

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
31 May 2001 (31.05.2001)

PCT

(10) International Publication Number
WO 01/38934 A2

(51) International Patent Classification⁷: **G02F 1/313**

(21) International Application Number: PCT/EP00/11129

(22) International Filing Date:
9 November 2000 (09.11.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
99123328.9 23 November 1999 (23.11.1999) EP
60/167,912 30 November 1999 (30.11.1999) US

(71) Applicant (for all designated States except US): **OPTICAL TECHNOLOGIES ITALIA S.P.A.** [IT/IT]; Viale Sarca, 222, I-20126 Milano (IT).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **SCIANCELEPORE, Davide** [IT/IT]; Via Pasubio, 39 - Fr. Arè, I-10014 Caluso (IT).

(74) Common Representative: **OPTICAL TECHNOLOGIES ITALIA S.P.A.**; Viale Sarca, 222, I-20126 Milano (IT).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

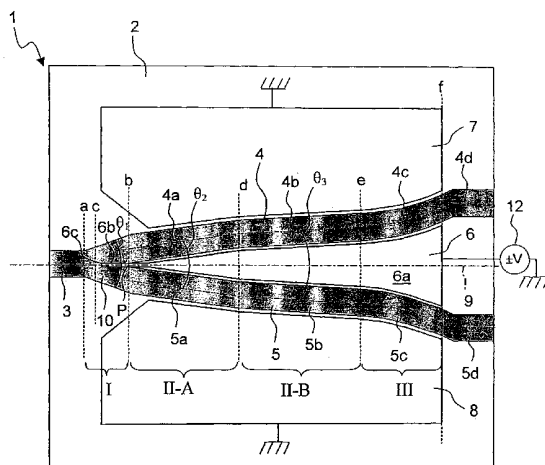
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:

— Without international search report and to be republished upon receipt of that report.

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: OPTICAL SWITCHING DEVICE



(57) Abstract: A digital optical switching device (1) has a longitudinal axis (9) and comprises a substrate (2); a first, a second and a third waveguide (3-5), connected by a connecting waveguide (10), the second and third waveguides (4, 5) having a first and second refractive index respectively, and forming two alternative branches for carrying the light from and/or towards the connecting waveguide; electrodes (6-8) associated with at least one of the second and third waveguides (4, 5) and capable of forming an electrical field region in which at least one of the first and second refractive indices can be varied as a function of a potential difference applied to the electrodes; and in which there is a first longitudinal region (I) in which the connecting waveguide (10) forms a first angle (θ_1), a second longitudinal region (II) consisting of a first longitudinal area (II-A), in which the second and third waveguides (4, 5) comprise respective first sections (4a, 5a) forming between them a second angle (θ_2) which is different from the first angle (θ_1), and a second longitudinal area (II-B) in which the second and third waveguides (4, 5) comprise respective second sections (4b, 5b) forming between them a third angle (θ_3) which is different from the second angle (θ_2).



WO 01/38934 A2

OPTICAL SWITCHING DEVICE

* * * * *

DESCRIPTION

The present invention relates to an optical switching
5 device.

There are known optical switches which can be used to
select alternative optical connections among light
waveguides. These include the known digital optical
switches (abbreviated to "DOSs"), which have a stepped
10 response to the drive voltage.

By comparison with other types of optical switching device,
DOSs are particularly useful because their particular
response characteristic enables them to operate without a
strict control of the drive voltage. It is also possible to
15 drive a large number of switches simultaneously by using a
single voltage source, to switch both light polarizations
(TE and TM) simultaneously, to operate in a way which is
essentially unaffected by the wavelength of the transmitted
light, and to avoid optical-electrical and electrical-
20 optical conversions.

DOSs are used increasingly in the optical
telecommunications sector, mainly as devices for the
selective direction of the signals transmitted in
telecommunications lines and networks. For example, DOSs
25 can be used to carry out protective functions in
telecommunications networks, or switching functions at
nodes of a network accessed by a plurality of users
("Access Switch"), or other known types of function ("Main
Distribution Frame", "Optical Cross Connect", etc.).

30 A DOS usually comprises a predetermined number of
waveguides formed on a common substrate, for example a
substrate of lithium niobate (LiNbO_3). The number and
arrangement of the waveguides can vary according to
requirements. In particular, there are known switches of

the "X" or "2x2" type, having two inputs and two outputs, and switches of the "Y" type which can be used either as "1x2" switches, in other words with one input and two outputs, or as "2x1" switches, in other words with two inputs and one output.

A DOS can also be used as an elementary unit for building more complex switching structures, for example a switching matrix comprising a plurality of DOSs integrated on a single chip.

10 A DOS generally comprises one or two input waveguide(s), one or two output waveguide(s) and a connecting waveguide for physically and optically connecting the input waveguide(s) and output waveguide(s). The input and output waveguides are also usually connected (at their ends
15 opposite the connecting waveguide) to optical fibres suitable for carrying the transmitted signals, for example optical fibres of the monomodal type. A switch constructed in this way typically has a longitudinal axis of virtual symmetry.

20 X (or 2x2) switches have a first operating condition in which a first input is optically connected to a first output while a second input is optically connected to a second output, and a second operating condition in which the first input is optically connected to the second output
25 and the second input is optically connected to the first output.

Y switches of the 1x2 type have a first operating condition in which the single input is optically connected to a first output, and a second operating condition in which the input
30 is optically connected to a second output. The two outputs therefore operate alternatively to receive the optical signal from the input.

Y switches of the 2x1 type have a first operating condition in which a first input is optically connected to the single

- 3 -

output, and a second operating condition in which a second input is optically connected to the output. The two inputs therefore operate alternatively to supply optical signals to the output.

5 DOSs formed on lithium niobate substrates typically comprise waveguides made from diffused titanium, and use the electro-optic effect to switch the light between the different waveguides. The electro-optic effect is associated with a variation of the refractive index in a
10 waveguide due to a variation of the electrical field present in the region occupied by the waveguide. The transmission characteristics of the waveguide vary with its refractive index. It is therefore possible to control the optical power of the light rays transmitted in these
15 guides, by applying variations of refractive index of opposite sign to the alternative waveguides of the switch (such as those forming the two input branches or the two output branches of a Y switch). For example, in the case of a Y switch of the 1x2 type, in the aforesaid first
20 operating condition the refractive indices of the two output waveguides are such that practically all of the light passes from the input to the first output, while in the second operating condition the refractive indices of the two output waveguides are such that practically all of
25 the light passes from the input to the second output. The change from the first to the second operating condition and vice versa is made by varying the drive voltage of the switch in such a way as to cause the desired variations of refractive index.

30 In order for the switch to operate correctly, a condition of adiabaticity, corresponding to an absence of coupling between the local normal modes of the optical structure, must be satisfied. This condition is met by designing the waveguides in such a way that there are no abrupt changes
35 in the direction of propagation of the signal. In particular, the angles at the branches (in other words

between two alternative waveguides for switching) must be particularly small. The condition of adiabaticity is a necessary condition for achieving a low level of crosstalk between the different waveguides. This crosstalk
5 (measurable in dB) causes the undesirable presence of a non-zero optical power at the output of a waveguide when the electrical field has been applied in such a way that all the optical power is carried in the alternative waveguide.

10 As an alternative to crosstalk, a parameter commonly used to describe the quality of a switch is the extinction ratio (abbreviated to "E.R."). The extinction ratio provides a measure of the maximum obtainable ratio between the optical powers in two alternative branches in one of the two
15 switching conditions. In the simplest case of a 1x2 switch, in which the light enters through the input waveguide and leaves alternatively through one or the other of the two output waveguides, naming P_L and P_H the minimum and the maximum optical power which are extracted through one of
20 the two waveguides in the two operating conditions described above, the extinction ratio is defined thus: $E.R. = 10 \log P_H/P_L$. The behaviour of the switch improves as the value of the extinction ratio increases, since there is a decrease in the optical power carried in the undesired
25 branch.

There are various known types of digital optical switch, which differ from each other in the shape of the electrodes and/or in the shape of the waveguides.

The article "Digital Optical Switch", by Y. Silberberg, P. Perlmutter and J.E. Baran, Appl. Phys. Lett., vol. 51, no. 16, pp. 1230-1232, July 1978, describes a digital optical
30 switch made from $Ti:LiNbO_3$ with an X structure. The structure is based on an asymmetric waveguide junction, consisting of two unequal waveguides, a bimodal central region and a symmetrical output branching. The symmetry of
35 the output branching can be broken by applying an external

electrical field. This field can be applied by supplying a non-zero voltage between the central electrode and the lateral electrodes. Care must be taken to ensure that the applied field is not such that the condition of
5 adiabaticity of propagation is infringed. For this purpose, as shown in Figure 1, the electrodes are shaped in such a way that the electrical field is incremented gradually towards the junction area. In practice, the central electrode has a longitudinal extension which passes
10 completely through the bimodal central region, and the outer electrodes (having the same length as the central electrode) are such that they progressively approach the longitudinal extension.

US 5,623,568 proposes an optical switch comprising a first
15 waveguide portion, a plurality of intermediate waveguide portions connected to the first portion, with each intermediate portion associated with a first angle of less than about 2° , and a plurality of branch waveguide portions, each connected to a respective intermediate
20 waveguide portion and each associated with a second angle which is less than the first and is less than about 0.3° . Between the intermediate waveguide portions there is an electrically insulating "gap" which, together with the intermediate waveguide portions, forms an essentially
25 trapezoidal structure.

US 5,757,990 relates to an optical switch comprising an optical waveguide with a tapered shape forming an angle of θ_1 , connected to an input waveguide and two branch optical waveguides with an aperture angle of θ_2 connected to the
30 tapered waveguide, in which the centre-to-centre interval between the branch waveguides where they are connected to the tapered waveguide is equal to a predetermined multiple of the width of the branch waveguide. The tapered waveguide may be replaced with a Y-shaped branch guide having a
35 branch angle of θ_1 . Control electrodes (110, 111) are placed above the branch waveguides, and further control

electrodes (112, 113) are placed laterally with respect to the first electrodes.

US 5,123,069 describes an optical switch comprising a first and a second waveguide route, forming a branch angle
5 between them, and each comprising a bending portion, an initial portion which the light can enter, and a terminal portion through which the light can pass. The branch angle is enlarged in the initial portions and is reduced in the bending portions towards the terminal portions. Electrodes
10 are placed near the first and second waveguide routes along the bending portions, in such a way as to act on the light which is propagated from the initial portion to the terminal portion.

US. 5,163,106 relates to an optical switch of the waveguide
15 type having a Y-branch structure consisting of a Y-waveguide and branch waveguides provided with electrodes, in which the branch waveguides form a converging angle of θ_1 and the Y-waveguide has a branching angle of $\theta_2 > \theta_1$ and is connected to the branch waveguides. In the disclosed switch
20 it is possible to identify a region I in which the optical power of incident light is split, and a region II in which the optical field is controlled, by regulating the voltage applied to an electrode, in such a way as to improve the characteristics in terms of crosstalk. One object of that
25 invention is to shorten the region I by optimizing a branching angle in such a way as to provide a waveguide optical switch of small dimensions without degrading the crosstalk characteristics.

The article by W.K. Burns, "Shaping the Digital Switch",
30 IEEE Photonics Technology Letters, Vol. 4, No. 8, August 1992, pp. 861-863, describes a process, based on ordinary coupled mode theory (or "CMT"), for shaping the branches of a 1x2 digital switch in such a way as to reduce the product of voltage and length for predetermined values of
35 crosstalk. As shown in Figure 2 of this article, the branching angle of the switch can vary with the length. In

particular, this switch has an initial region and a final region in which the angle assumes maximum values, and an intermediate region in which the angle assumes a minimum value.

5 The applicant has noted that, with the substrates typically used for making digital optical switches, such as LiNbO_3 substrates, the electro-optic effect is a function of the direction of the incident optical field and of the applied electrical field with respect to the principal axes of the
10 substrate, and the intensity of the effect is correlated with the values of the matrix of the electro-optic coefficients of the substrate. For example, with an LiNbO_3 substrate of the x-cut (cut perpendicular to the x axis) y-propagating (propagating the light essentially along the y
15 axis) type, and with electrodes adjacent to the optical waveguides, the optical field parallel to the z axis (in other words that having TE polarization) "sees" a variation of the refractive index proportional to the electro-optic coefficient r_{33} which is equal to approximately 31×10^{-6}
20 $\mu\text{m}/\text{V}$, while the optical field parallel to the x axis (TM polarization) "sees" a variation of the refractive index proportional to the electro-optic coefficient r_{13} which is equal to approximately 9×10^{-6} $\mu\text{m}/\text{V}$, in other words equal to approximately a third of the value of r_{33} . Consequently,
25 the device has a response which is a function of the polarization of the light.

In particular, the applicant has observed that, for devices formed on LiNbO_3 substrates, the characteristic P/V (where P is the output power in one of the branches of the device
30 and V is the drive voltage of the device) for the TE mode has a steeper rising edge than that of the TM mode and, therefore, the power associated with the TE mode reaches saturation (as is generally required for switching to take place) at lower values of potential difference than those
35 required for the TM mode. In practice, therefore, the voltage required to switch TE polarization is lower than

that required to switch TM polarization. To operate independently of polarization with this type of device, sufficiently high drive voltages to permit the switching of both polarizations are typically used. The applicant has
5 observed that operation in this way means that at least one of the two polarizations is driven with a higher voltage than that required to reach saturation, and this has an adverse effect on the efficiency of the device.

For example, the switch described in the aforesaid article
10 by Burns has branches whose shape is a function of a parameter $\Delta\beta$ defining the asynchronism of the guides. This parameter is a function of the polarization, since it is proportional to the product of the electro-optic coefficient of the polarization mode in question and the
15 applied voltage. As specified in the article, the dependence of $\Delta\beta$ on the polarization is compensated with the voltage. In practice, a voltage value which permits the switching of both polarizations is selected.

According to US Patent 5,303,315, one approach to making
20 switches which are independent of polarization consists in using orientations of the crystal for which the conditions are similar for both polarizations. This patent proposes, in particular, an optical switch in which the substrate is formed from an x-cut or near y-cut monocrystalline wafer of
25 electro-optical material and in which waveguides of LiNbO_3 are diffused into the wafer to form ribbon waveguides such that light propagates in a direction near the Z axis of the wafer. These waveguides form a Y structure and their refractive indices are controlled by electrodes adjacent to
30 them. One of the proposed embodiments comprises an x-cut monocrystalline wafer of electro-optical material and waveguides forming a Y structure and having a direction of propagation which forms an angle θ with the z axis of the wafer. With an angle θ of approximately 10° , the electro-
35 optic coefficient (r coefficient) is the same for both TE and TM polarizations.

The applicant observes that the solution proposed in US Patent 5,303,315 requires either the use of substrate wafers having an orientation different from that present in the substrates generally fabricated for applications of this type, or the making of waveguides with a direction of propagation which is inclined with respect to the principal axes of the substrate. In the first case, the switch has the disadvantage, according to the applicant, that the making of the substrate is more expensive than in the case of substrates with a cut along one of the principal axes. In the second case, the switch has the disadvantage, according to the applicant, of having propagation losses exceeding those normally obtainable with standard orientations of the waveguides (in other words those coinciding with one of the principal axes of the crystal). This fact is confirmed by the study of light propagation in anisotropic media described in the article "New Leaky Surface Waves in Anisotropic Metal-Diffusion Optical Waveguides", Kazuhiko Yamanouchi, Toshiaki Kamiya, Kimio Shibayama, IEEE Transactions on microwave theory and techniques, Vol. MTT-26, No. 4, April 1978. In this article, a particular study is made of the properties of light propagation with a variation of the angle of propagation with respect to the axes of the substrate.

The applicant has tackled the problem of making a digital optical switch (DOS) in which the direction of propagation of the signals is essentially aligned with one of the principal axes of the substrate and whose response to the drive voltage (and therefore the P/V characteristic) is essentially the same for the TE and TM polarization modes.

The applicant has observed that, generally, in digital optical switching device of known types the TE and TM polarization modes are confined in different ways within the waveguides; in other words, the electromagnetic fields associated with the TE and TM modes are distributed differently with respect to the lateral boundaries of the

waveguides.

The applicant has also observed that, owing to the fact that the electro-optic effect typically acts with different intensities on the two polarization modes TE and TM
5 (according to the values of the matrix of the electro-optic coefficients of the substrate) and the fact that the TE and TM modes are typically confined in different ways in the waveguides, the electro-optic effect can act, according to the type of substrate in question and its directions of cut
10 and propagation, in a more intense way on the more confined or on the less confined mode.

The applicant has also noted that, in a device of the type considered here, the electro-optic effect is manifested in different longitudinal regions for the two polarization
15 modes TE and TM. In particular, the applicant has observed that, in a typical digital optical switching device, it is possible to identify two contiguous longitudinal regions, namely one, adjacent to the connecting waveguide, in which the electro-optic effect acts predominantly on the mode (TE
20 or TM) which is more confined in the waveguide, and another, following the first, in which the electro-optic effect acts predominantly on the less confined mode.

For example, in the case of a device formed on an LiNbO_3 substrate of the x-cut and y-propagation type, the
25 applicant has observed that the electro-optic effect acts in a more intense way on the TE mode than on the TM mode, and that the TM mode is less confined within the waveguides than the TE mode, and, consequently, that the electro-optic effect acts on the TE mode predominantly in the section of
30 the branch waveguides contiguous to the connecting waveguide, while it acts on the TM mode predominantly in a following section of the waveguides.

The applicant has also observed that the drive voltage and the optical power carried alternatively in one or other of
35 the two branching waveguides depend on the angle formed by

these waveguides. In particular, when this angle is decreased it is possible to use a smaller potential difference to obtain the same power in one of the two output waveguides, or, in an equivalent way, it is possible to obtain a higher power in one of the two output waveguides for the same applied potential difference. This behaviour is found for both the TE mode and the TM mode. Typically, it is necessary to find a compromise between the value of this angle and the length of the device, to prevent the latter from becoming excessive.

The applicant has found that, by designing the waveguides in such a way that they form an angle in the longitudinal region in which the electro-optic effect is more intense, and a different angle, smaller than the former one, in the longitudinal region in which the electro-optic effect is less intense, it is possible to make a digital optical switching device which is essentially independent of polarization.

Since the position of these two longitudinal regions with respect to each other depends on the type of substrate used and on the orientation of its principal axes, the device according to the present invention comprises a first longitudinal region, which is formed by the connecting waveguide and in which the connecting waveguide itself forms a first angle, and a second longitudinal region, contiguous to the first, consisting of a first longitudinal area in which the branching waveguides form a second angle and a second longitudinal area in which the waveguides form a third angle, which is smaller or greater than the second angle according to whether the electro-optic effect in the second longitudinal area is smaller or greater than in the first longitudinal area. The first angle, formed by the lateral walls of the connecting waveguide, is preferably selected to be as large as possible while compatible with the condition of adiabaticity, and the second and third angles are selected to be smaller than the first angle. The

device according to the invention also comprises a third longitudinal region contiguous to the second, in which the branching waveguides have directions and lengths such that the waveguides are essentially optically decoupled from each other at the exit from this region.

Therefore, by using an x-cut and y-propagation LiNbO_3 substrate for example, the applicant has found that a digital optical switching device which is essentially independent of polarization can have a configuration of the waveguides like that described immediately above, in which, since the electro-optic effect is more intense in the first longitudinal area (in which it acts predominantly on the TE mode) than in the second longitudinal area (in which it acts predominantly on the TM mode), the third angle is smaller than the second angle.

The proposed device also comprises electrodes associated with the branching waveguides and capable of forming an electrical field region for controlling the refractive indices of the branching waveguides. The extension of the electrodes is such that the said electrical field region is at least partially superimposed on the second and the third longitudinal regions. Preferably, the electrical field region is also at least partially superimposed on the first longitudinal region and, more preferably, one longitudinal end of the electrodes terminates within the longitudinal boundaries of a multimodal propagation region lying within the connecting region. This is because the applicant has found that it is possible in this way to obtain a relatively high extinction ratio (E.R.).

In a first aspect, the present invention relates to a digital optical switching device having a longitudinal axis and comprising:

- a substrate;
- at least a first, a second and a third waveguide for light, formed on the said substrate;
- a connecting waveguide formed on the said substrate and

connecting the said first, second and third waveguides to each other, the said second and third waveguides having a first and a second refractive index respectively, and forming two alternative branches for carrying the light
5 from and/or towards the said connecting waveguide;

- electrodes associated with at least one of the said second and third waveguides and capable of forming, in response to a potential difference applied to them, an electrical field region in which at least one of the said
10 first and second refractive indices can be varied;

and additionally comprising:

- a first longitudinal region in which the said connecting waveguide forms a first angle;
- a second longitudinal region adjacent to the said first
15 longitudinal region and consisting of a first and a second longitudinal area extending through the said electrical field region, in which the said second and third waveguide form a second angle and a third angle, respectively, between them, the values of these angles being smaller than
20 the value of the said first angle and lying within respective separate ranges; and
- a third longitudinal region adjacent to the said second longitudinal region, in which the said second and third waveguides extend up to a longitudinal boundary of the said
25 electrical field region.

Preferably, the device is such that:

- the said second angle is greater than the said third angle;
- the said second and third angles have respective mean
30 values which differ from each other by a predetermined quantity;
- at each point of the said first area, the said second angle is greater than the difference between the mean value of the said second angle and half of the said predetermined
35 quantity;
- at each point of the said second area, the said third

- 14 -

angle is smaller than the sum of the mean value of the said third angle and half of the said predetermined quantity.

The said first area can be adjacent to the said first longitudinal region and the said substrate can be made from
5 lithium niobate.

Alternatively, the said first area can be adjacent to the said third longitudinal region.

In the said first and second areas, the said second and third waveguides preferably have an essentially rectilinear
10 configuration.

In the said third longitudinal region, the said second and third waveguides preferably have a curvilinear configuration.

Each one of the said first longitudinal region, the said
15 first area and the said second area has a longitudinal dimension which is preferably less than 50 mm, and more preferably in the range from 100 μm to 5000 μm .

The longitudinal dimension of the said first area is preferably in the range from 30% to 70% of the longitudinal
20 dimension of the said second region, and more preferably in the range from 40% to 60% of the longitudinal dimension of the said second region.

The said first, second and third angles are preferably less than 2° , and more preferably in the range from 0.01° to 1° .

25 The said predetermined quantity is preferably more than 25% of the value of the said second angle.

Preferably, the said connecting waveguide comprises a multimodal transmission region confined between a first and a second longitudinal position, and the said electrodes
30 comprise at least one electrode having a longitudinal end placed between the said first and second longitudinal position.

The said electrodes may comprise a first, a second and a third electrode, the said third electrode forming a central electrode interposed between the said second waveguide and the said third waveguide and the said first and second electrodes forming outer electrodes placed on opposite sides of the said second waveguide and, respectively, the said third waveguide, with respect to the said central electrode.

Alternatively, the said electrodes may comprise a first and a second electrode, partially superimposed on the said second waveguide and on the said third waveguide respectively.

The said first, second and third waveguides are preferably made by the diffusion of titanium into the substrate.

The device may comprise a fourth waveguide, forming an angle of less than 2° with the said first waveguide.

According to a further aspect, the present invention relates to an optical transmission system, comprising at least one transmitter for transmitting an optical signal, at least one receiver for receiving the said optical signal, and an optical connection for carrying the said optical signal from the said transmitter to the said receiver, characterized in that the said optical connection comprises at least one optical switching device according to Claim 1 for switching the said optical signal between alternative optical paths.

Further details can be found in the following description, which refers to the attached figures listed below:

- Figure 1a shows, schematically and not to scale, a device with a Y structure formed according to the principles of the present invention;
- Figures 1b and 1c show possible variants of the device of Figure 1a;
- Figure 2 shows, for guidance, the response curve of the

device of Figure 1;

- Figure 3 shows an optical ring network in which the device of Figure 1 can advantageously be used as a switch;

- Figure 4 shows a possible structure of one of the nodes
5 of the network of Figure 3, comprising devices of the type shown in Figure 1;

- Figure 5 shows a switching device used for a comparison of performance with the device of Figure 1;

- Figure 6 shows, according to numerical simulations, the
10 dependence of the output power of the device of Figure 5 on the potential difference applied between its electrodes, for both the TE and the TM polarizations;

- Figure 7 shows, according to numerical simulations, the
15 dependence of the output power of the device of Figure 1 on the potential difference applied between its electrodes, for both the TE and the TM polarizations;

- Figure 8 shows an experimental apparatus used to make experimental measurements on the device of Figure 1;

- Figure 9 shows the dependence of the output power of
20 the device of Figure 1 on the potential difference applied between its electrodes for the TE and TM polarizations, determined experimentally by means of the apparatus of Figure 8;

- Figure 10 a switching device with an X structure;

- Figure 11 shows a possible structure of a node of the
25 network of Figure 3, comprising devices of the type shown in Figure 10;

- Figures 12a and 12b relate to a device with a Y structure, made according to the invention on a substrate
30 with a cut orientated differently from that of the device of Figure 1;

- Figure 13 shows the variation, as a function of a longitudinal axis, of the angle formed by the waveguides in one embodiment of the device of Figure 1; and

- Figure 14 shows the variation, as a function of a
35 longitudinal axis, of the angle formed by the waveguides of a switching device made according to the prior art.

- 17 -

Figure 1a shows a device 1 for the digital switching of optical signals.

The device 1 comprises a substrate 2, preferably of electro-optic material, a first, a second and a third
5 waveguide 3-5 for carrying the light, and electrodes 6, 7 and 8 for the electrical control of the device 1. The device 1 has a plane of virtual symmetry orthogonal to the plane of the figure, and forming an axis 9 in the plane of the figure.

10 The substrate 2 can be made from materials with different optical properties. Preferably, the substrate 2 is made from lithium niobate (LiNbO_3) or from another material which, like lithium niobate, has an electro-optic effect, such as lithium tantalate (LiTaO_3). Alternatively, the
15 substrate 2 can be made from a polymeric material.

If a substrate 2 made from lithium niobate is used, this structure is advantageously orientated with the cut perpendicular to the x axis (x-cut) and the direction of propagation of the light is preferably chosen to coincide
20 with the y axis (y-propagation). Alternatively, the structure may comprise a substrate with a cut perpendicular to the y axis (y-cut) and with propagation of the light essentially along the x axis (x-propagation). This structure shows smaller thermal drift phenomena (in other
25 words smaller variations of the operating point due to variations of temperature) and requires relatively small values of potential difference for switching or attenuating the light. As a further alternative, the substrate can be of the type with a cut perpendicular to the z axis (z-cut)
30 and with the direction of propagation along the x axis (x-propagation) or along the y axis (y-propagation), as will be described subsequently with reference to Figure 12.

The waveguides 3-5 are formed by depositing a layer of titanium having a thickness of less than 500 nm, more
35 preferably in the range from 50 nm to 150 nm, on the

substrate 2; their profiles are then formed by photolithographic techniques, and finally the titanium remaining within the underlying substrate 2 is thermally diffused. Preferably, the waveguides 3-5 have an
5 essentially constant width, such that the propagation of a single mode is permitted.

The device of Figure 1a is a Y switch which can operate either as a 1x2 switch (if the light enters from the first waveguide 3 and leaves either from the second waveguide 4
10 or from the third waveguide 5) or as a 2x1 switch (if the light entering from either the second or the third waveguide 4, 5 leaves from the first waveguide 3). The invention described below is equally applicable to an X switch, as will be explained below with reference to Figure
15 10.

The first waveguide 3 extends essentially along the axis 9, while the second and third waveguides 4, 5, which form the two arms of the Y or in other words the two branching waveguides, are preferably symmetrical with each other
20 about the axis 9 and are separated after a point P of bifurcation (located on the axis 9).

Alternatively, the second and third waveguides 4, 5 can be positioned asymmetrically with respect to the axis 9 or can have different widths.

25 The waveguides 3-5 are connected by means of a connecting waveguide 10, delimited in an approximate way in Figure 1a by the segments of broken lines a and b orthogonal to the axis 9. The connecting waveguide 10 widens progressively as it passes from the area communicating with the first
30 waveguide 3 to the area communicating with the second and third waveguides 4, 5, and essentially forms an isosceles trapezium which is symmetrical about the axis 9 and has a shorter base side positioned along the segment a and a longer base side positioned along the segment b. The
35 lateral walls of the connecting waveguide 10 (forming the

oblique sides of the trapezium) are inclined in such a way as to form between them a first angle θ_1 whose value is selected to be as large as possible while ensuring that the aforesaid condition of adiabaticity is met. The first angle
5 θ_1 is preferably less than 2° , and more preferably in the range from approximately 0.01° to approximately 1° (for example, it may be 0.4°).

The connecting waveguide 10 comprises a multimodal waveguide region delimited approximately in Figure 1a by
10 the segments of broken lines c and b which are orthogonal to the axis 9. The multimodal region is a region in which the width of the connecting waveguide 10 is such as to allow the transmission of at least one higher-order mode.

The second and third waveguides 4, 5 both have sections
15 with different inclinations with respect to the axis 9. For convenience of description, the device 1, from the point at which the first waveguide 3 is connected to the connecting waveguide 10, can be divided into longitudinal regions, particularly into a first longitudinal region I, whose
20 longitudinal limits coincide with those of the connecting waveguide 10, and into subsequent regions II and III, forming a second and a third longitudinal region respectively, in which the second and third waveguides 4, 5 have sections with different inclinations. The second
25 region II, in turn, consists of a first and a second longitudinal area II-A, II-B in which the waveguides 4, 5 form different angles between them. The areas II-A, II-B and the region III are delimited respectively by the pairs of segments of broken lines (b, d), (d, e), (e, f); all the
30 aforesaid segments are orthogonal to the axis 9.

In detail, in the first longitudinal area II-A the second and third waveguides 4, 5 have respective first sections 4a, 5a which are essentially rectilinear and form between them a second angle θ_2 which is smaller than the first
35 angle θ_1 , and preferably in the range from approximately 0.01° to 1° . The first area II-A has a length, measured

parallel to the axis 9, which is less than 50 mm, and preferably in the range from approximately 100 μm to approximately 5000 μm .

5 In the second longitudinal area II-B, the second and third waveguides 4, 5 have respective second sections 4b, 5b which are essentially rectilinear and form between them a third angle θ_3 , which is smaller than the first angle θ_1 and different from the second angle θ_2 , preferably in the range from 0.01 to 1°. The second area II-B has a length,
10 measured parallel to the axis 9, which is less than 50 mm, and preferably in the range from 100 μm to 5000 μm .

The longitudinal dimension of the first area II-A is preferably in the range from 30% to 70% of the longitudinal dimension of the second longitudinal region II, more
15 preferably in the range from 40% to 60% of this value, and even more preferably approximately 50% of this value.

In the case considered here, in which the substrate is made from x-cut y-propagation LiNbO_3 , the third angle θ_3 is smaller than the second angle θ_2 .

20 The second longitudinal region II forms the longitudinal region of the device in which the electro-optic effect acts most intensely. The applicant has observed that, since the TM mode is less confined than the TE mode within a waveguide of the type of the waveguides 4, 5, the electro-
25 optic effect (and therefore the transfer of power from one guide to the other) acts in a different way on the two modes. In particular, in the case of an x-cut y-propagation LiNbO_3 substrate, the electro-optic effect acts on the TE mode predominantly within the first longitudinal area II-A
30 and acts on the TM mode predominantly within the second longitudinal area II-B.

The applicant has also observed that the drive voltage which enables the device to switch (in the way described below) and the optical power which is carried in one or

- other of the two waveguides 4, 5 depends on the angle formed by the waveguides 4, 5. In particular, as this angle decreases it is possible to use a smaller potential difference to obtain the same optical power in one of the two waveguides 4, 5, or, in the same way, it is possible to obtain a greater optical power in one of the two waveguides 4, 5 for the same applied potential difference. This behaviour is found both for the TE mode and for the TM mode.
- 10 The applicant has found that the particular configuration of the waveguide adopted in the device 1, in other words the selection of two different angles θ_2 and θ_3 for the areas II-A and II-B, in this particular case such that $\theta_3 < \theta_2$, makes it possible to compensate, as a result of the
- 15 different electro-optic effect in these regions, the aforesaid difference in behaviour of the TE and TM modes. Thus it is possible to obtain a response of the device 1 which is essentially independent of polarization and optimized in terms of applied potential difference.
- 20 The applicant has found that, in the first area II-A and in the second area II-B, the waveguides 4 and 5 can have configurations different from the rectilinear configuration. In the more general case, the angle formed between the two guides 4 and 5 in the first area II-A has a
- 25 mean value $\theta_{2,ave}$ and the angle formed between the two guides 4 and 5 in the second area II-B has a mean value $\theta_{3,ave}$. The difference between these two values is a quantity $\Delta\theta_{ave}$ which is preferably greater than 25% of the larger of the values of the second and third angles θ_2 , θ_3 .
- 30 The second angle θ_2 is, at each point of the first area II-A, greater than the difference between the mean value $\theta_{2,ave}$ and half of the quantity $\Delta\theta_{ave}$ (in other words, $\Delta\theta_{ave}/2$), and the third angle θ_3 is, at each point of the second area II-B, smaller than the sum of the mean value $\theta_{3,ave}$ and half of
- 35 the quantity $\Delta\theta_{ave}$. In other words, the angles θ_2 and θ_3 can vary within respective ranges, but are such that θ_2 is

always greater than θ_3 , in other words such that the said ranges are separated.

These relations between the angles θ_2 and θ_3 are inverted (and therefore θ_2 is smaller than θ_3 , but always within
5 respective separate ranges) when use is made of substrates such that the electro-optic effect acts more intensely in the area of the second region II adjacent to the third region III than in the area of the second region II adjacent to the first region I. In general, if the area in
10 which the electro-optic effect is more intense is identified as the first area, then in the case of a lithium niobate substrate this first area is adjacent to the first region I, while in the case of other substrates this first area can be adjacent to the third region III.

15 The third region III delimits the extension of the electrodes 6-8. In the third region III, the second and third waveguides (4, 5) have respective third sections 4c, 5c which extend to a longitudinal limit of the electrical field region. The direction and the length of the third
20 sections 4c, 5c are such that the waveguides 4, 5 are essentially decoupled from each other at the exit from the third region III.

In the particular case shown in Figure 1, the third sections 4c, 5c are curvilinear and diverge from the axis
25 9. The length and bend of the third sections 4c, 5c can, however, be varied as required. The third region III has a length, measured parallel to the axis 9, of less than 50 mm, preferably in the range from 100 μm to 5000 μm (for example, it may be 2740 μm). The curvature of the
30 waveguides 4, 5 in the third region III is selected in such a way as to obtain, in the smallest possible space, the desired separation between the waveguides 4, 5.

Beyond the third region III, the second and third waveguides 4, 5 have respective fourth sections, or
35 terminal sections, 4d, 5d, extending up to a corresponding

face of the substrate 2 and both terminating essentially parallel to the axis 9 in such a way as to form a correct coupling with external waveguides, for example optical fibres. The fourth sections 4d, 5d can if necessary be
5 completely rectilinear and parallel to the axis 9 from the segment *f* onwards.

The electrodes 6-8 include a central electrode 6 located between the second the third waveguide 4, 5 and a first and a second outer electrode 7, 8 located on opposite sides of
10 the second waveguide 4 and of the third waveguide 5, respectively, from the central electrode 6. The electrodes 6-8 are capable of forming an electrical field region to control (by means of the electro-optic effect) the refractive indices of the second and third waveguides 4, 5.
15 The extension of the electrodes is such that the said electrical field region is at least partially superimposed on the first and second area II-A and II-B and, preferably, partially superimposed on the first region I. Preferably, the electrodes 6-8 have the same length *L* measured along a
20 direction parallel to the axis 9.

The central electrode 6 comprises a principal portion 6a having an essentially triangular shape, with two sides which are symmetrical about the axis 9, one being adjacent to the second waveguide 4 and the other being adjacent to
25 the third waveguide 5, and with the vertex between these sides located near the point P of bifurcation of the second and third waveguides 4, 5.

Additionally, the central electrode 6 has an essentially rectilinear extension 6b of predetermined length *l*, which
30 extends along the axis 9 and into the multimodal region from the vertex of the principal portion 6a located near the point P. The length of the extension 6b is preferably selected in such a way that a first end 6c of it is located inside the multimodal region, for the reason stated below.

35 Preferably, the outer electrodes 7 and 8 are symmetrical

- 24 -

with each other about the axis 9 and each of them has one side adjacent to a corresponding waveguide 4 or 5 on the side opposite the central electrode 6.

As shown in Figure 1a, in the multimodal region, the distance between the outer electrodes 7 and 8 can decrease progressively from their ends facing the first waveguide 3, in such a way that a gradual electrical field is introduced into the multimodal region. In the variant shown in the partial view in Figure 1b, the distance between the electrodes 7, 8 can be essentially constant, at least in the multimodal region. The applicant has observed that this solution is preferable in the case in which the extension 6b terminates within the multimodal region and that, with this configuration of the electrodes 7, 8, it is possible to have an essentially constant electrical field with a relatively high value in the area occupied by the electrodes, without adverse effects on the condition of adiabaticity.

The electrodes 6-8 extend to a longitudinal position at which the coupling of the modes between the second and third waveguides 4, 5 is essentially zero. This position coincides with the position marked by the segment of broken line *f*. Preferably, as stated previously, the second and third waveguides 4, 5 extend beyond the ends of the electrodes 6-8 up to a corresponding face of the substrate 2, so that they can be optically coupled to external waveguides (not shown), for example optical fibres.

The outer electrodes 7 and 8 can both be connected directly to earth, as shown in Figure 1a, or can be connected electrically to each other (in a way which is not illustrated) by means of a conducting link which keeps them at the same potential. The central electrode 6 is electrically connected to a voltage generator 12. Thus it is possible to establish an electrical potential difference ΔV between the central electrode 6 and the two outer electrodes 7, 8, which induces a controllable

electrical field in the region occupied by the waveguides 4 and 5 in the multimodal region.

5 The electrodes 6-8 are capable of forming, over their whole length, an electrical field region in which the refractive indices of the second and third waveguide 4, 5 can be varied as a function of the electrical potential difference ΔV applied to the electrodes.

10 The electrodes 6-8 can be made by depositing a layer of conducting material, for example titanium, on the surface of the substrate 2 which has previously been covered with a layer of insulating material, for example silicon oxide SiO_2 , and then using a photolithographic technique of a known type to form the electrodes into the desired shape. The electrodes 6, 7 have a thickness which is preferably
15 less than approximately 500 nm, and more preferably in the range from approximately 50 nm to approximately 150 nm.

The applicant has observed that the extinction ratio of the device 1, as defined by the relation $\text{E.R.} = 10 \log P_H/P_L$, where P_L and P_H are the minimum and maximum powers which
20 can be extracted through one of the two waveguides in opposite switching conditions, is a function of the length of the extension 6b, particularly of the position of the end 6c of the extension 6b within the multimodal region.

In particular, the applicant has found that, for some
25 values of the length of the extension 6b, the extinction ratio is particularly high; in other words, the curve representing the extinction ratio as a function of the length of the extension 6b has relatively high peaks at the aforesaid values of the length. This behaviour is
30 observable for both polarizations of the light, namely TE and TM. The length of the extension 6b (and consequently the position of the end 6c) is therefore preferably chosen to be equal to one of the aforesaid values, in order to obtain the highest possible value of the extinction ratio.

If necessary, the length of the central electrode 6 could be different from that of the outer electrodes 7 and 8. In this case, at least the central electrode or the outer electrodes has its length selected in such a way that it
5 terminates in one of the aforesaid positions between the segments c and b.

Figure 1c shows, in a partial view, a possible variant of the device 1, in which the connecting region, indicated here by 10', is Y-shaped, with a portion 10'a of tapered
10 shape connected to the first waveguide 3 and a first and second branch 10'b, 10'c connected to the second and third waveguide 4, 5 respectively. The branches 10'b and 10'c form between them an angle θ_1 equal to the angle formed by the outer walls of the portion 10'a. In this case also, the
15 distance between the electrodes in the connecting region 10' may be substantially constant (as shown in Figure 1c) or may decrease continuously (as shown in Figure 1a).

Possible dimensions for a device made with the device 1c are provided below, purely by way of example:

- 20 - length of the first region I: approximately 1200 μm ;
- length of the portion 10'a: 1000 μm ; length of each branch 10'b and 10'c: approximately 200 μm ;
- angle θ_1 : approximately 0.4° ;
- length of the first area II-A: approximately 2070 μm ;
- 25 - angle θ_2 : approximately 0.117° ;
- length of the second area II-B: approximately 5640 μm ;
- angle θ_3 : approximately 0.088° ;
- length of the third region III: 915 μm ;
- width of each waveguide 3-5: approximately 6 μm ;
- 30 - centre-to-centre distance between the waveguides 4 and 5 at the segment f: approximately 28.5 μm .

The device 1 operates in the following way.

Operation as a 1x2 switch will be considered. If the potential difference ΔV applied to the electrodes 6-8 is
35 zero, the light entering the device 1 through the first

waveguide 3 is equally divided between the second and the third waveguides 4, 5 when it leaves the device 1. However, if a non-zero potential difference ΔV is applied between the electrodes 6 and 7, the electrical field which is thus
5 generated induces, by the electro-optic effect, an increase $+\Delta n$ in the refractive index in one of the waveguides 4, 5 and an equivalent decrease $-\Delta n$ in the refractive index in the other waveguide 5, 4. Consequently there is an increase in the optical power guided by the waveguide with the
10 higher refractive index and, at the same time, a reduction in the optical power guided by the other waveguide. In practice, the power of the monomodal signal supplied to the connecting region 10 from the first waveguide 3 will be distributed between the waveguides 4, 5 in a way which is
15 correlated with the aforesaid potential difference. In particular, if the applied potential difference ΔV is sufficient to provide complete switching, the monomodal signal leaving the waveguide with the higher refractive index will have an optical power which is essentially equal
20 to that of the signal entering the device 1, while the optical power at the output from the waveguide with the lower refractive index will be essentially zero.

Similarly, when used as a 2x1 switch, the device 1 is capable of selecting, from the monomodal signals entering
25 through the waveguides 4 and 5, the signal to be sent to the output through the first waveguide 3. In practice, when a potential difference ΔV sufficient to provide complete switching is applied, the monomodal signal entering through the waveguide with the lower refractive index will be
30 radiated into the substrate 2, and the first waveguide 3 will receive only the monomodal signal from the waveguide with the higher refractive index.

Figure 2 shows the variation of the difference of optical power ΔP between the two waveguides 4, 5 as a function of
35 the potential difference ΔV applied between the electrodes 6 and 7. The characteristic $\Delta P/\Delta V$ is essentially

symmetrical about a central point at which $\Delta V = 0$ and $\Delta P = 0$ (balanced distribution of the optical power in the case of zero potential difference) and includes:

- a first region of essential saturation, indicated as
5 region A, distinguished by values of potential difference which are smaller than a predetermined threshold value $-\Delta V_{TH}$, in which the optical potential difference ΔP takes an essentially constant minimum value;
 - an essentially linear region, indicated as region B,
10 distinguished by values of potential difference in the range from the first threshold value $-\Delta V_{TH}$ to a second threshold value $+\Delta V_{TH}$ whose absolute value is equal to the first, in which the characteristic is essentially linear and rising; and
 - 15 - a second region of essential saturation, indicated as region C, distinguished by values of potential difference which are greater than the second threshold value $+\Delta V_{TH}$, in which the difference in optical power ΔP takes an essentially constant maximum value.
- 20 The threshold potential differences $-\Delta V_{TH}$ and $+\Delta V_{TH}$ are selected according to the value of some parameters, such as the angles defined above between the waveguides 4, 5, the width of the waveguide 3, 4, 5 and the distance between the electrodes in the connecting region 10. Typical values for
25 the threshold potential differences $-\Delta V_{TH}$ and $+\Delta V_{TH}$ are, for example, -40 V and +40 V.

The device 1 is normally used in the regions of saturation A and C to provide digital switching of the light between the waveguides 4 and 5, while the linear region B forms a
30 transition region for changing from one switching condition to the other. In practice, when there are rapid variations of the potential difference ΔV from one to the other of the threshold values $-\Delta V_{TH}$ and $+\Delta V_{TH}$ defined above, it is possible to vary the refractive indices of the waveguides 4
35 and 5 in such a way that the optical power entering the device 1 is supplied to only one of the waveguides 4, 5.

A possible application of the device 1 as a digital switch is in a self-protected optical ring network, in other words an optical network configured essentially in the form of a ring in which a suitable protection method enables the correct flow of data to be ensured even in the presence of a fault. A network of this type is shown in Figure 3 and is indicated there by the number 30. In a network such as the network 30, the device 1 can be used, for example, at a signal add/drop node to carry out the optical redirection of the signals in case of a fault.

In detail, the network 30 comprises a first and a second optical fibre ring 31, 32 (the outer ring and the inner ring respectively), capable of carrying optical signals in opposite directions of transmission (anti-clockwise and clockwise respectively), and a plurality of optically reconfigurable nodes 33 which are optically connected along the first and second rings 31, 32. The nodes 33 are designed for adding and dropping the signals at the locations of users connected to the network or of interconnections with further optical networks.

The network 30 can be used either for short-distance communications (e.g. a LAN, or "local area network") or for long-distance communications (e.g. transoceanic communications). In the latter case, the network is usually provided with optical amplifiers to re-establish the correct power level of the signals after transmission through a long section of optical fibre (usually of the order of hundreds of kilometres).

The network 30 is suitable for the transmission of wavelength multiplexed signals (or WDM signals), in other words signals distributed among a predetermined number of channels at different wavelengths. In particular, a set of N wavelengths $\lambda_1, \lambda_2, \dots, \lambda_N$ in a predetermined waveband in which the optical fibres and optical components of the network 30 can operate (between 1520 nm and 1610 nm, for example) is considered.

Owing to a modular structure which is described subsequently, each of the nodes 33 is configurable in such a way that it can control a corresponding subset of wavelengths selected from the set $\lambda_1, \lambda_2, \dots, \lambda_N$ and can
5 provide, by using these wavelengths, bi-directional communications with one or more of the other nodes of the network. A generic pair of communicating nodes has a corresponding pair of wavelengths λ_x, λ_y (indicated below as the first and second wavelengths) associated with it for
10 the exchange of signals. The following description will refer principally to this generic pair of communicating nodes, but each consideration can be extended to any number of such pairs.

In conditions of correct operation of the network 30, the
15 two nodes of the pair in question are capable of exchanging signals in a single arc of the network (in other words in a single arc-shaped path along the two rings 31, 32), using the first wavelength λ_x in the first ring 31 and the second wavelength λ_y in the second ring 32. The first wavelength
20 λ_x in the second ring 32 and the second wavelength λ_y in the first ring 31 are reserved for protection and are not used in normal operating conditions (in other words in the absence of faults). In Figure 3, the wavelengths used in normal operating conditions have the suffix "w", while the
25 wavelengths reserved for protection have the suffix "p". The pair of wavelengths λ_x, λ_y used previously by one pair of nodes in the network 30 can be used by a further pair of nodes in the network 30, provided that the arcs of the network in which the corresponding communications take
30 place in normal operating conditions are not superimposed. The wavelengths $\lambda_{x,p}, \lambda_{y,p}$ reserved for protection are shared between all the pairs of nodes which use the frequencies $\lambda_{x,w}, \lambda_{y,w}$ in normal operating conditions.

Each node 33 of the network 30 is structured in such a way
35 that, in addition to the normal functions of extraction, insertion and transmission without modification (or with

amplification if necessary), it is also capable of performing a function of redirecting the signals in case of fault. In a ring network of this type, a fault may occur as a result of damage to the optical fibres which form the rings, or as a result of the malfunction of one of the devices present in the nodes of the network.

In particular, in case of a fault at one point of the network 30, each node 33 which communicates with other nodes through arcs of the network comprising this point is capable of redirecting each of these communications along the corresponding complementary arc, using for this purpose the wavelengths previously reserved for protection.

For a clearer understanding of the structure and operation of the network 30, reference should be made to Figure 4, which shows in detail one of the nodes 33.

The node 33 includes:

- a first and a second OADM (optical add/drop multiplexer) device 35, 36 for adding and/or dropping optical signals into and/or from the first ring 31 and into and/or from the second ring 32 respectively, at the wavelengths at which the node 33 is designed to operate (in the specific case, λ_x and λ_y); the OADMs 35, 36 do not operate on the other wavelengths used in the network 30, and transmit these wavelengths unchanged (or with amplification if necessary); the OADMs 35, 36 are, for example, of the Pirelli Optical Systems OADM/P4-R1 type (of the WaveMux6400 group of products); and
- at least one transmission/reception module 34 for the transmission of optical signals into the network 30 at the wavelengths λ_x , λ_y and the reception of optical signals from the network 30 at the wavelengths λ_x , λ_y ; in practice, there will be one module 34 for each pair of wavelengths which the node 33 has to control, in other words for each different connection which this node has to form within the network 30.

- 32 -

In turn, the transmission/reception module 34 includes:

- a first and a second transmitter Tx_1 , Tx_2 for transmitting signals at the first wavelength λ_x and at the second wavelength λ_y respectively; in normal operating conditions, the first and the second transmitter Tx_1 , Tx_2 are connected to the first ring 31 and to the second ring 32 respectively;
 - a first and a second receiver Rx_1 , Rx_2 , for receiving signals at the second wavelength λ_y and at the first wavelength λ_x respectively; in normal operating conditions, the first and the second receiver Rx_1 , Rx_2 are connected to the second ring 32 and to the first ring 31 respectively;
 - a first, a second, a third and a fourth transmission signal regenerator ("transmitting transponder") $TxT_1(\lambda_x)$, $TxT_1(\lambda_y)$, $TxT_2(\lambda_x)$, $TxT_2(\lambda_y)$ to vary the wavelengths of the transmitted signals in such a way as to make them suitable for transmission into the network 30;
 - a first, a second, a third and a fourth reception signal regenerator ("receiving transponder") $RxT_1(\lambda_x)$, $RxT_1(\lambda_y)$, $RxT_2(\lambda_x)$, $RxT_2(\lambda_y)$ to vary the wavelengths of the signals received from the network 30 in such a way as to make them suitable for reception by the receivers Rx_1 , Rx_2 ;
 - a switch unit 37 for optically connecting the transmitters Tx_1 , Tx_2 and the receivers Rx_1 , Rx_2 to the OADMs 35, 36 in a selective way; and
 - a central processing unit (CPU) 38 for controlling the operation of the switch unit 37 and for controlling the operations of the transmitting regenerators TxT and the receiving regenerators RxT .
- The transmitters Tx_1 , Tx_2 and the receivers Rx_1 , Rx_2 represent the points of access of external users to the network 30 for the insertion and extraction of data. This insertion and extraction of data can be carried out at wavelengths different from the wavelengths used for the transmission of signals in the network 30 (in other words, different from the wavelengths λ_1 , λ_2 , ..., λ_N), since the transmission signal regenerators TxT and reception signal

regenerators RxT are designed to vary the wavelengths of the transmitted and received signals, respectively, in a predetermined way. The transmitters Tx_1 , Tx_2 and the receivers Rx_1 , Rx_2 can be, for example, terminals of the
5 Sonet OC-48/SDH STM-16 type (of the type produced by the Nortel company, for example).

The first and second transmission signal regenerators $TxT_1(\lambda_x)$, $TxT_1(\lambda_y)$ are optically connected to the first ring 31 by means of the first OADM 35 and are capable of
10 supplying signals at the first wavelength λ_x and at the second wavelength λ_y respectively to the first ring 31. The third and fourth transmission signal regenerators $TxT_2(\lambda_x)$, $TxT_2(\lambda_y)$ are optically connected to the second ring 32 by means of the second OADM 36 and are capable of supplying
15 signals, at the first wavelength λ_x and at the second wavelength λ_y respectively, to the second ring 32.

Each transmission signal regenerator $TxT_1(\lambda_x)$, $TxT_1(\lambda_y)$, $TxT_2(\lambda_x)$, $TxT_2(\lambda_y)$ is capable of receiving optical signals from the switch unit 37, of converting them to electrical
20 signals to enable them to be processed by the processing unit 38 and of re-converting them to optical signals having, as stated above, an associated wavelength suitable for transmission. The processing of the signals, in this case, includes the supplying of data for network protection
25 purposes (for example channel identifiers, information for transmission efficiency monitoring, protection protocol, etc.) to the transmitted signals (in the part of the signal known as the "channel overhead").

The first and second reception signal regenerators
30 $RxT_1(\lambda_x)$, $RxT_1(\lambda_y)$ are optically connected to the first ring 31 by means of the first OADM 35 and are capable of receiving from the first ring 31 signals at the first wavelength λ_x and at the second wavelength λ_y respectively. The third and fourth reception signal regenerators
35 $RxT_2(\lambda_x)$, $RxT_2(\lambda_y)$ are optically connected to the second ring 32 by means of the second OADM 36 and are capable of

receiving from the second ring 32 signals at the first wavelength λ_x and at the second wavelength λ_y respectively.

Each reception signal regenerator $RxT_1(\lambda_x)$, $RxT_1(\lambda_y)$, $RxT_2(\lambda_x)$, $RxT_2(\lambda_y)$ is capable of receiving optical signals
5 from the rings 31, 32, of converting them to electrical signals to enable them to be processed by the processing unit 38, and of re-converting them to optical signals having, as stated above, an associated wavelength suitable for reception by a corresponding receiver Rx_1 , Rx_2 . The
10 processing of the signals, in this case, includes the extraction from the received signal of the previously inserted information (in the "channel overhead" of the signal) for the network protection functions.

The transmission signal regenerators TxT and reception
15 signal regenerators RxT can be, for example, of the Pirelli Optical Systems WCM/F-xxx type (of the WaveMux6400 group of products, where xxx is the output wavelength code). Alternatively, the signal regenerators can be wholly optical devices, for example of the S.O.A. (abbreviation of
20 "semiconductor optical amplifier") type, capable of controlling information associated with the signal, for example a pilot tone which overmodulates the wavelength carrying the signal.

The processing unit 38 is capable of communicating with the
25 transmission signal regenerators TxT to supply them with information to be added to the signals, and with the reception signal regenerators RxT to receive information extracted from received signals to be processed, and is also capable of carrying out checks on the conditions of
30 the various connections, and of monitoring the state of the switch unit 37. In Figure 4, the logical connections between the processing unit 38 and the other units controlled by it are represented by broken lines.

The switch unit 37 provides the suitable switching
35 functionality for network protection, by means of its

capacity for selectively connecting the transmitters Tx and the receivers Rx to the transmission and reception signal regenerators TxT, RxT.

As mentioned above, the architecture of Figure 4 is modular, in the sense that each node 33 can include a plurality of transmission/reception modules 34 to control the same number of wavelengths, and, consequently, the same number of connections. In this case, the various pairs of wavelengths which the generic node 33 has to control are separated from each other by the OADMs 35, 36 and directed to the corresponding transmission/reception modules 34.

The switch unit 37 comprises eight switching devices 1a-1h made according to the present invention, operated by the CPU 38 by means of an appropriate control logic.

- 15 The switching devices 1a-1h form selective connections between the transmitters Tx_1 , Tx_2 , the receivers Rx_1 , Rx_2 , the transmission signal regenerators $TxT_1(\lambda_x)$, $TxT_1(\lambda_y)$, $TxT_2(\lambda_x)$, $TxT_2(\lambda_y)$ and the reception signal regenerators $RxT_1(\lambda_x)$, $RxT_1(\lambda_y)$, $RxT_2(\lambda_x)$, $RxT_2(\lambda_y)$. In detail,
- 20 - a first switching device 1a has its first waveguide 3a connected to the first transmitter Tx_1 and its third waveguide 5a connected to the first transmission signal regenerator $TxT_1(\lambda_x)$;
- a second switching device 1b has its first waveguide 3b connected to the second receiver Rx_2 and its second waveguide 4b connected to the first reception signal regenerator $RxT_1(\lambda_x)$;
- 25 - a third switching device 1c has its first waveguide 3c connected to the second reception signal regenerator $RxT_1(\lambda_y)$;
- 30 - a fourth switching device 1d has its first waveguide 3d connected to the third transmission signal regenerator $TxT_2(\lambda_x)$ and its third waveguide 5d connected to the second waveguide 4a of the first switching device 1a;
- 35 - a fifth switching device 1e has its first waveguide 3e connected to the second transmitter Tx_2 and its third

- 36 -

waveguide 5e connected to the fourth transmission signal regenerator $TxT_2(\lambda_y)$;

- a sixth switching device 1f has its first waveguide 3f connected to the first receiver Rx_1 , its second waveguide 4f connected to the fourth reception signal regenerator $RxT_2(\lambda_y)$ and its third waveguide 5f connected to the second waveguide 4c of the third switching device 1c;
 - a seventh switching device 1g has its first waveguide 3g connected to the third reception signal regenerator $RxT_2(\lambda_x)$, its second waveguide 4g connected to the third waveguide 5b of the second switching device 1b, and its third waveguide 5g connected to the second waveguide 4d of the fourth switching device 1d; and
 - an eighth switching device 1h has its first waveguide 3h connected to the second transmission signal regenerator $TxT_1(\lambda_y)$, its second waveguide 4h connected to the third waveguide 5c of the third switching device 1c, and its third waveguide 5h connected to the second waveguide 4e of the fifth switching device 1e.
- The switching devices 1a-1h can be integrated on a single substrate.

In Figure 4, the connections within the switch unit 37 relating to normal operating conditions are shown in continuous lines, while the connections usable in case of a fault are shown in broken lines.

In operation, the connection between two nodes of the network 30 of Figure 3 (for example between the nodes C and F) is established by using a first wavelength λ_x in the first ring 31 in such a way as to form a first operating channel $\lambda_{x,w}$, and using a second wavelength λ_y in the second ring 32 in such a way as to form a second operating channel $\lambda_{y,w}$. The same wavelengths can be used, in the same way, for further connections not superimposed on the previously formed connection. In the first ring 31, the second wavelength λ_y can be used to form a protection channel $\lambda_{y,p}$ and can be shared among all the connections operating at

λ_x , λ_y . In the same way, the first wavelength λ_x can be used in the second ring 32 to form a further protection channel $\lambda_{x,p}$ and can be shared among all the connections operating at λ_x , λ_y . Conversely, connections superimposed on the one
5 formed previously must use pairs of wavelengths other than λ_x , λ_y .

In case of a fault between a first and a second node communicating with each other (for example, a fault located between the nodes 33a and 33b, if the communicating nodes
10 are 33c and 33f), both communicating nodes are reconfigured in such a way as to invert the connections between the corresponding transmitters Tx and receivers Rx and the rings 31, 32. This reconfiguration is commanded by the processing unit 38 and takes place by means of the
15 switching of some of the switches 1 present in the switch unit 37. In practice, the first transmitter Tx₁ of the first node and the second receiver Rx₂ of the second node, which previously communicated with each other via the operating channel $\lambda_{x,w}$ in the first ring 31, are optically
20 connected to the second ring 32 in such a way as to occupy the protection channel $\lambda_{x,p}$. This takes place by the switching of the devices 1a and 1d of the first node and the devices 1b and 1g of the second node.

In the same way, the second transmitter Tx₂ of the second
25 node and the first receiver Rx₁ of the first node, which previously communicated with each other via the operating channel $\lambda_{y,w}$ in the second ring 32, are connected optically to the first ring 31 in such a way as to occupy the protection channel $\lambda_{y,p}$. This takes place by the switching
30 of the devices 1e and 1h of the second node and of the devices 1c and 1f of the first node. In this way, the transmission between the two nodes is switched to the part of the network 30 not affected by the fault. Any other connections passing through the point of the network at
35 which the fault is present are modified in a similar way to that of the first and second node. In general, for each

connection affected by a fault, only the terminal nodes of the connection are reconfigured, while the intermediate nodes of the connection remain unchanged.

5 This condition is maintained until the fault is identified and repaired. During this fault condition, the protection channel used cannot be used simultaneously by other connections which may request this, for example because of the presence of further faults. After the fault has been repaired, the original situation is restored.

10 With reference to Figure 10, the number 40 indicates an alternative configuration of the device according to the invention. The device 40 differs from the device 1 in that the waveguides are arranged in an X configuration instead of in a Y configuration.

15 The device 40 comprises a first, a second, a third and a fourth waveguide 43-46, of which the third and the fourth (45, 46) are equivalent to the second and third waveguides 4, 5 of the device 1. The other parts of the device 40 are essentially equivalent to the corresponding parts of the
20 device 1 and are therefore indicated by the same reference numbers. In particular, the device 40 comprises regions I, II (with the corresponding areas II-A and II-B) and III similar to those of the device 1. As in the device 1, the angles θ_1 , θ_2 and θ_3 can be formed in the region I and in
25 the areas II-A and II-B, and, in the case of LiNbO_3 substrates of the x-cut y-propagation type, we find θ_1 , θ_2 < θ_1 and θ_3 < θ_2 .

The substrate 2 of the device 40 may have a larger area than the substrate 2 of the device 1, so that it can also
30 accommodate the first and second waveguides 43, 44.

The first and second waveguides 43 and 44 are inclined with respect to each other at an angle of θ' which is preferably less than 2° , and more preferably less than 1° , so that the condition of adiabaticity is preserved. Additionally, the

- 39 -

first and second waveguides 43 and 44 are preferably symmetrical about the axis 9 and are preferably rectilinear. Unlike the third and fourth waveguides 45, 46, which preferably have equal widths, the first and second
5 waveguides 43, 44 preferably have different widths from each other. For example, the first waveguide 43 may have a width equal to the width of the third and the fourth waveguide 45, 46, while the second waveguide 44 may have a width smaller than that of the first waveguide 43. The
10 difference in width between the first and second waveguides 43, 44 reduces the optical coupling between them, since it causes a difference in the refractive index. The fundamental modes of propagation of the waveguide 43, 44 therefore have different propagation constants and are
15 therefore "asynchronous". This condition of asynchronism can alternatively be achieved by making one of the waveguides 43, 44 curved.

The device 40 comprises a region 10" connecting the waveguides 43-46 and delimited by the segments of broken
20 lines a' and b' (orthogonal to the axis 9); this region has a larger area than the connecting region 10 of the device 1, since it additionally comprises a portion containing the connection with the first and second waveguides 43, 44. The connecting region 10" has a continuously variable width and
25 comprises a multimodal transmission region whose limits are essentially the same as those of the connecting region 10".

The portion of the connecting region 10" connected to the third and fourth waveguides 45, 46 can have a configuration similar to that of the connecting region 10 shown in
30 Figures 1a and 1b or to that of the connecting region 10' shown in Figure 1c.

As for the device 1, the applicant has observed that the device 40 has an extinction ratio (E.R.) which is a function of the longitudinal dimensions of the extension 6b
35 of the central electrode 6, and more particularly of the longitudinal position of the end of the extension 6b of the

central electrode 6 within the multimodal region. In particular, the applicant has observed that the value of the extinction ratio is particularly high for some values of the longitudinal dimensions of the extension 6b. The
5 applicant has observed that this behaviour is demonstrable for both polarizations of the light, namely TE and TM, as for the device 1.

The thickness of the electrodes 6-8 is preferably less than approximately 500 nm, and is more preferably in the range
10 from approximately 50 nm to 150 nm, and the electrodes are formed as described above with reference to the device 1.

In the region I, in other words in the connecting region 10", the distance between the electrodes 52, 53 can decrease progressively from their ends facing the first and
15 second waveguides 43, 44, in such a way that the electrical field is introduced gradually into the region in question.

In a variant, which is similar to that described for the device 1 and illustrated in Figure 1b and is therefore not illustrated here, the distance between the electrodes 7, 8
20 may be essentially constant in the region I. The applicant has found that this solution is preferable if the extension 6b is selected to have a length such that it terminates in one of the aforesaid positions within the multimodal region. In this case also, this selection of the length of
25 the extension 6b makes it possible to obtain high values of the extinction ratio.

In the particular example shown in Figure 10, the waveguides 4, 5 extend parallel to the axis 9 from the segment *f* to the end of the substrate 2. Alternatively, in
30 this area the waveguides 4, 5 may have portions having an extension different from that shown.

The operation of the device 40 is similar to the operation described previously for the device 1, except for the fact that, since two input guides and two output guides are

present, the device 40 is preferably used as a 2x2 switch. The operating principle of an X switching device is described, for example, in the aforesaid article by Silberberg et al. In practice, the mode carried by the
5 first waveguide 43 is converted, in the connecting region 10", into the normal first-order local mode (fundamental mode), while the mode carried by the second waveguide 44 is converted, in the connecting region 10", into the normal second-order local mode (first higher-order mode). The
10 first-order mode is converted into the fundamental mode of the output guide with the higher index and the second-order mode is converted into the fundamental mode of the output guide with the lower index. If no voltage is applied to the electrodes, the signals from the first and second
15 waveguides 43, 44 are separated equally ("3 dB splitting") between the third and fourth waveguides 45, 46.

The device 40 can be used, for example, to switch the optical signals in a ring network such as that described previously with reference to Figure 3. Figure 11 shows a
20 node 33' which can be used in the network of Figure 3, comprising a switch unit 37' in which a plurality of devices 40 is present instead of the plurality of devices 1 present in the switch unit 37 of Figure 4.

The switch unit 37' comprises a group of devices 40a-40d according to the present invention, operated by the CPU 38
25 by means of an appropriate control logic (not shown). The remaining parts of the node 33' are similar to the corresponding parts of the node 33 of Figure 4 and are therefore indicated by the same names and reference
30 numbers.

In detail, the group of devices 40a-40d comprises:
- a first device 40a having its second waveguide 44a connected to the first transmitter Tx_1 , its third waveguide 45a connected to the third transmission signal regenerator
35 $TxT_2(\lambda_x)$ and its fourth waveguide 46a connected to the first transmission signal regenerator $TxT_1(\lambda_x)$;

- 42 -

- a second device 40b having its first waveguide 43b connected to the third reception signal regenerator $RxT_2(\lambda_x)$, its second waveguide 44b connected to the first reception signal regenerator $RxT_1(\lambda_x)$, its third waveguide 5 45b connected to the first waveguide 43a of the first device 40a, and its fourth waveguide 46b connected to the second receiver Rx_2 ;
 - a third device 40c having its second waveguide 44c connected to the second transmitter Tx_2 , its third 10 waveguide 45c connected to the second transmission signal regenerator $TxT_1(\lambda_y)$ and its fourth waveguide 46c connected to the fourth transmission signal regenerator $TxT_2(\lambda_y)$; and
 - a fourth device 40d having its first waveguide 43d connected to the second reception signal regenerator 15 $RxT_1(\lambda_y)$, its second waveguide 44d connected to the fourth reception signal regenerator $RxT_2(\lambda_y)$, its third waveguide 45d connected to the first waveguide 43c of the third device 40c, and its fourth waveguide 46d connected to the first receiver Rx_1 .
- 20 The operation of the node 33' is similar to that of the node 33. By comparison with the node 33, the node 33' has the advantage of requiring a smaller number of switching devices (4 instead of 8), but has the disadvantages of having a bulkier switch unit (since X switches are bulkier than Y switches) and of forming superfluous connections, 25 not used for signal transmission, during its operation.

With reference to Figure 12a, the number 50 indicates a device made according to the invention, comprising an $LiNbO_3$ substrate of the "z-cut" type, with propagation 30 along the x axis or along the y axis. The device 50 has a guide structure of the Y type, similar to that of the device 1 described previously. In particular, the device 50 comprises a first, a second and a third waveguide 54, 55, 56, corresponding to the waveguides 3, 4 and 5 of the device 1, formed by diffusing titanium on to a lithium niobate substrate 51 with a cut along the z axis. Like the 35

device 1, the device 50 has a region I delimited by segments a and b comprising a connecting region, again indicated by 10, similar to that shown in Figure 1a for the device 1. The connecting region 10 enables the first
5 waveguide 54 to be optically connected to the second and third waveguides 55, 56, and comprises a multimodal region delimited by the segments c and b. Alternatively, the connecting region can be Y-shaped, like that shown in Figure 1c.

10 The first waveguide 54 has a longitudinal axis 57 which forms an axis of essential symmetry for the device 50. The device 50 also comprises areas II-A, II-B and a region III in which the second and third waveguides 55, 56 have a configuration similar to that of the waveguides 4 and 5 of
15 the device 1. In this case also, the angles between the waveguides 4 and 5 are selected according to the characteristics of the substrate 2.

The device 50 could alternatively comprise a waveguide structure of the X type, similar to the structure of the
20 device 40 described above.

The device 50 also comprises a first and a second electrode 52 and 53, identical to each other and formed on top of the substrate 51, preferably in positions symmetrical about the axis 57. The electrodes 52 and 53, unlike the electrodes of
25 the device 1, extend on top of the waveguides 55, 56. The electrodes 52 and 53 are capable of establishing an electrical field within the waveguides 55, 56, and are both connected to a voltage generator (not shown) by means of respective contact pads 58, 59 of conductive material,
30 preferably gold.

The electrodes 52 and 53 extend longitudinally (along the direction defined by the axis 57) between a first predetermined position and a second predetermined position defined by the segment of broken line f. The first
35 predetermined position preferably lies in the multimodal

transmission region, in other words between the segments *c* and *b*, but can also be on the left of the segment *c* or on the right of the segment *b* in the plane of the figure. In other words, the electrodes 52 and 53 preferably terminate
5 within the multimodal region, but may also terminate before or after this region. This is because the applicant has observed that the device 50, like the device 1, has an extinction ratio (E.R.) which is a function of the longitudinal dimensions (measured parallel to the axis 57)
10 of the electrodes 52, 53. In particular, the extinction ratio of the device 50 has particularly high values when one end of the electrodes 52, 53 is placed in a predetermined longitudinal position of the multimodal region. In this case also, the applicant has observed that
15 this behaviour is demonstrable for both polarizations of the light, namely TE and TM.

The longitudinal dimensions (measured parallel to the axis 57) of the electrodes 52, 53 are therefore selected in such a way as to optimize the extinction ratio (E.R.). The
20 operation and any applications of the device 50 are entirely similar to the applications described above for the device 1 and will not be described further.

In the region I, the distance between the electrodes 52, 53 may decrease progressively towards the second and third
25 waveguides 55, 56, in such a way that the electrical field is introduced gradually into the region in question.

In a variant shown in the partial view of Figure 12b, the distance between the electrodes 52, 53 can be essentially constant in the region I. In this case also, this variant
30 is preferable when the length of the electrodes is selected as described above to optimize the extinction ratio (E.R.).

The applicant observes that the embodiments described and illustrated above relate to devices made on a lithium niobate (LiNbO_3), but that the present invention can also
35 be applied effectively to other types of substrate,

provided that they have different behaviours of the TE and TM polarization modes in the waveguides. For example, a device according to the invention could be made on a substrate having such properties and orientations and such waveguides that there is a more intense electro-optic effect in the second area II-B than in the first area II-A, provided that the branching waveguides are designed in such a way that the angle θ_3 associated with the second area II-B is greater than the angle θ_2 associated with the first area II-A.

In practice, in a device made according to the invention, the waveguides must form one angle in the longitudinal region in which the electro-optic effect is more intense and another angle, smaller than the former, in the longitudinal region in which the electro-optic effect is less intense.

NUMERICAL SIMULATIONS AND EXPERIMENTAL MEASUREMENTS

In order to verify the improvements which can be obtained with the waveguide configuration proposed by the present invention, the applicant initially carried out numerical simulations on a device in which all the waveguides were rectilinear, in order to obtain data for comparison. In particular, these simulations were carried out for the case of a device of the type shown in Figure 5 and indicated there by 1', using a mathematical model of the device 1, of the type described in the article by D. Sciancalepore, F. Dell'Orto and I. Montrosset, "Novel theoretical approach for Y digital optical switch", in Proc. ECIO '99, pp. 413-415, Apr. 1999.

The device 1' differs from the device 1 in that the second and third waveguides, indicated here by 4' and 5', are rectilinear and form a constant angle throughout the area occupied by the electrodes, indicated here by 6', 7' and 8'. The remaining parts of the device 1' are indicated by the same reference numbers as those used for the device 1.

It is assumed that the substrate is of the x-cut y-propagation LiNbO₃ type.

The following characteristic values were chosen for the numerical simulation:

- 5 - width of waveguides 3, 4', 5': 6 μm ;
- length (along the axis 9) of the connecting region 10:
 2 mm;
- length of waveguides 4 and 5: 8 mm;
- width of the extension 6b: 2 μm ;
- 10 - length of the portion of the extension 6b extending
 into the multimodal region: 400 μm ;
- potential difference ΔV variable from -100 V to +100 V
 in steps of 2.5 V;
- angle between waveguides 4' and 5': 0.2°; and
- 15 - centre-to-centre distance between the waveguides 4' and
 5' at their exit from the device 1' (in other words at the
 ends of the electrodes 6'-8'): 35 μm .

The total length of the device is approximately 10 mm.

Figure 6 shows the variation of the output power in one of
20 the two guides 4', 5' as a function of the potential
difference ΔV , for both polarizations TE and TM.

As may be seen, the characteristic curves of the TE and TM
polarizations have different shapes. In particular, the
curve representing TE polarization has a steeper leading
25 edge than the curve represent TM polarization, and reaches
its minimum and maximum values at a potential difference
having an absolute value of approximately 45 V, while for
TM polarization a potential difference having an absolute
value of approximately 90 V is required. In a real
30 application of this device, it would be necessary to select
a potential difference intermediate between those
indicated (with an absolute value of 70 V, for example), in
such a way as to obtain a compromise between the two
polarizations. In this compromise condition, both TE and TM
35 polarizations would be switched at power levels below those

theoretically obtainable according to the curves in Figure 6, and there would also be a waste of energy in the switching of the TE polarization.

In order to evaluate the performance of the device 1, the applicant used a numerical model of the device 1. The following characteristic values were selected for the construction of this model:

- total length: approximately 10.3 mm;
- length of the first region I: approximately 1000 μm ;
- 10 - angle θ_1 : 0.4° ;
- length of the first area II-A: 3330 μm ;
- angle θ_2 : 0.14° ;
- length of the second area II-B: 3230 μm ;
- angle θ_3 : 0.085° ;
- 15 - length of the third region III: 2740 μm ;
- width of each waveguide 3, 4 and 5: 6 μm ;
- potential difference ΔV variable from -80 V to +80 V in steps of 2.5 V;
- length of the extension 6b: 2 μm ; and
- 20 - length of the portion of the extension 6b extending into the multimodal region: 320 μm .

The variation of the angles of the waveguides 4 and 5 as a function of a longitudinal axis z measured from the start of the waveguides 4 and 5 (in other words from the segment of broken line b) is shown in Figure 13. This figure shows, in particular, the areas II-A and II-B of the region II, and the region III; the hatched rectangles indicate ranges I_1 and I_2 within which the angles θ_2 and θ_3 can be varied in the areas II-A and II-B respectively while still providing advantages in terms of independence of polarization. It will be observed that the ranges I_1 and I_2 relating to the two angles θ_2 and θ_3 are separate from each other.

For comparison, Figure 14 shows the variation of the angle of the waveguides of an optical switching device made according to the teachings of the article by Burns cited above. The position from the start of the branching

waveguide is indicated on the z axis, as for Figure 13. This variation, for the electro-optic interaction area of the device, was reconstructed by numerical simulation by the applicant, using the formulae described in the said
5 article.

In the graph in Figure 13, although the variation of the angle in region I is absent, there is a clear asymmetry in the curve representing the angle in region II, in other words in the intermediate region of the device 1, owing to
10 the presence of the two areas II-A and II-B in which the angle between the waveguides 4, 5 lies within separate ranges. This variation is not present in the characteristic shown in Figure 14.

Figure 7 shows the variation of the output power in one of the two guides 4, 5 as a function of the potential difference ΔV for both polarizations TE and TM. When the results of the numerical simulation carried out on the device 1 (Figure 7) are compared with the results of the numerical simulation carried out on the device 1' (Figure
20 6), it will be noted that the device 1 made according to the invention is more independent of polarization than the device 1'. This is because the curves for the TE and TM polarizations are very close to each other, and the potential difference at which switching takes place is
25 essentially the same for both polarizations (with an absolute value of 40 V).

The applicant has also conducted an experiment to confirm the results previously obtained by numerical simulation.

Figure 8 shows a measuring apparatus used to carry out
30 experimental measurements. This apparatus comprises:

- a laser source 61 capable of emitting at 1550 nm,
- an optical fibre 62 forming a "polarization controller" connected to the laser source 61; the optical fibre 62 is a standard optical fibre wound in such a way as to form three
35 loops and having a twist controlled in such a way as to

- 49 -

have a desired polarization of the electromagnetic field at the output;

- a first lens 63 for shaping the optical beam leaving the fibre 62;
- 5 - a polarizer 64 positioned facing the first lens 63 and capable of allowing only one polarization of the optical beam to pass;
- a second lens 65 positioned facing the polarizer 64 on the opposite side from the first lens 63 and capable of
- 10 focusing the optical beam on the first waveguide 3 of the device 1;
- a third lens 66 positioned facing the second waveguide 4 of the device 1 and capable of shaping the optical beam leaving the device 1;
- 15 - a fourth lens 67 facing the third lens 66 and capable of receiving the optical beam shaped by the third lens 66;
- a photodiode 68, for receiving the optical beam and consequently generating an electrical signal;
- a voltage generator 69 for driving the device 1; and
- 20 - a processor 70 connected to the voltage generator 69 and to the photodiode 68.

The measurements were made on a device similar to the device 1, having the same characteristic values as those used for the numerical model. The measurements were made

25 with an optical power of approximately 0 dBm supplied to the device 1. The results of the measurements are shown in Figure 9, in which the variation of the output power in one of the two guides 4, 5 is shown as a function of the potential difference ΔV for both polarizations TE and TM.

30 As may be observed, the experimental results of Figure 9 essentially confirm the results of the numerical simulation of Figure 8.

CLAIMS

1. Digital optical switching device having a longitudinal axis (9; 57) and comprising:
- a substrate (2);
 - 5 - at least a first, a second and a third waveguide (3-5; 43-46; 54-56) for light, formed on the said substrate (2);
 - a connecting waveguide (10; 10'; 10'') formed on the said substrate (2) and connecting the said first, second and third waveguides (3-5; 43-46; 54-56) to each other, the
 - 10 said second and third waveguides (4, 5; 45, 46; 55, 56) having a first and a second refractive index respectively, and forming two alternative branches for carrying the light from and/or towards the said connecting waveguide (10; 10'; 10'');
 - 15 - electrodes (6-8; 52, 53) associated with at least one of the said second waveguide (4; 45; 55) and third waveguide (5; 46; 56) and capable of forming, in response to a potential difference (ΔV) applied to them, an electrical field region in which at least one of the said
 - 20 first and second refractive indices can be varied;
- characterized in that it comprises:
- a first longitudinal region (I) in which the said connecting waveguide (10; 10'; 10'') forms a first angle (θ_1);
 - 25 - a second longitudinal region (II) adjacent to the said first longitudinal region (I) and consisting of a first and a second longitudinal area (II-A, II-B) extending through the said electrical field region, in which the said second and third waveguides (4, 5; 45, 46; 55, 56) form a second
 - 30 angle (θ_2) and a third angle (θ_3), respectively, between them, the values of these angles being smaller than the value of the said first angle (θ_1) and lying within respective separate ranges (I_1 , I_2); and
 - a third longitudinal region (III) adjacent to the said
 - 35 second longitudinal region (II), in which the said second and third waveguides (4, 5; 45, 46; 55, 56) extend up to a longitudinal boundary of the said electrical field region.

- 51 -

2. Device according to Claim 1, characterized in that:
- the said second angle (θ_2) is greater than the said third angle (θ_3);
 - the said second and third angles (θ_2 , θ_3) have
5 respective mean values which differ from each other by a predetermined quantity ($\Delta\theta$);
 - at each point of the said first area, the said second angle (θ_2) is greater than the difference between the mean value of the said second angle (θ_2) and half of the said
10 predetermined quantity ($\Delta\theta$);
 - at each point of the said second area, the said third angle (θ_3) is smaller than the sum of the mean value of the said third angle (θ_3) and half of the said predetermined quantity ($\Delta\theta$).
- 15 3. Device according to Claim 1, characterized in that the said first area (II-A) is adjacent to the said first longitudinal region (I).
4. Device according to Claim 3, characterized in that the said substrate (2) is made from lithium niobate.
- 20 5. Device according to Claim 1, characterized in that the said first area (II-A) is adjacent to the said third longitudinal region (III).
6. Device according to Claim 1, characterized in that, in the said first and second areas (II-A, II-B), the said
25 second and third waveguides (4, 5; 45, 46; 55, 56) preferably have an essentially rectilinear configuration.
7. Device according to Claim 1, characterized in that, in the said third longitudinal region (III), the said second and third waveguides (4, 5; 45, 46; 55, 56) preferably have
30 a curvilinear configuration.
8. Device according to Claim 1, characterized in that each of the said first longitudinal region (I), the said first area (II-A) and the said second area (II-B) has a longitudinal dimension which is less than 50 mm.

- 52 -

9. Device according to Claim 8, characterized in that each of the said first area (II-A) and the said second area (II-B) has a longitudinal dimension which is in the range from 100 μm to 5000 μm .
- 5 10. Device according to Claim 1, characterized in that the longitudinal dimension of the said first area (II-A) is in the range from 30% to 70% of the longitudinal dimension of the said second region (II).
- 10 11. Device according to Claim 10, characterized in that the longitudinal dimension of the said first area (II-A) is in the range from 40% to 60% of the longitudinal dimension of the said second region (II).
- 15 12. Device according to Claim 1, characterized in that the said first, second and third angles (θ_1 , θ_2 , θ_3) are less than 2° .
13. Device according to Claim 12, characterized in that the said first, second and third angles (θ_1 , θ_2 , θ_3) are in the range from 0.01° to 1° .
- 20 14. Device according to Claim 1, characterized in that the said predetermined quantity is more than 25% of the value of the said second angle (θ_2).
- 25 15. Device according to Claim 1, characterized in that the said connecting waveguide (10; 10'; 10'') comprises a multimodal transmission region (14) confined between a first and a second longitudinal position (c, b), and in that the said electrodes (6, 7, 8; 52, 53) comprise at least one electrode (6) having a longitudinal end (6c) placed between the said first and second longitudinal positions (c, b).
- 30 16. Device according to Claim 1, characterized in that the said electrodes (6-8) comprise a first, a second and a third electrode (6-8), the said third electrode (6) forming a central electrode interposed between the said second

waveguide (4; 45) and the said third waveguide (6; 46) and the said first and second electrodes (7, 8) forming outer electrodes placed on opposite sides of the said second waveguide (4; 45) and, respectively, the said third
5 waveguide (6; 46), with respect to the said central electrode (6).

17. Device according to Claim 1, characterized in that the said electrodes (52, 53) comprise a first and a second electrode (6-8), partially superimposed on the said second
10 waveguide (55) and on the said third waveguide (56) respectively.

18. Device according to Claim 1, characterized in that the said first, second and third waveguides (3-5; 44-46; 54-56) are preferably made by the diffusion of titanium into the
15 substrate (2).

19. Device according to Claim 1, characterized in that it comprises a fourth waveguide (43), forming an angle of less than 2° with the said first waveguide (44).

20. Optical transmission system, comprising at least one transmitter (Tx1, Tx2) for transmitting an optical signal, at least one receiver (Rx1, Rx2) for receiving the said optical signal, and an optical connection (31, 32) for carrying the said optical signal from the said transmitter to the said receiver, characterized in that the said
25 optical connection comprises at least one optical switching device (1; 50) according to Claim 1 for switching the said optical signal between alternative optical paths.

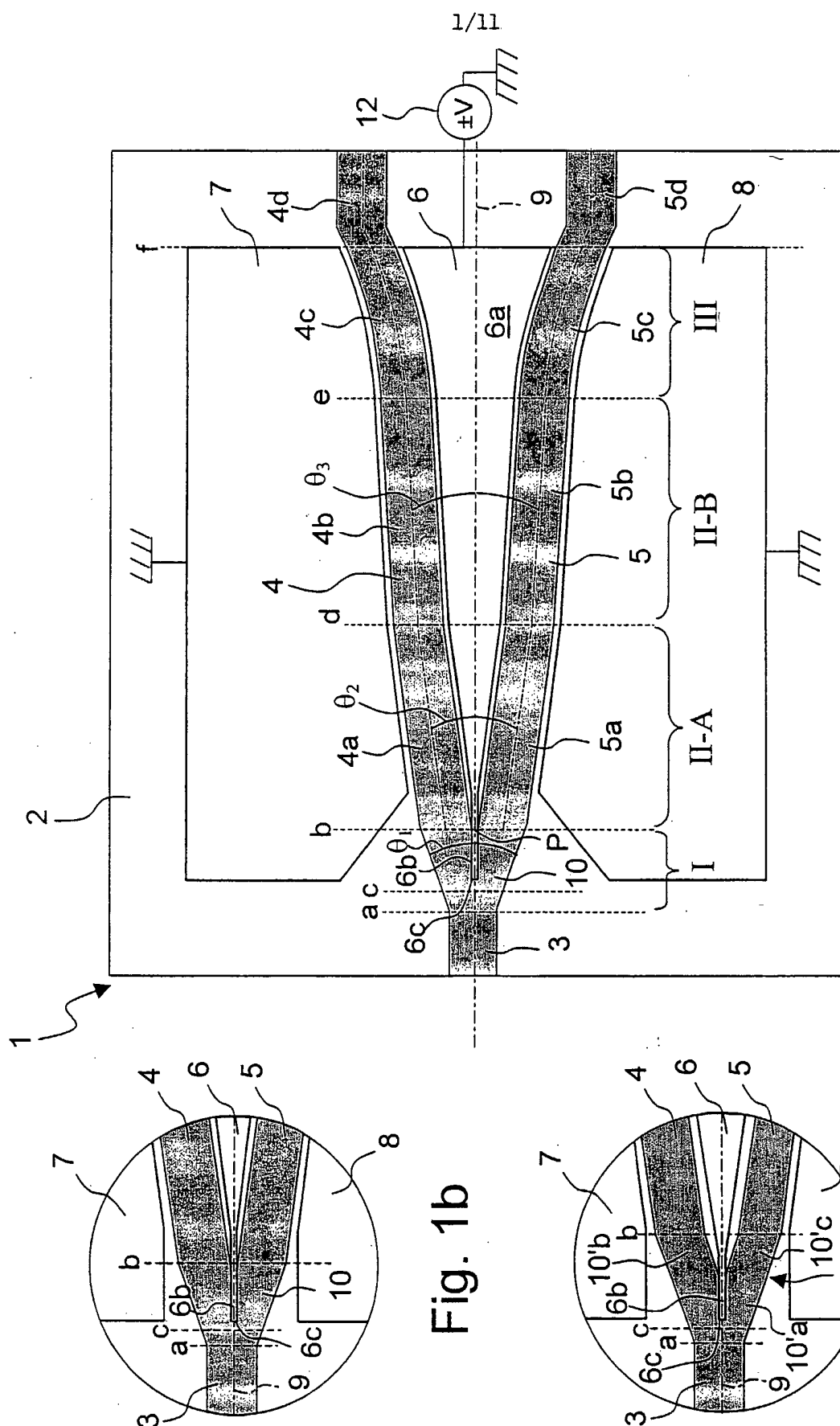


Fig. 1b

Fig. 1c

Fig. 1a

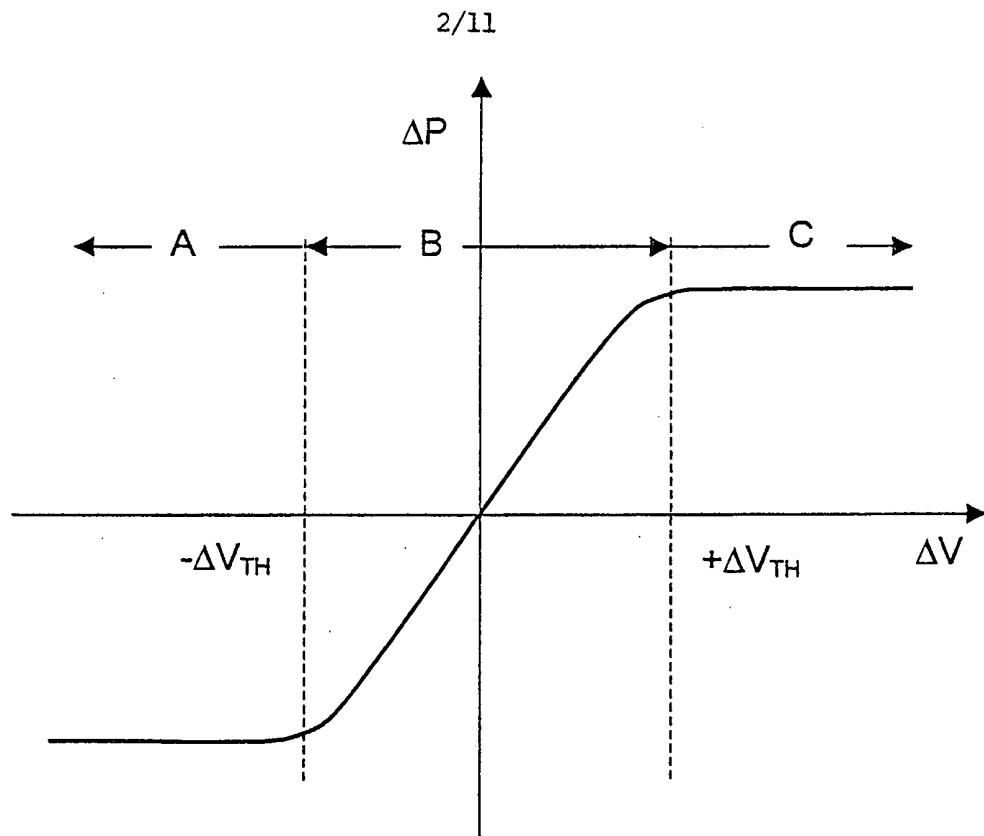


Fig. 2

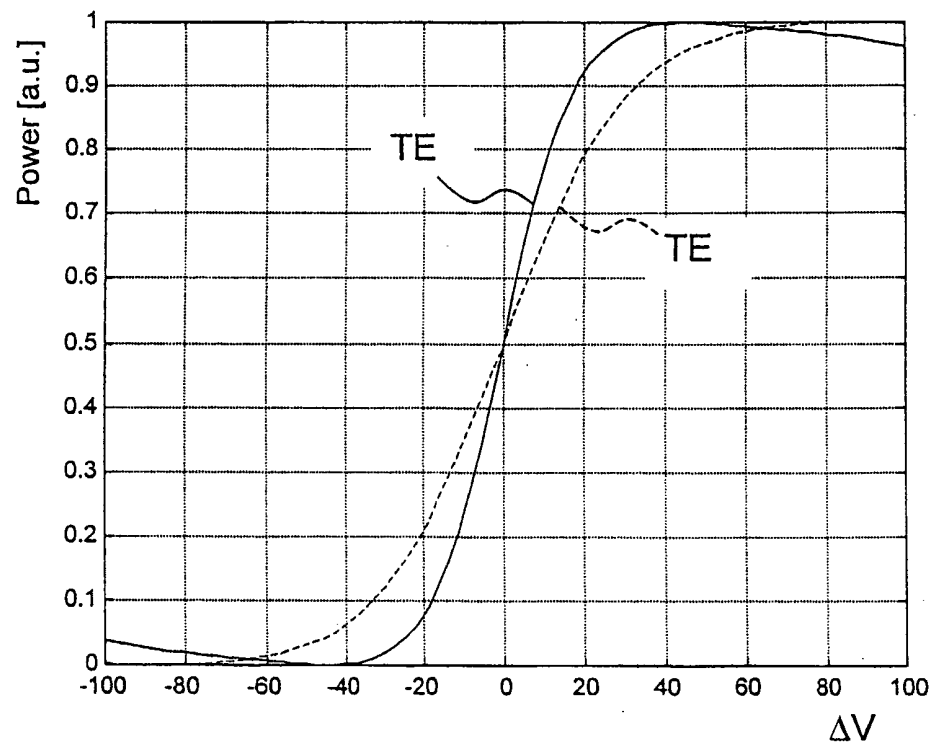


Fig. 6

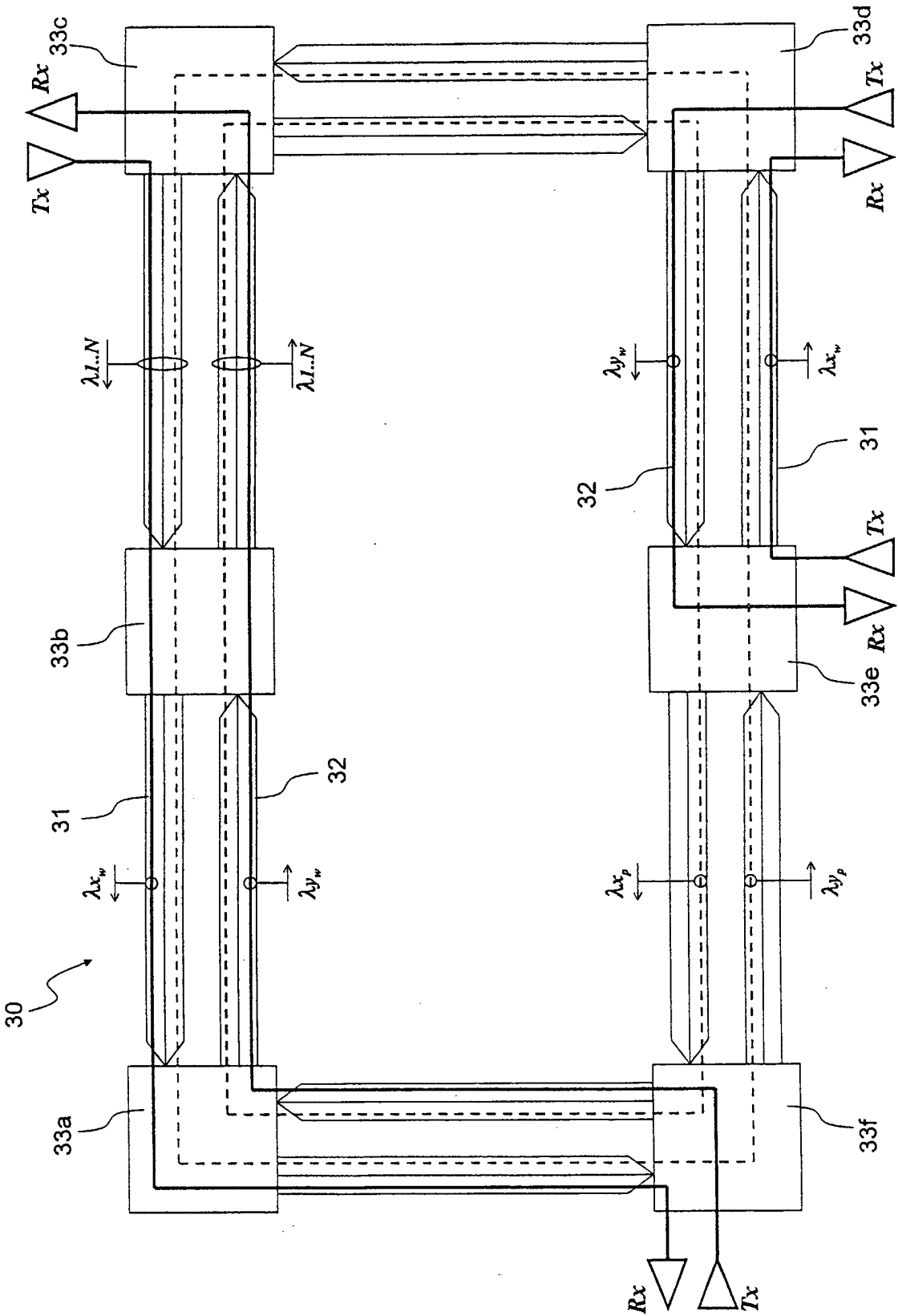


Fig. 3

4/11

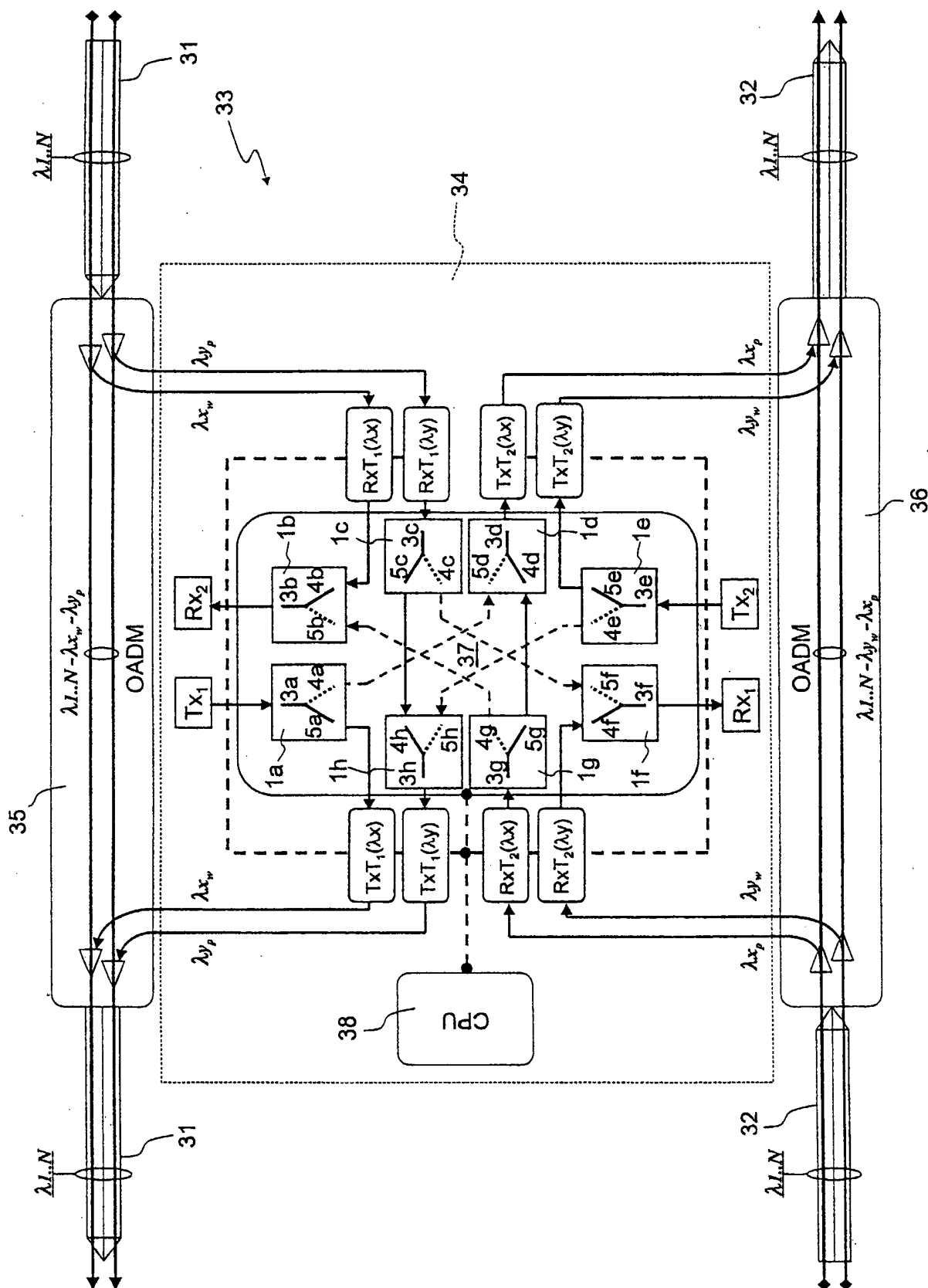


Fig. 4

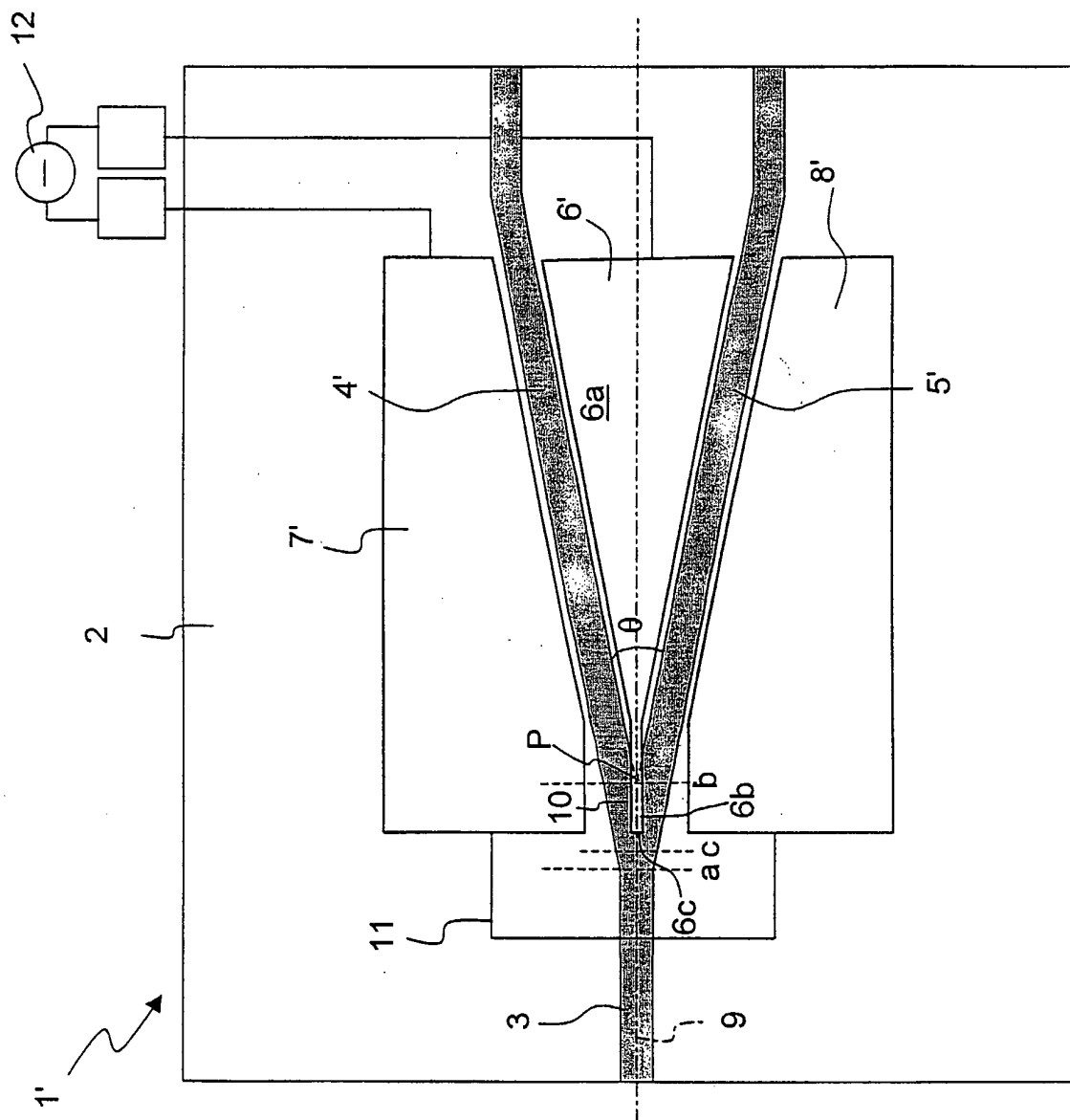


Fig. 5

6/11

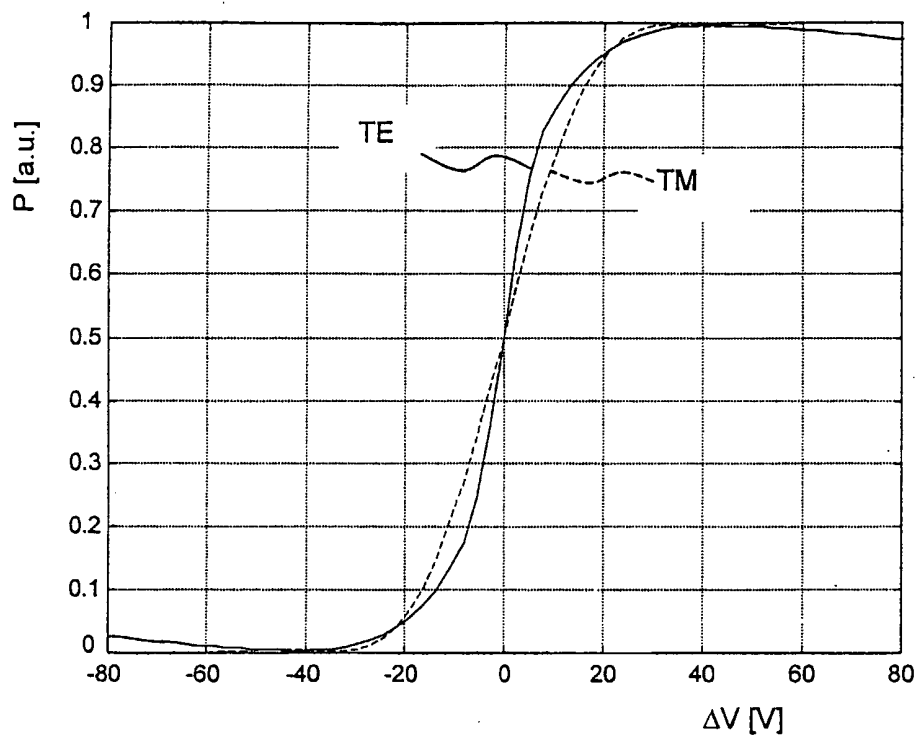


Fig. 7

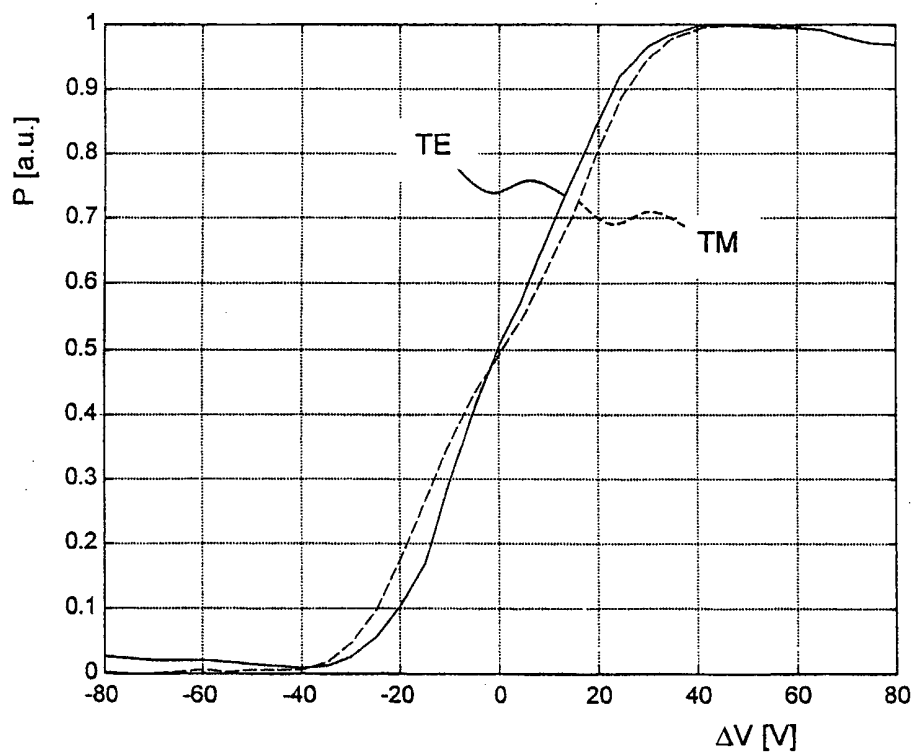


Fig. 9

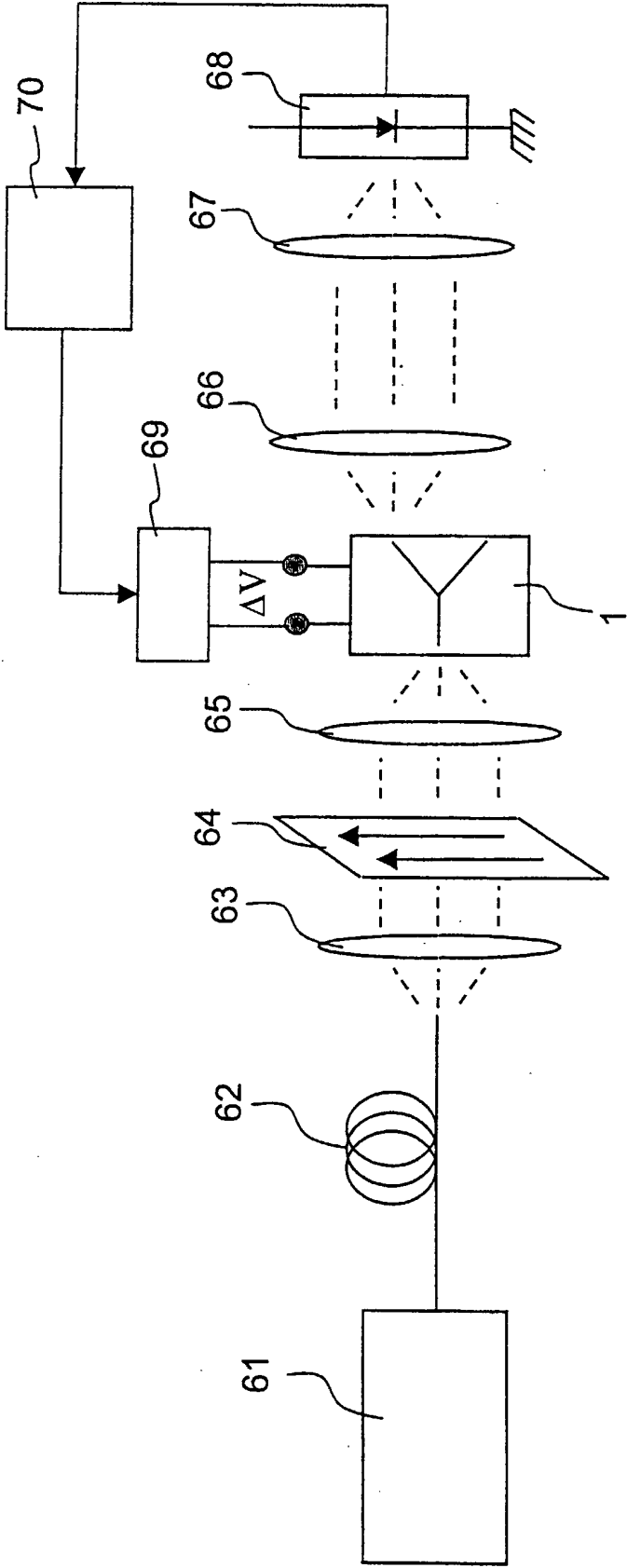


Fig. 8

8/11

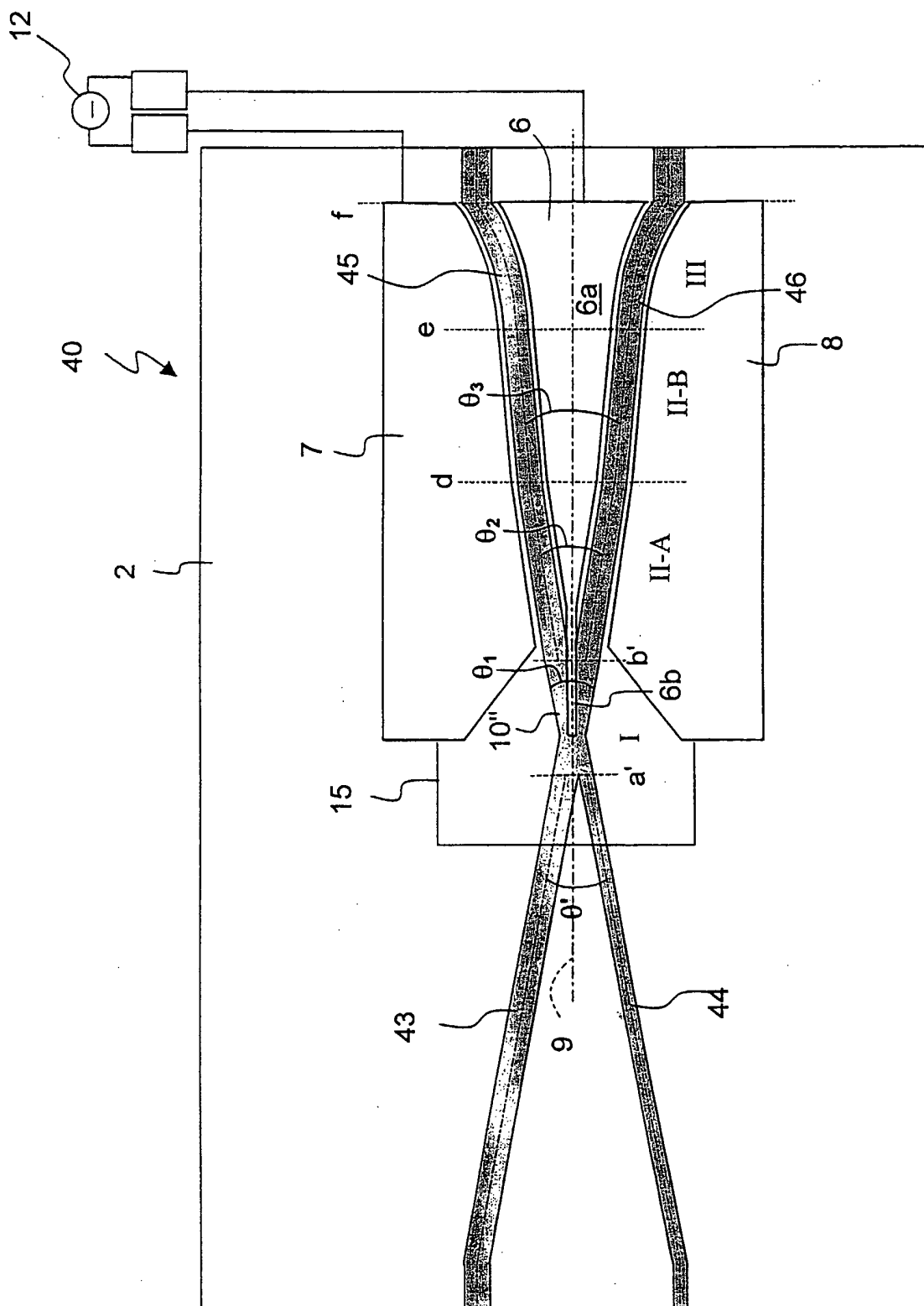


Fig. 10

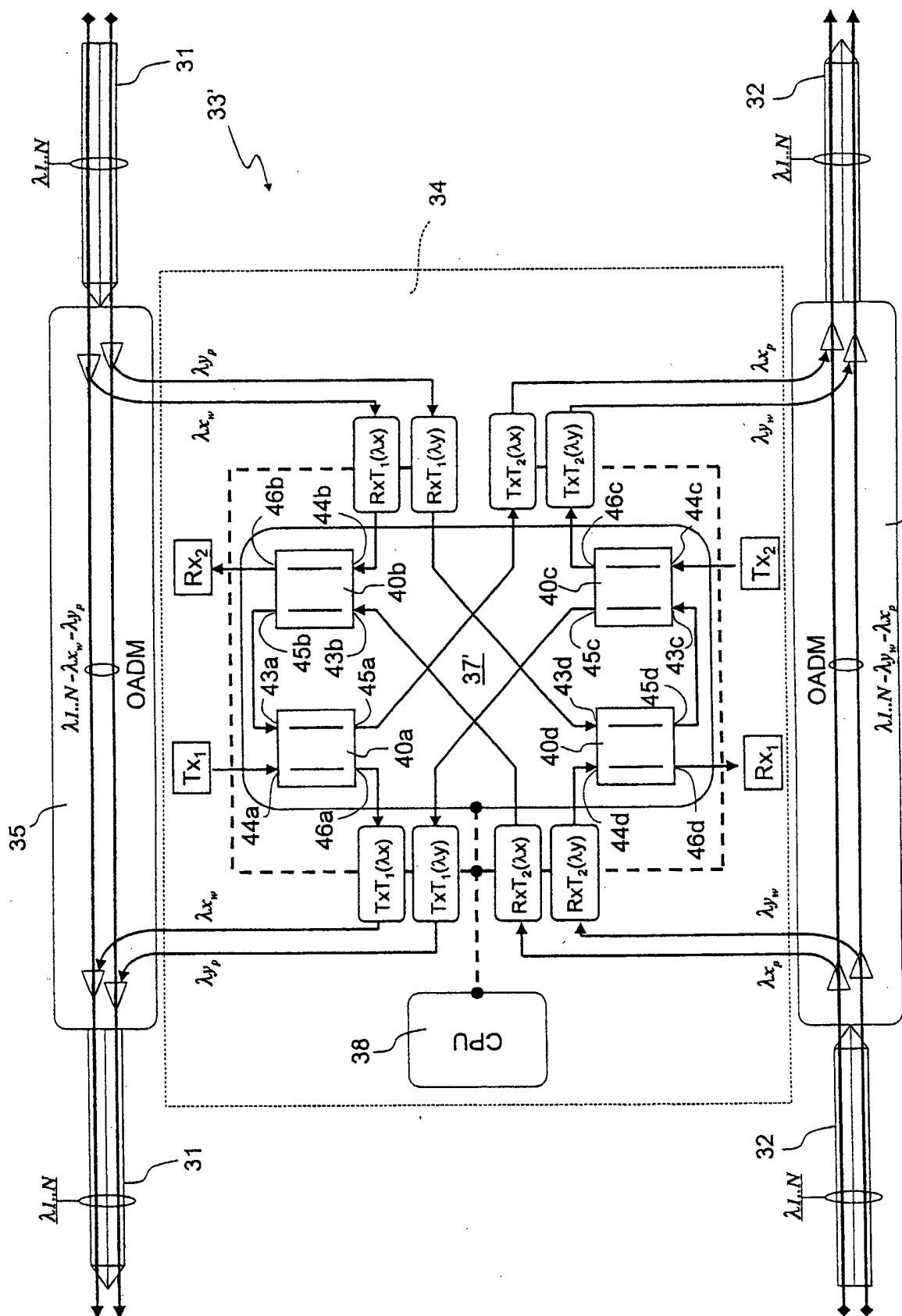


Fig. 11

10/11

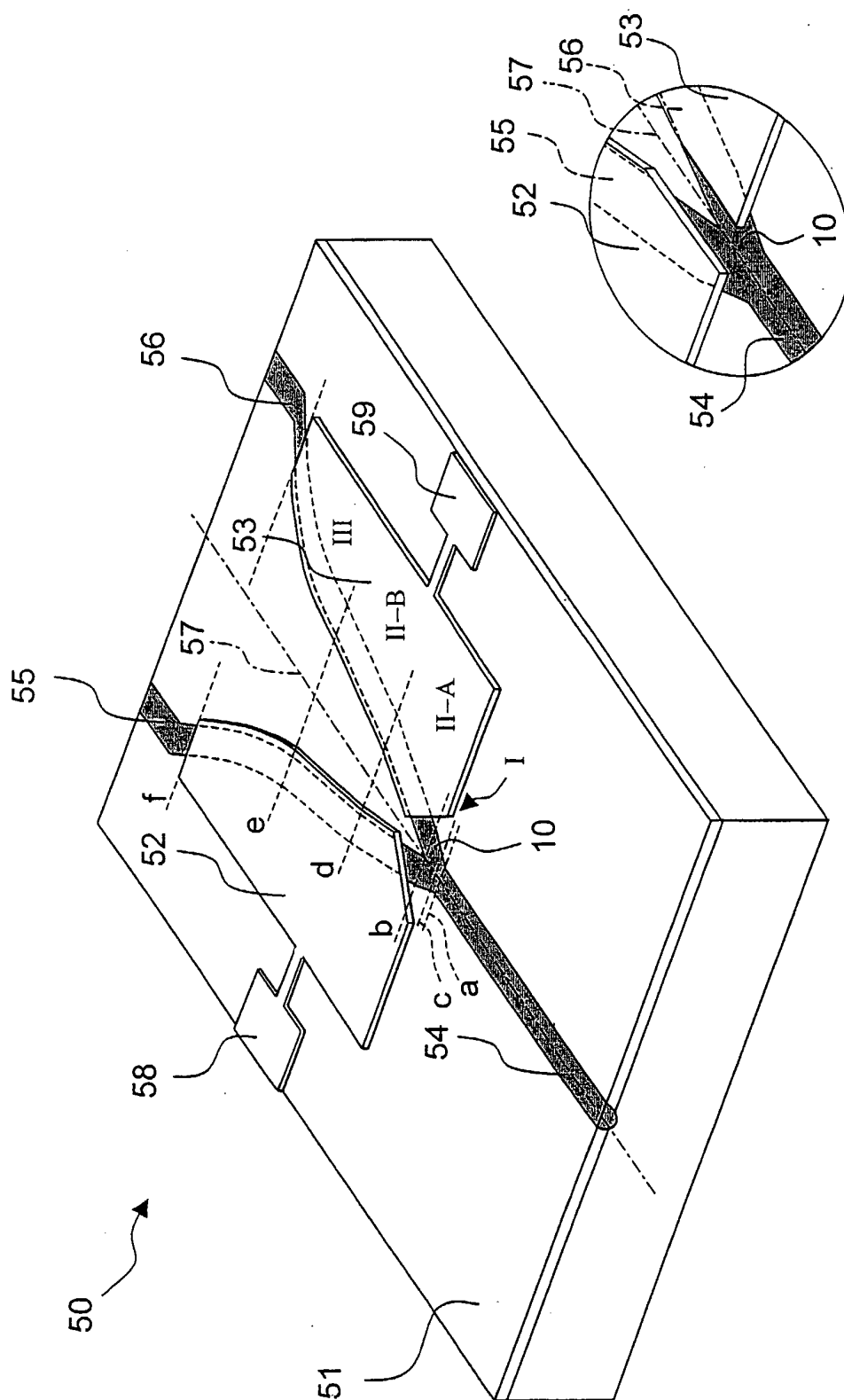


Fig. 12b

Fig. 12a

11/11

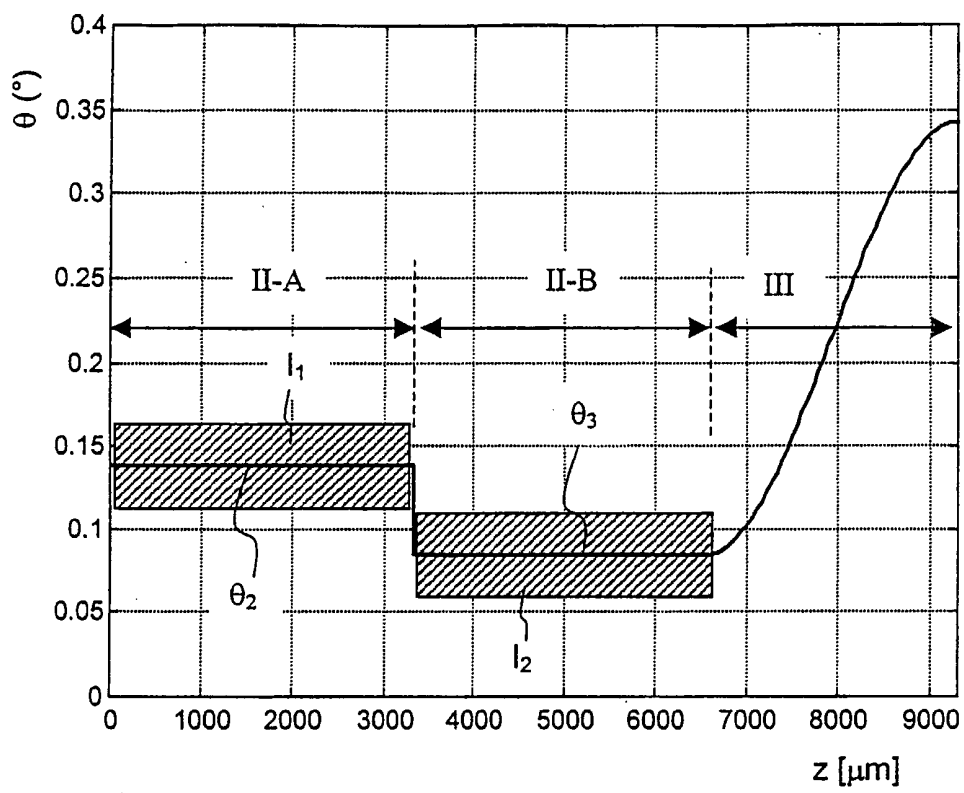


Fig. 13

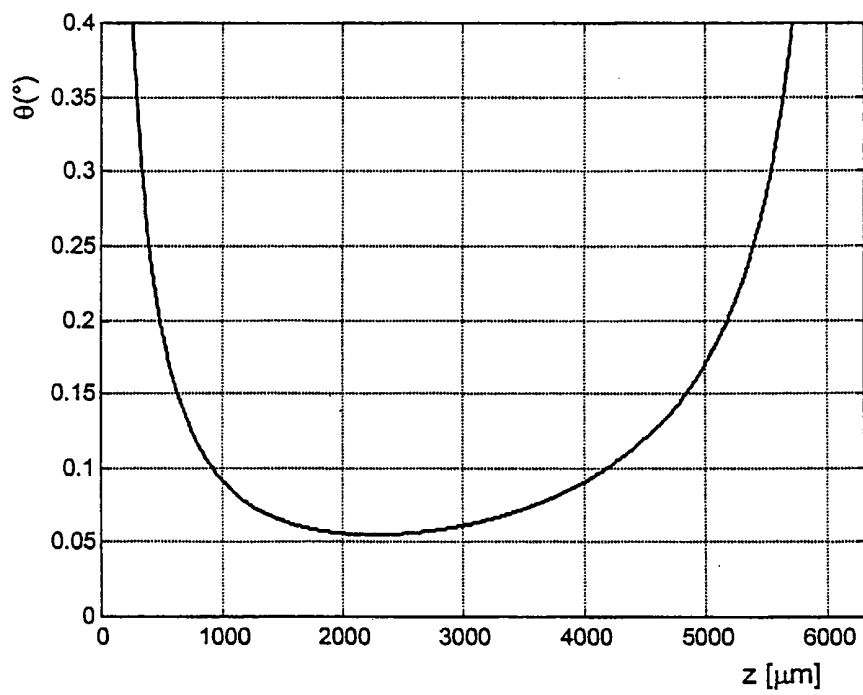


Fig. 14