Plasmonic slot ferroelectric MZIR modulator on Si_3N_4 in the O-band

(Student paper)

Dimitrios Chatzitheocharis[1,2], Dimitra Ketzaki[2,3], Georgios Patsamanis[1,2], and Konstantinos Vyrsokinos[1,2]

[1]School of Physics, Aristotle University of Thessaloniki, A.U.Th. Campus, Thessaloniki, 54124, Greece
[2]Center for Interdisciplinary Research and Innovation, Aristotle University of Thessaloniki, Thessaloniki, 57001, Greece
[3]Department of Informatics, Aristotle University of Thessaloniki, A.U.Th. Campus, Thessaloniki, 54124, Greece
*email: dchatzit@auth.gr

Herein, we present the performance analysis of a ferroelectric plasmonic Mach-Zehnder in a Ring (MZIR) modulator on Si_3N_4 for gold (Au), silver (Ag) and copper (Cu) based phase shifters targeting O-band interconnects. The Cu based MZIR featuring a 5μm long slot, exhibits Insertion Losses of 6.85dB, an Extinction Ratio of 9dB for a differential applied voltage of 2.74V_{pp} and a Comparison Factor of 0.7x vs. a symmetric MZI with equal phase shifter length.
Keywords: *MZI-Ring Modulator, Silicon Nitride, Plasmonic Slot, Coupling Interface*

INTRODUCTION

Silicon nitride (Si_3N_4), with its low propagation losses, low cost, and high compactness, has emerged as a very promising platform for photonic integrated circuits (PICs) over the last few years. One of the key components missing from the Si_3N_4 library though is a CMOS compatible modulator, eliminating in this way the main advantage currently possessed by SOI based PICs. Towards this direction many studies have focused on the co-integration of Si_3N_4 with ferroelectric materials and as such in [1] a hybrid lithium niobate ($LiNbO_3$) allowed operation with sub-volt half-wave voltage (V_π), a half-wave voltage-length product ($V_\pi L$) of 2.11 V*cm, and 5.4dB insertion losses (IL). In [2] a Si_3N_4 loaded $LiNbO_3$ modulator exhibited a $V_\pi L$ of 2.24 V*cm, and an extinction ratio (ER) up to 20dB. The evolution of PICs in terms of compactness has brought on surface the development of hybrid photonic-plasmonic PICs and in this direction miniaturized CMOS compatible modulators have been demonstrated [3], featuring though Si as the basic underlying material platform [4]. In this paper we numerically demonstrate a ferroelectric Mach-Zehnder in Ring (MZIR) modulator for the O-band in Si_3N_4 that requires as low as 0.44x voltage for maximum extinction ratio versus symmetric MZIs [5]. The performance analysis investigates two low loss noble metals well known in the plasmonics literature, Au [6], Ag [7] and CMOS compatible Cu [8] for the formation of the plasmonic waveguide. Simulation results reveal that Ag presents the best performance, followed by Au and then by Cu. The Cu based MZIR modulator exchanges performance for CMOS compatibility and for a 5μm phase shifter features insertion losses of 6.85dB with an extinction ratio of 9dB for 2.74Vpp applied voltage to the arms of the MZI.

NUMERICAL RESULTS

The proposed plasmonic slot ferroelectric MZIR configuration is shown in a 3D-schematic in Fig. 1(a). The basis of the integrated optical device is Si_3N_4 waveguide, supporting a fundamental TE-mode with an effective index close to Re(n_{eff}) = 1.773 and 0.2dB/cm propagation losses. The two 2x2 O-Band MMIs that form the MZI of the MZIR are assumed to induce 0.2dB/MMI according to 3D-FDTD simulations at λ = 1310nm. The MZIR cavity is formed by directly connecting one of the output MMI ports to the one input port of the input MMI. The loop length includes approximately 300μm from the two MMIs, 186μm from the two Si_3N_4 to plasmonic coupling interfaces and the variable length L_{slot} of the plasmonic phase shifter. Fig. 1(b) presents in detail the cross section of the phase shifter that is based on a plasmonic slot formed by two metals with the gap filled by barium titanate ($BaTiO_3$ or BTO) material. The metal for the plasmonic waveguide in this work is either Au, or Ag targeting low loss with a noble material or Cu for CMOS compatibility. To bridge the two platforms, an amorphous silicon intermediate waveguide vertically transfers light in a multi-layer fashion where, initially, an adiabatic coupler with a coupling length of 90μm transfers the TE-mode from the Si_3N_4 waveguide to a 350nm x 220nm aSi waveguide featuring a TE mode of Re(n_{eff}) = 2.45034. In the next step, a directional coupling step transfers the light from aSi to the plasmonic slot. The SiO_2 gaps between SiN and aSi and between aSi and BTO are 100nm.

The performance analysis of the three MZIRs layouts starts from the extraction of the propagation characteristics in the plasmonic slot waveguides for the three metals via 2D eigenvalue calculations. Fig. 2(a) shows that the effective index Re(n_{eff}) is similar for Cu, Au, and Ag for increasing slot widths w_{slot} with only small differences observed between the three. The plasmonic slots are almost phase-matched with the aSi waveguide mode for w_{slot} = 90nm for Ag and for 100nm for Au/Cu, allowing in this way efficient directional vertical coupling between the

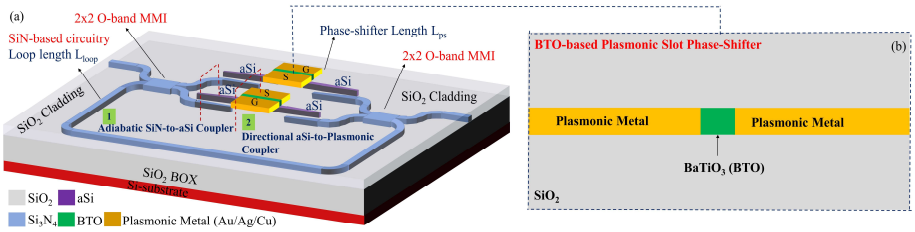

Fig. 1. 3D-schematic of the proposed ferroelectric plasmonic slot MZI-Ring configuration

two waveguides. Fig. 2(b) reveals the propagation losses of the three slot waveguides for widths between 25nm and 200nm. The Ag-based slot in symphony with theory and other experimental works [7] exhibits the lowest propagation losses of the three with 0.33dB/µm for w_{slot} = 90nm, while for Au with w_{slot} = 100nm this value is slightly increased to 0.5dB/µm. For Cu on the other hand the losses are now more than doubled versus Ag to 0.78dB/µm, but now there is CMOS compatibility for low-cost mass scale fabrication. Fig. 2(c) illustrates that the power confinement is almost exclusively determined by the slot width with values ranging between 80% and 45%, while the metal type has almost negligible effect on the confinement factor of the electric field. For the calculation of the electro-optic characteristics of the plasmonic slot phase-shifters, Poisson's equation was solved in a 2D-FEM eigenvalue solver for applied voltage between 0V and 5V for slot widths of 90nm for Ag and 100nm for Au/Cu. The E-field components of the FEM solution were interpolated and fed to 2D-FDE optical eigenvalue simulations at 1310nm wavelength to extract the modified effective index for each voltage. Fig. 2(d) shows that the trend is almost linear as expected for all three metals. The Ag-based slot has the largest effective index difference vs. applied voltage due to a higher overlap between the RF and optical fields. From the relation $\Delta\phi = (2\pi/\lambda_0)\Delta Re(n_{eff})L$, the half-wave voltage product was calculated to 25.51V*µm for Ag, 28.06V*µm for Au, and 27.33V*µm for Cu. The effective electro-optic coefficient for the BTO is assumed to be 300pm/V.

In terms of coupling interfaces, the numerical simulations indicate that the adiabatic coupler transfers the light from the Si_3N_4 to the aSi efficiently with only 0.06dB losses. Fig. 2(e) showing the sideview of the electric field |**E**| verifies this result with the very smooth transition between the two layers. For the next step a directional coupler has been designed for each metal, with the coupling length calculated by detailed 3D-FDTD simulations. For Ag the optimum value is 2.78µm, for Au 2.71µm and for Cu 2.67µm, with the close proximity expected from the almost identical $Re(n_{eff})$ values of Fig. 2(a). Fig. 2(f) shows the sideview of the electric field |**E**| from aSi to the Cu-based slot, indicating efficient and seamless light transfer to the slot. Similar graphs are produced for the other two metals. The coupler exhibits coupling losses calculated at x = 3µm from the initiation point of the slot waveguide in the x-axis (x=0) as 0.71dB for Ag, 0.86dB for Au and 1.23dB for Cu.

All the above simulation parameters were inserted in our in-house scattering-matrix based model for the DC-analysis of the MZIR modulator. A length difference $\Delta L = L_{FSR}/2 = \lambda_0/(2Re\{n_{eff}(SiN)\})$ has been inserted between the two arms of the MZIR, so as to set the initial state of the MZIR at minimum insertion losses. The calculated relation providing the transmission spectrum at the output of the MZIR is the following:

$$\left|\frac{b_1}{a_1}\right|^2 = A_{Lop''}^2 \frac{A_{TOT}^2 + \cos^2\left(\frac{\Delta\varphi}{2}\right) - 2A_{TOT}\cos\left(\frac{\Delta\varphi}{2}\right)\cos(\beta_0 L_{OPT})}{1 + A_{TOT}^2\cos^2\left(\frac{\Delta\varphi}{2}\right) - 2A_{TOT}\cos\left(\frac{\Delta\varphi}{2}\right)\cos(\beta_0 L_{OPT})} \quad (1)$$

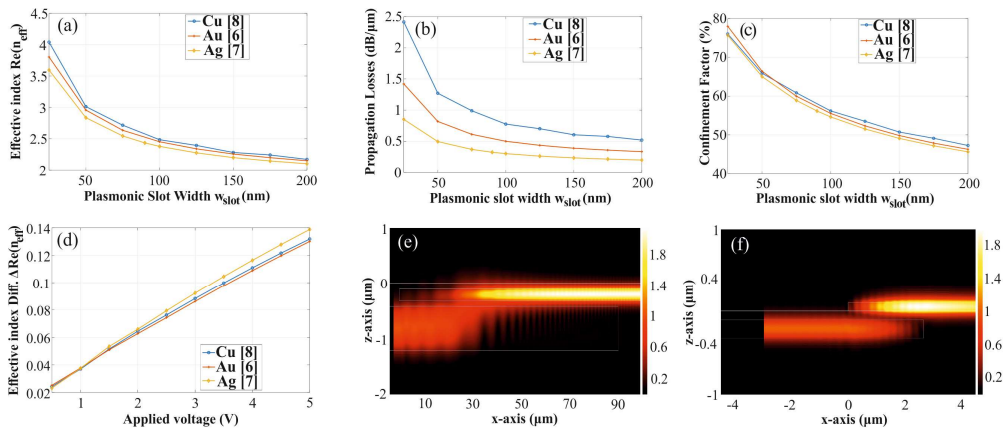

Fig. 2. (a) Effective index $Re(n_{eff})$, (b)Propagation Losses (dB/µm), and (c) Confinement factor (%) for increasing plasmonic slot width, (d)Effective index difference $\Delta Re(n_{eff})$ for increasing applied voltage V, (e) Sideview of |E| field distribution for the transition from SiN to aSi, (f) Sideview of |E| field distribution for the transition from aSi to Cu-based plasmonic slot

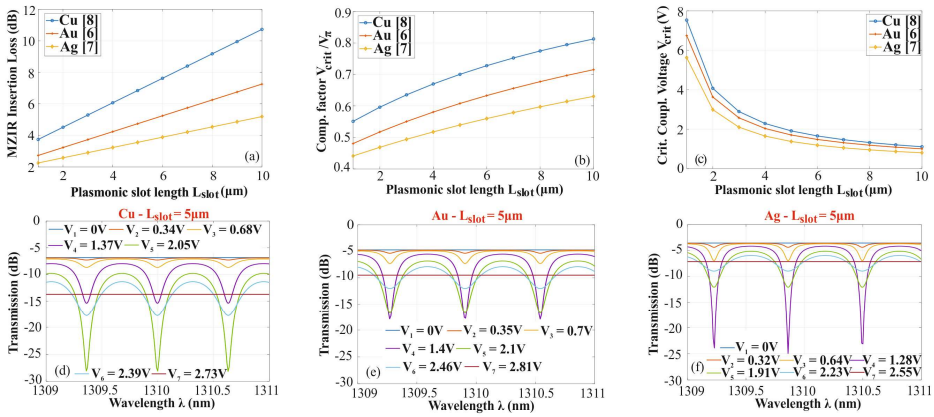

Fig. 3. (a) MZIR Insertion losses IL (dB), (b) Comparison factor CF = V_{crit}/V_π, and (c) Critical coupling voltage V_{crit} (V) for increasing plasmonic slot phase shifter length L_{slot} (µm), (d) Power transfer functions of the MZIR for Cu-based slot, (e) Au-based slot and (f) Ag-based slot with 5µm length for various applied voltages at the two arms

where $A_{Lop''}$ is the coefficient related with the efficiency coming from the transition through one MZI branch, A_{TOT} is the coefficient containing the coupling efficiency coming from the transition through the whole cavity, β_0 is the wavenumber $\beta_0 = 2\pi/\lambda_0$, L_{OPT} is the total optical path length of the whole MZIR cavity, and $\Delta\phi$ is the phase difference between the two MZI branches of the MZIR. The IL come directly out of the MZIR transfer function. The Comparison factor CF = V_{crit}/V_π can be calculated at resonance as CF = $2\cos^{-1}(A_{TOT})/\pi$, signifying the fraction of voltage needed for the maximization of the ER in an MZIR vs a symmetric MZI. The voltage for critical coupling in the MZIR modulator is $V_{crit} = V_\pi\cos^{-1}(A_{TOT})/\pi$. The results for the three plasmonic metals can be seen in Fig. 3(a)-(c). Fig. 3(a) indicates that the best in terms of performance is Ag providing IL values below 5dB for slot lengths between 1µm and 10µm. For Au the IL lie between 2.7dB and 7.3dB, while Cu provides IL between 3.7dB and 11dB. Fig. 3(b) shows the performance improvement of the MZIR over a symmetric MZI. The Ag based MZIR requires 0.44x the voltage V_π needed to achieve maximum ER in the MZI for a 1µm long slot, while this value is 0.63x for slot lengths up to 10µm. For Au these values are between 0.48x and 0.72x, while for Cu are between 0.55x and 0.81x. Finally, as seen in Fig. 3(c) V_{crit} becomes sub-volt for Ag for slot lengths higher than 7µm, for Au higher than 9.5µm and close to 1.1V for a 10µm Cu based plasmonic phase shifter. Fig. 3(d)-(f) illustrate the transmission spectra for various voltages applied for Cu, Au, and Ag plasmonic slots with 5µm phase shifter length, respectively. For the Cu-based MZIR shown in Fig. 3(d) the IL are close to 6.85dB, with an ER of 9dB for an applied voltage of 2x1.37Vpp and a CF of 0.7. The Au-based MZIR exhibits IL of 4.74dB, a 13.04dB ER for a 2x1.4Vpp differential voltage and a CF of 0.61. Finally, the Ag-based MZIR has the best performance with 3.56dB IL only, an ER of 21.4dB for 2x1.28Vpp differential voltage and a 0.54x required voltage for maximum ER in comparison with the symmetric MZI.

CONCLUSIONS

This paper presents the performance improvement of a plasmonic slot ferroelectric MZIR modulator design on the Si_3N_4 photonic vs. a symmetric plasmonic MZI, for Au, Ag and Cu as metals for the plasmonic phase shifter. The optimum CMOS compatible device is based on Cu, achieving IL of 6.85dB, ER as high as 9dB for 2.34V_{pp} differential applied voltage and a 0.7x required voltage for critical coupling compared with the V_π of a symmetrical MZI.

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