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AN INTEGRATED ELECTRO-OPTICAL ABSORPTION MODULATOR

Abstract

The present disclosure is related to an integrated electro-optical absorption modulator. A two-dimensional (2D) material is employed for forming electrodes of the modulator, and a material with a non-zero off-diagonal electro-optic tensor coefficient may be employed for forming a waveguide core of the modulator. The modulator comprises a cladding, a waveguide core arranged at least partly in the cladding to guide light, and a first electrode and a second electrode arranged on opposite sides of the waveguide core. Each electrode is formed of the 2D material on a surface of the cladding or in the cladding, and extends into the waveguide core. The electrodes are configured to apply an electric field across a modulation region of the waveguide core, and thereby to convert at least a part of the energy of the light in the modulation region between two orthogonal modes, wherein one of the two orthogonal modes is polarized perpendicular to the plane of the 2D material.

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Background/Summary

TECHNICAL FIELD

[0001] The present disclosure is related to an integrated electro-optical absorption modulator. A two-dimensional (2D) material is employed for forming electrodes of the modulator, and a material with a non-zero off-diagonal electro-optic tensor coefficient may be employed for forming a waveguide core of the modulator.

BACKGROUND

[0002] Electro-optical modulators are at the heart of today's information technology, as these modulators represent gateways between electronics for computation and optics for communication. In the past, the application of electro-optical modulators was limited to long-haul communications, while high cost, large footprint, and high energy consumptions prevented their application to short reach distance communication.

[0003] In the meantime integrated electro-optical modulator technologies have enabled also optical communications over much shorter communication channels, for instance, within datacenters. However, even shorter communication distances are now targeted, such as chip-2-chip communications. Thus, the current research focuses on steadily improving the electro-optical modulator technologies, which means particularly achieving low optical insertion loss (IL), low driving voltages, and a compact footprint to reduce cost.

[0004] Conventionally, two major electro-optical modulation techniques are applied. The first technique is based on shifting the phase of an optical signal by applying a voltage via the Pockels effect or the free carrier dispersion effect. This phase shift allows utilizing constructive and destructive interference to modulate light within, for example, a Mach Zehnder interferometer or an optical resonator configuration.

[0005] The performance metric for this modulation technique is the voltage-length-loss product (αUL [VdB])—wherein U is the voltage applied for effecting the modulation and L is length of the modulation region in which light is modulated—and the voltage-length-product (UL [Vm]), respectively. The former product quantifies the trade-off between optical loss (in dB) and driving voltage U (in V), while the latter product indicates the trade-off between device footprint (depending on the length L, in μm) and the driving voltage U (in V). The ideal technology should feature as low as possible values for both products. Conventional inorganic Pockels modulators feature UL of a few Vmm to a few Vcm, while the voltage-length-loss product is on the order of one VdB. However, their large footprint prevents a dense large-scale integration, as it will be needed for short-distance and high-throughput communication channels. A further miniaturization could be achieved by applying a reduced electrode spacing, however, this would come at the cost of intolerable optical loss.

[0006] The second technique is based on a voltage induced change of the material absorption by utilizing the free-carrier dispersion effect, or epsilon near zero materials, or 2D materials, or the Franz Keldish effect, or the Quantum confined Stark effect. While such modulators typically feature micron-scaled footprints, they suffer from a unity ratio between the signal's extinction ratio

(ER) and insertion loss (IL). Furthermore, their wavelength operation window is limited to a few 10's of nanometers for the most prominent solution based on the Franz Keldish effect and Quantum confined Stark effect.

SUMMARY

[0007] In view of the above, an objective of this disclosure is to realize an electro-optical modulator, which has a compact footprint, which is suitable for broadband operations, which shows low insertion loss, and which requires a low-driving voltage. In particular, the electro-optical modulator envisaged by this disclosure should have a low voltage-length-loss product and/or a low voltage-length product. Another goal of this disclosure is to provide the electro-optical modulator with a large ratio between the extinction ratio and the insertion loss.

[0008] These and other objectives are achieved by the solutions of this disclosure as provided in the independent claims. Advantageous implementations are defined in the dependent claims.

[0009] A first aspect of this disclosure provides an integrated electro-optical absorption modulator comprising: a cladding; a waveguide core arranged at least partly in the cladding and configured to guide light along an extension direction of the waveguide core; and a first electrode and a second electrode arranged on opposite sides of the waveguide core and each formed of a 2D material on a surface of the cladding or in the cladding; wherein each of the first electrode and the second electrode extends into the waveguide core; and wherein the first electrode and the second electrode are configured to apply an electric field across a modulation region of the waveguide core, and thereby to convert at least a part of the energy of the light in the modulation region between two orthogonal modes, wherein one of the two orthogonal modes is polarized perpendicular to the plane of the 2D material.

[0010] The waveguide core may protrude from the cladding or may be embedded in the cladding. When the waveguide core is embedded in the cladding, i.e., when it is fully arranged in the cladding, the 2D material may be also formed in the cladding. The 2D material may be a material that has a strong anisotropic response, wherein the response is metallic or semiconducting in-plane of the plane of the 2D material and is dielectric or isolating out-of-plane of the plane of the 2D material. The 2D material may be fabricated by atomic layer deposition, printing or transferred from a seed wafer. The 2D material can be single-layered or multi-layered. That is, the first electrode and/or the second electrode may be formed by one layer of the 2D material or may be formed by multiple layers of the 2D material.

[0011] Each of the first electrode and the second electrode may be at least partly arranged in the waveguide core.

[0012] Each of the first electrode and the second electrode may extend into a volume and/or a material of the waveguide core. For example, each of the first electrode and the second electrode may be partly embedded in the volume and/or the material of the waveguide core.

[0013] The waveguide core may comprise a first plane. The first plane and the plane of the 2D material may be coplanar. The two-dimensional material of the first electrode may form a second plane. The two-dimensional material off the second electrode may form a third plane. The second plane and the third plane may be coplanar. The first plane and the third plane may be coplanar. The first plain and the second plane may be coplanar.

[0014] A part, for example, an entire part, of the first electrode extending into the waveguide core may form a first part of the first electrode and a part, for example, an entire part, of the second electrode extending into the waveguide core may form a second part of the second electrode.

[0015] The first part of the first electrode and the second part of the second electrode may be embedded in the waveguide core.

[0016] Each of the first electrode and the second electrode may have a rectangular shape. The first part of the first electrode and the second part of the second electrode may be surrounded by the waveguide core on at least three sides, for example, five sides, respectively.

[0017] An entire cross section of the waveguide core may be arranged in between at least a part of

the first electrode and at least a part of the second electrode.
[0018] Converting at least a part of the energy of the light in the modulation region between the two orthogonal modes may mean that, when the electric field is applied across the modulation region, all of the light (i.e., the entire light energy) in the modulation region is converted from a first mode to a second mode, wherein the first mode is orthogonal to the second mode. Alternatively, converting at least a part of the energy of the light in the modulation region between the two orthogonal modes may mean that only a first part of the energy of the light in the modulation region is converted from the first mode to the second mode, when the electric field is applied across the modulation region, while a second part of the energy of the light in the modulation region is not converted. For instance, only some of the light in the modulation region is mode-converted, while also some of the light in the modulation region is not mode-converted.
[0019] The orthogonal mode, which is polarized perpendicular to the plane of the 2D material (e.g., the first mode), is not affected by the 2D material, as it is polarized perpendicular to the 2D material's in-plane conductivity. This achieves limited propagation losses for this orthogonal mode, which may define the on-state of the modulator of the first aspect. The propagation losses of the other orthogonal mode may be orders of magnitude higher. For example, the other orthogonal mode (e.g., the second mode) may be polarized in-plane of the plane of the 2D material. The higher losses of the other mode of the two orthogonal modes are beneficial, however, as it means that light is absorbed, which may define the off-state of the modulator of the first aspect.
[0020] Therefore, the use of the 2D material to form the electrodes, and the fact that the light in the modulation region can be converted between the two orthogonal modes, enables the modulator of the first aspect to have a high ratio of extinction ratio to insertion loss, for instance, of about ER/IL ≥50, particularly higher than the ratio of a conventional absorption modulator which is ER/IL ≈1. Moreover, the modulator of the first aspect has a high voltage-length product UL, for example, in the range of 10-100 Vμm or more, particularly, compared to conventional phase modulators that have at most a UL in the range of 2-20 Vmm. For the modulator of the first aspect, U may be the voltage applied to the electrodes to apply the electric field across the modulation region, and L may be the length of the modulation region.
[0021] In an implementation of the modulator, one of the two orthogonal modes is a transverse magnetic (TM) mode polarized perpendicular to a plane of the 2D material, and the other one of the two orthogonal modes is a transverse electric (TE) mode polarized in the plane of the 2D material.
[0022] That is, the electric field across the modulation region of the waveguide core can convert at least a part of the energy of the light in the modulation region between the TM mode and the TE mode. The TM mode may define the on-state and the TE mode may defined the off-state of the modulator of the first aspect.
[0023] In an implementation of the modulator, the waveguide core comprises a first material having a non-zero off-diagonal electro-optic tensor coefficient, wherein at least a part of the first material is arranged between the first electrode and the second electrode.
[0024] The first material may be arranged completely between the first electrode and the second electrode. Notably, since the first electrode and the second electrode are 2D electrodes (made of 2D material), “between the electrodes” means between the electrodes in a direction in-plane of the 2D material, for instance, in a top-view on the modulator. The planes of the first electrode and the second electrode may be the same plane. Alternatively, they could be parallel planes.
[0025] The use of the first material facilitates the conversion of at least a part of the energy of the light in the modulation region from one orthogonal mode to the other, for instance, from TM mode to TE mode, when applying a voltage to the first and second electrode to produce the electric field. The first material may be epitaxially grown.
[0026] In an implementation of the modulator, the waveguide core further comprises a second material, the second material having a similar or an identical refractive index than the first material.
[0027] The use of the second material may reduce losses for the orthogonal mode, which is

polarized perpendicular to the plane of 2D material, for instance, the TM mode. The second material may be epitaxially grown.
[0028] In an implementation of the modulator, the waveguide core comprise a lower part arranged in a trench formed in the cladding and an upper part protruding from the surface of the cladding.
[0029] The lower part and the upper part may be made of the same material, for example, the first material, or of different materials, for example, the first and the second material.
[0030] In an implementation of the modulator, the first material is arranged at least in the lower part of the waveguide core; and/or the second material is arranged at least in the upper part of the waveguide core.
[0031] Such a modulator shows a very good performance, in particular, in terms of the ratio ER/IL and the product UL.
[0032] In an implementation of the modulator, a ratio of a height of the lower part to a height the upper part of the measured from a center of the 2D material perpendicular to the plane of the 2D material is in a range of 0.75-1.25.
[0033] The center of the 2D material the center in direction perpendicular to the 2D material plane. Notably, the 2D material may be very thin (e.g., a single atomic layer or a few atomic layers). For instance, the height of the lower part can be similar or even identical to the height of the upper part of the waveguide core. That is, the ratio of the heights may be about 0.5.
[0034] In an implementation of the modulator, the first material is barium titanate, for example, crystalline barium titanate.
[0035] This material has non-zero off-diagonal electro-optic tensor coefficients, and thus allows an efficient conversion between the two orthogonal modes.
[0036] In an implementation of the modulator, the 2D material is graphene or a material with an anisotropic behavior being dielectric out-of-plane and conductive in-plane.
[0037] This material enables an efficient implementation of the on-state and off-state of the modulator, respectively, when switching between the orthogonal modes by applying the electric field.
[0038] In an implementation of the modulator, the cladding is made of silicon oxide, a silicon-based oxide, and aluminum oxide, or a hafnium oxide.
[0039] In an implementation of the modulator, the electric field is substantially parallel to the plane of the 2D material.
[0040] In an implementation of the modulator, the TM mode and the TE mode are phase-matched on the length of the modulation region in the extension direction.
[0041] This improves the interaction between the two orthogonal modes.
[0042] A second aspect of this disclosure provides a method for fabricating an integrated electro-optical absorption modulator according to the first aspect or any implementation form thereof, the method comprising: forming the cladding and the waveguide core at least partly in the cladding; and forming the first electrode and the second electrode of the 2D material on the surface of the cladding or in the cladding.
[0043] In an implementation form of the method, the method comprises: epitaxially growing and patterning the lower part of the waveguide core on a silicon-based substrate, and encapsulating the lower part of the waveguide core with the cladding; or epitaxially growing the lower part of the waveguide core on a silicon-based substrate and into a trench of the cladding provided on the silicon-based substrate; wherein the method further comprises: forming the first electrode and the second electrode on the surface of the cladding and on a part of the lower part of the waveguide core; and growing, using a mask, the upper part of the waveguide core onto the lower part of the waveguide core and the parts of the first electrode and the second electrode formed on the lower part of the waveguide core.
[0044] Since the method of the second aspect can be used to fabricate the modulator of the first aspect, it may achieve the same advantages as described above for the modulator of the first aspect.

Furthermore, the method of the second aspect is of low complexity, and can be well implemented with available tools and process flows.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0045] The above described aspects and implementations are explained in the following description of embodiments with respect to the enclosed drawings:

[0046] FIG. **1** shows a general embodiment of an electro-optical modulator according to this disclosure in a side-view.

[0047] FIG. **2** shows the electro-optical modulator of FIG. **1** in a top-view.

[0048] FIG. **3** shows an exemplary embodiment of an electro-optical modulator according to this disclosure in a side-view.

[0049] FIG. **4** plots power vs. propagation length of (a) the TM mode and (b) the TE mode in a modulator according to this disclosure.

[0050] FIG. **5** shows exemplary embodiments of electro-optical modulators according to this disclosure in a side-view.

[0051] FIG. **6** shows exemplary embodiments of electro-optical modulators according to this disclosure in a side-view.

[0052] FIG. **7** shows exemplary embodiments electro-optical modulators according to this disclosure in a side-view.

[0053] FIG. **8** shows a general embodiment of a method for fabricating an electro-optical modulator according to this disclosure.

[0054] FIG. **9** shows an exemplary embodiment of a method for fabricating an electro-optical modulator according to this disclosure.

[0055] FIG. **10** shows an exemplary embodiment of a method for fabricating an electro-optical modulator according to this disclosure.

[0056] FIG. **11** shows an exemplary embodiment of a method for fabricating an electro-optical modulator according to this disclosure.

DETAILED DESCRIPTION OF EMBODIMENTS

[0057] FIG. **1** shows a general embodiment of an electro-optical modulator **10** according to this disclosure in a side-view. FIG. **2** shows the same modulator **10** in a top-view. Same elements in FIG. **1** and FIG. **2** are labelled with the same reference signs. The modulator **10** is, in particular, an integrated electro-optical absorption modulator, and may be used to modulate light. The modulated light can be used for the purpose of optical communication. The modulator **10** may be configured to convert and electrical signal with information into an optical signal including the same information.

[0058] The modulator **10** comprises a cladding **11**. This cladding **11** may, for example, be made of a silicon oxide, or a silicon-based oxide, or an aluminum oxide, or a hafnium oxide.

[0059] Further, the modulator **1***o* comprises a waveguide core **12**, wherein the waveguide core **12** is arranged at least partly in the cladding **11**. For instance, the waveguide core **12** may be partly arranged in the cladding **11**, i.e., a part of the cladding **11** is in the cladding **11**. This also means that another part of the cladding **11** may not be arranged in the cladding, for instance, may protrude from the cladding **11**. The waveguide core **12** may even be fully arranged in the cladding **11**, e.g., embedded in the cladding **11**, wherein the waveguide core's surface may be exposed at the cladding surface, or may be deep-embedded into the cladding **11** and surrounded completely by cladding material. In any case, the waveguide core **12** is configured to guide light along an extension direction **21** of the waveguide core **11**. The extension direction **21** may be the same as the propagation direction of the light guided in the waveguide core **12**. This extension direction **21** is indicated in FIG. **2**, in FIG. **1** it is into the plane of the drawing. The extension direction **21** may be parallel to a z-direction of a coordinate system comprising an x-direction, y-direction, and z-direction, as indicated. The modulator **10** may built up along the y-direction.

[0060] The modulator **10** also comprises a first electrode **13** and a second electrode **14**, which are respectively arranged on opposite sides of the waveguide core **12**. That means, the first electrode **13** is arranged on one side of the waveguide core **12**, and the second electrode **14** is arranged on the other side of the waveguide core **12**. The two electrodes **13** and **14** may sandwich the waveguide core **12** in the x-direction. Each electrode **13** and **14** may extend along the extension direction **21** of the waveguide core **12** along a certain length, which defines the length of a modulation region **20** (see FIG. **2**).

[0061] Both electrodes **13** and **14** are formed of a 2D material, wherein the 2D material is arranged on a surface of the cladding **11** (as shown in FIG. **1**), or is arranged in the cladding **11** (see, e.g., FIG. **5**). In particular, the 2D material may be arranged in the cladding **11**, if the waveguide core **12** is arranged at least to its largest part in the cladding **11**. The 2D material may be graphene or graphene-based, or may be any suitable material that has an anisotropic behavior, in particular, dielectric out-of-plane and conductive in-plane of the plane of the 2D material. Moreover, each of the first electrode **13** and the second electrode **14** extends into the waveguide core **12** (as shown in FIG. **1**). In particular, the first electrode **13** and the second electrode **14** extend into the waveguide core **12** from opposite sides of the waveguide core **12**. The extension into the waveguide core **12** may be along the x-direction.

[0062] The first electrode **13** and the second electrode **14** are configured to apply an electric field **15** across the modulation region **20** of the waveguide core **12**. The modulation region **20** is the region of the waveguide core **12**, in which a modulation of the light that is guided in the waveguide core **12** can be affected. The electric field **15** may be substantially parallel to the plane of the 2D material, which forms the first electrode **13** and the second electrode **14**, and is indicated in FIGS. **1** and **2**. The electric field **15** may be perpendicular to the extension direction **21**, but this is not a must. Accordingly, the electric field **15** may be along the x-direction.

[0063] By applying the electric field **15** across the waveguide core **12**, the first electrode **13** and the second electrode **13** are able to convert at least a part of the energy of the light in the modulation region **20** between two orthogonal modes. That is, the energy of the light, which is guided in the waveguide core **12**, can be converted in the modulation region **20** between a first mode and a second mode, wherein the first mode is orthogonal to the second mode. One of the two orthogonal modes—for example, the first mode—is polarized perpendicular to the plane of the 2D material. The other mode—for example, the second mode—may be polarized in-plane of the plane of the 2D material. The first mode may be a TM mode polarized perpendicular to the plane of the 2D material, and the second mode may be a TE mode polarized in-plane of the plane of the 2D material.

[0064] The waveguide core **12** may comprise a first material, which has a non-zero off-diagonal electro-optic tensor coefficient. At least a part of the first material may be arranged between the first electrode **13** and the second electrode **14** (in the x-direction, e.g., in the top view of the modulator **10**). The waveguide core **12** may comprise a Pockels material. The first material may be the Pockels material. A Pockels material is a material that allows employing the Pockels effect for modulating the light. Accordingly, the modulator **10** may be a Pockels modulator, which is based on the Pockels effect.

[0065] The Pockels effect may conventionally be modelled as a change in the refractive index

[00001] $n = \frac{rn^3 U}{2d}$

[0066] In the above formula, n is the refractive index (of the Pockels material, which may be used for the waveguide core of a modulator) and r represents the electro-optical coefficient (of the Pockels material). The efficiency of an electro-optical modulator based on the Pockels effect is proportional to the strength of the electric field (U/d), which is stronger for smaller electrode distances d (e.g., the distance between first and second electrode across the waveguide core) and for larger voltages U applied to the electrodes to generate the electric field across the waveguide core.

[0067] However, this comes at the expanse of higher propagation losses, which may be quantified by $L_{prop} \propto 1/\alpha$. Conventional Pockels modulators, which are mostly based on ferroelectrics, have an electrode spacing of a few microns. This results in a voltage length product of UL of about 0.2 Vcm and $L_{prop} \approx 1$ cm for a $r_{42}=923$ pm/V.

[0068] The physical interaction behind the Pockels effect may be described by photon generation and annihilation. An applied radio frequency (RF) electric field contains photons at a frequency ω_{RF} which are mixed with an optical input field having a frequency ω_{C}. The 2nd order nonlinearity of suitable Pockels materials enables up and down conversion of optical photons to the Stokes (ω_{S}) and anti-Stokes (ω_{AS}) side band. This conversion can encode a phase information onto the optical signal depending on the polarization of the RF electric field.

[0069] The electro-optical modulators **10** according to embodiments of this disclosure utilizes the 2D material, wherein the 2D material is specifically a conductive material, o form the first electrode **13** and the second electrode **14**. Further, the modulator **10** also uses a waveguide core **12** that allows converting the light between the two orthogonal modes, e.g., a Pockels material that features a non-zero electro-optical off-diagonal coefficient (e.g. $r_{42} \neq 0$) may be used for the waveguide core **12**. This type of coefficient may, for example, be found in c-axis barium titanate (BTO). Accordingly, the first material mentioned above may be barium titanate, for example, crystalline barium titanate.

[0070] An exemplary embodiment of the electro-optical modulator **10** according to this disclosure is shown in a side-view in FIG. **3**. Same elements in FIG. **3** and FIG. **1** are labelled with the same reference signs.

[0071] In the embodiment of FIG. **3**, the waveguide core **12** of the modulator **10** comprises the first material **31**, which has the non-zero off-diagonal electro-optic tensor coefficient. The first material **31** may be a Pockels material. A part of the first material **31** is arranged between the first electrode **13** and the second electrode **14**. The waveguide core **12** of the modulator **10** may further comprise a second material **32**, as shown in FIG. **3**. The second material **32** may have a similar or an identical refractive index than the first material **31**. The first material **31** may be arranged in a lower part **12***a* of the waveguide core **12**. The second material **32** may be arranged in an upper part **12***b* of the waveguide core **12**. The lower part **12***a* may be arranged in the cladding **11**, and the upper part **12***b* may protrude from the cladding surface.

[0072] The two orthogonal modes of the light in the modulation region **20** may be the TM mode and the TE mode, which are schematically illustrated next to the modulator **10** (TM mode on the left side, and TE mode on the right side). The light is guided within the waveguide core **12** comprising the first material **31** and the second material **32** that matches the refractive index of the first material **31**. The mode of the light can be switched by applying a voltage to the electrodes **13**, **14** to produce the electric field **15**. In particular, this may be an RF voltage and RF electric field **15** accordingly.

[0073] The modulators **10** of this disclosure shows a unique ability to combine highly confined RF electric fields **15** with low optical losses in the on-state of the modulator **10**. This can be achieved by reducing the distance between the first electrode **13** and the second electrode **14** across the waveguide core **12** (e.g., in x-direction), for example, to a range of 10-100 nm. This compares to several μm for a conventional modulator. This short distance may boost the nonlinear conversion from above 1 Vmm (for a conventional modulator) to 0.1Vμm or less for the modulators **10** of this disclosure. The non-zero off-diagonal coefficient of the first material **31** (e.g., $r_{ij}, i \neq j$) allows an efficient orthogonal conversion from the, e.g., TM-polarized optical carrier to TE-polarized side bands.

[0074] The energy carried by the two orthogonal modes of the light versus the propagation length of the light in the modulation region **20** is shown in FIG. **4**. In particular, energy versus propagation length of the TM mode is shown in (a). In addition, energy versus propagation length of the TE mode is shown in (b). Before the modulation region **20**, all energy of the light is in the TM mode in this case. The different curves in (a) and (b) represent different driving voltages of the electrodes **13**, **14**, to generate different electric fields **15**. It can be seen that already a driving voltage of 0.4 V allows to convert all energy from the TM to the TE mode. Under 0 V the absorption of the TM mode is negligible, which enables large ER/IL ratios.

[0075] Low losses are achieved in the modulator **10**, since the 2D material such as graphene is used to form the electrodes **13** and **14**, respectively, wherein such 2D material only absorbs the in-plane polarized second mode, e.g., the TE mode (off-state of the modulator **10**) while not affecting the out-of-plane polarized first mode, e.g. the TM mode (on-state of the modulator **10**). This is, because the latter mode is specifically polarized perpendicular to the in-plane conductivity of the 2D material. This enables limited propagation losses for the first mode, while the propagation losses of the second mode may be orders of magnitude higher. The higher losses of the second mode are beneficial, as it allows efficiently absorbing light in the modulator's off-state.

[0076] Notably, the waveguide core symmetry (e.g., refractive index of the first material **31** and the second material **32** being matched; and/or the heights of the upper part **12***b* and the lower part **12***a* of the waveguide core **12** being the same or similar in the y-direction with respect to the 2D material plane) allows to achieve very low-losses for the first mode, as the longitudinal field component of this first mode can be engineered to feature an electrical field node at the position of the 2D material. For instance, the symmetry can be adjusted by increasing the upper part's **12***a* height while reducing its refractive index.

[0077] Two exemplary embodiments of the electro-optical modulator **10** according to this disclosure are shown in FIG. **5** in a side-view. Same elements in FIG. **1**, FIG. **3** and FIG. **5** are labelled with the same reference signs.

[0078] In particular, FIG. **5**(*a*) shows a modulator **10**, which comprises the first material **31** and the second material **32** in the waveguide core **12**. The first material **31** and the second material **31** are in this embodiment arranged symmetrically to the 2D material of the first electrode **13** and the second electrode **14**, respectively, in the y-direction. The first material **31** forms the lower part **12***a*, and the second material **32** forms the upper part **12***b* of the waveguide core **12**. The lower part **12***a* may also be smaller/narrower in the x-direction than the upper part **12***b*, as illustrated.

[0079] Further, FIG. **5**(*b*) shows a modulator **10**, which has only the first material **31** that completely forms the waveguide core **12**. This modulator **10** shows best performance. The waveguide core **12** may have a width in the x-direction, which is larger than the gap between the first electrode **13** and the second electrode **14** in the x-direction, as illustrated. However, this is not mandatory.

[0080] Two exemplary embodiments of the electro-optical modulator **10** according to this disclosure are shown in FIG. **6** in a side-view. Same elements in FIG. **1**, FIG. **3** and FIG. **6** are labelled with the same reference signs.

[0081] In particular, FIG. **6**(*a*) shows that the waveguide core **12** can be asymmetric in the y-direction with respect to the first and second electrodes **13**, **14**. In particular, the height in the y-direction of the lower part **12***a* of the waveguide core **12** can be smaller than the height of the upper part **12***b* of the waveguide core **12** in the y-direction. The lower part **12***a* may comprise the first material **31**, and the upper part **12***b* may comprise the second material **32**. This modulator **10** of FIG. **6**(*a*) may be optimized for minimum loss for the first mode, e.g., the TM mode. Moreover this modulator **10** may have a larger voltage-length product than the modulator shown in FIG. **5**(*b*), for example.

[0082] FIG. **6**(*b*) shows a modulator **10**, which comprises an upper part **12***b* of the waveguide core **12** comprising the second material **32**, and a lower part **12***a* comprising both the second material **32** and the first material **31**. That is, the first material **31** may be only a fraction of the lower part **12***a* of the waveguide core **12**, for example, may form 50% or less of the lower part **12***a* of the waveguide core **12**.

[0083] Two exemplary embodiments of the electro-optical modulator **10** according to this disclosure are shown in FIG. **7** in a side-view. Same elements in FIG. **1**, FIG. **3** and FIG. **7** are labelled with the same reference signs.

[0084] FIG. **7**(*a*) shows a modulator **10**, which comprises a waveguide core **12** that comprises both the first material **31** and the second material **32**. The first material **31** may be embedded into the second material **32**, and may be arranged such that it is arranged between the first electrode **13** and the second electrode **14** in the x-direction.

[0085] FIG. **7**(*b*) shows a modulator **10** with a waveguide core **12** that comprises a lower part **12***a* made of the first material **31**, and an upper part **12***b* made of the second material **32**. The first material **31** form only a fraction of the total height of the waveguide core **12** in the y-direction, in particular, it is arranged over 50% or less of the height of the waveguide core **12**. For instance, as shown, the first material **31** may be arranged beneath the first electrode **13** and the second electrode **14** in the y-direction.

[0086] FIG. **8** shows a method **80** for fabricating an integrated electro-optical absorption modulator **10** according to this disclosure.

[0087] The method **80** starts with a first step, which has two alternative implementations.

[0088] As shown in (a), the lower part **12***a* of the waveguide core **12** may be epitaxially grown and patterned on a silicon-based substrate **50**, and can then be encapsulated with cladding **11** to reach (c). Alternatively, as shown in (b), the lower part **12***a* can be grown on a silicon-based substrate **50** and particularly into a trench **51** of a cladding **11**, wherein the cladding **11** is provided on the silicon-based substrate **50**, in order to reach (c). Then, the first electrode **13** and the second electrode **14** are formed on the surface of the cladding **11** and on a part of the lower part **12***a* of the waveguide core **12**, in order to reach (d). Then, the upper part **12***b* of the waveguide core **12** is grown onto the lower part **12***a* of the waveguide core **12** and onto the parts of the first electrode **13** and the second electrode **14**, which are formed on the lower part **12***a* of the waveguide core **12**, to reach (e).

[0089] FIG. **9** shows another method **90** for fabricating a modulator **10** according to this disclosure.

[0090] The method **90** initially provides a silicon-based substrate **50**, on which a dielectric layer **51**, a strontium titanate (STO) layer **53**, and a BTO layer **52** (as first material **31**) are arranged one on the other in this order, as shown in (a). The STO layer **53** and the BTO layer **52** are then etched and formed into the dimensions (in x-direction and z-direction) of the lower part **12***a* of the later waveguide core **12**, to reach (b). Then, a cladding **11** is deposited that surrounds the lower part **12***a* to reach (c). Then, the first electrode **13** and the second electrode **14** are formed on the surface of the cladding **11** and on the lower part **12**(*a*) to reach (d). The 2D material may herein be transferred and patterned. The 2D material may also be deposited by atomic layer deposition (ALD). Then, a further cladding **11** is provided onto the first and second electrodes **13**, **14**, and a trench **54** is etched into the further cladding **11**, to reach (e). Then, the trench **54** is filled with a material for forming the upper part **12***b* of the waveguide core **12**, for instance, with the second material **32**, to reach (f). Then, wafer bonding and removal of the silicon-based substrate **50** and the STO layer **52** may be performed to reach (g).

[0091] FIG. **10** shows another method **100** for fabricating a modulator **10** according to this disclosure.

[0092] First, a silicon-based substrate **50** is provided with a cladding **11** arranged on its surface, and with the lower part **12***a* of the waveguide core **12** already formed in the cladding **11**, as shown in (a). Then, the first and the second electrode **13**, **14** may be formed by, for example, transfer printing and patterning, or by ALD, to reach (b). Then, a further cladding **11** may be provided onto the electrodes **13**, **14** and the lower part **12***b*, and a trench **61** is etched into this additional cladding **11** to reach (c). Then, the upper part **12***b* of the waveguide core **12** is formed in the trench **61**, for

instance, by growing second material **32**, to reach (d).
[0093] FIG. **11** shows another method **110** for fabricating a modulator **10** according to this disclosure.
[0094] At first, as shown in (a), a silicon-based substrate **50** with a dielectric layer **51** on its surface, and cladding **11** arranged on the dielectric layer **51** are formed along the y-direction The cladding **11** may be silicon oxide. A trench **71** is provided in the cladding **11**. Then, STO **52** and BTO are grown in the trench **71** to form the lower part **12***a* of the waveguide core **12**, and α-BTO **72** is grown on the cladding **11**, so as to reach (b). The α-BTO **72** is then removed, for example, by CMP or etching, to reach (c). The first electrode **13** and the second electrode **14** are then formed, for instance, by ALD, on the surface of the cladding **11** and on the lower part **12***a*, to reach (d).
[0095] Then, in a first alternative (1) of the method **110**, a further cladding **11** is deposited, for instance, by plasma-enhanced chemical vapor deposition (PECVD), and a trench **73** is etched into the cladding **11**, wherein the trench **73** ends on the upper surface of the lower part **12***b*, to reach (e). Into this trench **73**, a further BTO is grown, for instance, by molecular beam epitaxy (MBE) α-BTO **74** is also grown on the cladding **11** to reach (f).
[0096] In a second alternative (2) of the method **110**, the trench **73** is etched to reach (g), and then second material **32** is grown into the trench **73** to form the upper part **12***b* and to reach (h). The silicon-based substrate **50** and the dielectric layer **51** and the STO **52** are then removed to reach (i).
[0097] In summary, an idea of this disclosure is the combination of the 2D material, such as graphene as a transparent electrode material, for forming the electrodes **13**, **14**, with a material, like the first material **31**, which allows a large light matter interaction with low-insertion loss. This may result in major advantages of the modulator **10** in terms of performance (e.g., the modulator **10** has a large ER/IL and has a small voltage-length-loss product). Contrary to conventional modulator implementations, which try to maximize the light interaction, this disclosure tries to minimize the light interaction with the 2D material, and to leverage the light matter interaction of the waveguide core material (e.g., the first material **31**).
[0098] The modulator **10** may comprise a single graphene layer as the 2D material, and a gap between the first electrode **13** and the second electrode **13** (along the x-direction) can be patterned with a simple dry-etching process. To the contrary, other graphene work normally focuses on stacking multiple graphene sheets, which increases fabrication complexity and cost.
[0099] The interaction between two orthogonal modes normally requires a high-level of phase-matching, and thus devices using such interaction are sensitive to fabrication imperfections. This need is due to the small nonlinear interaction that requires device lengths on the order of millimeters to centimeters. To the contrary, the embodiments of the modulator **10** according to this disclosure feature very strong nonlinear interactions, and thus a sub 100 μm modulator becomes feasible. Such short lengths reduce the requirements on the fabrication accuracy. Furthermore, the non-dominant electro-optical tensor coefficient of the first material **31** can be used to adjust the effective refractive index of one polarization, without affecting the other.
[0100] A challenge may be that a short length results in a limited absorption by the 2D material of the second mode, which is polarized in-plane of the 2D material, for example the TE mode, within a short propagation distance. A solution for this may be incorporating multiple layers of the 2D material, or extending the modulator **10** by a photonic polarization splitter.
[0101] Normally, BTO grown, for instance, on silicon requires a STO seed layer to reduce propagation losses from dB/mm to dB/cm. Another advantage is that this disclosure enables short modulators **10** that can tolerate the dB/mm propagation losses, thereby enabling a simplified fabrication compared to conventional modulators.
[0102] In this disclosure, the word “comprising” does not exclude other elements or steps and the indefinite article “a” or “an” does not exclude a plurality. Further, the fact that certain features are recited in mutual different dependent claims does not indicate that a combination of these measures cannot be used in an advantageous implementation.

Claims

1. An integrated electro-optical absorption modulator (**10**) comprising: a cladding (**11**); a waveguide core (**12**) arranged at least partly in the cladding (**11**) and configured to guide light along an extension direction (**21**) of the waveguide core (**12**); and a first electrode (**13**) and a second electrode (**14**) arranged on opposite sides of the waveguide core (**11**) and each formed of a two-dimensional, 2D, material on a surface of the cladding (**11**) or in the cladding (**11**); wherein each of the first electrode (**13**) and the second electrode (**14**) extends into the waveguide core (**12**); and wherein the first electrode (**13**) and the second electrode (**14**) are configured to apply an electric field (**15**) across a modulation region (**20**) of the waveguide core (**11**), and thereby to convert at least a part of the energy of the light in the modulation region (**20**) between two orthogonal modes, wherein one of the two orthogonal modes is polarized perpendicular to the plane of the 2D material.
2. The modulator (**10**) according to claim 1, wherein one of the two orthogonal modes is a transverse magnetic, TM, mode polarized perpendicular to a plane of the 2D material, and the other one of the two orthogonal modes is a transverse electric, TE, mode polarized in the plane of the 2D material.
3. The modulator (**10**) according to claim 1, wherein: the waveguide core comprises a first material (**31**) having a non-zero off-diagonal electro-optic tensor coefficient, wherein at least a part of the first material (**31**) is arranged between the first electrode (**13**) and the second electrode (**14**).
4. The modulator (**10**) according to claim 3, wherein: the waveguide core (**11**) further comprises a second material (**32**), the second material (**32**) having a similar or an identical refractive index than the first material (**31**).
5. The modulator (**10**) according to claim 4, wherein: the waveguide core (**12**) comprises a lower part (**12***a*) arranged in a trench formed in the cladding (**11**) and an upper part (**12***b*) protruding from the surface of the cladding (**11**).
6. The modulator (**10**) according to claim 5, wherein: the first material (**31**) is arranged at least in the lower part (**12***a*) of the waveguide core (**12**); and/or the second material (**32**) is arranged at least in the upper part (**12***b*) of the waveguide core (**12**).
7. The modulator (**10**) according to claim 6, wherein: a ratio of a height of the lower part (**12***a*) to a height of the upper part (**12***b*) of the waveguide core (**12**) measured from a center of the 2D material perpendicular to the plane of the 2D material is in a range of 0.75-1.25.
8. The modulator (**10**) according to claim 3, wherein: the first material (**31**) is barium titanate, for example, crystalline barium titanate.
9. The modulator (**10**) according to claim 1, wherein: the 2D material is graphene or a material with an anisotropic behavior being dielectric out-of-plane and conductive in-plane.
10. The modulator (**10**) according to claim 1, wherein: the cladding (**11**) is made of silicon oxide, a silicon-based oxide, and aluminum oxide, or a hafnium oxide.
11. The modulator (**10**) according to claim 1, wherein: the electric field (**15**) is substantially parallel to the plane of the 2D material.
12. The modulator (**10**) according to claim 2, wherein: the TM mode and the TE mode are phase-matched on the length of the modulation region (**20**) in the extension direction (**21**).
13. A method (**80**, **90**, **100**, **110**) for fabricating an integrated electro-optical absorption modulator (**10**) according to claim 1, the method (**80**, **90**, **100**, **110**) comprising: forming the cladding (**11**) and the waveguide core (**12**) at least partly in the cladding (**11**); and forming the first electrode (**13**) and the second electrode (**14**) of the 2D material on the surface of the cladding (**11**) or in the cladding (**11**).
14. The method (**80**) according to claim 13, wherein the method (**80**) comprises: epitaxially growing and patterning the lower part (**12***a*) of the waveguide core (**12**) on a silicon-based substrate

(**50**), and encapsulating the lower part (**12***a*) of the waveguide core (**12**) with the cladding (**11**); or epitaxially growing the lower part (**12***a*) of the waveguide core on a silicon-based substrate (**50**) and into a trench (**51**) of the cladding (**11**) provided on the silicon-based substrate (**50**); wherein the method (**80**) further comprises: forming the first electrode (**13**) and the second electrode (**14**) on the surface of the cladding (**11**) and on a part of the lower part (**12***a*) of the waveguide core (**12**); and growing, using a mask, the upper part (**12***b*) of the waveguide core (**12**) onto the lower part (**12***a*) of the waveguide core (**12**) and the parts of the first electrode (**13**) and the second electrode (**14**) formed on the lower part of the waveguide core (**12**).