Analysis of a tunable CMOS-compatible multilayer waveguide structure for dual polarizer-modulator operation

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Abstract
A multilayer structure using graphene on a silicon waveguide is introduced and optimized to operate as a tunable TE-pass polarizer at 1310 nm or 1550 nm, a tunable TE/TM modulator at 1310 nm or 1550 nm, and a dual operation as a modulator at 1310 nm and a polarizer at 1550 nm. Analysis and optimization are based on the waveguide structure modal loss, geometry, and the 2D graphene layer optical properties dependency on the applied chemical potential. The polarizer tunability at 1310 nm or 1550 nm is attainable setting the applied chemical potential range from 0.55–0.65 eV or 0.45–0.55 eV, respectively. For the modulator tunability at 1310 nm or 1550 nm, the applied chemical potential ranges from 0.45–0.55 eV or 0.35–0.45 eV, respectively. The optimized waveguide silicon layer around 210 nm guarantees an extinction ratio better than 0.056 dB/µm for the polarizer and better than 0.045/0.133 dB/µm for the TE/TM modulator at 1310 nm, and better than 0.034 dB/µm for polarizer and better than 0.053/0.137 dB/µm for TE/TM modulator at 1550 nm. The dual polarizer-modulator operation, e.g., a modulator operating at 1310 nm and a polarizer operating at 1550 nm, is attained at the 0.45–0.55 chemical potential range with an extinction ratio better than 0.045 dB/µm and 0.034 dB/µm, respectively. Compared with other similar devices, the advantage of the structure relies on its versatility to operate as both modulator and polarizer, at different wavelengths, via a proper choice of applied chemical potential, with an insertion loss lower than 0.007 dB/µm.

Keywords Polarizer · Modulator · Graphene · Multilayer structure · Silicon photonics

1 Introduction

In recent years, Silicon on Insulator (SOI) platforms has attracted much interest since it favors miniaturization of high-density Photonic Integrated Circuits (PICs) due to the strong confinement provided by the high refractive index difference between silicon and the silica substrates (Azzam et al. 2014). Furthermore, SOI-based devices are usually compatible with Complementary Metal Oxide Semiconductor (CMOS) fabrication process, which...
allows manufacturing at lower costs than other typical semiconductors for optoelectronics since it is a very mature fabrication technology.

Another material that has been drawing attention since its experimental discovery in 2004 (Novoselov et al. 2004) is graphene, which has been extensively studied for applications in several fields given its unique properties, among which its high thermal conductivity (10 times higher than copper) and its high mechanical resistance (Nguyen and Zhao 2014). In optoelectronics, graphene, due to its properties like high electronic mobility (250 times higher than silicon), high electrical conductivity (35% higher than copper) and high transparency in the visible spectrum (around 97%) (de Oliveira and de Matos 2015; Liu et al. 2011), appears as a suitable choice of material for use in integrated optics devices, where its reduced thickness (0.34 nm for a single graphene layer) provide it an additional advantage over other materials since it allows the development of integrated optic devices without significantly increasing footprint (Vakil and Engheta 2011; Novoselov et al. 2012).

Several research papers combine a SOI platform with graphene to devise some devices like modulators, polarizers, and so on (de Oliveira and de Matos 2015; Liu et al. 2011; Vakil and Engheta 2011; Hao et al. 2015; Gosciniak and Tan 2013; Mohsin et al. 2014; Santos et al. 2018).

In (He and Liu 2017), He and Liu proposed a broadband polarizer based on a graphene-coated surface silicon-core microfiber in an elliptical silica cladding, achieving extinction ratios of the order of 30 dB, with a graphene length of 1.5 mm, where the TE or TM-pass behavior can be tuned by adjusting the core radius of the silicon-core. In (de Oliveira and de Matos 2015), de Oliveira and de Matos showed how waveguide design plays an essential role in graphene devices characteristics by simulating a rib waveguide structure with different dimensions and superstrates. The device can operate as a TE-pass or TM-pass polarizer depending on the superstrate. In (Hao et al. 2015), Hao et al. proposed a TE/TM independent polarizer based on Mach–Zehnder interferometer, whereby coating the interferometer arms with graphene, on top, bottom, and lateral sides, the chemical potential dependence of graphene’s permittivity can be explored by applying a voltage on top and bottom layers or on lateral layers, changing electric field component losses, thus leading to TE or TM-pass behavior. The achieved extinction ratio is on the order of 20 dB, with the device length of some tens of μm. In (Yin et al. 2015), Yin et al. propose an ultra-compact TE-pass polarizer with multilayer graphene embedded in a silicon slot waveguide, based on graphene epsilon-near-zero effect, with an extinction ratio as high as 4.5 dB/μm and an insertion loss of only 0.01 dB/μm. In (Zhang et al. 2016), Zhang et al. have shown a polarization beam splitter utilizing a graphene-based asymmetrical directional coupler combining a silicon waveguide and a graphene multilayer embedded silicon waveguide, obtaining extinction ratios of 18.2 dB and 21.2 dB and insertion losses of 0.16 and 0.36 dB for the thru and cross ports, respectively. In (Yin et al. 2016), Yin et al. have shown a TE-pass polarizer using a cascade of multiple few-layer graphene embedded silicon waveguides, where graphene’s epsilon-near-zero effect is used to attenuate the TM mode more than TE mode, obtaining an extinction ratio of 20 dB for an insertion loss lower than 0.13 dB.

In (Liu et al. 2011), Liu et al. demonstrated a broadband, graphene-based electroabsorption optical modulator using a silicon-core waveguide coated with a graphene layer separated by a thin alumina spacer. The device performance is similar to that of traditional semiconductor materials, with the advantage of a small footprint and easy integration of graphene to novel optoelectronic materials. The modulation depth of 0.1 dB/μm is achieved with a device footprint under 25 μm². In (Gosciniak and Tan 2013), Gosciniak, and Tan investigated theoretically the behavior of a graphene electroabsorption modulator based on a silicon ridge waveguide with two graphene sheets separated by a spacer,
with simulations being realized for several configurations of the ridge, concluding that the modulator can be significantly optimized by choosing appropriate dimensions, and achieving 3 dB modulation with a device length of 600 nm, power consumption as low as 1 fJ/bit and a figure of merit (Extinction Ratio/Insertion Loss) as high as 220. In (Mohsin et al. 2014), Mohsin et al. demonstrated a graphene-based SOI electroabsorption modulator with insertion loss as low as 3.3 dB while achieving an extinction ratio of 16 dB. In (Hu and Wang 2017), Hu and Wang demonstrated a high figure of merit graphene modulator based on plasmonic slot waveguide, evaluating the device for different materials and geometries. The optimized device proposed has an extinction ratio of 8.257 dB/µm and an insertion loss of 0.0376 dB/µm, which leads to an overall figure of merit of 218. The device also has a power consumption as low as 0.008 fJ/bit.

Overall, graphene-based waveguide structures are highly optimized for operation either as a modulator or polarizer at a specific wavelength. Nevertheless, many optical systems use multiple wavelengths. Thus, more versatile approaches to waveguide structures for optical systems are needed. In this work, a single SOI-based, CMOS compatible multilayer waveguide structure is analyzed and optimized to operate as: (i) a TE-pass polarizer tunable to operate at 1310 nm or 1550 nm; (ii) a modulator tunable to operate at 1310 nm or 1550 nm; (iii) either a modulator or a TE-pass polarizer to operate either at 1310 nm or 1550 nm, respectively. The analysis is done by simulating the behavior of the waveguide regarding the applied chemical potential as well as waveguide height for both wavelengths. The structure is evaluated via figures of merit such as the Extinction Ratio and Insertion Loss. It can be shown that the structure versatility relies upon a proper choice of graphene chemical potential range, multilayer waveguide structure design parameters and selective modal losses.

The CMOS compatible multilayer waveguide structure is presented in Sect. 2, along with the modeling approach used in the analysis. Section 3 shows the results obtained for the polarizer, modulator, and dual-mode operations, as well as considerations about the optimal dimensions for each case. In Sect. 4, conclusions of the work are presented.

2 Multilayer waveguide structure and graphene modeling

In (Santos et al. 2018), we reported on the performance of a CMOS compatible multilayer structure, composed of a silica substrate, a silicon core, a graphene layer, and an alumina superstrate, as a tunable TE-pass polarizer with a 6 dB/cm extinction ratio over a 600 nm band. In this work, the proposed reduced dimensionality multilayer structure is redesigned as a rib waveguide to operate as a tunable TE-pass polarizer at 1310 nm or 1550 nm wavelengths, as shown in Fig. 1. The design is based on the structure presented in (Liu et al., 2011), with the electrodes placed more than 500 nm away from the waveguide core to minimize the electrode influence on the field.

The structure modal losses are accounted for by applying the Effective Index Method (Okamotto 2006; Kawano and Kitoh 2001; Marcatili 1974; Ramaswamy 1974) for finding the effective index in both confinement directions separately and solving Maxwell’s equations and applying boundary conditions to the tangential electric and magnetic fields components for TE and TM modes. The complex effective index \( n_{eff} \) is defined as

\[
 n_{eff} = \gamma/k_0 = (\beta + ja)/k_0
\]

and is a function of the wavelength-dependent materials refractive indexes and layers thicknesses, \( \gamma \) is the complex propagation constant, \( \alpha \) is the absorption coefficient, \( \beta \) is the phase constant, and \( k_0 \) is the free space wavenumber.
The graphene layer is treated as an isotropic material (Kim et al. 2019; Xiao et al. 2018; Yin et al. 2015; Zhang et al. 2016), and its electrical and optical properties are modeled (de Oliveira and de Matos 2015; Vakil and Engheta 2011; Hao et al. 2015; He and Liu 2017; Kim et al. 2019) by Kubo’s formula, that takes into account the inter and intraband transitions contribution to 2D graphene conductivity (Hanson 2008), given by:

$$\sigma_{\text{intra}}(\omega, \mu_c, T, \Gamma) = -j \frac{e^2 k_B T}{\pi \hbar^2 (\omega - j2\Gamma)} \left( \frac{\mu_c}{k_B T} + 2\ln \left( e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right)$$  \hspace{2cm} (1)

$$\sigma_{\text{inter}}(\omega, \mu_c, \Gamma) = -j \frac{e^2}{4\hbar \pi} \ln \frac{2|\mu_c| - (\omega - j2\Gamma)\hbar}{2|\mu_c| + (\omega - j2\Gamma)\hbar}$$  \hspace{2cm} (2)

where $e$ is the electron charge, $\hbar$ is Planck’s reduced constant, $\omega$ is the angular frequency, $\mu_c$ is the chemical potential, which is defined by $\mu_c = \mu + \mu_{\text{cp}}$, where $\mu$ is the applied chemical potential and $\mu_{\text{cp}}$ is the chemical potential change caused by charge puddles and topographic corrugations that appear when graphene is deposited on a dielectric substrate (Zhang et al. 2009; Lewkowicz and Rosenstein 2009). $k_B$ is Boltzmann constant, $T$ is the temperature and $\Gamma$ is the scattering parameter, which is linked to carrier relaxation time ($\tau$) by $\Gamma = \frac{\hbar}{\tau}$. In this work, we consider $\Gamma = 5$ meV, as referenced in literature as a reasonable estimate of scattering parameter for graphene (Lu and Zhao 2012; Kuzmenko et al. 2008).

Graphene’s refractive index is defined as relative permittivity is defined as (Xu et al. 2015)

$$n_g = \sqrt{1 - \frac{\sigma}{\omega \mu_0 \delta_g}}$$

where $\delta_g$ is the graphene layer thickness, and $\sigma = \sigma_{\text{intra}} + \sigma_{\text{inter}}$.

Graphene’s chemical potential is typically changed via an applied voltage, in a capacitive arrangement where at least one of the electrodes is in contact with graphene, changing carrier density in graphene (and thus, the chemical potential) according to the applied voltage (Liu et al. 2011; Hao et al. 2015; Gosciniak and Tan 2013; Mohsin et al. 2014).
3 Results and discussion

The rib waveguide losses (in dB/μm), defined as $20\log_{10} e^{-k_0 \text{Im}(n_{eff})}$ for wavelength given in μm, for both fundamental TE and TM modes as a function of wavelength for four different chemical potential values, and waveguide structure height, $H_{Si}$, equal to 230 nm, are shown in Fig. 2.

The structure behaves differently for the TE and TM modes. It can be seen that there are resonant-like peak losses for TM modes around the frequencies of 0.7, 0.8, 0.95 and 1.5 eV, for the chemical potentials of 0.435, 0.492, 0.585 and 0.917 eV, respectively, which are nonexistent for the TE modes. The chemical potentials were chosen due to the appearance of these losses at the wavelengths of 1.8, 1.55, 1.31 and 0.8 μm, corresponding to the end of the analyzed range, the wavelengths of interest and the beginning of the analyzed range, respectively. These tunable and highly selective losses for TM mode occur at the wavelengths where graphene permittivity is near zero (de Oliveira and de Matos 2015; Mahmoud and Engheta 2014; Ziolkowski 2004), as shown in Fig. 3. As graphene permittivity approaches zero, the fraction of the structure electric field normal ($E_n$) to the core-graphene interface increases within the graphene layer, leading to highly selective losses. As the normal electric field component is only present for TM modes, consequently, the near-zero effects do not affect TE modes. In the inset of Fig. 3, the near-zero region is highlighted, showing that, for higher values of chemical potential, graphene’s permittivity is closer to zero, leading to higher losses.

In Fig. 2, other losses, not as selective as those mentioned above, but tunable as well, exist for TE and TM modes around 0.9, 1.05 and 1.2 eV, for chemical potentials values

![Fig. 2](image)

Fig. 2 Losses (in dB/μm) as a function of wavelength, and correspondent value in eV, for the fundamental TE mode (solid lines) and TM mode (doted lines), for the chemical potentials of 0.435 eV (inverted triangle), 0.492 eV (triangle), 0.585 eV (circle) and 0.917 eV (square)
of 0.435, 0.492 and 0.585 eV, respectively. Differently from the resonant-like ones, these losses decrease with chemical potential but also affect the TM mode more intensely. This wavelength-dependent losses behavior follows the real part of graphene’s refractive index, e.g., it increases with wavelength, getting even higher than silicon’s. After this point, it decreases, as shown in Fig. 4.

### 3.1 A tunable TE-pass polarizer to operate at 1310 or 1550 nm

The multilayer structure can operate as a tunable TE-pass polarizer at 1310 nm or 1550 nm if the chemical potential values of 0.585 eV or 0.492 eV are selected, respectively. Graphene’s chemical potential is typically changed via an applied voltage, in a capacitive arrangement where at least one of the electrodes is in contact with graphene, changing carrier density in graphene (and thus, the chemical potential) according to the applied voltage (Liu et al. 2011; Hao et al. 2015; Goscinskiak and Tan 2013; Mohsin et al. 2014).

The waveguide core height impact on the tunable TE-pass polarizer performance is analyzed. In Fig. 5, the calculated losses for TE and TM modes as a function of silicon waveguide core height are shown for 1310 nm and 1550 nm wavelengths.

In Fig. 5, we observe that the silicon core height that maximizes TM mode losses is around 195 nm for 1310 nm wavelength and 235 nm for 1550 nm wavelength. Nonetheless, to further elucidate the operation of the structure as a polarizer, it is essential to observe the figure of merit of the structure for this mode of operation (Extinction Ratio/Insertion Loss – ER/IL), which is shown in Fig. 6. Extinction ratio for the polarizer is defined as the difference between TM and TE mode losses (ER = \( L_{TE} - L_{TM} \)) and insertion loss is defined...
Fig. 4 Real part of graphene refractive index (solid lines) as a function of wavelength, for the chemical potentials of 0.435 eV (inverted triangle), 0.492 eV (triangle), 0.585 eV (circle) and 0.917 eV (square), and the refractive SiO$_2$ (dotted line-square), Si (dotted line-circle) and Al$_2$O$_3$ (dotted line-triangle) layers.

Fig. 5 TE (solid line) and TM (dotted lines) modes normalized absorption coefficient as a function of silicone core height for $\lambda = 1310$ nm and $\lambda = 1510$ nm.
as the losses for TE mode ($IL = L_{TE}$). It is shown that the silicon core heights which effectively optimize the use of the structure as a polarizer are around 215 nm (for 1310 nm) and 260 nm (for 1550 nm), respectively.

There is a clear difference in the figure of merit between the 1550 nm and 1310 nm wavelengths, being it higher (around 100% higher) for the 1310 nm wavelength. If we observe Fig. 3 again, we perceive that this difference is because the epsilon-near-zero effect is more pronounced at the chemical potential of 0.585 eV (corresponding to the 1310 nm wavelength) in comparison to the chemical potential of 0.492 eV (corresponding to the wavelength of 1550 nm). Table 1 summarizes the polarizer figures of merit for the optimized core layer height at each wavelength for the single structure ($H_{si} = 260$ nm) to operate at both wavelengths. It can be noticed that, for the single structure, the performance penalty in comparison to the optimized case for 1310 nm is only 8.3%.

### 3.2 A tunable modulator to operate at 1310 or 1550 nm

The multilayer structure can also operate as a tunable modulator at 1310 nm or 1550 nm. For instance, for operation at 1310 nm or 1550 nm, we set the chemical potential within

![Figure 6](image)

*Fig. 6  Figure of merit as a function of silicon core height for $\lambda = 1310$ nm and $\lambda = 1550$ nm*

| & Optimized Structure & Single Structure |
|---|---|---|
| $\lambda$ (nm) & 1310 & 1550 & 1310 & 1550 |
| $H_{si}$ (nm) & 215 & 260 & 260 & 260 |
| ER (dB/µm) & 0.0644 & 0.0312 & 0.0418 & 0.0312 |
| IL (dB/µm) & 0.0013 & 0.0013 & 0.000952 & 0.0013 |
| FOM & $\cong 48$ & $\cong 23.5$ & $\cong 44$ & $\cong 23.5$ |
the 0.450–0.550 eV or 0.350–0.450 eV ranges, respectively. Although the use of lower chemical potentials can enhance the extinction ratio of the structure, operation for much lower chemical potentials impairs the dual modulator-polarizer operation intended, as the chemical potential ranges used would fall way below the polarizer chemical potential ranges. The structure normalized absorption coefficient as a function of core waveguide height for the two operating conditions are shown in Figs. 7 and 8.

For the TE mode, Figs. 7a and 8a, the best modulation depth, e.g., the higher contrast between the maximum and minimum absorption coefficients in the chemical potential range, occurs around 200 nm (for 1310 nm) and 190 nm (for 1550 nm). Nevertheless,

**Fig. 7** Normalized absorption coefficient as a function of silicon core height and chemical potential for $\lambda = 1310$ nm. a TE mode b TM mode
for TM mode, as shown in Figs. 7b and 8b, the width which optimizes the operation as a modulator is around 210 nm (for 1310 nm) and 220 nm (for 1550 nm).

In Figs. 9 and 10, the normalized absorption as a function of chemical potential, for the two ranges values for tunable operation, are shown for the TE and TM modes, for three different core waveguides heights (including the optimized ones), respectively. For TE mode, the increase in height decreases extinction ratio, and extinction ratios of 0.0695 dB/μm and 0.0734 dB/μm are achieved for 1310 nm and 1550 nm wavelengths, respectively. For TM mode, the values for extinction ratio are around 0.16 dB/μm and 0.14 dB/μm for the wavelengths of 1310 and 1550 nm, respectively.

Table 2 summarizes the ER and IL values for the heights of silicon core, which maximizes ER for TE and TM modes at the 1310 and 1550 nm wavelengths. The Extinction Ratio for
the modulator is defined as the difference between the maximum and minimum losses in the range of chemical potentials analyzed, and insertion loss is defined as the minimum loss. We notice that when the structure is optimized, the figures of merit are better for TE mode (27%
higher than TM mode for 1310 nm and 10% higher for 1550 nm). A single structure to operate at both wavelengths is set to waveguide structure height for the 1310 nm TM mode, which guarantees the performance for the worst-case analyzed. The figures of merit, considering a single structure capable of operating as a modulator at both wavelengths, are also depicted. It is also noticeable that for the single structure, the overall figure of merit changes only slightly compared to the optimized structures.

### 3.3 Modulator operating at 1310 nm and TE-pass polarizer operating at 1550 nm

In previous sections, we analyzed the structure operation as a tunable polarizer and a modulator at different wavelengths. The operation as a modulator or polarizer is selected by a proper choice of chemical potential. For instance, for the 1310 nm wavelength, the structure works as a TE-pass polarizer at 0.585 eV chemical potential and as a TE/TM modulator at the chemical potential range between 0.45 and 0.55 eV. For the 1550 nm wavelength, the structure works as a TE-pass polarizer at 0.492 eV chemical potential and a TE/TM modulator at the chemical potential range between 0.35 and 0.45 eV. Additionally, the structure can be operated in both modes (modulator and polarizer) at the same range of chemical potential at different wavelengths, as shown in Table 3.

The figures of merit for a single structure, dual modulator/polarizer operation are shown in Table 4 for a silicon core height of 230 nm. Using the 230 nm height, we notice that the performance (figure of merit) as a polarizer is around 11% lower for 1550 nm wavelength and less than 1% lower for 1310 nm wavelength compared to the 260 nm height (see Table 1). Thus, the performance penalty for the single structure compared to the optimized cases presented is around 11% (worst case is from 23.5 to 21 for the polarizer operation at 1550 nm).

Another critical detail lies in the operation bandwidth of the device. Considering the values for device resistance and capacitance presented in (Liu et al. 2011) as 600 Ω and 0.22 pF, respectively, the device’s frequency response is based on the RC model of the device is shown in Fig. 11. The estimated modulation speed is around 2 GHz.

### Table 2
Figures of merit, considering the operation as a modulator for the optimized and single structure, at the 1310 nm and 1550 nm wavelengths

| λ (nm) | Optimized Structure | | | | Single Structure | | |
|---|---|---|---|---|---|---|---|
| | 1310 | 1550 | 1310 | 1550 | 1310 | 1550 |
| Mode | TE | TM | TE | TM | TE | TM | TE | TM |
| HSi (nm) | 170 | 200 | 170 | 230 | 230 | 230 |
| ER (dB/μm) | 0.0023 | 0.0072 | 0.0023 | 0.0069 | 0.0015 | 0.0060 | 0.0024 | 0.0069 |
| IL (dB/μm) | 0.0023 | 0.0072 | 0.0023 | 0.0069 | 0.0015 | 0.0060 | 0.0024 | 0.0069 |
| FOM | ≅ 30 | ≅ 22 | ≅ 22 | ≅ 20 | ≅ 30 | ≅ 22 | ≅ 22 | ≅ 20 |

### Table 3
Modes of operation for the structure, according to chemical potential, for different wavelengths

| Chemical potential range (eV) | Chemical potential range (eV) |
|---|--- |
| 0.35–0.45 | 0.45–0.55 | 0.55–0.65 |
| Wavelength | 1310 nm | Modulator | Polarizer |
| 1550 nm | Modulator | Polarizer | X |
Table 4  Summary of the figures of merit, considering both modes of operation (modulator and polarizer), for the proposed structure at the 1310 nm and 1550 nm wavelengths

|                  | TE-Pass Polarizer | Modulator |
|------------------|-------------------|-----------|
| $\lambda$ (nm)   | 1310              | 1550      |
| $\mu_c$ (eV)     | 0.55–0.65         | 0.45–0.55 |
| Mode             | –                 | TE        |
| $H_{Si}$ (nm)    | 230               |           |
| ER (dB/μm)       | 0.0567            | 0.0346    |
| IL (dB/μm)       | 0.0012            | 0.0016    |
| FOM              | $\approx 47$      | $\approx 21$ |

Fig. 11  Estimated frequency response of the structure

Table 5  Comparison of the parameters of the proposed structure with selected works from the literature for the TE-pass polarizer operation

|                  | This Work | He and Liu | De Oliveira and de Matos | Yin et al |
|------------------|-----------|------------|--------------------------|-----------|
| ER (dB/μm)       | 0.0346    | 0.021      | 0.006                    | 4.47      |
| IL (dB/μm)       | 0.0016    | –          | 0.02979                  | 0.2       |
| Wavelength range | 0.85–1.71 | 0.7–1.7    | –                        | 1.546–1.599 |
In order to make it easier to compare the proposed structure with others in the literature, Tables 5 and 6 summarize the main parameters, considering the 1550 nm wavelength and TE mode for the modulator.

Overall, the figures of merit of the proposed structure are on par with other selected works from the literature. Figures of merit much lower than the ones in the literature, particularly when this work is compared to (Yin et al. 2015) in the case of the TE-pass polarizer and (Hu and Wang 2017) for the modulator must be treated with caution since these designs are more complex and highly optimized for the proposed polarizer or modulator operation. (Yin et al. 2015) shows an ultra-compact TE-pass polarizer with multilayer graphene embedded in a silicon slot waveguide and (Hu and Wang 2017) demonstrate a graphene modulator based on plasmonic slot waveguide. Besides being more complex than the structure presented in this work, none of the designs in the literature shows the possibility to operate as a dual polarizer-modulator structure as shown in this work.

Lastly, both polarizer and modulator characteristics can be further elucidated by observing the field intensity distribution for both polarizer and modulator operation, as shown in Figs. 12 and 13.

Table 6  Comparison of the parameters of the proposed structure with selected works from the literature for the modulator operation

| Modulator | This work | Liu et al | Gosciniak and Tan | Hu and Wang |
|-----------|-----------|-----------|-------------------|-------------|
| ER (dB/μm) | 0.0531 | 0.1 | 0.29 | 8.257 |
| IL (dB/μm) | 0.0024 | – | 0.023 | 0.0376 |
| Wavelength range | 0.85–1.71 | 1.35–1.6 | – | 1.26–1.93 |
| Modulation Speed | 2 GHz (est.) | 1.2 GHz | 0.5 THz | – |

Fig. 12  Field intensity for TE (upper row) and TM (lower row) modes for polarizer operation, at the beginning of the waveguide (first column) and after 1 mm (second column) for 1550 nm and 0.492 eV chemical potential
Regarding the polarizer operation, observing Fig. 11, it is clear how the TM mode suffers stronger attenuation in the waveguide than the TE mode. TE mode loses around 35% of its intensity after 1 mm, as TM mode loses more than 90%.

As for the modulator, it can be seen in Fig. 12 that the field intensity decays more than 90% after 1 mm for the 0.45 eV chemical potential at 1310 nm. Nevertheless, it decays only around 35% for 0.55 eV at the aforementioned wavelength.

4 Conclusion

We analyzed the performance of SOI-based, CMOS compatible rib waveguide single structure as a TE-pass polarizer tunable to operate at 1310 nm or 1550 nm, a modulator tunable to operate at 1310 nm or 1550 nm, and a TE-pass polarizer to operate at 1550 nm and a modulator to operate at 1310 nm. We optimized the height of the waveguide core and showed that the structure is capable of operating in both wavelengths as a polarizer via a suitable choice of chemical potential, and with penalties as low as 8.3% when compared to the optimized height for each wavelength (ER/IL of 48 for the dual-wavelength structure versus 44 for the optimized height for 1310 nm). Also, in another chemical potential range, it can be used as a modulator for both TE and TM modes and both wavelengths with a change in the figure of merit lower than 1% compared to the optimized height cases (ER/IL higher than 20 in all cases). Further, the waveguide multilayer structure allows simultaneous operation as a modulator at 1310 nm and a polarizer at 1550 nm via the tuning of chemical potential with a penalty in the figure of merit of around 11% when compared to the optimized height cases (ER/IL of 21 compared to 23.5 for the optimized case of the polarizer for 1550 nm). The extinction ratio for the dual structure is on the order of 0.05 dB/µm for the polarizer operation, which is on par with some of the reported devices in literature (He and Liu 2017), although lower than some devices based on structures such as Mach–Zehnder interferometer or slot waveguides (Hao et al. 2015; He and Liu 2017). For the modulator, the extinction ratio is on the order of 0.10 dB/µm, higher than
reported, for instance, in (Mohsin et al. 2014), and on par with the values of (Liu et al. 2011), although lower than the values obtained in (Gosciniak and Tan 2013) or (Ren and Chen 2019), the latter using a plasmonic slow light configuration in order to perform the modulation. It is important to highlight that the aforementioned works present highly optimized structures for operation as polarizers or modulators. The present work can serve as a starting point for optimizing dual polarizer-modulator devices based on graphene. The optimized waveguide structure layer heights were on the order of hundreds of nm, therefore within modern CMOS fabrication techniques critical feature size around 7 nm (Schoot and Schift 2017; Moore 2018, Narasimba et al. 2017). The impact of treating the graphene layer as an anisotropic material (de Oliveira and de Matos 2015; Kwon 2014; Chang and Chiang 2016) should be further investigated.

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Declaration

Conflicts of interest  The authors declare that they have no conflict of interest.

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