Simulation of electro optic modulators based on plasmonic directional couplers

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***Abstract*—In this paper, a new concept and geometry are proposed for plasmonic modulators, whose operation is based on the coupling between two plasmonic slots. An electro-optic polymer is exploited as an active material, and the device can be implemented within a Silicon Photonics platform. The device operates at 1550 nm wavelength, typical of data center or long-haul telecommunication systems. For a device length of around 16 μm, the simulated extinction ratio and optical insertion loss are 20.98 dB and 4.26 dB, respectively. Both performances compare favourably with those of Mach-Zehnder plasmonic modulators from the literature. The simulation is based on the Time Domain Finite Differences (FDTD) and Finite-Difference Eigenmode (FDE) methods.**

I. Introduction

Electro-optic (EO) modulators play an essential role in high-speed, high-capacity telecommunication systems. In this context, plasmonic modulators show great potential for next-generation integrated photonic platforms and have higher speed and potentially lower V_π than conventional solutions, like lithium-niobate based MZ modulators [1]. Several plasmonic-based devices have been proposed, such as the Mach-Zehnder (MZ) modulator [2] based on plasmonic phase shifters [3], the directional coupler modulator [4], and the ring modulator [5]. One of the most appealing features of plasmonic modulators is their micron-scale size, small enough to allow for co-integration with CMOS electronics [6]. On the other hand, these devices exhibit a larger optical insertion loss compared to conventional solutions, because of the strong intrinsic plasmonic losses and the photonic–plasmonic mode conversions.

In this work we present a plasmonic modulator based on directional couplers. After preliminary studies on coupled plasmonic slot waveguides, the plasmonic coupler modulator geometry is presented and simulated with FDTD and FDE codes [7].

II. Analysis of the plasmonic directional coupler

The plasmonic slot consists of an EO dielectric layer sandwiched between two metal layers. The simulations are monochromatic, at 1.55 μm, and the refractive index of materials are: $n_{\mathrm{Si}} = 3.5$, $n_{\mathrm{SiO_2}} = 1.44$ and $n_{\mathrm{Au}} = 0.2524{+}10.4386\,\mathrm{j}$ [2]. Fig. 1 shows the plasmonic slot geometry and the propagation constant β of the fundamental mode versus the voltage V applied across the slot. The propagation constant β is

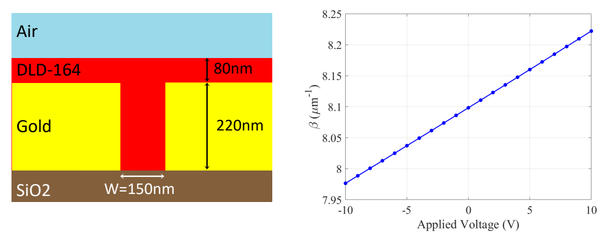

Fig. 1. Left: geometry of one plasmonic slot. Right: propagation constant of fundamental mode versus the applied voltage.

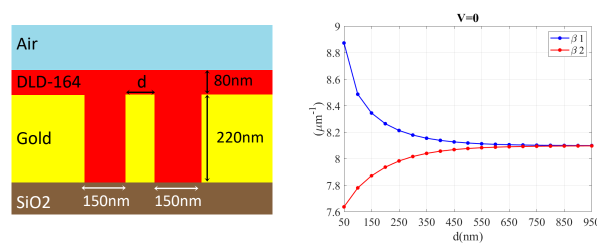

Fig. 2. Left: Geometry of plasmonic directional coupler. Right: Propagation constant of first and second coupled modes versus the slot separation d.

computed through the FDE method. The EO material used in the simulation is DLD-164, a highly nonlinear organic polymer with zero-field refractive index $n_{\mathrm{mat}} = 1.83$, that exhibits a strong Pockels effect. When an electric field E is applied, n_{mat} changes according to (from [2]):

$$\Delta n_{\mathrm{mat}} = 0.5 r_{33} n_{\mathrm{mat}}^3 E \approx 0.5 r_{33} n_{\mathrm{mat}}^3 \frac{V}{W} \tag{1}$$

where $r_{33} = 180\ \mathrm{pm{\cdot}V^{-1}}$ is the linear EO coefficient of DLD-164 [2] and W is the slot width. The plasmonic β exhibits an almost linear variation with the applied voltage as shown in Fig. 1.

If two plasmonic slots are close enough (the slot separation is d), the slot modes interact and a directional coupler is obtained, see Fig. 2, left. After propagating for a certain interaction (coupling) length (L_c), mode coupling leads to complete power transfer between the slots. The coupling length L_c depends on the difference between the propagation constants

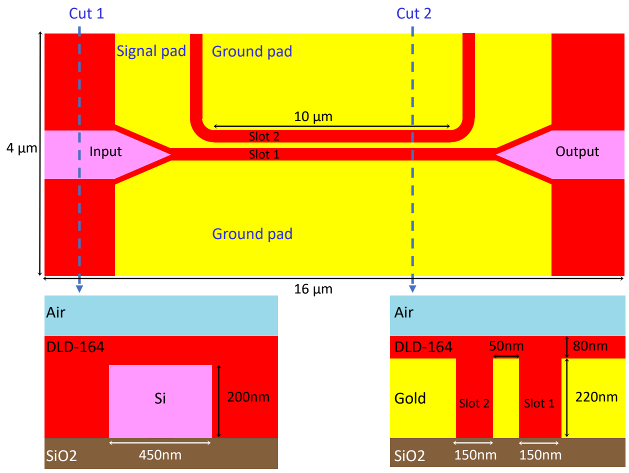

Fig. 3. Geometry of the proposed plasmonic directional coupler modulator.

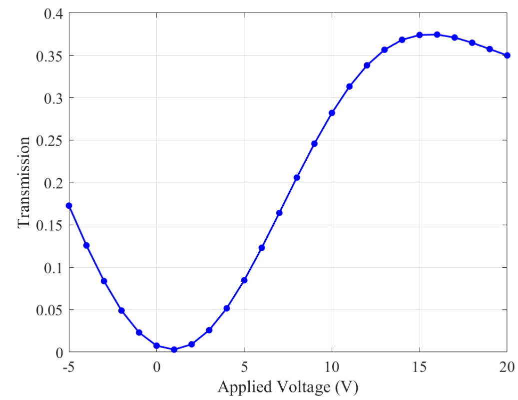

Fig. 4. Modulator DC transmission versus applied voltage.

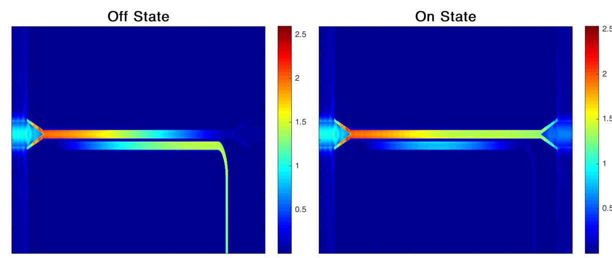

Fig. 5. Magnitude of electric field at OFF (left) amd ON (right) states.

of the modes of the coupled slots (β_1 and β_2) according to [4]:

$$L_c = 2\pi/(\beta_1 - \beta_2). \quad (2)$$

When $d \geq 700$ nm, coupling is negligible, so that $\beta_1 \approx \beta_2$ and $L_c \to \infty$. For $d < 700$ nm, β_1 and β_2 exhibit an increasing difference for decreasing slot separation (see Fig. 2, right), leading to a decrease of L_c. If the refractive index in the slots changes due to the EO effect, the interaction length L_c changes. By controlling L_c in a suitable geometry, modulation occurs.

III. New modulator geometry

The geometry of the proposed modulator is shown in Fig. 3. The total device length is 16 μm; the slot separation is $d = 50$ nm, a value that may be technologically challenging. The optical power enters the modulator from the input Si photonic waveguide and is converted to a plasmonic mode into Slot 1. The optical power is then coupled from Slot 1 to Slot 2. At the device output, the power in Slot 1 is finally converted to the output Si waveguide. By applying a voltage to the signal pad, n_{mat} changes in both slots in an opposite way, due to the balanced coplanar layout imposing opposite E-fields in the two slots. As a result, the difference between β_1 and β_2 is affected and the value of the interaction length L_c leading to complete power transfer between slots changes, thus affecting the power that enters the output Si waveguide. In the OFF modulator state, power is completely converted from Slot 1 to Slot 2 and almost no power is coupled to the output Si waveguide. Conversely, in the ON state, power is converted to Slot 2 and then back to Slot 1; thus, the optical power coupled into the output Si waveguide is maximum. In order to avoid power saturation and reflection in Slot 2, both ends of Slot 2 should be terminated by an optical absorber or let radiate out of the device.

The DC E/O transmission response of the proposed device is estimated with a 2D FDTD method and is shown in Fig. 4 for a coupler length of 10 μm. The simulated V_π is around 15 V. The extinction ratio is 20.98 dB and the optical insertion loss is 4.26 dB. The magnitude of the electric field for the ON state and OFF states are shown in Fig. 5.

IV. Conclusions

In this simulation study, the proposed directional coupler EO plasmonic modulator has been shown to exhibit promising features when compared to MZ counterparts: simpler transitions to photonic input and output, avoiding splitter and combiners, that lead to lower insertion losses; high extinction ratio, unaffected by layout asymmetries. The low ridge width may be a technological challenge. Further work will concern a parametric layout study aimed at identifying an optimum structure in terms of driving voltage and insertion loss.

Acknowledgments

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