Characterization of GeSbSe Based Slot Optical Waveguides

Muddassir Iqbal1*, YouQiao Ma1, Delin Zhao1 and Babak Parvaei2

1School of Physics & Optoelectronic Engineering, Nanjing University of Information Science & Technology, Nanjing-210044, China; 2Department of Electrical Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

Abstract: Background: Among various chalcogenides, GeSbSe shows a good transmittance in the visible, NIR and, midIR spectrum from 1-20 μm and also demonstrates excellent moldability. Objective: In current work, we have characterized GeSbSe glass for use in sensor mechanism and for adaptive polarization control. Methods: After analysing an earlier work regarding GeSbSe based Silicon on insulator optical waveguide, we implemented GeSbSe in a low refractive index slot region of SOI slot optical waveguide. Change in waveguide geometry can cause a shift in the dispersion profile, but a relatively distinct pattern has been observed. T-slot waveguide structure has also been analysed, where GeSbSe has been implemented in low refractive index slot regions with the Graphene layer beneath the horizontal slot region for enhancement in tailoring ability of the birefringence parameters. Results: Literature review led to the presence of absorption resonance wavelength in SOI slot optical waveguide with our proposed composition, which is attributed to the single average harmonic oscillator property of the chalcogenides. In the T-slot waveguide structure, it was found that a shift in Fermi energy and Mobility values can bring a change in birefringence, even with constant waveguide geometry and operating wavelength. Conclusion: Absorption resonance wavelength in GeSbSe slot optical waveguide has been exploited for proposing the refractive index dispersion sensor. Our design approach regarding T-slot waveguide may lead to the provision of automated polarization management sources for the light on chip circuits.

Keywords: Chalcogenides, silicon on insulator, slot optical waveguide, refractive index, modal effective index, single average harmonic oscillator.

1. INTRODUCTION

In any dispersive material, the speed of light is frequency dependent, which is mainly attributed to frequency-controlled permittivity (ε)/permeability (μ). Optical dispersion deals with the dependence of the complex index of refraction on the wavelength. The real part of the refractive index (RI) can be determined by the phase velocity and the imaginary part can be determined by the absorption. Being critical about transforming dispersion profile knowledge into a sensor system, search for a thermally mouldable material with an impact on polarization manipulation took us to Chalcogenides and especially the GeSbSe within it [1-6]. Chalcogenides are famous for a wide transmission window, which ranges from visible to near IR and then mid IR, making them suitable for sensitive detection of clinical or environmental changes, inherently mouldable chalcogenides are competitive in terms of processing costs. An optical waveguide exhibits resonance reflection at a given wavelength (λ) due to the propagating light experiencing the refractive indices of the device and cladding materials [7, 8]. Contrary to only calculating modal effective indices, dispersion measurement at the corresponding wavelength (λ) yields additional information about the process being monitored, and offers the capability for monitoring multiple processes at once [9]. An easy application for dispersion sensing may lie in atmospheric changes due to added/induced/transmitted gases/ingredients. Accidental or intentional releases of contaminants into the atmosphere pose risks to human health, the environment, the economy, and national security [10-12]. This may be attributed to a single release, or it could be defector emissions from single(multiple) known/ un-known source(s).

Working parallel in two relatively closer directions; the literature study made it evident to us that, any material’s refractive index is dependent on its molecular composition by virtue of its polarizability in the attendance of an electric field, which is due to its electric susceptibility. Any electrically susceptible material (such as Graphene) can bring a change in the velocity of the incident light, or electromagnet-
ic radiation and vice versa. Materials that demonstrate some sort of attenuation while light passes through them are to be characterized using the complex refractive index [13-15]. Index of Refraction (IOR), comprises of real refractive index (n), and imaginary component namely extinction coefficient (κ): \( \Re(\omega) = n(\omega) + i \kappa(\omega) \). Here \( \kappa(\omega) \) is the wavelength dependent extinction coefficient (absorption coefficient), which is being absorbed by the material (\( \kappa(\omega) = \lambda \alpha(\omega)/4\pi \)). Loss coefficient \( \alpha(\omega) \) explains the absorbance \( A(\omega) \) of a medium with path length \( l (A(\omega) = \alpha(\omega)l) \).

Mostly, the complex refractive index fluctuates with the operating wavelength, which is commonly termed as dispersion, and studies in the Abbe number can help in its comprehension \( \left( V = (n_{\text{yellow}} - 1)/(n_{\text{blue}} - n_{\text{red}}) \right) \), where \( n_{\text{yellow}}, n_{\text{blue}}, \) and \( n_{\text{red}} \) are the refractive index values in respective wavelength regions [16-20]. Other empirical models are also used to describe the refractive index dispersion including the Cauchy and Sellmeier equations. The Cauchy model \( (n(\lambda) = A + B\lambda^2+C\lambda^4, \) where \( A, B, \) and \( C \) are constants) can be used to describe the refractive index of a transparent material (\( \chi = 0 \)) [21-23]. It is pertinent to mention that dispersion engineering is the main facilitator for two-octave frequency comb generation [24-29], three-octave supercontinuum generation [24, 30-32], and octave-spanning amplification [24, 33-35]. Governing optical waveguides dispersion properties is not an easy task as dispersion is originated by light interaction with the constituent materials, further augmented by the device structures and in use wavelength [24].

2. METHODS

In this research work, we have characterized GeSbSe usage in the slot region of the basic SOI slot optical waveguide as well as in slot regions of the T-slot waveguide for possible usages as a refractive index dispersion sensor and automated birefringence management, subsequently.

Remaining part of the article is as follows: section two constitutes prior art and the analysis method, self results and analysis are presented in section three, section four comprises of the conclusion.

2.1. Mathematical Background and Prior Art

Mode characteristics depend upon geometry and refractive index profile, where the refractive index profile relies upon permittivity and permeability values within an optical waveguide, due to its’ tenacity of light and material interaction. In an optical waveguide with an arbitrary cross-section \( \Omega \) in transverse xy-plane, the full-vectorial Helmholtz wave equation, based on Maxwell’s equations with an indirect time dependence \( \exp (j\omega t) \), is shown in Eq. (1) [36]:

\[
\nabla \times (\mu \nabla \times \phi) - k_0^2 |q| \phi = 0
\]

(1)

Where \( \phi \) is the electric field (E-) or the magnetic field (H-). Material’s dielectric constant is associated with the permittivity \( [p] \) and permeability \( [q] \) tensors, mathematical relation is presented in Eq. (2) [37]:

\[
[p] = \begin{bmatrix} p_x & 0 & 0 \\ 0 & p_y & 0 \\ 0 & 0 & p_z \end{bmatrix} \quad [q] = \begin{bmatrix} q_x & 0 & 0 \\ 0 & q_y & 0 \\ 0 & 0 & q_z \end{bmatrix}
\]

(2)

\( p_x = p_y = p_z = 1, q_x = n_x^2, q_y = n_y^2, q_z = n_z^2 \), for \( \phi = E \).

\( q_x = q_y = q_z = 1, p_x = 1/n_x^2, p_y = 1/n_y^2, p_z = 1/n_z^2 \), for \( \phi = H \). Where \( n_x, n_y, n_z \) are refractive indices along x-axis, y-axis and z-axis, respectively.

Functional for Eq. (1) is as per Eq. (3), below [38]:

\[
F = \iint \left( (\nabla \times \phi) \times \nabla \times \phi - k_0^2 |q| \phi \right) d\Omega \quad (3)
\]

Complex conjugates are mentioned by using an asterisk.

For constant tangential and linear nodal (CT-LN) element (1st order mixed element); and (b) linear tangential and quadratic nodal (LT-QN) element (2nd order mixed element).

Fig. (1). Mixed-interpolation-type triangular elements: (a) constant tangential and linear nodal (CT-LN) element (1st order mixed element); and (b) linear tangential and quadratic nodal (LT-QN) element (2nd order mixed element).

For constant tangential and linear nodal (CT-LN) elements (Fig. 1a), and for linear tangential and quadratic nodal (LT-QN) elements (Fig. 1b); functions \( \{U\} \) and \( \{V\} \) for nedlec edge elements [38] are briefly described in Eq. (4) [39]:

\[
i_x \{U\} + i_y \{V\} = \begin{bmatrix} |V_1 L_3| (L_1 V_1 + L_2 V_2) \\ |V_1 L_2| (L_2 V_1 + L_3 V_2) \end{bmatrix}
\]

(4)

Applying the transverse (\( \phi_\perp \)) and longitudinal (\( \phi_\parallel \)) components of field (\( \phi \)); in the form \( \phi_\perp = \phi_\parallel + i \phi_\perp \), full-vector wave equation, Eq. (1) can be separated into two parts (ref. Eq. 6 and 7) [41]:

\[
\nabla \times (\mu \nabla \phi_\perp) + \frac{\partial}{\partial z} \left( \mu \phi_\perp \frac{\partial \phi_\perp}{\partial z} \right) - k_0^2 |q| \phi_\parallel = 0
\]

(6)

and,

\[
\nabla \times \left( \mu \phi_\parallel - \frac{\partial \phi_\parallel}{\partial z} \right) = k_0^2 |q| \phi_\perp = 0
\]

(7)

Transverse permittivity and permeability are as per Eq. (8) [42]:

\[
[p]_k = \begin{bmatrix} p_x & 0 \\ 0 & p_y \end{bmatrix} \quad \text{and,} \quad [q]_k = \begin{bmatrix} q_x & 0 \\ 0 & q_y \end{bmatrix}
\]

(8)
A novel T-slot waveguide was proposed for polarization tailoring with SOI structure. We have carried out Full-vectorial (FV-) analysis to learn strongly-hybrid modes for the following cases:

- Silicon dioxide (Eq. 12) [45]
- Silicon (Eq. 13) [45]
- Chalcogenide glass (Fig. 2a) with four zero-dispersion wavelengths was proposed by Guo et al., GeSbSe (chalcogenide glass) was used in conjunction with SOI structure.

(b) T-slot optical waveguide for polarization tailoring [44]: A novel T-slot waveguide was proposed for polarization tailoring (Fig. 2b) by Bian et al. [44].

2.2. Numerical Computations and Analysis

For time-harmonic fields at angular frequency  \( \omega \), the phasor electric and magnetic fields in a medium with permeability (\( \mu \)) and permittivity (\( \varepsilon \)), and no sources are required to satisfy Eqs. (10 and 11):

\[
\nabla \times E = -j \omega \mu H \\
\nabla \times H = -j \omega \varepsilon E
\]

Since relative permittivity (\( \varepsilon_r \)) and relative permeability (\( \mu_r \)) are more frequently used to describe microwave materials, the symbol H is re-defined as \( \eta_0 H \) where \( \eta_0 \) is the intrinsic impedance of free space. Prior to calculating results of the waveguides’ (Fig. 2) analysis, such as dispersion, optical confinement factor in bi-layer waveguide and birefringence for the T-slot waveguide; Sellmeiers’ equation coefficients for Silicon, fused silica were taken from the work of Zhang and colleagues [45], Sellmeier’s equation coefficients for GeSbSe (Chalcogenide glass) were consulted from the corresponding author of the bi-layer dispersion flattened waveguide [43]. Wavelength dependent refractive index of silicon, silica, chalcogenide glass and corresponding material dispersion values using Eq. (12) till Eq. (15) are computed for the wavelength range (1.2-2.4 \( \mu m \)) and are presented in Fig. (3a-3c) respectively.

Second-order dispersion curve and the upper layer confinement factor for bilayer dispersion flattened waveguide is computed and presented in Fig. (4a), which is in close proportion with the earlier published work by Guo et al. [43]. Parameters for the T-slot waveguide (Fig. 2b) were set at: \( W_1 = 175 \) nm, \( W_2 = 400 \) nm, \( h_1 = 200 \) nm, \( h_2 = 100 \) nm, \( t_s = 50 \) nm. In order to calculate the birefringence parameters, symmetric quasi TE and symmetric quasi TM modes were computed by us, using a full vector FEM algorithm (Fig. 4b).

After observing strong light confinement in respective parts of T-shaped low refractive index slot regions, we proceeded with further computations of modal effective index values and found that for a structural width of 400 nm (\( W_2 \)) with varying vertical slot/slabs height (\( h_i \)), the birefringence values (\( \Delta n = n_{TE} - n_{TM} \)) are in conformity with the already published results by Bian et al. [44].

Chalcogenide glass demonstrates huge optical translucency for the infrared frequencies, jointly with thermo-mechanical characteristics makes it easy to transform into
optical gadgets such as lenses, fibers, and optical waveguides [49-51]. Having known about the importance of chalcogenides in forming multi-function optical waveguides and available fabrication methods for developing optical waveguides, we are proposing the use of GeSbSe as low refractive index slot region material in conventional SOI slot optical waveguide [52], as well as in T-slot optical waveguide [44], where fused silica (SiO$_2$) is in substrate, and Silicon (Si) is used in slabs.

Modal effective index values ($n_{eff}$) for the single slot waveguide structure with GeSbSe as low refractive index slot material has been computed by varying the slot width from 100nm to 10nm around the wavelength limit 1.2-2.5 $\mu$m. Modal effective index values were exploited to calculate dispersion values using Eq. (15) (Fig. 5).

During the process of computing dispersion curve, it was observed that the normal dispersion curve abruptly changed to the anomalous dispersion curve at a specific wavelength,

**Fig. (3).** Refractive index (RI) and Dispersion; (a).Silicon (Si), (b).SiO$_2$, (c).GeSbSe.

**Fig. (4).** (a) Dispersion and upper layer confinement in bi-layer dispersion flattened waveguide [43]. (b) Birefringence in SOI T-slot waveguide [44].
Anomalous dispersion region shifting with a change in wavelength in optical power confinement as well as in an effective area profile. Subsequently, we presented two closely linked factors in Fig. (5): the transformation of normal dispersion into anomalous dispersion, and shift in dispersion profile attributed to multiple variants effecting characteristics of an optical waveguide. In this research work, we are exploiting a distinctive shift in the dispersion profile for proposing a Refractive Index dispersion sensor. 

An application-specific optical waveguide array can be utilized for knowledge regarding the presence of certain specific wavelengths in any constituent material (atmosphere/liquid/solid), which is formulating the cladding region.

While segregating the dispersion profile for each waveguide structure, knowledge of relative shift in dispersion profile can help in creating a comprehensive refractive index dispersion sensing system. Where the said system comprises of array-based SOI slot optical waveguides with varied slot width; (Fig. 6a), with a reduction in slot structure height absorption resonance phenomenon ($\lambda_{\text{resonance}}$) is occurring for the visible part of the spectrum, but an increase in structure height is shifting the $\lambda_{\text{resonance}}$ towards near IR. Higher-order dispersion characteristics of the slot waveguide array starting from 10 nm to 100 nm at a step of 10 nm are probed using Eq. (16) [48].

$$S = \left(\frac{n a c}{\lambda^2}\right)^2 \beta_3 + \left(\frac{n a c}{\lambda^2}\right) \beta_2$$  \hspace{1cm} (16)

It was found that the higher-order dispersion value is almost zero at the absorption resonance wavelength (Fig. 6b).

Anomalous dispersion region shifting with a change in optical waveguide height and zero higher-order dispersion at the specific wavelength value validated presence of the absorption resonance wavelength at specified parameters [54], which are being studied.

In an extended probe into the matter, optical power confinement inside the GeSbSe region of the specific optical waveguides was calculated (Fig. 7a), this also led us in finding corresponding effective area values (Fig. 7b). Effective area values provide awareness regarding the nonlinearity index of the specific optical waveguide, and nonlinearity index knowledge is of paramount importance in various light on-chip circuits as well as for transmission of the information at desired speeds. Referring to Fig. (7), there is an evident turning point in the curve at the absorption resonance earlier identified in the literature as absorption resonance wavelength [53] which may be attributed to the single average harmonic oscillator (SAHO) property of the chalcogenides [51]. In order to check the validity of the results, several mesh parameters were employed, and different waveguide parameters were used. More specifically, the slot width was varied and a gradual shift in the normal and anomalous dispersion curves was observed.

**Fig. (5).** Refractive Index Dispersion values around the near-IR window.

In order to validate our results in Fig. (5), we searched for a shift in dispersion profile at a slot width of 30 nm with variation in structure height, three values of 200 nm, 300 nm and 400 nm were considered. A gradual shift in dispersion profile is observed (Fig. 6a), with a reduction in slot structure height absorption resonance phenomenon ($\lambda_{\text{resonance}}$) is occurring for the visible part of the spectrum, but an increase in structure height is shifting the $\lambda_{\text{resonance}}$ towards near IR. Higher-order dispersion characteristics of the slot waveguide array starting from 10 nm to 100 nm at a step of 10 nm are probed using Eq. (16) [48].

**Fig. (6).** (a) Refractive Index Dispersion values at different slot height; (b) Higher-order dispersion.
width, low refractive index slot region comprises of GeSbSe. With the use of available technologies, proposed array waveguide output can be analyzed for the presence of certain specific wavelengths, which may be attributed to chemical agents, some specific fuels, nuclear materials in the constituent cladding region, etc. In Fig. (8), the x-axis indicates the absorption resonance wavelength, which is varying with a shift in dispersion values and vice versa. The same circumstances hold for the optical waveguide structural geometry.

![Graph](image)

**Fig. (8).** Proposed refractive index dispersion sensing system.

In a further quest for tailoring the birefringence parameter without shifting waveguide geometry or the operating wavelength, we introduced a Graphene layer in the T-slot optical waveguide structure (Fig. 10) as a Ferro-electric layer.

![Graph](image)

**Fig. (9).** (a) Modal Effective Index TE & TM (b) Corresponding Birefringence parameters.

3. RESULTS AND DISCUSSION

In order to have a comprehensive review of the GeSbSe based slot optical waveguide structures, we have implemented GeSbSe in low refractive index slot regions of the T-slot waveguide and computed birefringence values for the SiO₂ cladding as well as air cladding SOI and GeSbSe waveguide. In order to do a search between few choices, we probed into birefringence calculations a little further with chalcogenide glass (GeSbSe) in low refractive index slot region and cladding comprising of air as well as SiO₂. Modal effective index values (n_eff) are presented in Fig. (9a) and the birefringence values are presented in Fig. (9b). Birefringence values in respect of optical waveguide with GeSbSe as low refractive index region are comparatively linear than SOI optical waveguides. The linear behavior has an edge over nonlinear behaviour for use in some of the applications.
Modal effective index values have been calculated for the optical wavelength at 1550 nm and keeping the T-slot waveguide parameters fixed at $W_1 = 175$ nm, $W_2 = 400$ nm, $h_1 = 200$ nm, $h_2 = 100$ nm, $t_s = 50$ nm. With the application of Ferro-electric material, a shift in modal effective index values viz-a-viz $E_f$ and mobility is observed (Fig. 11), which is independent of the waveguide parameters and the operating wavelength. Our proposed method for polarization tailoring, while keeping all material paraphernalia constant, is a relatively easy approach for varying polarization of the light sources. With the injection of automated polarizer type light in optical fibers, one can easily change the polarization of the specific signals depending upon the requirements and availability of the space. As the method can lead us for polarization tailoring light sources in photonic integrated circuits, besides further rigorous research on the subject, a little more discussion on the subject is also presented below.

A shift in modal effective index values of the T-slot waveguide structure has been observed without varying structural geometry or the operating wavelength. The quiet encouraging results merit further investigation for the design and fabrication of an automated Modal Effective Index changing optical waveguide. It is pertinent to mention that change in modal effective index values will bring a change in birefringence values which will subsequently change the polarization of the propagating optical signal. As optical waveguides are the building blocks of photonic integrated circuits, hence design and fabrication of an automated birefringence control optical waveguide will provide an edge in generating light for the future ultra-high speed communication systems.

**CONCLUSION**

Refractive index ($n$) directly influences the device performance, as it decides how the light interacts with materials/devices but dispersion profile aids in comprehensive data extraction from the proposed system/mechanism. A simple and matured optical waveguide structure has been used with the implementation of chalcogenides in relatively low refractive index slot region(s). Where strong evidence of chalcogenides integration with SOI optical waveguide is available. Variation in dispersion profile was found linked with low refractive index slot width. The key motivation behind current research work is dispersion profile importance in comprehending any medium’s permittivity and permeability index. The proposed sensor mechanism can respond to a wide range of wavelengths of interest and it can be tailored for a specific case as well. Our method for measuring the refractive index dispersion profile using an array of slot optical waveguides can distinguish between materials with the same RI at a particular wavelength but different dispersion profiles, thus it may become a probable candidate for lab-on-chip circuits.

We have also proposed photonic integrated circuits for manipulating the polarization of light using GeSbSe based T-slot optical waveguide with the graphene layer. Automated polarization manipulation of the optical signal may place our approach a likely candidate for use in future high speed optical fiber communication systems.

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**Fig. (10).** T-slot waveguide with graphene layer implementation.

**Fig. (11).** Birefringence shift in T-slot optical waveguide due to (a) Fermi energy; (b) Mobility.
EThics Approval and consent to PartiCIPate

Not applicable.

human and animal rights

No Animals/Humans were used for studies that are the basis of this research.

conSenT for publication

Not applicable.

aVailabilitY of data and materials

The authors confirm that the data supporting the findings of this study are available within the article.

fUnding

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conFlict of interest

The authors declare no conflict of interest, financial or otherwise.

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