Ultra-compact High Speed Plasmonic Mach-Zehnder Modulator Utilizing Three-Waveguide Directional Couplers

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Abstract— **In this paper we propose a high speed, low energy consumption, Mach-Zehnder interferometer modulator. Bend-less three-waveguide directional couplers are employed as splitter/combiner to diminish the overall footprint while keeping the insertion loss of the structure negligible. Si-polymer-metal hybrid plasmonic waveguide is used for the Mach-Zehnder arms where the phase shift will occur. Strong confinement of the optical mode inside the hybrid plasmonic waveguide and its low group velocity propagation facilitate achieving the phase shift required for optical modulation within small propagation length. This reduces the overall length of the Mach-Zehnder modulator and therefore decreases the resistor-capacitor time constant of the structure which in turn increases the achievable modulation speed. Based on our calculations proposed modulator shows high modulation speed of ~1.1 THz, very low energy consumption of ~12 fJ/bit, and 5.5 dB loss at drive voltage of ±3 V (which is applied in push-pull scheme). Apart from electrodes, the overall footprint of modulator is ~1.5×37 μm^2. Compared to conventional electro-optical modulators the proposed structure offers very high modulation speed and low energy consumption with compact overall foot-print.**

Keywords- hybrid plasmonic waveguide, Mach-Zehnder interferometer, modulator

I. INTRODUCTION

Optical modulators play a key role in optical interconnections expecting to have high speed, low energy consumption and small footprint. Many structures have been proposed for achieving optical modulation among which Mach-Zehnder interferometer (MZI) is a attractive structure for realization of high bandwidth modulators because of its relatively high tolerance against fabrication errors and temperature variation [1]. The operating principle of the MZI optical modulator is based on destructive or instructive interference between optical waves passed through two MZI arms. This interference can be controlled by introducing different phase shifts in waves propagating in two MZI arms. As one of the most efficient methods for creating the mentioned phase shift, the free carrier dispersion effect can be employed to actively control the optical properties of Si. But this method has its own drawbacks which affect the overall modulation performance, demands relatively high power consumption and needs large propagation lengths for the required phase shift (which increases the overall length of the MZI modulator).

Advent of plasmonic has opened up a promising way to merge the advantages of electro-optic polymer, such as high electro-optic coefficient (and therefore their potential to realize high speed and low energy consumption devices), with mature SOI technology at nano-scale dimensions and beyond fundamental diffraction limit. Especially, Si-Polymer-Metal hybrid plasmonic waveguide (HPW) because of enabling high confinement of light while keeping the optical loss relatively low, have recently drawn considerable attention[2, 3]. Furthermore, it has been shown that the HPWs can be coupled to conventional Si waveguides with minimal insertion loss [4]. Because of these specifications, phase [5] and intensity modulators [6, 7] based on HPW have been investigated, during the recent years.

In this paper, we propose a compact high speed plasmonic phase shifter-based MZI (PPMZI) modulator with low energy consumption using Si-Polymer-Metal HPW. In most of the conventional MZI based modulators the splitter/combiner at input and output of the MZI is usually formed by using Y-junction splitters or multimode interferometers (MMIs). But the former needs S-bends with large radii to resolve bending loss that increases the overall footprint of MZI modulator [8] and the latter increases the insertion loss [9]. By utilizing three-waveguide coupler as splitter/combiner, the S-bend can be removed while keeping low loss. In the proposed structure, we utilize three-waveguide directional couplers as splitter/combiner of MZI which according to our simulations provide low loss and small footprint at the same time.

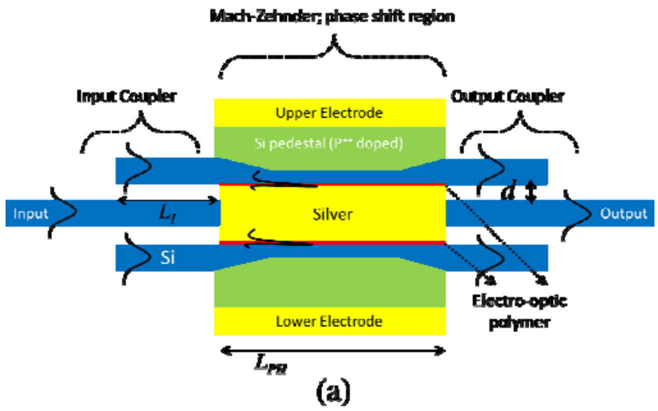
The remainder of the paper is organized as follows. In section 2, the structure of PPMZI modulator is discussed. The theoretical modelling and performance simulation of PPMZI modulator is presented in sections 3 and 4, respectively. Finally, in Sec. 5, a brief summary and the concluding remarks are provided.

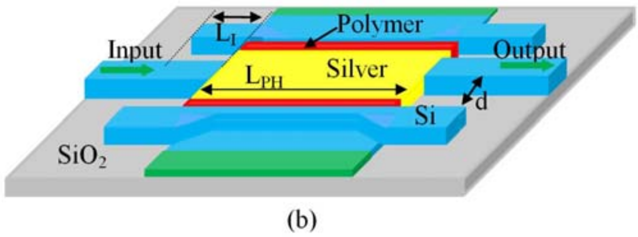
II. Structure of the Optucal Modulator

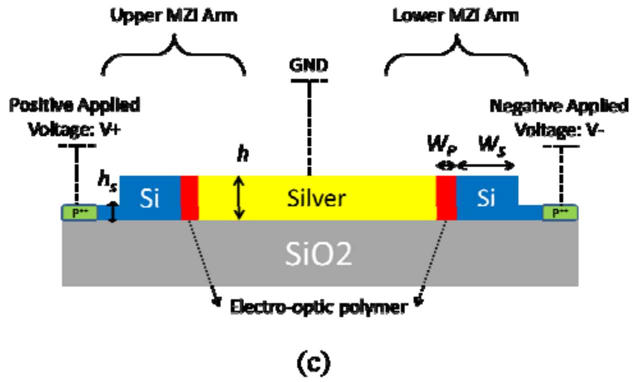
The perspective view of PPMZI modulator is depicted in Fig.1(a) and (b). As it can be seen the proposed modulator is formed by placing two bend-less splitter/combiners based three-waveguide directional coupler at both ends of the MZI arms. The MZI arms where the required phase shifts will happen are made by HPWs. In our design we have used standard SOI Si waveguides with a cross section of 450×200 nm^2 as the input/out waveguides of the modulator. As the first step of the modulator design the interaction length L_I of two coupling sections were appropriately designed to achieve a 50% - 50% power splitting between output waveguides of the coupler at the interest wavelength of λ=1.55 µm.

Output waveguides of the power splitter then should be coupled to the HPWs forming the MZI arms. Here it is done by using taper couplers, which gradually couple the optical field of the Si waveguide to that of the horizontal Si-polymer-Metal HPW in the phase shift region. The HPW consists of a polymer layer sandwiched between a Si layer and silver as shown in Fig.1 (c). In order to apply voltage and introduce a refractive index change in the polymer region, the Si core of HPW is doped with boron at concentration of 10^{18} cm^{-3}. As mentioned earlier we design the modulator for a SOI wafer with silicon layer thickness of 200 nm and therefore consider h = 200 nm throughout this paper.

The electric field profile of the HPW waveguide is plotted in Fig.1(d), which shows confinement of the optical field in the polymer nano-slot and significant field enhancement due to excitation of surface plasmon polariton (SPP) at Ag-polymer interface and electric field discontinuity at Si-polymer interface.







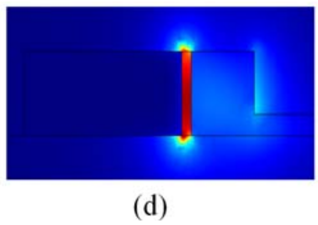


Figure 1. (a) Top view and (b) the perspective view of the proposed PPMZI modulator. Gaussian curves in (a) represent form of the optical filed profile inside the waveguides. (c) The structure of HPWs in MZI arms and electrodes needed for applying voltages. (c) The electric field of HPW.

III. Theoretical Modeling

The transfer matrix of three identical waveguides directional coupler in which the outer waveguides are spaced at the same distance d from the center waveguide is given by [10]:

$$\begin{bmatrix} A_1(L) \\ A_2(L) \\ A_3(L) \end{bmatrix} = \begin{bmatrix} (1+A)/2 & jB/\sqrt{2} & (A-1)/2 \\ jB/\sqrt{2} & A & jB/\sqrt{2} \\ (A-1)/2 & jB/\sqrt{2} & (1+A)/2 \end{bmatrix} \begin{bmatrix} A_1(0) \\ A_2(0) \\ A_3(0) \end{bmatrix} \qquad (1)$$

where $A_i(L)$ and $A_i(0)$ are the output field amplitude of the i-th waveguide; WG_i, and the input field amplitude of WG_i, respectively for i=1, 2, 3. L is the coupler length, A and B are given by $A=cos^2(\sqrt{2}\kappa L)$ and $B=sin^2(\sqrt{2}\kappa L)$, respectively, and κ is the coupling coefficient between adjacent waveguides.

According to Eq. (1), the input power at the center waveguide can be divided equally between two outer waveguides for $L_I=\pi/(2\sqrt{2})\kappa=L_C/2$ where L_C is the coupling length for complete power transfer between two outer HPWs i.e. HPW1 and HPW3, and can be obtained from (1) as $L_C=\pi/\sqrt{2}\kappa=\lambda/(n_a-n_c)$,where n_a and n_c are the real part of the effective refractive indices of the first and third super modes of three HPW directional coupler. So, three-waveguide directional coupler can be utilized as splitter or combiner.

Now we consider the MZI. Neglecting loss, the transmission ratio of the MZI modulator is given by:

$$P_{out}/P_{in} = \cos^2(\Delta\varphi/2) \quad (2)$$

where $\Delta\varphi$ is the phase difference between optical waves in two arms at the output end of the MZI. Equation (2) indicates that by introducing controlled changes in the phase difference between two arms of PPMZI modulator, amplitude of the input light can be modulated at the output.

IV. Simulation Results

In our simulation, the refractive index of Si, SiO2 and silver are assumed to be n_{SiO2} = 1.444, n_{Si} = 3.476 [11] and n_{silver} = 0.14+11i [12], respectively at wavelength of λ=1.55 µm. In addition, we have used an electro-optic polymer with refractive index of $n_{polymer}$ = 1.6 and r_{33} = 200 pm/V which has been reported in [13] to have good stability.

To achieve the optimized splitter/combiner structure, the coupling length of three waveguides L, and the distance d between inner and outer waveguide were changed and output power of the splitter was measured. Fig. 2(a) shows the coupling length of splitter L as a function of the distance d for the structures in which 50-50% is achieved. As it is expected larger distance between waveguide, d, results in weaker coupling hence larger coupling length L is needed for complete coupling of the input light into two output waveguides. Here, to keep the coupler length as low as possible and at the same time avoid very small waveguide distances d (which can be practically impossible to realize), we have chosen d=100 *nm* leading to L_I=10 µm.

As it can be seen in Fig. 1(c), two equal voltages with opposite polarizations will be applied to two MZI arms. Therefore the optical phase difference between waves of the two arms is simply twice the phase shift introduced by applying voltage to each arm. Thus the induced phase difference between two arms can be calculated as; $\Delta\varphi = 2\times(2\pi\, \Delta n_{eff} L_{PH}/\lambda)$, where Δn_{eff} is the real refractive index change of polymer and is given by [14]:

$$\Delta n_{eff} = -\Gamma r_{33} n_{polymer}^{3} V / 2\,\mathrm{Wp} \quad (3)$$

where Γ is the electro-optical overlap factor, V is the voltage applied to the polymer layer and L_{PH} is the length of phase shifter section. Fig. 2(b) shows the electro-optical overlap Γ as a function of silicon width in the HPW; W_{si} for different values of polymer width; W_p. As can be seen, maximum value of Γ occurs for the W_{si} values around 200 nm. To calculated the optimum value of W_p we have set the W_{Si} = 200 nm and changed W_p. It is shown in Fig. 2(c) that with W_{si} = 200 nm, the maximum value of Γ occurs at W_P = 30 nm.

To summarize the above paragraph, based on simulation results given in Fig. 2 the geometrical parameters of the structure are chosen to be: L_I = 10 µm, d = 100 nm, W_{si} = 200 nm and W_P = 30 nm.

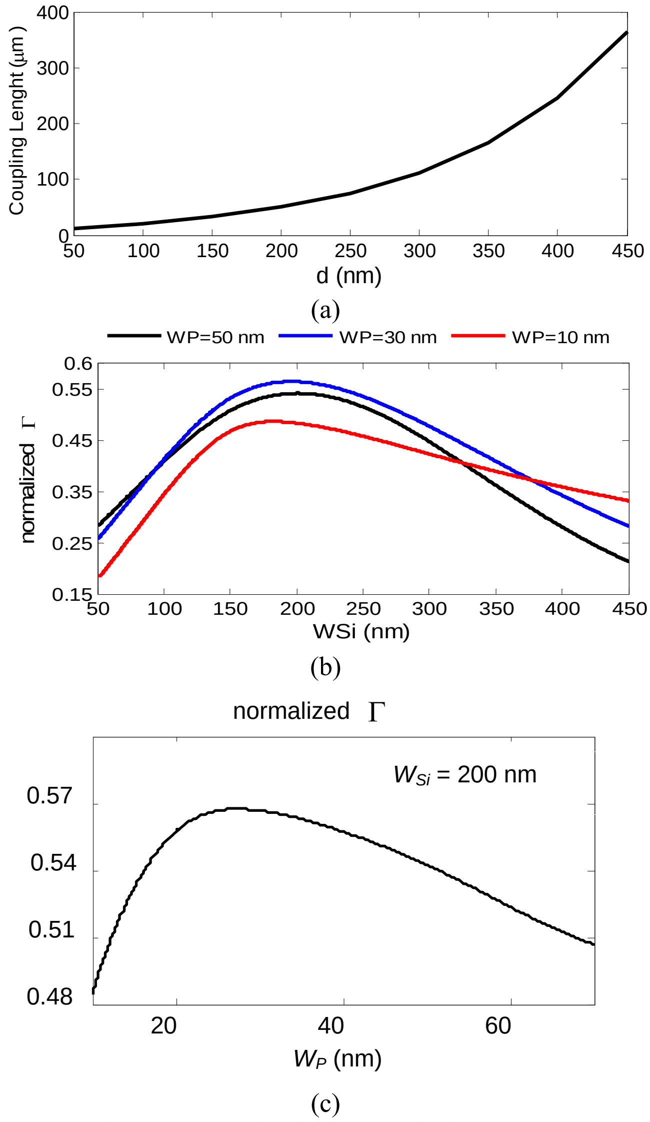


Fig.2 (a) The coupling length of three-waveguide directional coupler as a function of the distance d between inner and outer waveguides for splitters with 50 – 50 % splitting. (b) The normalized electro-optical overlap Γ versus W_{Si} for different values of W_p. (c) Normalized Γ versus W_p for the fixed value of W_{Si} = 200 nm.

Neglecting the inherent response time of polymer (in order of femtosecond), the modulation speed of the modulator is limited by RC response of the structure.

The capacitor is formed by a polymer layer as the dielectric sandwiched between silver and doped silicon as two electrodes of the capacitor. Capacitance of the structure can be approximated by $C=\varepsilon_0 n_{polymer}^{3} A/W_p$, where $A = h\times L_{PH}$ is the product of the polymer height; h, and its length; L_{PH} (see Fig. 1). L_{PH} is actually the propagation length in MZI arms required or achieving desired phase difference of $\Delta\phi = \pi$ between two arms. The total resistance R_t is equal to sum of silicon core resistance R_c and 50 nm slab resistance R_s and can be individually estimated through $R=\rho L/A$ where ρ is the resistivity of doped silicon and L and A are the corresponding length and cross sectional area of each region. We calculated the *RC* response time as ~0.9 ps corresponding to modulation speed of ~1.1 THz.

The energy consumption per bit is another key performance parameter of the optical modulators. This parameter can be estimated as [15]:

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

where C is the capacitance of the structure and V_{pp} is peak-to-peak value of the applied voltage.

Table 1 presents the required propagation length L_{PH} for different values of the applied voltage along with the overall insertion loss of the structure, modulation speed and the energy consumption per bit. According this table by increasing the applied voltage required MZI length can be L_{PH} reduced which in turn results in lower insertion loss but energy consumption of the structure will be increased. Therefore there is a trade-off between energy consumption, insertion loss and overall foot-print of the proposed modulator.

TABLE I. THE SIMULATED PERFORMANCE OF PPMZI MODULATOR FOR DIFFERENT APPLIED VOLTAGES

Drive Voltage (V)	L_{PH} (μm)	Loss (dB)	Speed (THz)	Energy/bit (fJ/bit)
±1	50	12	1.1	3.8
±2	25	7	1.1	7.6
±3	17	5.5	1.1	11.6

V. CONCLUSION

We proposed a high speed, low energy consumption, Mach-Zehnder interferometer modulator based on bend-less three-waveguide directional couplers and HPWs as the Mach-Zehnder arms. Our simulations showed that high modulation speed of ~1.1 THz, very low energy consumption of ~12 fJ/bit, and 5.5 dB insertion loss at drive voltage of ±3 V is achievable by using the proposed modulator. It is worth mentioning that apart from the electrodes, the overall footprint of modulator is ~1.5×37 μm^2. Proposed electro-optical modulator offers very high modulation speed and low energy consumption with compact overall foot-print.

REFERENCES

[1] L. Guoliang, A. V. Krishnamoorthy, I. Shubin, *et al.*, "Ring Resonator Modulators in Silicon for Interchip Photonic Links," *IEEE Journal of Selected Topics in Quantum Electronics, ,* vol. 19, pp. 95-113, 2013.

[2] D. Dai and S. He, "A silicon-based hybrid plasmonic waveguide with a metal cap for a nano-scale light confinement," *Optics Express,* vol. 17, pp. 16646-16653, 2009.

[3] F. Lou, D. Dai, L. Thylen, *et al.* , "Design and analysis of ultra-compact EO polymer modulators based on hybrid plasmonic microring resonators," *Optics Express,* vol. 21, pp. 20041-20051, 2013.

[4] M. Wu, Z. Han, and V. Van, "Conductor-gap-silicon plasmonic waveguides and passive components at subwavelength scale," *Optics Express,* vol. 18, pp. 11728-11736, 2010.

[5] X. Sun, L. Zhou, X. Li, *et al.*, "Design and analysis of a phase modulator based on a metal-polymer-silicon hybrid plasmonic waveguide," *Applied Optics,* vol. 50, pp. 3428-3434, 2011.

[6] S. Xiaomeng, Z. Linjie, Z. Haike, *et al.*, "Design and Analysis of a Miniature Intensity Modulator Based on a Silicon-Polymer-Metal Hybrid Plasmonic Waveguide," *IEEE Journal Photonics,* vol. 6, pp. 1-10, 2014.

[7] A. Pitilakis and E. E. Kriezis, "Longitudinal 2 x 2 Switching Configurations Based on Thermo-Optically Addressed Dielectric-Loaded Plasmonic Waveguides," *Journal of Lightwave Technology, ,* vol. 29, pp. 2636-2646, 2011.

[8] Q. Xu, D. Fattal, and R. G. Beausoleil, "Silicon microring resonators with 1.5-?m radius," *Optics Express,* vol. 16, pp. 4309-4315,2008.

[9] J. Van Campenhout, W. M. Green, S. Assefa, *et al.*, "Low-power, 2×2 silicon electro-optic switch with 110-nm bandwidth for broadband reconfigurable optical networks," *Optics Express,* vol. 17, pp. 24020-24029, 2009.

[10] P. Ganguly, J. C. Biswas, S. Das, *et al.*, "A three-waveguide polarization independent power splitter on lithium niobate substrate," *Optics Communications,* vol. 168, pp. 349-354, 1999.

[11] E. D. Palik, *Handbook of Optical Constants of Solids*: Academic Press, 1998.

[12] P. B. Johnson and R. W. Christy, "Optical Constants of the Noble Metals," *Physical Review B,* vol. 6, pp. 4370-4379, 1972.

[13] T.-D. Kim, J.-W. Kang, J. Luo, *et al.*, "Ultralarge and Thermally Stable Electro-Optic Activities from Supramolecular Self-Assembled Molecular Glasses," *Journal of the American Chemical Society,* vol. 129, pp. 488-489, 2007.

[14] P. Rabiei, W. H. Steier, C. Zhang, *et al.*, "Polymer micro-ring filters and modulators," *Journal of Lightwave Technology, ,* vol. 20, pp. 1968-1975, 2002.

[15] S. Xiao, F. Wang, X. Wang, *et al.*, "Electro-optic polymer assisted optical switch based on silicon slot structure," *Optics Communications,* vol. 282, pp. 2506-2510, 2009.