Active Waveguiding Core Structure

Input tapering waveguide region between  $z1=z1ALS$  22300z1ALS and  $z1=g_{ITWCo}$  22300g, Tapering waveguide core width  $w_{ITWCo-z}$  22300w varies down to a smaller value of  $w_{ITWCo-g}=50nm$  at  $z1=g_{ITWCo}$  22300g from its value at  $z1=z1ALS$  22300z1ALS.

Clearly  $W_{ITWCo-g} \ll \lambda_{bm}/(2 * n_{ITWCo})$ , with  $\lambda_{bm}=1550nm$  and  $n_{ITWCo}=3.6$ , where \* is number  
15 multiplication.

## Output Connecting Waveguide

Output connecting waveguide core OCWCo 28200 has averaged Refractive Index  $n_{OCWCo}=n_{aOCWCo}=3.6$ , thickness  $d_{OCWCo}$  28200d is  $d_{OCWCo}=250nm$ , and width  $W_{OCWCo}$  28200w is  
20  $W_{OCWCo}=400nm$ .

Output connecting waveguide OCWG 28200WG has Output connecting-waveguide bottom cladding material OCWBCd 28200B that is silicon dioxide ( $SiO_2$ ) for which the refractive index  $n_{OCWBCd}$  28200Bn is  $n_{OCWBCd}=1.45$ .

Output connecting waveguide top cladding material OCWTCd 28200T is silicon dioxide  
25 for which the refractive index  $n_{OCWTCd}$  28200Tn is  $n_{OCWTCd}=1.45$ .

Output connecting waveguide left cladding material OCWLCd 28200L is silicon dioxide for which the refractive index  $n_{OCWLCd}$  28200Ln is  $n_{OCWLCd}=1.45$ .

Output connecting waveguide right cladding material OCWRCd 28200R is silicon dioxide for which the refractive index  $n_{OCWRCd}$  28200Rn is  $n_{OCWRCd}=1.45$ .

30 The resulted averaged cladding refractive Index  $n_{aOCWCD}$  28200aCdn is  $n_{aOCWCD}=1.45$ .

Output optical beam OBM 28140

### Output Beam Coupler Structure (OBCS) Region

Output tapering waveguide core OTWCo 28300 is made of silicon. Its width at a location  $z_2$  OTWCo- $z_2$  is denoted as width  $w_{\text{OTWCo-}z_2}$  28300w- $z_2$ . This width is tapered from width at  $z_2=0$   $w_{\text{OTWCo-}z_2=0}$  28300w- $z_2=0$  that has a value of  $w_{\text{OTWCo-}z_2=0}=400\text{nm}$  to a width at  $z_2>0$

5  $w_{\text{OTWCo-}z_2>0}$  28300w- $z_2>0$  that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{\text{OTWCo-}z_2}$  28300d- $z_2$  made of silicon is  $d_{\text{OTWCo-}z_2}=250\text{nm}$  with a refractive index  $n_{\text{OTWCo-}z_2}$  28300n- $z_2$  that is  $n_{\text{OTWCo-}z_2}=3.6$ .

The total length of tapering waveguide  $g_{\text{OTWCo}}$  28300g is  $g_{\text{OTWCo}} = 20$  micrometers ( $\mu\text{m}$ ). The width of the waveguide core at the end of the tapering at  $z_2 = g_{\text{OTWCo}}$  is  $w_{\text{OTWCo-g}}$  28300w-g with

10  $w_{\text{OTWCo-g}}=50\text{nm}$ .

Output supporting structure OSTR 29200 has width  $w_{\text{OSTR}}$  29200w with  $w_{\text{OSTR}}=50\text{nm}$  and thickness  $d_{\text{OSTR}}$  29200d with  $d_{\text{OSTR}}=250\text{nm}$  and length  $g_{\text{OSTR}}$  29200g with  $g_{\text{OSTR}}=20$  micrometers. It has an effective layer averaged refractive index  $n_{\text{laOSTR}}$  29200nla with  $n_{\text{laOSTR}}<2.5$ .

The top cladding OTWTCd- $z_2$  28300T- $z_2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{\text{OTWTCd-}z_2}$  28300Tn- $z_2$  with  $n_{\text{OTWTCd-}z_2}=1.45$  before going into the ALS region.

15  $n_{\text{OTWTCd-}z_2}$  28300Tn- $z_2$  with  $n_{\text{OTWTCd-}z_2}=1.45$  before going into the ALS region.

The bottom cladding OTWBcd- $z_2$  28300B- $z_2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{\text{OTWBcd-}z_2}$  28300Bn- $z_2$  with  $n_{\text{OTWBcd-}z_2}=1.45$ .

The left cladding OTWLCd- $z_2$  28300L- $z_2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{\text{OTWLCd-}z_2}$  28300Ln- $z_2$  with  $n_{\text{OTWLCd-}z_2}=1.45$ .

20 The right cladding OTWRCd- $z_2$  28300R- $z_2$  is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{\text{OTWRCd-}z_2}$  28300Rn- $z_2$  with  $n_{\text{OTWRCd-}z_2}=1.45$ .

In this exemplary embodiment,  $n_{\text{OTWTCd-}z_2} = n_{\text{OTWBcd-}z_2} = n_{\text{OTWLCd-}z_2} = n_{\text{OTWRCd-}z_2} = n_{\text{OCWTCd}}$ , and  $n_{\text{OCWTCd}} = n_{\text{OCWBcd}} = n_{\text{OCWLCd}} = n_{\text{OCWRCd}}$

Output tapering waveguide core OTWCo 28300 starting at  $z_2=z_2\text{ALS}$  28300z2ALS, is laid with an active layer structure ALS 22500.  $0 < z_2\text{ALS} < g_{\text{OTWCo}}$ .

25 laid with an active layer structure ALS 22500.  $0 < z_2\text{ALS} < g_{\text{OTWCo}}$ .

Most of the output optical beam energy of beam OBM 28140 is transported to output tapering waveguide core OTWCo 28300 from the electro-active waveguiding core structure EWCos 22600, through the output tapering waveguide region between  $z_2=z_2\text{ALS}$  28300z2ALS and  $z_2 = g_{\text{OTWCo}}$  28300g, where the output tapering waveguide core width  $w_{\text{OTWCo-}z_2}$  28300w- $z_2$  varies down to a smaller value of  $w_{\text{OTWCo-g}}$  at  $z_2 = g_{\text{OTWCo}}$  28300g from its value at  $z_2=z_2\text{ALS}$ , 28300z2ALS. The tapering waveguide core width is reduced to well below half the optical wavelength in the waveguide core given by  $\lambda_{\text{bm}}/(2 \times n_{\text{OTWCo}})$  so that  $w_{\text{OTWCo-g}} \ll \lambda_{\text{bm}}/(2 \times n_{\text{OTWCo}})$ .

30 varies down to a smaller value of  $w_{\text{OTWCo-g}}$  at  $z_2 = g_{\text{OTWCo}}$  28300g from its value at  $z_2=z_2\text{ALS}$ , 28300z2ALS. The tapering waveguide core width is reduced to well below half the optical wavelength in the waveguide core given by  $\lambda_{\text{bm}}/(2 \times n_{\text{OTWCo}})$  so that  $w_{\text{OTWCo-g}} \ll \lambda_{\text{bm}}/(2 \times n_{\text{OTWCo}})$ .

After the energy transported from the electro-active waveguiding core structure EWCoS 22600 that contains the electro-active layer EC 21500 down to the output taper at  $z_2=0$  where the taper core width is  $w_{OTWCo-z_2=0} = 28300w_0$  and  $w_{OTWCo-z_2=0} = w_{OCWCo}$  28200, the optical beam is denoted as output optical beam or beam OBM 28140.

5

### Length of Active Layer Structure

The length of the active layer structure  $SL_{mod}$  22550 is approximately 500 micrometers..

### High Refractive Index Contrast and Mode Overlapping

10 For the bottom cladding:

Waveguide core refractive index is  $n_{BCo}=3.6$

Waveguide bottom cladding is  $n_{BCd}=1.45$  (given by layer ISTRBC with  $n_{ISTRBCd}=1.45$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{BCd}^2) = 10.86$ .

15 Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{BCd}^2) = 0.7$ , which is in the very-strongly guiding regime.

For the top cladding:

Waveguide core refractive index is  $n_{co}=3.6$

20 Waveguide bottom cladding is  $n_{TCd}=1.7$  (given by TVSCOC layer which is  $In_2O_3$  with  $n_{TVSCOC}=1.7$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{TCd}^2) = 10$ .

Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{TCd}^2) = 0.64$ , which is in the very-strongly guiding regime.

### 25 A Third Exemplary Device of Electro-Optic Modulator with Transparent Conductor Geometry

A preferred embodiment of an exemplary device is Modulator Device 20000 with the following specifications referred to as a third exemplary device of electro-optic modulator with Ohmic transparent conductor geometry: The main difference between this and the Second Exemplary Device is in Table 3-3, in which the active layer is designed for electro-optic modulation.

30

Substrate SUB 21100 is silicon wafer substrate with a thickness of about 0.3mm.

Input connecting waveguide core ICWCo 22200 is made of silicon for which its averaged material refractive index  $n_{ICWCo}$  22200n is around  $n_{ICWCo} = 3.6$ , thickness  $d_{ICWCo}$  22200d is  $d_{ICWCo} = 250\text{nm}$ , and width  $W_{ICWCo}$  22200w is  $W_{ICWCo} = 400\text{nm}$ .

Input connecting-waveguide bottom cladding material ICWBCd 22200B is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWBCd}$  22200Bn is  $n_{ICWBCd} = 1.45$ .

Input connecting waveguide top cladding material ICWTCd 22200T is silicon dioxide ( $\text{SiO}_2$ ) for which its refractive Index  $n_{ICWTCd}$  22200Tn is 1.45.

Input connecting waveguide left cladding material ICWLCd 22200L is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWLCd}$  22200Ln is 1.45

10 Input connecting waveguide right cladding material ICWRCd 22200R is silicon dioxide ( $\text{SiO}_2$ ), for which its refractive Index  $n_{ICWRCd}$  22200Rn is 1.45

The above form an input connecting waveguide ICWG 22200WG . The core-cladding refractive-index difference  $n_{Rd}$  defined by  $n_{Rd}^2 = (n_{Co}^2 - n_{Cd}^2)$  for waveguide ICWG 22200WG is  $n_{Rd}^2 = (3.6^2 - 1.45^2) = 10.86$  with  $n_{Co} = 3.6$  and  $n_{Cd} = 1.45$ . Its averaged Cladding Refractive Index is  
 15 given by  $n_{aICWcd} = (n_{ICWBCd}^2 \times A_{ICWBCd} + n_{ICWTCd}^2 \times A_{ICWTCd} + n_{ICWRCd}^2 \times A_{ICWRCd} + n_{ICWLCd}^2 \times A_{ICWLCd}) / (A_{ICWBCd} + A_{ICWTCd} + A_{ICWRCd} + A_{ICWLCd})^{0.5} = 1.45$ . Its averaged Core Refractive Index is given by  $n_{aCo} = (n_{Co1}^2 \times A_{Co1} + n_{Co2}^2 \times A_{Co2} + n_{Co3}^2 \times A_{Co3} + \dots + n_{Com}^2 \times A_{Com}) / (A_{Co1} + A_{Co2} + A_{Co3} + \dots + A_{Com})^{0.5} = 3.6$ .

The input optical beam IBM 22140 has propagating refractive index  $n_{IBM}$  22140n, for  
 20 which  $n_{IBM}$  is approximately 2.8 with optical power  $P_{bm}$  22140P approximately 1mW, electric field polarization  $E_{bm}$  22140E to be in the horizontal direction parallel to the substrate surface. It has a beam effective area  $A_{bm}$  22140A of  $A_{bm} = 0.04 \mu\text{m}^2$  and an optical wavelength centered at  $\lambda_{bm}$  22140L with  $\lambda_{bm} = 1550\text{nm}$  with plurality of (N) frequency channels  $\lambda_{bm1} = 1548\text{nm}$ ,  $\lambda_{bm2} = 1549\text{nm}$ ,  $\lambda_{bm3} = 1550\text{nm}$ ,  $\lambda_{bm4} = 1551\text{nm}$ , and  $\lambda_{bm5} = 1552\text{nm}$  centered at  $\lambda_{bm} = 1550\text{nm}$ .

25

### Input Beam Coupler Structure (IBCS) Region

The input tapering waveguide core ITWCo 223000 is made of silicon. Its width at a location  $z1$ , ITWCo- $z1$  22300z1 is denoted as width  $w_{ITWCo-z1}$  22300w-z1. This width is tapered from width at  $z1=0$   $w_{ITWCo-z1=0}$  22300w-z1=0 that has a value of  $w_{ITWCo-z1=0} = 400\text{nanometers (nm)}$   
 30 to a width at  $z1>0$   $w_{ITWCo-z1>0}$  22300w-z1>0 that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{ITWCo-z1}$  22300d-z1 made of silicon is  $d_{ITWCo-z1} = 250\text{nm}$  with a refractive index  $n_{ITWCo-z1}$  22300n-z that is  $n_{ITWCo-z1} = 3.6$ .

The total length of tapering waveguide  $g_{ITWCo}$  22300g is  $g_{ITWCo} = 20$  micrometers ( $\mu m$ ). The width of the waveguide core at the end of the tapering at  $z1 = g_{ITWCo}$  is  $w_{ITWCo-g}$  22300w-g with  $w_{ITWCo-g} = 50nm$ .

Input supporting structure ISTR 21200 has width  $w_{ISTR}$  21200w with  $w_{ISTR} = 50nm$

- 5 and thickness  $d_{ISTR}$  21200d with  $d_{ISTR} = 250nm$  and length  $g_{ISTR}$  21200g with  $g_{ISTR} = 20$  micrometers. It has an effective layer averaged refractive index  $n_{laISTR}$  21200nla with  $n_{laISTR} < 2.5$ .

- Left cladding material ISTRLCd 21200L is air and has a refractive index  $n_{ISTRLCd}$  21200Ln given by  $n_{ISTRLCd} = 1$ , and Right cladding material ISTRRCd 21200R is air and has a refractive index  $n_{ISTRRCd}$  21200Rn given by  $n_{ISTRRCd} = 1$ . Its bottom cladding ISTRBCd 21200B is silicon dioxide (this is part of a Buried-Oxide BOX layer in a typical Silicon-On-Insulator SOI wafer) with averaged refractive index  $n_{ISTRBCd}$  21200Bn of  $n_{ISTRBCd} = 1.45$ .

The top cladding ITWTCd-z1 22300T-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWTCd-z1}$  22300Tn-z1 with  $n_{ITWTCd-z1} = 1.45$ .

- 15 The bottom cladding ITWBCd-z1 22300B-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWBCd-z1}$  22300Bn-z1 with  $n_{ITWBCd-z1} = 1.45$ .

The left cladding ITWLCd-z1 22300L-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWLCd-z1}$  22300Ln-z1 with  $n_{ITWLCd-z1} = 1.45$ .

The right cladding ITWRCd-z1 22300R-z1 before going into the ALS region is silicon dioxide ( $SiO_2$ ) has refractive index  $n_{ITWRCd-z1}$  22300Rn-z1 with  $n_{ITWRCd-z1} = 1.45$ .

- 20 In this exemplary embodiment,  $n_{ITWTCd-z1} = n_{ITWBCd-z1} = n_{ITWLCd-z1} = n_{ITWRCd-z1} = n_{ICWTCd}$  and  $n_{ICWTCd} = n_{ICWBCd} = n_{ICWLCd} = n_{ICWRCd}$ . Input tapering waveguide core ITWCo 22300 starting at  $z1 = z1ALS$  22300z1ALS, where  $z1ALS = 10$  micrometers, is laid with an active layer structure ALS 22500.  $0 < z1ALS < g_{ITWCo}$ .

## 25 Active Layer Structure-Beam Transport into the Structure

The active layer structure ALS 22500 is shown by the Table 3-3 below:

Table 3-3

| ALS 22500 Layer Number | Layer Thickness | NPNN TCO CASE                    | Doping/( $1/cm^3$ )    |
|------------------------|-----------------|----------------------------------|------------------------|
| BIM (21250)            | 100nm           | $In_2O_3$                        |                        |
| BSCOC 1                | 100nm           | InGaAsP 1.3um (Bottom layer-just | $N = 1 \times 10^{19}$ |

|                                  |                             |                                            |                         |
|----------------------------------|-----------------------------|--------------------------------------------|-------------------------|
| (21300)                          |                             | above the substrate)                       |                         |
| BIDC 2<br>(21350LN)              | 40nm                        | InP                                        | $N=1 \times 10^{19}$    |
| BVC 3<br>(21400)                 | 20nm                        | InGaAsP 1.3um                              | $N=1 \times 10^{19}$    |
| EC 4<br>(21500LN <sub>1</sub> )  | 10nm                        | AlGaInAs 1.3um                             | $N_1=1 \times 10^{19}$  |
| EC 5<br>(21500MLN <sub>1</sub> ) | 4nm barrier                 | AlGaInAs/1.1um/-0.8% tensile strained      | $MN_1=4 \times 10^{17}$ |
| EC 6<br>(21500MLN <sub>2</sub> ) | 2x7nm barrier<br>inside     | AlGaInAs/1.1um/-0.8% tensile strained      | $MN_2=4 \times 10^{17}$ |
| EC 7<br>(21500MLN <sub>3</sub> ) | 3x6.5nm Well<br>(PL=1350nm) | AlGaInAs/1.55um/0.9% compressive strained  | $MN_3=4 \times 10^{17}$ |
| EC 8<br>(21500MLN <sub>4</sub> ) | 4nm barrier                 | AlGaInAs/1.1um/-0.8% tensile strained      | $MN_4=4 \times 10^{17}$ |
| EC 9<br>(21500MLN <sub>5</sub> ) | 43nm                        | AlGaInAs 1.3um                             | $MN_5=4 \times 10^{17}$ |
| EC 10<br>(21500LP <sub>1</sub> ) | 20nm                        | AlGaInAs 1.3um                             | $P_1=1 \times 10^{18}$  |
| TVC 11<br>(21600P <sub>2</sub> ) | 25nm                        | InGaAsP 1.3 um                             | $P_2=1 \times 10^{18}$  |
| TVC 12<br>(21600N <sub>2</sub> ) | 20nm                        | InGaAsP 1.3 um                             | $N_2=1 \times 10^{19}$  |
| TIDC 13<br>(21650)               | 20nm                        | InP                                        | $N=1 \times 10^{19}$    |
| TVSCOC 14<br>(21700)             | 240nm                       | In <sub>2</sub> O <sub>3</sub> (Top layer) | $N=1 \times 10^{19}$    |
| Total                            | 580nm                       |                                            |                         |

In the table, the materials are unstrained (with InP as the substrate) if not specified as strained. The wavelength specified will be the material bandgap wavelength of the quaternary material involved (proper choice of the material composition is needed to achieve the required material bandgap and strain when grown on InP substrate).

#### Bottom Side Conduction and Ohmic Contact Layer

The active layer structure ALS 22500 has a bottom side conduction and Ohmic contact layer BSCOC 21300 that is InGaAsP layer given by layer 1 in Table 3-3 with thickness  $d_{BSC}$

21300d, where  $d_{\text{BSC}}=100\text{nm}$  and width  $w_{\text{BSC}}$  21300w, where  $w_{\text{BSC}}$  is approximately 54 micrometers along most of the length of the ALS. Its refractive index  $n_{\text{BSC}}$  21300n is  $n_{\text{BSC}}=3.4$ .

#### Bottom Interspaced Material Layer

5 The bottom interspaced material layer BIM 21250 is made of a Low-Refractive-Index Ohmic Transparent Conducting (LRI-OTC) material composed of Indium oxide ( $\text{In}_2\text{O}_3$ ) with thickness  $d_{\text{BIM}}$  21250d equals to  $d_{\text{BIM}} = 100\text{nm}$ , width  $w_{\text{BIM}}$  21250w equals to  $w_{\text{BIM}}=54$  micrometers, and average refractive index  $n_{\text{BIM}}$  21250n equals to  $n_{\text{BIM}}=1.7$ .

#### 10 Bottom Metal Contact Pads

The first bottom left metal contact pad FBLM 21900L is a multi-layer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-3. The total thickness of the metal contact pad is  $d_{\text{FBLM}}$  21900Ld, with  $d_{\text{FBLM}}=1068\text{nm}$ , and width  $w_{\text{FBLM}}$  21900Lw, where  $w_{\text{FBLM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBLM}}$  21900Lg is approximately 500 micrometers.

The first bottom right metal contact pad FBRM 21900R is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21300 given by layer 1 in Table 3-3. The total thickness of the metal contact pad is  $d_{\text{FBRM}}$  21900Rd, with  $d_{\text{FBRM}}=1068\text{nm}$ , and width  $w_{\text{FBRM}}$  21900Rw, where  $w_{\text{FBRM}}$  is approximately 20 micrometers. The length of the metal contact pad  $g_{\text{FBRM}}$  21900Rg is approximately 500 micrometers.

#### Bottom Metal Electrodes

25 On top of the first bottom left metal contact pad FBLM 21900L is deposited the first bottom left metal electrode FBLME 21120L which is gold of thickness of approximately 2 micrometer thick.

On top of the first bottom right metal contact pad FBRM 21900R is deposited the first bottom right metal electrode FBRME 21120R which is gold of thickness of approximately 2 micrometer thick.

### Bottom Interspaced Dielectric Current Conduction Layer

Bottom interspaced dielectric current conduction layer BDC 21350 is a n-doped InP given by layer 2 in Table 3-3 with thickness  $d_{BDC}$  21350d equals to  $d_{BDC}=40\text{nm}$ , width  $w_{BDC}$  21350w equals to  $w_{BDC}=54$  micrometers, and average refractive index  $n_{BDC}$  21350n equals to about  
 5  $n_{BDC}=3.0$ .

### Bottom Vertical Current Conduction Layer

Bottom vertical current conduction layer BVC 21400 is n-doped InGaAsP given by layer 3 in Table 3-3 with thickness  $d_{BVC}$  21400d equals to  $d_{BVC}=20\text{nm}$ , width  $w_{BVC}$  21400w equals to  
 10  $w_{BVC}=2\text{micrometers}$ , and an averaged refractive index  $n_{BVC}$  21400n equals to  $n_{BVC}=3.4$ .

### Electro-Active Layer

Electro-active layer EC 21500 is made up of layers 4,5,6,7,8,9,10 in Table 3-1 with an averaged refractive index of the entire layer given by  $n_{EC}$  21500n with  $n_{EC}$  equals to approximately  
 15  $n_{EC}=3.4$ . Under an applied electric field, there will be a change in averaged refractive index  $dn_{EC}$  21500dn. The average refractive index becomes  $n_{EC}(\text{new}) = n_{EC} + dn_{EC}$ .

The total thickness  $d_{EC}$  21500d of this Electro-active layer is  $d_{EC}=160\text{nm}$ . Its width  $w_{EC}$  21500w is equal to  $w_{EC}=2$  micrometers.

The electro-active layer has a PqN junction at layer 4 to 10 for which layer 4 is layer  
 20 21500LN<sub>1</sub> that is N-doped with a dopant density of  $21500N_1=1\times 10^{19}/\text{cm}^3$  and layer 10 is layer 21500LP<sub>1</sub> that is P-doped with a dopant density of  $21500P_1=1\times 10^{18}/\text{cm}^3$

The intermediate layers 21500MLN<sub>m</sub> are all N-doped with a dopant density of  $21500MN_m=4\times 10^{17}/\text{cm}^3$ .

The applied field  $E_{EC}$  21500E (which may cause a current  $C_{EC}$  21500C to flow) is across the  
 25 entire electro-active layer with a negative voltage applied to the top and positive voltage applied to the bottom of this entire electro-active layer known to those skilled in the art as reversed bias (with respect to the PN junction in the electro-active layer) of voltage  $V_R$  21500VR so the applied electro-active  $V_{EC}$  21500VEC is  $V_R$ .

The voltage applied to the electrodes of the modulator  $V_{MOD}$  20000V is approximately given by  
 30  $V_{EC}$ .

### Top Vertical Current Conduction Layer

Top vertical current conduction layer TVC 21600 is given by layer 11 and 12 in Table 3-3 made up of InGaAsP layer that is composed of 25nm-thick layer 21600LP<sub>2</sub> that is P-doped with dopant density 21600P<sub>2</sub>= $1 \times 10^{18}/\text{cm}^3$ , followed by 20nm-thick N-doped InGaAsP layer 21600LN<sub>2</sub> with dopant density 21600N<sub>2</sub>= $1 \times 10^{19}/\text{cm}^3$ . The total thickness for TVC 21600 is  $d_{\text{TVC}} 21600d$  with  $d_{\text{TVC}}=45\text{nm}$ . Its width is  $W_{\text{TVC}} 21600w$  equals to  $W_{\text{TVC}}=2$  micrometers, and its averaged refractive index is  $n_{\text{TVC}} 21600n$  equals to  $n_{\text{TVC}}=3.4$ . This N<sub>2</sub>P<sub>2</sub> junction forms a forward-Biased PN Junction (or Tunnel PN Junction). It forms a PN-changing PN junction (called PNCPN junction) 21600PNCPN.

### Top Interspaced Dielectric Current Conduction Layer

Top interspaced dielectric conduction layer TIDC 21650 is N-doped InP layer given by layer 13 in Table 3-3 with thickness  $d_{\text{TIDC}} 21650d$  equals to  $d_{\text{TIDC}}=20\text{nm}$ , width  $w_{\text{TIDC}} 21650w$  equals to  $w_{\text{TIDC}}=2$  micrometers, and averaged refractive index  $n_{\text{TIDC}} 21650n$  equals to  $n_{\text{TIDC}}=3.0$ .

### Top Vertical/Side Conduction and Ohmic Contact Layer

Top vertical/side conduction and Ohmic contact layer TVSCOC 21700 is made up of Low-Refractive-Index Ohmic Transparent Conductor (LRI-OTC) (In<sub>2</sub>O<sub>3</sub>) given by layer 14 in Table 3-3 with thickness  $d_{\text{TVSC}} 21700d$  equals to  $d_{\text{TVSC}}=240\text{nm}$ , width  $w_{\text{TVSC}} 21700w$  equals to  $w_{\text{TVSC}}=2$  micrometers, and an averaged refractive index  $n_{\text{TVSC}} 21700n$  equals to  $n_{\text{TVSC}}=1.7$ .

### Top Metal Contact Pads

The first top middle metal contact pad FTMM 21800M is multilayer metal made up of (17nm Au followed by 17nm Ge followed by 17nm Au followed by 17nm Ni followed by 1000nm Au) deposited on top of the top surface of n-doped layer 21700 given by layer 14 in Table 3-3. The total thickness of the metal contact pad is  $d_{\text{FTMM}} 21800Md$ , with  $d_{\text{FTMM}}=1068\text{nm}$ , and width  $w_{\text{FTMM}} 21800Mw$ , where  $w_{\text{FTMM}}$  is approximately 2 micrometers. The length of the metal contact pad  $g_{\text{FTMM}} 21800Mg$  is approximately 500 micrometers.

There is no top left or right metal contact pad FTLM 21800L or FTRM 21800R.

### Top Metal Electrodes

On top of the first top middle metal contact pad FTMM 21800M is deposited the first top middle metal electrode FTMME 21130M which is gold of thickness of approximately 2 micrometer thick.

5

### Beam Transport to Electro-Active Waveguiding Core Structure

Input tapering waveguide region between  $z1=z1ALS$  22300 $z1ALS$  and  $z1=g_{ITWCo}$  22300g, Tapering waveguide core width  $w_{ITWCo-z1}$  22300w varies down to a smaller value of  $w_{ITWCo-g}=50nm$  at  $z1=g_{ITWCo}$  22300g from its value at  $z1=z1ALS$  22300 $z1ALS$ .

10 Clearly  $W_{ITWCo-g} \ll \lambda_{bm}/(2 * n_{ITWCo})$ , with  $\lambda_{bm}=1550nm$  and  $n_{ITWCo}=3.6$ , where \* is number multiplication.

### Output Connecting Waveguide

15 Output connecting waveguide core OCWCo 28200 has averaged Refractive Index  $n_{OCWCo}=n_{aOCWCo}=3.6$ , thickness  $d_{OCWCo}$  28200d is  $d_{OCWCo}=250nm$ , and width  $W_{OCWCo}$  28200w is  $W_{OCWCo}=400nm$ .

Output connecting waveguide OCWG 28200WG has Output connecting-waveguide bottom cladding material OCWBCd 28200B that is silicon dioxide ( $SiO_2$ ) for which the refractive index  $n_{OCWBCd}$  28200Bn is  $n_{OCWBCd}=1.45$ .

20 Output connecting waveguide top cladding material OCWTCd 28200T is silicon dioxide for which the refractive index  $n_{OCWTCd}$  28200Tn is  $n_{OCWTCd}=1.45$ .

Output connecting waveguide left cladding material OCWLCd 28200L is silicon dioxide for which the refractive index  $n_{OCWLCd}$  28200Ln is  $n_{OCWLCd}=1.45$ .

25 Output connecting waveguide right cladding material OCWRCd 28200R is silicon dioxide for which the refractive index  $n_{OCWRCd}$  28200Rn is  $n_{OCWRCd}=1.45$ .

The resulted averaged cladding refractive Index  $n_{aOCWCD}$  28200aCdn is  $n_{aOCWCD}=1.45$ .

Output optical beam OBM 28140

### Output Beam Coupler Structure (OBCS) Region

30 Output tapering waveguide core OTWCo 28300 is made of silicon. Its width at a location  $z2$  OTWCo- $z2$  is denoted as width  $w_{OTWCo-z2}$  28300w- $z2$ . This width is tapered from width at

$z_2=0$   $w_{OTWCo-z_2=0}$  28300w-z<sub>2</sub>=0 that has a value of  $w_{OTWCo-z_2=0}=400\text{nm}$  to a width at  $z_2>0$   $w_{OTWCo-z_2>0}$  28300w-z<sub>2</sub>>0 that is narrower than 400nm in a linear fashion.

The thickness of the tapering waveguide core  $d_{OTWCo-z_2}$  28300d-z<sub>2</sub> made of silicon is  $d_{OTWCo-z_2}=250\text{nm}$  with a refractive index  $n_{OTWCo-z_2}$  28300n-z<sub>2</sub> that is  $n_{OTWCo-z_2}=3.6$ .

- 5 The total length of tapering waveguide  $g_{OTWCo}$  28300g is  $g_{OTWCo} = 20$  micrometers ( $\mu\text{m}$ ). The width of the waveguide core at the end of the tapering at  $z_2 = g_{OTWCo}$  is  $w_{OTWCo-g}$  28300w-g with  $w_{OTWCo-g}=50\text{nm}$ .

Output supporting structure OSTR 29200 has width  $w_{OSTR}$  29200w with  $w_{OSTR}=50\text{nm}$  and thickness  $d_{OSTR}$  29200d with  $d_{OSTR}=250\text{nm}$  and length  $g_{OSTR}$  29200g with  $g_{OSTR}=20$  micrometers.

- 10 It has an effective layer averaged refractive index  $n_{laOSTR}$  29200n<sub>la</sub> with  $n_{laOSTR}<2.5$ .

The top cladding OTWTCd-z<sub>2</sub> 28300T-z<sub>2</sub> is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWTCd-z_2}$  28300Tn-z<sub>2</sub> with  $n_{OTWTCd-z_2}=1.45$  before going into the ALS region.

The bottom cladding OTWBCd-z<sub>2</sub> 28300B-z<sub>2</sub> is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWBCd-z_2}$  28300Bn-z<sub>2</sub> with  $n_{OTWBCd-z_2}=1.45$ .

- 15 The left cladding OTWLCd-z<sub>2</sub> 28300L-z<sub>2</sub> is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWLCd-z_2}$  28300Ln-z<sub>2</sub> with  $n_{OTWLCd-z_2}=1.45$ .

The right cladding OTWRCd-z<sub>2</sub> 28300R-z<sub>2</sub> is silicon dioxide ( $\text{SiO}_2$ ) has refractive index  $n_{OTWRCd-z_2}$  28300Rn-z<sub>2</sub> with  $n_{OTWRCd-z_2}=1.45$ .

- 20 In this exemplary embodiment,  $n_{OTWTCd-z_2} = n_{OTWBCd-z_2} = n_{OTWLCd-z_2} = n_{OTWRCd-z_2} = n_{OCWTCd}$  and  $n_{OCWTCd} = n_{OCWBCd} = n_{OCWLCd} = n_{OCWRCd}$ .

Output tapering waveguide core OTWCo 28300 starting at  $z_2=z_2\text{ALS}$  28300z<sub>2</sub>ALS, is laid with an active layer structure ALS 22500.  $0 < z_2\text{ALS} < g_{OTWCo}$ .

- Most of the output optical beam energy of beam OBM 28140 is transported to output tapering waveguide core OTWCo 28300 from the electro-active waveguiding core structure EWCos 22600, through the output tapering waveguide region between  $z_2=z_2\text{ALS}$  28300z<sub>2</sub>ALS and  $z_2 = g_{OTWCo}$  28300g, where the output tapering waveguide core width  $w_{OTWCo-z_2}$  28300w-z<sub>2</sub> varies down to a smaller value of  $w_{OTWCo-g}$  at  $z_2 = g_{OTWCo}$  28300g from its value at  $z_2=z_2\text{ALS}$ , 28300z<sub>2</sub>ALS. The tapering waveguide core width is reduced to well below half the optical wavelength in the waveguide core given by  $\lambda_{bm}/(2\pi n_{OTWCo})$  so that  $w_{OTWCo-g} \ll \lambda_{bm}/(2\pi n_{OTWCo})$ .
- 30 After the energy transported from the electro-active waveguiding core structure EWCos 22600 that contains the electro-active layer EC 21500 down to the output taper at  $z_2=0$  where the taper

core width is  $w_{OTWC0-z2=0} = 28300w_0$  and  $w_{OTWC0-z2=0} = w_{OCWC0} = 28200$ , the optical beam is denoted as output optical beam or beam OBM 28140.

### Length of Active Layer Structure

- 5 The length of the active layer structure  $SL_{mod}$  22550 is approximately 500 micrometers..

### High Refractive Index Contrast and Mode Overlapping

For the bottom cladding:

Waveguide core refractive index is  $n_{co}=3.6$

- 10 Waveguide bottom cladding is  $n_{BCd}=1.45$  (given by layer ISTRBC with  $n_{ISTRBCd}=1.45$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{BCd}^2) = 10.86$ .

Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{BCd}^2) = 0.7$ , which is in the very-strongly guiding regime.

- 15 For the top cladding:

Waveguide core refractive index is  $n_{co}=3.6$

Waveguide bottom cladding is  $n_{TCd}=1.7$  (given by TVSCOC layer which is  $In_2O_3$  with  $n_{TVSCOC}=1.7$ )

Waveguide core-to-cladding refractive index difference square to be  $n_{rd}^2 = (n_{co}^2 - n_{TCd}^2) = 10$ .

- 20 Refractive index contrast ratio to be:  $R_{cts} = n_{rd}^2 / (n_{co}^2 + n_{TCd}^2) = 0.64$ , which is in the very-strongly guiding regime.

### Final Summary

The main parts of the embodiments can be summarized as follows:

- 25 1. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

30

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined

in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

5

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

10

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

15

20

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

25

2. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

30

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters

below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

5 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

10 The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both  
15 larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

20 The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

The electro-active layer has a low-refractive-index Ohmic transparent conductor (LRI-OTC) layer electrically connected from the top to the electro-active layer. The LRI-OTC forms part of the top electro-active waveguide cladding.

25 3. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and  
30 from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin region or very-thin such that  $d_{CORE} < (\lambda_{op}/n_{Co})$ .

4. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined

in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

5

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

10

The electro-active waveguide core and electro-active waveguide cladding structure is in an very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.5, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

15

20

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin or very-thin region such that  $d_{CORE} < (\lambda_{op}/n_{Co})$ .

(PqN case)

25

5. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

30

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters

below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

5 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

10 The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both  
15 larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

20 The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

25 A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

A voltage is applied across the first P-layer of this first PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

- 5 6. (PqN case plus Tunnel) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

10 The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

15 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

20 The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{\text{CORE}}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{\text{CORE}} < (2 * \lambda_{\text{op}} / n_{\text{Co}})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNC PN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

7. (NqN case) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{\text{op}}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined

in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first NqN junction in which a first N-layer with N-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the first q-layer is further connected to a second N-layer with N-dopant.

A voltage is applied across the first N-layer and the second N-layer of this first NqN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

8. (PqN case plus Tunnel plus TCO) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer.

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{ctb} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected

(vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCNP). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

The electro-active layer has a low-refractive-index Ohmic transparent conductor (LRI-OTC) layer electrically connected from the top to the electro-active layer. The LRI-OTC forms part of the top electro-active waveguide cladding.

9. (PqN case plus Tunnel plus taper WG) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide

core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWCo-z1}$ .

The width  $w_{ITWCo-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWCo-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWCo-z1})$ , so that  $w_{ITWCo-z1} < \lambda_{op}/(2 \times n_{ITWCo-z1})$  at some point under the electro-active layer.

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{ctb} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic

semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCPN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

10. (PqN case plus Tunnel plus taper WG plus QW) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ .

The width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$ , so that  $w_{ITWC0-z1} < \lambda_{op}/(2 \times n_{ITWC0-z1})$  at some point under the electro-active layer.

The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCNP). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

- 5 11. (PqN case plus Tunnel plus taper WG plus doped QW) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around an operating  
10 optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters  
15 below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ .

20 The width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$ , so that  $w_{ITWC0-z1} < \lambda_{op}/(2 \times n_{ITWC0-z1})$  at some point under the electro-active layer.

25 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an  
30 electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{\text{cts}} = (n_{\text{Co}}^2 - n_{\text{Cd}}^2) / (n_{\text{Co}}^2 + n_{\text{Cd}}^2)$  are both larger than about 0.2, where  $n_{\text{Cd}}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{\text{Co}}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{\text{CORE}}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{\text{CORE}} < (2 * \lambda_{\text{op}} / n_{\text{Co}})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

At least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the highly-doped, medium-highly-doped, very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $2 \times 10^{17} / \text{cm}^3$  with either N doping or P doping.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCPN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

- 5 12. (PqN case plus Tunnel plus taper WG plus very highly doped QW) A low-loss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around  
10 an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters  
15 below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ .

20 The width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$ , so that  $w_{ITWC0-z1} < \lambda_{op}/(2 \times n_{ITWC0-z1})$  at some point under the electro-active layer.

25 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an  
30 electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

At least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the medium-highly-doped, very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $5 \times 10^{17} / \text{cm}^3$  with either N doping or P doping.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCPN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

- 5 13. (PqN case plus Tunnel plus taper WG plus ultra-highly doped QW) A low-loss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or more optical wavelengths around  
10 an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters  
15 below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ .

20 The width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$ , so that  $w_{ITWC0-z1} < \lambda_{op}/(2 \times n_{ITWC0-z1})$  at some point under the electro-active layer.

25 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an  
30 electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

At least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $1.5 \times 10^{18} / \text{cm}^3$  with either N doping or P doping.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCPN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

A voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

- 5 14. (PqN case plus Tunnel plus taper WG plus ultra-highly doped QW plus top side conduction) A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate. The device has at least an input connecting waveguide core deposited on the substrate connecting the energy of an optical beam to and from an electro-active layer. The optical beam has one or  
10 more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ .

The input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer. The optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters  
15 below the electro-active layer. The optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer. The refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ .

20 The width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$ , so that  $w_{ITWC0-z1} < \lambda_{op}/(2 \times n_{ITWC0-z1})$  at some point under the electro-active layer.

25 The refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of the material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer. The electro-active layer is either part of or in spatial proximity to an  
30 electro-active waveguide core.

The electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cts} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

The electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

At least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $1.5 \times 10^{18} / \text{cm}^3$  with either N doping or P doping.

The first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCPN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

## CLAIMS

1. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate, comprising:

an input connecting waveguide core deposited on the substrate connecting an energy of an optical beam to and from an electro-active layer, the optical beam having one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ ;

the input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer, wherein the optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer, and the optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer; and

a refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $\alpha_{EC}$  of at least part of a material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer, wherein the electro-active layer is either part of or in spatial proximity to an electro-active waveguide core.

2. The device as claimed in claim 1, wherein the electro-active waveguide core and an electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that a refractive index contrast of the waveguide core layer with both a top and a bottom waveguide cladding defined by:  $R_{ctb} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.2, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

3. The device as claimed in claim 1, wherein the electro-active waveguide core and electro-active waveguide cladding structure is in an very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{ctb} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.5, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

4. The device as claimed in claim 1, wherein the electro-active waveguide core thickness  $d_{\text{CORE}}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{\text{CORE}} < (2 * \lambda_{\text{op}} / n_{\text{Co}})$ .

5. The device as claimed in claim 1, wherein the electro-active waveguide core thickness  $d_{\text{CORE}}$  is in the ultra-thin region or very-thin region such that  $d_{\text{CORE}} < (\lambda_{\text{op}} / n_{\text{Co}})$ .

6. The device as claimed in claim 1, wherein the electro-active layer has a low-refractive-index Ohmic transparent conductor (LRI-OTC) layer electrically connected from the top to the electro-active layer. The LRI-OTC forms part of the top electro-active waveguide cladding.

7. The device as claimed in claim 1, further comprising A structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

8. The device as claimed in claim 1, further comprising a structure electrically connected to the electro-active layer comprises at least a first NqN junction in which a first N-layer with N-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the first q-layer is further connected to a second N-layer with N-dopant.

9. The device as claimed in claim 1, wherein the first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNC PN). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

10. The device as claimed in claim 1, wherein a voltage is applied across the first P-layer of this first PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

11. The device as claimed in claim 1, wherein a voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

12. The device as claimed in claim 1, wherein a voltage is applied across the first N-layer and the second N-layer of this first NqN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

13. A lowloss-low-voltage-high-frequency optical phase or intensity modulator device deposited on a substrate, comprising:

an input connecting waveguide core deposited on the substrate connecting an energy of an optical beam to and from an electro-active layer, the optical beam having one or more optical wavelengths around an operating optical wavelength  $\lambda_{op}$ ;

the input connecting waveguide core becomes an input tapering waveguide core and enters below an electro-active layer, wherein the optical beam energy is well-confined in the input tapering waveguide core before the tapering waveguide core enters below the electro-active layer, and the optical beam energy is no longer well-confined in the input tapering waveguide core at some point after the tapering waveguide core enters below the electro-active layer and the refractive index of the tapering waveguide core is given by  $n_{ITWC0-z1}$ ;

a refractive index  $n_{EC}$  or the optical gain/absorption coefficient  $n_{EC}$  of at least part of a material in the electro-active layer can be altered by an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer, wherein the electro-active layer is either part of or in spatial proximity to an electro-active waveguide core; and

the width  $w_{ITWC0-z1}$  of the input tapering waveguide core after penetrating below the electro-active layer is reduced from a value approximately equal to or larger than half the wavelength in the material  $\lambda_{op}/(2 \times n_{ITWC0-z1})$  to a value smaller than half the wavelength in the

material  $\lambda_{op}/(2 \times n_{ITWCo-zl})$ , so that  $w_{ITWCo-zl} < \lambda_{op}/(2 \times n_{ITWCo-zl})$  at some point under the electro-active layer.

wherein the electro-active waveguide core and electro-active waveguide cladding structure is in a medium-strongly guiding or very-strongly guiding regime such that the refractive index contrast of the waveguide core layer with both the top and the bottom waveguide cladding defined by:  $R_{cls} = (n_{Co}^2 - n_{Cd}^2) / (n_{Co}^2 + n_{Cd}^2)$  are both larger than about 0.5, where  $n_{Cd}$  is the averaged material refractive index of either the top or the bottom waveguide cladding region, and  $n_{Co}$  is the averaged material refractive index of the waveguide core region.

14. The device as claimed in claim 13, wherein the electro-active waveguide core thickness  $d_{CORE}$  is in the ultra-thin, very-thin, medium-thin, or thin region such that  $d_{CORE} < (2 * \lambda_{op} / n_{Co})$ .

15. The device as claimed in claim 13, further comprising a structure electrically connected to the electro-active layer comprises at least a first PN junction in which a first P-layer with P-dopant is vertically connected (vertical means in a direction perpendicular to the substrate plane; horizontal means in a direction parallel to the substrate plane) to a first N-layer with N-dopant, or a PqN junction in which a first P-layer with P-dopant is connected to a first q-layer with either N or P dopant or that is undoped (i.e. being an Intrinsic semiconductor material) and the q-layer is further connected to a first N-layer with N-dopant.

16. The device as claimed in claim 13, wherein the first P-layer is electrically connected to a second P-layer with P-dopant of a second PN junction, referred to as the PN-changing PN junction (PNCNP). This second P-layer is electrically connected to a second N-layer with N-dopant of this second PN junction.

17. The device as claimed in claim 13, wherein a voltage is applied across the second N-layer of the second PN junction, and the first N-layer of the first PN junction to result in an applied electric field, an electric current, or either injection or depletion of carriers in the electro-active layer.

18. The device as claimed in claim 13, wherein at least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the

quantum well is in the highly-doped, medium-highly-doped, very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $2 \times 10^{17}/\text{cm}^3$  with either N doping or P doping.

19. The device as claimed in claim 13, wherein at least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the medium-highly-doped, very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $5 \times 10^{17}/\text{cm}^3$  with either N doping or P doping.

20. The device as claimed in claim 13, wherein at least one of the first P-layer, first N-layer, or the first q-layer contains at least one quantum well. The doping density at the quantum well is in the very-highly-doped, or ultra-highly-doped regime with a dopant density higher than about  $1.5 \times 10^{18}/\text{cm}^3$  with either N doping or P doping.

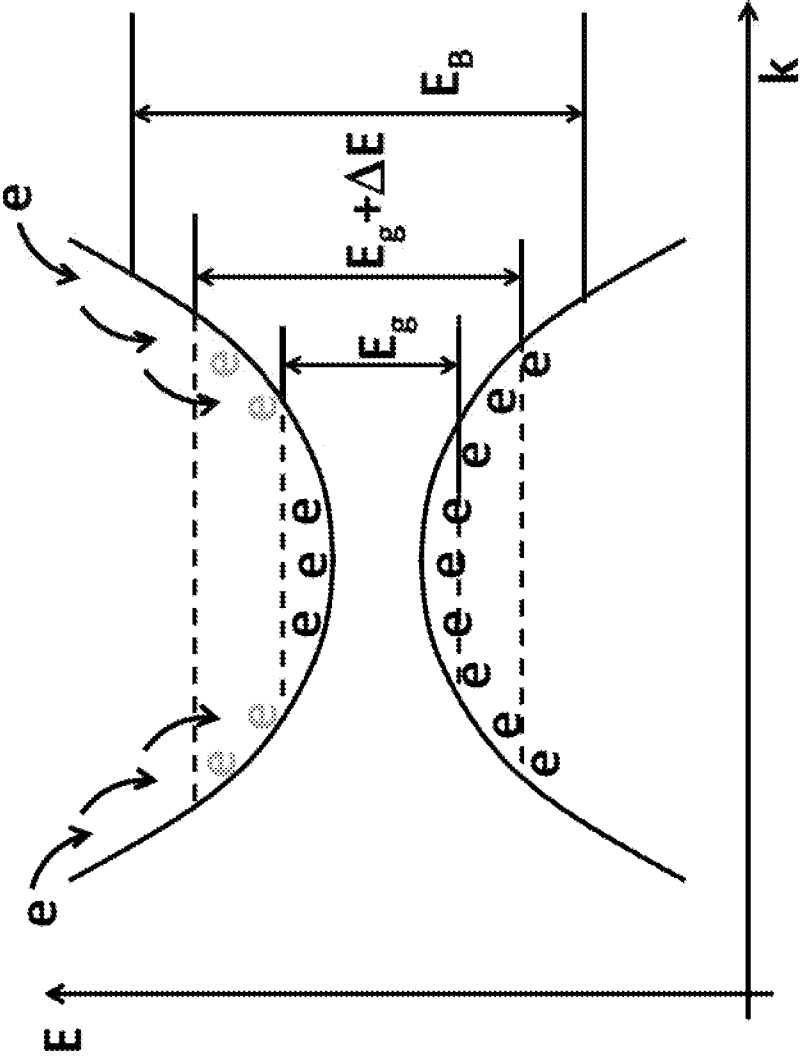


Fig. 1a

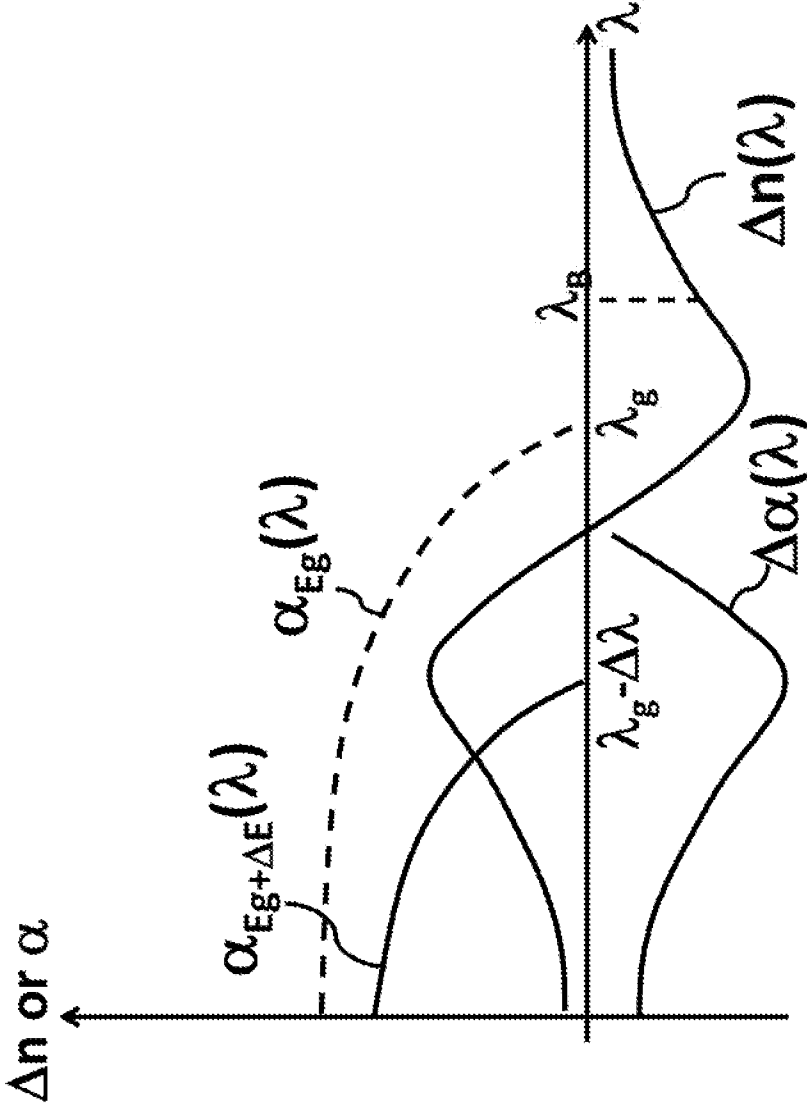


Fig. 1b

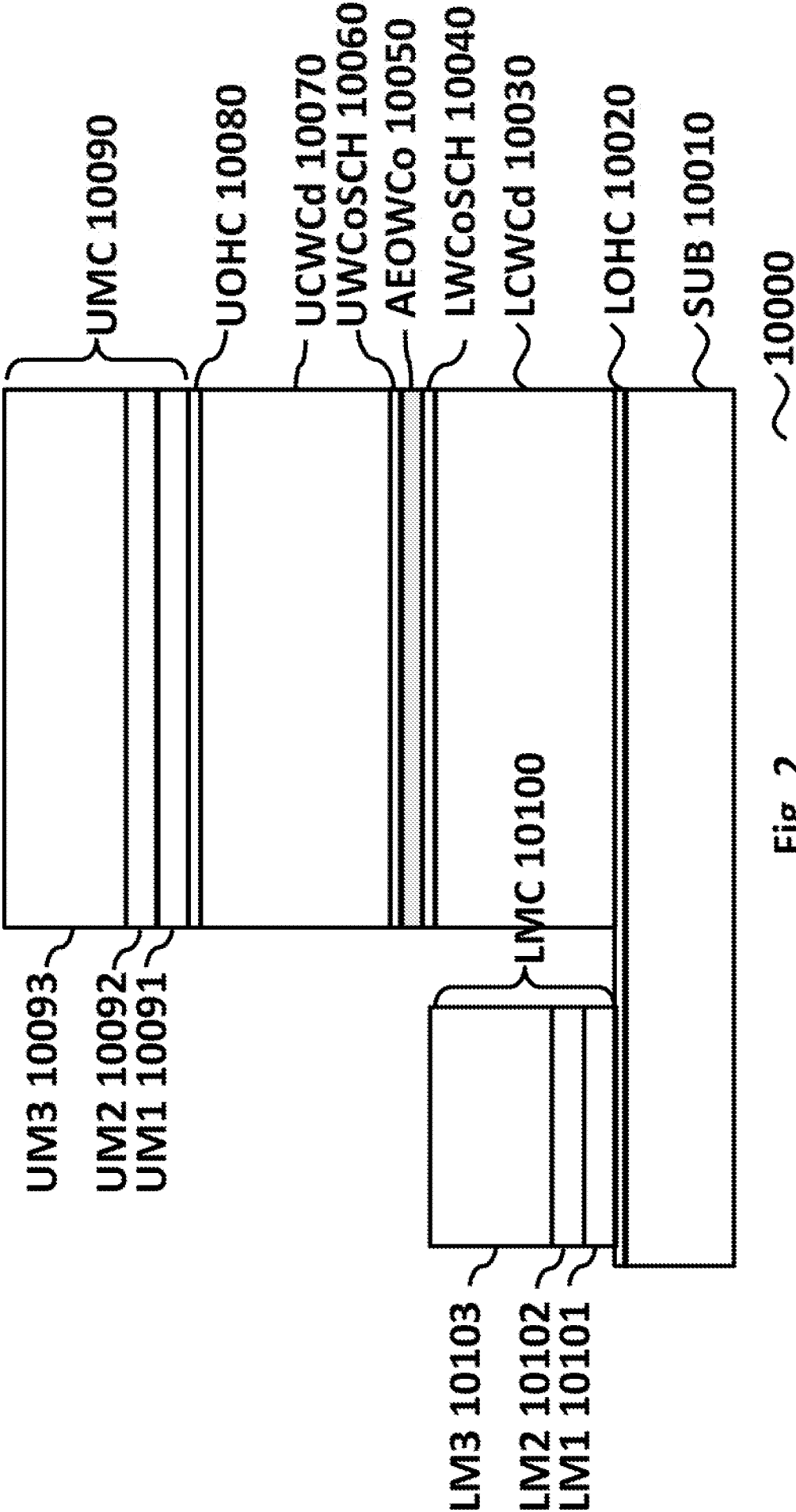


Fig. 2

|                  |                           |                                          |                    |   |      |
|------------------|---------------------------|------------------------------------------|--------------------|---|------|
| 1 n-Clad/contact | 110nm                     | InP                                      | $3 \times 10^{18}$ | n | 150  |
| 2 SCH            | 53nm                      | AlGaInAs 1.3um                           | $3 \times 10^{18}$ | n | 123  |
| 3 Barrier        | 5.5nm barrier             | AlGaInAs/1.1um/-0.8% tensile strained    |                    | I | 5.5  |
| 4 QWS AlInGaAs   | 14x7nm barrier inside     | AlGaInAs/1.1um/-0.8% tensile strained    |                    | I | 98   |
| 5                | 15x6.5nm Well (PL=1350nm) | AlGaInAs/1.5um/0.9% compressive strained |                    | I | 97.5 |
| 6 Barrier        | 5.5nm barrier             | AlGaInAs/1.1um/-0.8% tensile strained    |                    | I | 5.5  |
| 7 SCH            | 100nm                     | AlGaInAs 1.3um                           | $1 \times 10^{18}$ | p | 120  |
| 8 Cladding       | 1500nm                    | InP                                      | $1 \times 10^{18}$ | p | 1400 |
| 9 Contact        | 100nm                     | InGaAs                                   | $1 \times 10^{19}$ | p | 100  |
| 10 Buffer        | 200-300nm                 | InP                                      | $1 \times 10^{17}$ | p |      |
| 11 Substrate     | N+                        | c                                        |                    |   | 2000 |

Fig. 2b

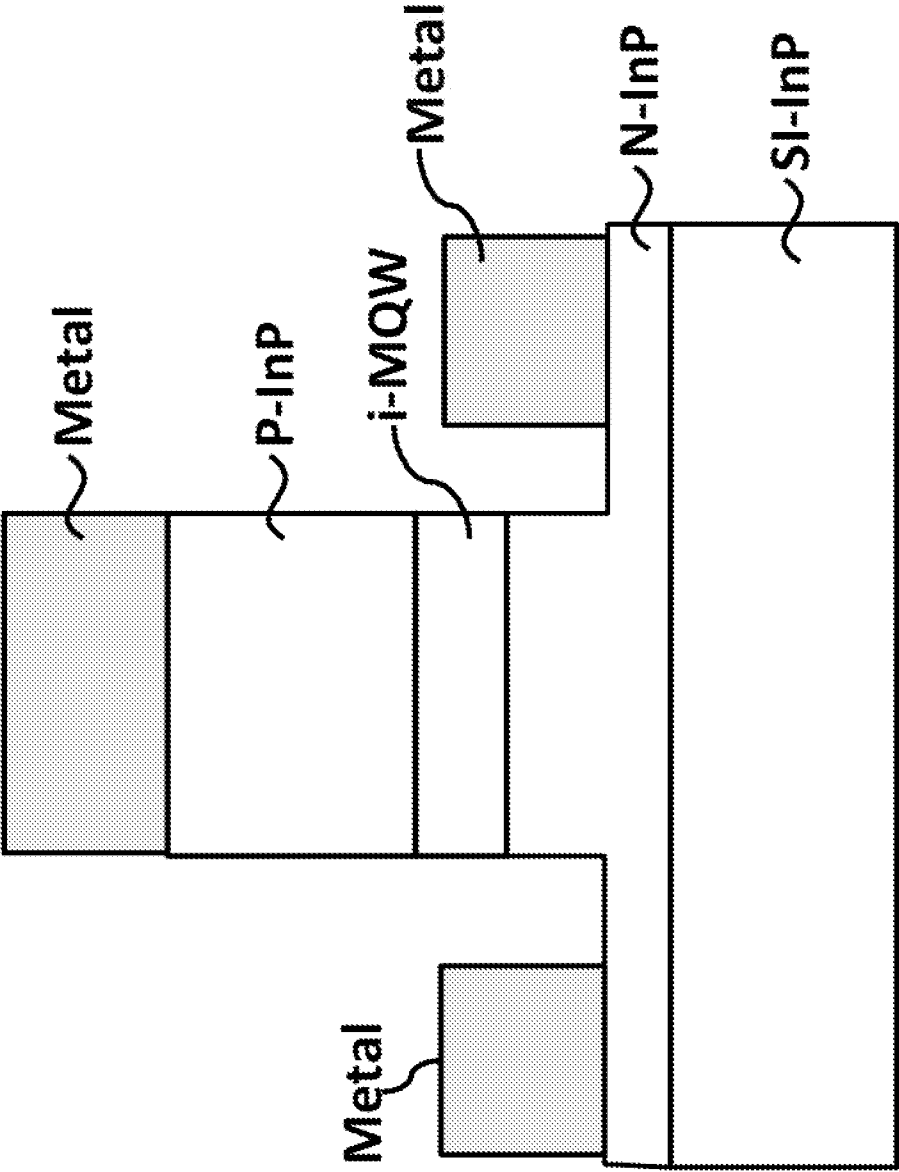


Fig. 3

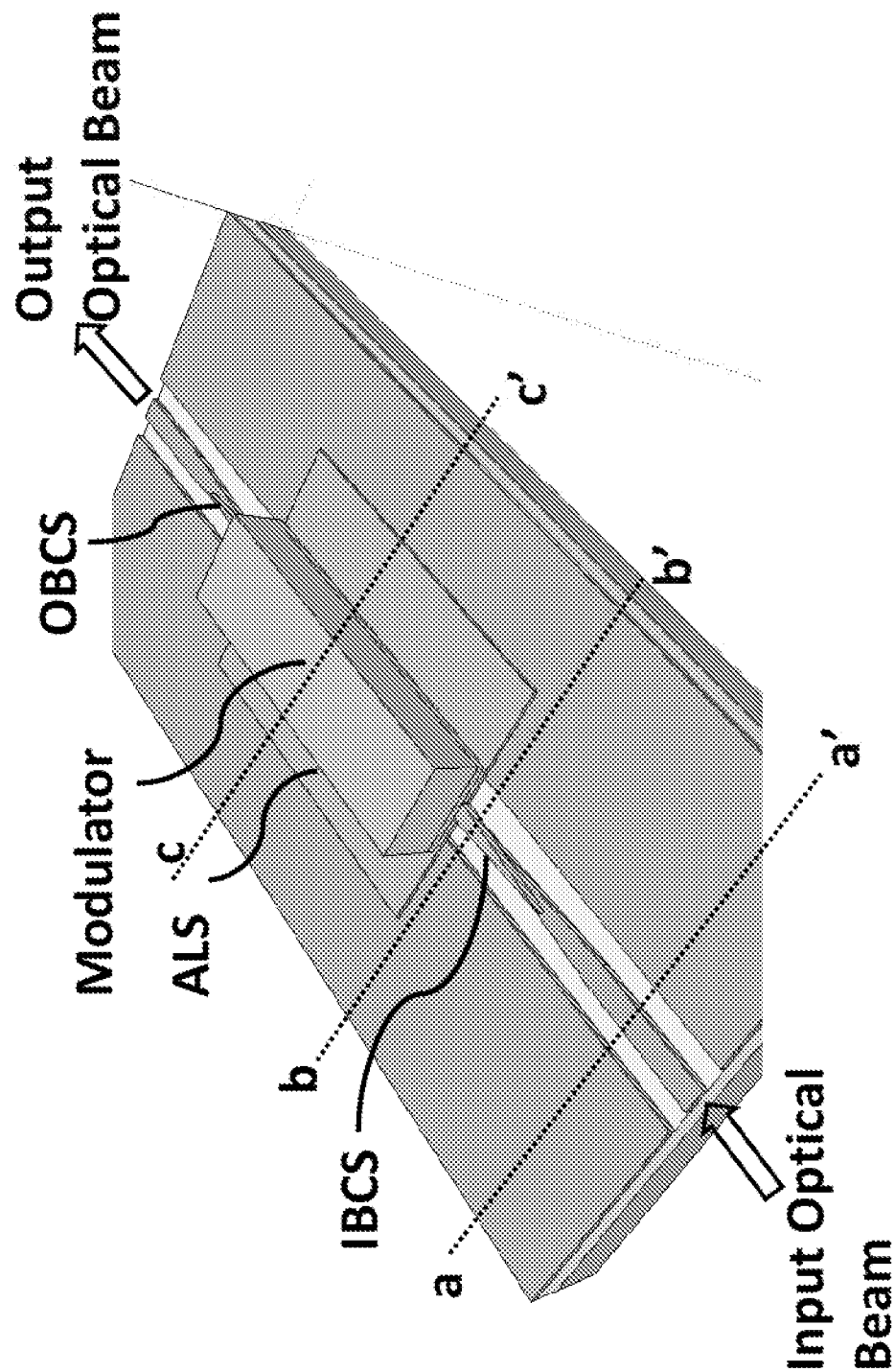


Fig. 4a

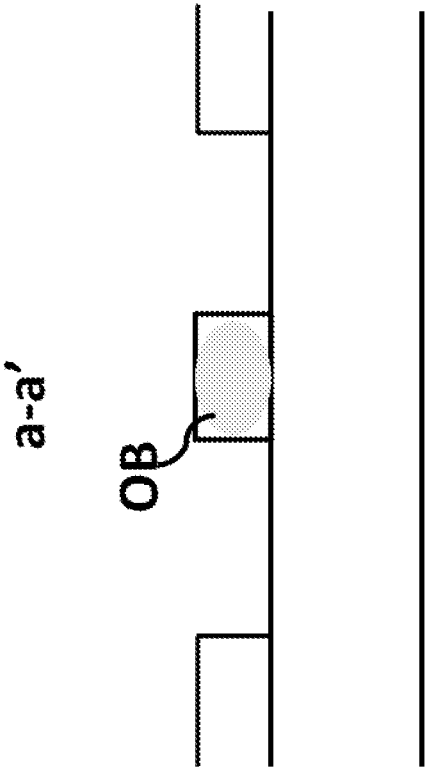


Fig. 4b

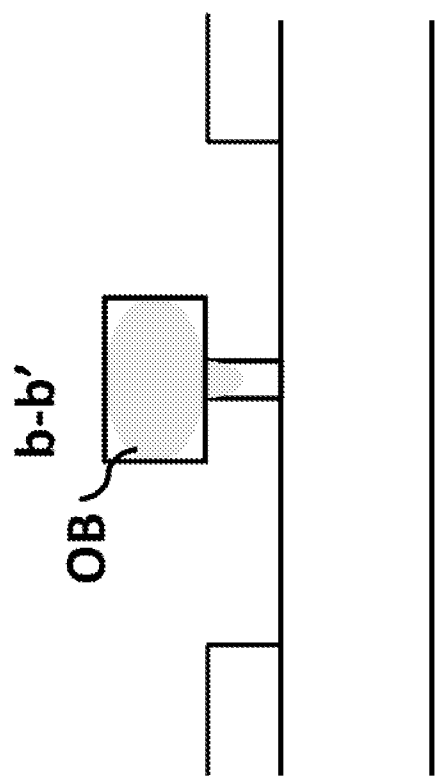


Fig. 4c

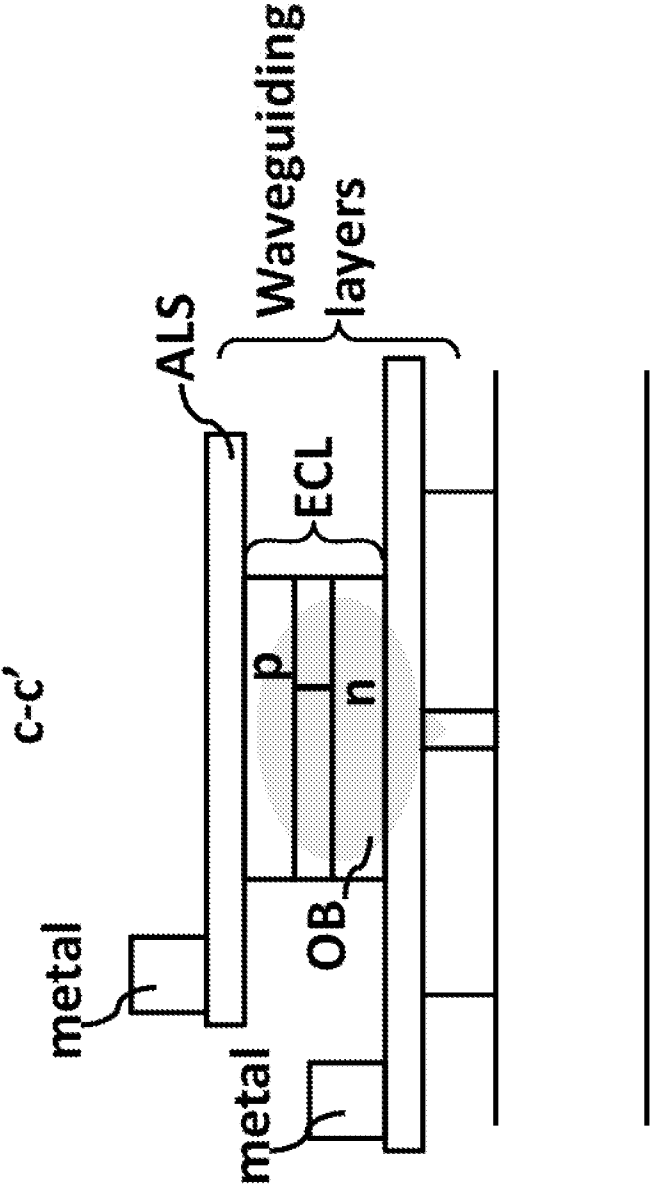


Fig. 4d

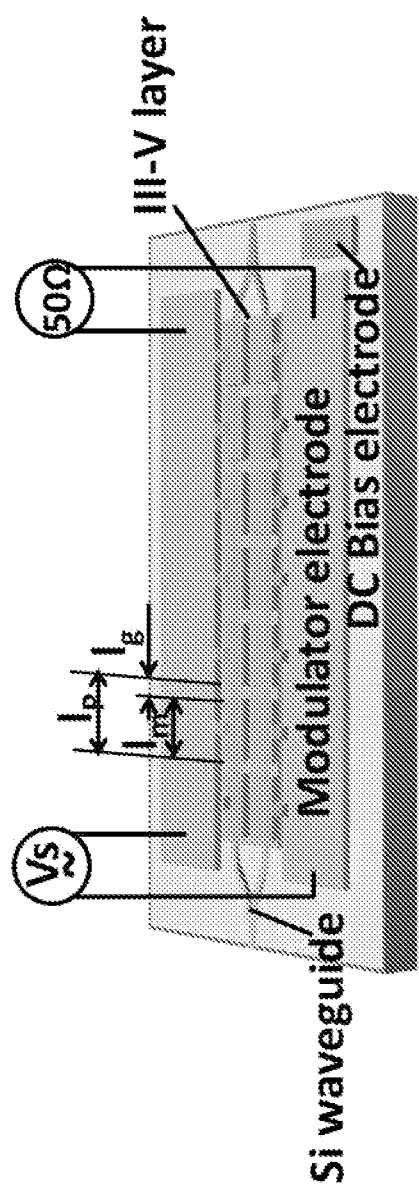


Fig. 5a

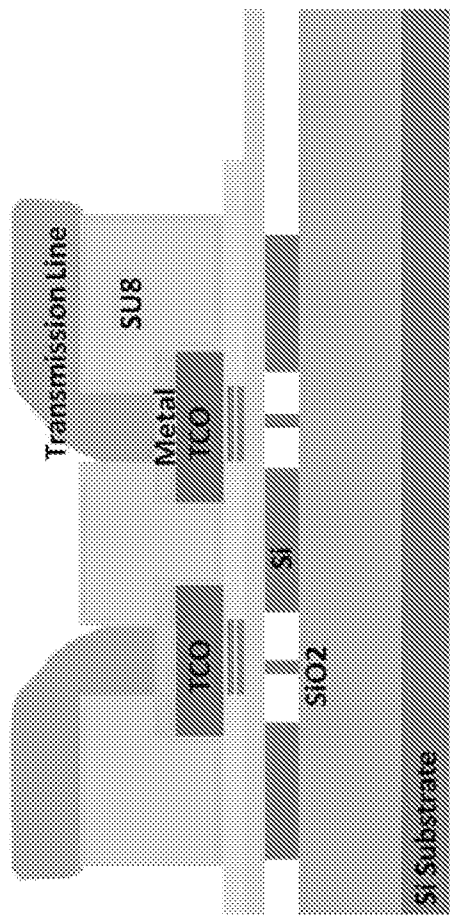


Fig. 5b

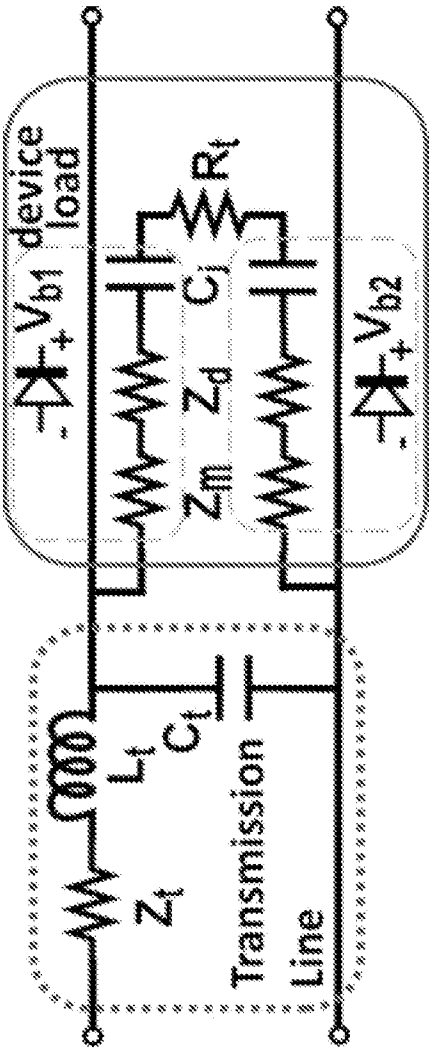


Fig.6a

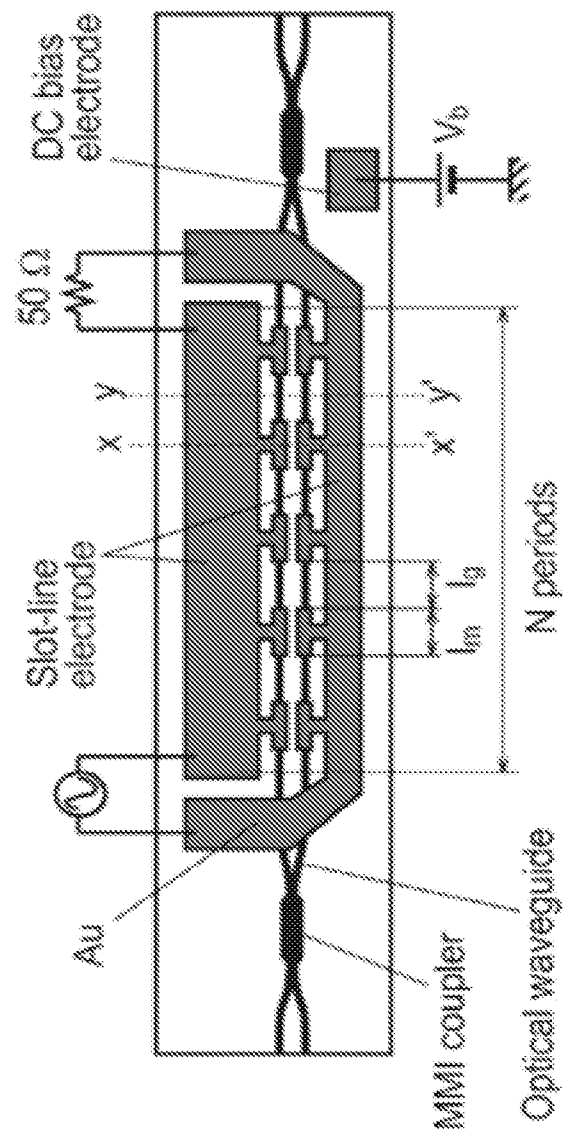


Fig. 6b

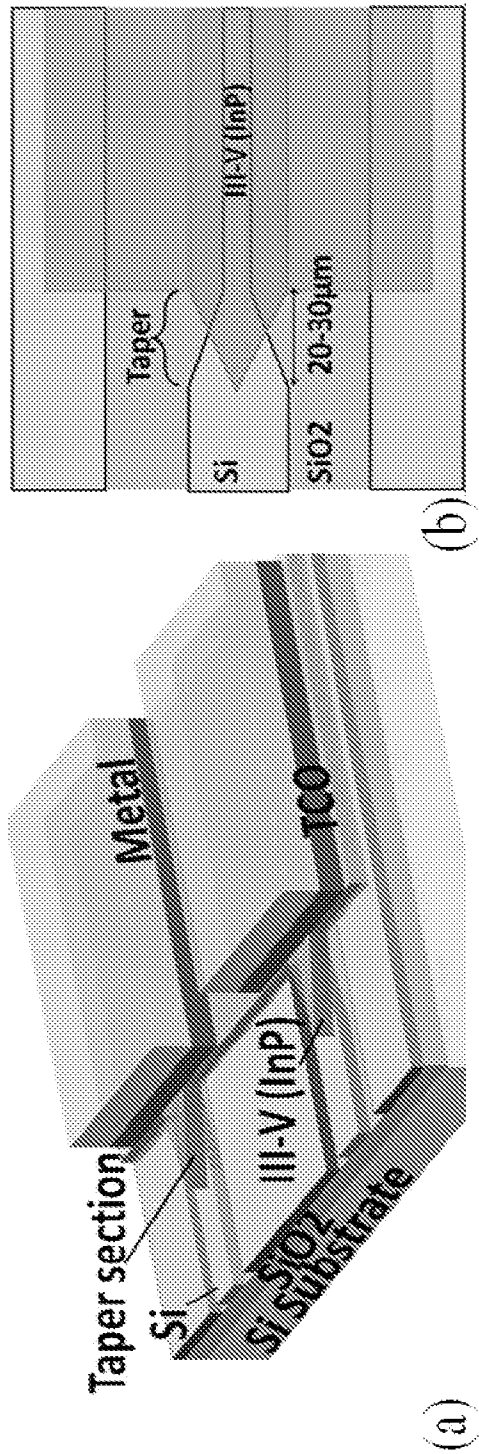


Fig.7

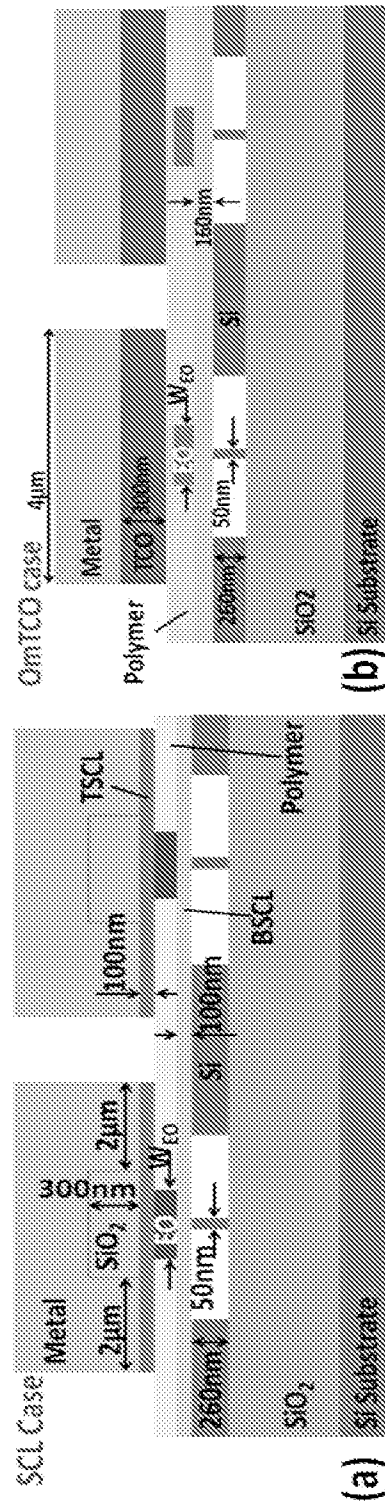


Fig. 8

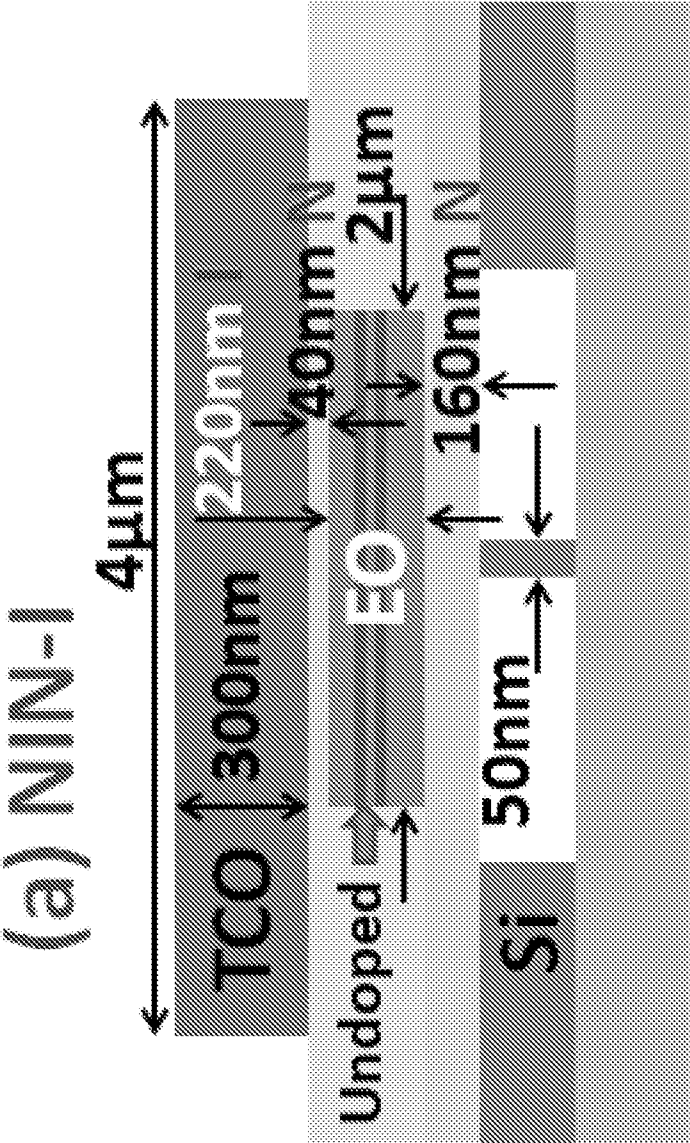


Fig.9a

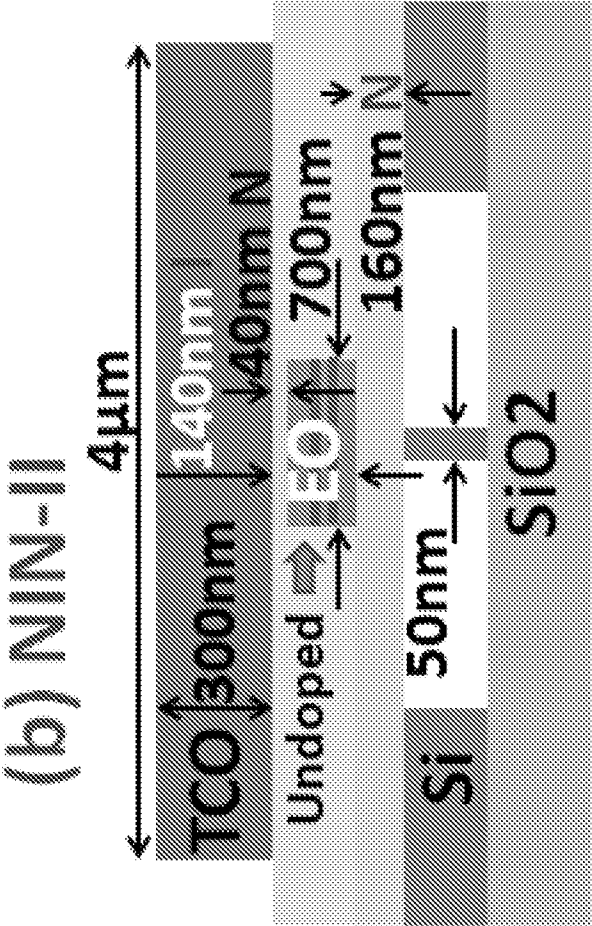


Fig.9b

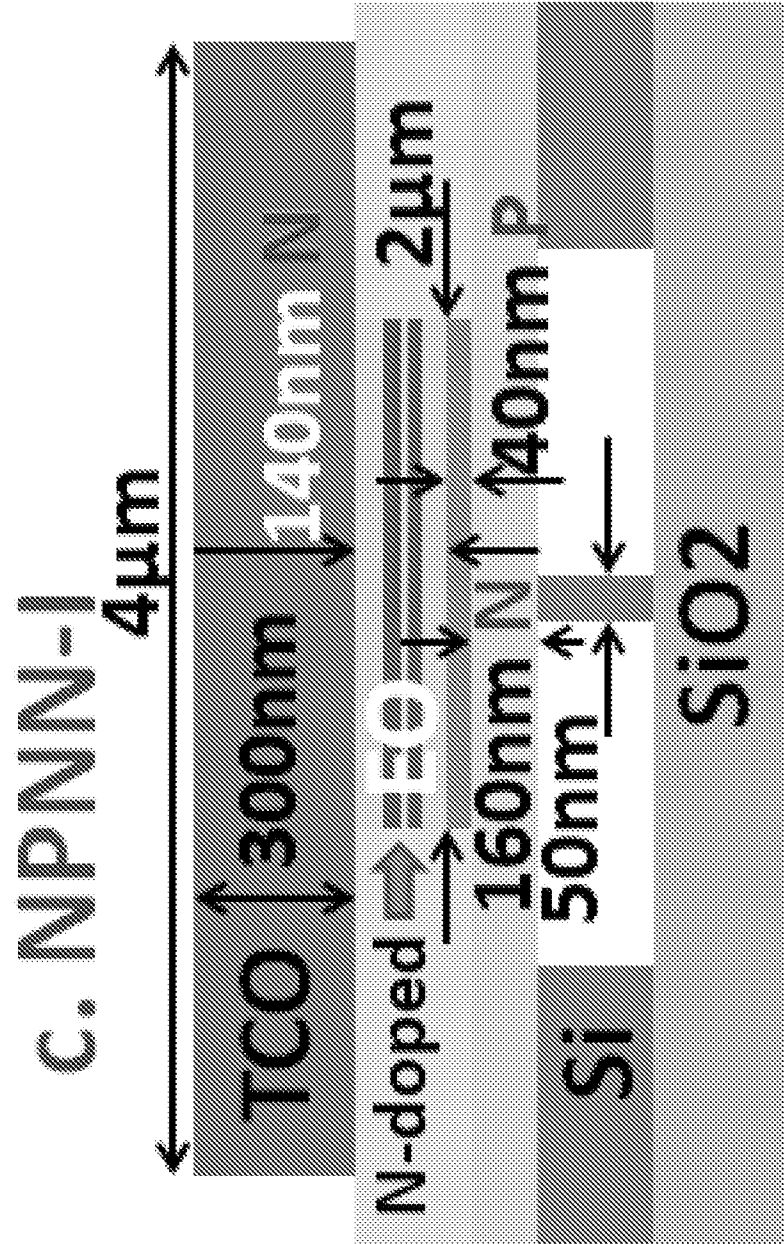


Fig.9c

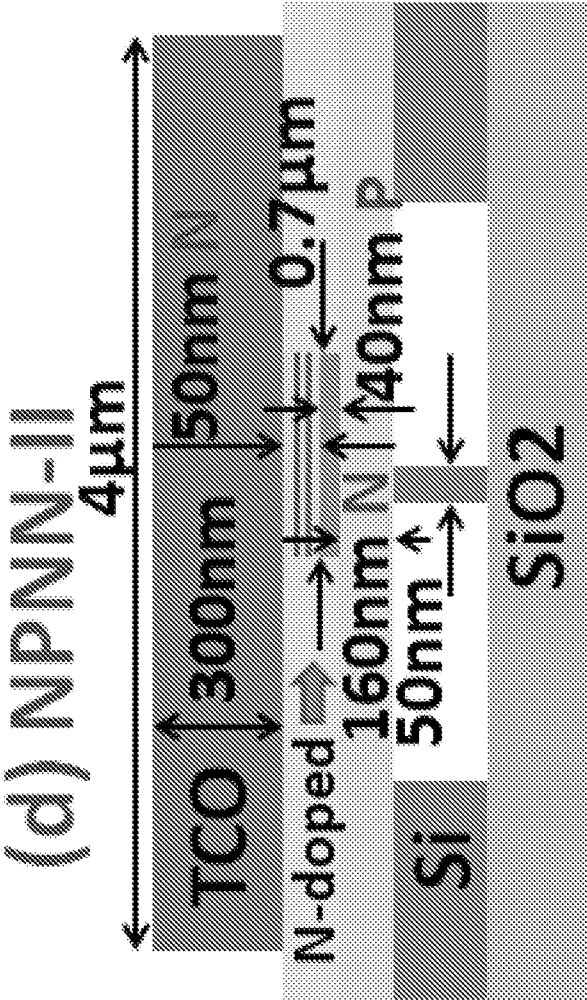
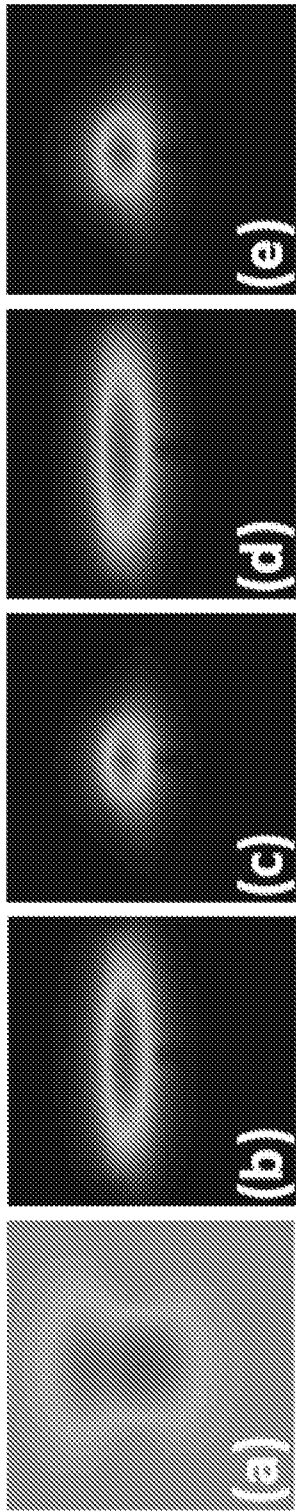


Fig.9d

**Fig. 10**

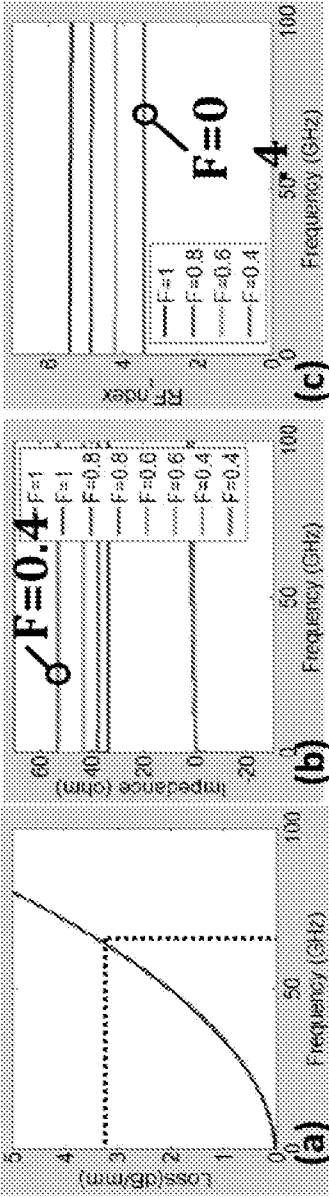


Fig. 11

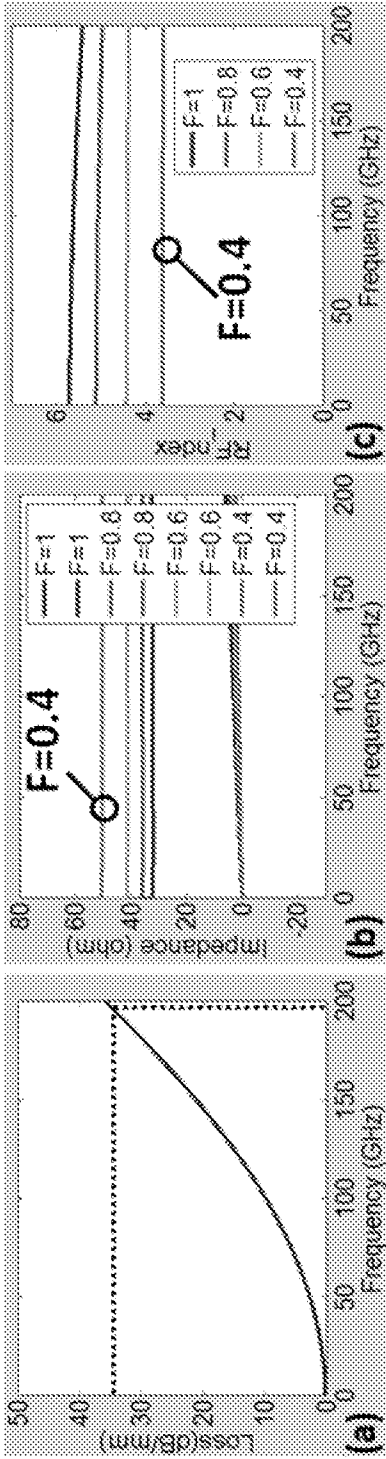
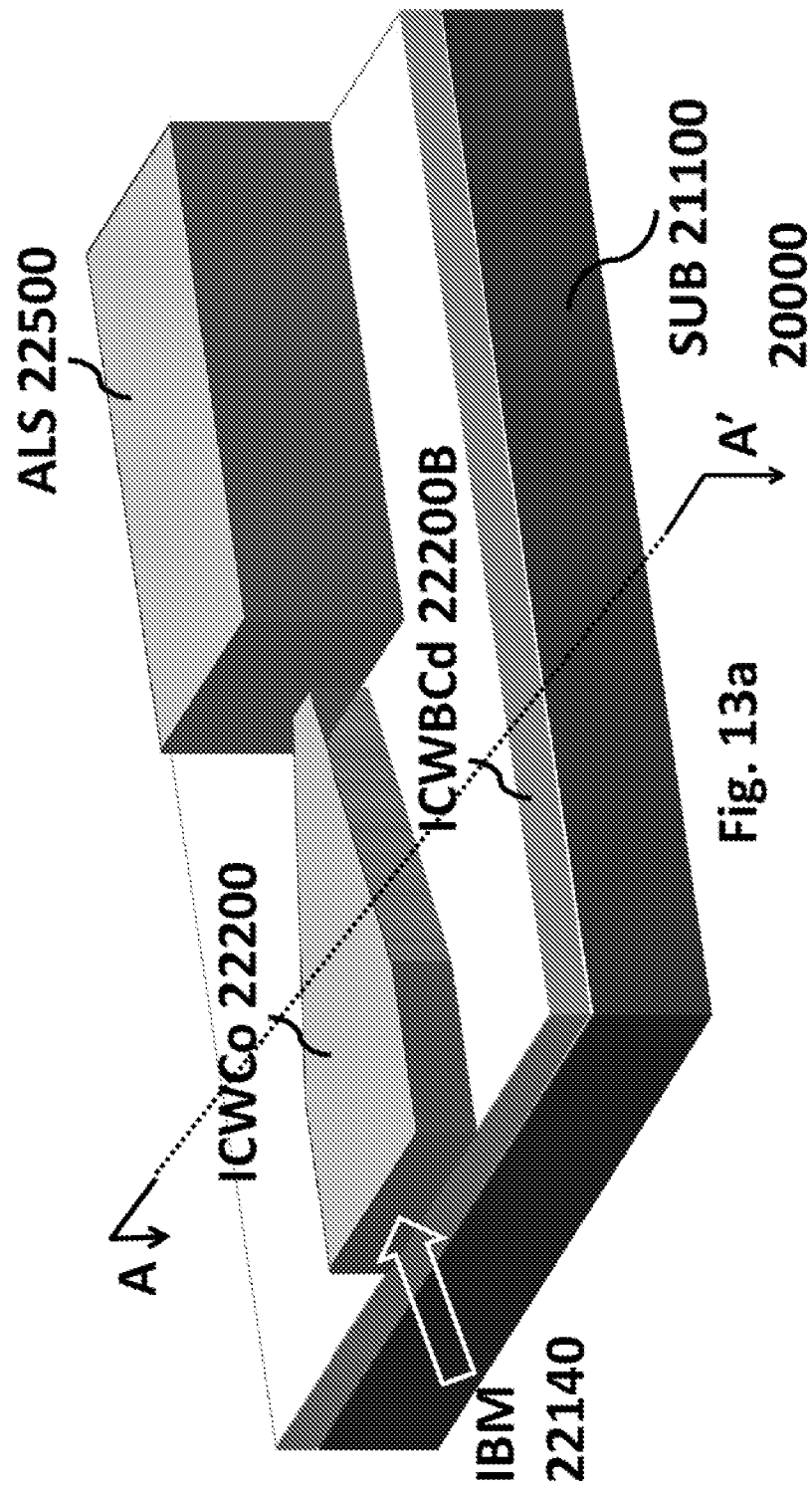
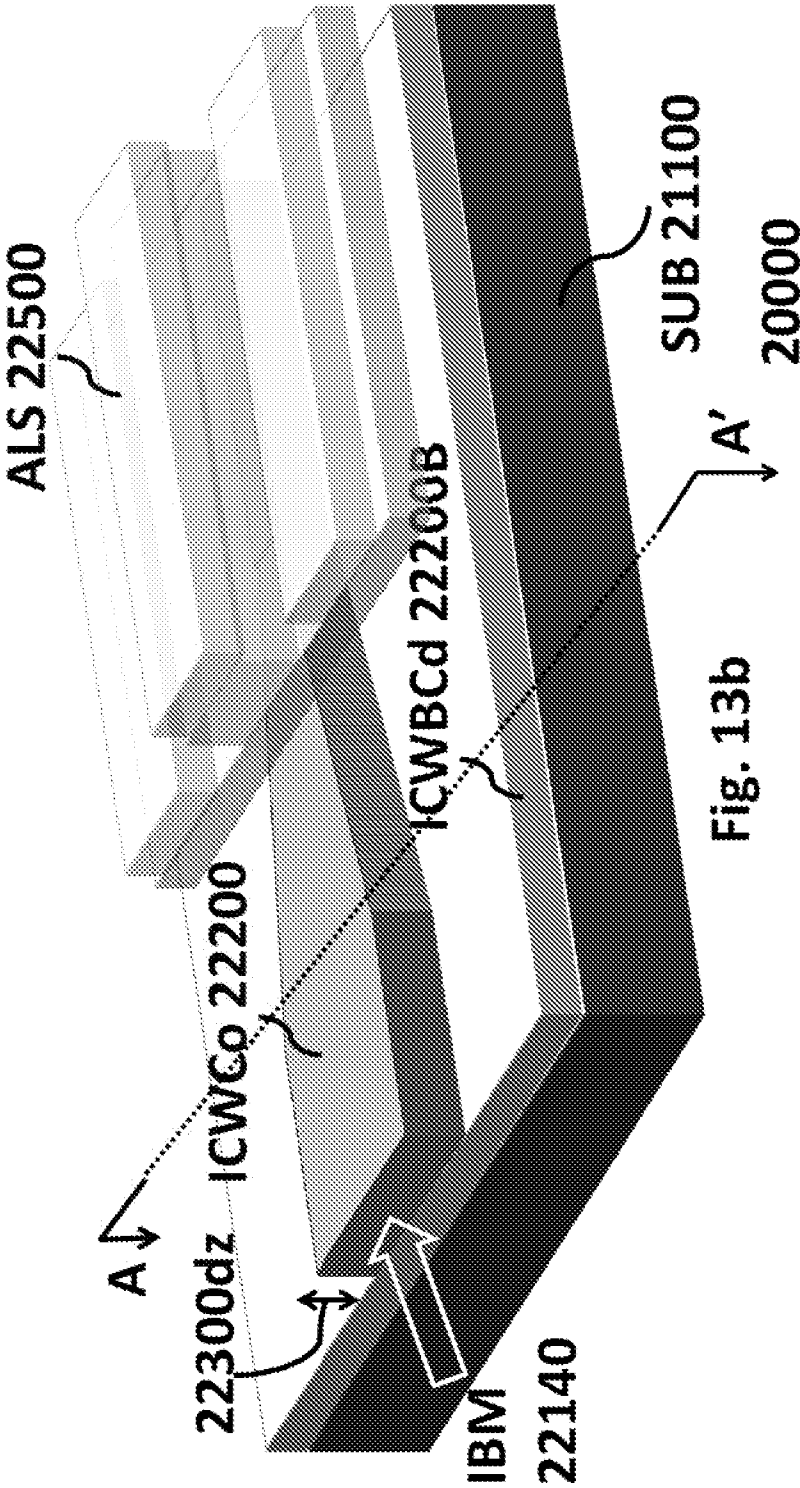


Fig. 12





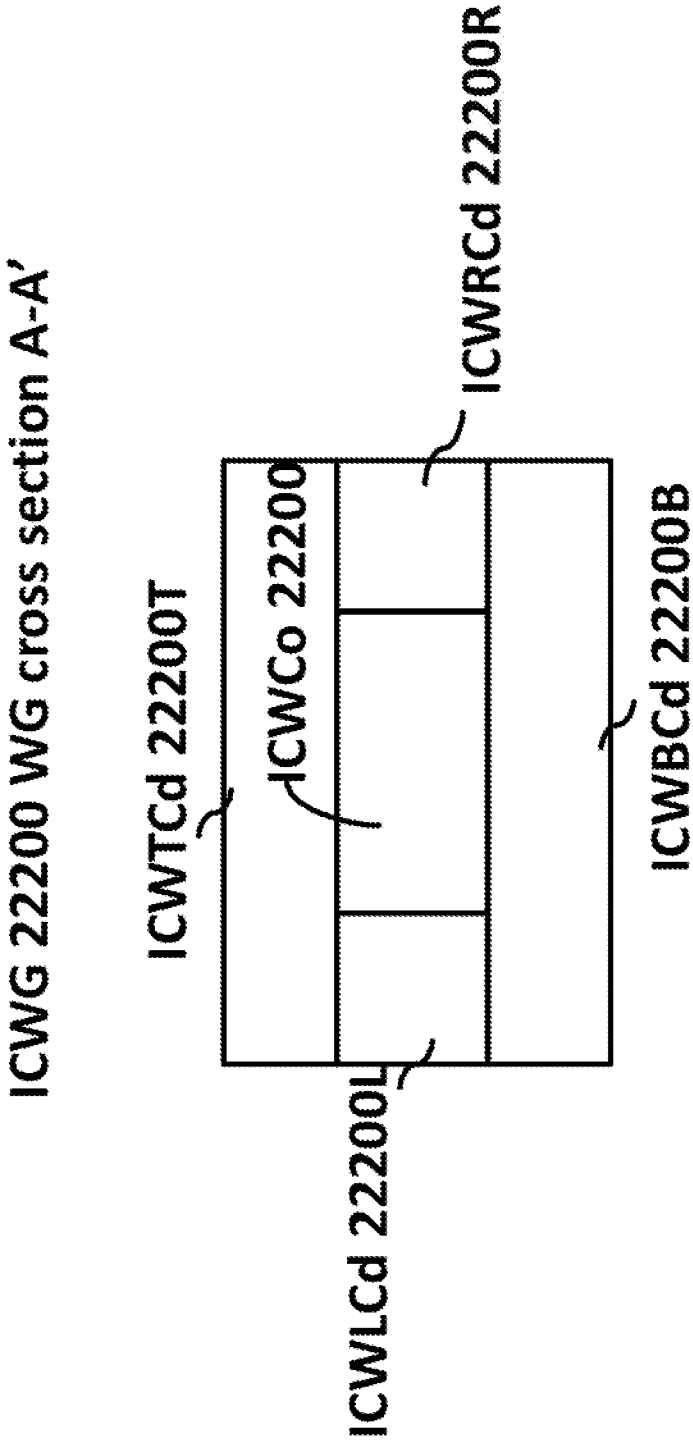


Fig. 14

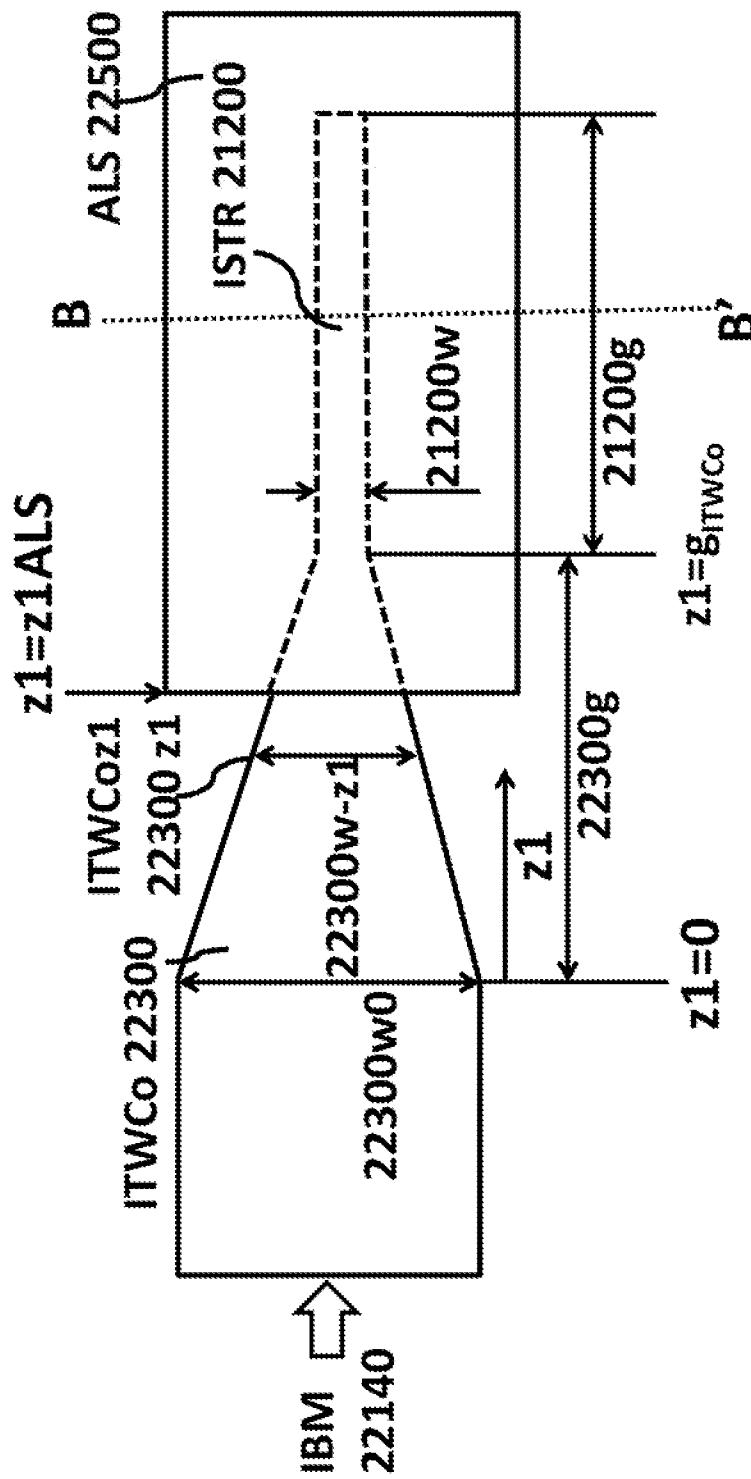


**Fig. 15a**

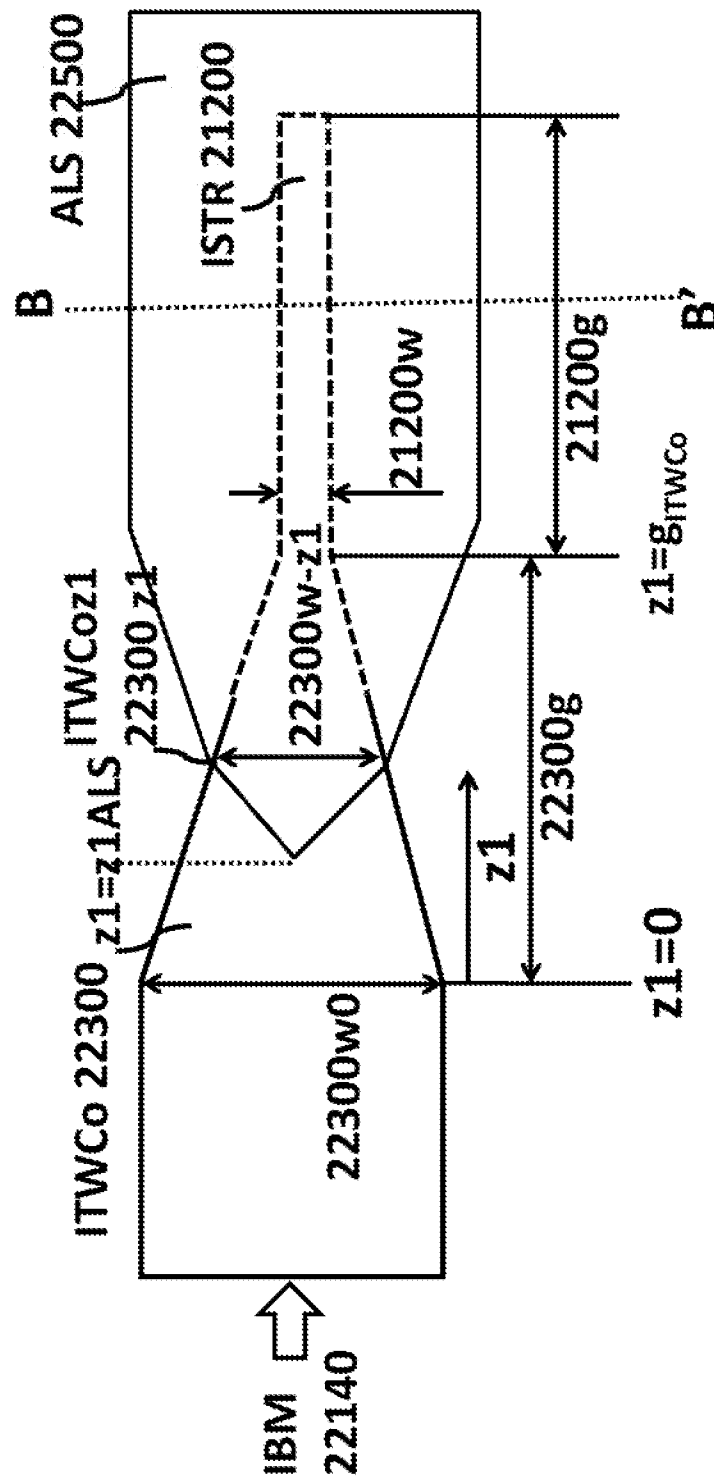


**Fig. 15b**

Cross Section of ALS 22500 at locatio B-B' of Fig. 15

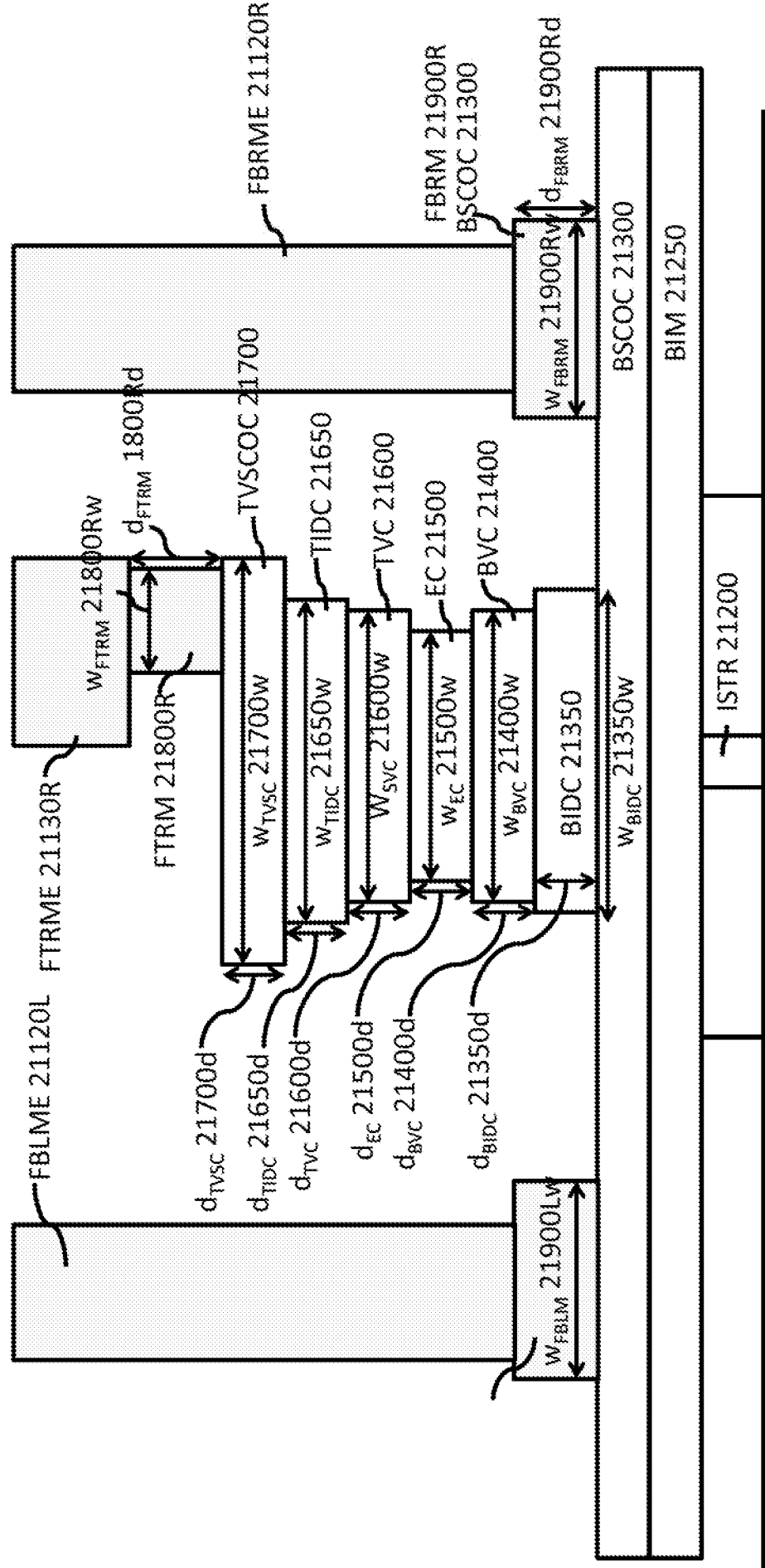
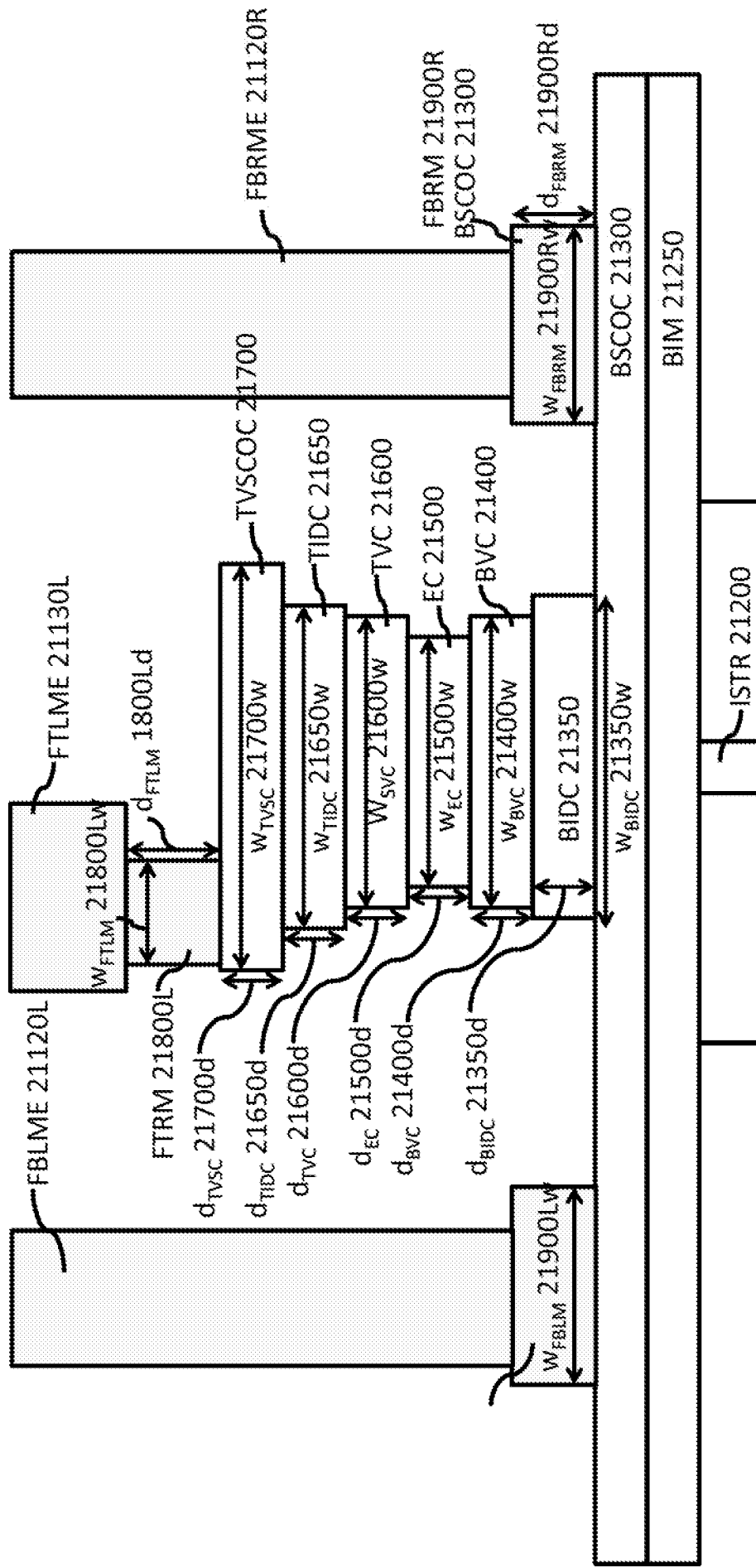


Fig. 16a

**Cross Section of ALS 22500 at locatio B-B' of Fig. 15**



**Cross Section of ALS 22500 at locatio B-B' of Fig. 15**

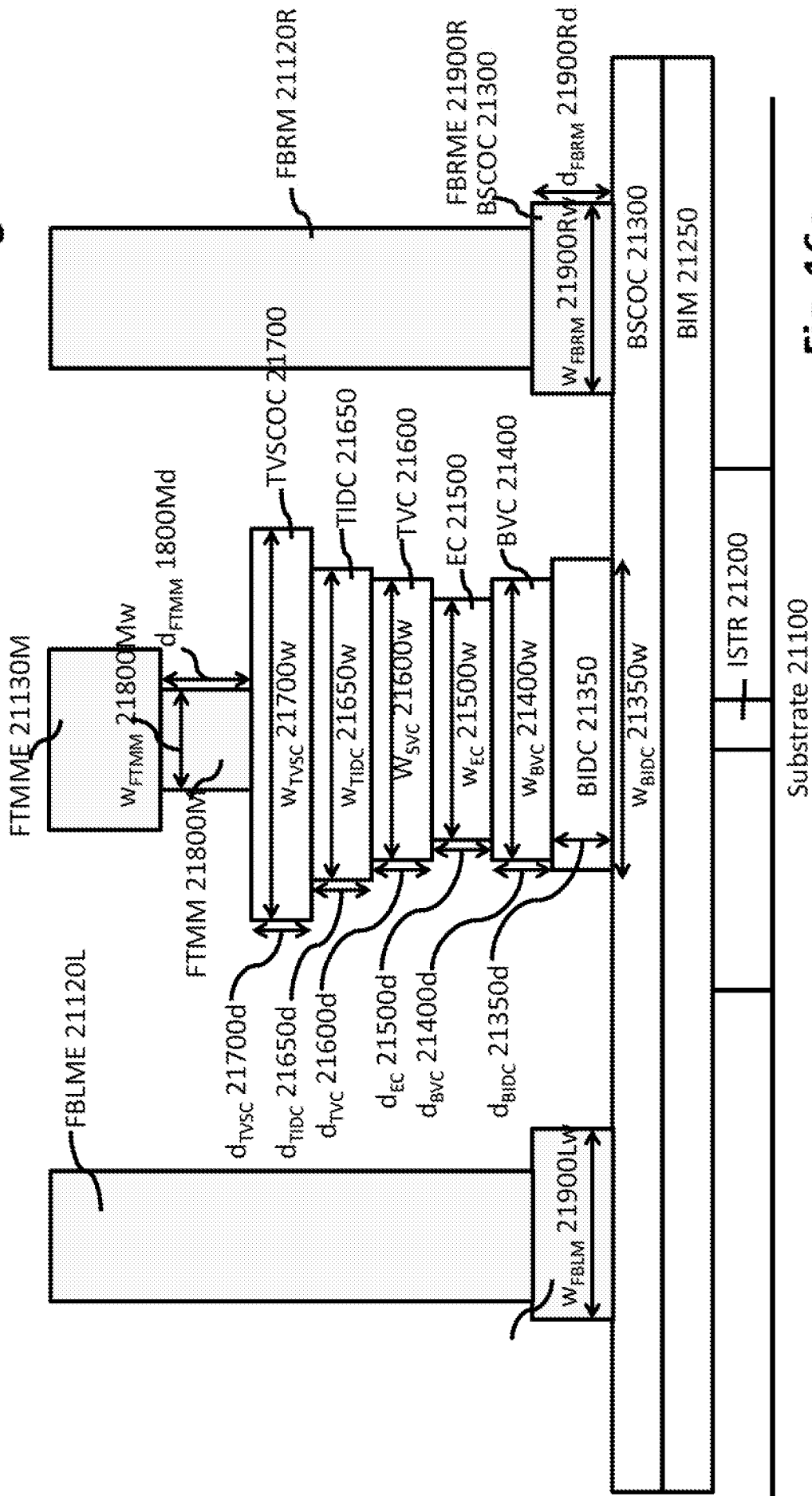


**Fig. 16C**

An Example of EWCoS 22600

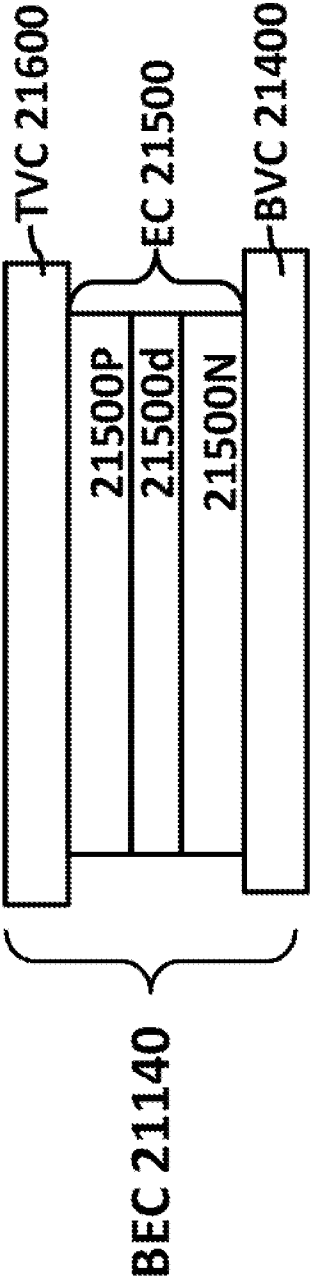


Fig. 17

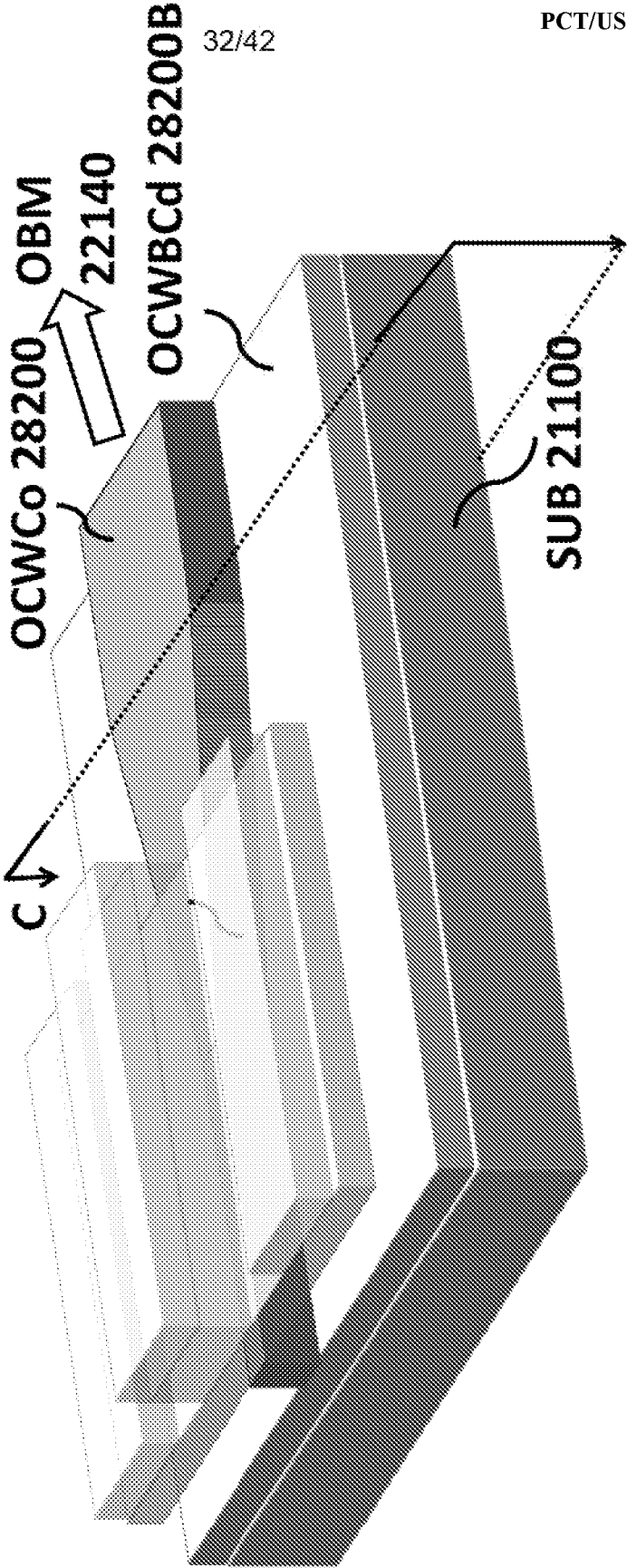


Fig. 18

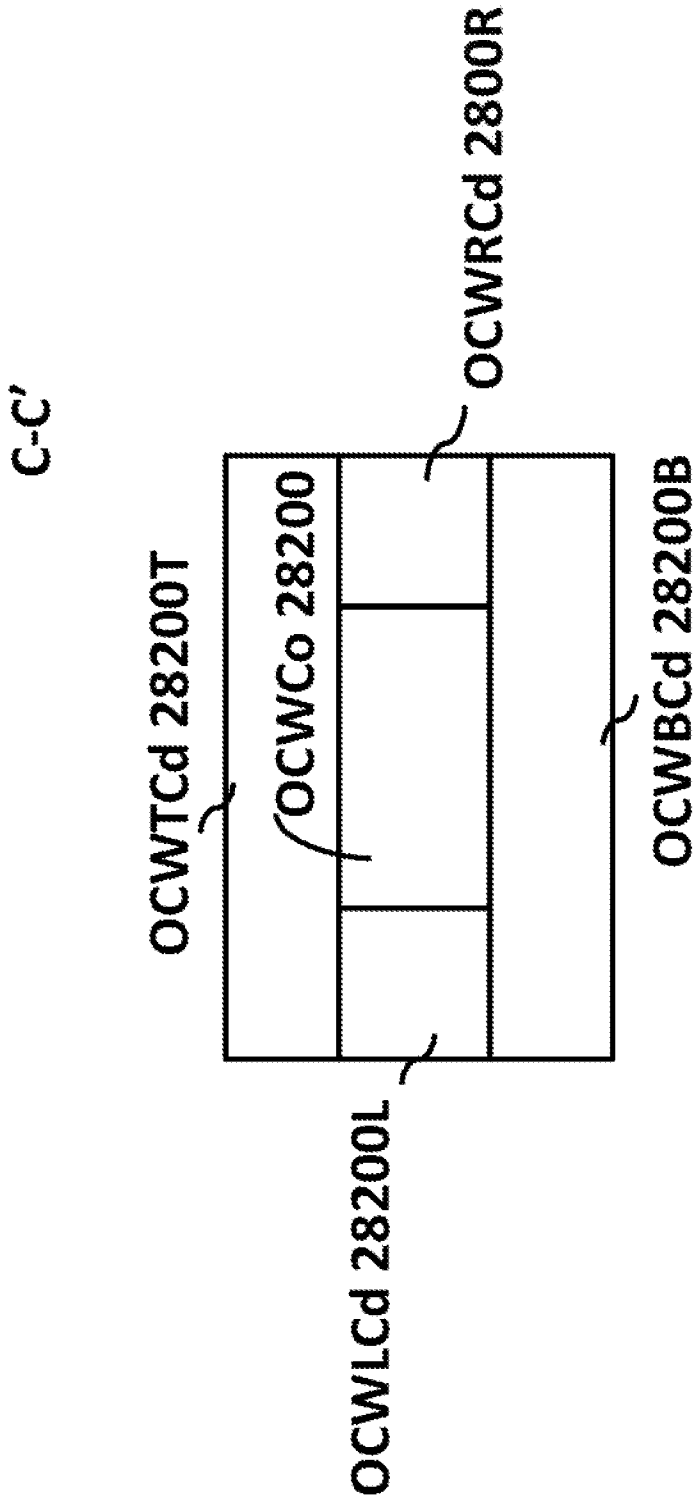


Fig. 19

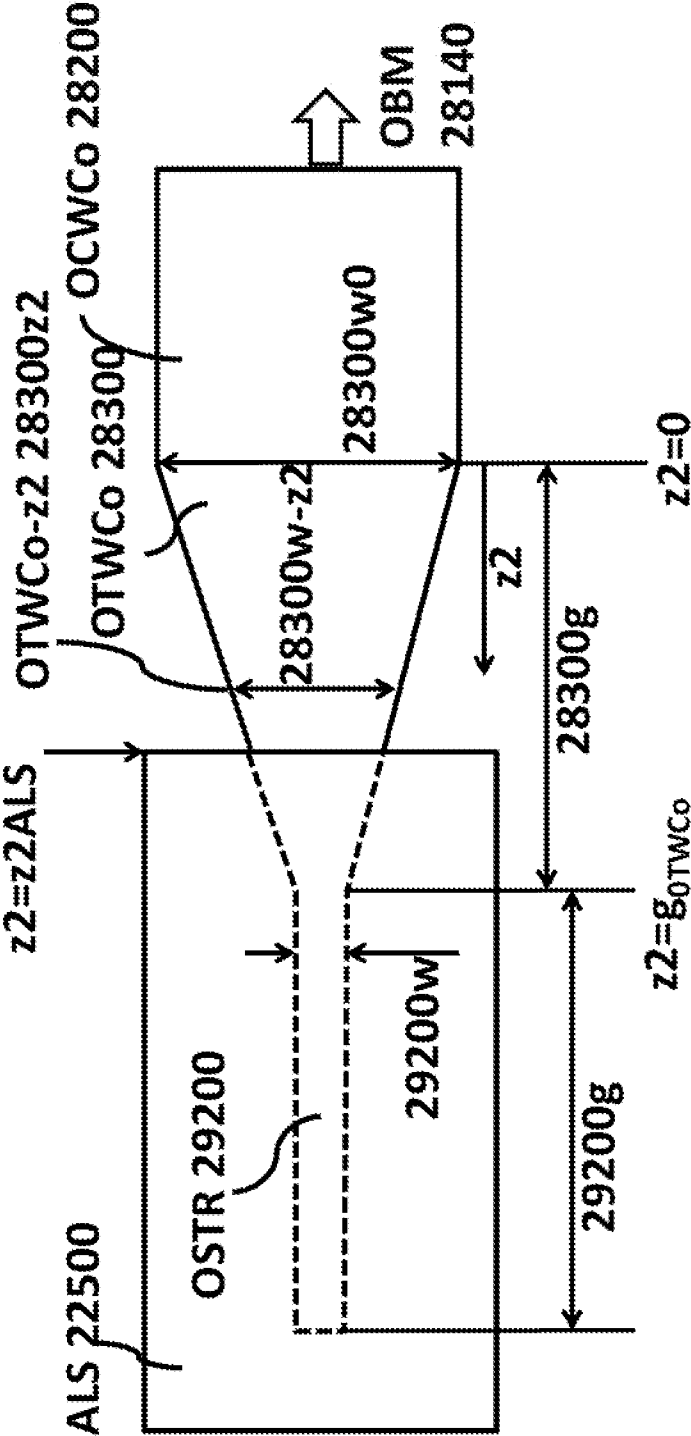


Fig. 20a

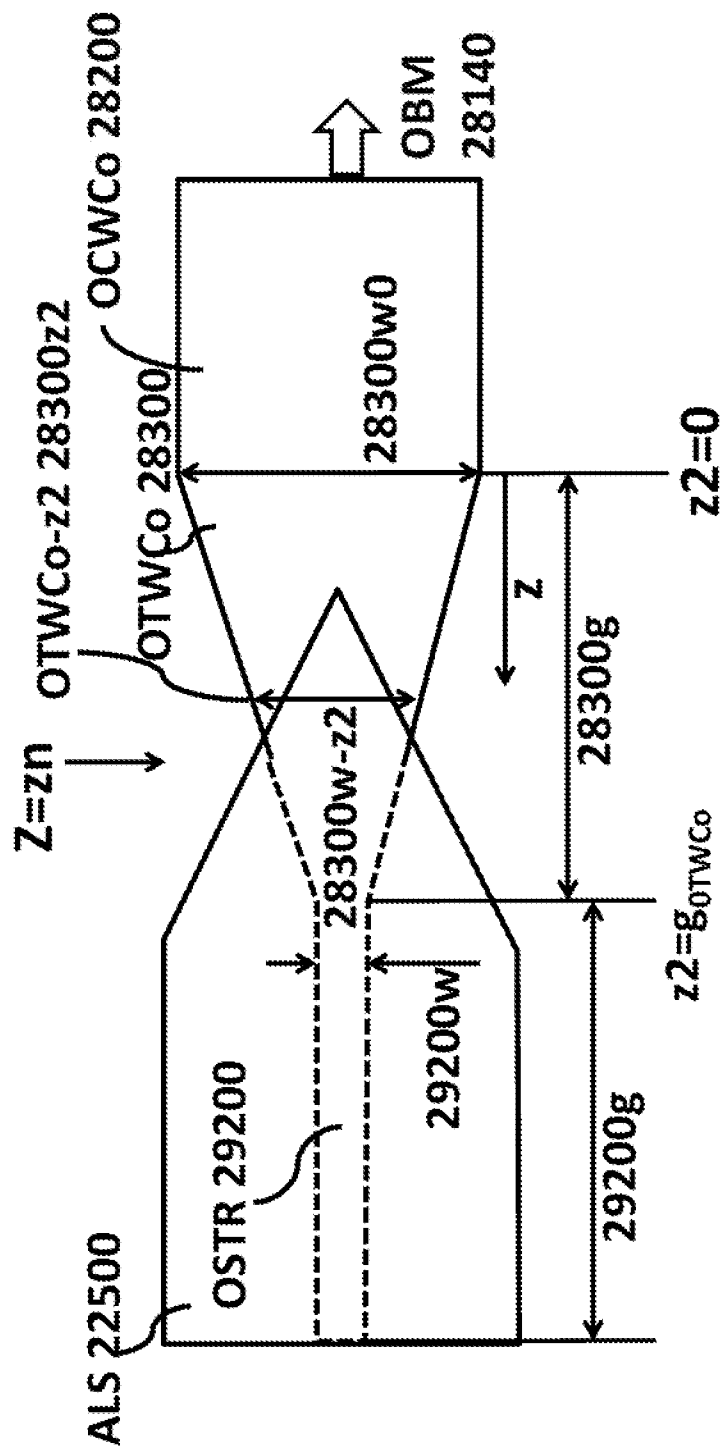


**Fig. 20b**

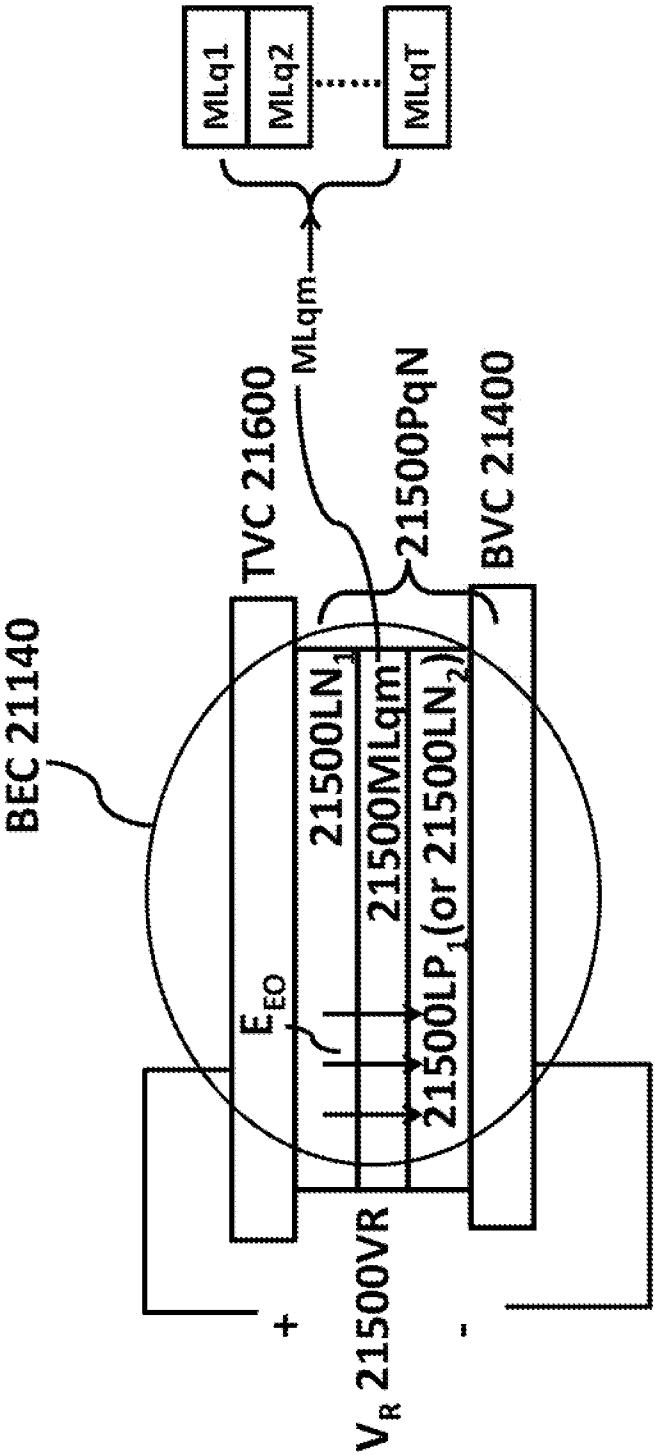


Fig. 21

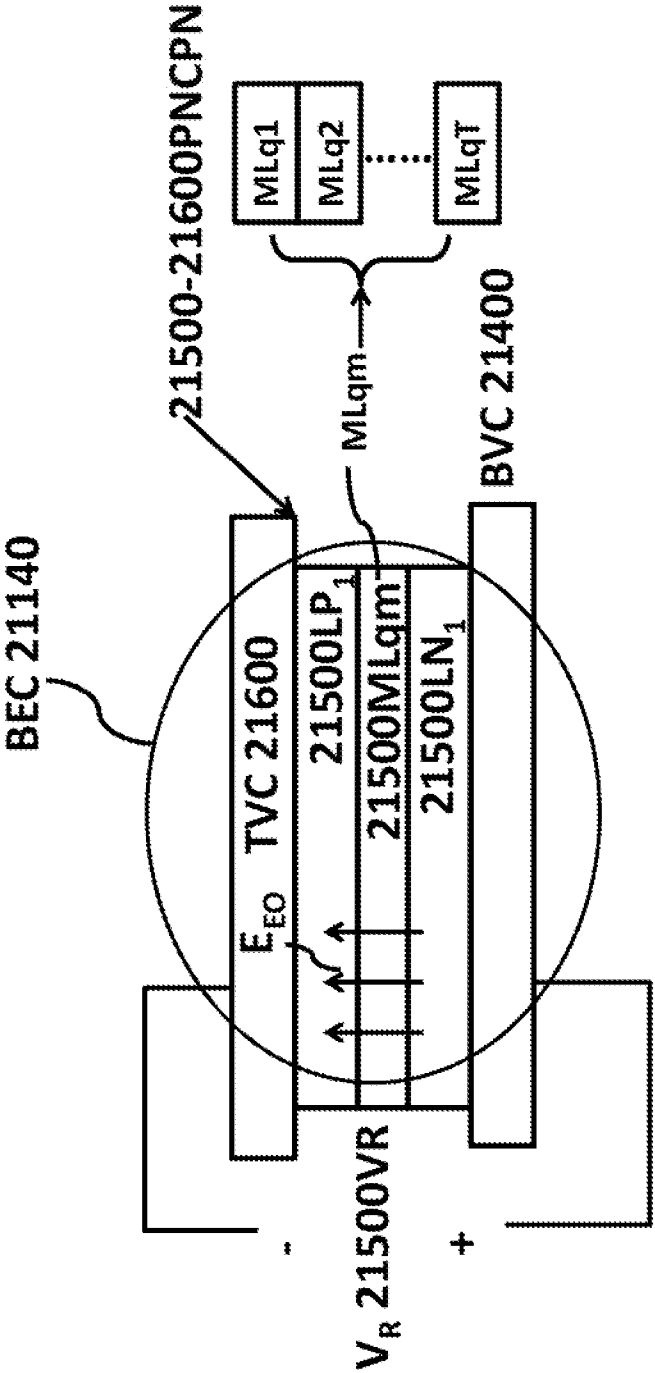


Fig. 22a

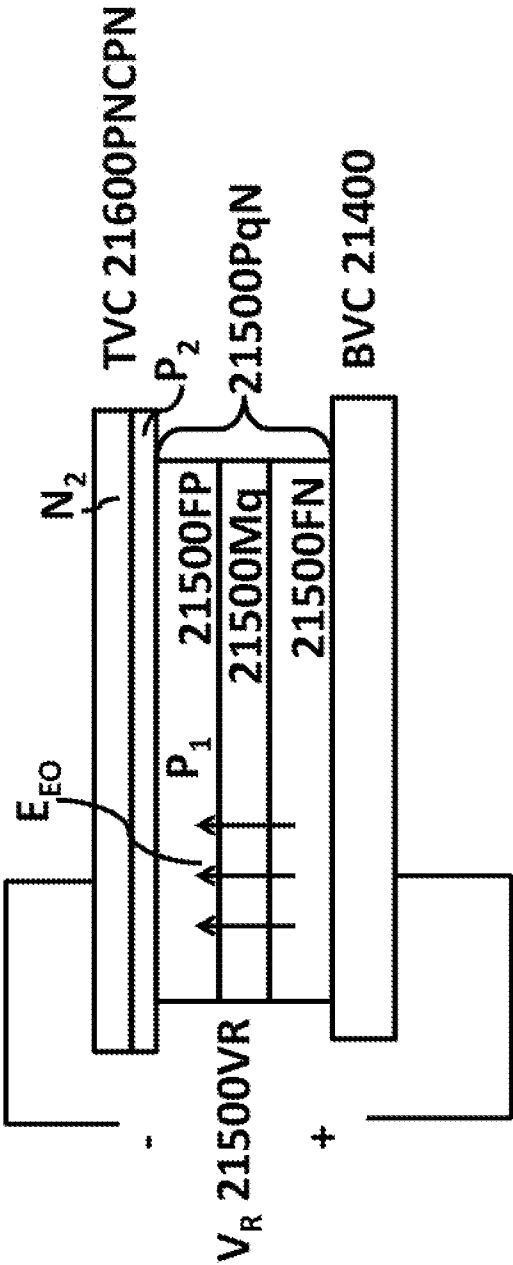


Fig. 22b

top side-conduction-metal contact case

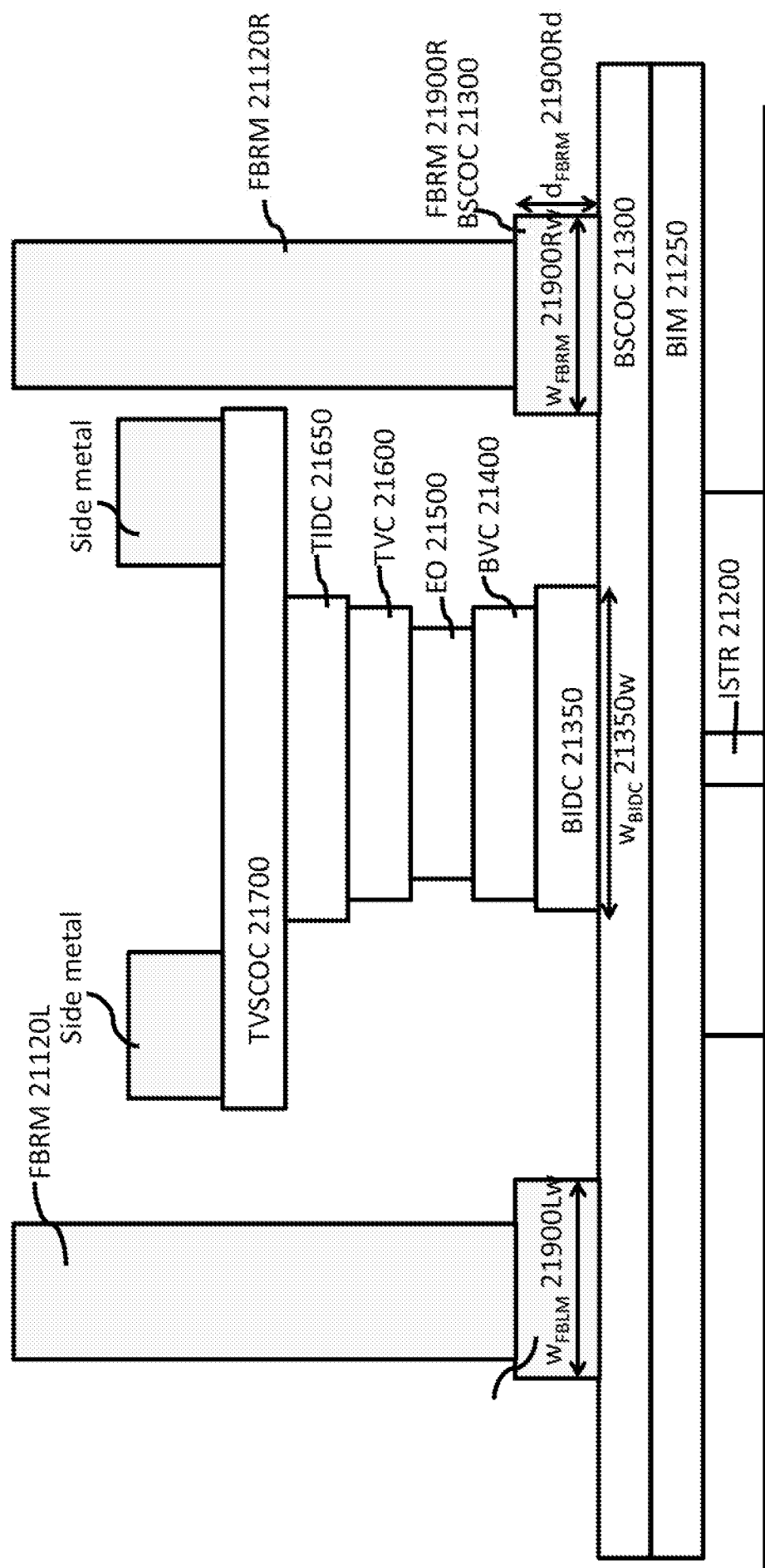


Fig. 23

top side-conduction-metal contact case

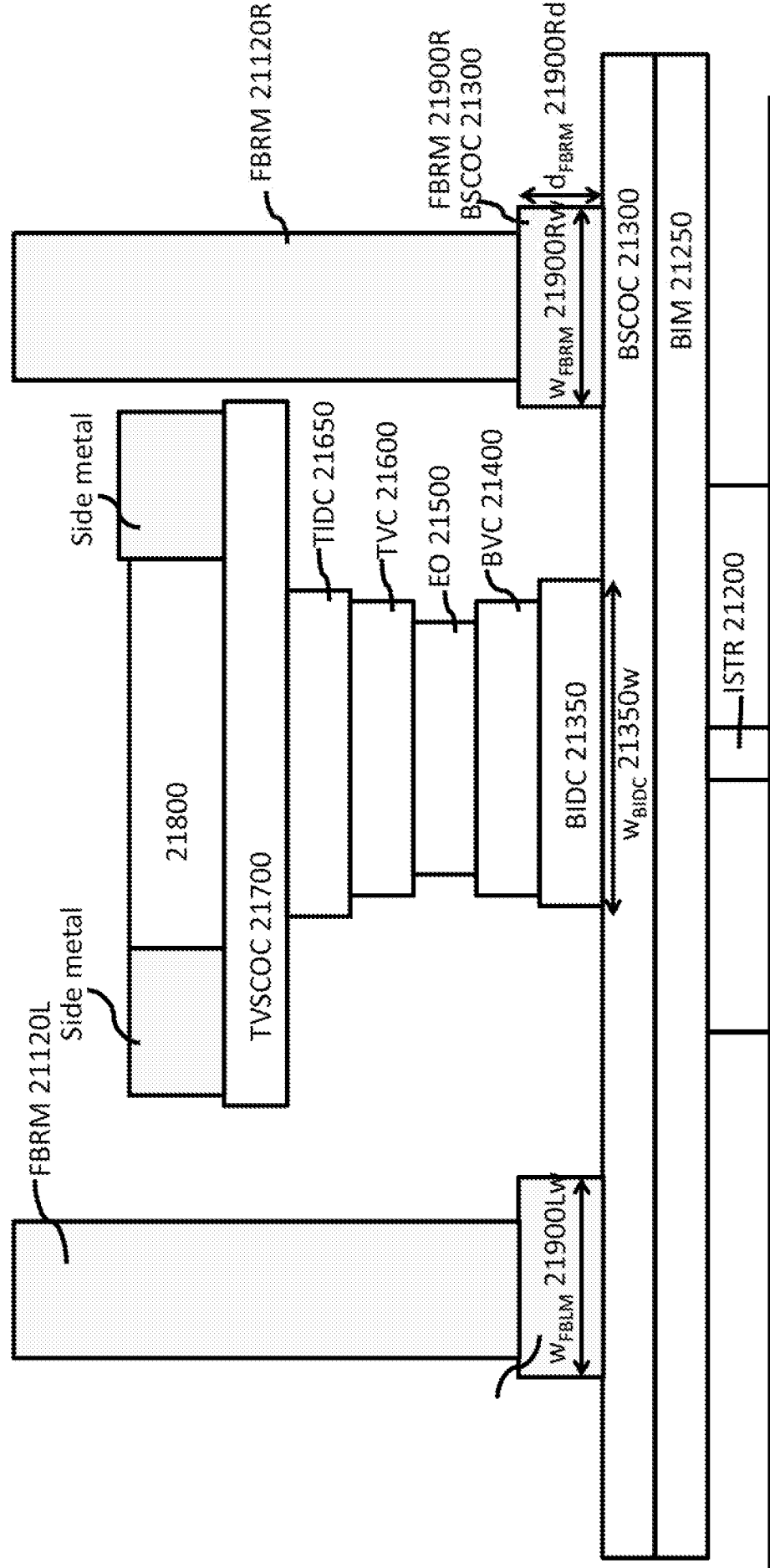


Fig. 24

