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Mid-infrared Transverse Electric (TE)-Pass Polarizer Based on Silicon-on-sapphire Platform

Ahmed El-Sayed Abd-Elkader[1,2],
Mohamed Farhat O. Hameed[3,4,5],
Salah S. A. Obayya[2,6]

[1]*Electronics and Communications Engineering Department, Faculty of Engineering, Delta University for Science and Technology, Gamasa, Dakahlia, Egypt.*
[2]*Centre for Photonics and Smart Materials, Zewail City of Science, Technology and Innovation, October Gardens 12578, Giza, Egypt.*
[3]*Nanotechnology and Nanoelectronics Engineering Program, Zewail City of Science, Technology and Innovation, October Gardens, 6th of October City, Giza 12588, Egypt*
[4]*Centre of Nanotechnology, Zewail City of Science, Technology and Innovation, October Gardens 12578, Egypt*
[5]*Department of Mathematics and Engineering Physics, Faculty of Engineering, University of Mansoura, Mansoura 35516, Egypt*
[6]*Department of Electronics and Communication Engineering, Faculty of Engineering, University of Mansoura, Mansoura 35516, Egypt*

Correspondence: Ahmed El-Sayed Abd-Elkader; Delta University for Science and Technology, International Coastal Road, Gamasa, 35712, Egypt; Tel +2 01220934392; Email: Ahmed.abdelqader@deltauniv.edu.eg

ABSTRACT
In this paper, a compact mid-infrared (MIR) transverse-electric (TE)-pass polarizer is presented and numerically examined. The introduced polarizer is built on silicon-on-sapphire (SOS) platform. Such platform boasts key features such as minimal power consuming, superior linearity, and transmission with high speed, making it particularly advantageous for various applications, especially in the MIR spectrum. The proposed design is complementary metal-oxide-semiconductor (CMOS)-compatible based on bi-metallic materials, aluminium doped zinc oxide and titanium nitride, as alternative plasmonic materials. Large coupling between the surface plasmon and fundamental transverse magnetic (TM) modes is occurred in the silicon core by the bimetallic effect. Nevertheless, the transverse-electric mode can travel with negligible losses. The suggested TE-pass polarizer attains, at a 2 µm operating wavelength, an extinction ratio (ER) of 17.5 dB accompanied by an insertion loss (IL) of 0.1 dB at a device length of 3 µm. Moreover, the introduced polarizer design is simple and has high resilience to fabrication errors.

Keywords*: polarization, surface plasmon, finite-element method, silicon-on-insulator*

1. Introduction

The mid-infrared (MIR) spectral region, particularly spanning from 2 µm to 20 µm, holds significant importance for a wide range of applications, such as free space communication, thermal imaging, and absorption spectroscopy (Schliesser et al. 2012; Lloyd 2013). Initially, challenges to work in this region were posed by laser source's bulky size and high expense. Nonetheless, recent developments have introduced miniature, inexpensive, and tunable quantum cascade lasers (Swillam et al. 2018). In the MIR spectrum range, silicon photonics platform can offer several benefits owing to the transparency of silicon for wavelengths extending to 8 µm. Moreover, silicon photonics exhibit far superior nonlinear characteristics in the MIR spectrum compared to near-infrared (NIR), as two-photon absorption drops to zero past 2 µm. Consequently, issues related to two-photon absorption, and the associated free carriers become negligible in the MIR region (Swillam et al. 2018). As a result, a great appreciation should go to photonic devices to work in MIR region.

Silicon on insulator (SOI) is the prevalently utilized silicon photonics platform owing to the notable difference in refractive indices between the silicon and the insulator. This index contrast between silicon and silicon dioxide enables effective optical mode confinement, leading to a more compact device footprint. An alternative to the SOI is the silicon on sapphire (SOS) platform, a modification which avoids using buried silicon dioxide as insulator. Instead, sapphire is utilized to achieve enhancement in the transparency especially for longer wavelengths beyond that are usable with SOI. Consequently, SOS platform emerges as an insistent option for integrated MIR silicon photonics. However, the significant contrast in refractive indices between sapphire and the silicon core results in large optical birefringence and devices that are highly dependent on polarization. To address this issue, the diversity scheme (Barwicz et al. 2007) with polarization handling devices can be used. Hence, photonic integrated circuits (PICs) can be realized to efficiently handle light waves whatever their polarization orientation, such as polarization splitters (Abadía et al. 2017) and polarization rotators (Abd-Elkader et al. 2019a). Nevertheless, this approach is quite complex and leads to a substantial increase in the overall system size. Therefore, another strategy may be employed by involves the utilization of a polarizer to remove one of the polarization states and efficiently enable the propagation of the other state. This method, as suggested by Chen et al. in 2008 (Chen et al. 2008), is straightforward and can be effectively applied in devices relying on a single polarization, albeit at the cost of losing approximately 50% of the power. In addition, the growing global demand for extensive information exchange in contemporary communication necessitates the development of communication systems with enhanced transmission and processing capabilities. Subsequently, there is a significant demand for optical communication systems employing ultra-compact and high-speed photonic integrated circuits and optical devices. In response to all of that, various optical polarizers have been proposed. Abd-Elkader *et al.* (Abd-Elkader et al. 2019b) have proposed a compact transverse-electric/ transverse-magnetic (TE/TM)-pass polarizers built on SOI platform with aluminum-doped zinc oxide (AZO) plasmonic material. These polarizers achieve a 20.6 dB extinction ratio (ER) with minimal insertion loss (IL) of 0.21 dB at a device length L_D of 3.5 µm when employing the TE-pass polarizer. Yet, the TM-pass polarizer demonstrates an ER of 22 dB and IL of 0.11 dB at L_D= 1.0 µm. Additionally, in (Kandeel et al. 2019), TE/TM-pass polarizers compatible with complementary metal-oxide-semiconductor (CMOS) compatible have been reported. Such polarizers are based on bi-metallic structure comprising zirconium nitride and indium tin oxide. The bi-metallic setup induces a strong coupling between specific polarized core mode and the surface plasmon mode, allowing the other polarized mode to travel with minimal propagation losses. At a compact L_D= 1.5 µm, the TE-pass polarizer exhibits an ER of 32.7 dB with IL of 0.13 dB at wavelength of 1.55 µm. while, the TM-pass polarizer achieves an ER of 31.5 dB and IL of 0.17 dB at L_D= 2 µm. Further, El Shamy *et al.*, (El Shamy et al. 2017) have introduced broad-spectrum and easily fabricable TM-pass and TE-pass polarizers for Mid-Infrared applications using the SOS platform. Both the TE/TM polarizers have a long L_D of 23 µm. Nevertheless, an ER = 69.77 dB with IL = 1.21 dB is achieved for the TM-pass polarizer, while the TE-pass polarizer has 25.57dB ER with 1. 92 dB high IL. Even though most of the polarizers based on plasmonics boast a compact footprint, they suffer from a notable drawback of increased IL due to the strong ohmic loss inherent in traditional plasmonic materials. Furthermore, commonly employed plasmonic polarizers rely on silver and gold, that are both non-CMOS-compatible and lack chemical stability. As a remedy, alternative plasmonic materials have gained widespread adoption in recent years, replacing the conventional counterparts. Transparent conducting oxides (TCOs) and transitional metal nitrides have emerged as main candidates to supplant traditional plasmonic materials. These novel plasmonic materials offer significant advantages, including enhanced design flexibility, reduced losses, tunability, and excellent compatibility with CMOS technology (Naik et al. 2013). In this paper, AZO and titanium nitride (TiN) are used as alternative plasmonic materials to design TE-pass polarizer. These plasmonic materials offer many advantages such as great flexibility in designing photonic devices, reduced losses, tunability, and high compatibility with standard fabrication and integration procedures. The proposed TE–pass polarizer achieves 17.5 dB ER with 0.1 dB IL at a device length of 3 µm at an operating wavelength of 2 µm. The advocated structure has advantages in terms of achieving high ER with low IL at a compact device size, simple in design, consistent with the CMOS standards and has high resilience to fabrication errors.

2. Design Considerations

Figure 1 depicts three-dimensional (3D) and two-dimensional (2D) schematic illustrations of the introduced TE-pass polarizer. The designed structure is specifically crafted to facilitate the transmission of TE mode only. It consists of 4 layers with the same width w_s = 1000 nm. The first layer is a silicon core with refractive index of 3.48 and hight of h_s= 700 nm. The core is followed by a sapphire layer with height h_p and 1.7377 refractive index. The sapphire layer is coated by an AZO layer with height of h_a and the top two layer of TiN with height of h_t. To enable coupling with the dominant component of the TM mode (E_y or H_x), the AZO and TiN layers are placed in the y-direction for the TE-pass polarizer. Initially, the sapphire layer has a uniform height (h_p) of 80 nm, with h_a = 60 nm and h_t = 60 nm for the heights of the AZO and TiN layers, respectively.

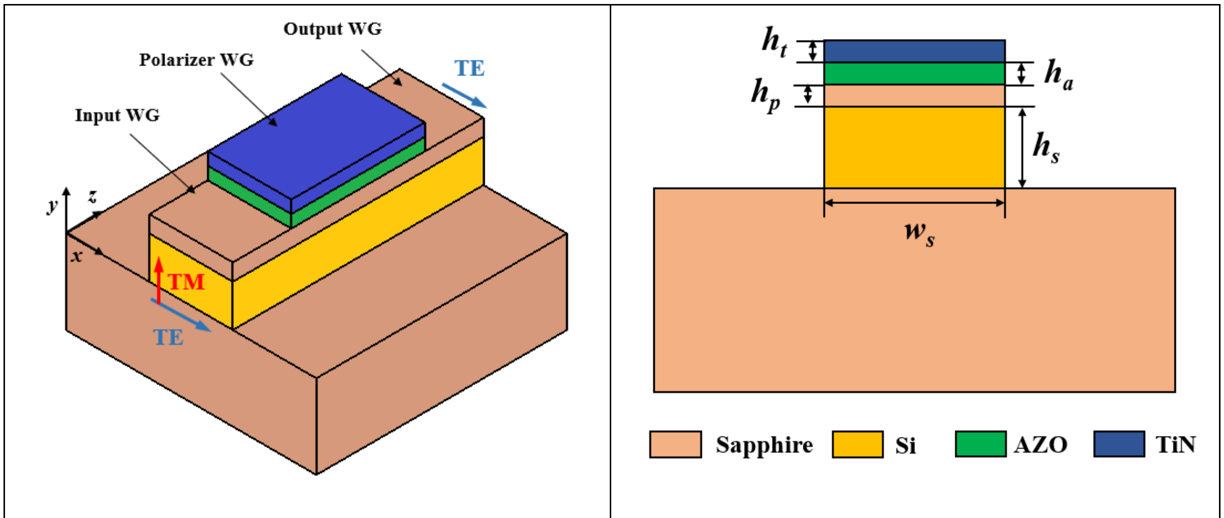

Fig. 1. The proposed TE-pass polarizer's 3D and 2D schematic diagrams.

The relative permittivity of the AZO and TiN are taken from the following Drude Lorentz model given in (Naik et al. 2013)

$$\varepsilon(\omega) = \varepsilon_b - \frac{\omega_p^2}{\omega(\omega + i\gamma_p)} + \frac{f_1\omega^2}{\omega_1^2 - \omega^2 - i\omega\gamma_1} \quad (1)$$

where Table 1 gives the parameters of AZO and TiN

Table 1. The parameters of the Drude-Lorentz model of AZO and TiN materials

Parameter	AZO	TiN
ε_b	3.5402	2.485
ω_p	1.7473 eV	5.953 eV
γ_p	0.04486 eV	0.5142eV
f_1	0.5095	2.0376
ω_1	4.2942 eV	3.9545 eV
γ_1	0.1017 eV	2.4852 eV

The magnetic field intensities of the dominant components, H_y for the quasi-TE and H_x of quasi-TM mode, are investigated in Fig. 2. It can be noticed that H_y of the quasi-TE mode is well confined in the silicon core. In contrast, the quasi-TM mode's H_x demonstrates increased leakage towards the plasmonic materials. As a result, heightened losses are specifically observed for the TM mode.

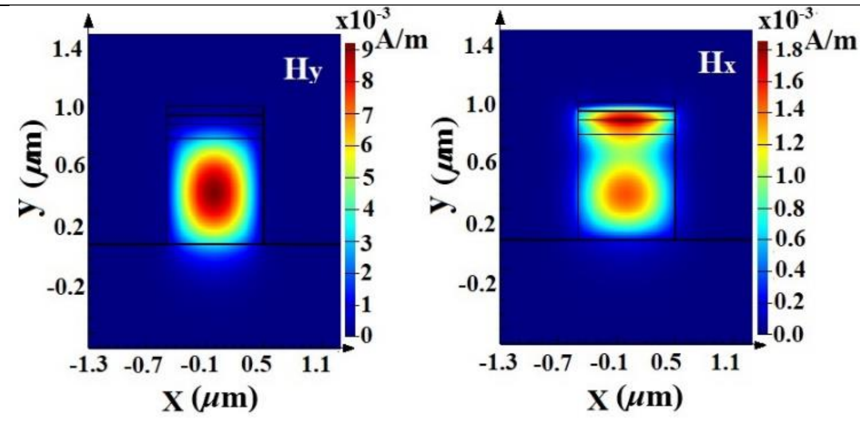

Fig.2. Plot of the magnetic field of the main components of (a) the quasi-TE mode (H_y) and (b) the quasi-TM mode (H_x) at h_p =of 80 nm, h_a = 60 nm, and h_t = 60 nm.

3. Simulation Results

The modal properties of the suggested polarizer are examined through a full-vectorial finite element method based on COMSOL 5.1 Multiphysics software (https://www.comsol.com) with perfect matched layer (PML) boundary conditions. To test the filtering characteristics of the reported polarizer, three dimensional FDTD method via Lumerical software package (https://www.lumerical.com) is used to calculate the extinction ratio (ER) (Abd-Elkader et al. 2022) and verify the suggested polarizer's propagation properties. The ER can be expressed as

$$\text{ER (dB)}=10 \log \left(\frac{P_{out}^{p}}{P_{in}^{p}} \text{ x } \frac{P_{in}^{c}}{P_{out}^{c}}\right), \tag{2}$$

where (P_{out}^{p}/P_{in}^{p}) represents is the proportion of the output power to the input power of the transmitted mode (TE-mode). However, (P_{in}^{c}/P_{out}^{c}) is the ratio of the filtered mode (TM-mode). Additionally, the insertion loss is calculated as (Abd-Elkader et al. 2022)

$$IL(dB) = 10 \ \log_{10}\left(\frac{P_{out}^{p}}{P_{in}^{p}}\right) \tag{3}$$

Here, P_{in}^{p} represents the input power of the transmitted polarization mode, while P_{out}^{p} denotes the power of the same polarization mode at the output of the polarizer.

The 3D FDTD is utilized with grid size of Δx= 10 nm, Δy= 10 nm, Δz=0.1 µm. It is worth mentioning that the TE-pass polarizer incurs significant losses for the TM mode, whereas the TE mode experiences minimal losses. Consequently, the main goal of the analysis is to optimize the figure of merit (FOM) for the proposed polarizer. The FOM can be given by (Abd-Elkader et al. 2022)

$$FOM = \frac{Propagation\ losses\ of\ TE\ mode\ \left(\frac{dB}{um}\right)}{Propagation\ losses\ of\ TM\ mode\ \left(\frac{dB}{um}\right)} \tag{4}$$

The theoretical analysis of the geometrical parameters of the proposed polarizer is conducted to optimize the Figure of Merit, aiming to enhance the filtering properties and maximize the ER within a compact device footprint. The sapphire layer height's effect is initially studied. Figure 3 investigates the relationship between ER and FOM concerning the height of sapphire layer (h_p) at L_D = 3.0 µm and λ=2 µm. As illustrated in Fig. 3(a), the ER shows a rise from 2.6 dB to 16.3 dB as the height of the sapphire layer (h_p) increases from 60 nm to 100 nm. Subsequently, the ER decreases to 2.5 dB when h_p is further increased to 140 nm. A parallel pattern is observed in the figure of merit, as seen in Fig. 3(b), where an FOM of 201 is attained at h_p = 100 nm.

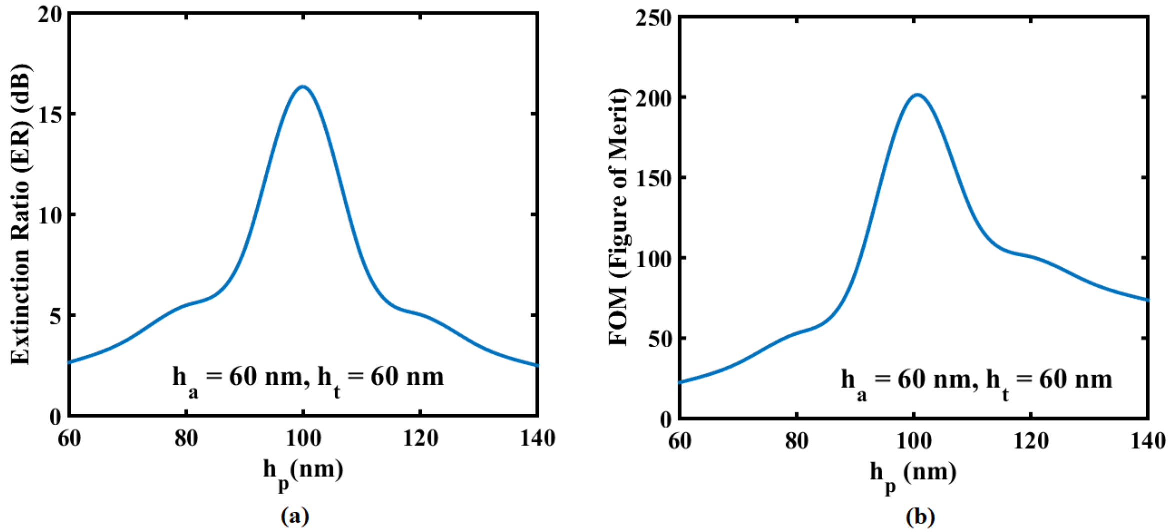

Fig. 3. Relation between the variations in (a) ER and, (b) FOM to the alterations in the height of the sapphire layer (h_p) at L_D= 3.0 μm and λ=2 μm.

Figure 4 depicts the ER and FOM variations concerning the heights of the AZO (h_a) and TiN (h_t) layers, considering a device length of 3.0 μm. In Fig. 4 (a), ER is plotted as a function of the AZO layer height (h_a) at different heights of TiN (h_t) layer, while Fig 4(b) shows the change of FOM with the AZO layer height (h_a) at different TiN (h_t) layer heights. It can be seen that as the AZO layer height h_a rises from 20 nm to 60 nm, an increase is occurred in both ER and FOM. However, a subsequent increase in h_a to 100 nm results in a decrease in both ER and FOM for different heights of the TiN layer (h_t). Additionally, Fig. 4 (a) and 4 (b) reveal that h_t has a marginal effect on the ER and FOM. The maximum values of ER (17.5 dB) and FOM (209) are achieved at h_a = 60 nm and h_t = 50 nm.

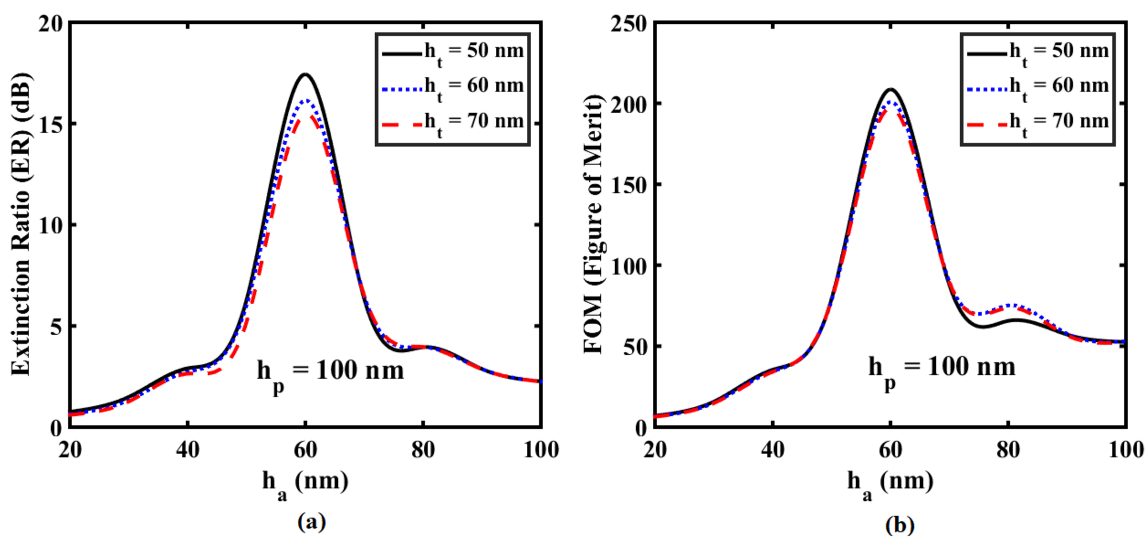

Fig. 4. Variations in the (a) ER, and (b) FOM in relation to the alterations in the heights of the AZO (h_a) and the TiN (h_t) layers at L_D= 3.0 μm and λ=2 μm

The variations in the ER and IL of the TE-pass polarizer are subsequently examined in relation to the device length, as illustrated in Fig. 5. It is noticed from the figure that as the device length of the TE-pass polarizer extends, both the ER and IL experience an increase. In order to attain an ER of 20 dB, the device length needs to be approximately 3.2 μm, resulting in an IL of 0.11 dB. The determination of these performance parameters is essential, considering the significance of the polarizer in its application.

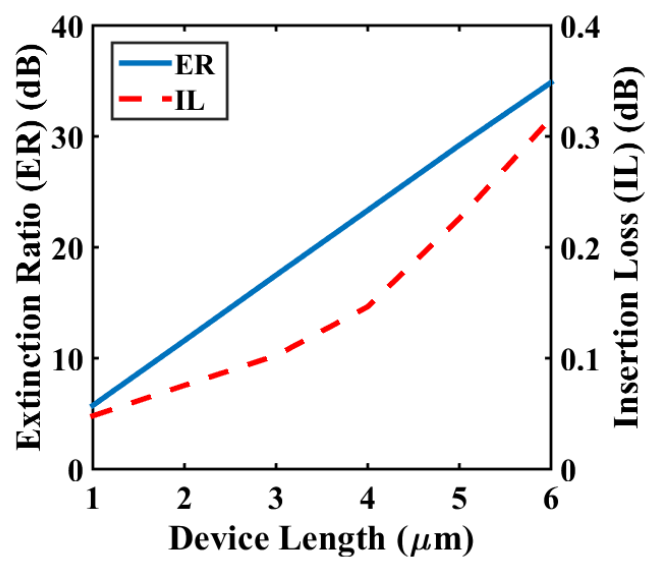

Fig. 5. Dependence of ER and IL achieved for the TE-pass on the polarizer length at h_{p}= 100nm, h_{a}=60nm, and λ=2.0 μm.

To validate the filtration capabilities of the introduced TE-pass polarizer, 3D Finite Difference Time Domain (FDTD) simulations were employed. Figure 6 shows the propagation of the TM and TE modes at h_s= 700nm, h_{p}= 100nm, h_{a}=60nm, h_{t}=50nm, w_{s}=1000nm and λ=2.0 μm. It is evident from this figure that the TE mode is propagated through the suggested design. However, the TM mode has high losses due to the coupling with the surface plasmon mode. The proposed TE pass polarizer at 3.0 μm device length can achieve 17.5 dB ER and 0.1 dB IL at an operating wavelength of 2μm.

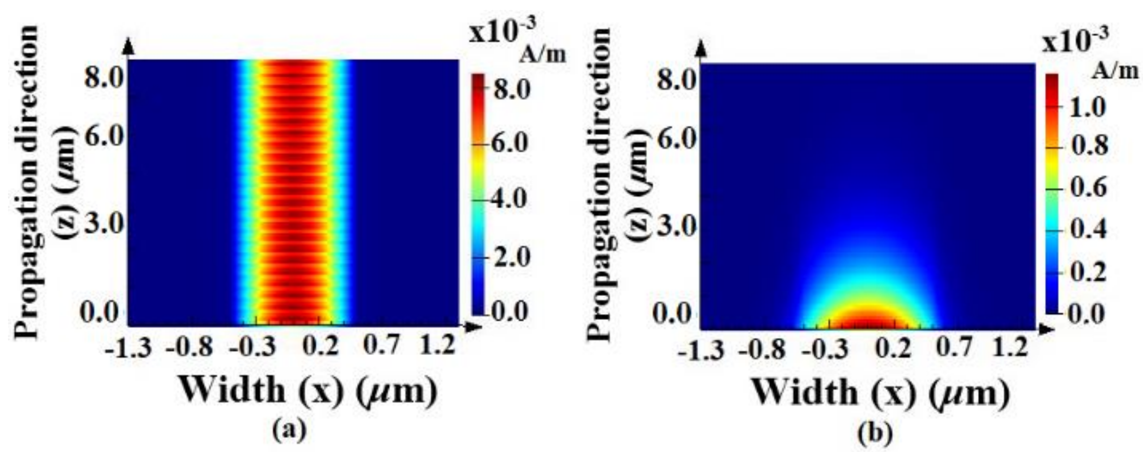

Fig. 6 Propagation of light through the TE-pass polarizer is illustrated for (a) Quasi-TE mode and (b) Quasi-TM mode.

Table 2 presents a comparative analysis between the suggested structure and those documented in existing literature, considering parameters such as device footprint (L_D), IL, ER, compatibility with CMOS, platform used, operating wavelength range, and the nature of the work (experimental or theoretical). The distinguishing factor of

MIR operation characterizes the introduced TE-pass polarizer on the SOS platform. Notably, most polarizers in literature rely on the SOI platform. Furthermore, the proposed design features a shorter L_D compared to findings in (Abd-Elkader et al. 2019b; Azzam and Obayya 2016; Fei et al. 2023; Hiza et al. 2023; El Shamy et al. 2017). A higher ER is also achieved than proposed in (Azzam and Obayya 2016) and a lower IL than reported in (Abd-Elkader et al. 2019b; Fei et al. 2023; Hiza et al. 2023; Kandeel et al. 2019; El Shamy et al. 2017).

Table 2. A comparison between the proposed design and other reported TE-pass polarizers in the literature.

Structure	L_D (μm)	ER (dB)	IL (dB)	compatibility with CMOS	Built on	Operating Wavelength spectrum	Numerical / Experimental
(Hiza et al. 2023)	3.5	36.6	0.8	Compatible	SOI	(Near-IR) 1.55μm	Numerical
(Kandeel et al. 2019)	1.5	32.7	0.17	Compatible	SOI	(Near-IR) 1.55μm	Numerical
(Azzam and Obayya 2016)	3.5	20	0.0635	Compatible	SOI	(Near-IR) 1.55 μm	Numerical
(Abd-Elkader et al. 2019b)	3.5	20.6	0.21	Compatible	SOI	(Near-IR) 1.55 μm	Numerical
(Fei et al. 2023)	7.5	32.8	0.22	Compatible	lithium-niobate-on-insulator	(Near-IR) 1.55 μm	Numerical
(El Shamy et al. 2017)	23	25.57	1.92	Compatible	SOS	(Mid-IR) [2-6] μm	Numerical
Proposed polarizer	3	20.3	0.14	Compatible	SOS	(Mid-IR) 2μm	Numerical

Conclusion

A highly efficient TE-pass polarizer has been suggested and explored for applications in the Mid-Infrared (MIR) spectrum. This polarizer is designed on the SOS platform based on a bi-metallic setup using AZO and TiN alternative plasmonic materials at a 2.0 μm operating wavelength. Extensive simulation studies were conducted to analyze and optimize the proposed structures for optimal performance. The designed polarizer showcases impressive features, including compact, 3.0 μm, device length with high ER of 17.5 dB and low IL of 0.1 dB. Importantly, the introduced polarizer aligns with contemporary CMOS fabrication methods and exhibits commendable performance across a broad bandwidth range while displaying resilience against fabrication errors.

Disclosure

The authors would like to make it clear that the work they have submitted for publication is free of any direct or indirect financial or non-financial conflicts. The author reports no conflicts of interest in this work.

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