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Design and Simulation of Electro-optic Modulator Associate with Directional Coupler for optical communication system

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Abstract: The Electro-optic Modulator Associate with Directional Coupler is important in optical communication systems because of its simplicity, linearity, extensive material availability, and small size. Its rapid response time, less than a few picoseconds, and broad wavelength bandwidth of several hundred nanometers add to its desirability. In our study, we designed and tested an optical delay generator using materials such as lithium niobate, DR1-doped SU-8 polymer, and doped polysilicon. Under a 100 V applied voltage, these materials show a refractive index shift of 0.01 to 0.02, which is sufficient to vary the optical path length. A 0.05 refractive index shift causes a 2.5 mm path length variation for a 50 mm length, indicating a promising future for optical communication applications.

Key Words: - MOEMS Delay generator, integrated optics, optical communication, silicon, Lithium Niobate, Electro-optics (EO).

1. Introduction

Electro-optic (EO) materials are another popular material which, exhibits their potential as optical waveguide for precise and continuous laser beam guiding, manipulation, signal processing and controlled light guiding capabilities [1]. Optical modulation is performed using bulk photo-refractive materials and also by adopting electro-optic, magneto-optic, thermo-optic effects or combination of these effects. However, the electro-optic effect is preferred over other optical effects due to its simplicity, linearity, easy availability of large number of material as well as due the size factor. Also, the fast response time of less than few picoseconds and an ultra-wide wavelength bandwidth of over several hundred nanometers make this more attractive. The EO modulators are being used in variety of applications including wave guiding, frequency manipulation, intensity or amplitude modulation, phase generation, polarization splitting, electro-optic switches, filters and other optoelectronic modulation device as optical communication [2].

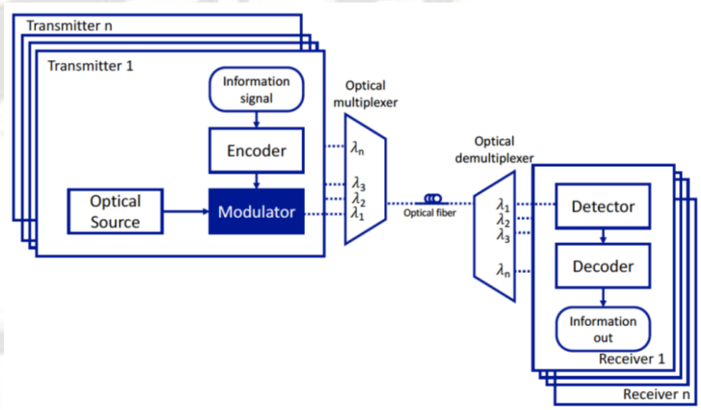

Figure 1.1 - A schematic of A general model of optical communication (transmitter/receiver) system with external modulator.

However, within the optical communication; The simplest optical modulation scheme is Direct Laser Modulation, which is based on directly controlling the drive current to change the intensity of the output optical wave. This technique has many limitations, like bandwidth and extension ratio limitations and signal distortion due to frequency chirping [3]. The second scheme is external modulation, in which a continuous wave laser emits an optical wave and an external modulator is control of modulating in the optical wave to switch it to pass or block. This type optical communication systems have many advantages. such as low cost, high bandwidth, and low transmission losses for long distances. Figure 1.1 displays a general optical communication system (transmitter/receiver) with an external modulator. A modulator is a key feature of any optical communication system; Its role is comparable to that of a transistor in electronic circuits [4]. As demand for optical communication systems evolves, so does the necessity to build external modulators. Modern optical communication systems are incorporating dense optical modulators to reduce both energy usage and cost. Many Si EOMs have been created based on the carrier concentration change effect, including Mach-Zehnder interferometers (MZIs), ring resonators, and metal-oxide-semiconductor capacitors [5-10].

Although Mach Zehnder Interferometer based modulators demonstrated potential in terms of modulation speed and optical bandwidth, their enormous device footprints limit and application. While modulator based on ring resonators have a very small bandwidth [11]. To address these limitations, various designs have been investigated [7], [12-16]. Modulators based on directional couplers are particularly attractive due to their small size and high bandwidth [17, 20]. Due to the light's diffraction limit, silicon photonics can only guide light at a minimum size of roughly 200 nm.

There are many popular materials used in in optical modulator results from, its low optical loss and high electro optic coefficient. These coefficients refer to the electro-optics, which occur in some material such as lithium Niobate, Doped silica, Polysilicon and Doped electro-optic polymer. The possibility to modify the refractive index of a material with an applied electric field allow in the optical light modulation for various applications. Lithium Niobate as optical modulator is widely used for long-haul communication systems and optical signal processing systems [21 – 22] and EO polymer [23, 24], is also a useful candidate for such applications. Currently, it appears that significant challenges remain for EO polymer material to be commercial used in long-haul optical communication. The linear EO phenomena, is capability of an anisotropic material, without an inversion symmetry, to linearly change the refractive index with an applied electric field. An applied electric field, parallel to the optical axis of an electro-optic material structure or poled electro-optic doped polymer chromospheres changes its index by: -

$$\Delta\mu = -\frac{1}{2}\mu_0^3 r_{33} E \tag{1}$$

Where, μ_0 is the refractive index of electro-optic responded material without applied electric field (E), r_{33} is an element of the linear electro-optic tensor or electro-optic coeffcient.

It is Well known that, Material cause light to travel in it, at the speed of inversely proportional to refractive index of material. Thus, if we could suddenly change the refractive index of material than we could slow/fast the light beam. Within electrooptic delay line, only the way to generate optical delay is change in refractive index by the electrooptic effect over the total physical waveguide path length. The change in refractive index by electrooptic effect is given by equation 1. Due to this change (increase) in refractive index, Then the change in path length ΔL is given by;

$$\Delta L = \Delta\mu L \tag{2}$$

Where $\boldsymbol{L}$ is the total waveguide length and the waveguide assumed as homogeneous medium. An example of various electro-optic materials such as LiNbO3 [25], Doped Polysilicon [26] and DR1 (Dye) doped SU-8 polymer with their refractive index are 2.3, 1.587, 1.45 respectively. Electro-optic coeffcient has to be assumed for simulation as follows;

Table 1: - Electro-optic material with their coefficients

S. No.	Electro-optic Materials	Electro-optics Coefficient
1	$LiNbO_3$	33.8×10^{-12} m/V
2	DR1 Doped SU-8	30.0×10^{-12} m/V
3	Doped Silica Glass	30.8×10^{-12} m/V
4	Doped Polysilicon	30.8×10^{-12} m/V

As displayed above table 1, The EO coeffcient for appropriate design and desired simulation result with this electro-optic material. however, the beam can be suffciently modulated with controlled voltage in order to realize light beam modulation. There are many challenges and advantages of EO MOEMS optical delay line over the conventional optical delay line.

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- An Optical modulator is a device, which can modify the properties of light by the changing in refractive index. So that device dimensions can be controlled by applying appropriate voltage.
- Electro -optic effects allows us to reproduce time delay without any physical change in waveguide dimension.
- Due to MOEMS fabrication technology, EO delay line will have to small size and mass production.
- Electro-Optics modulation processes may good technique for the wave modulation in the waveguides without optical loss and without change phase.
- Electro-Optic modulator fabrication may be diffcult. But it can be manageable with the different fabrication technology.
- Electro-Optic OCT could be fast scanning and repeatability with the measurements.

The design and development process are approached systematically using threefold method viz.,

1) To optimize design and simulation.
2) To fabricate the device with optimized values.
3) To generate optical delay in the waveguide such that the expected Doppler shift occurs in the medium.

2. Design Consideration of Optical MOEMS Delay Generator

A schematic of fiber optic optical communication setup being used by us is shown in figure 1.1. MOEMS (micro-opto-electro-mechanical system) based on Electro-Optic (EO) modulator designed associate with Multimode interferometer directional coupler integrated optical circuit for optical communication system is shown in figure 1.2. In the fiber optic setup; the reference and sample arms optical path length delay compensated by either mechanical motion of translational stages or using grating mirror combination whereas, In the MOEM system; the optical path length delay compensation carried out by electro-optically in reference arm. The EO induced change in refractive index, induces a path difference in the reference arm. While input (source), output (Detector) and back scattered light from the sample arm will be obtained through external ports as $P_{\#1}$, $P_{\#2}$ and $P_{\#3}$ respectively. Optical modulation is possible by the electrostatic applied low voltage with parallel plate electrode configuration with the linear optical waveguide or the proper waveguide structure and it is easy to fabricate from resent fabrication technologies. These characteristics are very attractive in device application for optical beam manipulation in many optoelectronic systems.

The design of the waveguide with suitable electrodes for EO modulator are shown in figure 1.3 top view (left) and Cross-sectional view of a strip waveguide in which copper electrode are kept either side above waveguide figure 1.3 (right). Waveguide designing parameter with suitable electrodes are palace with parallel plate scheme and the electro-optic effect discussed earlier is adopted here. The medium is assumed to be homogeneous and anisotropic. However, we limited to linear medium only.

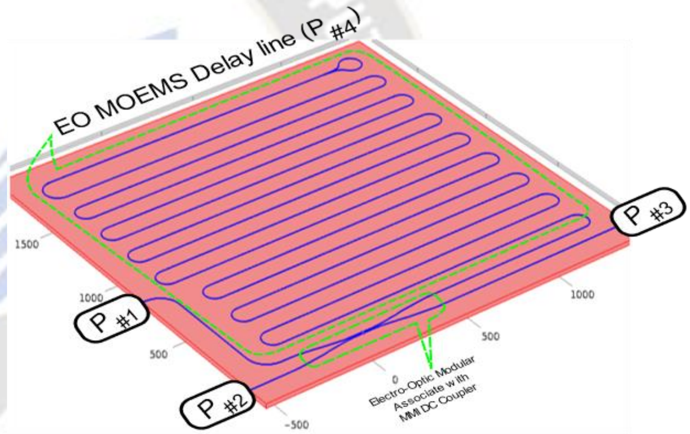

Figure 1.2 A schematic design of EO-Delay generator associated with Multi-Mode Interference Directional coupler.

3. Simulation of Optical MOEMS Delay Generator

Optical modulation is possible by the electrostatic applied low voltage with parallel plate electrode configuration with the linear optical waveguide or the proper waveguide structure and it is eases to fabricate from resent fabrication technologies. These characteristics are very attractive in device application for optical beam manipulation in many optoelectronic systems. The design of the waveguide with suitable electrodes of top view (in left) and cross-sectional view (in right) of a waveguide in which copper electrode are kept either side above waveguide are shown in Figure 1.3. The electro-optic modulation from the change in refractive index is simulated using COMSOL MultiPhysics. Appropriate material

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parameters are added to incorporate change in refractive index and waveguide losses occurring in the system. For electro-optic effect simulation, waveguide material refractive index is =1.58 and the one of electrode kept at higher potential and second electrode is ground state and executed the electrostatic model and after the electromagnetic wave model in COMSOL MultiPhysics. After execute both model, Figure 1.3 shown the electric field map along the waveguide. To observe change in refractive index, we generate cut line in Figure 1.3 (in left figure). As shown in Figure 1.4, the graph of refractive index changes along the cut line as a horizontal index prole of the waveguide at 100V applied voltage. On this simulating arrangement, a total change in refractive index of Δ = 0.0047 was obtained for an applied voltage 100V. With suitable modification in the design parameter of the optical MOEMS delay line, desire MOEMS delay line can be obtained for optical communication system.

In another experiment we demonstrated the linear change in refractive index for various materials such as Lithium Niobate, DR1 doped SU-8 polymer, and doped Polysilicon as shown in Figure 1.5 respectively. Graphs are plotted between applied potential and refractive index; external electric field is taking a range from 0 to 100 V. The change in refractive index of the order of 0.01 to 0.05 could be observed for an applied voltage of 100 V above respective material with specific electrode arrangement and design. This change is enough to generate few mm of optical path length change. As well known that the optical length is the product of refractive index and geometric length (equation 2), hence if the refractive index is varied, the optical length also varies. For a geometrical length of 50 mm, the change in optical path will be 2.5 mm, if the change in refractive index is 0.05. Such change could be achieved vary easily using the EO effect. It is seen, Poly-silicon is the stronger material candidate for generating maximum change in the refractive index in electro-optic effect with parallel plate capacitor configuration. Thus, it is decided that the all-optical communication system on a chip well bee fabricated with polyMUMPS process.

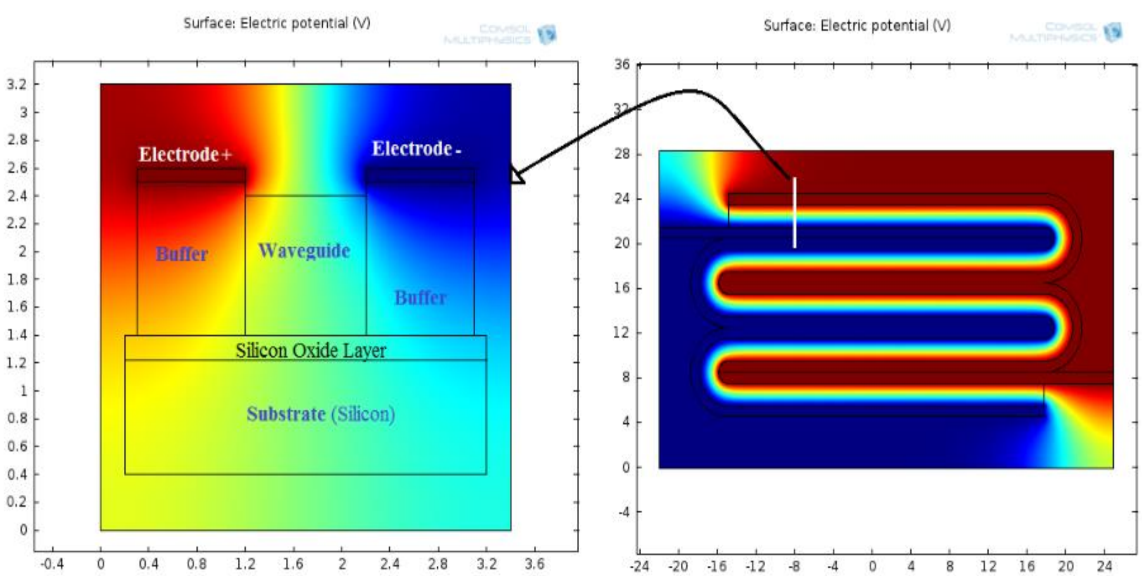

Figure 1.3 Design and simulation characteristics of EO-Delay generator. The left figure shows the cross-sectional view of one of the channels while the delay generation waveguide is shown on the right-hand side.

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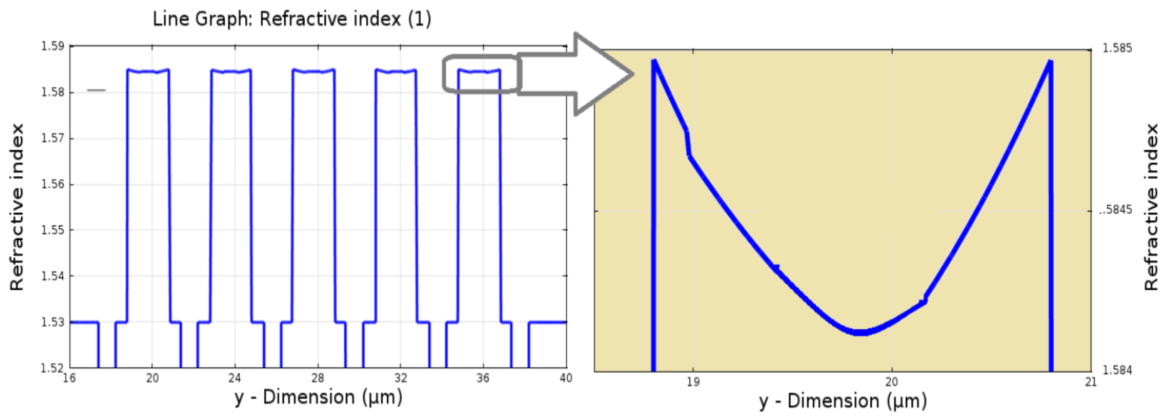

Figure 1.3 Design and simulation characteristics of EO-Delay generator. Simulation characteristics of EO-Delay generator. The figure on the left-hand side shows the refractive index prole at the cut-line from the figure 1.3, for an applied voltage of 100V. The magnified view of refractive index prole is shown on the right-hand side.

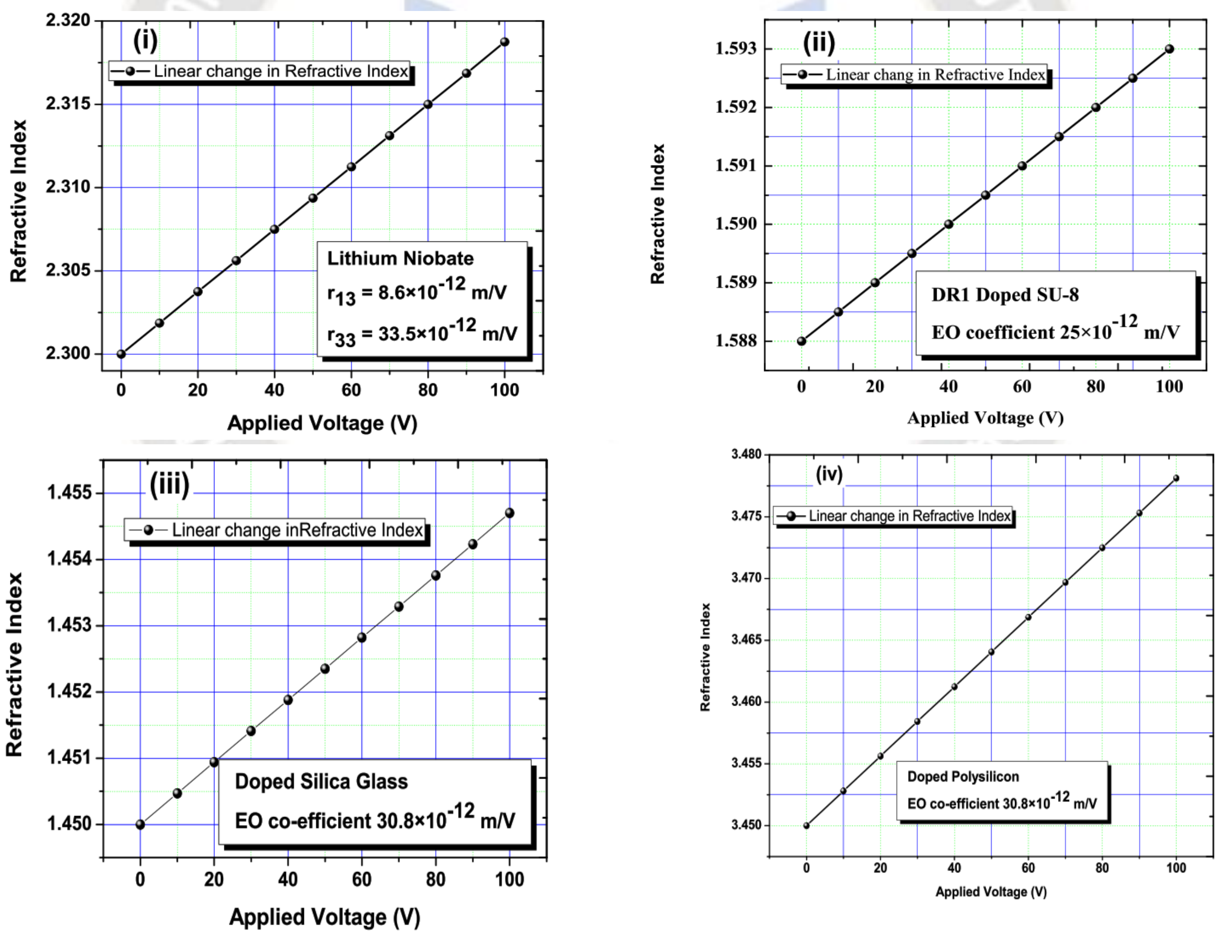

Figure 1.5: Graphs showing variation of refractive index in various material as (i) Lithium Niobate, (ii) DR1 Doped SU-8 polymer, (iii) Doped Silica Glass and (iv) Doped Polysilicon with applied varying Direct voltage across the electrodes.

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Table 2: Refractive index changes of material for optical MOEMS delay line

S. No.	Core Material	Refractive index (μ)	Cladding matrial	Buffer layer	$\mu+\Delta\mu$ (for 100 V)
1	Lithium Niobate	2.31	SiO_2	Air	0.01874
2	DR1/SU-8	1.588	SiO_2	Air	0.005
3	Doped silica glass	1.45	–	Air	0.0047
4	Doped Poly-silicon	3.45	SiO_2	Air	0.0281

We demonstrated the linear change in refractive index for various materials such as Lithium Niobate, DR1 doped SU-8 polymer, and doped Polysilicon as shown in table 2. The change in refractive index of the order of 0.01 to 0.02 could be observed for an applied voltage of 100 V above respective material with specific electrode arrangement and design. This change is enough to generate few mm of optical path length change. For a geometrical length of 50 mm, the change in optical path will be 2.5 mm, if the 0.05 change in refractive index, such change could be achieved vary easily using the EO effect. It is seen, Poly-silicon is the stronger material candidate for generating maximum change in the refractive index in electro-optic effect with parallel plate capacitor configuration. We demonstrate design and simulation of MOEMS delay line on a chip. Chip can be fabricated by adopting the MUMPs process.

4. Conclusion

To conclude, for optical communication applications, we used materials such as lithium niobate, DR1-doped SU-8 polymer, and doped polysilicon to design and analyze MOEMS optical delay generator. Under a 100 V voltage, these materials show a change in refractive index of 0.01 to 0.02, which is enough to cause changes in optical path length. A 0.05 change in refractive index causes a 2.5 mm change in optical path for a 50 mm length. The electro-optic (EO) effect for optical communication systems makes it simple to achieve this effect.

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