



## Original research article

# Rib chalcogenide glass waveguide with simultaneous dispersion flattening for both transverse electric and magnetic modes

Yuxiu Shi<sup>a,b</sup>, Peipeng Xu<sup>a,b,\*</sup>, Zenghui Yu<sup>a,b</sup>, Xiang Shen<sup>a,b</sup>, Qihua Nie<sup>a,b</sup><sup>a</sup> Infrared Materials and Devices Laboratory of Ningbo University, Ningbo University, Ningbo, Zhejiang 315211, China<sup>b</sup> Key Laboratory of Photoelectric Detection Materials and Devices of Zhejiang Province, Ningbo, 315211, China

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## ABSTRACT

A rib chalcogenide glass waveguide with simultaneous dispersion engineering for both fundamental quasi-TE mode and quasi-TM mode is numerically demonstrated. Dispersions of approximately  $\pm 100$  ps/nm/km over a 4200-nm bandwidth for the quasi-TE mode and of approximately  $\pm 120$  ps/nm/km over a 2350-nm bandwidth for the quasi-TM mode are observed. Dispersion design for both polarizations can be independently realized by tuning the structural parameters. Moreover, this waveguide can support broadband FWM processes and have potential applications from near-infrared to middle-infrared region based on the polarization effect.

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## 1. Introduction

Recently, planar waveguide fabricated from chalcogenide glasses (ChGs) have emerged as an excellent nonlinear platform for all-optical processing due to their attractive optical property combined of strong nonlinearity (nonlinear index  $n_2$  of  $\text{As}_2\text{S}_3$   $\sim 130$  times greater than silica [1]), good light confinement due to their high refractive index, intrinsically fast response time (not limited by free carriers as in silicon [2]), and negligible two-photon (TPA) absorption [3].

Many all-optical processes have now been demonstrated using dispersion-engineered chalcogenide waveguides, including supercontinuum generation [4,5], wavelength conversion [6,7] and parametric amplification [8,9]. Most of these functions involving four-wave mixing (FWM) are phase-sensitive nonlinear processes and their bandwidths are closely related to the group velocity dispersion (GVD) in the nonlinear medium [10]. Some efforts have been made to enhance the FWM bandwidth by reducing the phase mismatch in a broader wavelength region through optimising the waveguide geometry [11,12] or by designing special waveguide structures [13–16] to engineer GVD of the chalcogenide waveguides.

Strong polarization sensitivity is a major issue for the practical use of FWM-based functionalities. The FWM process is normally polarization dependent, and an efficient FWM process occurs when the input signal and pump waves are both aligned with either the transverse electric (TE) mode or transverse magnetic (TM) mode of the waveguide. Therefore, several additional components are necessary to convert the incident waves into the identical mode. For an integrated optical system wherein operation with versatile polarizations is required, it is desirable to be able to simultaneously reduce and control the dispersion of TE and TM modes. This would enable more efficient nonlinear applications.

\* Corresponding author at: Infrared Materials and Devices Laboratory of Ningbo University, Ningbo University, Ningbo, Zhejiang 315211, China.  
E-mail address: [xupeipeng@nbu.edu.cn](mailto:xupeipeng@nbu.edu.cn) (P. Xu).

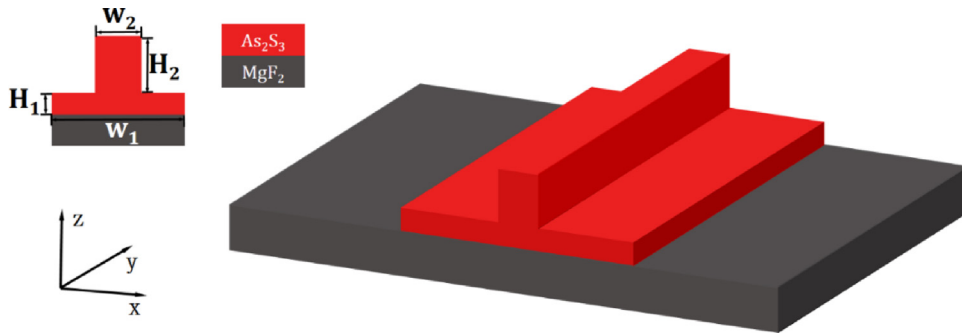


Fig. 1. Structure of the proposed rib  $\text{As}_2\text{S}_3$  waveguide.

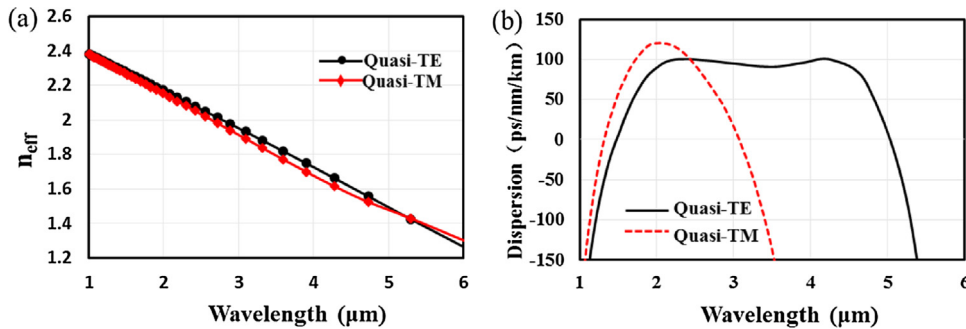


Fig. 2. (a) Effective index  $n_{\text{eff}}$  and (b) dispersion curve of both quasi-TE and quasi-TM modes in the rib waveguide with optimised structural parameters ( $W_1 = 2320$  nm,  $H_1 = 600$  nm,  $W_2 = 620$  nm and  $H_2 = 1220$  nm).

The use of a square cross-section nanowire waveguide is a straightforward way to achieve similar dispersion profiles for both the fundamental quasi-TE and quasi-TM modes [17]. However, only one zero-dispersion wavelength (ZDW) exists in the wavelength range of interest, thereby limiting the FWM bandwidths. The slot concept waveguide has been exploited to engineer the dispersion for both modes by utilizing mode transition and anti-crossing [18–20]. However, these proposed waveguide structures are based on complicated fabrication steps such as polycrystalline overlay or precise partial etching. Furthermore, the fabrication tolerance of these structures is limited, requiring nanometre control during fabrication. Hence, both dispersion properties and feasibility of fabrication should be considered in chalcogenide glass waveguide design.

In this paper, a novel chalcogenide glass ( $\text{As}_2\text{S}_3$ ) waveguide structure is proposed for the dispersion engineering of both modes. For an optimum structure, the fundamental quasi-TE and quasi-TM modes show a relatively low dispersion with dispersion values of approximately  $\pm 100$  ps/nm/km over a 4200-nm bandwidth for the fundamental TE mode and of  $\pm 120$  ps/nm/km over a 2350-nm bandwidth for the fundamental TM mode. This structure can be fabricated with only two lift-off steps on the chalcogenide glass film, showing great potential for developing nonlinear devices.

## 2. Waveguide structure and characteristics

The proposed waveguide and its structural parameters are shown in Fig. 1. To receive flat and ultra-broadband dispersion at long wavelengths, rib chalcogenide glass waveguides were designed with air on top and either  $\text{As}_2\text{S}_3$  or  $\text{MgF}_2$  glass as lower cladding material. This structure can be fabricated with photolithography and lift-off processes for transferring the waveguide pattern to the chalcogenide glass film. The lift-off technique avoids the use of the  $\text{NH}_4\text{OH}$ -based developer that will result in isotropic etching and relatively poor waveguide profiles, enabling the realization of high-quality chalcogenide glass waveguides by our process [21,22].

For both modes, properties such as effective indices and mode profiles are computed using the finite-element method. The dispersion for both TE and TM modes are studied by calculating the effective index  $n_{\text{eff}}$  with the material dispersion of  $\text{MgF}_2$  and  $\text{As}_2\text{S}_3$  taken into account [23,24].

Fig. 2(a) shows the calculated effective index  $n_{\text{eff}}$  of both quasi-TE and quasi-TM modes. The dispersion is calculated according to  $D = -(\lambda/c)(\partial^2 n_{\text{eff}}/\partial \lambda^2)$  [10]. The dispersion curves of both modes in the rib waveguide with optimised structural parameters ( $W_1 = 2320$  nm,  $H_1 = 600$  nm,  $W_2 = 620$  nm and  $H_2 = 1220$  nm) are shown in Fig. 2(b). For the TE mode, the flat dispersion is confined to values between  $-100$  ps/nm/km and  $+100$  ps/nm/km over a 4200-nm bandwidth from 1100 to 5300 nm. The two ZDWs of the dispersion profile are located at 1472 and 5002 nm. For the TM mode, the dispersion fluctuates between  $-120$  ps/nm/km and  $+120$  ps/nm/km over a 2350-nm bandwidth from 1100 to 3450 nm. The ZDWs are located at

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