

TRAVELING WAVE ELECTRODE MODULATOR AND PHOTONIC

INTEGRATED CHIP

TECHNICAL FIELD

[001] The present disclosure relates to the field of optical communication
5 technology and, more particularly, to a traveling wave electrode modulator and a
photonic integrated chip.

BACKGROUND

[002] In silicon-based integrated optoelectronic systems, traveling wave
electrode modulators are widely used due to their higher extinction ratio and ease of
10 integration. The traveling wave electrode modulators are usually manufactured as
silicon-based electro-optical modulators based on silicon-on-insulator (SOI)
technology. A traveling wave electrode modulator manufactured based on the SOI
technology is generally composed of an optical waveguide load and traveling wave
electrodes. An electromagnetic wave propagates between the traveling wave
15 electrodes, and an optical carrier wave propagates in a loaded optical waveguide.
As the optical carrier wave and the electromagnetic wave propagate, interactions
between the electromagnetic wave and the optical carrier wave cause a change in a
phase of the optical carrier wave, thereby completing a modulation from an
electrical signal to an optical signal. Main performance indicators of a traveling
20 wave electrode modulator are its electro-optical bandwidth and impedance. A

higher electro-optical bandwidth and an appropriate impedance are usually desired in a design. Two main factors affect the electro-optical bandwidth: the first factor is the loss in a loaded traveling wave electrode, and the second factor is a matching degree between a group velocity of a microwave and a group velocity of an optical carrier of the traveling wave electrode modulator. In actual use, the propagation speed of an electromagnetic wave in the traveling wave electrode is different from the propagation speed of an optical wave in an optical waveguide, and the former speed is typically higher than the latter speed. Therefore, there is a certain degree of mismatch between the electromagnetic wave and the optical wave. As a result of the mismatch, in a modulation process, a high-speed signal, cannot fully interact with an optical wave which it met when entering the traveling wave electrode in the entire process. This leads to a reduced electro-optical modulation bandwidth of the traveling wave electrode modulator overall, thereby apparently lowering performance of the modulator overall.

15 SUMMARY

Technical Problem

Solution of the Problem

Technical Solution

[003] Objects of the present disclosure are to provide a traveling wave
20 electrode modulator and a photonic integrated chip that have a higher degree of

electro-optical matching and are capable of providing a higher electro-optical modulation bandwidth.

[004] In order to achieve one aspect of the aforementioned objects, the present disclosure provides a traveling wave electrode modulator including a silicon
5 base, an optical waveguide disposed in the silicon base, a doped transitional area disposed on both sides of the optical waveguide and connected to the optical waveguide, and a traveling wave electrode structure electrically connected to the transitional area. The traveling wave electrode structure includes at least one layer of a continuous electrode continuously extending along a direction of extension of
10 the optical waveguide, at least one layer of a periodic electrode periodically changing along the direction of extension of the optical waveguide, and a conductive structure. The continuous electrode is electrically connected to the periodic electrode via the conductive structure, and the traveling wave electrode structure is electrically connected to the transitional area via the conductive
15 structure.

[005] As a further improvement of an embodiment, the traveling wave electrode structure includes two or more layers of the periodic electrode, and/or two or more layers of the continuous electrode.

[006] As a further improvement of the embodiment, the periodic electrode
20 and the continuous electrode are disposed in an alternating manner, or the two or more layers of the periodic electrode are disposed in an adjacent manner.

[007] As a further improvement of the embodiment, structural parameters of the periodic electrode at different layers are identical or different; and the structural parameters include a period and a duty cycle.

[008] As a further improvement of the embodiment, the continuous
 5 electrode and the periodic electrode each include a signal electrode and a ground electrode; and there is an electrode spacing distance between the signal electrode and the ground electrode at a same layer, and electrode spacing distances at different layers may be identical or different.

[009] As a further improvement of the embodiment, the conductive
 10 structure includes a conductive via.

[010] As a further improvement of the embodiment, the silicon base includes a silicon substrate, an insulation layer, and an optical waveguide layer which are layered sequentially, the optical waveguide and the transitional area are located in the optical waveguide layer, and the traveling wave electrode structure is
 15 disposed above the optical waveguide layer.

[011] As a further improvement of the embodiment, a groove is provided at a surface of the silicon substrate near the insulation layer, the groove being located below the optical waveguide and disposed along the optical waveguide;

[012] or, a channel penetrating through a top surface and a bottom surface
 20 of the silicon substrate is disposed in an area of the silicon substrate below the optical waveguide.

[013] As a further improvement of the embodiment, a cover layer is disposed on the optical waveguide layer, and the traveling wave electrode structure is disposed in the cover layer.

[014] The present disclosure further provides a photonic integrated chip including the traveling wave electrode modulator of any of the embodiments described above.

Beneficial Effects of the Invention

Beneficial Effects

[015] The present disclosure provides the following benefits: with addition of the electrode designed in a periodic pattern on the traveling wave electrode structure, a greater number of designable parameters are provided, flexibility in a design of the traveling wave electrode structure is increased, and a higher matching degree between the propagation speed of electromagnetic waves and the propagation speed of optical waves may be provided, thus effectively increasing an electro-optical modulation bandwidth of the modulator.

BRIEF DESCRIPTION OF THE DRAWINGS

Description of the Drawings

[016] FIG. 1 is a diagram illustrating a commonly used optical modulation system.

[017] FIG. 2 is a diagram illustrating a cross section of a modulator according to a first embodiment of the present disclosure.

[018] FIG. 3 is a diagram illustrating electromagnetic field distribution in a modulator of the present disclosure.

[019] FIG. 4 is a structural diagram illustrating the modulator according to the first embodiment of the present disclosure.

5 [020] FIG. 5 is a structural diagram illustrating a modulator according to a second embodiment of the present disclosure.

[021] FIG. 6 illustrates a cross-sectional view of an A-A line in FIG. 5.

[022] FIG. 7 is a diagram illustrating a variant of an electrode structure of the modulator according to the second embodiment of the present disclosure.

10 [023] FIG. 8 is a diagram illustrating another variant of the electrode structure of the modulator according to the second embodiment of the present disclosure.

[024] FIG. 9 is a structural diagram illustrating a modulator according to a third embodiment of the present disclosure.

15 [025] FIG. 10 is a diagram illustrating a variant of a structure of the modulator according to the third embodiment of the present disclosure.

EMBODIMENTS OF THE INVENTION

Embodiments of the invention

[026] The text below provides a detailed description of the present
20 disclosure in conjunction with specific embodiments illustrated in the attached drawings. However, these embodiments do not limit the present disclosure. The

scope of protection for the present disclosure covers changes made to the structure, method, or function by persons having ordinary skills in the art on the basis of these embodiments.

[027] In order to facilitate the presentation of the drawings in the present disclosure, sizes of certain structures or portions have been enlarged relative to other structures or portions. Therefore, the drawings in the present disclosure are only for the purpose of illustrating a basic structure of the subject matter of the present disclosure.

[028] Additionally, terms in the text indicating relative spatial position, such as “on,” “above,” “under,” “below,” and so forth, are used for explanatory purposes to describe a relationship between a unit or feature and another unit or feature as depicted in a drawing. Terms indicating relative spatial position may include positions of a device when being used or operated, other than those depicted in the drawings. For example, if a device shown in a drawing is flipped over, a unit which is described as being positioned “below” or “under” another unit or feature will be located “above” the another unit or feature. Therefore, the illustrative term “below” may include positions both above and below. The device may be oriented in other ways (rotating 90 degrees or facing another direction), and descriptive terms relating to space as used herein should be interpreted accordingly. When a component or layer is said to be “on” another member or layer or “connected to” another member or layer, it may be directly on the another member or layer or

directly connected to the another member or layer, or there may be an intermediate component or layer.

[029] Traveling wave electrode modulators are categorized into unipolar drive and bipolar drive by their drive mode, and into a series push-pull structure, a
 5 separate dual-arm structure, and other structures by their optical waveguide layout. As illustrated in FIG. 1, a general traveling wave electrode modulation system mainly includes a driver 200 and a traveling wave electrode modulator 100. Silicone-based traveling wave electrode modulators have become a top option because of their characteristics of being capable of obtaining a higher extinction
 10 ratio and easier to integrate. The silicon-based traveling wave electrode modulators are manufactured mainly based on CMOS-SOI technology, using complementary metal-oxide-semiconductor (CMOS) on the basis of silicon-on-insulator (SOI). FIG. 2 illustrates a cross-section of a modulation area of the traveling wave electrode modulator 100 manufactured based on the CMOS-SOI technology. The
 15 traveling wave electrode modulator 100 includes a silicon substrate 10, an insulation layer 20, and an optical waveguide layer 30 which are layered sequentially, and a traveling wave electrode structure 40 disposed above the optical waveguide layer 30. An insulating cover layer 50 may also be disposed on the optical waveguide layer 30. Here, the silicon substrate 10 generally uses low
 20 resistivity silicon; the insulation layer 20 generally uses an insulating oxide, such as silicon dioxide; and the optical waveguide layer 30 is generally formed by etching a top-layer silicon in SOI, and the optical waveguide layer 30 includes an optical

waveguide 31 and a transitional area 32 formed by doping on both sides of the
 optical waveguide 31. After the optical waveguide 31 is formed by etching the top-
 layer silicon, the transitional area 32 is formed by doping both sides of the optical
 waveguide 31 using semiconductor doping technology to form a PN junction at the
 5 optical waveguide 31. Then a dielectric material and a metal material are deposited
 on the optical waveguide layer 30 using CMOS technology, to form the cover layer
 50, metal layers deposited inside the cover layer 50 and on a top surface of the
 cover layer 50, and a conductive structure connecting the metal layers. In a process
 of depositing the metal material, the metal layers and the conductive structure are
 10 deposited according to a design of the traveling wave electrode structure to form a
 traveling wave electrode 42 and an electrically conductive structure 41. The
 traveling wave electrode 42 is electrically connected to the transitional area 32 on
 the both sides of the optical waveguide 31 via the conductive structure 41, and a
 plurality of metal layers may be deposited inside the cover layer 50 as needed to
 15 form two or more layers of the traveling wave electrode.

[030] The operating principle of the traveling wave electrode modulator is
 as follows: the driver 200 is electrically connected to the traveling wave electrode
 modulator 100 via bonding wires; the optical waveguide 31 is placed in an electric
 field of the traveling wave electrode structure 40; a high-speed digital signal is
 20 outputted from the driver 200, goes to the traveling wave electrode modulator 100,
 and propagates along electrodes of the traveling wave electrode structure 40; and an
 optical wave propagates in the optical waveguide 31. As illustrated in FIG. 3, the

digital signal is applied to the transitional area 32 on both sides of the optical waveguide 31 via the traveling wave electrode 42 and the electrically conductive structure 41, respectively, forming an electromagnetic field (represented by arrow-headed lines in FIG. 3) in the PN junction; at the same time, an electromagnetic

5 field between an adjacent signal electrode S and ground electrode G is very weak, resulting in little loss. A change of the electric field caused by the high-speed digital signal in the traveling wave electrode structure 40 changes the electromagnetic field in the PN junction, thereby changing concentration of charge carriers in the optical waveguide 31 to cause an effective refractive index of the optical waveguide 31 to

10 change. Therefore, when the high-speed digital signal propagates on the traveling wave electrode structure 40, the electric field of the high-speed digital signal causes the refractive index of the optical waveguide 31 to change and thereby changes a phase of optical carriers, causing the optical carriers to carry information from the digital signal. The optical carriers interfere in a Mach-Zehnder interferometer at a

15 rear end and thereby complete modulation.

[031] In the application, during the depositing process of the traveling wave electrode, an electrode with a periodic structure along a waveguide direction is formed by depositing different patterns at different metal layers in an alternating manner, and the periodic structure may slow down the propagation speed of an

20 electromagnetic wave. By controlling a number of the deposited metal layers and sizes of the patterns of the deposited metal layers, a matching degree between the electromagnetic wave and an optical wave is higher, thereby increasing a

modulation bandwidth of the traveling wave electrode modulator. Details are provided in the following embodiments.

[032] Embodiment 1

[033] As illustrated in FIGS. 2 and 4, the embodiment provides the
5 traveling wave electrode modulator 100 including the silicon base 300, the optical waveguide 31 disposed in the silicon base 300, the doped transitional area 32 disposed on both sides of the optical waveguide 31 and connected to the optical waveguide 31, and the traveling wave electrode structure 40 electrically connected to the transitional area 32. Here, the silicon base 300 uses a silicon-on-insulator
10 (SOI) structure and includes the silicon substrate 10, the insulation layer 20, and the optical waveguide layer 30 which are layered sequentially. Wherein, the optical waveguide layer 30 is formed by etching the top-layer silicon of the SOI structure and includes the optical waveguide 31 and the transitional area 32 formed by semiconductor doping on both sides of the optical waveguide 31; and the traveling
15 wave electrode structure 40 is disposed above the optical waveguide layer 30. The cover layer 50 is disposed between the optical waveguide layer 30 and the traveling wave electrode structure 40, and between various electrodes at different layers. In FIG. 4, the cover layer is omitted to clearly show a structure of the various electrodes at different layers. Here, the cover layer may be of a dielectric material,
20 such as silicon dioxide. In other embodiments, the cover layer may not be needed when the conductive structure is sufficient to support the various layers of the electrodes, in other words, air serves as the dielectric material between the optical

waveguide layer and the traveling wave electrode structure. The aforementioned traveling wave electrode structure 40 includes at least one layer of the continuous electrode 42 continuously extending along a direction of extension of the optical waveguide 31, at least one layer of a periodic electrode 43 periodically changing
 5 along the direction of extension of the optical waveguide 31, and the conductive structure 41. The continuous electrode 42 is electrically connected to the periodic electrode 43 via the conductive structure 41, and the traveling wave electrode structure 40 is electrically connected to the transitional area 32 via the conductive structure 41.

10 [034] In the embodiment, the traveling wave electrode structure 40 includes one layer of the continuous electrode 42, one layer of the periodic electrode 43, and the conductive structure 41. Here, the conductive structure 41 includes a conductive via that electrically connects the continuous electrode 42 and the transitional area 32, as well as a conductive via that electrically connects the
 15 continuous electrode 42 and the periodic electrode 43. Here, the conductive structure 41 between the continuous electrode 42 and transitional area 32 may be conductive vias arranged at intervals along a lengthwise direction of the continuous electrode 42, or a continuous bar-shaped conductive structure. A height spacing distance (height of the conductive structure) between the continuous electrode 42
 20 and the transitional area 32 may be made as small as possible. Given limitations associated with manufacturing technology and condition, the height spacing distance may be configured to be an extreme spacing distance as limited by the

manufacturing technology and condition, for example, 0.1 μm , or slightly larger than the extreme spacing distance, for example, between 0.1 μm and 10 μm . The continuous electrode 42 enables an electromagnetic wave to propagate along the direction of extension of the optical waveguide 31. The periodic electrode 43 slows
5 down the propagation speed of the electromagnetic wave to increase a matching degree between the propagation speed of the electromagnetic wave and the propagation speed of an optical wave propagating in the optical waveguide 31, thereby increasing a modulation bandwidth of the traveling wave electrode modulator. In the embodiment, the periodic electrode 43 is located above the
10 continuous electrode 42, with a period of the periodic electrode 43 in a range of 50 μm - 100 μm and a duty cycle of the periodic electrode 43 in a range of 90-99. In other embodiments, the period and the duty cycle of the periodic electrode may be designed in consideration of impact of other specific parameters of the modulator on the propagation speed of the electromagnetic wave, in order to achieve a higher
15 matching degree between the electromagnetic wave propagating on the traveling wave electrode structure and the optical wave propagating in the optical waveguide.

[035] In the embodiment, the traveling wave electrode structure 40 adopts a GS traveling wave electrode, and the continuous electrode 42 and periodic electrode 43 of the traveling wave electrode structure 40 each include the signal
20 electrode S and the ground electrode G. Of course, in other embodiments may optionally use different types of electrodes, such as GSG or GSSG. There is an electrode spacing distance between the signal electrode S and the ground electrode

G at a same layer (formed from a metal layer at a same height), and electrode spacing distances between different electrodes at different layers may be identical or different. In the embodiment, there is an electrode spacing distance D1 between the signal electrode S and the ground electrode G of the continuous electrode 42;

5 there is an electrode spacing distance D2 between the signal electrode S and the ground electrode G of the periodic electrode 43; and the electrode spacing distance D1 is identical to the electrode spacing distance D2. In other embodiments, the electrode spacing distances at different layers may be different. Widths (perpendicular to the direction of extension of the optical waveguide 31) of electrodes at different layers may be identical or different. The traveling wave electrode structure 40 that includes at least one layer of the continuous electrode 42 and at least one layer of the periodic electrode 43 adds a plurality of flexibly designable parameters that affect the propagation speed of the electromagnetic wave, such as the period, the duty cycle, the electrode spacing distance, the electrode width, and the conductive via, thereby enhancing design flexibility of the modulator and enabling a higher matching degree between the electromagnetic wave and the optical wave propagating in the optical waveguide. As a result, a higher modulation bandwidth for the traveling wave electrode modulator is achieved.

20 [036] Embodiment 2

[037] As illustrated in FIGS. 5 and 6, the embodiment differs from Embodiment 1 in that the traveling wave electrode structure 40 includes two layers

of the continuous electrodes 42 and two layers of the periodic electrodes 43, and that the periodic electrodes 43 and the continuous electrodes 42 are disposed in an alternating manner. In FIGS. 5 and 6, the cover layer is omitted to clearly show a structure of the various electrodes at different layers. The periods and duty cycles of the periodic electrodes 43 at different layers may be identical or different, and the electrode spacing distances between the signal electrode S and the ground electrode G of electrodes at different layers may be identical or different, all of which may be designed according to an actual structure of the modulator to achieve a full matching between the propagation speed of the electromagnetic wave and the propagation speed of the optical wave.

[038] In other embodiments, an arrangement sequence of various layers of the periodic electrodes and the continuous electrodes may be designed based on actual needs, rather than in an alternating manner. As illustrated in FIG. 7, above the transitional area 32, two layers of the periodic electrodes 43 and two layers of the continuous electrode 42 are connected by the conductive structure 41 sequentially. Of course, optionally, the layers of electrodes may be electrically connected by the conductive structure in an alternating manner, in other words, skip an adjacent electrode and are electrically connected to an electrode in a higher-level layer. As illustrated in FIG. 8, the transitional area 32 is electrically connected to the continuous electrode 42 at a first layer via the conductive structure 41, the continuous electrode 42 at the first layer skips the periodic electrode 43 in a second layer and is electrically connected to the continuous electrode 42 in a third layer,

and the continuous electrode 42 in the third layer is then electrically connected to the periodic electrodes 43 in the second and a fourth layer, respectively. In other words, electrical connection ways among electrodes at different layers are not limited, and different electrical connection ways may be designed according to actual needs. Of course, additional layers of the continuous electrodes and/or additional layers of the periodic electrodes may be configured, and a number of layers of the continuous electrodes and a number of layers of the periodic electrodes may be different. For example, two layers of the continuous electrodes and three layers of the periodic electrodes may be configured.

10 [039] Embodiment 3

 [040] As illustrated in FIG. 9, on the basis of any of the embodiments described above, the embodiment adds a groove 11 at a surface of the silicon substrate 10 near the insulation layer 20, the groove 11 being located below the optical waveguide 31 and disposed along the optical waveguide 31. By providing the groove 11 on the silicon substrate 10 below the optical waveguide 31, i.e., hollowing a portion of the silicon substrate 10 below the optical waveguide 31 and thus forming a hollow structure between the silicon substrate 10 and the insulation layer 20, electromagnetic field distribution in the silicon substrate 10 may be reduced, thereby reducing loss of the electromagnetic field in a substrate layer to reduce microwave loss of the traveling wave electrode, which may further improve an electro-optical bandwidth of the electro-optical modulator. Here, a shape of a cross-sectional area of the groove 11 may vary depending on actual manufacturing

technology. For example, the cross-section area of the groove 11 is a rectangle, as illustrated in FIG. 9. In other embodiments, the cross-section area of the groove 11 may be a semi-elliptical or other regular or irregular shapes. Of course, the groove may be filled with a lossless dielectric material, such as silicon dioxide, ceramic,

5 resin, and glue, to increase mechanical strength of the modulator.

[041] In other embodiments, the aforementioned groove may optionally be a channel that penetrates through the silicon substrate. As illustrated in FIG. 10, a channel 12 penetrating through a top surface and a bottom surface of the silicon substrate 10 is formed by hollowing an area of the silicon substrate 10 below the optical waveguide 31, in order to reduce the loss of the electromagnetic field in the substrate layer, thereby reducing the microwave loss of the traveling wave electrode, which may further improve the electro-optical bandwidth of the electro-optical modulator. Of course, the channel 12 may optionally be filled with a lossless dielectric material, such as silicon dioxide, ceramic, resin, and glue, to increase the

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15 mechanical strength of the modulator.

[042] Embodiment 4

[043] The embodiment provides a photonic integrated chip, the photonic integrated chip integrating into it the traveling wave electrode modulator in Embodiments 1-3. The photonic integrated chip may also be designed to include

20 active or passive optical devices, such as a photodetector, a wavelength division multiplexer/demultiplexer, a coupler, and/or a mode size converter.

[044] The series of detailed descriptions above is only intended to provide specific descriptions of feasible embodiments of the present disclosure. They are not to be construed as limiting the protection scope of the present disclosure. All equivalent embodiments or changes that are not detached from the spirit of the technology of the present disclosure should fall under the protection scope of the present disclosure.

CLAIMS

1. A traveling wave electrode modulator comprising: a silicon base, an optical waveguide disposed in the silicon base, a doped transitional area disposed
5 on both sides of the optical waveguide and connected to the optical waveguide, and a traveling wave electrode structure electrically connected to the transitional area; wherein: the traveling wave electrode structure comprises at least one layer of a continuous electrode continuously extending along a direction of extension of the optical waveguide, at least one layer of a periodic electrode periodically changing
10 along the direction of extension of the optical waveguide, and a conductive structure; and the continuous electrode is electrically connected to the periodic electrode via the conductive structure, and the traveling wave electrode structure is electrically connected to the transitional area via the conductive structure.
- 15 2. The traveling wave electrode modulator of claim 1, wherein the traveling wave electrode structure comprises two or more layers of the periodic electrodes, and/or two or more layers of the continuous electrodes.
- 20 3. The traveling wave electrode modulator of claim 2, wherein the periodic electrode and the continuous electrode are disposed in an alternating manner, or the two or more layers of the periodic electrodes are disposed in an adjacent manner.

4. The traveling wave electrode modulator of claim 2, wherein structural parameters of the periodic electrodes at different layers are identical or different; and the structural parameters comprise a period and a duty cycle.

5 5. The traveling wave electrode modulator of claim 1, wherein: the continuous electrode and the periodic electrode each comprise a signal electrode and a ground electrode; and there is an electrode spacing distance between the signal electrode and the ground electrode at a same layer, and electrode spacing distances at different layers are identical or different.

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6. The traveling wave electrode modulator of claim 1, wherein the conductive structure comprises a conductive via.

7. The traveling wave electrode modulator of claim 1, wherein: the silicon
15 base comprises a silicon substrate, an insulation layer, and an optical waveguide layer which are layered sequentially, the optical waveguide and the transitional area are located in the optical waveguide layer; and the traveling wave electrode structure is disposed above the optical waveguide layer.

20 8. The traveling wave electrode modulator of claim 7, wherein: a groove is provided at a surface of the silicon substrate near the insulation layer, the groove

being located below the optical waveguide and disposed along the optical waveguide;

or, a channel penetrating through a top surface and a bottom surface of the silicon substrate is disposed in an area of the silicon substrate below the optical

5 waveguide.

9. The traveling wave electrode modulator of claim 7, wherein a cover layer is disposed on the optical waveguide layer, and the traveling wave electrode structure is disposed in the cover layer.

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10. A photonic integrated chip, comprising the traveling wave electrode modulator of any of claims 1 through 9.