Ultra-Fast Compact Plasmonic Modulator based on Adiabatic Coupled Waveguides

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Abstract: Compact plasmonic modulator based on adiabatic coupled waveguides obtains insertion loss as low as <0.1 dB with the extinction ratio exceeding 40 dB. In addition the speed of 400 GHz with footprint of 2.7 μm^2 is expected. © 2018 The Author(s)

OCIS codes: (250.4110) modulators; (240.6680) surface plasmonics.

1. Introduction

In this work, we propose an atto-joule, low-loss; high-speed plasmonic optical modulator based on tunability of three adiabatically coupled waveguides (ACW). The optical power in the middle waveguide oscillates much faster in comparison to the other waveguides leading in no significant build up due to the large detuning between nearby waveguides despite the large coupling strength [1]. TM mode injected through one of the outer waveguides propagates merely in the other outer waveguide. Figure 1(b) confirms the adiabatic coupling condition, where the center plasmonic waveguide is in "dark state". The two identical outer waveguides are 350 nm-wide. 110 nm-wide intermediate waveguide is 50nm away and consists of a metallic Au-pad with a gate oxide of 20 nm-thick SiO$_2$ and an active Indium-Tin-Oxide (ITO) with the thickness of 10 nm sandwiched between them. The effective coupling strength between the two outer waveguides is $\kappa_{eff}=\kappa_{13}-(\kappa_{12}\ \kappa_{21})/(\Delta\ \beta_{21})$ [1-2].

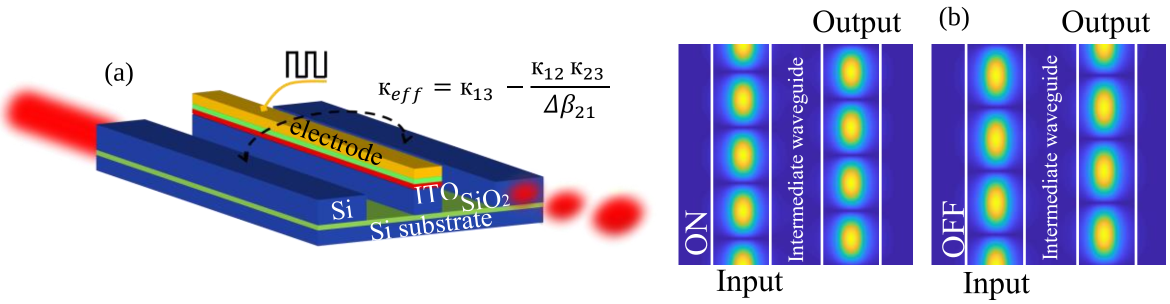

Fig.1. (a) Schematic structure and (b) fundamental TM mode of the ACW waveguides. The silicon layer is 550 nm thick.

2. Simulation and discussion

Figure 2 shows the optical absorption in the middle waveguide enlarges with the increasing of device length and applied bias voltage. However due to the phase detuning of the ON state from (2N+1)π in the output port, the overlap of optical power with the center waveguide reduces with the longer device length and higher bias voltage. As a result, insertion loss for longer device length first become smaller and then larger. For instance at driving bias voltage of 0.9 V, device length of 125 μm provides insertion loss of 0.9 dB, which is increasing with the larger length. In contrast, conventional ITO modulators [3] cannot provide sub-volt operation with a reasonable insertion loss. For instance as shown in figure 2 (c), even at driving bias voltage of 0.9 V a 16 dB insertion loss is expected to obtain a 10 dB extinction ratio. However, as shown in figure 2(a) our ACW modulator provides extinction ratio of exceeding 40 dB at driving bias voltage of as low as 0.1 V. Conventional ITO modulator at the bias voltage of 2.5 V provides extinction ratio of 10 dB with the insertion loss of 0.6 dB. In the other hand, in ACW modulator, with applied bias voltage of to 2.5 V, insertion loss of 0.04 dB corresponding to the device lengths of 3.5 μm is expected. Next, we explored the limit of modulation speed caused by parasitic elements. To this end, a full-wave three-dimensional simulation is performed via "Ansys Electronics Desktop". We modeled parasitic responses caused by both active region and RF pads. Dimensions of RF pads are optimized for a 50 Ω and 100 μm-pitch ground-signal-ground probe.

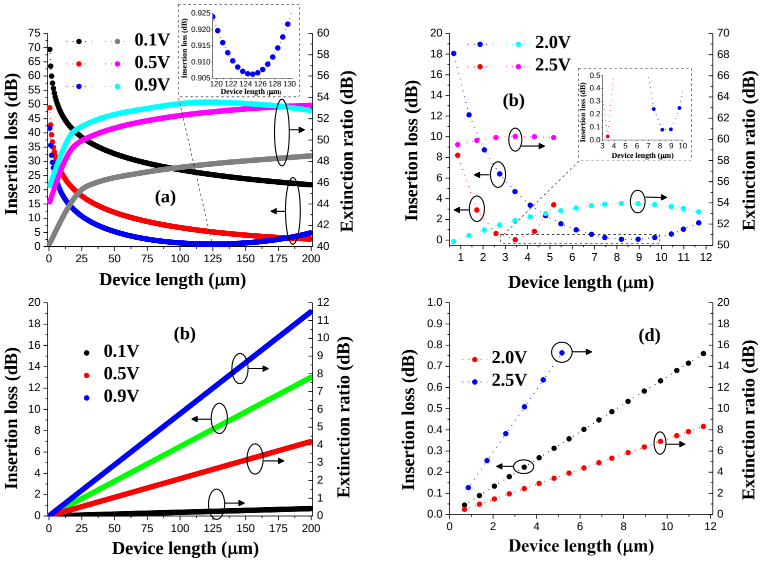

Fig.2. The evolutions of extinction ratio and insertion loss with the device length in the ACW- ITO modulator at the different bias voltages of (a) 0.1 V, 0.5 V, 0.9 V, (b) 2.0 V, 2.5 V, and the conventional ITO modulator at the bias voltage of (c) 0.1 V, 0.5 V, 0.9 V and (d) 2.0V, 2.5V. The wavelength is 1.55μm.

. As shown in figure 3 (a) we used the suspended air bridge to connect the pad to the top gold without interfering modes of the outer-waveguides [4]. The other contact is provided through the extension of the middle waveguide as demonstrated in the inset of figure 3 (a). Tapered lines are used for impedance matching of the device (50 Ω). To realize the highest modulation speed, we optimized the dimensions of pads and spacing between them. As can be seen in the figure 3 (b), a modulation speed higher than 400 GHz is expected crucial for millimeter wave range radio over fiber applications.

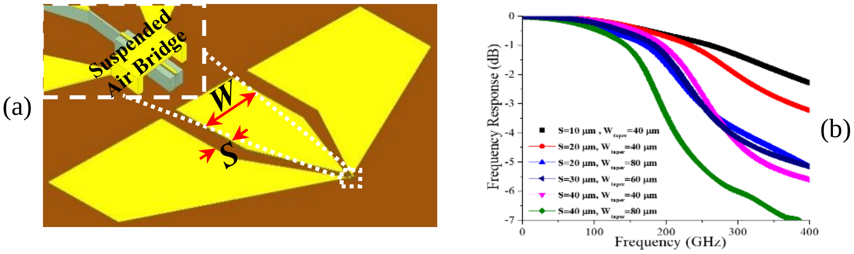

Fig. 3. (a) RF pads and suspended air bridge design, (b) frequency response of parasitic elements for different RF pad dimensions.

3. Conclusion

In conclusion, we have developed a new concept for an energy-efficient, high-speed and low-loss ITO plasmonic modulator. The underlying operation principle is based on the altering the coupling strength of an adiabatically coupled three-waveguide system. By voltage-tuning a plasmonic mode via carrier modulation of an active ITO layer of the center waveguide of the modulator, we show that tunability in and out-of an adiabatic elimination region in the index-design space enables dramatic modulation depth of 40 dB for just 100 mV of applied bias. This modulator opens a new era for electro-optic modulation in silicon photonics.

4. Acknowledgement

We are grateful for the support of Air Force Office of Scientific Research (AFOSR) Small Business Innovation Research (SBIR) program under award number FA9550-17-P-0014

5. References

[1] M. Mrejen, H. Suckowski, T. Hatakeyama, C. Wu, L. Feng, K. Brien, Y. Wang and X. Zhang, “Adiabatic elimination based coupling control in densely packed subwavelength waveguides,” Nature communication **6**, 7565 (2015).

[2] M. Mrejen, H. Suchowski, N. Bachelard, Y. Wang and X. Zhang, “Low-loss and energy efficient modulation in silicon photonic waveguide by adiabatic elimination scheme,” Applied Physics Letter **111**, 033105 (2017).

[3] V. J. Sorger, N. D. Lanzillotti-Kimura, R.-M. Ma, and X. Zhang, “Ultra-compact silicon nanophotonic modulator with broadband response,” Nanophotonics **1**, 1–6 (2012).

[4] Haffner, C. et al. All-plasmonic Mach-Zehnder modulator enabling optical high-speed communication at the microscale. Nat Photon **9**, 525-528, (2015).