Plasmonic Modulator Using CMOS-Compatible Material Platform

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Abstract – **In this work, a design of ultra-compact plasmonic modulator is proposed and numerically analyzed. The device layout utilizes alternative plasmonic materials such as transparent conducting oxides and titanium nitride which potentially can be applied for CMOS compatible process. The modulation is obtained by varying the carrier concentration of the transparent conducting oxide layer and exciting plasmonic resonance in the structure. The analysis shows that an extinction ratio of 46 dB/µm can be achieved at the telecommunication wavelength. Proposed structure is particularly convenient for integration with existing insulator-metal-insulator plasmonic waveguides as well as novel photonic/electronic hybrid circuits.**

I. INTRODUCTION

Metal-dielectric interfaces support surface plasmon polaritons (SPPs) which allow for the manipulation of light at the nanoscale, overcoming the diffraction limit and enable ultra-fast data processing in nanophotonics circuits [1]. Various designs have been proposed for the fabrication of nanophotonic building blocks such as waveguides, modulators, sources, amplifiers, and photodetectors aiming achieving the highest mode localization and the lowest propagation losses. However, their applicability is limiting because most of these structures use noble metals such as gold or silver, which are not CMOS-compatible.

Recent study on alternative plasmonic materials suggests that transition metal nitrides and transparent conducting oxides (TCOs) could represent promising platforms for future plasmonic devices [2]. Among these materials, titanium nitride (TiN) is one of the best candidates because it is chemically stable, bio-compatible, mechanically hard, and can be grown epitaxial on many substrates including silicon and sapphire [3]. On the other side, TCOs can provide extraordinary tuning and modulation of their complex refractive indices by changing the carrier concentration with the application of an electric field [4],[5].

In this work, by using this potentially CMOS-compatible material platform, we investigate a novel design for an ultra-compact plasmonic modulator. We define an intrinsic figure of merit (FoM) for plasmonic modulators, which takes into account both the modulation length and the mode size, and discuss the performance of the proposed device.

II. METRICS OF PERFORMANCE

The modulator core consists of a thin TiN layer that supports the SPPs inside the modulator at the interface with another thin silicon nitride (SiN) layer (Fig. 1). An additional upper TCO layer is used to control the attenuation while silicon is chosen as substrate and high-index cladding. This configuration presents important

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advantages such as ease of fabrication and tight modal confinement. It also allows for immediate integration with long-range SPP (LR-SPP) stripe waveguides with reduced coupling losses.

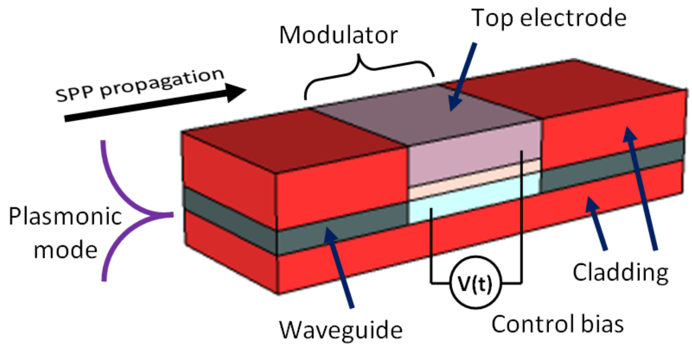

Fig. 1. Modulator layout. The picture also shows the interface with standard plasmonic strip interconnects and how the bias voltage is applied.

To perform numerical analysis, we consider the one-dimensional structure as an approximation to the two-dimensional stripe waveguide. The thickness of the internal TCO (in particularly, gallium doped zinc oxide, GZO), TiN, SiN layers was set as 10 nm. The top and bottom cladding layers are assumed to be infinitely thick. The dispersion equation was solved for the multilayer structures with varying carrier concentrations in the GZO. The permittivity of the GZO layer was taken from experimentally grown films and a carrier concentration in the GZO was determined using a Drude-Lorentz model fitting: $N_0 = 9.426\times10^{20}$ cm^{-3} [5]. For this work, we consider a range of carrier concentrations between $N = 0.5N_0 \ldots 2N_0$. The permittivity of TiN is taken as experimentally measured $\varepsilon_{TiN} = -83.3 + 21.3i$ at $\lambda = 1.55$ μm. The TiN films were deposited at 800°C and their optical properties were measured on a 20 nm thick film using spectroscopic ellipsometer.

To study performance of our device, few fundamental parameters should be set. First, the mode size is defined as the transversal section inside of which 86% of electrical energy is localized. The second parameter is the attenuation of the signal, which is calculated from the absorption coefficient as $\alpha = 8.68\mathrm{Im}(\beta_{eff})$ (in decibels), where β_{eff} is the complex propagation constant of the propagating wave along the multilayer structure. Therefore, the extinction ratio (ER) of the modulator can be defined as $ER = \alpha_{max} - \alpha_{min}$, where α_{min} represents the propagation loss in the off-state and α_{max} is the maximum of the propagation loss in the on-state. Here, we define the on-state as the carrier concentration which results in the maximum absorption (6.6×10^{20} cm^{-3}, Fig. 2). As opposite to the on-state we define the off-state as the minimum in the absorption.

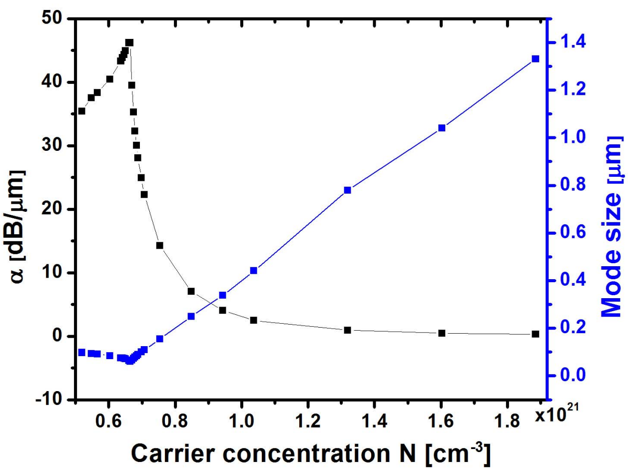

Fig. 2. Absorption coefficient α and mode size as a function of the carrier concentration for our modulator.

Thus, we can define the FoM for such a multilayer modulator as FoM=(ER /α_{min})*($\lambda_{eff,off}$/W_{off}) where $\lambda_{eff,off}$=2π/Re(β_{eff}) is the effective wavelength in the modulator in the off-state, and W_{off} is the off-state mode size. Our FoM reflects the trade-off between the modulation depth and the loss of the signal in the off-state (α_{min}), while giving additional weight to the device compactness.

III. Results and Discussion

The ER of our device is more than twice the highest ER obtained in previous works (Table 1). This is largely due to the fully plasmonic nature of the devices and mainly results from the increase in the ER. Ease of integration and coupling losses are at the center of our modulator. In addition, because these devices can efficiently be detuned from the plasmonic resonance, the absorption coefficient in the off-state can be relatively low while maintaining a mode size on the order of λ_{eff}.

Table 1: Comparison with respect to previously reported plasmonic modulators.

Device	ER [dB/µm]	α_{min} [dB/µm]	W_{off} [µm]	FoM
[5] Babicheva	46	0.29	1.3	51
[6] Lu	18	1	0.3	39
[4] Sorger	1	0.04	0.35	32
[7] Huang	6	0.7	0.2	19

IV. Conclusion

In conclusion, we designed and numerically studied an ultra-compact modulator based on potentially CMOS-compatible materials. One can achieve off-state losses of 0.29 dB/µm while maintaining a large ER of 46 dB/µm. This large ER requires only a 65 nm modulator length to achieve a 3 dB signal modulation.

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