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Modulation efficiency enhancement of an optical phase modulator using one dimensional photonic crystal structures

Seyedreza Hosseini*, Kambiz Jamshidi
Integrated photonic devices, Faculty of Electrical and Computer Engineering, Communications
Laboratory, Technische Universität Dresden
Helmholtzstraße 16 01069 Dresden

ABSTRACT

Slow light effect based rib silicon waveguide structures are studied in this paper to enhance modulation efficiency of an optoelectronic carrier plasma dispersion effect based phase modulator. Center frequency to achieve desired slow down factor and band width limitations of the structures are investigated through finite element method simulations. Optical modulation efficiency is modeled and the effects of doping, bias voltage and slow light on its performance are studied.

Keywords: Optical modulator, corrugated waveguide, slow wave structure, modulation efficiency

1. INTRODUCTION

By emerging CMOS compatible platform to realize photonic components, optical modulators with higher efficiencies are required to map the electrical signal to the optical signal in a more energy efficient way [1]. One approach to improve the efficiency of optical modulators is to use photonic crystals to enhance the optical field and increase the efficiency of the modulators [2]. Using two-dimensional photonic crystals higher slow down factors can be achieved, but they are very sensitive in terms of fabrication and cannot be realized using ordinary photolithography techniques.

In this paper, we will consider the effect of slow down factor on modulation efficiency of two optical phase modulator architectures. Based on the modal analysis, their dispersion diagram for TE like mode have been calculated and based on that, group velocity and group index of these designs have been determined. The voltage level requires to achieve π phase shift has been obtained through the semi analytical model. This model is based on modeling carriers in a P-N diode and using both Drude and Soref models for carrier plasma dispersion effect [3]. Sensitivity of the structures in terms of structure dimension variations has been investigated and limitations of these structures in terms of bandwidth and induced group velocity dispersion have been shown.

2. DEVICE STRUCTURES

Dispersion diagram of any optic device has great information about its wave propagation behavior. In periodic structures, Maxwell equations result band diagrams using Bloch boundary conditions [4]. Based on the shape of the waveguide structure, the electromagnetic modes curve's slope may be close zero which helps us get our desired features [5]. Based on the definition, group velocity (v_g) can be obtained from dispersion band diagrams which are related to slope of the band diagram. Group index is defined as ratio of speed of light to group velocity of the structure ($n_g=c/v_g$).

Principle of operation in many optical intensity modulators is based on phase interferometers and by involving slow light effect in their designs, modulation efficiency can be improved. In the simplest way, the phase shift of propagating wave in an optical device with length of L can be calculated as

$$\Delta\varphi = \frac{2\pi}{\lambda_0} n_{eff} L \tag{1}$$

With slow light effect, the effective index is boosted which means the same phase shift can be obtained by the less length or less driving voltage.

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*seyedreza.hosseini@tu-dresden.de; phone 49 351 463 34759; fax 49 351 463 37163

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In this paper, we study two different designs for slow light structures. First is periodic corrugated waveguide [6, 7] and second one is normal waveguide with circular hole in the middle. Their dispersion diagrams have been calculated using finite elements method simulations. Different electromagnetic modes have been considered during simulations and the chosen one is a transverse electric (TE) mode which is working at wavelength of 1550 nm. Bandwidth of the structure is obtained by finding the difference between frequencies which achieve n_g=15 and second at n_g=20. By varying dimension of structures, light interaction with structure inside material would be affected. Therefore the sensitivity analysis is required to find band width and operating center frequency in which slow down takes place.

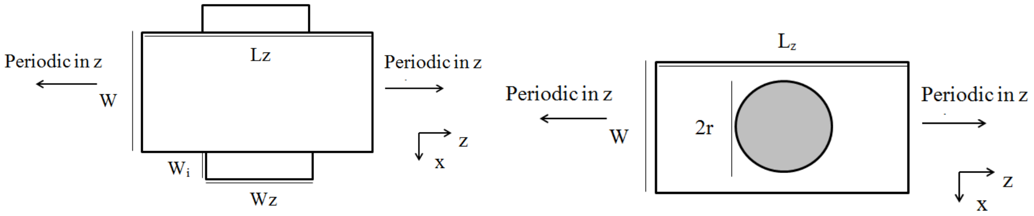
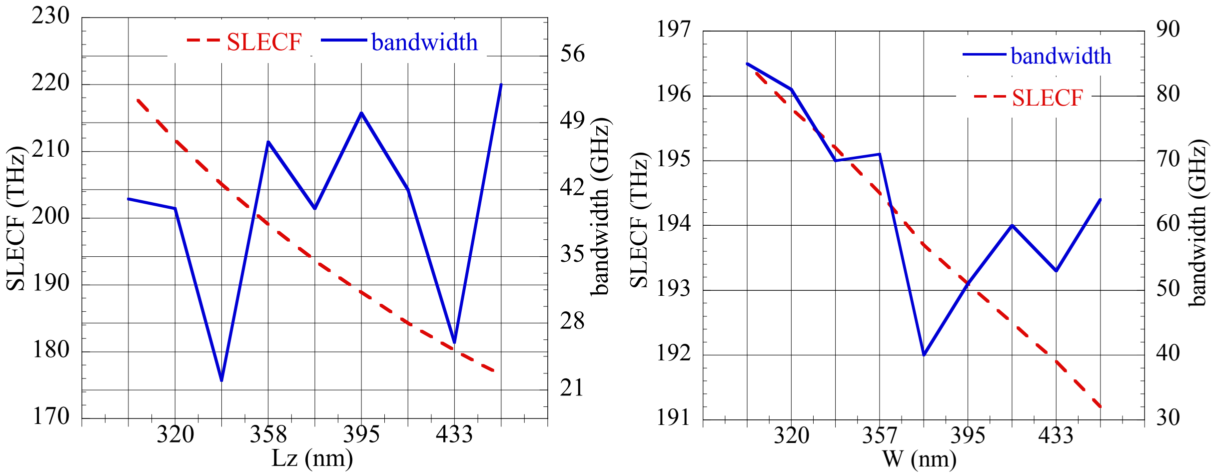


Figure 1. Top view of two unit cell designs for obtaining slow light effect

Figure 1. shows the top view of a single cell silicon rib waveguides which are cladded between silicon dioxide layers. The different parameters are chosen so that the slow light effect happens at desired wavelength. The corrugated parameters are: W=370nm, L_z=370nm, W_z=200nm and W_i=80 nm. The silicon waveguide height, etching depth and rib width are 220nm, 120nm and 500nm, respectively. The perforated design parameters are: W=490nm, L_z=420nm and r=150nm. The height of silicon dioxide layers in the top and bottom of silicon rib waveguide for FEM simulations were assumed 500nm.

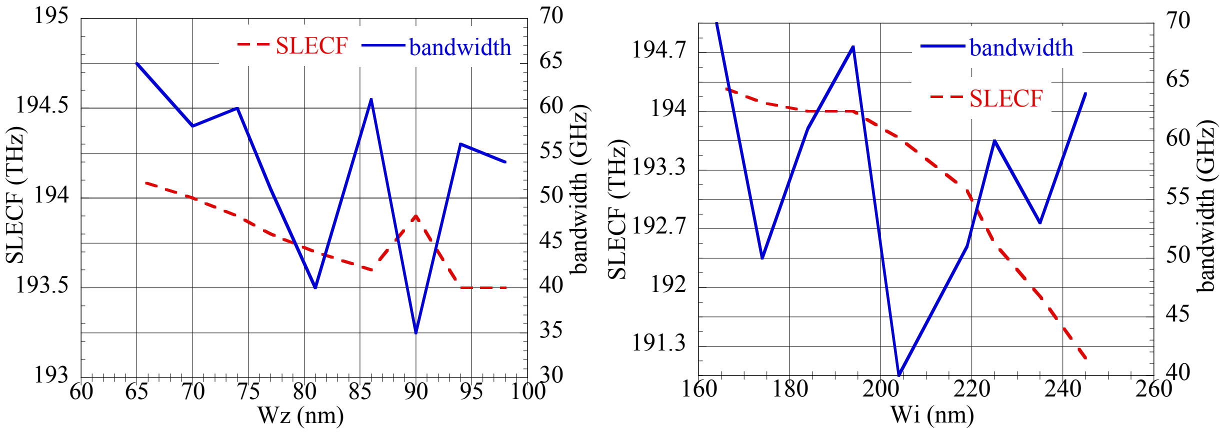


(a) (b)

Figure 2. Corrugated design L_z and W sensitivity analysis

Figure 2. shows the dependency of bandwidth and slow light effect center frequency (SLECF) on structure size (in W or L_z direction). Some kind of oscillatory bandwidth behavior versus L_z variations is observed which shows large sensitivity of bandwidth to L_z. Also, due to massive consuming computational resources for each simulation, the number of sweep procedure points are not large enough which could be the reason for the discrete and oscillatory bandwidth behavior.

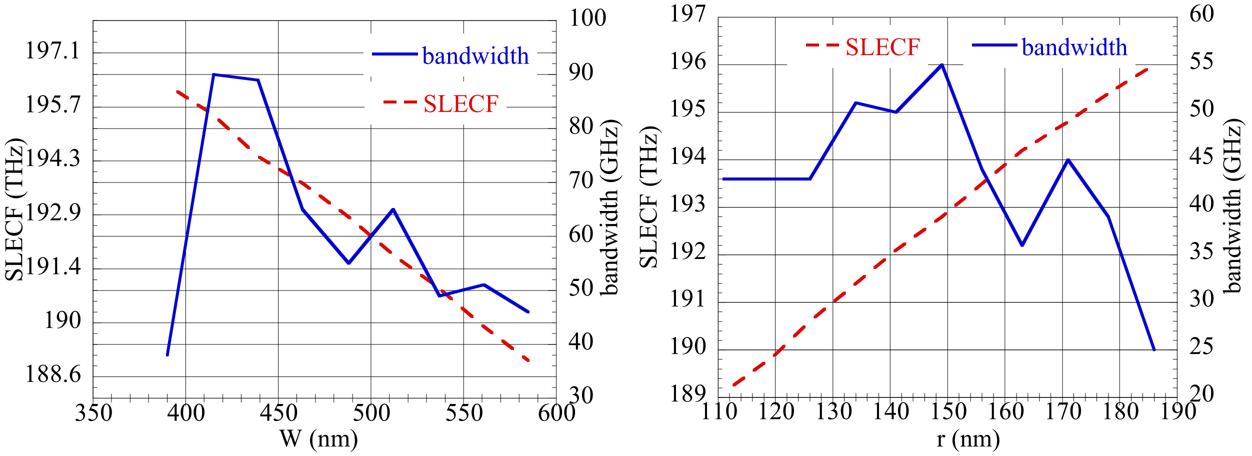
The maximum bandwidth of 85 GHz from corrugated design can be achieved as shown in figure 2b. Changing the dimensions in order to get more bandwidth is an interesting point and as we see, the higher bandwidth might be obtained if the changing of operating SLECF can be tolerated.



(a) (b)

Figure 3. Corrugated design Wz and Wi sensitivity analysis

As it is shown in figure 3, bandwidth and SLECF of corrugated waveguide design is less sensitive to W_z and W_i variations in comparison to W and L_z variations. SLECF decreases by increasing the structure size similar to SLECF behavior in figure 2.



(a) (b)

Figure 4. Hole defected design W and r (radius) sensitivity analysis

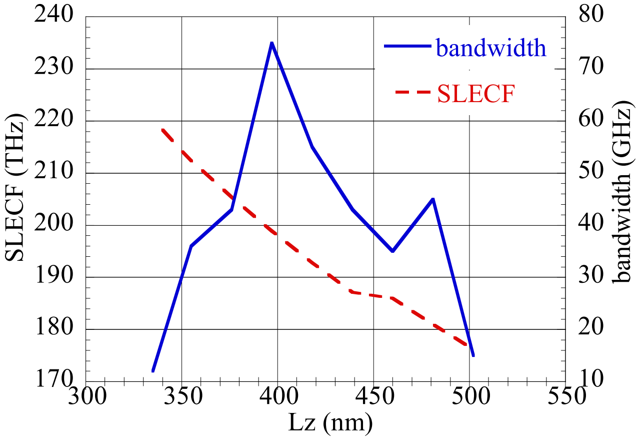


Figure 5. Hole defected design L_z sensitivity analysis

Figures 4,5. show the variation of bandwidth and SLECF for hole defected design. As it can be seen, SLECF is diminishing by increasing the structure size. The maximum bandwidth of 90 GHz has been obtained and the bandwidth is more sensitive to constitutive parameters changes.

3. PERFORMANCE ANALYSIS

Active parts of optical phase modulators are usually realized using P-N or P-I-N junctions. Based on P-N junction model, carrier concentrations change by varying external voltage and it causes change of the effective refractive index of silicon. This effect is called free carrier dispersion plasma effect which Drude and Soref models have been proposed for modeling this phenomenon [3]. The whole idea is to calculate total carrier concentration in each P and N side and then calculate their difference when external bias voltage is changing [8]. These variations (ΔN_e for electron and ΔN_h for hole), are being substituted to Soref equation:

$$\Delta n = -8.8\times10^{-22}\Delta N_e - 8.5\times10^{-18}\Delta N_h^{0.8} \tag{2}$$

Change in the refractive index value has been calculated and used to achieve the induced phase shift. The required DC voltage for obtaining π radian phase shift is shown V_π and according to proposed model can be achieved as:

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n(V)L\Gamma S \to \pi = \frac{2\pi}{\lambda}\Delta n(V)L\Gamma S \to V_\pi = \Delta n^{-1}\left(\frac{\lambda}{2L\Gamma S}\right) \tag{3}$$

where L is phase modulator length, S is structure light slow down factor(n_g/n_0) and Γ is optical confinement factor. Confinement factor is a dimensionless quantity, which specifies how much of light intensity is located inside the desired silicon waveguide and for simplicity it has been considered equal to unity in our model. The product of $V_\pi L$ is called modulation efficiency in this study.

Modulation efficiency enhancement using slow down factor has been shown in figure 6. It shows that modulation efficiency will decrease exponentially in relation to slow down factor (SD). According to figure 6 the value of needed modulation efficiency at slow down factor of 5 is 0.2 V.cm whereas at slow down factor of unity the modulation efficiency is 2.2 V.cm. This reduction in driving voltage results in reduction of energy consumption.

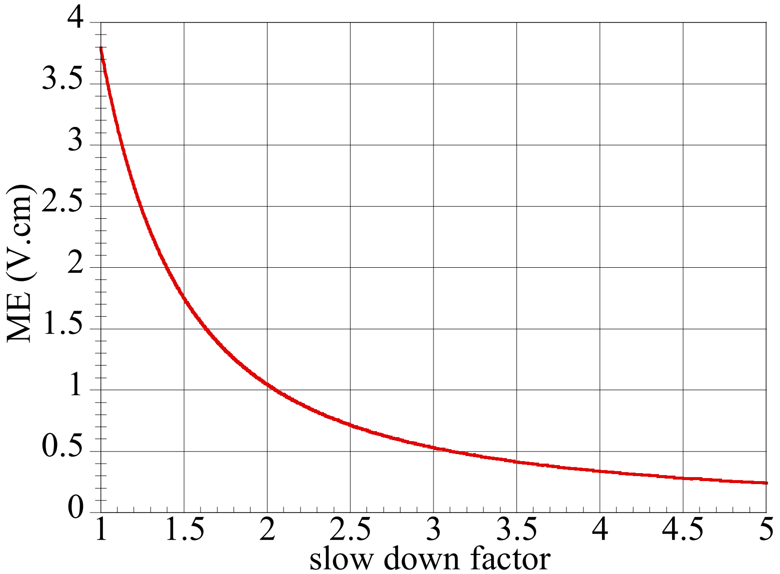
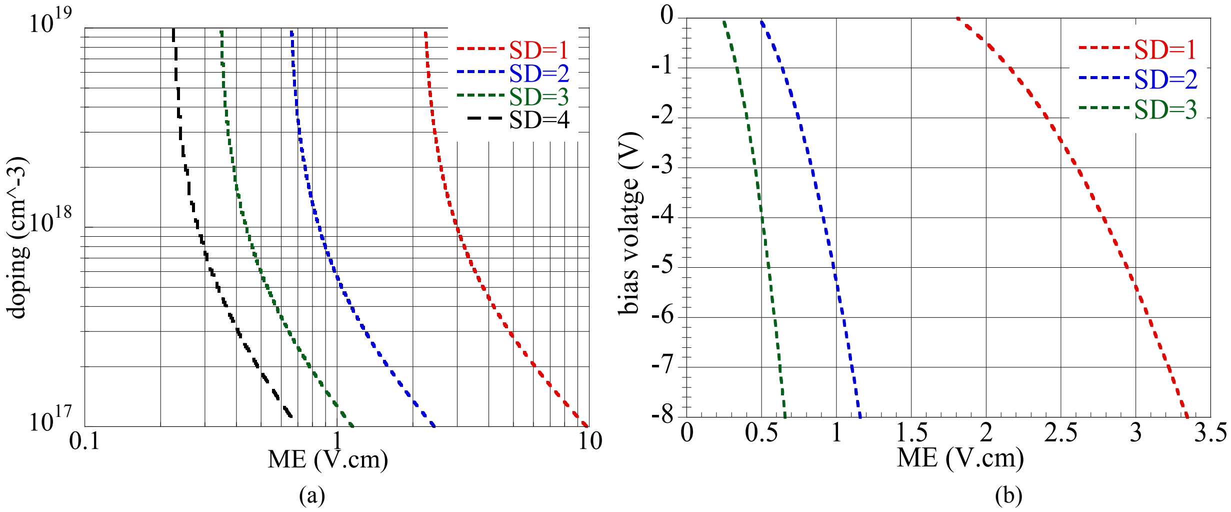


Figure 6. modulation efficiency (ME) of typical optical modulator versus slow down factor, the modulator length is 1mm, the bias voltage is 1v at reversed bias, the n type and p type doping are 5×10^{17} 1/cm^3.

The effects of doping and bias voltage on modulation efficiency have been studied through the model described before. Increasing doping levels makes depletion width larger, which causes carrier concentration and refractive index changes more. This results in a decrease in modulation efficiency as we discussed before. Modulation efficiency dependence on doping and bias voltage with different slow down factors using symmetrical doping levels have been sketched in figure 7.



(a) (b)

Figure 7. a) Modulation efficiency (ME) versus doping level of optical modulator with length of 1mm and reverse bias voltage of 1v b) Modulation efficiency (ME) versus reversed bias voltage of optical modulator with length of 1mm and doping levels of $N_A=N_D=10^{18}$ cm^{-3}

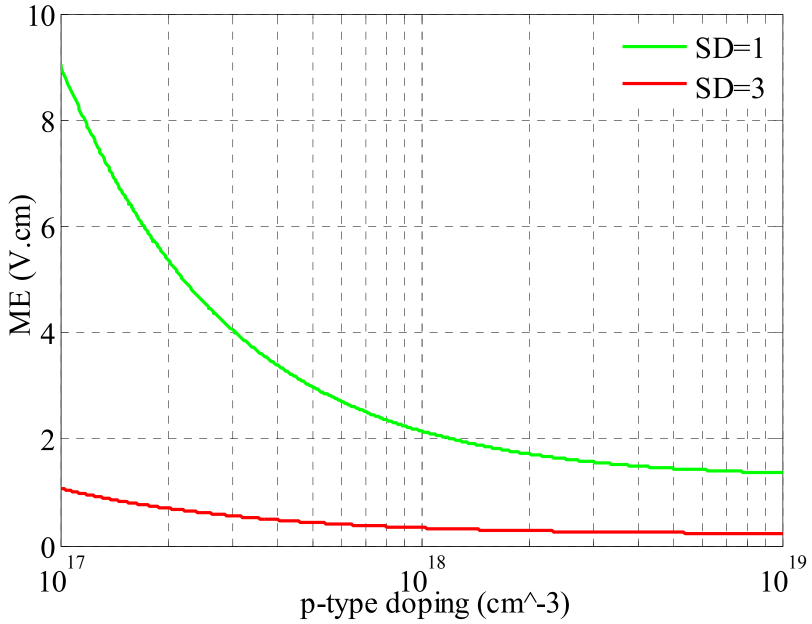


Figure 8. Modulation efficiency (ME) versus asymmetrical doping level of optical modulator with length of 1mm and reverse bias voltage of 1v, n-type doping level is 10^{18}cm^{-3}

In a more realistic case, p-type and n-type doping are different and this should affect the modulation efficiency as it is shown in figure 8. Our model shows increasing p-type doping decreases modulation efficiency as was expected. Slow down of the light group velocity can decrease modulation efficiency even more.

CONCLUSION

Two different periodic structures are studied to slow down the group velocity of light. Dispersion band diagrams and group velocities of both structures are obtained through finite element method. Slow Light Effect Center Frequency (SLECF) (center frequency in which desired slow down takes place) and bandwidth are extracted and sensitivity analysis is performed to find the optimum parameters for implementing this structure. Modulation efficiency of a typical optical phase modulator is obtained through an analytical model. Based on this model, dependency of modulation efficiency on doping, bias voltage and slow down factor is studied.

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REFERENCES

[1] Ding, J, Chen, H, Yang, L, Zhang, L, Ji, R, Tian, Y, Zhu, W, Lu, Y, Zhou, P, Min, R and Yu, M, "Ultra-low-power carrier-depletion Mach-Zehnder silicon optical modulator", Optics Express, 7081-7087 (2012)
[2] Nguyen, H. C, Hashimoto, S, Shinkawa, M and Baba, T, "Compact and fast photonic crystal silicon optical modulators" Optics Express, 22465-22474 (2012)
[3] Soref, R. A., Bennett, B.R., "Electro optical Effects in Silicon," IEEE J.Quantum Elect, 123-129 (1987)
[4] Prather, D.W, Sharkawy, A, Shi, S, Murakowski, J and Schneider, G, [Photonic Crystals, Theory, Applications and Fabrication], Wiley, (2009)
[5] Joannopoulos, J. D, Johnson, S. G, Winn, J. N and Meade, R. D, [Photonic Crystals: Molding the Flow of Light] Second Edition, Princeton university press, (2008)
[6] Brimont, A, Galán, J. V, Escalante, J.M, Martí and J, Sanchis, P, "Group-index engineering in silicon corrugated waveguides" Optics Letters, 2708-2710 (2010)
[7] Hosseini, S, Jamshidi, K, "Sensitivity analysis of high group index corrugated slow light waveguide for using in optical applications," IEEE MMWATT, (2014).
[8] S. L. Chuang, [Physics of Optoelectronic Devices], New York: Wiley, (1995)