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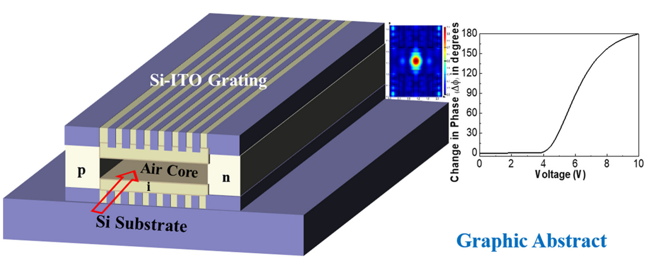

Graphic Abstract

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Slow Light Enhanced Phase Shifter Based on Low-Loss Silicon-ITO Hollow Waveguide

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Abstract: An optical phase shifter based on narrow-core hollow waveguide is proposed. The light is guided in an air core between the top and bottom reflectors made up of silicon and indium tin oxide (ITO) gratings. The proposed narrow-core hollow structure is able to guide slow light mode with a low loss of 0.2 dB/cm and a high group index of 64 in 0.8 μm thick air core. The presence of ITO enables electrically controlled phase shifting. In order to realize phase shifting, a p-i-n junction in ITO is used around the air core and in the top and bottom gratings. The geometry is optimized for enhanced interaction between the free charge carriers injected in the intrinsic region of ITO and the propagating optical mode. The proposed device shows a phase shifting of 180° for a 71-μm long device resulting from the slow-light effect.

Index Terms: Hollow waveguide, phase shifter, slow light, electro-optic modulation, indium tin oxide.

1. Introduction

On chip versions of hollow waveguide are promising for integrated photonics. Hollow core waveguides have found numerous applications in sensing, dispersion compensation in fiber optic links, tunable filters, spot size converters and Bragg reflectors [1]–[6]. Hollow-core waveguides offer inherent advantages of low nonlinearity, high thermal stability, wide tuning and low loss with strong optical confinement. Also, on-chip devices based on hollow waveguides are advantageous especially in case of small-scale integration of optical modules into core [8]–[9]. There have already been several reports on low-loss hollow waveguides based on distributed Bragg reflector (DBRs) and high index contrast gratings (HCGs) [3], [9]–[11]. Hollow waveguide based on grating reflectors can be considered as a basic module for many applications in integrated photonics [2], [8]–[10]. Grating based reflectors usually provide high reflectivity at different incidence angle for broad wavelength range [10]. In hollow waveguides, HCGs are used a top and bottom reflector for confining light in air-core. These reflectors when separated by air with periodicity being normal to the propagating light provides high reflectivity at grazing angles with low loss [3]–[5], [9], [12]. At the same time the temperature dependence of the hollow waveguide remains negligible considering the air core and hence can further be utilized for making temperature independent on-chip optical devices. [8], [11]–[14].

Optical modulation is a desired function which has been in demand and lot of efforts has been put to explore efficient optical modulation especially with silicon [15]–[19]. The discovery of new materials with unique properties is providing base for advancement in optoelectronic devices. Tremendous research has been done for the evolution of the materials whose refractive index can be changed remarkably with the application of low power optical signal. Most importantly these materials should be easily fabricated by utilizing existing complementary metal-oxide semiconductor (CMOS) fabrication platform. Transparent conducting oxides (TCO) are potential candidates to be used in active photonic devices like optical modulators. TCO's are widely used in optoelectronic technologies such as photovoltaics, optical modulator, flat panel displays etc. due to its optical transparency and conductivity. A unit order refractive index changes in TCO's gave direction to be used as an active material in an electro-optic modulator. This electro-optic modulation arises due to free carrier modulation which is related by Drude model [18]–[20]. Among various TCO's, Indium Tin Oxide (ITO) exhibits the refractive index change of the order unity making it a potential candidate to achieve efficient electro-optic modulation in optical waveguides. ITO exhibits unique properties for optoelectronics such as high carrier density for a tunable permittivity [18], [20]. Electrically induced phase changes in ITO can be utilized to make optical modulators and switches. Optical modulation efficiency can be further improved upon slowing the guided light [20]. Slow light is characterized by a large value of group index, $n_g = c/v_g = c\ dk/d\omega$ where k is wave number and ω is angular frequency. Group index shows the slow down factor of light in comparison to the speed of light in vacuum c. Slow light in high contrast grating based hollow waveguide can be used for numerous applications like optical buffers, optical delay lines etc [21]–[27].

In this work, a phase-shifter based on a hollow-core waveguide is proposed. Excellent properties of grating-based reflectors are used to compensate the losses in hollow waveguides. In the proposed design, Si-ITO HCGs is utilized as top and bottom reflector to guide light in the air core. A narrow core is most suitable to slow down the light in hollow waveguide with an optimized design of highly reflective top and bottom mirrors. A low loss of 0.2 dB/cm with a group index of 64 is reported. An efficient phase-modulation is realized with a 71-μm long device which utilizes slow light effect in a low-loss hollow waveguide with narrow air-core. Phase-shifting of the guided optical mode in the air-core is realized by electrical tuning of ITO which alters the refractive index of ITO. A p-i-n junction in ITO is utilized in between Si-ITO HCGs where left and right cladding of the hollow core is p-type ITO [29] and n-type ITO respectively. The accumulation of charge-carriers in intrinsic region of ITO under the air core leads to phase modulation of propagating optical mode. The simulation of HCGs for high reflectivity is based on Rigorous coupled wave analysis (RCWA). RCWA is a semi-analytical method applied to solve scattering from periodic structures. The modal and dispersion analysis of waveguide is performed with Finite Difference Eigen mode (FDE) method in Lumerical mode and electrical simulation of device is performed using charge transport solver in Lumerical device. The charge transport solver provides information about carrier accumulation in intrinsic region of ITO with respect to forward bias voltage. An np density grid attribute in Lumerical mode takes the carrier charge density from Lumerical device and corresponding changes in real and imaginary part of refractive index of ITO is calculated according to Drude model. The change in refractive index of ITO leads to change in effective index of propagating mode and consequently eigen mode solver calculates the optical mode at different voltages. For dispersion analysis the mode properties (group velocity and group delay) is swept over different wavelengths using frequency analysis in Finite difference eigen mode solver.

2. Proposed Design

The schematic of the proposed phase-shifter based on hollow waveguide is demonstrated in Fig. 1(a). The hollow waveguide is made up of Si-ITO HCGs placed as the top and bottom

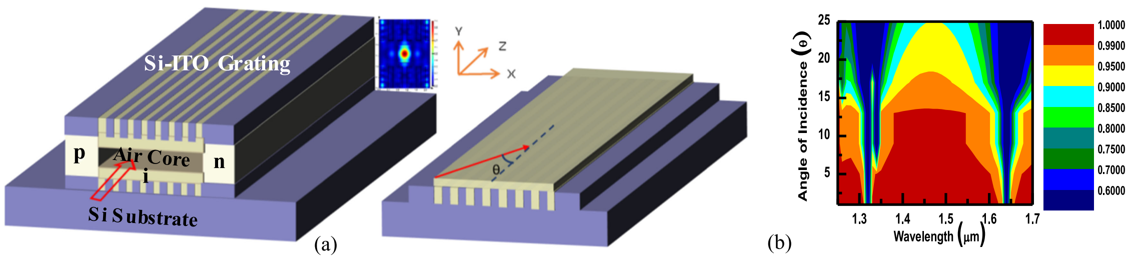

Fig. 1. (a) Schematic of phase-shifter based on hollow optical waveguide with grating reflectors of Si-ITO acting as top and bottom grating-based reflector on Si wafer designed for 1.55μm center wavelength and Air-core thickness D = 0.8μm. A p-i-n junction in ITO is utilized to alter the phase of guided optical mode in the air-core D. The left and right cladding of hollow region is p-type ITO and n-type ITO respectively. Inset image shows the mode-field distribution in the hollow core waveguide at 1.55μm center wavelength. (b) Calculated reflectivity spectra with respect to angle of incidence (θ) varying from 0°-25° for HCG in hollow waveguide when the air-core thickness D = 0.8μm, grating height $t_g = 1\mu$m, grating period $\Lambda = 0.4\mu$m and duty cycle is 0.5.

grating-based reflectors to guide the light strongly in an air-core. In this grating mirror many reflections add up constructively and procreate vertically high reflectivity. Because of the high refractive index contrast between Si and ITO as refractive index of Si is 3.48 and that of ITO is 1.827, so only 7 pairs of Si-ITO in both the gratings are sufficient to achieve a high reflectivity. A p-i-n junction in ITO is introduced near hollow core to change the phase of the guided optical mode in the narrow air core. The presence of p-type ITO [29] and n-type ITO as a cladding and intrinsic ITO under the core leads to accumulation of charge carriers in intrinsic region when forward biased. In grating-based reflector, the transmitted waves undergo destructive interference and grating parameters are optimized for efficient propagation of light through hollow waveguide. The critical design parameters for grating-based reflectors are grating period ($\wedge$), grating teeth width (W), grating height (t_g), and grating duty cycle(C). The total width of the higher index material and the surrounding lower index material is defined as Grating period ($\wedge$). Duty cycle (C) denotes the fraction of the grating teeth width of higher index material and grating period. The air-core thickness D is the air gap between two grating-based reflectors and is fixed at 0.8 μm which is small enough to show slow-light effect and still maintain low-loss operation at an operating wavelength of 1.55 μm. The optimum value of the grating period is $\Lambda = 0.4$ μm in the proposed design. In a hollow waveguide, the optical rays will be incident on shallow angles because of which it is crucial to design grating reflectors at shallow angles. This optical incidence on grating leads to excitation of many diffraction orders. Fig. 1(a) represents the propagation of field inside the hollow core due to the reflection form gratings. In hollow core waveguide, as optical beam propagates through the guiding region it undergoes several numbers of reflections. Because of these numerous zigzag reflections from HCGs, the loss of the propagating optical mode depends on the reflectivity of the designed HCG based mirrors. So, by utilizing these high reflectivity HCGs, light can be guided in the hollow core at different incident angles (0°-25°). From Fig. 1(b) it is evident that the Si-ITO HCG is optimized for high reflectivity at shallow angles for broad wavelength range. However, as angle of incidence increases there is decrement in reflectivity. The basic optimization of the device for low-loss is based on two critical parameters i.e., grating period (Λ) and air-core thickness D. The grating period (Λ) and grating height (t_g) is kept same for both top and bottom grating-based reflectors. The optical loss per unit propagation length L when material loss is not considered in the proposed device is given as [3]–[5], [14]:

$$\alpha(dB/cm) = -10\frac{\tan\theta}{D}\log R \tag{1}$$

where R is the reflectivity of the grating-based reflector at an incidence angle of θ. The loss of 0.2dB/cm is calculated for the proposed design which is quite a low value for practical applications. Hence a narrow core hollow waveguide with can be used for making numerous low-loss optoelectronic and photonic devices. For the fabrication of proposed slow light enhanced phase shifter based on Si-ITO hollow waveguide, the top and bottom Si-ITO grating based reflectors can be prepared by electron-beam lithography followed by dry reactive ion etching. Dual ion beam sputtering technique can be utilized for the deposition of ITO whereas for the fabrication of air-core in between top and bottom reflectors selective wet etching can be done [3], [7]–[8], [10]–[12].

3. Slow Light Characteristics

Slow light has opened much important functionality for variety of applications [21]–[27]. Hollow waveguides can be tailored to show slow light characteristics [4], [14]. Basically, large amount of first order dispersion give rise to slow light effect. First order dispersion is seen in coupled resonators optical waveguides; all pass cavity array, photonic wire waveguides etc. An optical signal is usually affected by change in group index n_g which produces controllable delays. Slow light is remarkably exhibited by low group- velocity (i.e., high group-index) arising from large first order dispersion. Group velocity is given as $v_g = c/n_g = c(d\omega/dk)$; where n_g is group index, ω and k denotes angular frequency and wave number respectively [4], [14], [21]–[27].

This group index signifies the slow-down factor from the velocity in vacuum (c) and is used to quantify the slow-light effect. Usually low group-velocity arises from immense first order dispersion due to optical-resonance from materials (i.e., material dispersion) or due to dispersion from periodic engineered structures mainly photonic-crystal-waveguides (i.e., Waveguide dispersion) [21], [25], [27]–[28]. In the proposed structure, periodic high contrast grating structures (1-D) are employed to produce slow light effect. The grating structure will give multiple reflections in the hollow core region. These reflections will result in slow-moving light due to its small forward components in case of narrow core.

The increase in group index with decreasing core thickness suggests slow light for a narrow hollow core [3], [14]. The proposed device is optimized for the narrow air core of thickness 0.8μm. Fig. 2(a-d) shows the calculated group velocity, group index, dispersion and group delay of propagating optical mode at different wavelengths. The lowest group velocity ($3.47*10^6$ m/s) was calculated at 1.554μm and group velocity at 1.55μm is $4.64*10^6$ m/s. The group velocity spectrum depicts lower group velocity around 1.55μm suggesting slow light mode near to band-edge in the proposed device. The inset graph Fig. 2(a) shows the photonic band diagram (ω-k) of the proposed device. The band diagram manifests the slow light mode near to band-edge (i.e., k = 0.258) corresponding to 1.55μm. The dispersion spectrum depicts sudden increase in dispersion around the wavelengths nearer to 1.55μm assuring the presence of slow light region. The calculated group index and dispersion at 1.55μm is 64 and $1.867*10^7$ ps/nm/km respectively. And the group index spectrum shows that slow-light bandwidth is approximately 8nm. Although in the proposed device the value of group index is 64 at 1.55μm and 86 at 1.554μm. But as our main aim is to modulate the propagating mode at 1.55μm and this moderate group index at 1.55μm is enough to achieve improvement in the phase modulation with practically low loss. Because stronger light-matter interaction resulting from slow light effect will lead to stronger electro-optic coupling in the device. At the same time the shift in the wave number Δk is more (enhances in proportion to n_g) in slow light as compared to fast light. And the phase shift $\Delta\Phi$ being proportional to ΔkL, hence slow light improves the modulation efficiency [25].

In the proposed device the optimization of grating period (Λ) is done to achieve high reflectivity $\sim$99%, so that there is strong optical confinement inside the air core of thickness 0.8μm with low loss of 0.2dB/cm calculated using equation (1) at the center wavelength of 1.55μm. Undoubtedly a narrow air core is best suited for slowing down the light, but propagation loss remains a major issue. The comparatively high loss in narrow core than broader core is due to decrease in reflectivity of grating because of which light leaks outside the core. The same has been simulated by increasing the core thickness and at different D, group index and loss has been calculated as shown in Fig. 2(e). Fig. 2(e) shows that loss at narrow air core is larger than that of broader core. On the other hand, larger group index (i.e., slow light regime) is achieved in case of narrow core as compared to broader core. Hence it is possible to further slowdown the light and achieve higher group index with narrower

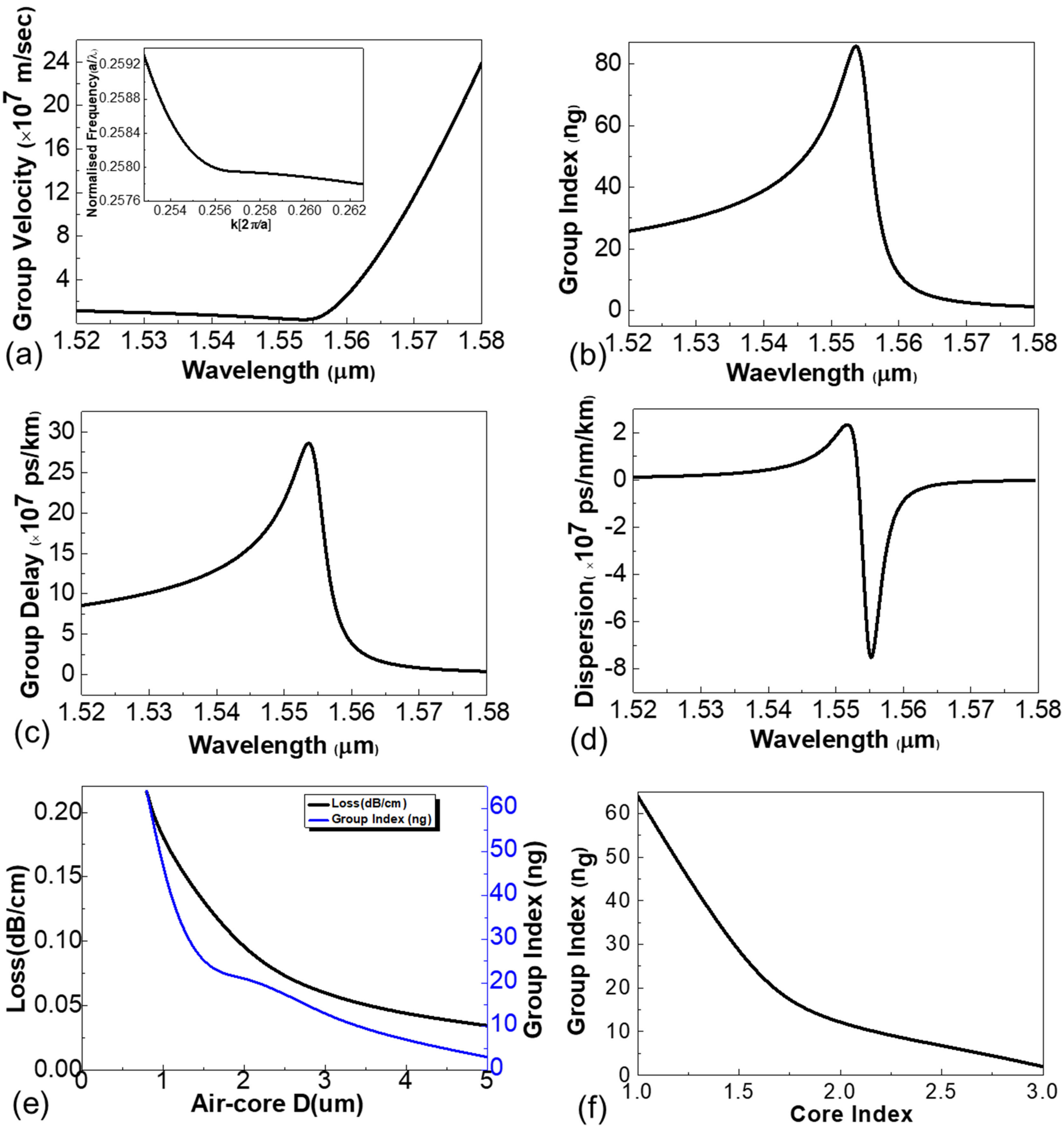

Fig. 2. (a) Calculated group velocity (inset graph shows photonic band diagram (ω-k diagram) (b) Group index (c) Group delay (d) Dispersion with respect to wavelength (1.52-1.58) μm of a proposed hollow waveguide. (e) Propagation loss and group index of the propagating optical mode at different air core thickness D (0.8μm-5μm) at an operating wavelength of 1.55 μm; grating thickness $t_g = 1\mu$m, grating period $\Lambda = 0.4\mu$m and duty cycle is 0.5. (f) Effect of material in the core on group index of the propagating optical mode at a core thickness of 0.8 μm at an operating wavelength of 1.55 μm; grating thickness $t_g = 1\mu$m, grating period $\Lambda = 0.4\mu$m and duty cycle is 0.5.

air core. But the propagation loss of the waveguide drastically increases on further narrowing the core size. Hence there is trade-off in between propagation loss and group index exhibiting slow light characteristics.

Fig. 2(f) represents the effect of material in the core on the group index of the guided mode in the waveguide. Refractive indices are varied from 1 to 3 at a core-thickness of 0.8μm. It is evident that the presence of air in the core-region can significantly reduce the group velocity in the waveguide resulting from a higher index contrast between core and cladding. The presence of higher refractive index at the core significantly reduce the group index of the light as it will be guided by total internal reflection instead of reflections from the high contrast grating allowing lesser interaction with the surrounding grating.

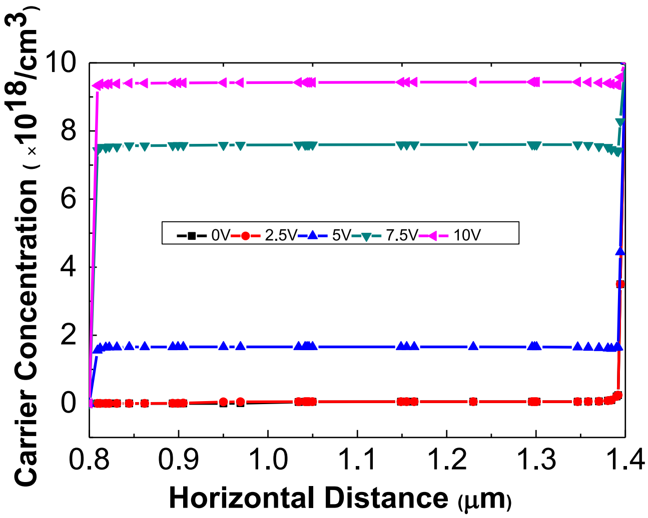

Fig. 3. Injected carrier density along horizontal direction ranging from 0.8μm-1.4μm, i.e., in intrinsic region under the 0.8 μm thick air-core.

4. Electro-optic Modulation in ITO

The possible strength of electro-optic modulation in ITO is based on Drude model which connects carrier concentration with refractive index. This model has been previously used for various TCOs including ITO and according to this model the complex permittivity is related to carrier concentration [15]–[16], [18]–[20]. The change in the permittivity ($\Delta\varepsilon$), results in change in the refractive index (Δn) which is given by $\Delta n = \Delta\varepsilon/2\sqrt{\varepsilon}$ [18], [20]. These changes become larger as the permittivity reduces. A large change in index will further lead to change in real part of index. The corresponding change in real part of refractive index due to change in carrier concentration is given as [15], [18], [20]:

$$\Delta n = \frac{-e^2\lambda_0^2}{8\pi^2}\left(\frac{n_e}{m_{ce}^*} - \frac{n_h}{m_{ch}^*}\right) \quad (2)$$

where Δn & $\Delta\alpha$ is change in real part of refractive index, n_e & n_h is electron and hole density respectively, e is electronic charge, m_{ce}^* & m_{ch}^* are effective mass of electron and holes respectively and λ_0 is center wavelength. To achieve carrier injection in the intrinsic region and reasonable change in refractive index and phase, there should be sustainable current flow through the device. Henceforth, a p-i-n junction in ITO is introduced around the air core to maximize the phase change of the optical mode via carrier injection, as shown in Fig. 1(a).

The application of forward bias voltage to the p-i-n geometry injects holes and electrons across the intrinsic region of ITO altering its charge carrier profile as shown in Fig. 3. The carrier injection usually depends on the doping concentration of the p and n regions. Initially, both n and p region were doped to a density of 1 x 10^{19}/cm^3 while the carrier density of intrinsic region was 5 x 10^{15}/cm^3 which got increased to 9.58 x 10^{18}/cm^3 with voltage. It is evident from Fig. 3 that there is sudden increase in carrier concentration in intrinsic region after 4Volts. According to Drude model, there will be sharp change in refractive index only above plasma frequency ω_p. However, plasma frequency is a function of charge carrier's density and minimum amount of charge carriers are required to bring plasma frequency near operating frequency. In the proposed device, knee voltage i.e., 4V is the onset point where plasma frequency shifts towards the operating frequency [20]. And according to the plasma dispersion relation discussed above this change in the carrier concentration profile alters the refractive index of ITO leading to a change in phase of guided mode.

For an efficient modulation, the change in ITO's index should influence the effective mode index of the device. Due to the carrier accumulation in intrinsic region of ITO, effective index changes

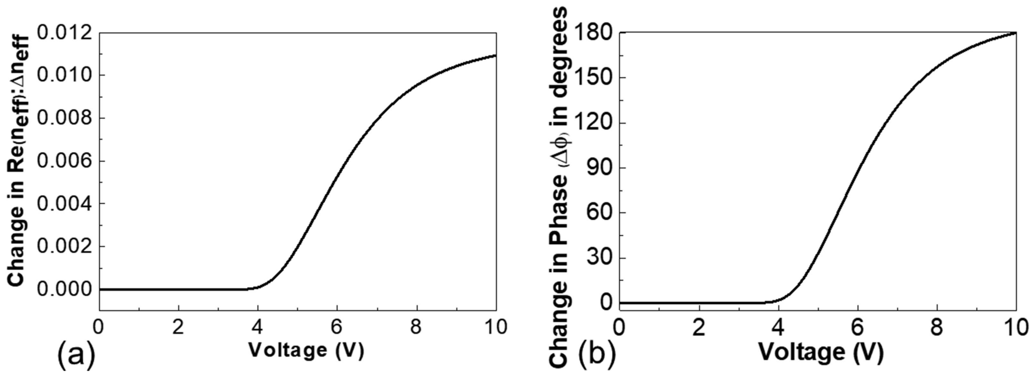

Fig. 4. (a) Change in real part of effective index with voltage due to accumulation of charge carriers in intrinsic region under the 0.8μm thick air-core. (b) Resulting change in phase of propagating optical mode with voltage due to change in real part of effective index.

from 0.0976+i0.6906 to 0.0866+i0.07799. It is evident that with increase in charge accumulation in intrinsic region there is decrease in real part of effective index. The real part of effective index denotes the phase velocity, so change in real part will lead to phase modulation. The change in phase of the propagating optical mode due to change in real part of effective index is given by $\Delta\phi = 2\pi\Delta nL/\lambda_0$ [16], [17], where L is the length of the active region of the device. The change in real part of the effective index and the corresponding change in phase of the propagating optical mode is shown Fig. 4(a) & (b) respectively. As the change in real part of the effective index (Δn_{eff}) is 1.09 x 10^{-02} for a maximum voltage of 10Volts, so a device of length 71μm is sufficient to achieve 180° phase shift in the propagating optical mode. The group index being directly proportional to Δk will give large Δk in the slow light region and small Δk for the fast light region [30]. Hence the decrease in group index will give larger modulation length as phase change $\Delta\phi$ being proportional to ΔkL concreating our view that slow light enhances modulation capability. This phase modulator can further be used as an intensity modulator by employing it into Mach-Zehnder interferometer. Secondly short modulation length due to slow light is accompanied with an added advantage of dispersion compensation in hollow waveguide allowing highly efficient phase modulation [30]–[33].

5. Conclusion

A hollow waveguide phase-shifter based on a simple approach is proposed. Grating structures, in top and bottom reflectors of hollow waveguide, use short gratings which is promising for cost-effective fabrication. A device length of 71μm is sufficient to achieve efficient phase-shifting property. The grating reflectors in hollow waveguide shows high reflectivity at shallow angles for a broad range of wavelength. A low-loss of 0.2dB/cm is reported in 0.8μm thick (narrow) air-core. Group index of 64 is reported which exhibits slow light characteristics in narrow core hollow waveguide. Considering the slow light effect, a narrow air core is best suited for slowing down the light, but larger propagation loss remains a major issue. The slow light effect usually increases the loss by a factor related to the group index ng and there is a trade-off in between propagation loss and group index exhibiting slow light characteristics. Other losses such as loss (scattering) due to roughness and coupling losses will be present in practical structures. Improved fabrication process with monolithic grating couplers can reduce these losses to acceptably low values for practical applications. An electrically tunable transparent conducting oxide i.e., ITO is used to achieve phase-modulation. Narrow air-core results in efficient modulation of phase as interaction of accumulated charge carriers and optical mode increases in the core region. Hence an effective index changes of the order $10^{-2} - 10^{-3}$ is sufficient to achieve phase modulation of light in grating based hollow core waveguide. The proposed device may open new applications of integrated hollow waveguides.

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