Demonstration of chalcogenide glass racetrack microresonators

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We have demonstrated what we believe to be the first chalcogenide glass racetrack microresonator using a complementary metal-oxide semiconductor-compatible lift-off technique with thermally evaporated As_2S_3 films. The device simultaneously features a small footprint of 0.012 mm × 0.012 mm, a cavity Q (quality factor) of 10,000, and an extinction ratio of 32 dB. These resonators exhibit a very high sensitivity to refractive index changes with a demonstrated detection capability of $\Delta n_{As2S3} = (4.5 \times 10^{-6} \pm 10\%)$ refractive index unit. The resonators were applied to derive a photorefractive response of As_2S_3 to $\lambda = 550$ nm light. The resonator devices are a versatile platform for both sensing and glass material property investigation. © 2008 Optical Society of America

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In an optical resonator, circulating light is confined within a small volume. When the resonant condition is met, the optical power becomes resonantly enhanced up to a factor approximating cavity finesse. Such resonant enhancement, combined with a significantly increased optical path length, makes ring and racetrack resonators an ideal device platform for both fundamental investigations and practical applications based on photon-matter interactions. The examples include all-optical switching [1], light emission [2], nonlinear optics [3], and biochemical sensing [4]. Chalcogenide (ChG) glasses have been identified as promising material candidates for the aforementioned applications owing to their unique optical properties in the infrared. Of particular relevance here are the photosensitivity, reduced phonon quenching, large Kerr optical nonlinearity, and wide infrared transparency window [5] of ChG materials. Thus, a microresonator in ChG glasses that maximizes the leverage of their properties becomes highly desirable.

Here we present the first, to the best of our knowledge, demonstration of ChG glass racetrack resonators in thermally evaporated As_2S_3 films. We have also shown that such resonators can be used as ultrasensitive probes of photosensitivity in ChG glass, providing an unprecedented high accuracy measurement [on the order of 10^{-6} refractive index unit (RIU)] of photorefractive index change.

The bulk preparation and film deposition process are described in [6,7]. These devices were patterned by lift-off, and the whole patterning process has been carried out on a 500 nm complementary metal-oxide semiconductor (CMOS) line [8]. The CMOS compatibility allows this process to be scaled up for mass production. The racetracks are comprised of strip waveguides with a width of 800 nm and a height of 450 nm. After patterning, a layer of 3-μm-thick SU8 polymer was spin coated to serve as the top cladding. The device was subsequently annealed at 130°C for 3 h to stabilize the glass structure. Figure 1 shows the top view of a fabricated resonator. The fabricated device has a small footprint of 0.012 mm × 0.012 mm, and the total cavity length is ~409 μm.

Transmission spectra of the fabricated device have been measured on a Newport AutoAlign workstation in combination with a tunable laser (optical vector anaylzer external laser, LUNA Technologies, Inc.). Lens-tip fibers are used to couple light from the laser into and out of the devices. Reproducible coupling is achieved via an automatic alignment system with a spatial resolution of 50 nm. The sample was mounted onto a thermostat stage and kept at 25°C for all measurements. Figure 2(a) shows a measured transmission spectrum of TM polarization. The resonator has a free spectral range (FSR) of 2.5 nm and a maximum extinction ratio of 32 dB near 1550 nm. Such a high extinction ratio indicates that the resonator works near the critical coupling regime. Cavity Q, defined as the ratio of wavelength against the 3 dB resonant peak width, was determined from Fig. 2(b) to be ~10,000. This Q value corresponds to an equivalent waveguide loss of 16.5 dB/cm. We expect that an optimized fabrication process with a minimized pattern

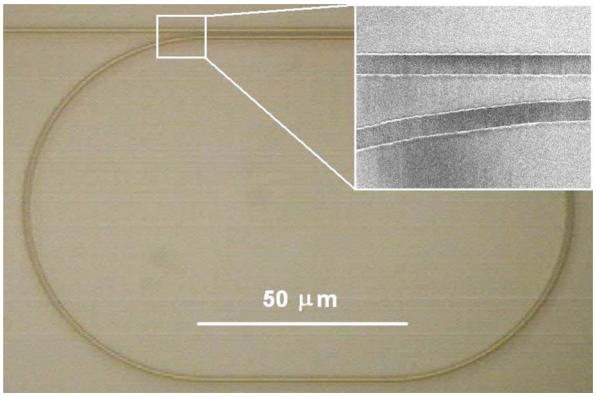

Fig. 1. (Color online) Optical micrograph of a fabricated resonator device; inset, scanning electron microscopy micrograph shows the coupling region between the coupling (bus) waveguide and the racetrack.

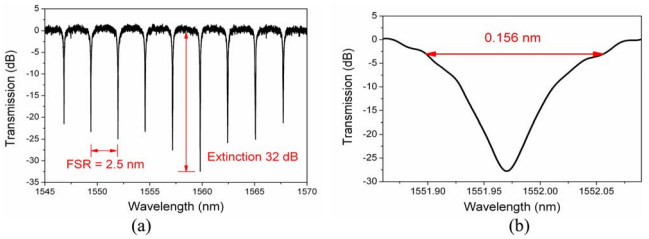

Fig. 2. (Color online) Transmission spectra of TM polarization in a resonator device: (a) resonator exhibits an FSR of 2.5 nm and an extinction ratio of 32 dB, (b) resultant spectrum averaged over 64 consecutive scans.

digitization error of waveguide bends [9], postfabrication smoothing, and gradient index (GRIN) waveguide design [10] could further reduce waveguide loss, leading to even higher Q factors. For comparison, photonic crystal cavities in $Ge_{33}As_{12}Se_{55}$ ChG glass have recently been demonstrated with a similar Q of 10,000 and an extinction ratio up to 2.6 dB [11].

An important feature of resonators is their extreme sensitivity to refractive index changes, and thus they have been proposed to be a promising candidate for miniaturized biochemical sensors [12]. This property can also be utilized to probe microstructural evolution in ChG glasses, since structural modifications in these glasses are often accompanied by a refractive index change [13]. In addition, accurate determination of the index change is also technically important for applications that rely on photoinduced index modifications such as direct laser writing. For example, Zoubir *et al.* [14] measured an index increase up to 0.08 at a 785 nm wavelength in femtosecond laser written As_2S_3 waveguides. Often, the spectrum from a single scan has a low signal-to-noise ratio (SNR) and does not allow accurate determination of index change. For this reason, we have used multiple scan averaging over a single resonant peak to improve the SNR and wavelength resolution. By averaging over 64 individual scans, noise in the transmission spectrum is suppressed, as is evident in Fig. 2(b).

To study the photosensitivity of an As_2S_3, the resonator device was exposed to timed near-bandgap light (~550 nm in wavelength with an irradiance of 6.2 mW/cm^2 from a bandpass filtered halogen lamp) to induce a controlled refractive index change using a setup schematically shown in Fig. 3(a), and the resulting peak shift was monitored *in situ*. A Lorentzian fit has been used to extract the accurate peak position. The refractive index change can be calculated via

$$\Delta n = \frac{\Delta\lambda}{\lambda} \times n_{\text{eff}}/\Gamma, \tag{1}$$

where $\Delta\lambda$ stands for the resonant peak shift, n_{eff} is the waveguide effective index, and Γ is the confinement factor in the As_2S_3 core. Finite-difference simulations give n_{eff} and Γ of TM polarization to be 1.88 and 0.77, respectively.

Figure 3(b) gives an example of two spectra with a peak shift of (3 ± 0.3) pm after light exposure, corresponding to an index increase of $4.5 \times 10^{-6} \pm 10\%$ in As_2S_3 at a 1597 nm wavelength. The wavelength resolution of 0.3 pm was statistically determined by repeating the experiment and comparing multiple measurement results. Such a high sensitivity is especially essential for an accurate photosensitivity measurement in annealed glass, which exhibits a much smaller photoinduced index change compared to its as-deposited counterpart [15].

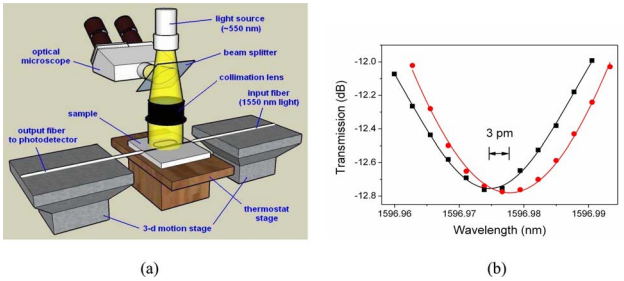

Fig. 3. (Color online) (a) Photosensitivity measurement setup, (b) transmission spectra of a resonator in the proximity of its resonant peak. Black squares represent experimental data points, and the filled circles (red online) are data measured in the same device after exposure to an ~550 nm wavelength light; the curves are fitted Lorentzian peaks. A wavelength shift of (3 ± 0.3) pm is determined by a peak fit, corresponding to an index change of $(4.5 \times 10^{-6} \pm 10\%)$ RIU in As_2S_3 at a 1597 nm wavelength.

Figure 4 shows the refractive index increase at a 1550 nm wavelength as a function of exposure dose for both as-deposited (without annealing) and annealed As_2S_3 devices. Excellent data reproducibility was confirmed by repeating the measurement on several resonators. In both cases the index increase can be well described with a single-exponential function:

$$\Delta n = \Delta n_{\text{sat}} \times [1 - \exp(-D/D_0)], \tag{2}$$

where Δn_{sat} is the maximum index change when the photorefractive effect has been fully saturated, D represents the exposure dose in J/cm^2, and D_0 is a material constant that depends on processing history. Our results confirm the validity of exponential em-

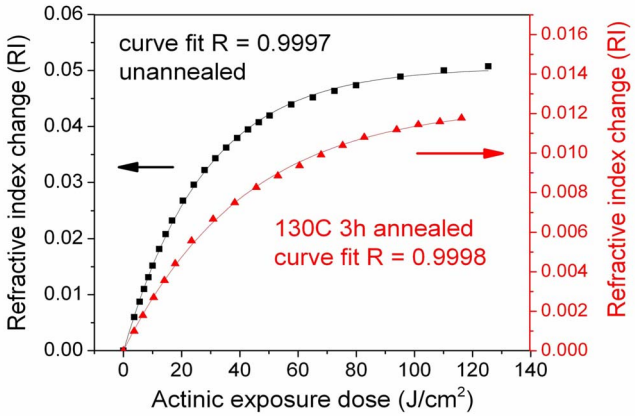

Fig. 4. (Color online) Photoinduced refractive index change as a function of exposure dose ($\lambda = 550$ nm) in an as-deposited unannealed resonator and in a resonator annealed at 130 °C for 3 h.

pirical fits in [16,17]. For unannealed As_2S_3, $\Delta n_{sat} = 0.0505 \pm 0.0002$, $D_0 = (0.036 \pm 0.001)$ J/cm^2, whereas for annealed As_2S_3, $\Delta n_{sat} = 0.0125 \pm 0.0001$, $D_0 = (0.024 \pm 0.001)$ J/cm^2. The smaller photoinduced index change in annealed glass has also been observed by Lopez [15] in As_2S_3 films prepared by the same deposition technique, irradiated with an 800 nm femtosecond laser and measured using an ellipsometer.

It is also important to note that the annealed and unannealed samples have distinctive D_0 values, which indicate different microstructural modifications. This finding confirms that the photosaturated and thermally annealed states are structurally dissimilar in ChG glasses [15,18].

To summarize, we have demonstrated the first, to the best of our knowledge, ChG glass racetrack microresonator in a thermally evaporated As_2S_3 film with a Q factor of 10,000 and an extinction ratio of 32 dB, providing a versatile platform for nonlinear optics, light emission, and sensing using ChG materials. These devices can detect a refractive index change as small as 4.5×10^{-6} in As_2S_3 with a good SNR and thus are also useful tools for probing microstructural evolution in glasses.

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