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High-Speed Low Power Plasmonic Mach-Zehnder Modulator with Small Foot-Print

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Abstract

In this manuscript a compact high speed optical Mach-Zehnder modulator with very low energy consumption based on hybrid plasmonic waveguide is presented. Compared to dielectric waveguide-based structures, large propagation constant of optical modes in hybrid plasmonic waveguides reduces the propagation length required for attaining necessary phase shift for proper operation of Mach-Zehnder interferometer. On the other hand, strong light confinement in hybrid plasmonic waveguide facilitates realization of relatively short bends (with small bend radius) and compact Y-junctions which in turn reduces the overall footprint of modulator. Our simulations show theoretical modulation speed of more than 1 THz and very low energy consumption about 17 fJ/bit. In addition, the modulation depths as high as 25 dB are achievable by applying voltages between + 3 V and -3 V, in a push-pull configuration. Apart from electrodes, the overall footprint is about ~120 μm^2 which is, based on our knowledge, very smaller than that of common Mach-Zehnder modulators.

Keywords: Hybrid plasmonic waveguide, Mach-Zehnder interferometer, Optical modulator.

Introduction

Plasmonic technology is expected to revolutionize optical interconnects by bringing several advantages such as high bandwidth, low energy consumption and light localization beyond fundamental diffraction limit which can potentially lead to optical device integration with sizes comparable to electronics. In recent years, among various kinds of proposed plasmonic waveguides, hybrid plasmonic waveguides (HPWs) have attracted significant attentions [1] because of introducing good tradeoff between light confinement and propagation length. A HPW is formed by sandwiching a dielectric region between a metal and Si, while the refractive index of the intermediate dielectric material is less than that of Si. Because of interesting properties of HPWs many researchers have investigated HPW-based passive optical elements such as directional coupler [2], power splitter [3], and polarizer [4], both theoretically and experimentally. Strong light confinement and therefore strong light matter interaction inside a HPW can also be used to reduce the overall footprint of optical active elements such as optical modulators. During recent years HPW-based optical phase modulator [5], electro-absorption modulator [6], and intensity modulator [7, 8] in metal-oxide-semiconductor (MOS) capacitor scheme, have been theoretically investigated. In these devices, free carrier dispersion effect in the silicon region is employed for achieving refractive index change and therefore realizing optical modulation. However, this effect is relatively weak and limits the modulator performance parameters such as modulation bandwidth and modulation depth. In addition, overall footprint of the device should be relatively large to compensate for weak interaction mechanism and large footprint of the device necessitates high power consumption. As an alternative structure, by using an electro-optic (EO) polymer with large EO coefficient as the low refractive index layer of HPW, the above mentioned limitations can be contravened. Although this approach has been employed in phase modulator [9] and directional-coupler-based intensity modulator [10], but to the best of our knowledge, plasmonic Mach-Zehnder modulator (PMZM) based on Si-polymer-metal HPW has not been presented.

In this paper, we propose a high-speed compact PMZM with low energy consumption based on Si-polymer-metal HPW. The strong light confinement

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in HPW allows to realize compact Y-splitter/combiner which has been previously demonstrated [3]. Moreover, high electro-optic coefficient of polymer reduces the propagation length required for achieving a specific phase change and therefore provides the possibility of realization of compact PMZM. Our simulations show modulation depth of more than ~25 dB, modulation speed of more than 1 THz, and energy consumption of~17 fJ/bit for the proposed device.

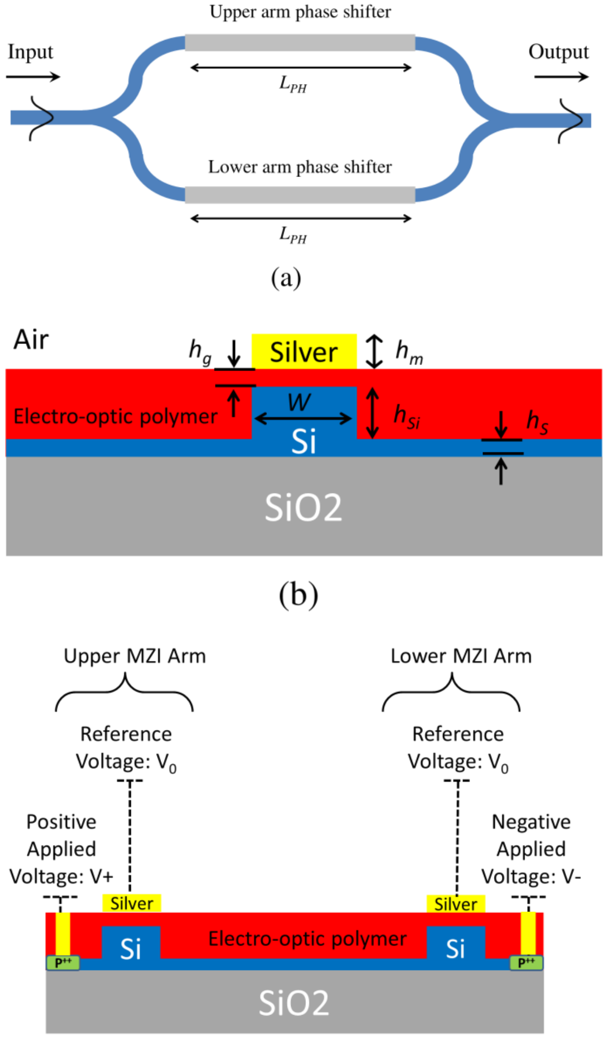
The rest of paper is organized as follows. In section 2, the structure and design of PMZM is discussed. The performance of PMZM is presented in section 3. Finally, in section 4, a brief summary and the concluding remarks are provided.

Device structure and design

The schematic of PMZM is depicted in Fig. 1(a). The modulator is made of two Y splitter/combiner sections with an interposed phase shifter region. The cross sectional view of proposed HPW is shown in Fig. 1(b). It is composed of a silicon rib waveguide buried in an EO polymer and a silver cap placed on silicon ridge. The structure is formed on a SiO_2 substrate. The refractive index of Si and SiO_2 are considered to be n_{Si}=3.476, and n_{SiO2}=1.444, respectively [11]. Using Drude-Lorentz model, the refractive index of 0.14+11.2i is estimated for silver at λ=1.55μm [12]. In addition, electro-optic coefficient and refractive index of polymer is considered to be r_{33} = 200 V/pm and $n_{polymer}$=1.6, respectively [10].

Fig. 1(c) shows the cross sectional view of phase shifter region. The phase difference between two arms of PMZM which is necessary for proper operation of the modulator is achieved by changing the refractive index of polymer through applying an electric field. Required electric field is formed by applying voltage to the contacts which are composed of doped silicon rib waveguide and silver cap over each waveguide. The silicon region is considered to be doped by Boron with concentration of 10^{18}cm^{-3}.Also,in order to achieve good ohmic contact and reduce the resistance, the outer side of 50 nm slab (pedestal) is highly doped (10^{21} cm^{-3}).It should be mentioned that reduction of waveguide resistance is desirable because lower resistance results in lower RC delay and therefore higher modulation speed.

As it was mentioned earlier in the proposed structure, Mach-Zehnder is implemented in push-pull scheme. It means that the voltage applied to each Mach-Zehnder arm introduces the same amount of phase shifts as in the other arm but with different sign (see Fig. 1(a)).



(a)

(b)

(c)

Fig. 1. (a) The schematic of PMZM. (b) The cross sectional view of proposed HPW. (c) The cross sectional view of phase shifter region.

The E_y field distribution of TM-like fundamental mode obtained by mode solution using FDTD method is illustrated in the inset of Fig. 2. It shows large electric field confinement in the gap region which confirms that the optical mode can be modulated through slightly changing refractive index of electro-optic polymer by applying relatively small voltages.

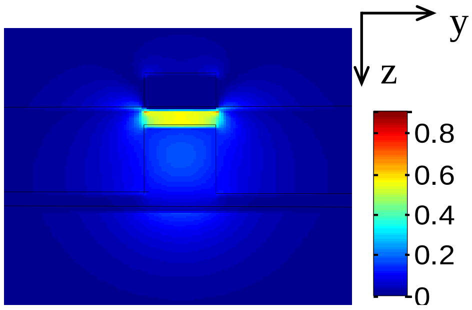


Fig. 2. The major electric field component E_y of fundamental TM-like mode

The effective refractive index changes of the polymer layer of the HPW, Δn_{eff}, due to an applied voltage V across the polymer (between silver cap and silicon) is given by [13]:

$$\Delta n_{eff} = -\Gamma n^3 r_{33} V / 2h_g \qquad (1)$$

Where Γ is the electro-optic modulation efficiency defined as ratio of the effective refractive index change of HPW to that of polymer and its value depends on geometry and material properties and can be obtained as [13]

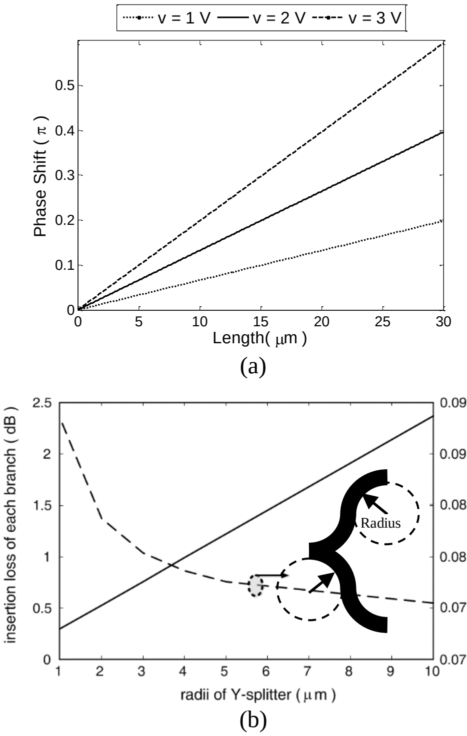
$$\Gamma = \frac{\iint\limits_{gap\ region} \left(E_V(x,y)/V\right) \left|E_{Opt}(x,y)\right|^2 dxdy}{\iint\limits_{\infty} \left|E_{Opt}(x,y)\right|^2 dxdy} \qquad (2)$$

Where $E_{Opt}(x,y)$ is the optical mode electric field distribution and $E_V(x,y)$ is the electric filed distribution under the applied voltage, V.

We choose the relevant geometrical dimensions, outlined in Fig. 1(b), as w = 200 nm, h_{si} = 200 nm, h_s = 50 nm, h_g= 50 nm and h_m = 100 nm in such a way that tight confinement, high propagation length, feasible fabrication and high modulation efficiency is achieved.

The change in the effective refractive index of the polymer layer Δn_{eff} introduces a phase change of the $\Delta\varphi(\lambda)$ in the optical mode after propagating a distance L_{PH} that is equal to; $\Delta\varphi(\lambda) = 2\pi \Delta n_{eff}(\lambda) L_{PH} / \lambda$, where in this equation λ is the wavelength of interest. The phase change $\Delta\varphi(\lambda)$ is shown in Fig. 3(a) as a function of propagation length for different values of applied voltage at λ=1.55 μm. As it can be seen, the propagation length needed for achieving π/2 phase shift in push-pull configuration is L_{PH}≈ 25 μm at the applied voltage of V= 3 V.

The Y-splitter is another important section of PMZM that should be designed in such a way that minimal loss and footprint attained. As shown in Fig. 3(b), the bending loss of HPW increases as bending radii decreases. But, loss of Y-splitter reduces because of decreasing the length. Since the loss due to propagation is much larger than the bending loss, we have chosen the radii of Y-splitter to be equal to 1 μm. In this way, the overall loss of the Y-splitter will be minimized. By setting radii of bends in the Y-splitter equal to 1μm and length of each Mach-Zehnder arm equal to 25 μm, the overall length and width of Mach-Zehnder will be 30 μm and 4 μm, respectively. Therefore, by using these values for geometrical dimensions of the structure, apart from electrodes needed for applying voltage, the overall footprint of PMZM is ~ 30×4=120 μm^{2}which is based on our knowledge very smaller than that of MZI-based modulator [14].



(a)

(b)

Fig. 3. (a) Phase shift versus the length of HPW for different applied voltages. (b) Bending loss and loss of each branch of Y-splitter at λ=1.55 μm. The inset shows the shape and radius of Y-splitter.

Simulation results

According to the interference theory of the Mach-Zehnder interferometer, the power transmission, $T(\lambda)$, can be obtained as follows, assuming unity power launched [15]:

$$T(\lambda)=\exp\left(-2\alpha_s(\lambda)L_s-\alpha_{PH}(\lambda)L_{PH}\right)\cos^2\left(\Delta\varphi(\lambda)\right) \tag{3}$$

Where α_s and L_s are the propagation loss and s-bend length of Y-splitter, respectively, and α_{PH} is the propagation loss of PMZM arm.

The power transmission spectrum of PMZM simulated by Lumerical software for various DC voltages applied to the arms is shown in Fig. 4. In this figure, overall applied voltage is considered i.e. V = ($V^+ - V^-$) in Fig. 1(c). As we can see, the modulation depth of more than 25 dB in a wide wavelength range is obtained at total applied voltage of V = 6 V (+3 V applied to one of the Mach-Zehnder arms and -3 V applied to the other). The insertion loss is calculated to be 4.6 dB which arises from inherent loss of HPW.

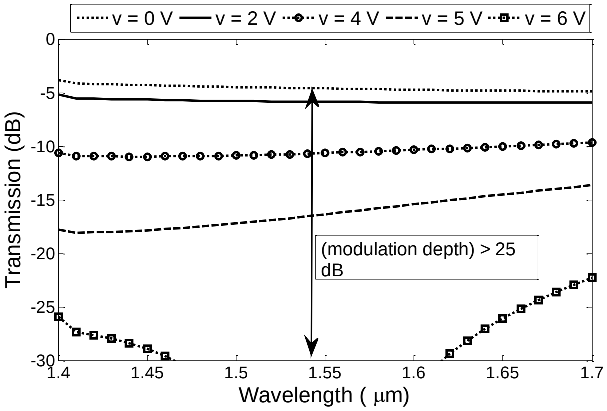


Fig. 4. Power transmission spectrum of PMZM for different voltages.

The modulation speed of PMZM depends on response time of electro-optic polymer and resistive-capacitive (RC) time delay of the structure.In the proposed structure, in each phase shift region a parallel plate capacitor is formed between the top silver layer and the doped silicon layer. The electro-optic polymer serves as dielectric layer of this capacitor. Electrostatic simulation of the structure shows the capacitance of ~3.7 fF for this structure. Also, the resistance of doped silicon ridge and 50 nm doped silicon slab is found to be ~150 Ω. Thus, the RC response time is about 555 fs which leads to a modulation speed of more than 1THz which is an order of magnitude larger than modulation speed of previously reported hybrid-plasmonic waveguide- based modulators [10]. This large value of modulation can be mainly attributed to the small resistance of the proposed structure obtained by relatively high level of doping in the silicon layer. In a normal dielectric waveguide such a high level of doping causes large optical losses while in the proposed hybrid-plasmonic waveguide, because of strong field confinement inside the polymer layer does not result in substantial loss.

The energy consumption per bit, as another important performance parameter of an optical modulator, can be calculated according to the following formula [16]:

$$Energy\ /bit = CV_{pp}^{2}/2 \tag{4}$$

Using the corresponding values for our PMZM in the above formula results in energy consumption per bit of 16.6 fJ/bit at voltage of ±3 V, which is smaller than values reported for HPW-based Mach-Zehnder optical modulators [7, 10].To sum up, low power consumption of 16.67 fJ/bit together with high modulation speed of 1 THz and small footprint of 120 □m^2 are main advantages of the proposed structure.

Conclusion

In this paper, we investigated a compact high speed PMZM with low energy consumption. The proposed PMZM is based on silicon-polymer-metal HPW. The overall footprint is about ~120 □m^2. Our simulation reveals that the theoretical speed of PMZM is more than of 1 THz and low energy consumption per bit of 16.6 fJ/bit is achievable with the applied voltage of ±3 V. In addition, the proposed structure offers modulation depth of more than 25 dB.

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