Chalcogenide waveguide structure for dispersion in mid-infrared wavelength

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We present a waveguide design with low dispersion in mid-infrared wavelengths. The design consists of slot-strip-slot structures horizontally, the strip structure is considered with high index and slot is considered with low index material. We show a dispersion of 0–350 ps/(km·nm) over a band width of 1375 nm, and the structure shows zero dispersions at 2512 and 3887 nm wavelength. The magnitude of dispersion can be fine-tuned by varying the waveguide parameters. Such a waveguide structure with low dispersion at mid-infrared wavelengths has a great potential for supercontinuum generation application. Apart this, we have also proposed dispersion compensation structure, the structure shows a high negative dispersion at 1510 nm wavelength. The structure should find application in the design of an integrated optic dispersion compensator for optical telecommunication and ultrafast waveguide lasers. © 2017 The Japan Society of Applied Physics

1. Introduction

Chalcogenide glasses have shown significant importance over the other materials, due to their large optical nonlinearity (several hundred times that of silica material), low transmission loss and wide transparent window in mid-infrared wavelength. Therefore, chalcogenide glasses are very attractive for fabricating fiber and waveguides in mid-infrared wavelengths.1–4) Recently, chalcogenide glasses have been used for various applications such as supercontinuum generation, dispersion engineering and sensing.5–8) In which dispersion parameter in nonlinear optics has a significant role, a flat and low dispersion is required for many nonlinear applications such as wavelength conversion,9,10) soliton formation,11,12) and comb generation.13,14) Flattening of dispersion in waveguides and nano-photonic wires is a difficult task, because of high confinement of light and strong waveguide dispersion. Zhang et al. have proposed a strip-slot silicon waveguide with silica slot structure and achieved a flat dispersion.15) Zhu et al. have studied the dispersion properties of strip/slot hybrid waveguide and shows a low dispersion over a bandwidth of 1098 nm.16) Bao et al. have demonstrated the double slot waveguide design and the structure showed dispersion over a bandwidth of 878 nm.17) A strip-slot hybrid waveguide design with silicon nanocrystal slots reported a low and flat dispersion over 845 nm bandwidth.18) Zhang et al. have investigated the As2S3 slot waveguide design. The structure reported a low dispersion over a bandwidth of 249 nm.19) Zhai et al. have proposed a reverse ridge/slot waveguide, the reverse structure shows dispersion over a bandwidth of 1370 nm.20) Karim et al. have demonstrated the Ge11.5As24Se64.5 chalcogenide glass waveguide structure with low dispersion, the structure shows supercontinuum generation in mid-infrared wavelength.21,22)

In this paper, we have proposed a horizontal slot-strip-slot waveguide structure, the strip structure is designed with high index material, and slot is designed with low index material. We have calculated the effective index of mode by utilizing the finite difference time domain (FDTD) method (Numerical MODE solutions),23) and dispersion of the structure has been calculated numerically. Our simulation results predict that by adjusting the waveguide design parameters, we can achieve a low dispersion of 0–350 ps/(km·nm) over a band width of 1375 nm and the structure shows zero dispersion at two wavelengths. The study should be useful for the application of supercontinuum generation. Along with we have also proposed dispersion compensating structure using coupled strip-slot design. The structure shows a high dispersion value at 1510 nm wavelength.

2. Design of proposed structure

We have proposed a slot-strip-slot waveguide structure, schematic of the structure is shown in Fig. 1. The design consists of a strip waveguide of Ge11.5As24Se64.5 material with height H2, and covered both sides with MgF2 slots. Thee lower slot designed with a height H1, and upper slot designed with height H3. Lower and upper slot structures are supported by Ge11.5As24Se64.5 slab material. The Ge11.5As24Se64.5 strip, MgF2 slots, and Ge11.5As24Se64.5 slabs have considered with a width of W, and all the structures are deposited on MgF2 substrate. By choosing the optimized waveguide design parameters the structure shows zero dispersions at 2512 and 3887 nm wavelength. The wavelength dependent refractive
index of Ge\(_{11.5}\)As\(_{24}\)Se\(_{64.5}\) material used in this simulation is calculated from the Sellmeier’s equation:\(^{21,22,30,31}\)

\[
n_2(\lambda) = \frac{1 + 5.78525\lambda^2}{\lambda^2 - 0.28795^2} + \frac{0.39705\lambda^2}{\lambda^2 - 30.39338^2},
\]

where \(\lambda\) is the wavelength in micrometers. The MgF\(_2\) material has also calculated from the Sellmeier’s function.\(^{24}\)

3. Results and discussion

3.1 Slot-strip-slot waveguide results

We have numerically analyzed the structure for the following values of waveguide parameters. Strip waveguide of height \((H_2)\) 760 nm, lower slot height \((H_1)\) 70 nm, upper slot height \((H_3)\) 58 nm and strip, slot, slabs are considered with a width \((W)\) of 1000 nm. The proposed structure is designed vertically using the above designed parameters. We have calculated the effective index \(n_{\text{eff}}\) of transverse magnetic modes at various wavelengths. In the calculation of \(n_{\text{eff}}\), material dispersion is considered into the process by using Sellmeier’s equations for Ge\(_{11.5}\)As\(_{24}\)Se\(_{64.5}\), and MgF\(_2\). The dispersion parameter \((D)\) of the structure has been calculated from the following equation:

\[
D = -\frac{1}{\lambda_0 c} \left( \frac{\lambda_0^2}{\lambda_0^2} \frac{d^2 n_{\text{eff}}}{d\lambda^2} \right).
\]

In Fig. 2 we have plotted the calculated \(n_{\text{eff}}\) and second order dispersion values as a function of wavelength. From the figure, we can see that, the effective index of the mode is decreasing with wavelength. Second order dispersion of the design is decreasing first and then increasing. Second order dispersion in the curve showing two zero dispersion wavelengths. Next, we have studied the dispersion parameter of the structure for various wavelengths, and calculated results are plotted in Fig. 3. From the results we noticed a low dispersion of \(\approx 350\) ps/(km·nm) over 1375 nm bandwidth, from 2512 to 3887 nm wavelength. From Fig. 3, we have also noticed two zero dispersion wavelengths, which are located around 2512 and 3887 nm. Formation of such dispersion is due to the mode transition and anti-crossing effect. To understand this, we next investigated the mode behavior at different wavelengths. In Fig. 4 we have plotted the modal field distribution of the mode at two different wavelengths. In shorter wavelength region the mode is concentrated in strip waveguide region. As we increase wavelength the mode transfers in to lower and upper slot regions. From Fig. 4 we can see that the power spreading into slots at 2200 nm wavelength.

We next investigated the effective mode area \(A_{\text{eff}}\) of the proposed strip-slot-strip waveguide. In Fig. 5, we have plotted the effective mode area as a function of wavelength. The effective mode area of the structure increases as wavelength increases, which means, as increasing wavelength power of waveguide mode spreads in the structure and hence the mode area increases for longer wavelengths.

Realization of structure with low dispersion over a wide wavelength range is a key point in designing the waveguide. Dispersion of waveguide can be tailored by altering the waveguide design parameters. To investigate this, we have fine-tuned the waveguide design parameters such as lower slot height, upper slot height and strip height. First, we have studied the effect of strip waveguide height \(H_2\) on dispersion.
As height $H_2$ increases dispersion moves up-side more at longer wavelengths, very small at shorter wavelength and also it maintains the same shape. Figure 6 shows that, increasing strip height from 760 to 800 nm the magnitude of dispersion changes from 350 to 430 ps/(km·nm), and band width changes from 1375 to 1510 nm. From the results it is clear that, band width and magnitude of dispersion increases with height $H_2$. Next, we have investigated the effect of width parameter. Optimized waveguide width for the proposed structure is 1000 nm, which is the width of all deposited waveguides on MgF$_2$ substrate. To investigate the width effect we have calculated the effective index and then dispersion of structure for three different values of width. The calculated results of the structure are shown in Fig. 7. As we increase width, dispersion curve at lower wavelengths is almost unaltered, but after crossing zero dispersion point the magnitude dispersion curve moves up. Changing width, $w$, from 1000 to 1050 nm changes the magnitude of dispersion from 350 to 405 ps/(km·nm). From the figure it is clear that, effect of width significantly changes the dispersion after crossing the zero dispersion.

Heights of slot waveguides have also significant importance in optimization. To elucidate slot height affect first we have analyzed the lower slot height effect on dispersion curve. In Fig. 8 we have plotted dispersion curve as a function of wavelength for three different heights of lower slot. As we increase height $H_1$ the dispersion curve increases in anomalous dispersion region, however from the figure we noticed that the dispersion change is small by changing the lower slot height. As we increase the height from 65 to 75 nm the magnitude of dispersion changes from 337 to 366 ps/(km·nm). In addition, we have also investigated the effect of upper slot height on dispersion and calculated results are plotted in Fig. 9. From the figure, we noticed that dispersion curve increases more in anomalous dispersion region compared to normal dispersion region. On increasing upper slot height from 48 to 68 nm, the magnitude of dispersion changes from 279 to 421 ps/(km·nm). Therefore Fig. 9 helps us to choose the suitable value of $H_3$ for low dispersion. Hence, the effect of waveguide design parameters on dispersion indicates a guide to design the waveguide with appropriate structure parameters and properties of dispersion could be sensitive in high-index contrast waveguide fabrication. From the above results, we evident that with the optimized waveguide parameters, such as strip height ($H_2$) 760 nm, lower slot height ($H_1$) 70 nm, upper slot height ($H_3$) 58 nm and strip, slot, slabs width ($W$) of 1000 nm, the structure shows a dispersion 0–350 ps/(km·nm) over 1375 nm bandwidth in mid-infrared wavelength region.

### 3.2 Dispersion compensation design

Next we investigated the applicability of waveguide for dispersion compensation using the strip-slot coupled design. 

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**Fig. 6.** (Color online) Dispersion of waveguide with variation of strip waveguide height.

**Fig. 7.** (Color online) Dispersion of structure with the variation of all waveguide widths.

**Fig. 8.** (Color online) Dispersion of waveguide with variation of lower slot height.

**Fig. 9.** (Color online) Dispersion of waveguide with variation of upper slot height.
Over the years we have designed various coupled waveguide structures for different applications. The designed structure is plotted in Fig. 10. We have analyzed the structure for the following values of optimized waveguide parameters. Strip height ($h$) of 360 nm, and strip-slot separation ($s$) of 560 nm, slot height ($w$) of 54 nm, and slabs height ($p$) of 160 nm. All the waveguides have considered with a width ($t$) of 400 nm.

By choosing the optimized waveguide parameters we have calculated the effective indices of modes. In the calculation of effective index we have used the Sellmeier’s equations for Ge$_{11.5}$As$_{24}$Se$_{64.5}$ and MgF$_2$ materials. The present structure shows resonance between the slot mode and strip mode, hence fundamental mode of strip waveguide coupled to the fundamental of slot waveguide. In Fig. 11 we have plotted the effective indices of modes as a function of wavelength. From the figure we can see that at the resonant wavelength the effective index curves are well separated, but at resonant wavelength the modes are coupled and close to each other. Sharp bending in effective index of symmetric and asymmetric modes results a high dispersion at resonance wavelength. Next, we have investigated the dispersion of corresponding modes and results are shown in Fig. 12. Present structure with symmetric mode shows a high negative dispersion of $-5.2 \times 10^4$ ps/(km-nm) and a full width half-maximum (FWHM) of 45.5 nm at 1510 nm wavelength. Our numerical results are comparable to the reported results.

Hence, the structure should be useful in designing the integrated optic dispersion compensator for optical telecommunication and ultrafast waveguide lasers.

4. Conclusions

We have proposed a slot-strip-slot optical waveguide, the strip waveguide is designed with Ge$_{11.5}$As$_{24}$Se$_{64.5}$ chalcogenide material. The effective index of modes have been calculated by using the FDTD method and the dispersion has been calculated numerically. We achieved a dispersion of 0–350 ps/(km-nm) over 1375 nm bandwidth, from 2512 to 3887 nm wavelength. We investigated the effect of various waveguide design parameters on dispersion. Such a waveguide structure should be useful for supercontinuum generation application at mid-infrared wavelengths. Apart this we have also investigated the dispersion compensation design and the structure shows a high dispersion of $-5.2 \times 10^4$ ps/(km-nm) with a FWHM of 45.5 nm and the design should be useful in integrated optic dispersion compensator for optical telecommunication.

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![Fig. 10](image-url) Design of dispersion compensating structure.

![Fig. 11](image-url) Variation of effective indices of symmetric and asymmetric modes.

![Fig. 12](image-url) Dispersion curve with wavelength.
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