High-Q ring resonators directly written in As$_2$S$_3$ chalcogenide glass films

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Planar ring resonator waveguides are fabricated in thin films of As$_2$S$_3$ chalcogenide glass, deposited on silica-on-silicon substrates. Waveguide cores are directly written by scanning the focused illumination of a femtosecond Ti:sapphire laser at a central wavelength of 810 nm, through a two-photon photo-darkening process. A large photo-induced index change of 0.3–0.4 refractive index units is obtained. The radius of the ring resonator is 1.9 mm, corresponding to a transmission free spectral range of 9.1 GHz. A high loaded (intrinsic) Q value of 110,000 (180,000) is achieved. The thermal dependence of the resonator transfer function is characterized. The results provide the first report, to the best of our knowledge, of directly written high-Q ring resonators in chalcogenide glass films, and demonstrate the potential of this simple technique towards the fabrication of planar lightguide circuits in these materials. © 2015 Chinese Laser Press

1. INTRODUCTION

Chalcogenides are a category of glass compounds that contain one of the chalcogen elements: S, Se, or Te. Chalcogenides are drawing increased attention in research and applications, due to their remarkable electrical and optical properties. Although amorphous, they can be semiconducting and display bandgap behavior [1,2]; they are characterized by a broad transparency window, from the visible to the middle infrared [3]; their refractive index can be as high as 3.5 refractive index units (RIU) [4]; and their nonlinear refractive index, Raman scattering, and Brillouin scattering coefficients are 100–1000 times larger than the corresponding values in silica [4–6]. Lastly, chalcogenide glasses are highly photosensitive [7,8]; direct laser-beam illumination of these glasses could cause permanent material changes, ranging from refractive index variations [9,10] through to reflow and mass transfer [11–14], depending on wavelength and intensity. Chalcogenides therefore constitute a favorale material platform for all-optical signal processing and sensing applications [15–18].

Fabrication technologies of planar lightguide circuits (PLCs) in chalcogenide glasses include lithography and dry etching [19], lift-off processes [20], thermal nano-imprinting [21,22], and direct laser-beam writing [23–28]. Direct laser-beam writing relies on the photo-darkening effect in chalcogenides to introduce a local increase in the refractive index of core regions. The process is simple, does not involve the exposure of the glass materials to chemicals, and does not introduce sidewall roughness. On the other hand, linear losses of directly written waveguides in chalcogenide glasses are higher than those of etched devices [19], and comparatively small index contrasts might lead to additional bending losses.

Ring resonator structures in PLCs of various electro-optic materials are widely employed as the basis for narrowband filters [29], recirculating delay lines [30], electro-optic modulators [31], and laser cavities [32]. The high sensitivity of the ring cavity to the refractive index of its surroundings is used in biochemical sensors [33]. Cavity enhancement of the pronounced nonlinearities of chalcogenides holds much promise in all-optical signal processing. Ring resonators were fabricated in chalcogenides using a lift-off process, with a reported Q of 10,000 [20]. Recently, loaded (unloaded) Q values of 150,000 (390,000) were achieved in As–Se family glass resonators of 100 μm radius using a nano-imprint fabrication method [21], and unloaded Q of 460,000 was obtained in micro-disc resonators [22]. As$_2$S$_3$ racetrack resonators were also fabricated on top of underlying LiNbO$_3$ waveguides [34]. The fabrication of high-Q ring resonators in chalcogenides using direct laser-beam lithography has not yet been reported.

Herein we present the fabrication and characterization of ring resonators in thin As$_2$S$_3$ films. Waveguide cores are defined using femtosecond Ti:sapphire laser illumination [10,26]. A large index modification of 0.4 RIU is achieved. The radius of the ring resonators is approximately 1.9 mm, providing a free spectral range (FSR) of 9.1 GHz. The transfer function of the ring resonators corresponds to a loaded (unloaded) Q value of 110,000 (180,000). The results demonstrate the applicability of direct laser-beam lithography to the fabrication of chalcogenide glass PLCs for all-optical signal processing and sensing applications.

2. CHARACTERIZATION OF PHOTON-INDUCED INDEX CHANGES

The layer structure of samples used in this work is shown schematically in Fig. 1. A core As$_2$S$_3$ layer of thickness $d_{ch} = 1.2$ μm was deposited on a silica-on-silicon substrate, by thermal evaporation of a bulk target from a quartz crucible.
in a 2 × 10^{-6} Torr vacuum [35,36]. The thicknesses of the underlying silica layer and of the silicon substrate were \( d_{\text{Si}} = 2.5 \mu m \) and \( d_{\text{SiO}} = 400 \mu m \), respectively. The refractive indices of \( \text{As}_2\text{S}_3 \), silica, and silicon at 1550 nm wavelength are \( n_{\text{Ch}} = 2.4 \text{ RIU} \), \( n_{\text{SiO}} = 1.45 \text{ RIU} \), and \( n_{\text{Si}} = 3.45 \text{ RIU} \) respectively.

Waveguide cores were directly written in the chalcogenide film by femtosecond Ti:sapphire laser illumination, operating at a central wavelength of 810 nm. The sub-bandgap irradiation introduces a permanent increase in the local refractive index through a two-photon, photo-darkening process [2.8 RIU]. The observed photo-induced index changes in the core \( \text{As}_2\text{S}_3 \) layer by \( \Delta n = 0.4 \text{ RIU} \), to approximately 2.8 RIU. The observed photo-induced \( \Delta n \) is five times larger than that observed in [10]. Note, however, that the accumulated laser irradiation in [\( \text{J}/\text{cm}^2 \)] used in this work is orders of magnitude larger.

Photo-darkening-induced index changes measurement configuration represents a modification of the Swanepoel method for the determination of the refractive index of thin films [37].

Figure 3 (top) shows the measured transmission through the sample under test as a function of wavelength, both within and outside the irradiated pattern. The transmission through the sample is dominated by reflections at the top and bottom surfaces, which introduce a response of a low-finesse Fabry–Perot etalon. The FSR of the transmission spectrum in reference regions that were not illuminated can be approximated as FSR_{0} = \( \Delta \lambda / (2 L_{\text{m}}) \), where \( \lambda_{\text{g}} \) is the central wavelength and \( L_{\text{m}} \equiv d_{\text{Ch}} n_{\text{Ch}} + d_{\text{SiO}} n_{\text{SiO}} + d_{\text{Si}} n_{\text{Si}} \) denotes the optical path length through the sample. The measured FSR_{0} is 0.86 nm. The FSR of transmission through the photo-darkened region is modified by

\[
\Delta \text{FSR} \approx \left( 2 \text{FSR}_{0} / \lambda_{\text{g}} \right) d_{\text{Ch}} \Delta n.
\]

Let us denote the wavelengths of maximum transmission as \( \{ \lambda_{m} \} \), where \( m \) is an integer. Figure 3 (bottom) shows the offsets \( \Delta \{ \lambda_{m} \} \) between the transmission spectra of reference and illuminated regions, for 50 FSR periods in the range of 1530–1570 nm. The slope of the \( \Delta \{ \lambda_{m} \} \) curve represents \( \Delta \text{FSR} \) of 0.338 nm. Direct writing therefore increases the refractive index of the \( \text{As}_2\text{S}_3 \) layer by \( \Delta n = 0.4 \text{ RIU} \), to approximately 2.8 RIU. The observed photo-induced \( \Delta n \) is five times larger than that observed in [10]. Note, however, that the accumulated laser irradiation in [\( \text{J}/\text{cm}^2 \)] used in this work is orders of magnitude larger.

Fig. 1. Schematic illustration of the layer structure of samples used in this work and an illustration of the transverse profile of photo-induced refractive index changes in the core \( \text{As}_2\text{S}_3 \) glass layer.

Fig. 2. Schematic illustration of the setup used in measurements of the photo-induced refractive index change in \( \text{As}_2\text{S}_3 \) films.

Fig. 3. Top: OVA measurements of the transmission of light through the layers of a silica-on-silicon sample coated with an \( \text{As}_2\text{S}_3 \) film (see Fig. 2). The red (blue) curve corresponds to a region outside (within) a photo-darkened area. Bottom: spectral offset in nanometers between peaks of maximum transmission outside and within the photo-darkened area. The linearly increasing offset corresponds to an increase in the refractive index within the photo-darkened region by 0.4 RIU.
of comparable magnitude in chalcogenides are known in the literature [36,38,39]. Bending losses in rings of millimeter-scale radii and such large $\Delta n$ values are negligible.

The modal profiles of directly written waveguides at different wavelengths were calculated using COMSOL multiphysics simulations. The waveguide supports multiple transverse-electric (TE) and transverse-magnetic (TM) modes; however, the coupling of light from tapered fibers to higher-order modes is considerably weaker [26] than coupling into the fundamental modes. Figure 4 shows the calculated effective indices $n_{\text{eff}}$ and group indices $n_g$ of the fundamental TM and TE modes of a 4-$\mu$m-wide waveguide at 1550 nm wavelength, as a function of the photo-induced core $\Delta n$. The expected values of the group indices of the fundamental TM and TE modes, with $\Delta n$ set to 0.4 RIU, are 2.9 and 2.85 RIU, respectively. For the relatively broad core widths of 2–4 $\mu$m, and for the comparatively large $\Delta n$, the exact profile of graded-index variations has a negligible effect on the calculated indices.

A top-view microscope image of segments of ring and bus waveguides is shown in Fig. 5. The width of the straight bus waveguide core is on the order of 2 $\mu$m, whereas that of the ring is approximately 4 $\mu$m. The broader width of the ring waveguide is due to its lower scanning speed using alternating $x$ and $y$ translation steps. The separation between the centers of bus and ring waveguides is approximately 2 $\mu$m, optimized for maximum extinction ratio (ER) in the transmission frequency response of the devices (see below). Figure 6 shows a top-view image of a ring resonator device of 200 $\mu$m radius, with red light coupled in for illustration purposes only. The radius of the specific ring used in subsequent characterization was measured as 1.888 mm, by precise translation of the sample under a microscope with large magnification.

3. TRANSFER FUNCTION MEASUREMENTS

The spectral transfer function of the ring resonator was measured using the OVA, with a spectral resolution of 2 pm. Light was coupled in and out of the devices using tapered fibers with a modal radius of 2 $\mu$m. The coupling losses to/from the devices at 1550 nm varied between 3 and 5 dB per facet, depending on the facet’s quality. Figure 7 shows the OVA measurement of the infinite impulse response of the ring resonator in the time domain. The 110 ps delay between successive impulses corresponds to a group index of 2.8 RIU, in general agreement with simulations. The measured group delay corresponds to a photo-induced $\Delta n$ value of 0.3–0.35 RIU (see Fig. 4). The attenuation between successive impulses is given by $|\kappa|^2 \cdot \exp(-\alpha L)$, where $\kappa$ is the coupling coefficient between the bus and ring waveguides, $\alpha$ denotes the loss coefficient per unit length, and $L$ is the circumference of the ring. The measurements suggest that $|\kappa|^2 \cdot \exp(-\alpha L) = 7.2$ dB.

Figure 8 (top) shows the measured spectral power transfer function of the ring resonator. A FSR of 9.1 GHz is observed, with an ER that reaches 25 (14 dB). Figure 8 (bottom) shows a magnified view of one spectral transmission notch. The full width at half maximum (FWHM) of the transmission notches is 14 pm, which corresponds to a loaded $Q$ value of approximately 110,000. The unloaded $Q$ value and the loss coefficient $\alpha$ may be estimated using the following relations [40]:

$$Q_{\text{int}} = 2Q_{\text{loaded}} / \left(1 + \sqrt{\text{ER}^{-1}}\right) = 180,000, \quad (2)$$

$$\alpha = (2\pi n_g) / (Q_{\text{int}} \lambda_0) = 2.7 \text{ dB/cm}, \quad (3)$$

where $Q_{\text{loaded}}$ and $Q_{\text{int}}$ denote the loaded and unloaded $Q$ values, respectively. The relatively high value of $Q$ is an order of

![Fig. 7. OVA measurement of the temporal impulse response of a ring resonator of 1.888 mm radius, directly written in a thin film of As$_2$S$_3$.](image)
magnitude better than that reported using a lift-off fabrication process [20], and a factor of 2 lower than the values obtained recently in As–Se glasses using thermal nano-imprinting [21,22].

Figure 9 shows the spectral power transfer functions of the ring resonator at different temperatures $T$ of an actively controlled mount. The observed thermal offset of a given resonance wavelength $\lambda_r$ was $d\lambda_r/dT = 0.022$ nm/$^{\circ}$C. The thermal offset is given by

$$d\lambda_r/dT = (\alpha_T + n_T/n_0)\lambda_r,$$

where $n_T \equiv dn_{\text{Ch}}/dT$ is the thermo-optic coefficient of As$_2$S$_3$ and $\alpha_T \equiv (dL/dT)/L$ denotes the coefficient of linear thermal expansion. Values of $n_T = 50 \times 10^{-6}$ RIU/$^{\circ}$C [41] and $\alpha_T = 21$ ppm/$^{\circ}$C [42] appear in the literature. Based on these values, a larger thermal change of 0.060 nm/$^{\circ}$C in the resonance wavelength could be expected. The reasons for this difference require further investigation. A possible explanation could be due to thermal expansion of the entire layer structure, which might be different from that of bulk As$_2$S$_3$.

The transfer function of the device was monitored over more than one year of storage in a standard laboratory environment. No changes were noted in $Q_{\text{loaded}}$ or ER. The devices support a coupled average power of 200 mW, and 500-ns-long pulses with coupled peak power of 2 W, without damage.

4. CONCLUSION

In summary, this work provides the first report, to the best of our knowledge, of high-$Q$ ring resonators in As$_2$S$_3$ glass PLCs, fabricated using direct laser-beam writing. The simple fabrication of high-quality resonators in highly nonlinear media carries much promise for all-optical signal processing applications. Ongoing work is being dedicated to the fabrication of resonators having different values of $\Delta n$, and to attempts to reduce losses. Losses may be improved with the deposition of upper capping layers, such as silica, which might prevent oxidization of the chalcogenide glass surface. Lastly, nonlinear propagation effects in the resonator devices are being investigated.

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