Journal of Applied Sciences and Nanotechnology, Vol. 2, No. 3 (2022)

Journal of Applied Sciences and Nanotechnology

Journal homepage: https://jasn.uotechnology.edu.iq/

Modal Analysis for Single-Mode Waveguides of Silicon on Sapphire (SOS) at Infrared Region Using Finite Element Method (FEM)

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Article information

Article history:
Received: October, 14, 2021
Accepted: March, 24, 2022
Available online: September, 10, 2022

Keywords:
Waveguide,
Refractive index(n),
Silicon on sapphire (SOS),
TE mode, TM mode

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Abstract

One of the recommended platforms for waveguide generation in the infrared region is silicon-on-sapphire (SOS). This paper proposes a modal of the optical waveguide of silicon on a sapphire from $\lambda = 2 - 5\ \mu m$, using FEM (finite-element method) solver simulation performed by FDTD [finite-different-time-domain]. The waveguide is directly based on the refractive index difference between the wave's guideline regions and surrounding media (cladding). The use of FEM to analyze a single waveguide mode of SOS at a certain size within multiple wavelengths is a unique aspect of this research. In addition, this project's objective is to discover how the waveguide size (dimension) impacts single-mode waveguides in the infrared region. The investigation includes single-mode polarization with both transverse-magnetic TM_0 and transverse-electric TE_0 polarization. The waveguide is reliant on the effective index of different mediums, and sizes of substances, they have a significant role in generating waveguide with minimum loss (minimum dispersion). The study's most crucial finding is that single-mode can be achieved in silicon with widths ranging from $0.4 - 4.5\ \mu m$ and height ranging from $0.4 - 0.7\ \mu m$ as well as analysis the characteristics of mode polarization and explain those parameters have a massive role in the waveguide like effective index, sizes of structure and wavelength. In keeping with our modal analysis, we also state the mode's characterization and direct some factors' influence on the waveguide.

DOI: 10.53293/jasn.2022.4357.1103, Department of Applied Sciences, University of Technology

1. Introduction

The waveguide could be a type of transmission line that directs waves across the size of a slab. In this case, the slab SOS provides a medium for transporting power (energy). To improve the coupling efficiency between two segments with different cross-sections, the optical waveguide is frequently required to change the size of the bright spot [1-3]. Due to its good nonlinear properties in the infrared region, silicon appears to be an attractive candidate to be employed as a foundation material for transparent wavelengths above mid-infrared. The non-linearity is reduced due to the low index variation of both the core and the cladding substrate. According to our modal analysis, TE and TM waveguides are simple to make modes in which MIR ($\lambda = 2 - 5\ \mu m$) are designed. Optical waveguide polarizers have a massive role in various applications like photonics circuits [5, 10]. The main actualization of

SOS width varied $(0.6 - 4\ \mu m)$ and thickness change between$(0.4 - 0.7\ \mu m)$, which is suitable for optical modes. The principle of our work is that the waveguides generate between interfaces caused by the different indexes of refraction, also calculated TE_0 and TM_0 mode about the width and high of silicon layers. Silicon on sapphire may very well be the most capable region, which may prolong radiation due to the visibility of the future. Because of its characteristics, silicon is a strong candidate for generation waveguide in photonics; a silicon waveguide layer is utilized as a core on top of sapphire, which acts as cladding. For a wavelength of $1550\ nm$, the refractive index of silicon and sapphire is $3.476\ and\ 1.7$, respectively, and it can carry more energy with less attenuation and has strong signal transfer power [4-6]. Figure 1 illustrates cross-section waveguide mode geometry, which supports modes that aren't affected by the substrate's spread losses. As can be seen, there is a dispersion of modes inside the infrared district intervals. This geometry has a dispersion wavelength that is close to zero as a result of a waveguide's form, it has an extremely low dispersion wavelength, and it's known as zero dispersion wavelengths (ZDW). In addition, chromatic dispersion is one of the most significant optical waveguide features, which combined with nonlinearity, influences pulse spectrum broadening by shaping the temporal waveform of an optical pulse flowing through the waveguide. Because of some parameters, the location of dispersion changes, which is a good offer to discover rich nonlinear effects on propagation. Because of poor interaction with the loss substrate, the modes of this waveguide are quite well concentrated in the silicon, resulting in minimal propagating losses [21, 22]. Silicon is transparent up to 6μm and will have the critical advantage of having significantly superior nonlinear characteristics inside the mid-IR than the near IR. This has prompted many interesting mid-IR nonlinear optics studies in SOS waveguides near 2μm. The sapphire cladding layer employed in the SOS framework, on the other hand, becomes much more substantially absorbing for applications at longer wavelengths [23]. Waveguide parameters such as width and thickness have been addressed. The main aim was to investigate and analyze the micro waveguide of silicon on sapphire at multiple ranging wavelengths from $(2 - 5)\mu m$. The structure's length (height and width) is optimized to determine which lengths are capable of developing micro waveguides with the minimum degree of dispersion. The dimensions of the construction material have an impact on the waveguide. Silicon, in the form of silicon-on-insulator (SOI) waveguides, has recently gained a lot of attention as a viable platform for mid-IR integrated optical systems.

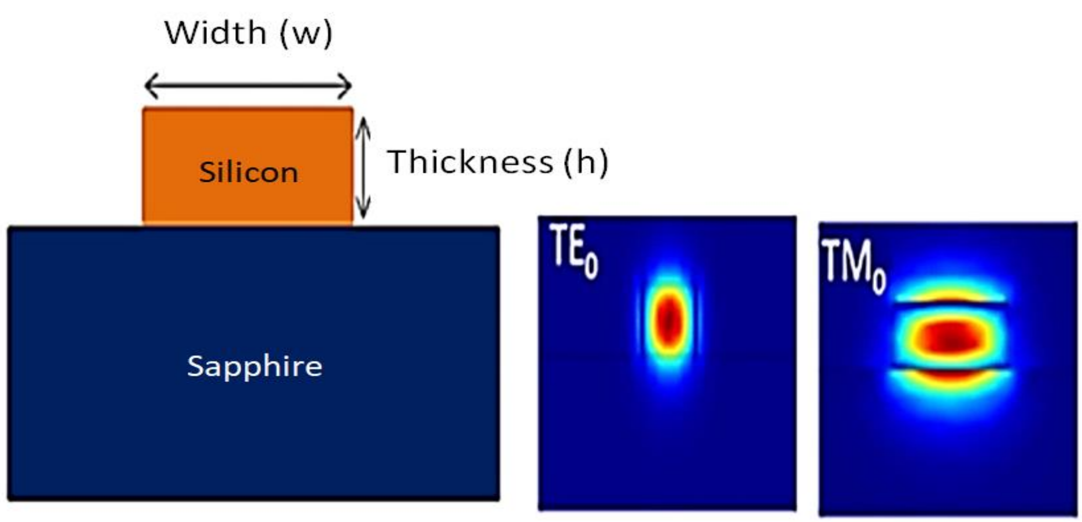

Figure 1: SOS waveguide cross section mode at $w = 1.5\ \mu m, h = 0.6\ \mu m\ and\ \lambda\ = 3\ \mu m$.

2. Waveguides Dispersion

The mode polarization can be achieved in a range of mid infrared from a large silicon layer; nevertheless, the absorption of SiO2 is about $700\ dB\ cm^{-1}\ at\ 5\ \mu m$ [18]. Because sapphire (Al_2O_3) provides for high-confinement waveguides at wavelengths in the mid-infrared range, the insulator material switched from silicon dioxide (SiO_2) to sapphire, but sapphire absorption smaller $1\ dB\ cm^{-1}$ under $6\ \mu m$ wavelength. As a high index material (core), silicon was chosen, whereas sapphire would be used as a low index substance (substrate) [11, 19-21]. Waveguide modes (mode profile) and effective index (TE_0 or TM_0) at specified operating wavelengths may be calculated using FEM solvers for certain refractive indices and waveguide lengths. The equation below for bulk silicon and sapphire, waveguides were constructed to have zero dispersion. Dispersion is calculated with parameters $w = 2.2$ µm $thickness = 0.42$µm and $n_{eff} = 2.55$ are the dimensions of the waveguide dispersion depicted in Figure 2 [21].

$$\mathbf{D} = -\left(\frac{\lambda}{c}\right)\frac{d^2neff}{d\lambda^2} \quad (1)$$

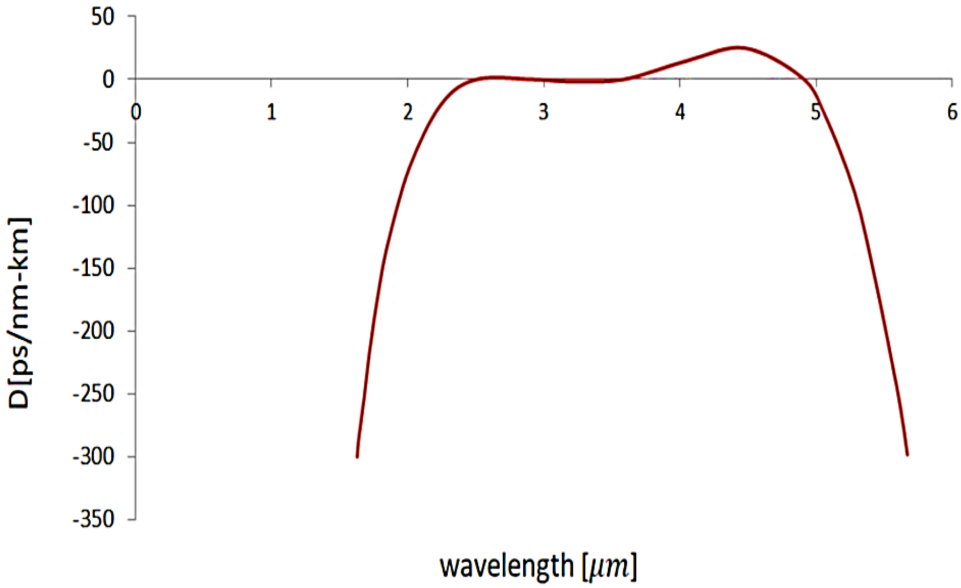

Figure 2: waveguide mode of SOS at zero dispersion (D) with $n_{eff} = 2.55$.

3. SOS Simulation Experiment and Structure Design

Waveguides have some of the optical field spreading that is constant on the propagation of the time and correspond it is in line with the so-called waveguide modes, which rely on the refractive index profile, dimension layers, and dispersion. At special lengths, the FEM solver would be ready to analyze the first waveguide mode TE_0 or TM_0, these are primarily used by the propagation of E&M energy over a micron-sized area. The material used in this work for building waveguides consists of $(0.6 - 4\mu m)$ width and $(0.4 - 0.7\,\mu m)$ thickness at infrared region $(2 - 5$ µm$)$. On the other side, radiation is transmitted over a waveguide section. Here are two field elements that are used are mutually perpendicular to each other that is an electric field and a magnetic field, the mode with electric-field polarization adjacent to the wafer direction, and thus the mode with magnetic-field polarization side by side to the wafer direction. The basic TE_0 mode should pass with minimal losses through the TE-pass polarizer, whereas TM_0 must be stopped, in the TM_0 mode the reverse is true. As a result, the Silicon on sapphire waveguide design must initially sustain both foundational TE_0 and TM_0 modes, so by having to change the waveguide lengths. Figure 3 also shows a color map of the basic model that expresses how the waveguide modes spread over medium with different refractive indexes [7]. Following the results of our modal study, led to the design of a wideband integrated waveguide TE-TM pass polarizers are constructed that operate in a range of the mid infrared spectrum. This is why in this paper we describe the waveguide dimensions (thicknesses and widths) that are capable of supporting optical modes in a range of the MIR, as well as their influence on the effective index. To maintain single modes TE_0 and TM_0 at range microns $width$ (w), the dimensions thickness was chosen at a specific wavelength. It is possible to have only one of each mode as seen in Figure 3 [5]. The effective index is another parameter that has a massive role in the performance waveguide in the infrared region. Keep in mind that any structure (design) will act as a polarizer around infrared wavelength. Waveguide would permit both modes $(TE_0\ and\ TM_0)$ at shorter wavelengths but not at larger wavelengths. Thus, degradation of performance will occur [5].

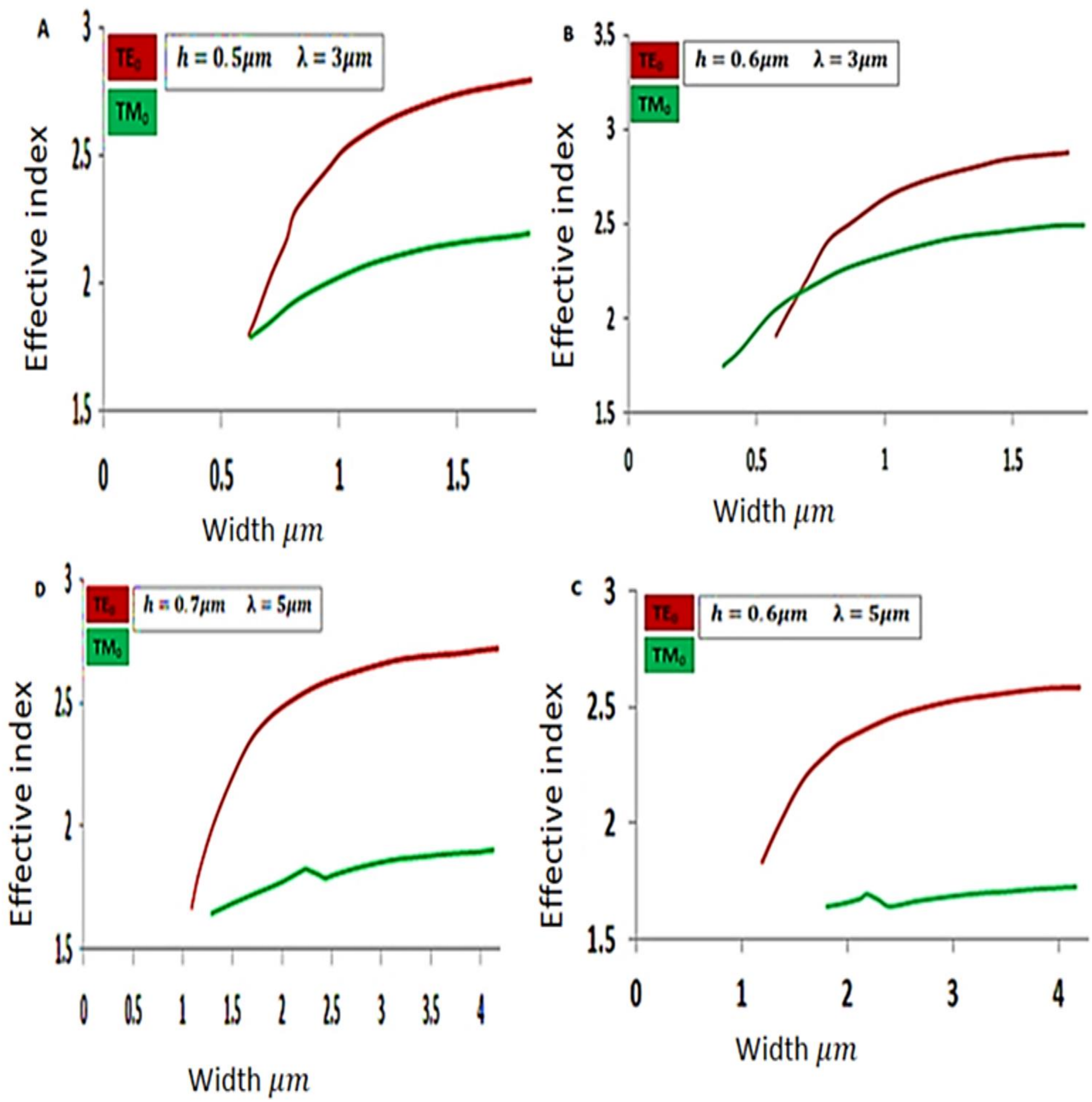

Figure 3: SOS waveguide dispersion: (a)$h = 0.5\ \mu m$, $\lambda = 3\ \mu m$, (b)$h = 0.6\ \mu m$, $\lambda = 3\ \mu m$, (c)$h = 0.6\ \mu m$, $\lambda = 5\ \mu m$, (d)$h = 0.7\ \mu m$, $\lambda = 5\ \mu m$.

4. Results and Discussion

A study is being conducted on the single-mode micro waveguide of the Silicon microstructure core, Sapphire layer is cladding to optimize waveguide features and optical refractive indices [TE_0, TM_0 polarization]. It appears that the effective index plays a significant role in providing waveguide along with the slab, according to the analyzed waveguide modes are confined within the higher index of refraction of the Silicon middle layer, which is illustrated in Figure 4a in 2D [8, 9]. Also, Figure 4b indicates how the mode distributes over (Silicon on sapphire) in 2D, and which depicted how the energy of modes accumulated in high refractive index, this is very useful for the optical fiber.

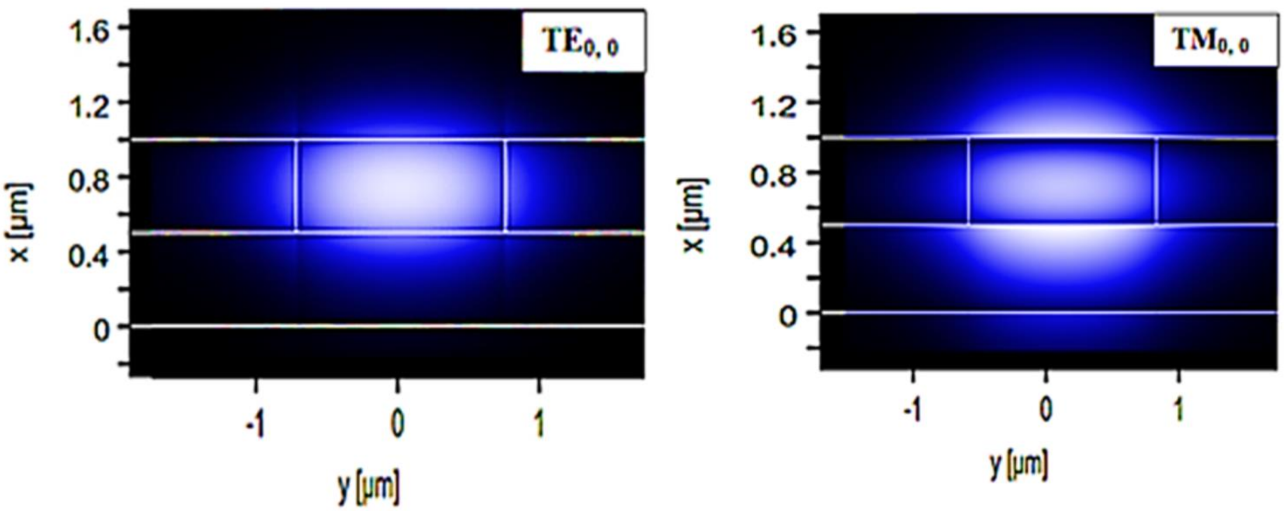

Figure 4a: 2D waveguide produces respect to the different refractive index, (x, y) is dimension in micron.

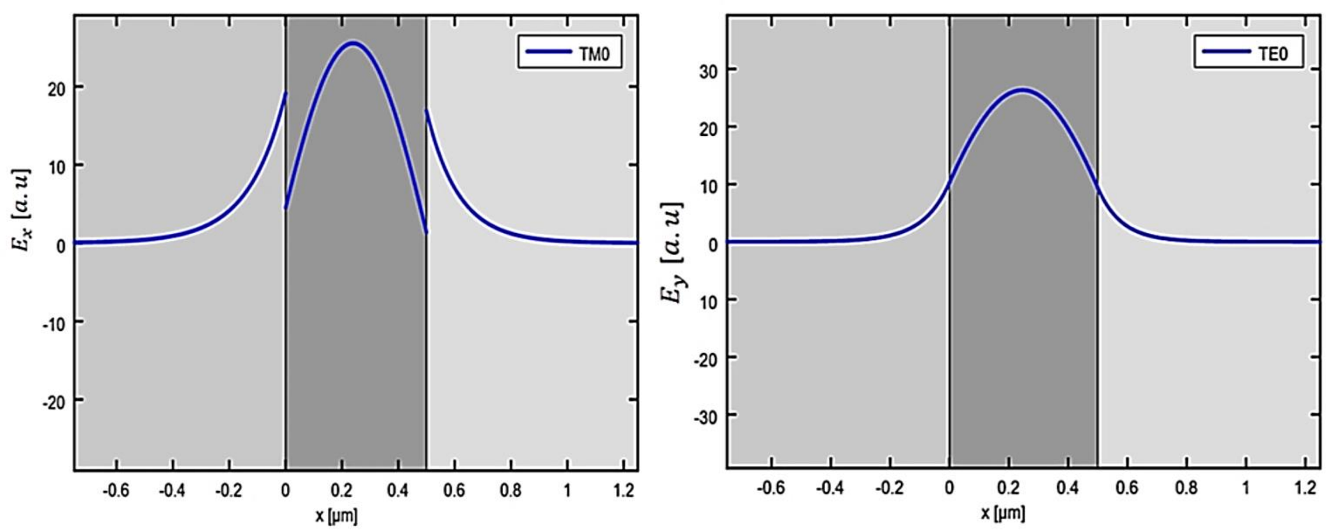

Figure 4b: One-dimension single-mode distributes over SOS waveguide.

In terms of transverse TE, the electrical field component is completely transverse to the direction of wave propagation through this whole mode of wave propagation, whilst the magnetic field component is not entirely transverse to the propagation track.

$$\mathbf{E_z=0;\ H_z\neq 0} \tag{2}$$

As for TE_0 mode could also pass with the smallest losses through the TE-pass polarizer, while TM_0 must be banned. For a TM_0 portion, the opposite statement is true.

$$\mathbf{E_z \neq 0\ ;H_z = 0} \tag{3}$$

From the analysis, it was confirmed that the dimensions were highly linked to waveguide modes, because of this, they were taken into consideration. There is a fascinating concept called wavelength, which is addressed in the section below. Dispersion is unique of the most important features of a waveguide, dispersion and waveform interact throughout non-linearity to influence pulse spectral narrowing, with zero dispersion wavelengths (ZDW) playing a significant role. Based on our studies, we have found that the dispersion can be varied and dependent on dimensions and effective index but the best zero-dispersion could be achieved in w = 2.2 μm.thickness = 0.42 μm and $n_{eff} = 2.55$. It is one good opportunity to propagate waveguide compared to normal dispersion of Silicon demonstrated in Figure 5 (blue line). We suggest a silicon waveguide that demonstrated ZDW within the IR region [21, 22]. The waveguides (h) have thicknesses varying from $0.5\ to\ 0.7\ \mu m$ for each wavelength (λ), were chosen such that they support single-mode TE0 and TM0 inside few microns wide, the wavelength interval between $3 - 5\mu m$ as shown in Figure 3, as about $\lambda = (2, 4)\ \mu m$ gave a similar result of Figure 3(a, d) that is why didn't scale. Figure 3 shows a pattern between waveguide width and effective index that is similar to other results in the [5, 24]. The mode energy quarantine at ZDW sees Figure 5(red line). In comparison to silicon material dispersion, the zero-dispersion wavelengths are$2.55, 2.9, 3.54, and\ 4.9\ \mu m$. [22]

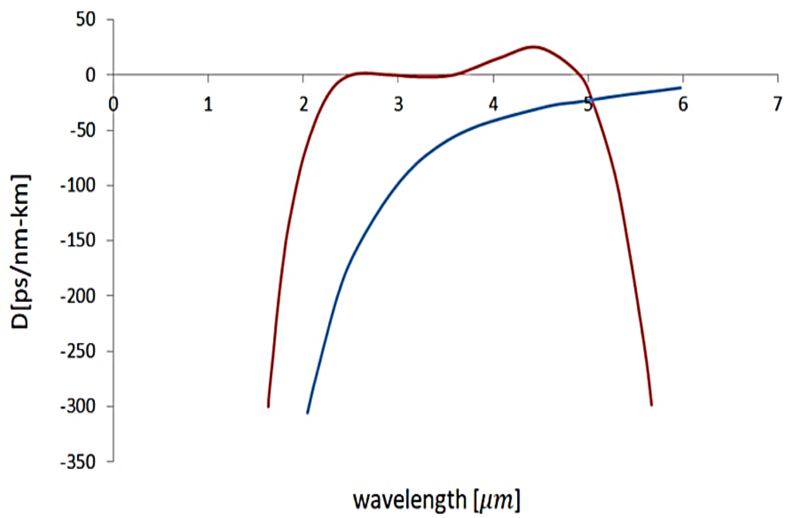

Figure 5: The zero dispersion (D) varies in the range $2.2 - 5\ \mu m$ (red line). Blue line is silicon material dispersion

Based on waveguide width (w) for each wavelength (λ) and thickness (h), the SOS waveguide supports various guided modes depicted in Figure 6.

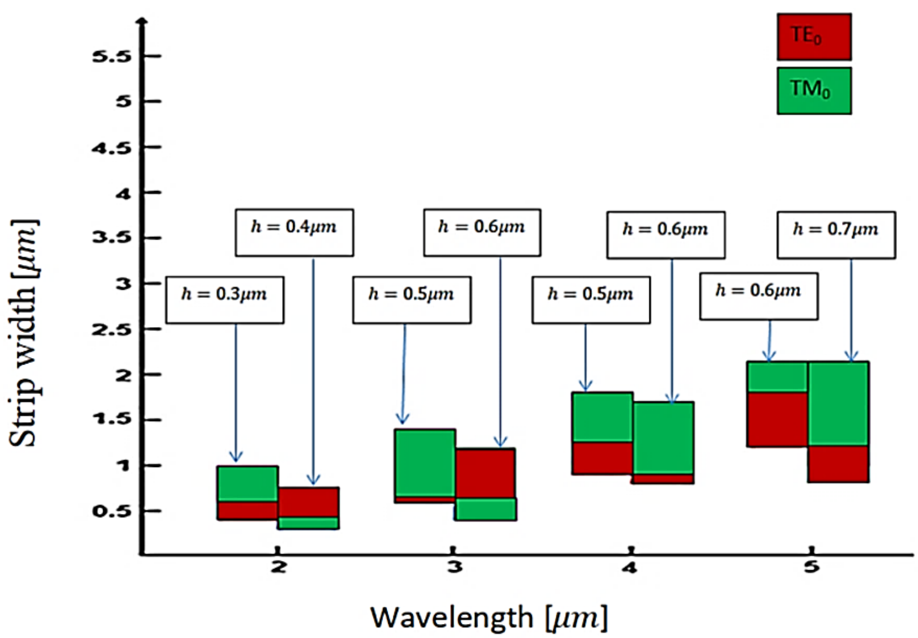

Figure 6: Width of various modes at different wavelengths (λ) and thicknesses (h)constant for each bar.

As we can see, each pair of bars represents a specific wavelength, but the thickness of each bar varies from bar to bar (h). The position of modes varies about width. As a result, this figure indicates the width of various modes at different wavelengths (λ) and thicknesses (h) [5]. As shown in Table.1, the width of waveguide $w = (1.6, 1.4)\mu m$ for TE_o & TM_o and height $h = 0.6\ \mu m$ for both polarization modes at a certain wavelength, they are close to other results $h = 0.6\mu m$ and width $w = 0.85\ \mu m$ that are found in [5, 23]

Table 1: Waveguide width and height values at which the fundamental modes (TE_O&TM_O).

	Width (µm)	Thickness (height) (µm)	Wavelength (µm)
TE_O	1.60	0.6	4
TM_O	1.40	0.6	4

Not only does the effective index depend on the waveguide material, but it also relies on how it's designed in general. Wavelength has a huge influence on frequency. The typical outcome that a lower effective index, as well as a lower mode crossover in lower wavelengths, can be seen in Figure 3 However, the infrared waveguide has been obtained in SOS with low dispersion also we have analyzed the characteristics of the modes concerning several parameters.

5. Conclusion

The structure of silicon waveguides on a sapphire substrate was discussed and designed properly. Also, a significant investigation was carried out on TE-pass and TM-pass optical waveguides in silicon for the mid-infrared frequency range. This dispersion process creates ZDW in particular dimensions in a silicon waveguide, which is given the best promise to make modes across an IR region and normal dispersion at the same region in a silicon waveguide. We found that the refractive index affects waveguide mode. Within the scope of this paper, the importance of an effective index to generate waveguide mode polarization was examined and provided how it works. After describing numerous aspects such as substance width and length, it was established how size (dimension) is appropriate for the generation waveguide in the infrared area. Since they can be tuned for multiple wavelength regimes, including the near-IR, they could be used in mid-IR sensing, nonlinear investigations, or even a broadband light source that operates over the entire silicon transparency. To end we achieved waveguide fundamental modes with width range $(0.4 - 4.5)\ \mu m$. the waveguide has several applications in the physics area such as communication, optical fiber, and electronic circuits.

Acknowledgement

I would like to express my heartfelt gratitude to my friend “Rebwar Salih” for his able guidance and for providing me with all facility that was required in completing my paper.

Conflict of Interest

No conflict of interest.

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