Silicon-on-sapphire (SOS) waveguide modal analysis for mid-infrared applications

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Abstract
Mid infrared photonics is a very promising field with many applications in various areas. Silicon-on-sapphire (SOS) is one of the proposed platforms for this region. This paper present a novel and rigorous modal analysis of the SOS strip waveguide in the mid-infrared range from \(\lambda = 2\) to \(6\ \mu m\) using finite element method solver. The analysis include fundamental and higher modes with both transverse-electric (TE) and transverse-magnetic (TM) polarization, where the dependence of these modes on the waveguide dimensions have been studied. Based on our modal analysis, a compact, wideband and easy to fabricate TE-pass and TM-pass integrated silicon waveguide polarizers have been designed. The different polarizer designs spans the whole mid-infrared transparency region of the SOS waveguide (\(\lambda = 2–6\ \mu m\)). The TE-pass polarizer reaches 35.14 dB polarization extinction ratio while the TM-pass polarizer reaches 69.77 dB polarization extinction ratio with structure length of only 23 \(\mu m\).

1. Introduction
Mid infrared is the wavelength region which contains the characteristic absorption fingerprint of many biological and chemical molecules, which makes mid-IR photonics capable for rapid and high sensitivity detection of chemical and biological species. Thus mid IR photonics have recently received attention as it offers a platform for portable sensors where photonic and electronic functions are integrated on the same chip [1].

One of the challenges for working in the mid infrared region was the laser source of this region which have been bulky and expensive. However recently compact, inexpensive and tunable quantum cascade lasers up to 14 \(\mu m\) wavelength are available commercially with powers up to 1 W [2, 3], in addition to, proposed quantum cascade laser with power of 1.6 W emitting at 4.6 \(\mu m\) [4].

Moreover, MIR silicon photonics platform offers additional advantages because silicon is transparent for wavelength up to 8 \(\mu m\) [5] and have much better nonlinear properties in the MIR region than near-infrared (NIR) because beyond 2 \(\mu m\) two-photon absorption drops to zero, and so the well-known problem of TPA and the associated free carriers becomes negligible. As a result, some recent demonstrations of nonlinear optics in the mid IR in SOI waveguides are done [6]. Another advantage for working in the MIR region is that MIR components have higher immunity to fabrication tolerance than NIR components due to longer wavelengths.

Consequently, mid-IR silicon photonics offers many applications like thermal imaging, infrared spectroscopy and toxic gas or chemical detection, which have impact in diverse areas such as medicine, astronomy, environmental sensing and pollution monitoring, industrial process control, security and defense [7–9]. Hence optical components already known in near infrared region have been shifted to work in mid infrared region and are recently employed and published [3, 10].

Silicon-on-Sapphire (SOS) is one of the most promising platforms that can extend silicon photonics to mid infrared region till 6.2 \(\mu m\) [11], due to sapphire transparency along this region.

In this paper we present novel and rigorous modal analysis of SOS strip waveguide in the mid-IR region from 2 to 6 \(\mu m\). In this analysis the cut-off conditions of the fundamental and higher order TE and TM modes are
defined. Hence we present the waveguide dimensions (thicknesses and widths) that can support optical modes in the MIR region and study the effect of this dimensions on the effective index of different modes. This work is considered an exhaustive analysis of our previously published paper [12], where we had studied SOS waveguide at single dimension and wavelength.

Our analysis is very useful in the design of various devices using the SOS platform in the MIR range, such as multimode interferometers MMIs, ring resonators and Mach–Zehnder interferometers, etc which are the main building blocks in lots of applications.

As a direct outcome of our modal analysis, a compact, wideband, easy to fabricate integrated waveguide TE and TM-pass polarizers working in the mid-infrared region (\( \lambda = 2–6 \mu m \)) are designed. Optical waveguide polarizers are widely used components in integrated photonics circuits [13].

Various designs have been proposed for integrated waveguide TE and TM pass polarizers in the NIR region using different techniques with both dielectric and plasmonic waveguides [14–18]. To the best of our knowledge no effort has been done in the mid-infrared region polarizer design. Our designs are based simply on the fundamental idea of different cut-off [19]. Using this idea different polarizers (with different dimension) have been designed to cover the whole mid-infrared transparency region of the SOS waveguide (\( \lambda = 2–6 \mu m \)).

A wideband TE polarizer working around 2.49 \( \mu m \) wavelength which achieves PER as high as 35.14 dB and IL of only 1.77 dB has been designed. While, a wideband TM polarizer working around 3.25 \( \mu m \) wavelength which achieves PER as high as 69.77 dB and IL of only 1.21 dB has been also designed.

The detailed modal analysis of the structure of the SOS waveguide has been performed using finite element method (FEM) based solver [20]. The final polarization design based on the results of this detailed analysis has been verified using 3D full wave electromagnetic solution using finite difference time domain (FDTD) solver [21].

In section 2, the dispersion analysis of SOS waveguide in the mid-infrared region at different widths and thicknesses are illustrated. Sections 3 and 4 show the design and FDTD simulation results of a TE-pass and TM-pass polarizer, respectively.

2. Dispersion analysis

The widespread SOI technology with \( h = 220 \) nm is not suitable for the mid infrared. The small silicon thickness cannot support guided modes at the MIR region. Although larger silicon layer thicknesses of the SOI can support modes in the MIR however SiO\(_2\) exhibit high absorption beyond 3.6 \( \mu m \) wavelength which reach about 700 dB cm\(^{-1}\) at 5 \( \mu m \) wavelength [22]. Hence, to get efficient waveguides in the mid-infrared region we changed the insulator material from silicon dioxide (SiO\(_2\)) to sapphire (Al\(_2\)O\(_3\)), as the sapphire offers the ability to build high-confinement waveguides for wavelengths from 1.1 \( \mu m \) to around 6.2 \( \mu m \) [11], with sapphire absorption loss less than 1 \( dB \) cm\(^{-1}\) till 5.8 \( \mu m \) wavelength [22]. Also, the new dimensions that can support guided modes in the mid infrared region have to be explored. In our analysis silicon has been used as a high index material (core) using equation (1) from [23] and sapphire as a low index medium (substrate) using equation (2) from [24]:

\[
n_{Si} = \frac{0.159 \, 906}{\lambda^2 - 0.028} - 0.123 \, 109 \left( \frac{1}{\lambda^2 - 0.028} \right)^2 + 1.268 \, 78 \times 10^{-6} \lambda^2 - 1.951 \, 04 \times 10^{-9} \lambda^4 + 3.419 \, 83, \tag{1}
\]

\[
n_{Al2O3}^2 = 1 + \frac{1.431 \, 3493 \lambda^2}{\lambda^2 - 0.072 \, 6631^2} + \frac{0.650 \, 547 \, 13 \lambda^2}{\lambda^2 - 0.119 \, 324^2} + \frac{5.341 \, 4021 \lambda^2}{\lambda^2 - 18.028 \, 251^2}. \tag{2}
\]

A detailed dispersion analysis has been performed using FEM solver [19] to analyze the performance of the SOS waveguide (see figure 1, note that the mode profiles do not have the same scale) in the MIR range \( \lambda = 2–6 \mu m \) for both polarizations. Due to the different boundary conditions for each polarization most of waveguide devices are polarization dependent [25]. Typically, TE and TM modes propagate with different propagation constants and have different cut-off conditions.

For certain refractive indices and waveguide dimensions the FEM solver is able to get the modes (mode profile and effective index) supported by this waveguide at certain operating wavelength. For each wavelength and SOS thickness we start with small width were no guided modes can be resolved by the FEM solver and then we start increasing the waveguide width, with certain width step. At certain width \((w_{1cut-off})\) the FEM solver would be able to get the first guided mode (TE\(_0\) or TM\(_0\)), we record this width as the first mode cut-off width, i.e. below it the waveguide cannot support this mode at this wavelength and thickness. Then we continue to increase the waveguide width and record the first mode effective index \((neff)\). At another width \((w_{2cut-off})\) the FEM solver would be able to get the second guided mode (TM\(_0\) or TE\(_0\) or TE1 or TM1), we record this width as the second mode cut-off width. Similarly we continue to increase waveguide width to get the cut-off widths and the effective indices of the different SOS waveguide guided modes. The width step in this analysis is in general 0.2 \( \mu m \), but to
determine the cut-off width we used smaller width step (also smaller width step was used in regions of mode hybridization). Perfectly matched layer boundary conditions were used with predefined triangular ‘finer’ mesh used in the waveguide core.

At each wavelength ($\lambda$) the thicknesses of the waveguides ($h$) ranging from 0.4 to 0.7 $\mu$m were chosen such that they support fundamental and higher order TE and TM modes within few microns width ($w$). Similar dimensions where published for SOS waveguides [11, 26].

At each wavelength and thickness the width of the strip waveguide ($w$) was spanned till the width were the SOS waveguide can support higher order TE and/or TM modes as shown from figure 2. Note that ripples in the TM modes dispersion curve at certain widths (see figures 2(c), (d), (f)) are due to mode hybridization at these widths. By mode hybridization we mean that the mode cannot be defined clearly as TE or TM.

Figure 3 shows the guided modes supported by the SOS strip waveguide according to its strip width ($w$) for each wavelength ($\lambda$) and thickness ($h$). Each couple of bar represent certain wavelength but at different thickness ($h$). As the width increase as additional modes (represented by the colored rectangles) can be guided by the strip waveguide. Thus, this figure define the cut-off width of different modes at different wavelengths ($\lambda$) and thicknesses ($h$).

3. TE-pass polarizer

3.1. Design rules

An efficient polarizer is characterized by low insertion loss (IL) for the pass polarization which is the ratio between the output and the input power and high polarization extinction ratio (PER) which is the ratio between the output power of the pass and blocked polarization.

For the TE-pass polarizer, the fundamental TE$_{0}$ mode should pass with minimum losses while TM$_{0}$ should be blocked. Hence, using the dispersion analysis results from section 2, the design of the SOS waveguide has to initially support both fundamental TE and TM modes (input waveguide) and by changing the waveguide dimensions (output waveguide) the TM$_{0}$ mode should get blocked, enters the cut-off range, while TE$_{0}$ can pass with minimum IL.

As the difference between the cut-off width/thickness of the TE$_{0}$ mode, the width/thickness which below it the TE$_{0}$ mode ceases to exist, and the cut-off width/thickness of the TM$_{0}$ mode increase as the polarizer performance is enhanced (i.e. lower IL and higher PER).

As shown in figure 2(d) at wavelength $\lambda = 5 \mu$m, thickness $h_1 = 0.7 \mu$m and width around 1.2–2 $\mu$m the SOS waveguide supports TE$_{0}$ and TM$_{0}$. On the other hand, at same wavelength and widths, for $h_2 = 0.6 \mu$m (figure 2(c)) the waveguide only supports TE$_{0}$ while TM$_{0}$ is in cut-off region. As a result, a TE-pass polarizer operating at wavelength around 5 $\mu$m can be simply designed as shown in figure 4. An SOS waveguide with uniform width $w = 1.2–2 \mu$m and starting with $h_1 = 0.7 \mu$m and then etch a step reduction in the thickness from $h_1 = 0.6$ to $h_2 = 0.4 \mu$m to block the TM$_{0}$.

Note that any design will perform as a polarizer around a specific wavelength (here 5 $\mu$m). At far larger wavelengths the O/P waveguide will not support any of the modes (not TM0 nor TE0, cut-off) and at far smaller wavelengths the O/P waveguide will support both modes (TE0 and TM0). So the polarizer performance will degrade.
3.2. Simulation Results

The validity of the structure and the design’s performance is analyzed using 3D full wave electromagnetic simulation based on FDTD method [21]. For each polarizer design we run two FDTD simulation. In the first simulation the polarizer (figure 4) is excited by its TE$_0$ mode along the wavelength range of interest. After simulation finish we get the output transmission (at the end of polarizer) of the TE$_0$ mode along the wavelength. In the second simulation we excite the polarizer with TM$_0$ mode and get the output transmission of this mode along the wavelength. Using the output transmission of both modes from these simulations the IL of each mode and the PER of the polarizer can be calculated directly. Perfectly matched layer boundary conditions were used with maximum mesh size of 10% the object dimensions.

Figure 2. Dispersion curves for SOS waveguide with: (a) $h = 0.5 \, \mu m$ at $\lambda = 3 \, \mu m$, (b) $h = 0.6 \, \mu m$ at $\lambda = 3 \, \mu m$, (c) $h = 0.6 \, \mu m$ at $\lambda = 5 \, \mu m$, (d) $h = 0.7 \, \mu m$ at $\lambda = 5 \, \mu m$, (e) $h = 0.4 \, \mu m$ at $\lambda = 2 \, \mu m$, (f) $h = 0.5 \, \mu m$ at $\lambda = 4 \, \mu m$. 
Increasing the width \((w)\) and thickness \((h_2)\) of the output waveguide will result in decreasing the IL of the TE\(_{0}\) mode. On the other hand, the PER decreases because cut-off TM\(_{0}\) mode becomes closer to its guiding conditions.

For high performance polarizer we need the PER to be larger than 20 dB with TE\(_{0}\) IL lower than 3 dB over large bandwidth and also we need it to be as compact as possible. We started with relatively small \((\text{compared to operating wavelength } \lambda)\) polarizer length \(L = 23 \, \mu m\) which simulation shows to ensure high performance. This length was fixed in order to compare the different designs. However, further increase in the polarizer length \((L)\) will result in higher PER with almost linear dependence till 30 \(\mu m\), while the IL is almost the same (see figure 5(a)) but at the expense of device compactness.

Figures 5(b) and (c) shows the simulation results, IL and PER for different polarizer designs with \(L = 23 \, \mu m\) in the wavelength range 4–6 \(\mu m\) in which we expect to have high PER as suggested by the modal analysis (operating wavelength around 5 \(\mu m\)).

By changing both the width and the thicknesses while keeping \(h_1 > 0.7 \, \mu m\), in the single mode region, the results did not show significant enhancements. In addition, utilizing slanted wall with \(\theta = 4^\circ\), in order to
output TM0 mode with minimum of around 18 dB. Also, cross sectional view of the waveguide mode at the polarizer mode with IL comparable to that of slanted transition. On the other hand, it introduce very high losses for the decrease the IL did not show signifcant change as shown in fi gures 6(a) and (c). Two step stair transition were proposed, Δh = 0.1 μm and ΔL = 2.5 μm, as shown in fi gure 6(b). The slanted design and the stair transition cause a slight reduction in the IL. However, it also reduces the PER as shown in fi gure 6(c). Slanted Si can be done with 54.7°, 35.3° and 4° [27, 28] depending on the type of silicon wafer (100, 110 and 111) used, due to the wafer angle with the slow etching rate [111] plane. It requires more fabrication steps with minimal improvement though.

Figure 7(a) shows the polarizer with w = 1.7 μm, h1 = 0.7 μm and h2 = 0.5 μm, which achieve IL lower than 2.2 dB and PER greater than 20 dB up to 27.25 dB at L = 23 μm and wavelength region from 5.32 to 6 μm with bandwidth of 680 nm. Figures 7(c) and (d) shows the electric field profile in the x–z plane, along the propagation, at the core of the polarizer for both TE0 and TM0 mode respectively. We need to note that these simulation results show that the abrupt step thickness reduction used provides a minimal mismatch for the TE0 mode with IL comparable to that of slanted transition. On the other hand, it introduce very high losses for the TM0 mode with minimum of around 18 dB. Also, cross sectional view of the waveguide mode at the polarizer output fi gure 7(b) show that the fundamental TE0 mode can appear clearly without any distortion. Finally, step reduction in the waveguide thickness has been always fabricated for bragg gratings with high quality by many groups with different techniques and etch step up to 600 nm [29–31].

A 10% misalignment was introduced between the intermediate etch and the waveguide etch. Simulation results fi gure 8 show (as expected) that this misalignment will results in PER reduction by maximum of 2.1 dB which correspond to 7.78% and increase in the IL by maximum of 0.069 dB which correspond to 3.6%. Results show that this misalignment effect is not signifcant for the performance of our TE-pass polarizer.

This design approach can be generalized to span the whole SOS waveguide mid-IR transparent region (λ = 2–6 μm) by changing the input and output SOS waveguide dimensions. The following table 1 show the input and output waveguide dimensions of the designed TE-pass polarizers that work in different wavelength ranges (λ = 2–6 μm) and their performance (PER and IL). All the designs show PER larger than 20 dB and IL lower than 2.5 dB at length L = 23 μm. Also note that, the reflections of our devices, have not been studied rigorously because simulations show a maximum reflection of only 5% over all the wavelength range and all the designs. Figure 9 show the PER and IL versus wavelength of some polarizer’s designs. The rest of fi gures can be found in the appendix (see fi gure A1).
4. TM-Pass polarizer

4.1. Design rules

For the TM-pass polarizer the TM$_0$ mode needs to pass with minimum losses while blocking the TE$_0$ mode. Hence, using the dispersion analysis results in section 2, the design of the SOS waveguide has to initially support both fundamental TE and TM modes (input waveguide). Changing the waveguide width ($w$), or thickness ($h$), or both (output waveguide), the TE$_0$ mode can be blocked (cut-off range) while the TM$_0$ can pass with minimum IL.

Figure 7. TE-pass polarizer with $w = 1.7 \ \mu m$, $h_1 = 0.7 \ \mu m$ and $h_2 = 0.5 \ \mu m$ with transition $(h_1 - h_2)$ at $z = 0 \ \mu m$ and $L = 23 \ \mu m$: (a) PER (solid line) and IL (dashed line), (b) field ($x$-$y$) profile of the TE$_0$ mode at the output of the polarizer $z = L = 23 \ \mu m$ at $\lambda = 5.5 \ \mu m$, (c) field ($x$-$z$) profile of the TE$_0$ mode at $\lambda = 5.5 \ \mu m$ and (c) field ($x$-$z$) profile of the TM$_0$ mode at $\lambda = 5.5 \ \mu m$.

Figure 8. (a) PER (solid line) and IL (dashed line) of TE-pass polarizer with $w = 1.7 \ \mu m$, $h_1 = 0.7 \ \mu m$, $h_2 = 0.5 \ \mu m$ and $L = 23 \ \mu m$ with 10% misalignment and (b) PER (solid line) and IL (dashed line) difference between the polarizer with and without misalignment.
Table 1. PER and IL of different TE-pass polarizer in the wavelength ranges $\lambda = 2-6 \ \mu m$.

| Polarizer width $w_1 = w_2 (\mu m)$ | Polarizer thickness (\mu m) | PER (dB) | IL (dB) | Operating wavelength (\mu m) |
|-------------------------------------|-----------------------------|----------|---------|-----------------------------|
| $w = 0.65$                          | $h_1 = 0.7, h_2 = 0.5$      | 25.12–41.41 | 1.77–2.5 | 2.38–2.55                   |
| $w = 0.65$                          | $h_1 = 0.7, h_2 = 0.35$     | 20.3–26.6  | 1.1–2.5  | 2.63–2.74                   |
| $w = 0.7$                           | $h_1 = 0.7, h_2 = 0.35$     | 20.2–30.5  | 1.31–2.36| 2.7–2.9                     |
| $w = 0.9$                           | $h_1 = 0.7, h_2 = 0.4$      | 20.2–31.7  | 0.72–2.5 | 3.23–3.57                   |
| $w = 1.1$                           | $h_1 = 0.7, h_2 = 0.4$      | 23.13–32.29| 0.74–2.48| 3.56–4.04                   |
| $w = 1.5$                           | $h_1 = 0.7, h_2 = 0.4$      | 20–21.5    | 2–2.5    | 4.26–4.59                   |
| $w = 1.7$                           | $h_1 = 0.7, h_2 = 0.4$      | 20–21.4    | 2.2–2.48 | 4.61–4.83                   |
| $w = 1.4$                           | $h_1 = 0.7, h_2 = 0.5$      | 20–24      | 1.7–2.5  | 5.02–5.46                   |
| $w = 1.7$                           | $h_1 = 0.7, h_2 = 0.5$      | 20–27.25   | 1.4–2.2  | 5.32–6                      |

Figure 9. PER (solid line) and IL (dashed line) of TE-pass polarizer with $L = 23 \ \mu m$ and: (a) $w = 0.65 \ \mu m, h_1 = 0.7 \ \mu m, h_2 = 0.3 \ \mu m$ and (b) $w = 1.1 \ \mu m, h_1 = 0.7 \ \mu m, h_2 = 0.4 \ \mu m$.

Figure 10. (a) 3D view, (b) top view and (c) side view of the TM-pass polarizer and its parameters.

As shown in figure 2(b), at wavelength $\lambda = 3 \ \mu m$, thickness $h = 0.6 \ \mu m$ and width $w_1$ between 0.6 and 1.1 $\mu m$, the SOS waveguide supports both TE$_0$ and TM$_0$. On the other hand, at the same wavelength and thickness, for a width $w_2$ between 0.4 and 0.6 $\mu m$, the waveguide only supports TM$_0$, while TE$_0$ is in cut-off. As a result, our TM-pass polarizer can be simply designed to work at wavelength around 3.1 $\mu m$ as shown in figure 10. The SOS waveguide with uniform thickness $h = 0.6 \ \mu m$, and starting with $w_1$ between 0.6 and 1.1 $\mu m$, then reducing the width from $w_1$ to $w_2$ between 0.4 and 0.6 $\mu m$.

Note that any design will perform as a polarizer around a specific wavelength (here 3 $\mu m$). At far larger wavelengths the O/P waveguide will not support any of the modes (not TM0 nor TE0, cut-off) and at far smaller wavelengths the O/P waveguide will support both modes (TE0 and TM0). So the polarizer performance will degrade.
4.2. Simulation results

FDTD technique [21] is utilized to validate the design and calculate the IL and the PER. The simulation method used here is similar to that of the TE-pass polarizer in section 3.2. Increasing the thickness \( h \) and width \( w_2 \) results in decreasing the IL of the TM\(_0\) mode decrease. On the other hand, the PER also decreases due to the same effect. Again a polarizer length of \( L = 23 \) \( \mu \)m was used as simulation show that it ensure high performance with relatively compact size. This length was fixed in order to compare the different designs. In addition, as the length \( L \) of the polarizer increases, the PER increases with almost linear dependence, while the IL has negligible dependence (see figure 11(a)) however on the expense of the device compactness. The taper length \( (L_{tap}) \) used in all simulations was fixed at 2 \( \mu \)m. Note that, the polarizer length include the tapered section.

Figure 11(b) shows the simulation’s results (IL and PER) for different polarizer’s designs with \( w_1 = 0.8 \) \( \mu \)m, \( w_2 = 0.5 \) \( \mu \)m and \( L = 23 \) \( \mu \)m in the wavelength range 2.5–5 \( \mu \)m and expecting to have high PER around 3 \( \mu \)m (as suggested by the modal analysis). Figure 11(b) illustrates that the wavelength region of interest is that with \( \lambda < 3.3 \) \( \mu \)m because farther increasing in the wavelength will result in a degradation of the PER and an increase in the IL, which was expected from our modal analysis.

As shown in figure 12(a), for \( w_1 = 0.8 \) \( \mu \)m and \( w_2 = 0.5 \) \( \mu \)m and \( h = 0.7 \) \( \mu \)m, a TM-pass polarizer can be achieved with PER greater than 20 dB up to 69.77 dB and IL lower than 1.22 dB and wavelength region from 3.06 to 3.252 \( \mu \)m. The polarizer length \( L \) is only 23 \( \mu \)m. Figures 12(b) and (c) show the electric field profile in the \( x-z \) plane at the core of the polarizer for both TM\(_0\) and TE\(_0\) mode respectively.

We also investigated the effect of the tapering length \( L_{tap} \) on the polarizer performance. FDTD simulation results show that further increasing in the tapered section length \( (L_{tap}) \) while keeping the same polarizer length \( (L = 23 \) \( \mu \)m) will degrade the polarizer performance. Increasing the taper length will not affect the TM\(_0\) mode IL significantly however it will reduce the IL of the TE\(_0\) mode significantly resulting in PER reduction, see figure 13.

This design approach can be generalized to span the whole SOS waveguide mid-IR transparent region (\( \lambda = 2–6 \) \( \mu \)m) by changing the input and output SOS waveguide dimensions. Table 2 show the input and output waveguide dimensions of the designed TM-pass polarizers that work in different wavelength ranges.

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**Figure 11.** (a) IL and PER versus polarizer length \( L \) with \( w_1 = 0.8 \) \( \mu \)m, \( w_2 = 0.5 \) \( \mu \)m and \( h = 0.7 \) \( \mu \)m at \( \lambda = 3.07 \) \( \mu \)m, and (b) PER and IL of TM-pass polarizer for different thicknesses with \( w_1 = 0.8 \) \( \mu \)m, \( w_2 = 0.5 \) \( \mu \)m and \( L = 23 \) \( \mu \)m.

**Figure 12.** (a) PER (solid line) and IL (dashed line) of TM-pass polarizer with \( w_1 = 0.8 \) \( \mu \)m, \( w_2 = 0.5 \) \( \mu \)m, \( h = 0.7 \) \( \mu \)m and \( L = 23 \) \( \mu \)m. Field profile of the (b) TM\(_0\) mode and (c) TE\(_0\) mode in TM-pass polarizer with \( w_1 = 0.8 \) \( \mu \)m, \( w_2 = 0.5 \) \( \mu \)m and \( h = 0.7 \) \( \mu \)m at \( \lambda = 3.2 \) \( \mu \)m with transition \((w_1 - w_2)\) at \( z = 0 \) \( \mu \)m.
\[ \lambda = 2 - 6 \mu m \] and their performance (PER and IL). All the designs show PER larger than 20 dB and IL lower than 2.5 dB at length \( L = 23 \mu m \). Also note that, the reflections of our devices, have not been studied rigorously because simulations show a maximum reflection of only 5% over all the wavelength range and all the designs. Figure 14 shows the PER and IL versus wavelength of some polarizer’s designs. The rest of figures can be found in the appendix (see figure A2).

5. Conclusion

A novel, easy to fabricate, and compact silicon-based TE-pass and TM-pass integrated waveguide MIR polarizers proposed. These polarizers have been fully analyzed using 3D full electromagnetic wave FEM and FDTD
techniques. The TE polarizer reaches 25.57 dB PER with only 1.92 dB IL. On the other hand, the TM polarizer reaches 69.77 dB PER with only 1.21 dB IL. Both structure length of only 23 μm. A detailed dispersion analysis of these structures are introduced using SOS platform.

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Appendix

The following figures show the PER and IL versus wavelength of the TE-pass polarizers of table 1 (figure 13) and the TM-pass polarizers of table 2 (figure 14) that spans the whole mid-IR transparency region of the SOS waveguide.
The following figures show the PER and IL versus wavelength of the TM-pass polarizers of table 2 that spans the whole mid-IR transparency region of the SOS waveguide.

**Figure A2.** PER (solid line) and IL (dashed line) of TM-pass polarizer with $L = 23 \, \mu m$ and: (a) $w_1 = 0.75 \, \mu m$, $w_2 = 0.35 \, \mu m$, $h = 0.55 \, \mu m$, (b) $w_1 = 0.8 \, \mu m$, $w_2 = 0.4 \, \mu m$, $h = 0.6 \, \mu m$, (c) $w_1 = 0.8 \, \mu m$, $w_2 = 0.5 \, \mu m$, $h = 0.6 \, \mu m$, (d) $w_1 = 0.8 \, \mu m$, $w_2 = 0.5 \, \mu m$, $h = 0.9 \, \mu m$ and (e) $w_1 = 0.8 \, \mu m$, $w_2 = 0.5 \, \mu m$, $h = 1.3 \, \mu m$.

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