Ultra-strong, well-apodised Bragg gratings in chalcogenide rib waveguides

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The first ultra-strong, near-perfect, raised-apodised Bragg gratings in As_2S_3 chalcogenide rib waveguides using $\lambda = 532$ nm light and a modified Sagnac holographic writing setup are demonstrated. Good agreement is achieved between the experimental results and the numerical modelling of the gratings using the transfer matrix analysis for thin film structures.

Introduction: Chalcogenide glasses show great promise for all-optical devices in the optical telecommunications window (1528–1628 nm) because of their large (up to ~900 times silica glass [1]) third-order nonlinearity, low two-photon absorption (and hence good figure of merit), transparency in the infrared, in addition to photosensitivity to visible light [1, 2]. In particular, the combination of high nonlinearity and photosensitivity raises the exciting possibility of all-optical devices, such as 2R regenerators, based on a combination of nonlinear propagation and either linear filtering or dispersion management [3, 4]. For these applications, however, the requirements for grating filtering performance, in terms of strength, uniformity and apodisation (elimination of sidelobes) are very high. Whilst there have been reports recently of Bragg gratings written in chalcogenide glass fibres and waveguides [5–7], they have not been of adequate quality for these advanced applications, despite reported material index changes of up to 10^{-2}.

In this Letter, we demonstrate high quality, ultra-strong Bragg gratings in As_2S_3 rib waveguides with near-perfect apodisation (near absence of sidelobes), achieved by using a modified Sagnac interferometer with a short coherence-length (~4 mm), frequency-doubled, Nd:YAG laser ($\lambda_w = 532$ nm). This highly stable writing system allowed us to fabricate ultra-strong, well-defined, near-perfectly apodised Bragg gratings, via photosensitivity in the chalcogenide waveguides. Previous reports of Bragg gratings in chalcogenide glasses (As_2S_3 and As_2Se_3) have employed Mach-Zehnder interferometers for holographic grating writing, based on photodarkening at 513 nm (Ar^+) and 632 nm (He-Ne) [5–7]. Mach-Zehnder interferometers are vulnerable to environmental disturbances (mechanical vibrations, thermal gradients, and air currents) which affect the stability of the interference pattern over time and hence the quality of the written Bragg grating.

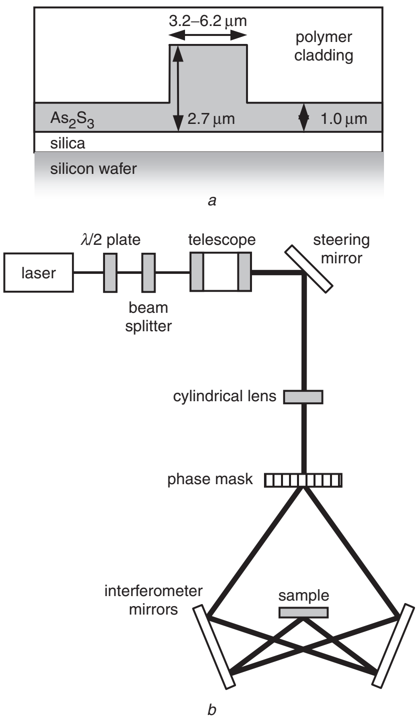

Fig. 1 *Schematic views of structure and writing setup*

a Waveguide structure
b Writing setup based on modified Sagnac interferometer

Waveguide structure: The cross-section of the As_2S_3-based rib waveguide is shown in Fig. 1*a*. The As_2S_3 layer was deposited on a silica-on-silicon wafer by ultrafast pulsed laser deposition (PLD) and patterned by photolithography followed by a dry etching process [8]. A polymer overcladding layer was then deposited to protect the chalcogenide layer. The widths of the rib waveguides varied from 3.2 to 6.2 µm. According to beam propagation method (BPM) simulations, these waveguides support multiple modes in each orthogonal polarisation (TE and TM). The propagation loss was typically 0.1 to 0.5 dB/cm for the wider waveguides, determined by measuring the visibility of fringes produced by the waveguide cavity [7]. The insertion loss using high-NA fibre coupling was typically between 5 and 10 dB (fibre to fibre), largely determined by poor mode-overlap between the high-NA fibre and the As_2S_3 rib waveguides, in addition to 16% Fresnel reflection from each facet.

Grating writing and characterisation: Fig. 1*b* shows the layout of the grating writing setup. We used a modified Sagnac interferometer, because of its stability and tunability (Bragg wavelength), in combination with a CW, frequency-doubled, diode-pumped Nd:YAG laser at $\lambda = 532$ nm, with a maximum available power at the sample of 50 mW. The (linearly polarised) beam was telescopically expanded, cylindrically focused and split using a phase mask ($\Lambda_m = 1063.3$ nm). The +1 and −1 diffracted orders (from the phase mask) were reflected from a pair of mirrors and interfered at the surface of the waveguide sample (TE polarised) with a spot size at the writing plane of 5.5×0.6 mm^2. The laser's short coherence length (~4 mm) limited the length of the interference pattern, resulting in a nearly ideally apodised (constant average photoinduced index change) grating ~4 mm in length. Tuning the grating Bragg wavelength was achieved by changing the angle of mirrors, with commensurate adjustment of the sample holder.

The gratings were characterised with an unpolarised high-power EDFA-ASE source, butt-coupled into the waveguide via high-NA fibre. A second high-NA fibre coupled the transmitted output to an optical spectrum analyser with 60 pm resolution to measure the transmission spectra. A bulk optics polarisation controller placed between the sample and light source was adjusted to obtain the maximum polarisation extinction ratio.

Experimental results: Fig. 2 shows the transmission spectra for two orthogonal polarisations of a grating written on a 3.2 µm-wide waveguide with high exposure conditions (writing power 6.8 mW and exposure time of 60 s) resulting in a spectrally wide (4.0 nm), deep grating. The measured grating strength of −27 dB was limited by our measurement capability, due primarily to a combination of birefringence splitting and limited control of the degree of polarisation. From Fig. 2, the very low sidelobe levels are a clear indication that we have achieved near-perfect apodisation, with very little residual self-chirp. From the spectral width of the grating, we estimate that an index change of 0.006 was achieved. Also, a shift in the central Bragg wavelength for various exposure conditions was observed, owing to the average index change (which is of the order of the a.c. index variation).

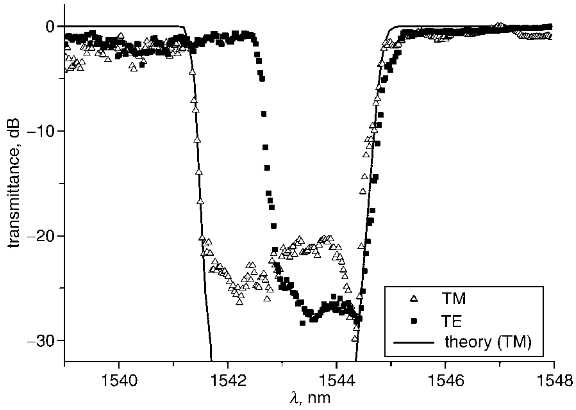

Fig. 2 *Grating transmission spectra for TE and TM polarisations*

Numerical simulation of TM polarisation using transfer matrix method shown by solid line

The observed spectral splitting (0.7 nm) with polarisation seen in Fig. 2 may be related mainly to inherent geometrical waveguide birefringence. Beam propagation analysis indicates an effective index difference of 9.7×10^{-4} between the two polarisations, which results in the above-mentioned difference in Bragg wavelengths. However, the spectral splitting, and the difference between grating spectral width for two polarisations may be affected by the limited absorption length for As_2S_3 at 532 nm (~3 μm [9]), that may result in a nonuniform refractive index profile in the vertical direction, and/or the film stress (either inherent or photo-induced). Fig. 2 also shows the transmission spectra for the TM polarisation calculated using the transfer matrix method for thin film filters [10], showing good agreement with the experiment.

Conclusion: We report the strongest and best apodised Bragg gratings in chalcogenide rib waveguides reported to date. Our gratings were written at 532 nm using a modified Sagnac interferometer and are of high enough quality to be used for advanced filtering applications for all-optical devices. We found good agreement between the experiment results and numerical modelling of the Bragg gratings using the transfer matrix method.

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