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Review of Silicon-on-Insulator based Phase Modulator for Photonic Integrated circuits

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Abstract

An integrated circuit is a chip that contains electronic components that forms a functional circuit, such as those embedded inside your smartphone, computer, and other electronic devices; a photonic integrated circuit (PIC) is a chip that contains *photonic* components, which are components that work with light (photons).In an electronic chip, electron flux passes through electrical components such as resistors, inductors, transistors, and capacitors; in a photonic chip, photons pass through optical components such as waveguides (equivalent to a resistor or electrical wire), lasers (equivalent to transistors), polarizers, and phase shifters.

Light can be modulated externally with the help of physical mechanisms which subsequently depend on the materials. Some of those materials change their optical properties when they are stimulated by external changes such as electric field E or increase in temperature. Some materials change their real and complex refractive index when a wave of sound passes within it, known as acoustic optical effect. Sometimes the refractive index changes with temperature known as thermo-optical effect. Electro-optic effect is based on the change of the optical properties upon applying external electric field E to the material. When this effect is linear it is Pockels effect and when it is quadratic, it is known as Kerr effect.[2]

Keywords: Silicon photonics; Integrated Photonic; Optical waveguides; Silicon-on-Insulator waveguides; Beam Splitter.

Introduction

The continuously growing speed of real-time computing generates constant need for much faster processors than those that are currently available in the market. The speed is mainly limited by unavoidable circuit parameters like large resistance and capacitance. The advantage of light consists in its high propagation velocity, reduced cross talk and the absence of noise coupled by electrical inductance and capacitance. Such devices which run on the photonics can operate at very low operational power and have parallel processing capabilities.

- SILICON as a photonic medium has unique advantages. It is transparent in the range of optical telecommunications wavelengths (1.3 and 1.55 m) and has a high index of refraction, which allows for the fabrication of high-index-contrast sub micrometer structures [5]. In addition, the mature Si integrated circuit [bipolar or complementary metal–oxide semiconductor (CMOS)] technology enables the implementation of dense silicon-based integrated optics and electronics on-chip. In order to achieve low-loss compact (sub-micrometer size) devices, high refractive index contrast is required. For this purpose, silicon-on-insulator (SOI) strip waveguide technology may be employed. The use of crystalline Si (c-Si) instead of polysilicon or amorphous Si as the waveguide core reduces scattering and absorption losses. Silicon micro photonics has generated an increasing interest in the recent years, as it can profit from mature complementary metal–oxide–semiconductor (CMOS) technology with high production volume. Furthermore, the integration of optics and electronics on a same chip would allow the enhancement of integrated circuit (IC) performances. Optical telecommunications can benefit from the development of low-cost and high-performance solutions for high-speed optical links. In microelectronic chips, with the extreme miniaturization of transistors, performance limitations come more and more from electrical interconnects, which suffer from RC delay, signal distortion, and power consumption. Photonics is **the physical science of light waves**. It deals with the science behind the generation, detection and manipulation of light. Light has a dual nature known as the wave-particle duality. That is to say that light has characteristics of both a continuous electromagnetic wave and a particle (photon). Photonics materials are **materials that emit, detect, or manipulate or control light. Photonics replaces electrons in the field of modern devices.** Photonic crystals are periodic dielectric structures that are designed to form the energy band structure for photons, which either allows or forbids the propagation of electromagnetic waves of certain frequency ranges, making them ideal for light-harvesting applications.

Photonic crystals are periodic optical nanostructures that can control light, specifically photons. PCW (photonic crystal waveguide) can be formed by removing one or several lines of scatterers from the PhC lattice. Light confinement is obtained due to a complete photonic bandgap (PBG).

Mach-Zehnder modulator is a typical example of phase modulator.

Actually, there are 4 types of electro-optic effect which includes Pockels, quadrature/Kerr, electro-absorption, carrier density effects.

Pockels effect is found in materials with crystals that do not possess inversion symmetry. Pockels effect is sensitized with electric field E as well as polarization of propagation of light. Generally used materials which are based on this effect include $LiNbO_3$ (libonte) and III-V semiconductors. On the other hand, Kerr effect is based when applied electric field E breaks the symmetry of the crystal and sequentially allows for change in refractive index. Electro-absorption effect is caused when an applied electric field causes a distortion of the energy bands i.e., Conduction and valence in semiconductors. Thus, the photo-absorption coefficient rises when the band edge energy threshold shifts towards lower energy. photons which are inside bands can pass across it. This results in both phase and intensity modulation. Carrier density effect is there when the optical properties can be changed by injecting free carriers to the undoped materials or by altering free carriers from the doped materials.

Materials: Materials modulators should have some basic requirements such as transparency at the operating wavelength and strong electro-optic effect.

Inorganic crystals, semiconductors, polymers, transparent conducting oxides.

1. Inorganic crystal: $LiNbO_3$ it is transparent over a wide range of frequencies, has strong Pockels effect and can be easily fabricated. It is also a ferroelectric material and has an electric dipole which drastically depends on temperature. KTP (potassium titanyl phosphate) and lithium tantalite, both have better power handle capability. Vanadium dioxide (VO_2) is a very crucial and significant material which is popularly known as phase change material. When potential difference is applied and undergoes change in temperature it transforms from semiconductor to metallic state/nature. Widely accepted as an optical modulation material and integrated with photonics.
2. Semiconductors: It possesses more electro-optic effect compared to insulators. They offer integration not only with electronic circuitries but also with lasers too. III-V semiconductors include GaAs and InP available in wafers. In these types of materials quadrature EO effect is better than linear EO effect. For silicon its electro-absorption effect is very weak. Mainly carrier density effect is used to achieve modulation in silicon kind of material. It is the best material for designing optical modulators.
3. Polymers: It uses linear Pockels effect to modulate light. Generally, they are being prepared in liquid form, put over the substrate and treated to handle them to thin films. They have very high electro-optic effect which is typically 5 times higher than linobate. Major drawbacks of this kind are thermal instability and weak power handling.
4. Transparent conducting oxides: They are typically CMOS compatible i.e., it is widely used and optimistic in its very nature. ITO (Indium Tin Oxide) exhibits high electrical conductivity and can reach up to plasma frequency when applying electric voltage which results in Epsilon near zero (ENZ) effect.
5. Optical waveguides play a crucial role for interconnection of various photonic components on the integrated photonics circuit. A waveguide is an optical structure which allows the light confinement within its boundaries by

total internal reflection. The total internal reflection may occur if the refractive index of the core medium is higher than the refractive index of the surrounding medium. The geometries of the waveguide structures include planar waveguides, channel waveguides, optical fibers and photonic crystals

Device Design and Theory

Phase modulators is widely used for transmitting radio waves and is an integral part of many digital transmission coding schemes that underlie a wide range of technologies like wi-fi, GSM and satellite television. Electro-optic modulator is a modulator based on a Pockels cell which acts as a phase modulator. The phase modulator is then typically transformed into an intensity modulation by sending light through polarizer. Intensity modulator is a form of modulation in which the optical power output of a source is varied in accordance with some characteristics of the modulating signal. Pulse code modulation is used in optical fiber, modulation. Mach- Zehnder modulator is used for controlling the amplitude of an optical wave. The input waveguide is split into two waveguides interferometer arms. If a voltage is applied across one of the arms, a phase shift is induced for the wave passing through that arm. Pockels cells are used for preventing the feedback of a laser cavity by using a polarizing prism. this prevents optical amplification by directing light of a certain polarization out of the cavity. Sharp bending is avoided in optical fiber because the energy associated with this part of the mode is lost through radiation. thus, it is absolutely critical that sharp bends with a radius of curvature approaching the critical radius are avoided when optical fiber cables are installed. Only materials exhibiting the Pockels effect are called electro -optic modulator examples are $LiNbO_3$, $LitaO_3$, KTP. An electro -optic modulator is based on Pockels cell which acts as a phase modulator. The phase modulator is then transformed to intensity modulation by sending light through the polarizer.

Critical characteristics of an optical modulator are extinction ratio, insertion loss and energy consumption and modulation speed limit.

fabrication

Based on the lithium niobate which has a very high modulation bandwidth, but device switching speeds are limited by many constraints. Modulation is produced by a voltage induced change in refractive index. For achieving sufficient modulation large voltage or long electrode length are needed. required materials include the electrooptic substrate, electrode metal, electrode adhesion layer, buffer layer and dopant used for the fabrication of the optical waveguide.
following are the major steps for fabrication:

1.$linbo_3$ wafers
2.waveguide fabrication
3.electrode fabrication
4.dicing and polishing
5.pigtaining, packaging and test

- LiNbO$_3$ Wafers: It is the most frequent material for fabrication of electrooptic modulators due to its nature(mainly of 2 reasons)high electro-optic coefficient and high optical transparency used for communication purposes near infrared wavelengths.as far this material is concerned it is thermally, chemically and mechanically stable and is compatible with traditional IC processing technology.it has high curie temperature makes it very optimistic for practical fabrication of low loss optical waveguide through in diffusion of metals. Its wafers are obtained from boules grown using the czochralski method. Diameters up to 100 nm are commercially available in different crystals cuts(x,y,z) with the choice of its cut depending upon the application for which to be used.
- Waveguide fabrication: Previously fabricated by diffusion of metal Ti at high temperature of 373 Kelvin. A li deficient surface results in an unwanted planar waveguide for z polarized light and can affect modulators performance, due to its metallic nature it increases both refractive index (ordinary and extraordinary).
  Hence optimal doping concentration of both TE and TM modes will be propagating along the waveguide.
- Electrode fabrication: radio frequency-based electrodes are fabricated either directly on the surface of $LiNbO_3$ wafer are on an optically transparent buffer layer to reduce optical loss due to metal loading and provide a way for optical/rf velocity matching.in general adhesion layer such as that of Ti is first vacuum deposited on the wafer, followed by the deposition of a base layer of a metal in which the electrodes are to be made. Generally, gold is used as the electrode metal. plating process yielding high purity metal, small grain size, minimum feature distortion and reasonable plating rate are best features for obtaining good Rf performance.
- Dicing and polishing: $LinbO_3$ substates do not cleave readily. Substates containing an array of finished modulators are cut from the $LiNbO_3$ wafer using conventional water-cooled diamond saws. The substrate end faces are cut at an angle to the waveguide in order to eliminate and are then polished to obtain an optical finish.to ensure good fiber-to-waveguide coupling a good optical finish and sharp edge are required at both the input and output optical faces of the device. debris from dicing a particular from

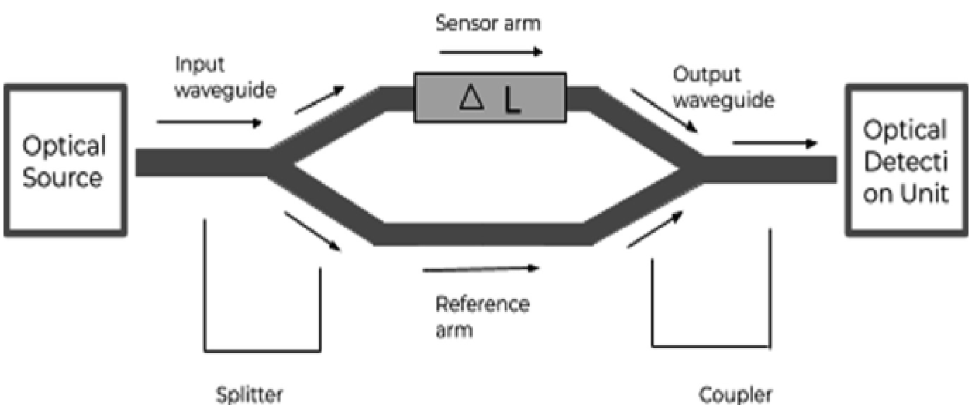
polishing compounds are contaminants that can negatively impact the performance and long-term reliability of the modulators and therefore must be clean during chip cleansing operation.

- pig tailing, packaging and test: pig tailing is a wiring method that allows electrical device to connect 2 or more circuit wires. Test includes: optical loss, switching voltage, bias stability, optical on/off modulators, scattering parameter

$LiNbO_3$ modulators can be packaged in either parametric and nonparametric housings, depending upon the application, operating environment and method of materials utilized in the modulator's manufacturing process.
Due to its polarization dependence of the EO effect the polarization state of the input light supplied to the modulators must be carefully controlled and maintained to achieve optimal performance.
such as s11 and s21.

Mach Zehnder Interferometer Work

The Mach Zehnder interferometer is a particularly simple device for demonstrating interference by division of amplitude. A light beam is first split into 2 parts by a beam splitter and then recombined by a second beam splitter.
depending upon the relative phase acquired by the beam along the 2 paths the second beam splitter will reflect the beam with efficiency between 0 and 100%. The effective way to improve metrological properties and enhance performance capabilities of laser control systems is modulation shift of information signal spectrum to intermediate frequency with low noise level of photo detector. For such spectrum transformation it is important to decide a point of realization two-frequency radiation with high stability of difference frequency and amplitude of spectral components. The most perspective conversion methods of single frequency radiation into symmetrical two frequency radiation are methods, based on Pockels effect in non-linear electro-optic crystals.[3]
The **Mach-Zehnder modulator** (MZM) is an interferometric structure made from a material with strong electro-optic effect (such as $LiNbO_3$, GaAs, InP).
MZM use the phase change to modulate the intensity directly. Light enters the modulator from one waveguide then the light splits into 2 waveguides of the interferometer. Linear and/or quadratic electro-optic effect are used to modulate the phases of the light travelling in one arm to be completely out of phase with respect to the other arm.
At the output, the 2-arms merge recombining the light again.



Operation Methods

In the high-extinction ratio lithium–niobate Mach–Zehnder (MZ) intensity modulator, the optical frequency difference between two optical signals is exactly twice (or four times) the modulation frequency, and the output signal is equivalent to frequency shift-keying (FSK) spectrum. Compared to the optical phase-locked scheme, the MZ modulator has significant advantages in terms of robustness to mechanical vibration and acoustic noise, stability (free from the influence of the input laser linewidth), and capability of maintaining the polarization state of the input laser. The MZ modulator is so reliable that it has been used for optical submarine cables.
1.SETUP: the collimated beam is split into 2 halves of a silvered mirror. The two resulting beams (the “sample beam" and “reference beam”) are each reflected by a mirror. The two beams then pass through a second half-silvered mirror and enter 2 detectors.
2.PROPERTIES: the Fresnel equation for reflection and transmission of a wave at dielectric imply that there is a phase change for a reflection when a wave propagating in a lower refractive-index medium reflects from a higher-refractive index medium but not in the opposite case.

Two operation modes of the MZ modulator

The output spectrum depends on the dc-bias voltage applied to the electrodes in the MZ structure. The MZ modulator has the following two operation modes.

A. **Null-Bias Point Operation Mode:** When the bias of the MZ modulator is set to a minimum transmission point (null-bias point), the first-order upper sideband (USB) and lower sideband (LSB) components are strengthened, and the carrier is suppressed. The frequency difference between the two spectral components is twice the modulation sinusoidal signal frequency. As the spectral components generated by the optical modulation are phase-locked, it is possible to construct a robust system without using any complicated feedback control technique. However, as the modulation frequency is limited by the frequency response of the modulator, the frequency upper limit of the two optical signals cannot be higher than 100 GHz in the null-bias point operation mode. For this reason, the null-bias point operation mode is suitable for the low-frequency application.

B. **Full-Bias Point Operation Mode:** When the bias is set to a maximum transmission point (full bias point), the second-order USB and LSB are strengthened, and the carrier is not suppressed. If the extinction ratio of the MZ modulator is high, undesired odd-order USB and LSB components can be successfully suppressed with this technique. When the odd-order sideband components are suppressed in this mode, the optical frequency of even-order (zeroth- and second-order) components is remained. Eliminating the zeroth-order component (carrier), the remaining is a two-tone optical spectrum whose frequency is four times the modulation frequency or (is the modulation frequency of the RF signal applied to the modulator). The frequency difference between the zeroth- and second-order components is. When GHz, the frequency difference is large enough that the zeroth-order component can be eliminated with a conventional optical filter. The optical signal filtered by the optical filter is amplified by an optical amplifier. At this point, the first-order components are suppressed by the MZ modulator with high extinction ratio to prevent undesired spurious signals.

Electro-optic modulator

Refractive index changes with applied voltage-electro-optic effect. Changes in refractive index leads to phase change. At the combiner destructive interference occurs. Electro-optic intensity modulator is based on Pockels cell.

An **electro–optic effect** is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light.

a) change of the absorption

Electro absorption: general change of the absorption constants

Franz–Keldysh effect: change in the absorption shown in some bulk semiconductors

Quantum-confined Stark effect: change in the absorption in some semiconductor quantum wells

Electrochromic effect: creation of an absorption band at some wavelengths, which gives rise to a change in color

b) change of the refractive index and permittivity

Pockels effect (or linear electro-optic effect): change in the refractive index linearly proportional to the electric field. Only certain crystalline solids show the Pockels effect, as it requires lack of inversion symmetry

Kerr effect (or quadratic electro-optic effect, QEO effect): change in the refractive index proportional to the square of the electric field. All materials display the Kerr effect, with varying magnitudes, but it is generally much weaker than the Pockels effect

electro-gyration: change in the optical activity.

Electron-refractive effect or EIPM.

Pockels effect

Found in materials with crystals that doesn't have Centro-symmetric structure (inversion symmetry). Pockels effect is sensitive to the direction of E (electric vector) and P (polarization vector). Si doesn't show Pockels effect due to its Centro-symmetric structure.

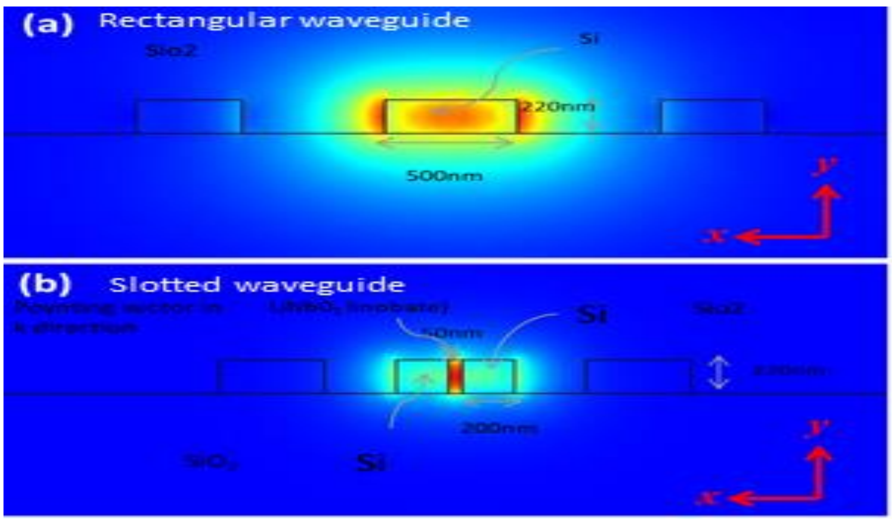
Properties

180-degree phase shift occurs.

Refractive index behind the mirror (glass)has a high refractive index than the medium the light is travelling (in air).

Speed of light cause phase shift increases which is proportional to (n-1) times length travelled.

Simulation



For rectangular and slot waveguide implementation of phase modulator (modal analysis). Typical analysis on COMSOL software[4],[1].

Conclusion

Phase modulator is developed using two different waveguides. Gap *G* is optimized using absorption loss as a deciding parameter. Further, phase change is studied with respect to voltage. V_π for rectangular waveguide is more than V_π for slotted waveguide. Based on this result, it can be concluded that slotted waveguide-based design is the best option for phase modulation.

On a combined note, photonics has a broad scope and pervasive and widespread in its nature. Photonics is a true substitute of electronics in almost all major and minor aspects.

Reference

[1] R. R. Singh, N. Malviya, and V. Priye, "Parametric analysis of silicon nanowire optical rectangular waveguide sensor," *IEEE Photonics Technol. Lett.*, vol. 28, no. 24, pp. 2889–2892, 2016, Doi: 10.1109/LPT.2016.2624501.

[2] C. R. Doerr, N. Dupuis, and L. Zhang, "Optical isolator using two tandem phase modulators," *Opt. Lett.*, vol. 36, no. 21, p. 4293, Nov. 2011, Doi: 10.1364/OL.36.004293.

[3] B. Kumar and N. Mandal, "Study of an Electro-Optic Technique of Level Transmitter Using Mach-Zehnder Interferometer and Float as Primary Sensing Elements," *IEEE Sens. J.*, vol. 16, no. 11, pp. 4211–4218, 2016, Doi: 10.1109/JSEN.2016.2544960.

[4] R. R. Singh and V. Priye, "Modal characteristics of conventional slot and silicon nanowire optical rectangular waveguide," in *2018 3rd International Conference on Microwave and Photonics (ICMAP)*, Feb. 2018, pp. 1–2, Doi: 10.1109/ICMAP.2018.8354632.

[5] B. Jalali and S. Fathpour, "Silicon Photonics," *J. Light. Technol.*, vol. 24, no. 12, pp. 4600–4615, Dec. 2006, Doi: 10.1109/JLT.2006.885782