Photo-induced trimming of coupled ring-resonator filters and delay lines in As_2S_3 chalcogenide glass

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Received July 29, 2011; revised September 7, 2011; accepted September 12, 2011;
posted September 12, 2011 (Doc. ID 152041); published October 6, 2011

Selective exposure to visible light is used to permanently trim the resonant wavelengths of coupled ring-resonator filters and delay-lines realized on a chalcogenide As_2S_3 platform. Post-fabrication manipulation of the circuit parameters has proved an effective tool to compensate for technological tolerances, targeting demanding specifications in photonic integrated circuits with no need for always-on power-hungry actuators. The same approach opens a way to realize photonic integrated circuits that can be reconfigured after fabrication to fulfill specific applications. © 2011 Optical Society of America

OCIS codes: 230.3120, 230.4555, 160.2750, 160.5335.

Coupled ring-resonator structures have been demonstrated as powerful photonic architectures for a variety of advanced applications, including, among others, wavelength-division-multiplexing filters [1], tunable delay lines [2], and all-optical wavelength converters [3]. The proper operation of such devices requires that all the rings resonate precisely at a well defined wavelength, this condition being a challenging issue even for state-of-the-art fabrication processes [4]. Post-fabrication treatments are needed to compensate for technological tolerances without the use of always-on power-hungry tuning mechanisms, such as local waveguide heating or carrier injection. Recently, several "set-and-forget" trimming techniques, like electron beam exposure [5] or oxidation by the tip of an atomic force microscope [6], have been successfully applied to silicon microring resonators, but at the price of quite sophisticated equipments that are hardly in line with low-cost manufacturing. Irradiation of UV photosensitive polymer films used as waveguide cladding materials has also been widely employed, but most polymers suffer from poor time stability and optical degradation at relatively low temperatures [7].

Photosensitivity to visible light is a well-known property of chalcogenide glasses (ChGs), a class of amorphous semiconductor compounds that are now emerging as promising materials for photonic integrated circuits (PICs) [8]. Light exposure of ChGs has been used to directly write optical waveguides and Bragg gratings and, more recently, to adjust the resonance of a racetrack microresonator [9] and a photonic crystal cavity [10]. In this Letter, we apply a selective photo-induced trimming technique [11] to modify the response of coupled ring-resonator structures realized on a As_2S_3 ChG platform. A twofold objective is accomplished: not only are technological tolerances counteracted and the desired response restored, but the realization of PICs that can be reconfigured after fabrication is also demonstrated.

The devices described in this work were fabricated by using ChG channel waveguides with the cross section schematically shown in Fig. 1(a). A 450 nm thick film of As_2S_3 with refractive index 2.4 was thermally evaporated on a silica buffer oxide. The 800 nm wide waveguides, optimized for tranverse-magnetic (TM) polarization, were then patterned by lift-off lithography and covered by a SU8 polymer with refractive index 1.57 according to the fabrication technique described in [9]. Coupled-resonator structures were realized by cascading identical racetrack resonators with 100 μm bending radius, 150 μm long straight sections, and $350 \times 200\,\mu m^2$ footprint, providing a free spectral range $FSR = 130\,GHz$ (i.e., 1.04 nm). The ring-to-ring coupling sections have a gap distance of 700 nm and are optimized by laterally shifting the rings, as in the picture of Fig. 1(b).

Cascaded resonators coupled to two bus waveguides are suitable structures for realizing high-order bandpass filters, provided that all the rings resonate at the same resonance wavelength. Figure 2 shows the wavelength domain transmission of a four-ring As_2S_3 filter at both

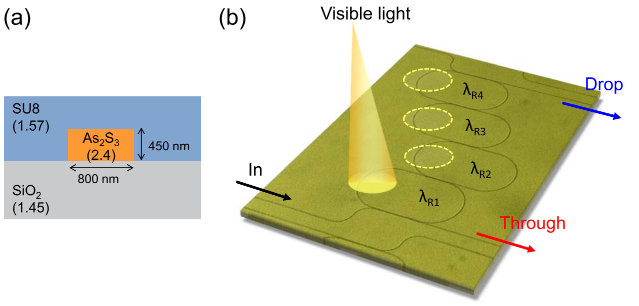

Fig. 1. (Color online) (a) Cross section of the As_2S_3 channel waveguide. (b) Schematic of the selective photo-induced trimming technique applied to coupled ring-resonator circuits.

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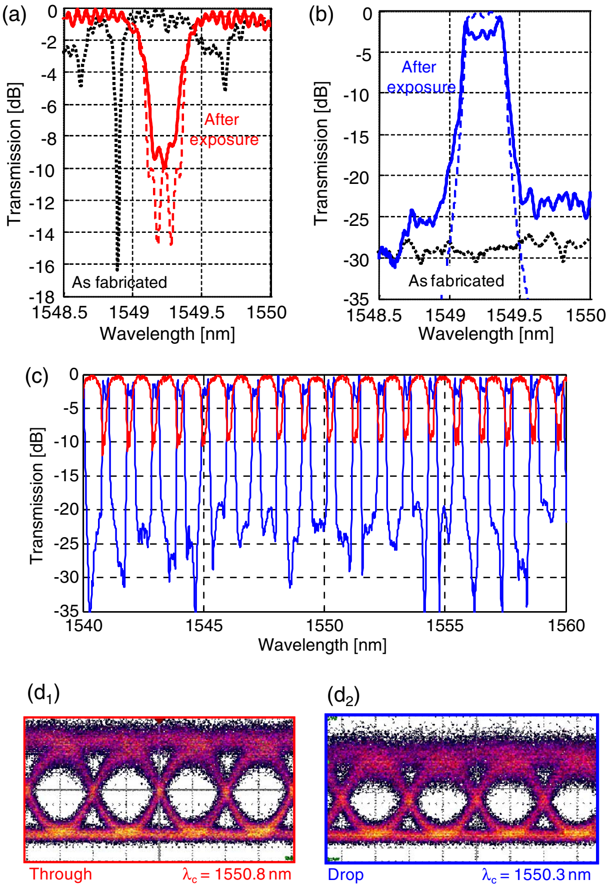

Fig. 2. (Color online) Normalized spectral response of a four-ring As_2S_3 filter at (a) the Through and (b) the Drop ports: measurement before (dotted lines) and after (solid lines) photo-induced trimming are compared with theoretical curves (dashed lines). (c) Measured response at Through (red) and Drop (blue) ports over a 20 nm wide wavelength range. (d) Eye diagrams of a 10 Gbit/s OOK signal (d$_1$) at the Through port ($\lambda_c = 1550.8$ nm) and (d$_2$) at the Drop port ($\lambda_c = 1550.3$ nm).

Through (a) and Drop (b) ports for TM input polarization. The ring-to-ring power coupling coefficients are $\{0.26, 0.20, 0.26\}$, while the ring to bus coupling is 0.57. Black dotted lines refer to the filter as fabricated, before any light exposure treatment. Because of fabrication tolerances, the mismatch of the resonance wavelengths λ_{R_i} (i being the ring number) severely distorts the response with respect to the theoretical shape (dashed lines) and no light is transmitted to the Drop port.

To recover the desired transfer function, the resonance spread was compensated by individually trimming each resonance λ_{R_i} to the same wavelength $\lambda_0 = 1550.3$ nm, following the same procedure used in previous works for the thermo-optical tuning of coupled resonators [2–4]. A multimode optical fiber with a 30 μm mode field diameter was coupled to a halogen lamp and was vertically placed on top of the chip, the position of its end facet being controlled by a micro-positioning stage in order to expose only one ring at a time. The spectrum of the lamp is centered in the visible region (from 450 nm to 650 nm) and the light intensity can be varied from 0.3 mW/cm^2 to 10 mW/cm^2. After light exposure, the transmission of the filter [solid lines in Fig. 2(a) and 2(b)] is in a very good agreement with the theoretical curves. At the Drop port the filter exhibits almost flat passbands with a bandwidth $B = 35$ GHz and with more than 23 dB extinction ratio. The insertion loss in the passbands of the filter is about 8 dB, corresponding to an average loss figure of 2 dB/ring. The residual ± 2 dB in-band ripple is due to deviations from the designed coupling ratios, resulting in an imperfect apodization of the device. At the Through port, the in-band return loss is nearly as high as 10 dB. As shown in Fig. 2(c), these properties are maintained over a wavelength range larger than 20 nm, except for a 17% increase in the bandwidth due to the wavelength sensitivity of the directional couplers.

The system performance of the trimmed filter was evaluated through the transmission of a 10 Gbit/s intensity modulated on-off keying (OOK) signal ($2^7 - 1$ pseudorandom bit sequence). Figure 2(d$_1$) shows the measured eye diagram at the Through port when the carrier wavelength $\lambda_c = 1550.8$ nm is out of the band of the filter, that is when the signal propagates in the bus waveguide only. When the signal spectrum lies within a passband of the filter ($\lambda_c = \lambda_0 = 1550.3$ nm), the signal is transmitted to the Drop port. As shown in Fig. 2(d$_2$), despite a slightly higher optical noise level, which is essentially due to the higher insertion loss, no significant distortion is observed in the dropped signal, proving the effectiveness of the trimming procedure.

Photo-induced trimming of As_2S_3 waveguides was also exploited to demonstrate a permanent reconfiguration of coupled ring-resonator structures. A reconfigurable delay line was fabricated according to the sketches of Fig. 3, where only one bus waveguide is coupled to the rings' chain. As described in [2], a light signal can propagate through the structure only if its carrier wavelength matches the resonant wavelength of the rings, i.e., if $\lambda_{R_i} = \lambda_c$. The first off-resonant ring reflects the signal toward the bus waveguide, the overall delay linearly increasing with the number N of on-resonance rings. Figure 3 shows transmission experiments through a four-ring delay-line with bandwidth $B = 50$ GHz, having

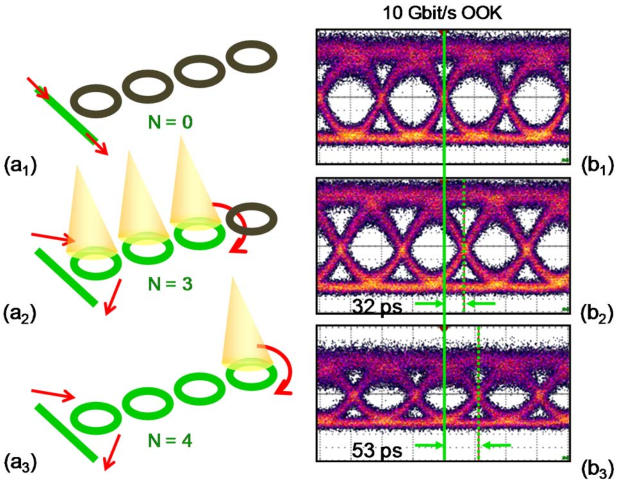

Fig. 3. (Color online) (a) Photo-induced reconfiguration of a coupled-resonator delay line. (b) Eye-diagrams of a 10 Gbit/s OOK signal transmitted through a four-ring As_2S_3 delay-line when the number N of on-resonance rings is set to (b$_1$) $N = 0$, reference delay; (b$_2$) $N = 3$, 32 ps delay; and (b$_3$) $N = 4$, 53 ps delay.

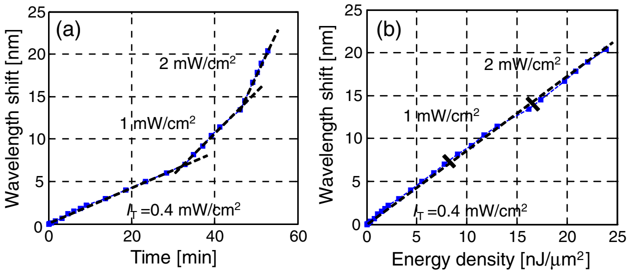

Fig. 4. (Color online) Photo-induced shift of the resonant wavelength of As_2S_3 microrings versus (a) exposure time and (b) energy density at increasing trimming intensity $I_T = 0.4$, 1, and $2\,\mathrm{mW/cm^2}$.

0.71 power coupling between the bus and the first ring, and ring-to-ring coupling coefficients $\{0.47, 0.35, 0.33\}$. The reference eye diagram of Fig. 3(b_1) is measured in the case of minimum delay, when all the rings are off-resonance ($\lambda_{R_i} \neq \lambda_c$ and $N = 0$) and the signal propagates in the bus waveguide only. The delay of the device is then set to a higher value by selectively trimming the resonance of an increasing number N of rings. For example, Fig. 3(b_2) shows the eye-diagram delayed by 32 ps when the first three rings are trimmed to resonate at λ_c and in Fig. 3(b_3) the delay is increased to 53 ps by also exposing the fourth ring. As in thermally actuated architectures [2], the delay can be adjusted continuously between the minimum ($N = 0$) and the maximum ($N = 4$) value. Once the desired delay has been set, the visible light source is switched off and the structure holds the selected delay with no need for any powered actuator.

To check the time stability of the trimming process, the devices described above were stored in the dark for several weeks after light exposure. Measurements performed after the storage period revealed that the shape of the frequency domain response was well preserved, and neither distortions nor time drifts occurred in the eye-diagrams. The only relaxation effect we observed was a slight rigid shift of the spectrum that can be easily counteracted by keeping the whole chip at a controlled temperature. Regarding photosensitivity to IR light, no effects are expected up to 1 W optical power inside the waveguide [12].

Finally, we investigated the performance of the trimming technique in terms of maximum refractive index change and photo-writing speed. As shown in Fig. 4, resonant wavelength shifts as large as 20 nm were achieved, corresponding to about 20 FSRs and an effective index change of 3.2×10^{-2}. Up to this wavelength shift, no saturation effects were observed. Such a large index variation enables several reconfigurations of the devices. Figures 4(a) and 4(b) point out that the speed of the wavelength shift linearly increases with the trimming light intensity I_T, while the total shift depends only on the energy density. A resonance shift velocity of 1 nm/min needs only $I_T = 2\,\mathrm{mW/cm^2}$ and less than $25\,\mathrm{nJ/\mu m^2}$ energy density is required to cover a shift wider than 20 nm.

In conclusion, we have demonstrated that selective photo-induced trimming is a powerful tool to compensate for fabrication tolerances in coupled ring-resonator devices realized on a As_2S_3 platform. With respect to alternative approaches, the presented technique is simple, fast, power effective and low-cost, requiring only a common halogen lamp, without any additional fabrication step. An effective index change exceeding 10^{-2} was obtained with less than $25\,\mathrm{nJ/\mu m^2}$ energy density. What we have shown is also an example of passive reconfigurable PIC, whose response can be modified after fabrication to fulfill specific applications. Compared to programmable active platforms [13], loss and gain can not be arbitrarily controlled: this implies a lower flexibility in the reconfiguration, but the device functionality is held after trimming without continuous power consumption.

The Milano and MIT authors acknowledge the Progetto Roberto Rocca for partial financial support. The U.S. co-authors acknowledge support from the U.S. Department of Energy [Contract No. DE-NA000421].

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