Miniature Intensity Modulator Based on a Silicon-Polymer Hybrid Plasmonic Waveguide

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ABSTRACT

We present a novel micrometer-sized intensity modulator based on a silicon-polymer hybrid plasmonic waveguide. The field enhancement in the low-index high-nonlinear polymer layer provides a nano-scale optical confinement and a fast optical modulation speed. After applying a voltage, the surface plasmon waves experience different phase delays, resulting in an intensity variation at the output waveguide. Due to its small capacitance and parasitic resistance, the RC delay time is <6 ps, corresponding to a modulation bandwidth of >40 GHz. The intensity modulator can find potential applications in optical telecommunication and interconnect.

Keywords: Plasmonics, Polymer active devices, Modulators

1. INTRODUCTION

Silicon Mach-Zehnder modulators (MZM) usually have an mm-long length due to the relatively small free carrier plasma dispersion effect utilized in silicon refractive index tuning [1]. To reduce the modulator size, resonance structures are used to enhance its transmission sensitivity to a small refractive index change at the expense of a narrower operation window [2]. Photonic crystal (PhC) structures are also used to reduce the modulator size, and however fabrication is a great challenge for PhC devices. Due to these limitations, plasmonics is revolutionizing the development of nanophotonics in many aspects at an extraordinarily fast pace. Surface plasmon polaritons (SPPs) are electromagnetic (EM) excitations, being coupled to surface collective oscillations of free electrons in a metal, are bound to and propagate along metal-dielectric interfaces at the optical and near-infrared frequency range. Surface plasmons exhibit extremely small wavelengths and high local field intensities, and optical confinement can scale to deep subwavelength dimensions in plasmonic structures [3-7]. Hence, modulators based upon SP can naturally have a compact size.

Here we present a novel micrometer-sized intensity modulator based on a silicon-polymer hybrid plasmonic waveguide. The intensity modulation is enabled by mode beating between symmetric and asymmetric plasmonic modes. As the two modes are possessed by one hybrid plasmonic waveguide, it is naturally more compact compared to MZM structures where two separate waveguides are needed for optical interference. Meanwhile, it retains the broadband modulation feature as essentially it is an interference structure rather than a resonance structure. Our proposed modulator combines the merits of low propagation loss of silicon waveguides, high confinement of plasmonic modes, and high EO effect of polymer materials to obtain a high-speed and low-power modulation.

2. DEVICE STRUCTURE AND WORKS MECHANISM

Fig. 1 (a) and (b) show the schematic and cross-sectional views of the proposed plasmonic intensity modulator. The plasmonic waveguide is composed of a metal-dielectric-silicon stack where the two metal blocks have different lengths. When light enters the input-end silicon waveguide, the optical energy is well-confined in the silicon core. When it sees the first metal block, the optical energy is gradually pushed to the slot region between the metal and the silicon core, as the electric field is greatly enhanced in the slot (polymer) region for TE polarization due to the electric field discontinuity at the silicon-dielectric interface and surface plasmon polariton (SPP) excitation at the metal-dielectric interface. The silicon core is adiabatically tapered to reduce the mode transform loss from dielectric to hybrid plasmonic modes. When the second metal block is positioned along the other side, the optical energy is then gradually attracted from one slot to the other, resulting in a periodic energy transfer between the two slots. The energy transfer resembles that in a directional

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coupler except that here the coupling is radioactive rather than evanescent, and hence the coupling is much stronger with a shorter coupling length. In another way, the dual-slot coupling can be regarded as a mode-beating between the symmetric (even) and asymmetric (odd) super-modes of the hybrid plasmonic waveguide. As the front end, both modes are excited and they propagate with a different propagation constant, leading to an oscillatory interference pattern. Compared to MZI structures where interference is enabled by two separate optical paths, our structure uses the two modes beating in a single hybrid plasmonic waveguide to generate the interference, and therefore it is more compact.

The silver, polymer and silicon layers form a lateral capacitor with the silver and silicon core as the two electrodes. Due to the high linear EO effect of the polymer material, the refractive index of the polymer infiltrated in the slots can be tuned by an applied voltage. Because optical energy is mainly localized in the slot region, the plasmonic modes are very sensitive to the applied voltage, which is in favor of a miniature high-performance modulator. It should be noted that phase change is different for the two plasmonic modes upon a certain voltage because of their distinct mode profiles. It is such difference that makes the intensity modulation possible using our proposed structure.

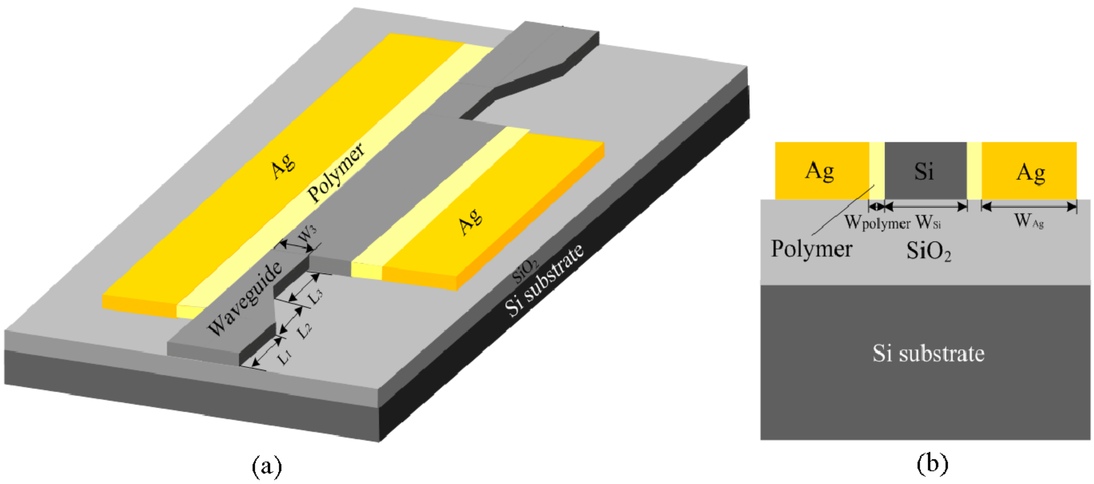

Fig. 1. (a) Schematic perspective view of the proposed active plasmonic waveguide. (b) Cross-sectional view of the active plasmonic waveguide.

3. SIMULATION

We use the finite element method (FEM) to numerically calculate the hybrid plasmonic waveguide modes at the 1550 nm wavelength. In our simulation, we choose silver as the metal material with its permittivity ε_{Ag} = -133.75+3.337i around 1550 nm wavelength [8]. The refractive indices for SiO_2, Si and polymer are n_{SiO2} = 1.46, n_{Si} = 3.48 and $n_{Polymer}$ = 1.6, respectively. We use molecular glasses based on the reversible self-assembly of aromatic/perfluoroaromatic (Ar-ArF) dendron-substituted nonlinear optical (NLO) chromophores as the electro-optic polymer to actively tune the plasmonic mode, which has an electro-optic coefficient r_{33} > 200 pm/V with good alignment stability [9]. The polymer refractive index change Δn to an external electric field E is given by [10]:

$$\Delta n = -r_{33} n^3{}_{polymer} E / 2 \qquad (1)$$

and

$$E = U / W_{polymer} \, . \qquad (2)$$

where U is the voltage applied on the polymer layer. According to the simulations, When the central silicon ridge width is small ($W_{si} \lesssim$ 200 nm), the plasmonic waveguide can support only one mode, with the electric field having even vector polarity. As the width increases, the mode with the electric field having odd vector polarity appears. Fig. 2 shows the transverse electric field patterns of the quasi-even and quasi-odd modes in the plasmonic waveguide. The geometric parameters are chosen as: W_{si} = 450 nm, $W_{polymer}$ = 50 nm, and W_{Ag} = 450 nm, respectively. The complex effective refractive indices of the even and odd modes are 2.59+4.79×10^{-4}i and 1.97+2.26×10^{-3}i, where the real parts are associated with the light propagation constants and the imaginary parts with the propagation losses. After applying a voltage, not only the refractive indices of both modes are changed due to the high linear EO effect of the polymer, but the refractive index difference of the two modes is also changed, or in other words, the even and odd SP waves experience different phase delays. As a result, the optical field intensity at the output ridge waveguide is modulated by the applied voltage.

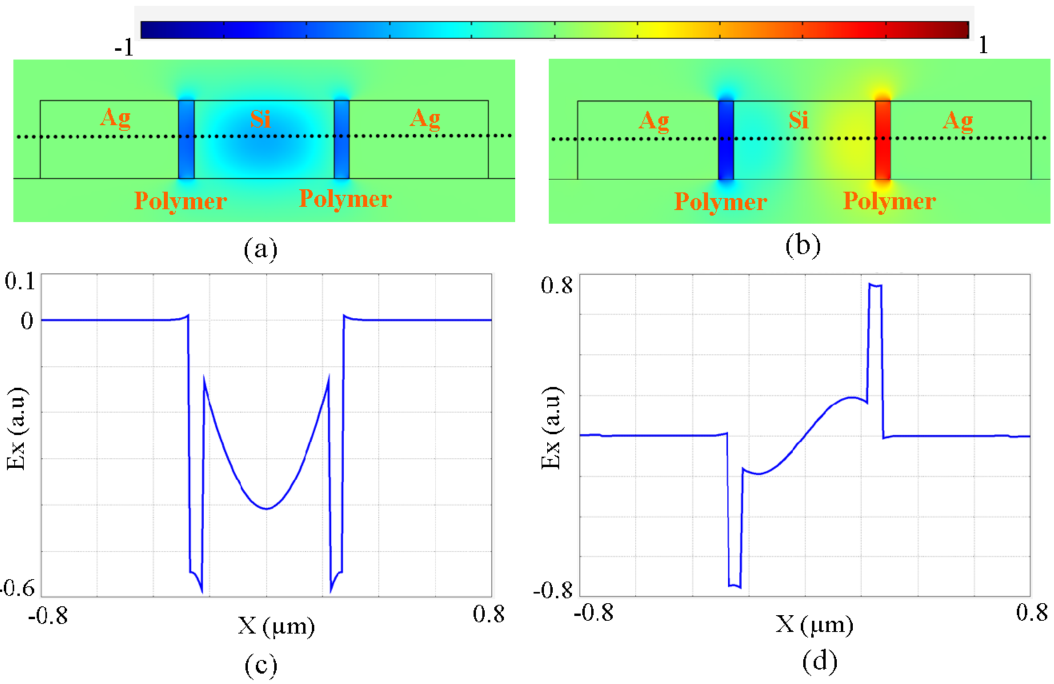

Fig. 2. (a) and (b) Transverse electric field mode pattern for (a) even and (b) odd modes. (c) and (d) Electric field distribution along a horizontal line for the even and odd modes.

As described in the previous section, the input silicon dielectric waveguide is first transformed to a single slot plasmonic waveguide, with the purpose to excite nearly symmetrically both the even and odd modes in the modulator central part. Similarly, at the output end, the single slot plasmonic waveguide is used to interfere the even and odd modes. Fig. 3(a) shows the mode of the input/output dielectric silicon waveguides, and Fig. 3(b) shows the single slot hybrid plasmonic mode with the slot width 50 nm, *Si* width 225 nm, and *Ag* width 450 nm, respectively.

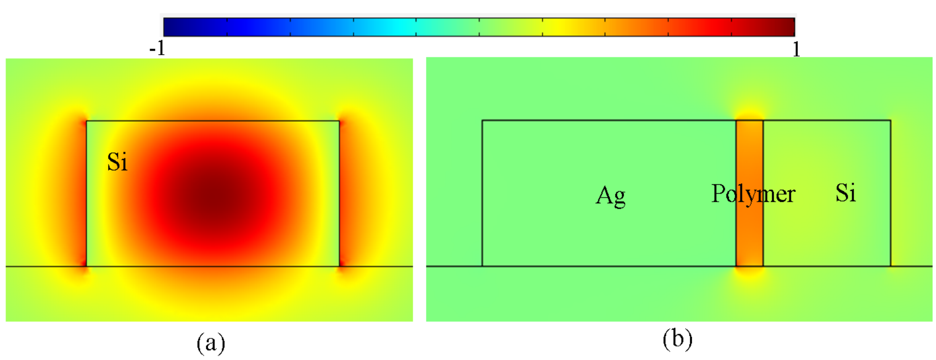

Fig. 3. Transverse electric field mode patterns for (a) the input/output dielectric silicon waveguides and (b) the single slot hybrid plasmonic waveguide.

Considering the fabrication feasibility, modulation efficiency, and propagation loss, the device geometric parameters labeled in Fig. 1 can be chosen as: W_{si} = 450 nm, $W_{polymer}$ = 50 nm, W_{Ag} = 450 nm, L_1 = 800 nm, L_2 = 700 nm, L_3 = 500 nm, and W_3 = 220 nm. Fig. 4(a)-(c) shows the 3D simulated optical power flow in the device with various applied voltages. The optical energy can be coupled from the input silicon waveguide to the plasmonic waveguide and then back to the output silicon waveguide with different output intensities, showing that phase difference eventually results in an intensity variation at the output waveguide. The transmission efficiency, defined as the percentage of energy transmitted through, is ~16% without applying voltage, and ~1% with 6V applied voltage. Fig. 5 shows the normalized intensity as a function of the applied voltage. An extinction ratio of ~ 12 dB is achieved at 6V.

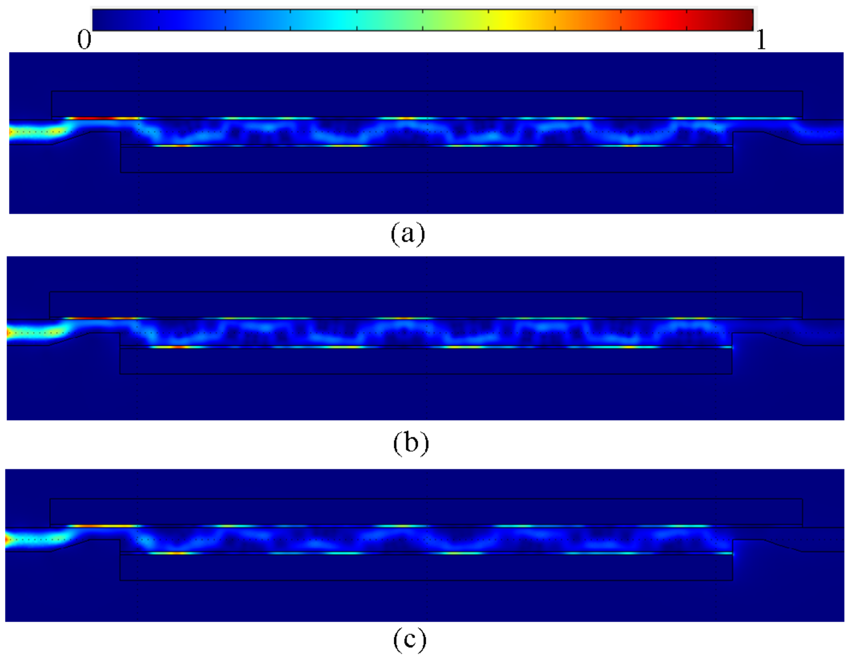

Fig. 4. 3D simulated power flow pattern in the device with various voltages of (a) 0V, (b) 3V, and (c) 6V.

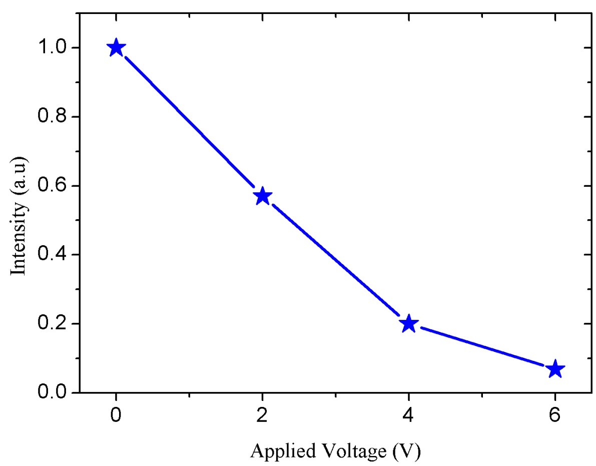

Fig. 5. Normalized intensity changes with the applied voltage.

Assuming the silicon core is n-type doped with a concentration of 3×10^{18} cm^{-3}, the total resistance and capacitance is thus estimated to be 7 kΩ and 0.74 fF, respectively, and the RC delay time is <6 ps, corresponding to a modulation bandwidth of >40 GHz. At 6V applied voltage, the power consumption is $P = 0.25fCV^2 = 0.27$ mW, assuming the modulation frequency is $f = 40$ GHz, here, the factor 0.25 is due to the fact that the 0-1 transition only happens with a probability of 0.25 for all bit sequences [11, 12]. The high performance of the modulator can satisfy the future requirements for fast modulation speed and low power consumption in optical telecommunication and interconnect applications.

4. FABRICATION FEASIBILITY

The proposed phase modulator can be realized by using existing fabrication technologies. Here we give a feasible fabrication process flow that can produce such a device. First, the photoresist thin film is patterned by electron-beam lithography (EBL) which can then act as a mask for the underlying silicon layer dry etch. The silicon core doping can be done by ion implantation. Then a thin layer of metal is deposited by sputtering and patterned by lift-off to obtain the desired metal pattern. Finally, a layer of polymer can be deposited in the void slot regions by using molecular beam epitaxy or spinning coating. In order to enhance the electro-optic coefficient of the polymer, the polymer should be properly poled before device operation. The poling can be accomplished by applying a high electric field across the polymer nanoslot layer using the patterned electrodes.

5. CONCLUSION

A novel optical intensity modulator based on a hybrid plasmonic slot waveguide comprising Ag-dielectric-Si stacking layers is proposed. The optical field is strongly confined in the nanometer thin layer for the TE polarization. Due to the high electro-optic effect of the polymer material and the mode beating in the dual-slot silicon hybrid plasmonic waveguide, the output intensity is dependent on the phase difference of the plasmonic waveguide modes, which are utilized to realize plasmonic intensity modulators. The proposed miniature plasmonic optical intensity modulators can serve as a basic building block for future hybrid integration of silicon photonic and plasmonic devices for optical signal processing and interconnection applications.

6. ACKNOWLEDGMENTS

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