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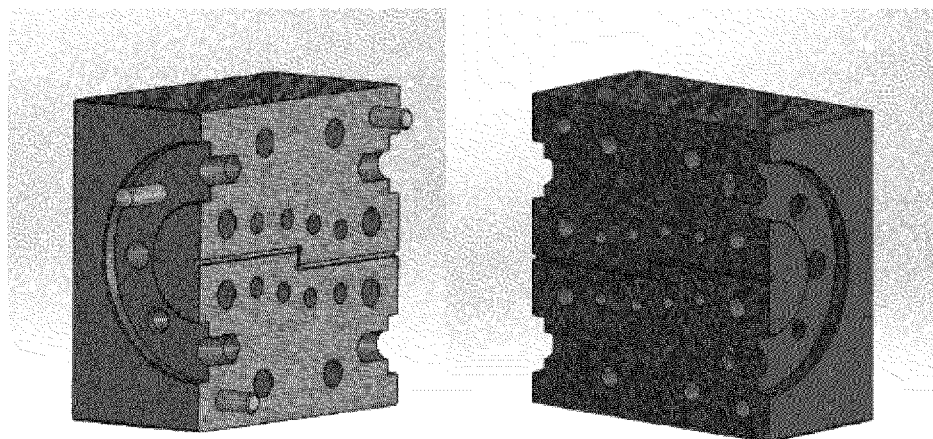


FIG. 1

(57) Abstract: An optically controlled waveguide device is disclosed. The device includes a first waveguide, a second waveguide, and a semiconductor chip positioned between the first waveguide and the second waveguide. The semiconductor chip includes a transmission line having a first end and the second end, a first waveguide probe antenna disposed adjacent to the first end of the transmission line and configured to receive a first electrical signal from the first waveguide, and a second waveguide probe antenna disposed adjacent to the second end of the transmission line and configured to transmit the first electrical signal to the second waveguide. The semiconductor chip is configured to absorb light illuminating the semiconductor chip and attenuate the first electrical signal transmitted between the first waveguide, the transmission line and the second waveguide based on an amount of the light being absorbed.



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- *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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OPTICALLY CONTROLLED WAVEGUIDE PROBE BASED ATTENUATOR AND MODULATOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of and priority to U.S. Provisional Patent Application 62/471,223, filed March 14, 2017, which is incorporated herein by reference in its entirety.

BACKGROUND

[0002] An attenuator is an electronic device that reduces the amplitude of a signal without substantially distorting the waveform of the signal. In circuits, attenuators are used to lower voltage, dissipate power, and to improve impedance matching. In measuring signals, attenuators are used to lower the amplitude of the signal a known amount to allow measurements, or to protect the measuring device from signal levels that might damage it.

SUMMARY

[0003] A millimeter wave optically controlled modulator and attenuator device is discussed herein. The device has low insertion loss in the off-state of the optical source. In some embodiments, the device can have at least about 50 dB dynamic range with less than 100 mW incident optical power. In some embodiments, the device can have about 2 MHz modulation bandwidth. In some embodiments, the device can have a stability of about 1 part in 10000 over several hours. In some embodiments, the device can be used as a drop-in replacement for micrometer driven attenuators in modular waveguide circuits, including mm-wave transmitters and receivers.

[0004] In some embodiments, as a variable attenuator, the device can incorporate one or more of the following features: optimization for optical coupling, Si surface passivation, anti-reflection coating, heat sinking of probe chip, optimization for dynamic range, large area diffuse illumination and a sinuous transmission line. In some embodiments, as a modulator, the device can incorporate one or more of the following features: optimization for carrier lifetime, a thinner

substrate, GaAs substrate or other semiconductor with a short carrier lifetime, and fiber coupling of light.

[0005] At least some embodiments of the present disclosure relates to an optically controlled waveguide device. The device includes a first waveguide, a second waveguide, and a semiconductor chip positioned between the first waveguide and the second waveguide. The semiconductor chip includes a transmission line having a first end and the second end, a first waveguide probe antenna disposed adjacent to the first end of the transmission line and configured to receive a first electrical signal from the first waveguide, and a second waveguide probe antenna disposed adjacent to the second end of the transmission line and configured to transmit the first electrical signal to the second waveguide. The semiconductor chip is configured to absorb light illuminating the semiconductor chip and attenuate the first electrical signal transmitted between the first waveguide, the transmission line and the second waveguide based on an amount of the light being absorbed.

[0006] At least some embodiments of the present disclosure relates to an optically controlled attenuator. The attenuator includes a light source configured to emit a light, a first waveguide, a second waveguide, and a semiconductor component disposed between the first waveguide and the second waveguide. The semiconductor component includes a transmission line and at least two waveguide probes coupled to ends of the transmission line. The waveguide probes are configured to transmit a first electrical signal from the first waveguide to the second waveguide. The semiconductor component is configured to absorb at least a portion of the light and attenuate the first electrical signal transmitted from the first waveguide to the second waveguide through the transmission line based on an amount of the light being absorbed.

[0007] At least some embodiments of the present disclosure relates to a method of attenuating or modulating signals. The method includes receiving, at a semiconductor chip coupled between a first waveguide and a second waveguide, a light illuminating at least a portion of the semiconductor chip; coupling, by a plurality of waveguide probes of the semiconductor chip, the light to induce loss in a transmission line of the semiconductor chip; and attenuating or modulating with the loss induced in the transmission line, by the semiconductor chip, an electrical signal transmitted from the first waveguide to the second waveguide.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a better understanding of the nature and objects of some embodiments of this disclosure, reference should be made to the following detailed description taken in conjunction with the accompanying drawings.

[0009] FIG. 1 illustrates two halves of a waveguide block to be assembled.

[0010] FIG. 2A illustrates a silicon chip that bridges the gap between the two waveguides.

[0011] FIG. 2B illustrates light focused onto the transmission line of the silicon chip during operation.

[0012] FIG. 2C illustrates a microscopic image of the silicon chip disposed between the two waveguides.

[0013] FIG. 2D illustrates dimensions of a sample silicon chip fabricated using an etching process.

[0014] FIG. 3 illustrates the two halves of a waveguide block that have been assembled.

[0015] FIG. 4 illustrates an internal structure of the assembled waveguide block.

[0016] FIG. 5 illustrates an aluminum jig on top of the assembled waveguide block.

[0017] FIG. 6 illustrates a perspective view of internal structures of the aluminum jig and the upper waveguide block half.

[0018] FIG. 7 illustrates a side view of the internal structures of the aluminum jig and the upper waveguide block half.

[0019] FIG. 8 illustrates a side view of the focusing lens, the collimating lens and the light source, without showing the aluminum jig and the upper waveguide block half.

[0020] FIG. 9A illustrates focused light onto the chip within the lower waveguide block half.

[0021] FIG. 9B illustrates dynamics of charge carriers in silicon caused by photoconductive effect.

[0022] FIG. 10 illustrates a plot of zero-illumination insertion loss versus frequency when the light source is off.

[0023] FIG. 11 illustrates plots of relative attenuations at a frequency range while being illuminated by the diode at different current levels of from 0 mA to about 1 A.

[0024] FIG. 12 illustrates plots of phase shifts at a frequency range while being illuminated by the diode at different current levels of from 0 mA to about 1 A.

[0025] FIG. 13 illustrates the diode output power measured at different locations.

[0026] FIG. 14 illustrates the I-V curve of the diode for reference.

[0027] FIG. 15 illustrates plots of relative attenuations vs. optical power for different frequencies.

[0028] FIG. 16 illustrates plots of phase shifts vs. optical power for different frequencies.

[0029] FIG. 17 illustrates a modulation response of the attenuator device, compared to a current source driving the light source.

DETAILED DESCRIPTION

[0030] At least some embodiments of the present disclosure relate to design and measurement of an optically controlled waveguide modulator. The symmetric device includes offset input and output waveguides connected by silicon chip mounted in an E-plane split waveguide block. The thickness of the silicon chip can be, e.g., about 5 μm , about 10 μm , about 25 μm , or about 50 μm or about 75 μm or about 100 μm , depending on the design frequency. Patterned on the chip is a pair of radial stub waveguide probes connected by a section of microstrip transmission line. The length of the section can be, e.g., about 0.5 mm, about 1 mm, about 2 mm, or about 5 mm. The transmission line can be straight or it can be sinuous depending on the application. The waveguide probes provide return losses of at least better than about -25 dB over more than a standard waveguide band. . Illumination of the chip at photon energies that are larger than the silicon bandgap generates free charge carriers in the silicon substrate, modulating its conductivity and dielectric constant. For example, an 805 nm (nanometer) multimode laser diode driven by a voltage controlled current source can be used for illumination. The photoconductive effect allows for the modulation of the millimeter-wave loss along the microstrip transmission line. For example, a system of lenses can be used to produce a focused or collimated laser beam which is incident on the semiconductor chip. Measurements can be made using, e.g., a coherent source/receiver scheme or an mm-wave vector network analyzer allowing for the extraction of

the complex scattering parameters for the disclosed device.

[0031] The modulation bandwidth of this device can be measured to be approximately 2 MHz at moderate modulation depths. The modulation bandwidth can be varied (e.g., increased) in other embodiments through use of a different semiconductor material, chip thickness, or chip surface treatment. The modulation bandwidth can be measured by observing the carrier to sideband ratio of a down-converted received signal on a spectrum analyzer. The bandwidth of such a device is specified by, e.g., the minority carrier lifetime in the semiconductor substrate.

[0032] At a low modulation frequency, the disclosed device can operate as a continuously variable attenuator. Compared to optically-controlled dielectric-loaded waveguide attenuators, the increased millimeter-wave power density in microstrip transmission line and focused optical illumination allows the disclosed device to achieve a wide dynamic range with modest optical powers. For example, at an incident optical power of about 100 mW, the attenuation of up to about 50 dB can be achieved. With no illumination, the device exhibits an insertion loss between about 1 dB and about 1.5 dB, partially due to loss in the flange matings and input and output waveguide transmission loss. The measured attenuation varies linearly and slowly with frequency and is a smooth monotonically increasing function of incident optical power. Such properties make this device an ideal candidate for use in conjunction with a directional coupler as a source leveling-loop or a DC-stabilized modulator or “chopper”. These applications may find use in varied areas such as millimeter wave antenna mapping or millimeter-wave vector network analyzer extenders.

[0033] Furthermore, the disclosed attenuator device includes designed light coupling features on the waveguide probe circuitry, which allow the penetration of light photons into the active area of the circuit where the attenuation and modulation occur. In some embodiments, the light coupling features comprise a number of holes patterned into the conductor portion of the microstrip transmission line that allow photons to enter the region of the semiconductor under the conductor portion of the microstrip transmission line. The position and pattern of the holes is chosen so as to not affect the performance of the microstrip transmission line. As a result, the device can operate with a very low optical power. For example, in some embodiments, with only about 100 mW of available laser power, an attenuation of up to about 50 dB can be obtained in a

WR-10 waveguide block, operating in the frequency range of from about 75 to about 110 GHz. This is significantly more efficient than comparative devices which use many Watts of laser power to achieve attenuation.

[0034] In some embodiments, the attenuator device is applicable in the terahertz (THz) band (from about 100 GHz to about 1 THz). The attenuator is symmetric and includes an input and output waveguide connected by a microstrip transmission line patterned on a thin semiconductor chip.

[0035] In some embodiments, the attenuator device includes a waveguide block, which can be assembled from two halves. FIG. 1 illustrates two halves of a waveguide block to be assembled. As shown in FIG. 1, the waveguide block (also referred to as an E-plane split block) can be assembled using alignment pins to match the waveguide features on one half to the waveguide features on the other half.

[0036] A semiconductor chip can be disposed in a shallow slot in the left block bridging the gap between two waveguides. FIG. 2A illustrates a silicon chip that bridges the gap between the two waveguides. The thickness of the silicon chip can be between about 5 μm and about 100 μm depending on the design frequency. A pattern on the silicon chip includes a waveguide probe antenna on each end for coupling THz radiation onto the transmission line. The chip sits in a thin shallow cavity machined into structure containing the waveguide sections. When the waveguide block halves are assembled, a cavity in the opposite (right) block half is disposed directly on top of the chip and holds the chip in place, creating the well-defined transmission line. FIG. 2B illustrates light focused onto the transmission line of the silicon chip during operation. FIG. 2C illustrates a microscopic image of the silicon chip disposed between the two waveguides. FIG. 2D illustrates dimensions of a sample silicon chip fabricated using an etching process.

[0037] FIG. 3 illustrates the two halves of a waveguide block that have been assembled. Once assembled, the silicon chip is held securely in place, e.g. using a conductive epoxy, as the two halves of the block are assembled. For example, the two block halves can be clamped together using a number of strategically placed screws. The circular indent and the area inside it comprise a waveguide flange, which can be used to interface this waveguide component with other

waveguide components of the same waveguide band. Alignment pins on the top side allow for efficient optical alignment of a light source.

[0038] FIG. 4 illustrates an internal structure of the assembled waveguide block. As shown in FIG. 4, a lens for focusing light down onto the silicon chip is disposed in the center of the block half. The focusing lens can be screwed into the side of the waveguide block half opposite the waveguide block half containing the silicon chip. This arrangement allows for a top-down illumination of the chip through a small hole in the top wall of the chip cavity.

[0039] FIG. 5 illustrates an aluminum jig on top of the assembled waveguide block. The aluminum jig can hold a collimating lens and a light source. FIG. 6 illustrates a perspective view of internal structures of the aluminum jig and the upper waveguide block half. FIG. 7 illustrates a side view of the internal structures of the aluminum jig and the upper waveguide block half. As shown in FIG. 6, the collimating lens is disposed on top of the focusing lens, and the light source is disposed on top of the collimating lens. The light source can be a near visible or visible wavelength light source that is integrated into the device for illumination of the waveguide probe chip. The light source can be, e.g., a laser diode with an optical output power between about 50 mW and about 1 W.

[0040] FIG. 8 illustrates a side view of the focusing lens, the collimating lens and the light source, without showing the aluminum jig and the upper waveguide block half. As shown in FIG. 8, light emitted by the light source (e.g., a laser diode) is collimated by the collimating lens and further focused by the focusing lens. In some other embodiments, a similar result optimized for large dynamic range can be achieved with a single lens to produce a wider collimated beam on a larger semiconductor substrate.

[0041] FIG. 9 illustrates focused light onto the chip within the lower waveguide block half. The lens system is designed to focus as much of the light output of the light source onto the chip as possible. As shown in FIG. 9A, the light envelope can assume excellent alignment and focus. In some other embodiments, a portion of the chip can be illuminated, to provide high attenuation levels.

[0042] In some embodiments, the attenuator device operates by modulating the power produced

by the near visible or visible wavelength laser diode whose light output is focused onto the short microstrip transmission line section connecting the two waveguide probes. Through the photoconductive effect, light impinging upon the waveguide probe chip creates charge carriers inside the silicon, which temporarily change the effective dielectric constant and conductivity of the silicon substrate of the chip. FIG. 9B illustrates dynamics of charge carriers in silicon caused by photoconductive effect. The change of the conductivity causes the microstrip transmission line patterned onto the silicon wafer to become lossy, thus attenuating the electrical signals carried by the transmission line. The back-to-back waveguide probe couples radiation from the input waveguide onto this transmission line and then back into the output waveguide. In this way, the attenuation of millimeter wave signals in waveguide can be achieved through optical control.

[0043] FIG. 10 illustrates a plot of zero-illumination insertion loss versus frequency when the light source is off. The data marked as time domain gated can be derived by Fourier transforming the frequency-space data and applying a windowing filter before inverting the original Fourier transform. The window corresponds to the transmission through the entire block.

[0044] As shown in FIG. 10, measurements on a fabricated attenuator demonstrate at least about 30 dB (a factor of about 1000 in relative power) of attenuation with a “zero-attenuation” state loss of about 1.5 dB (that is the loss when the light source is off). The attenuation data is relative to the zero-attenuation state loss.

[0045] FIG. 11 illustrates plots of relative attenuations at a frequency range while being illuminated by the diode at different current levels of from 0 mA to about 1 A. FIG. 12 illustrates plots of phase shifts at a frequency range while being illuminated by the diode at different current levels of from 0 mA to about 1 A. As shown in FIGs. 11 and 12, the attenuation smoothly varies and monotonically increases with increasing light source power. The attenuation is also relatively flat and smoothly varies with signal frequency across the entirety of the WR3.4 waveguide band. Thus, the rate at which the attenuation can be changed can also be measured. By modulating a voltage controlled current source driving our laser diode, a modulation bandwidth of at least about 1 MHz can be achieved.

[0046] FIG. 13 illustrates the diode output power measured at different locations. The diode

output power measured at a plane of the bottom of the aluminum jig is marked as “Collimated.” The diode output power measured at a plane of the silicon chip is marked as “Focused.” As shown in FIG. 13, almost all collimated output power is focused onto the silicon chip. In some embodiments, about one half of the optical power is coupled onto the silicon chip due to either shifted focus or misalignment. This can be improved to increase the dynamic range. FIG. 14 illustrates the I-V curve of the diode for reference. The non-linearity of the I-V curve leads to the use of a voltage controlled current source for stable operation.

[0047] FIG. 15 illustrates plots of relative attenuations vs. optical power for different frequencies. FIG. 16 illustrates plots of phase shifts vs. optical power for different frequencies. In some embodiments, The “Focused” plot (FIGs. 13 and/or 14) can be used to calibrate the current to incident optical power relationship. The attenuation is a smooth function and monotonic function of optical power, which allows an efficient integration into a source levelling feedback loop. The ripples in the phase shift can be caused by a lack of precise vector calibration in the measurement set-up, and is not an artifact of the attenuator device itself.

[0048] FIG. 17 illustrates a modulation response of the attenuator device, compared to a current source driving the light source. The similarity in the roll-offs indicate the majority of the device roll-off is in fact caused by the current source driving the light source (e.g., laser diode or LED). For example, a 20MHz 5mW IR LED source can be used. As shown in FIG. 18, a 3dB bandwidth of more than 2MHz is measured corresponding to a carrier lifetime of about 77ns.

[0049] The sizeable attenuation and modest modulation bandwidth of the device opens a range of application opportunities. Besides use of the disclosed device as a basic low-maintenance (since the device has no moving parts) waveguide attenuator, the device has a number of possible applications. For example, the device may be operated in conjunction with a waveguide directional coupler (which taps a small amount of millimeter wave power off from a waveguide) to form a source leveling loop, allowing the stabilization of the output power of a millimeter wave source. This has applications in systems such as millimeter wave vector network analyzers or antenna beam mappers. The device may also be used as a modulator, allowing information to be encoded by modulating a millimeter-wave carrier, much like AM radio broadcasting. The device can be also used in place of traditional waveguide switches, operating both at low

switching frequency like many mechanical waveguide switches or at high switching frequency such as a PiN diode switch. Such use as a fast modulator can be applicable to lock-in mapping of millimeter wave horns and antennas.

[0050] Furthermore, the device utilizes a waveguide probe method, which allows for large achievable attenuations at low optical power, owing to the small area that is to be illuminated and simple scalability to other waveguide bands.

[0051] It is to be understood that the term “design” or “designed” (e.g., as used in “design wavelength,” “design focal length” or other similar phrases disclosed herein) refers to parameters set during a design phase; which parameters after fabrication may have an associated tolerance.

[0052] As used herein, the singular terms “a,” “an,” and “the” may include plural referents unless the context clearly dictates otherwise.

[0053] As used herein, the terms “couple,” “coupled,” and “coupling” refer to an operational connection or linking. Coupled objects can be directly connected to one another or can be indirectly connected to one another, such as via one or more other objects.

[0054] Spatial descriptions, such as “above,” “below,” “up,” “left,” “right,” “down,” “top,” “bottom,” “vertical,” “horizontal,” “side,” “higher,” “lower,” “upper,” “over,” “under,” and so forth, are indicated with respect to the orientation shown in the figures unless otherwise specified. It should be understood that the spatial descriptions used herein are for purposes of illustration only, and that practical implementations of the structures described herein can be spatially arranged in any orientation or manner, provided that the merits of embodiments of this disclosure are not deviated by such arrangement.

[0055] As used herein, the terms “approximately,” “substantially,” “substantial” and “about” are used to describe and account for small variations. When used in conjunction with an event or circumstance, the terms can refer to instances in which the event or circumstance occurs precisely as well as instances in which the event or circumstance occurs to a close approximation. For example, when used in conjunction with a numerical value, the terms can refer to a range of variation less than or equal to $\pm 10\%$ of that numerical value, such as less than or equal to $\pm 5\%$,

less than or equal to $\pm 4\%$, less than or equal to $\pm 3\%$, less than or equal to $\pm 2\%$, less than or equal to $\pm 1\%$, less than or equal to $\pm 0.5\%$, less than or equal to $\pm 0.1\%$, or less than or equal to $\pm 0.05\%$. For example, two numerical values can be deemed to be “substantially” the same if a difference between the values is less than or equal to $\pm 10\%$ of an average of the values, such as less than or equal to $\pm 5\%$, less than or equal to $\pm 4\%$, less than or equal to $\pm 3\%$, less than or equal to $\pm 2\%$, less than or equal to $\pm 1\%$, less than or equal to $\pm 0.5\%$, less than or equal to $\pm 0.1\%$, or less than or equal to $\pm 0.05\%$.

[0056] Additionally, amounts, ratios, and other numerical values are sometimes presented herein in a range format. It is to be understood that such range format is used for convenience and brevity and should be understood flexibly to include numerical values explicitly specified as limits of a range, but also to include all individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly specified.

[0057] While the present disclosure has been described and illustrated with reference to specific embodiments thereof, these descriptions and illustrations do not limit the present disclosure. It should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the present disclosure as defined by the appended claims. The illustrations may not be necessarily drawn to scale. There may be distinctions between the artistic renditions in the present disclosure and the actual apparatus due to manufacturing processes and tolerances. There may be other embodiments of the present disclosure which are not specifically illustrated. The specification and drawings are to be regarded as illustrative rather than restrictive. Modifications may be made to adapt a particular situation, material, composition of matter, method, or process to the objective, spirit and scope of the present disclosure. All such modifications are intended to be within the scope of the claims appended hereto. While the methods disclosed herein have been described with reference to particular operations performed in a particular order, it will be understood that these operations may be combined, sub-divided, or re-ordered to form an equivalent method without departing from the teachings of the present disclosure. Accordingly, unless specifically indicated herein, the order and grouping of the operations are not limitations of the present disclosure.

CLAIMS

What is claimed is:

1. An optically controlled waveguide device, comprising:
 - a first waveguide;
 - a second waveguide; and
 - a semiconductor chip positioned between the first waveguide and the second waveguide, comprising:
 - a transmission line having a first end and the second end,
 - a first waveguide probe antenna disposed adjacent to the first end of the transmission line and configured to receive a first electrical signal from the first waveguide, and
 - a second waveguide probe antenna disposed adjacent to the second end of the transmission line and configured to transmit the first electrical signal to the second waveguide;wherein the semiconductor chip is configured to absorb light illuminating the semiconductor chip and attenuate the first electrical signal transmitted between the first waveguide, the transmission line and the second waveguide based on an amount of the light being absorbed.
2. The optically controlled waveguide device of claim 1, further comprising:
 - a light source positioned to illuminate at least a portion of the transmission line.
3. The optical controlled waveguide device of claim 2, further comprising:
 - a current source configured to control a power output of the light source.
4. The optical controlled waveguide device of claim 2, further comprising:
 - a lens configured to focus light from the light source onto at least the portion of the transmission line.
5. The optical controlled waveguide device of claim 1, the light being absorbed having photons

that have energy levels higher than a bandgap energy of the semiconductor chip creates charge carriers in the semiconductor chip and increases a conductivity of the semiconductor chip through a photoconductive effect.

6. The optically controlled waveguide device of claim 1, wherein the semiconductor chip is configured to induce loss in the transmission line based on the amount of the light being absorbed.

7. The optical controlled waveguide device of claim 6, wherein
the first waveguide is configured to transmit the first electrical signal,
the semiconductor chip is configured to receive and attenuate the first electrical signal from the first waveguide with the loss induced from the light illuminating the semiconductor chip to generate an attenuated electrical signal, and
the second waveguide is configured to receive the attenuated electrical signal.

8. The optical controlled waveguide device of claim 7, wherein the attenuated electrical signal is attenuated by up to 50 dB at a frequency, compared to the first electrical signal.

9. The optical controlled waveguide device of claim 1, wherein the first waveguide and the second waveguide are configured to transmit electrical signals in a terahertz band.

10. The optical controlled waveguide device of claim 1, wherein the light being absorbed is within a near-visible or visible spectrum.

11. An optically controlled attenuator, comprising:
a light source configured to emit a light;
a first waveguide;
a second waveguide; and
a semiconductor component disposed between the first waveguide and the second waveguide, the semiconductor component comprising a transmission line and at least two

waveguide probes coupled to ends of the transmission line, the waveguide probes configured to transmit a first electrical signal from the first waveguide to the second waveguide;

wherein the semiconductor component is configured to absorb at least a portion of the light and attenuate the first electrical signal transmitted from the first waveguide to the second waveguide through the transmission line based on an amount of the light being absorbed.

12. The optically controlled attenuator of claim 11, wherein at least some photons of the light emitted from the light source have energy levels higher than a bandgap energy of the semiconductor component.

13. The optically controlled attenuator of claim 11, wherein the semiconductor component is configured to absorb at least a portion of the light emitted from the light source illuminating the semiconductor component and create charge carriers in the semiconductor component through a photoconductive effect.

14. The optically controlled attenuator of claim 13, wherein charge carriers from the photoconductive effect induce loss that attenuates the first electrical signal transmitted from the first waveguide to the second waveguide through the transmission line.

15. The optically controlled attenuator of claim 11, wherein the semiconductor component is configured to attenuate the first electrical signal by up to 50 dB at a frequency.

16. The optically controlled attenuator of claim 11, wherein the semiconductor component is configured to attenuate the first electrical signal by up to 50 dB at a frequency within a terahertz waveguide band.

17. The optically controlled attenuator of claim 11, wherein the light emitted by the light source is within a near-visible or visible spectrum.

18. A method of attenuating or modulating signals, comprising:

receiving, at a semiconductor chip coupled between a first waveguide and a second waveguide, a light illuminating at least a portion of the semiconductor chip;

coupling, by a plurality of waveguide probes of the semiconductor chip, the light to induce loss in a transmission line of the semiconductor chip; and

attenuating or modulating with the loss induced in the transmission line, by the semiconductor chip, an electrical signal transmitted from the first waveguide to the second waveguide.

19. The method of claim 18, wherein the electrical signal is attenuated linearly with a range of frequencies in a terahertz band.

20. The method of claim 18, wherein an attenuation of the electrical signal increases monotonically with an incident optical power of the light illuminating at least the portion of the semiconductor chip.

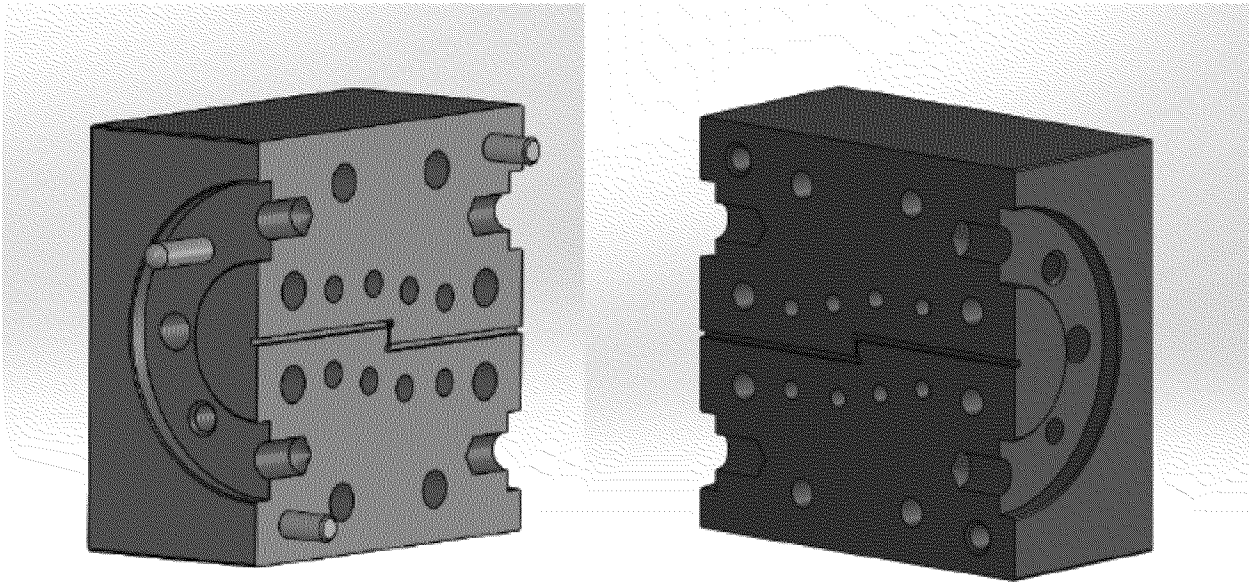


FIG. 1

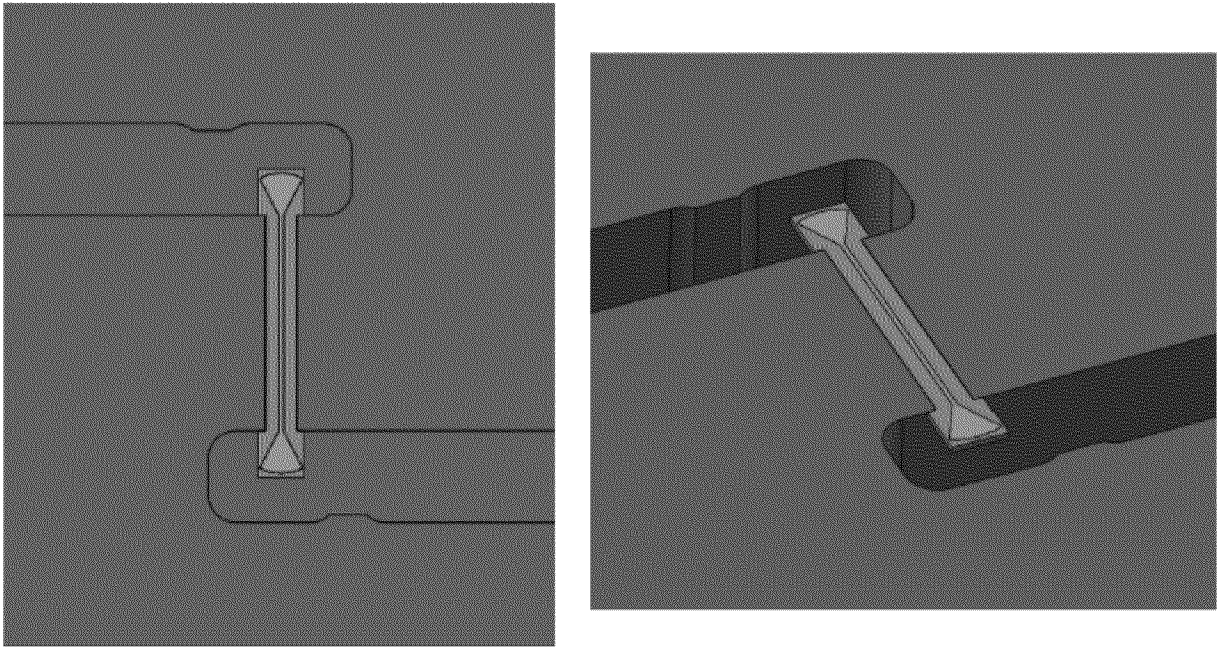


FIG. 2A

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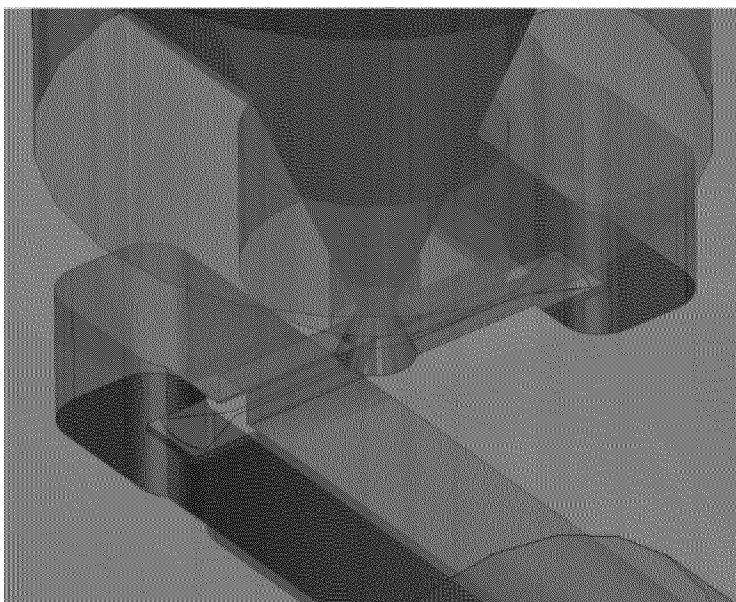


FIG. 2B

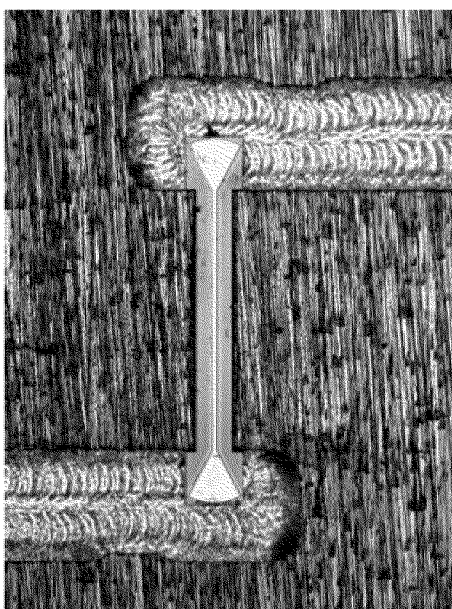


FIG. 2C

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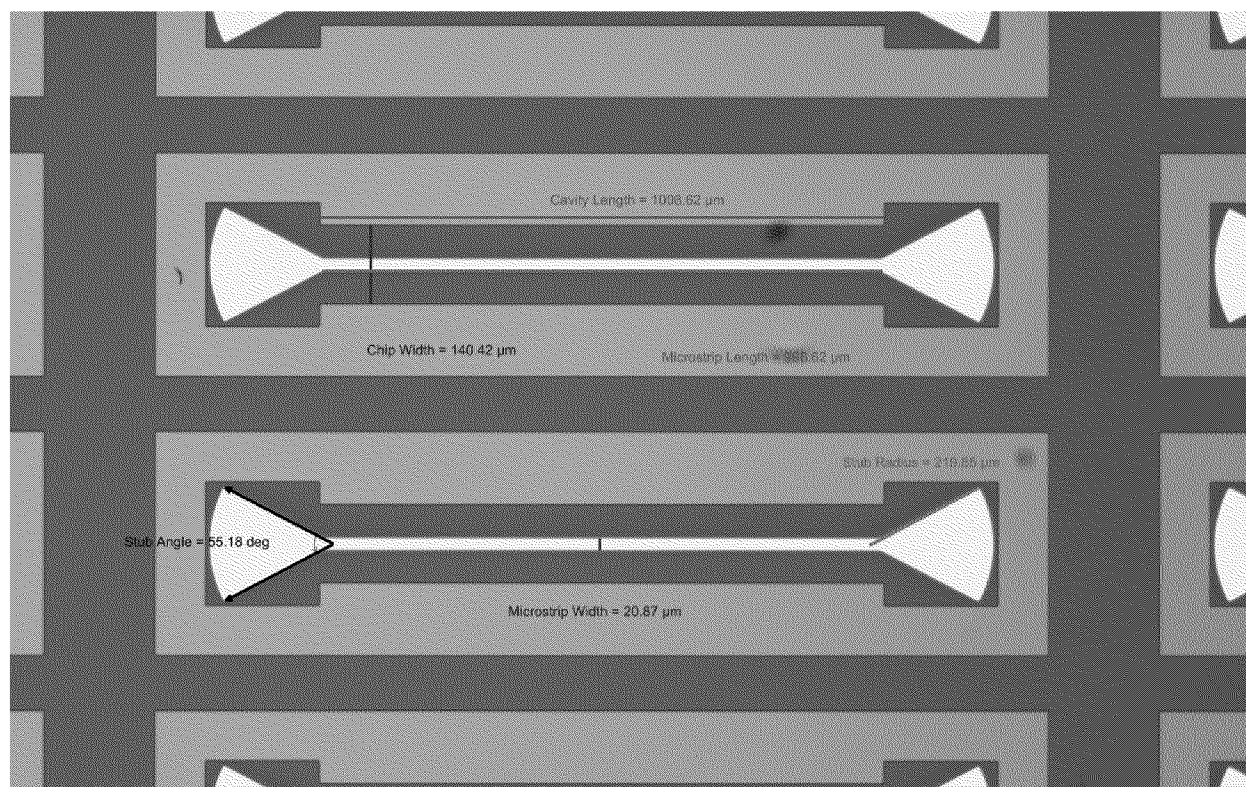


FIG. 2D

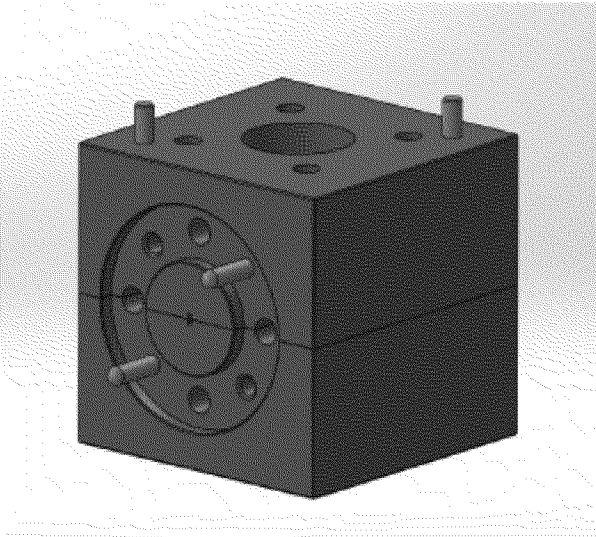


FIG. 3

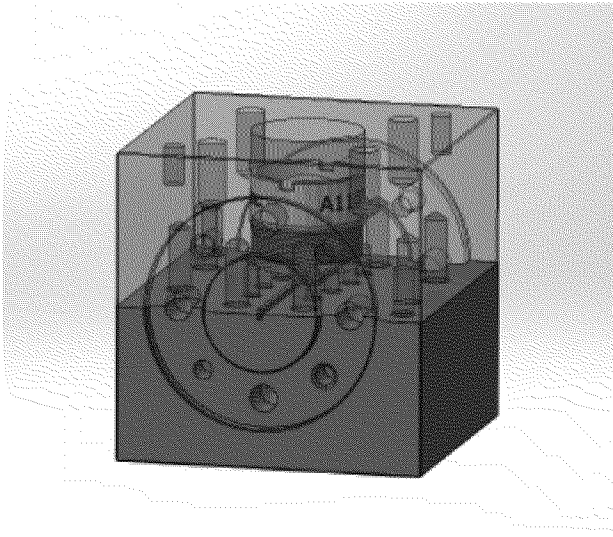


FIG. 4

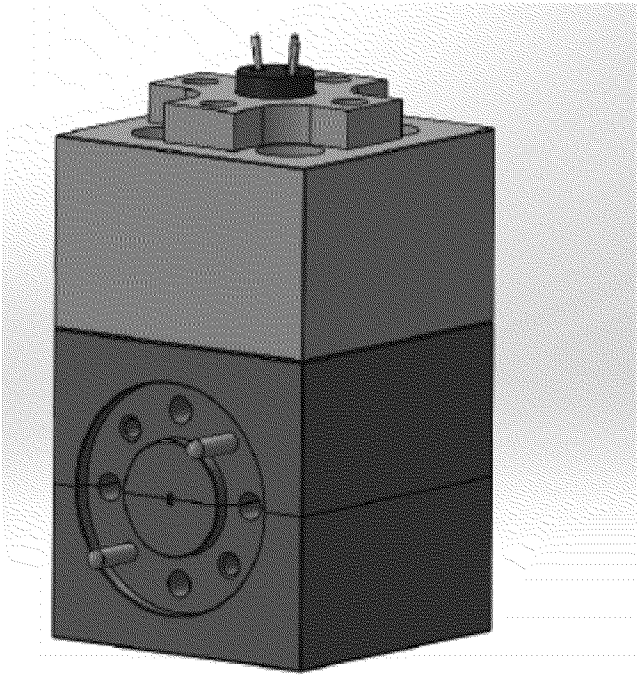


FIG. 5

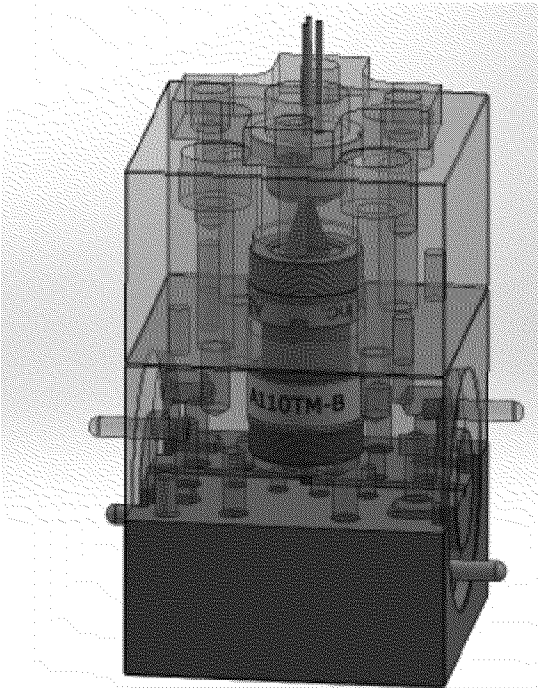


FIG. 6

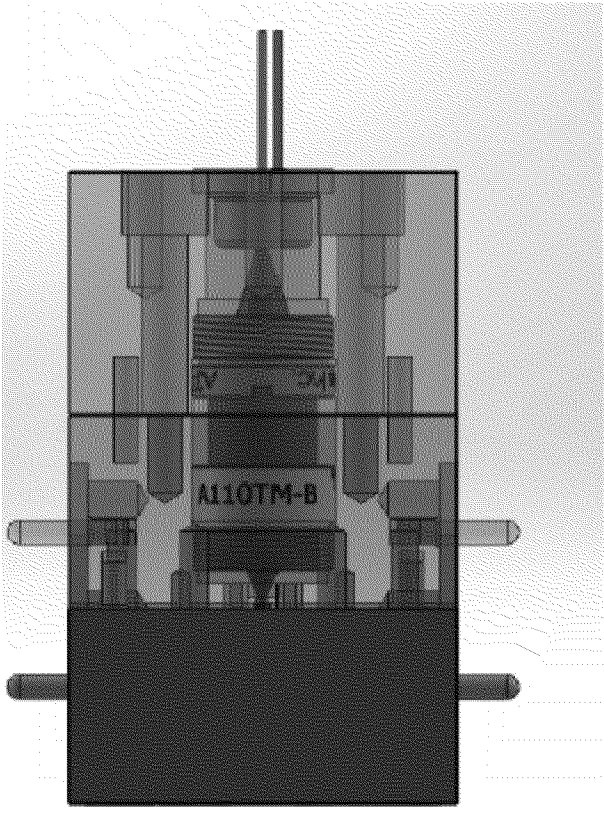


FIG. 7

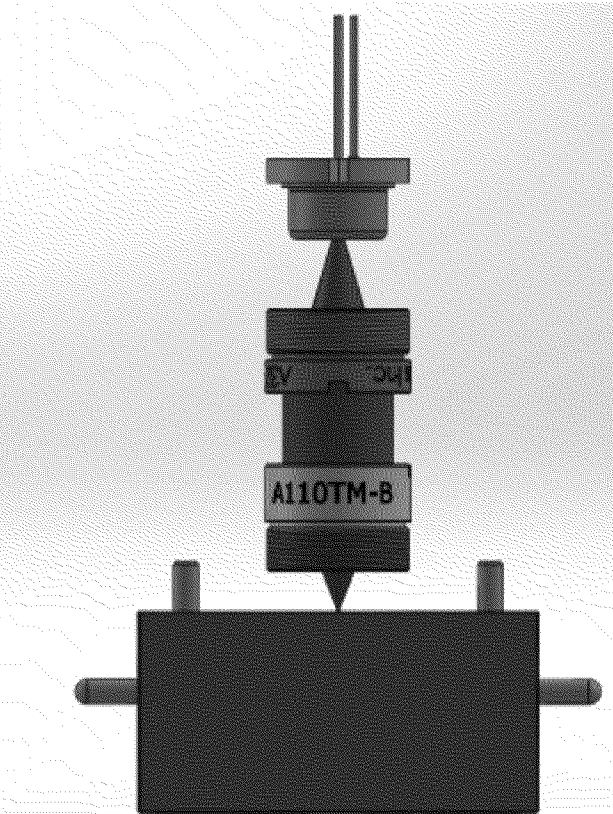


FIG. 8

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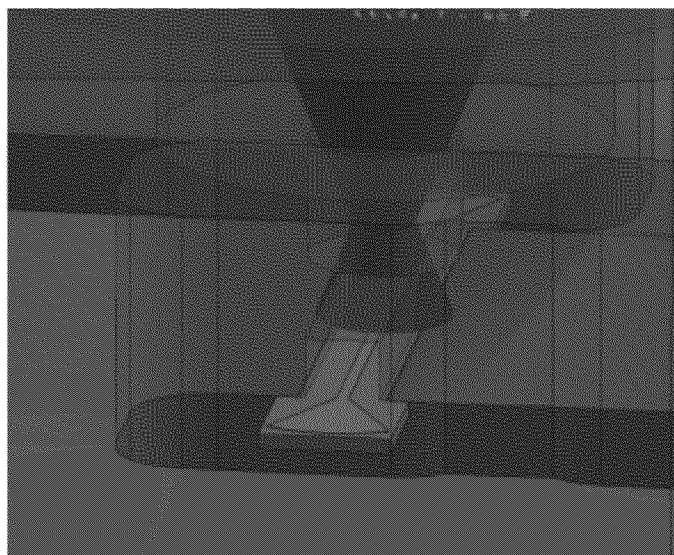


FIG. 9A

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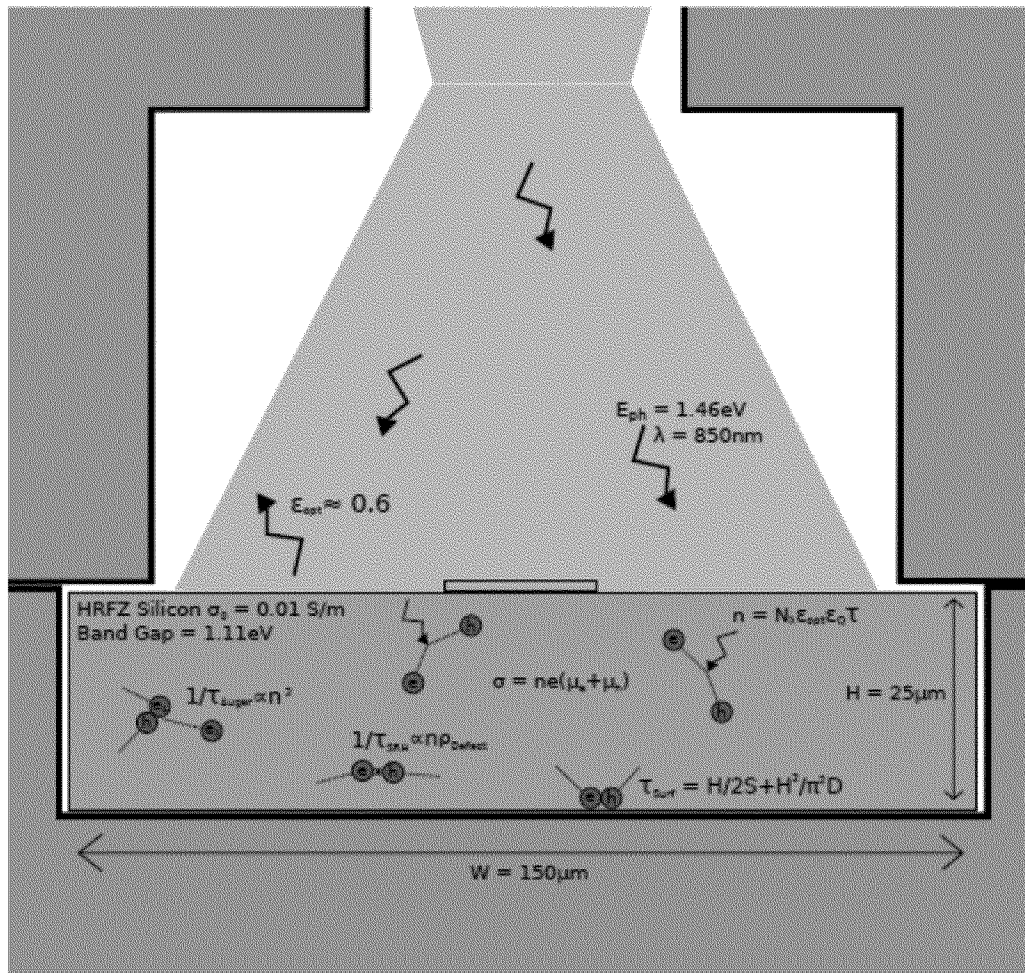


FIG. 9B

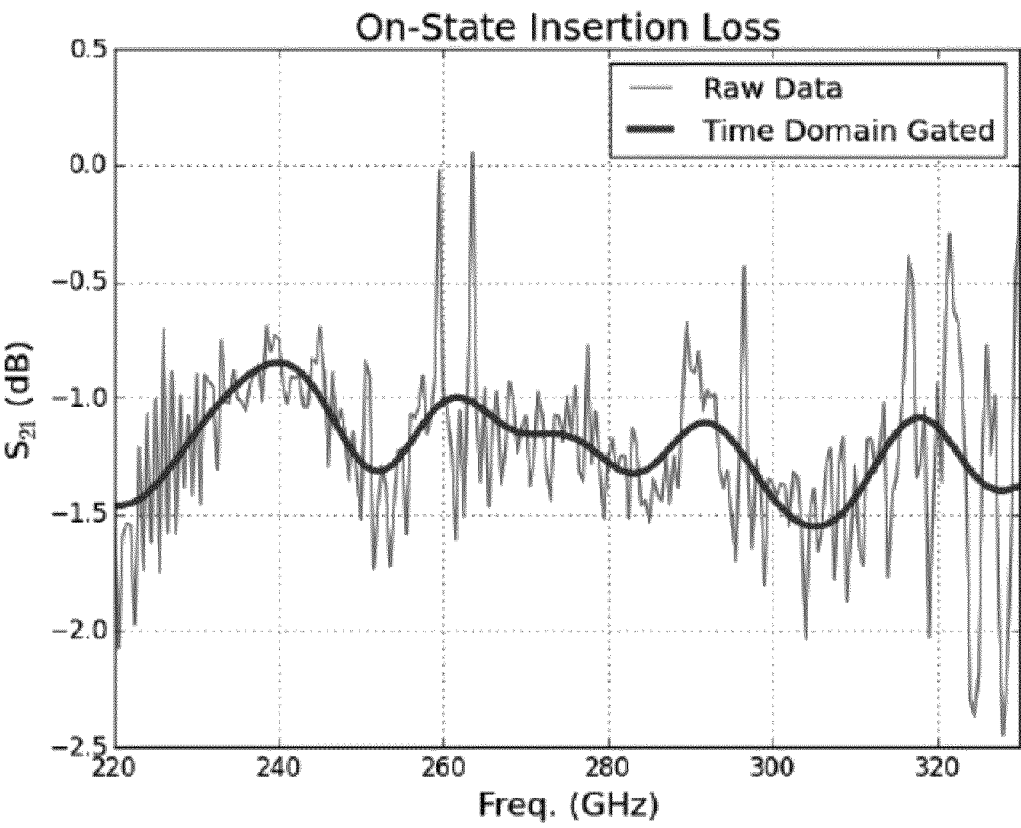


FIG. 10

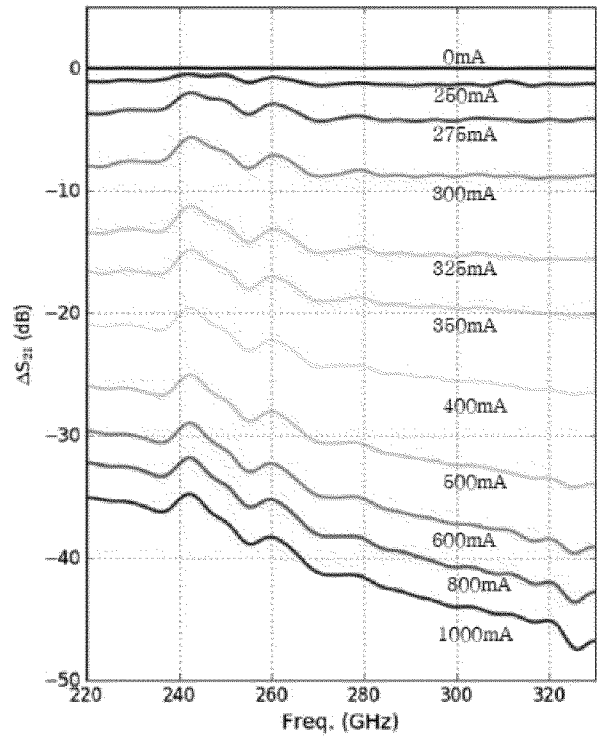


FIG. 11

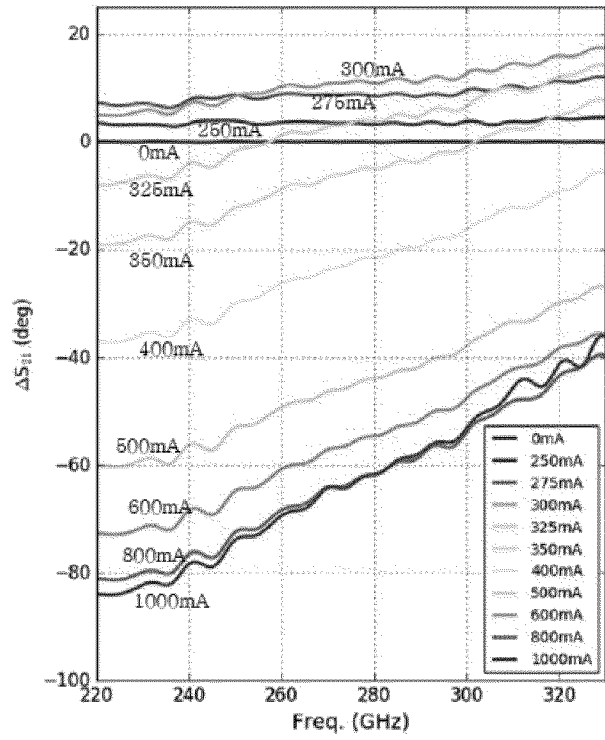


FIG. 12

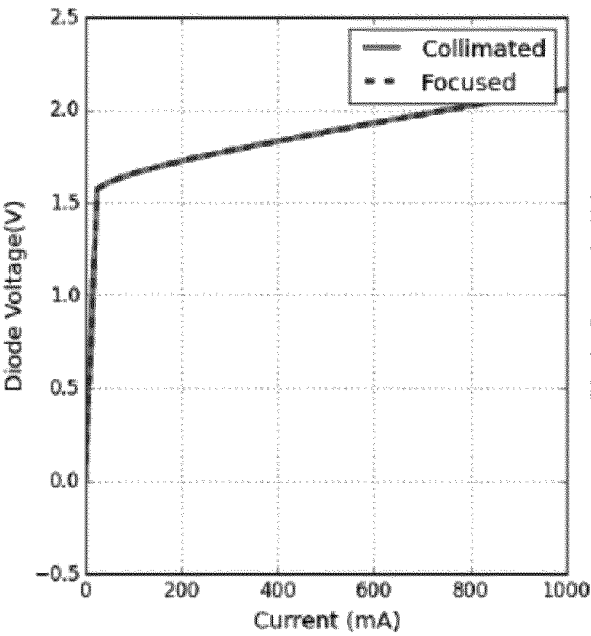


FIG. 13

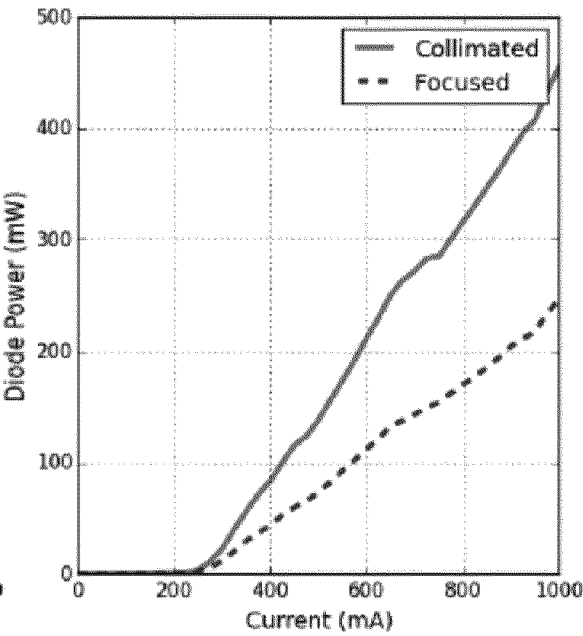


FIG. 14

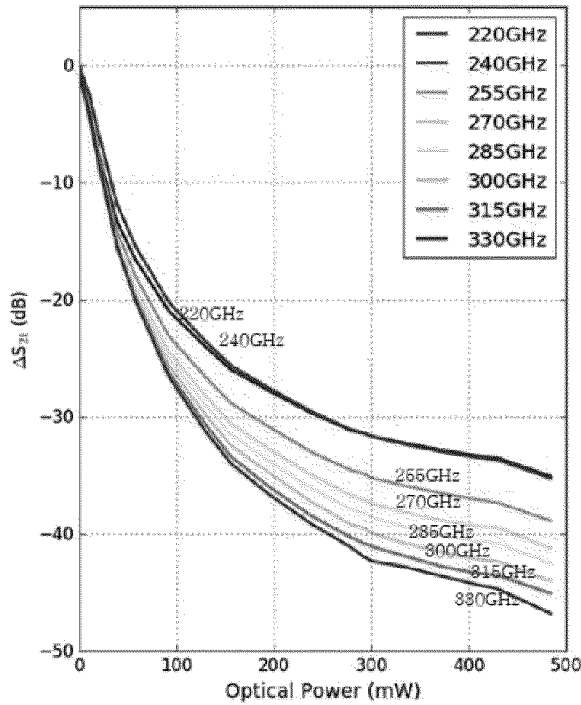


FIG. 15

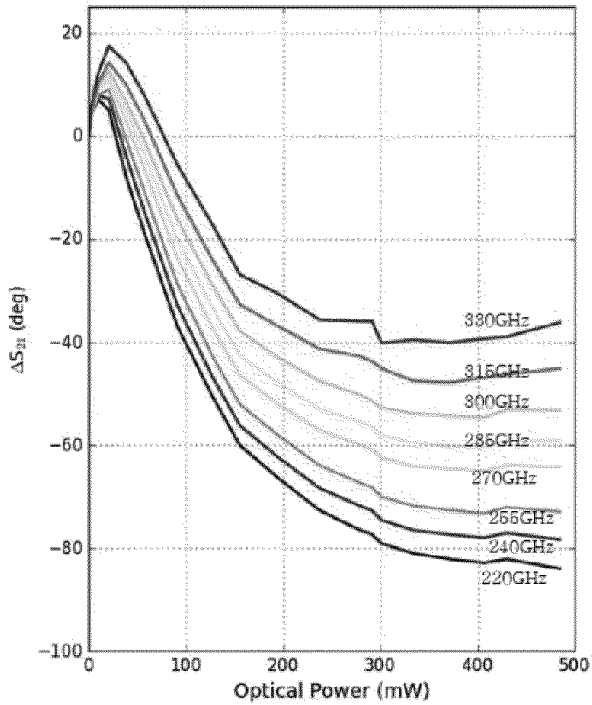


FIG. 16

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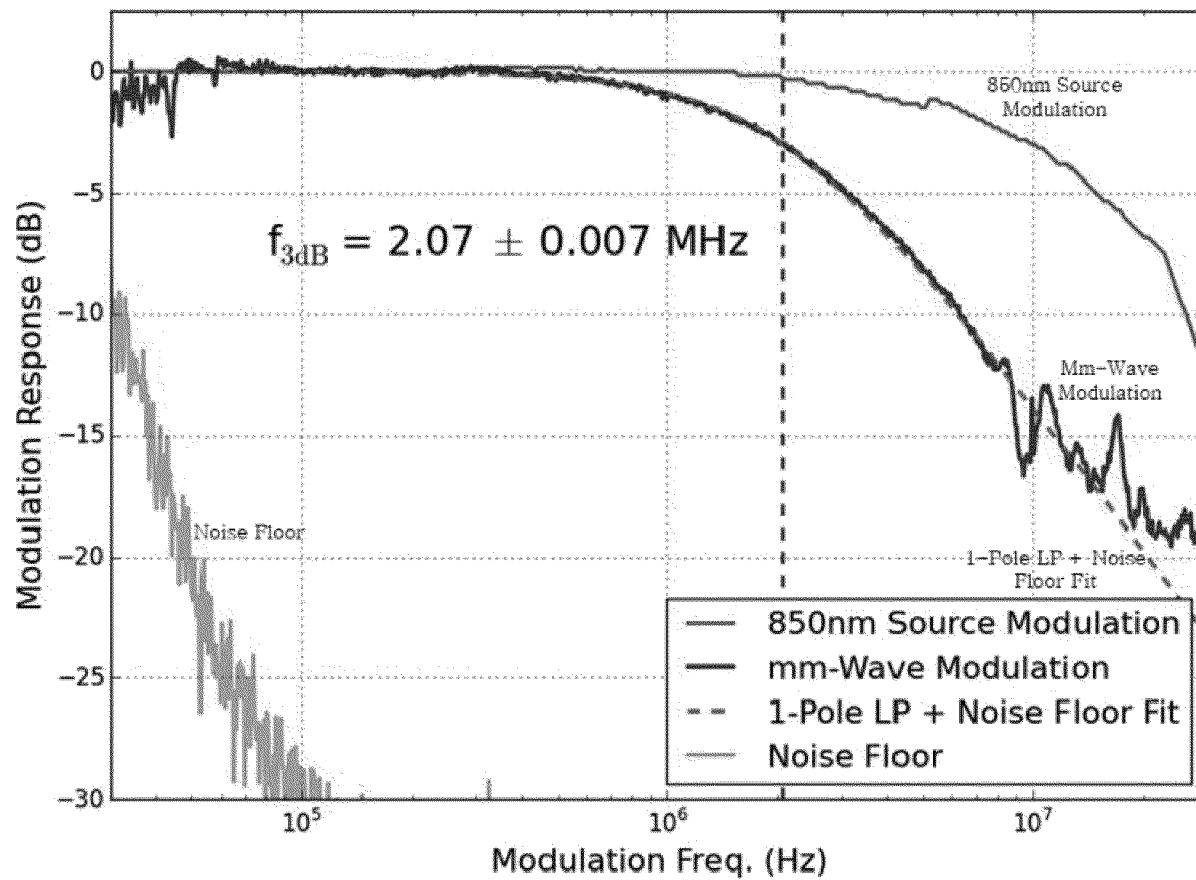


FIG. 17

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 18/22486

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H04B 7/00 (2018.01)

CPC - H04B 7/02; H04B 3/52; H05K 1/0239; H05K 1/024; H01Q 3/2658; H01Q 21/068; H01Q21/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History Document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

See Search History Document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History Document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y ---	YU, Bo et al., "High Efficiency Micromachined Sub-THz Channels for Low Cost Interconnect for Planar Integrated Circuits." escholarship.org, 01 January 2016, pp 2-9	1-3, 5-18, 20
A	[online][retrieved on 2018-05-17] <URL: https://cloudfront.escholarship.org/dist/prd/content/qt9vm907zv/qt9vm907zv.pdf>	4, 19
Y ---	JIANG, Zhenguo et al., "Investigation and Demonstration of a WR-4.3 Optically Controlled Waveguide Attenuator." IEEE Transactions on Terahertz Science and Technology, Vol. 7, No. 1, 01 January 2017, pp 20-25	1-3, 5-18, 20
A	[online][retrieved on 2018-05-16]<URL: https://ieeexplore.ieee.org/abstract/document/7801980/>	4, 19
A	US 2012/0306587 A1 (STRID et al.) 06 December 2012 (6.12.2012), entire document	1-20
A	US 2016/0149312 A1 (AT&T INTELLECTUAL PROPERTY I, L.P.) 26 May 2016 (26.05.2016), entire document	1-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

22 May 2018

Date of mailing of the international search report

20 JUN 2018

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