Large one-time photo-induced tuning of directional couplers in chalcogenide-on-silicon platform

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Abstract: The stable one-time tuning of silicon-photonic directional couplers, over a broad range of coupling ratios, is achieved through the selective photo-removal of an upper cladding layer of chalcogenide glass. Analysis shows that the coupling coefficient per unit length between two parallel fully-etched silicon waveguides may be changed by 45%. The power coupling ratio of a 50 µm-long directional coupler between two such waveguides may be tuned arbitrarily between 0 and 1, with weak residual wavelength dependence. Smaller modifications in the coupling coefficient per unit length are obtained between two partially-etched ridge waveguides, on the order of 10%. The proposed procedure is demonstrated in the post-fabrication tuning of transmission notches of a race-track resonator, from over-coupling through critical coupling to weak coupling. The extinction ratio of specific resonances is varied between 4 and 40 dB. The coupling ratio of a tuned device remains stable following three months of storage.

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coupling ratio can be obtained, at the expense of increased footprint and complexity [3]. If balanced MZIs with adjustable differential phases [3] are used, the promise of close integration between photonic and micro-electronic circuits is realized. One potential application of SOI PICs is in the front-end processing, multiplexing and de-multiplexing filters of channels in high-rate optical interconnects [2]. Directional couplers are among the most fundamental building blocks of integrated photonics filters. They are used to combine or split incoming light between waveguide paths, cascaded to form Mach-Zhender interferometers (MZIs), and linked to provide feedback in ring resonators [3]. The performance metrics of filters depend critically on precise coupling ratios which may vary due to inevitable fabrication tolerances [4]. Tunable couplers can be implemented, for example, by balanced MZIs with adjustable differential phases [3]. A wavelength-independent, arbitrary coupling ratio can be obtained, at the expense of increased footprint and complexity [3].

1. Introduction

Photonic integrated circuits (PICs) on the silicon-on-insulator (SOI) material platform have been a subject of much interest for decades [1,2]. Research efforts in this area are driven by the promise of close integration between photonic and micro-electronic circuits. One potential application of SOI PICs is in the front-end processing, multiplexing and de-multiplexing filters of channels in high-rate optical interconnects [2]. Directional couplers are among the most fundamental building blocks of integrated photonics filters. They are used to combine or split incoming light between waveguide paths, cascaded to form Mach-Zhender interferometers (MZIs), and linked to provide feedback in ring resonators [3]. The performance metrics of filters depend critically on precise coupling ratios which may vary due to inevitable fabrication tolerances [4]. Tunable couplers can be implemented, for example, by balanced MZIs with adjustable differential phases [3]. A wavelength-independent, arbitrary coupling ratio can be obtained, at the expense of increased footprint and complexity [3].

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possible, the post-fabrication tuning of a single directional coupler, over a broad range of coupling ratios, would represent a useful alternative.

Active tuning of photonic devices relies on localized heating [5–7], injection of free carriers into p-i-n junction structures [8,9], or use of liquid crystals [10]. Several of these methods were also employed in the active tuning of couplers [10,11]. Active tuning approaches, however, increase the complexity of passive devices and require constant feedback. While many approaches had been proposed for the one-time trimming of phase delays [12–19], comparatively few works addressed the one-time adjustment of directional couplers. In one notable example, the splitting ratio of polymer waveguide Y-junctions was modified by photo-bleaching [20].

In this work, we report the photo-induced tuning of SOI directional couplers that are covered by an upper cladding of chalcogenide glass. Chalcogenide glasses are a family of amorphous semi-conducting materials, characterized by a broad transparency window, high refractive index, and pronounced optical nonlinearities [21–23]. In addition, chalcogenide glasses are extremely photo-sensitive [24,25]. The use of chalcogenide glasses as photosensitive upper cladding layers on top of SOI PICs was previously proposed and demonstrated by Canciamilla et al., who were able to modify the resonance wavelengths of SOI ring resonators via photo-induced index changes [17]. The illumination of chalcogenide glasses with focused laser beams can also lead to photo-removal [26], in which absorption raises the temperature of illuminated regions above the glass transition value, and the temperature gradient initiates a fast lateral flow of the liquid layer from hot to cold regions. Recently, we employed this effect in the selective photo-removal of an As10Se90 cladding layer from above the cores of individual underlying SOI waveguides [27]. The group delay index of the waveguides was varied by 0.07 refractive index units (RIU).

In the following, we show that the coupling ratio of SOI directional couplers may be modified by the selective photo-removal of the upper cladding layer from above part of their lengths. Numerical analysis shows that the coupling coefficient per unit length between the transverse-electric (TE) modes of two parallel, partially-etched ridge waveguides can be modified by over 10%. Changes in the coupling coefficient between TE modes of fully-etched waveguides reach 45%. The power coupling ratio of a 50 µm-long directional coupler comprised of two such waveguides may be tuned to any value between 0 and 1, with comparatively weak wavelength dependence. The response and dimensions of these couplers are compatible with practical device requirements.

The method is demonstrated experimentally in the post-fabrication tuning of SOI race-track resonators: the extinction ratios of resonances at specific wavelength ranges are adjusted in several steps, between 4 and 40 dB. The measured transfer functions following photo-removal are in good agreement with the predictions of simulations. The coupling ratios of tuned devices changed little following three months of storage. Preliminary results were briefly reported in [28].

2. Numerical analysis

We consider first a directional coupler between a pair of 700 nm-wide, partially etched SOI ridge waveguides. Compared with fully-etched nano-wires, ridge waveguides provide lower losses per unit length. The thickness of the silicon device layer is 220 nm, and it is etched to a residual thickness of 150 nm outside core regions. The lateral gap between the cores is 300 nm-wide. The thickness of the buried oxide layer of the SOI substrate is 2 µm. The cores are covered by a 50 nm-thick silica buffer layer, followed by a 700 nm-thick upper cladding layer of As10Se90. The refractive indices of silicon, silica and As10Se90 at 1550 nm wavelength are 3.45, 1.45 and 2.35 RIU, respectively. A schematic cross-section of the coupler is shown on the left panel of Fig. 1. The upper cladding layer may be locally removed by focused illumination of green laser light (Fig. 1, right panel).
The transverse profiles and effective indices of the TE even and odd super-modes of the coupler were calculated using COMSOL multi-physics 2D simulations [29]. The coupling coefficient per unit length \( \kappa \) between the two waveguides, with the upper cladding layer intact, is given by [29]:

\[
\kappa(\lambda) = \frac{\pi (n_{\text{even}} - n_{\text{odd}})}{\lambda},
\]

(1)

where \( \lambda \) is the wavelength of incident light and \( n_{\text{even}} (n_{\text{odd}}) \) is the effective index of the even (odd) super-mode. The calculated effective indices at 1560 nm wavelength are 2.7909 and 2.7631 RIU, respectively, corresponding to \( \kappa \) of 0.056 \( \mu m^{-1} \). Sections not covered by the upper cladding are characterized by \( n_{\text{even}} (n_{\text{odd}}) \) of 2.7402 (2.7154) RIU at the same \( \lambda \). The coupling coefficient in these regions is reduced by \( \Delta \kappa \) of 0.006 \( \mu m^{-1} \), or about 11\% of \( \kappa \).

The fraction of the incident optical power that is coupled to the through port of the device is given by:

\[
r(\lambda) = \cos^2 \left[ \int_0^L \kappa'(x') \, dx' \right] = \cos^2\left( \kappa L - \Delta \kappa \cdot x \right).
\]

(2)

Here \( L \) is the overall length of the coupler, and \( x \) is the length of the segment that is not covered by chalcogenide upper cladding. The position-dependent coupling coefficient \( \kappa' \) in Eq. (2) equals \( \kappa \) for \( 0 \leq x' \leq (L - x) \), and \( \kappa - \Delta \kappa \) for \( (L - x) \leq x' \leq L \). Figure 2 shows the calculated \( r(\lambda) \) between ridge waveguides of the geometry described above, over a length \( L = 300 \mu m \) and for different values of \( x \). The simulations take into consideration the chromatic dispersion of \( n_{\text{even}} \) and \( n_{\text{odd}} \). The dashed, horizontal line in Fig. 2 denotes \( r = 0.69 \), the value
of critical coupling into the race-track resonators fabricated in this work (see next section). The simulation results suggest that $r(\lambda)$ may be tuned over a comparatively broad range of values above and below critical coupling, between 0.4 and 1 at 1560 nm, through changing $x$. The long coupler is, however, strongly wavelength-dependent.

The calculated overlap integral between the mode in regions covered by the upper cladding and the mode in uncovered regions is 99%. This large overlap suggests that transition losses would only become significant within high-Q micro-ring resonators, in which round-trip losses are below few percent. The calculated power reflectivity in the transition between regions is on the order of $-40$ dB.

Larger relative changes in coupling coefficient can be achieved using fully-etched silicon rib waveguides. We considered typical waveguides of 500 nm width and 220 nm height, separated by a 200 nm-wide transverse gap between their cores and covered by a silica buffer layer and an upper cladding of $\text{As}_{10}\text{Se}_{90}$ as detailed earlier. The calculated value of $\kappa$ between two such waveguides is 0.060 $\mu$m$^{-1}$ at 1560 nm. The coupling coefficient is reduced by $\Delta\kappa$ of 0.027 $\mu$m$^{-1}$, or about 45% of its value, when the upper cladding is removed. Figure 3 shows the calculated power coupling ratio to the through port of a 50 $\mu$m-long coupler of the above geometry, for several values of $x$. The large ratio $\Delta\kappa/\kappa$ allows for the arbitrary tuning of $r(\lambda)$ between 0 and 1, with much weaker wavelength dependence than that of Fig. 2.

The overlap integral between the modes in covered and exposed regions of the rib waveguide is 96%. The results of Fig. 3 demonstrate the potential of the proposed method in the tuning of practical devices.

![Fig. 3. Calculated power coupling ratios of a 50 $\mu$m-long directional coupler formed between two 500-nm wide, fully-etched silicon-photonic rib waveguides. The transverse separation between the waveguides cores is 200 nm. Different curves correspond to different length $x$ of sections not covered by chalcogenide upper cladding (see legend).](image)

### 3. Experimental demonstration

A proof-of-concept experimental demonstration of the proposed tuning method of directional couplers is provided in the post-fabrication changes of the transfer function of race-track resonators. The characterization of devices was also used to validate the predictions of simulations for the photo-induced changes in $\kappa$, and to monitor the stability of the modified response over time. Resonators were fabricated using partially-etched ridge waveguides, with a coupler geometry following that of the calculations leading to Fig. 2. Although fully-etched waveguides would support a larger ratio of $\Delta\kappa/\kappa$, our current process for the fabrication of these waveguides results in losses per unit length that are exceedingly high.

Patterns were defined in the silicon device layer using electron beam lithography and subsequent reactive ion etching. The circumference $C$ of the resonators was 1.55 mm, and the bending radii within the race-track shape were 20 $\mu$m. A 50 nm-thick layer of silica was
deposited on the entire sample by ion-beam evaporation, and a 700 nm-thick upper cladding layer of As\textsubscript{10}Se\textsubscript{90} was locally deposited on top of specific regions. The deposition regions were defined using photo-lithography and subsequent lift-off. The specific chalcogenide composition was chosen for its pronounced mass transfer effect [26, 27]. Details of the fabrication process are provided in [27]. A top-view, optical microscope image of a device is shown in Fig. 4.

Fig. 4. Top-view, optical microscope image of a fabricated race-track resonator in silicon-on-insulator. An upper cladding layer of chalcogenide glass covers the lighter-colored region. This upper layer was subsequently removed from above a small section of the coupler region, using focused laser beam illumination. A magnified view is shown in the inset.

Light was coupled in and out of the TE mode of the devices, from/to the cleaved facets of standard fibers, using vertical grating couplers that were patterned at both ends of the bus waveguides. Grating coupler losses and propagation losses of straight waveguides were measured separately as 9 dB per facet and 3.5 dB/cm, respectively. The end-to-end insertion loss of the resonators was 22 dB, attributed primarily to input/output coupling losses. The deposition of the silica buffer layer and the chalcogenide upper cladding layer over short sections introduced negligible additive end-to-end loss.

Selective photo-removal of the upper cladding was carried out using continuous-wave laser light at 532 nm wavelength, focused by a desktop microscope with 50 \times magnification to a spot-size diameter of 1.5 \mu m. The intensity of the focused beam was on the order of 1 MW/cm\textsuperscript{2}. The device was translated through the focused laser beam by a motorized linear stage in 0.1 \mu m steps and at 200 \mu m/s speed. The longitudinal resolution of the photo-removal process was on the order of 1 \mu m. The laser irradiation removed the chalcogenide layer from parts of the directional coupler length, in 20 \mu m-long increments. In order to examine the device after illumination, a cross section was made by focused ion beam (FIB) processing.
Figure 5 shows a scanning electron microscope (SEM) image of this cross-section demonstrating that the chalcogenide layer is entirely removed from irradiated segments. The mass transfer process is associated with the flow of heated glass. While the edges of the removed sections were not examined, it is anticipated that the process does not result in rough edges.

The power transfer functions of resonators were measured by a LUNA OVAe-8000 optical vector analyzer, with 2.5 pm spectral resolution. Figure 6(left, red trace) shows the initial transfer function of the device, in which an $x = 125 \mu m$ long section of the coupler was not covered by the upper cladding. The loaded $Q$ value of the resonator is 30,000, suggesting that critical coupling is achieved at a power coupling ratio of [29,30]:

$$ r = \exp\left(\frac{-\pi n_g C}{Q\lambda}\right) = 0.69. $$

Here $n_g = 3.6$ RIU is the group index of the ridge waveguides. The value of critical coupling is noted in Fig. 2. The extinction ratios of the transmission resonances (Fig. 6) vary between 4 to 40 dB, with $r(\lambda)$ passing through the critical value at 1558 nm. The exact wavelength of critical coupling allows for the calibration of the coupling coefficient as $\kappa = 0.055 \mu m^{-1}$, or 2% lower than the prediction of simulations. This value was used in the calculations of Fig. 2 and Fig. 6(right). The gradual decrease in transmission with $\lambda$ is due to the spectral dependence of the vertical grating couplers.

![Fig. 6. Left - Measured spectral transfer functions of a silicon-on-insulator race-track resonator. Different curves correspond to different lengths $x$ of sections within the directional coupler that are not covered by chalcogenide upper cladding (see legend). Right – corresponding simulations](image)

Each photo-removal step of the upper cladding shifted the wavelength of critical coupling by about 4 nm, reaching 1569.5 nm for $x = 185 \mu m$. The shift in wavelength is about 10% smaller than the prediction of simulations (see Fig. 6, right-hand panel [29]), suggesting that $\Delta\kappa$ is 10% smaller than expected. Nevertheless, the step-wise tuning of $r(\lambda)$ over a broad range is demonstrated (Fig. 7). The extinction ratio of the resonance at 1558 nm was modified between 40 dB and 4 dB. The coupling ratio at 1569 nm was adjusted between 0.4 and 1, from initial over-coupling for $x = 125 \mu m$, through critical coupling, to under-coupling for $x = 245 \mu m$, as anticipated.
The tuning of $r(\lambda)$ is accompanied by offsets in resonant wavelengths $\lambda_i$: 
$$\frac{\partial \lambda_i}{\partial x} = \left(\frac{\lambda_i}{C}\right)(\Delta n/n).$$
Here $n = 2.775$ RIU is the effective index of the waveguide mode with the upper cladding in place, and $\Delta n = -0.049$ RIU is the change in $n$ following photo-removal, as obtained in simulations (average between $n_{even}$ and $n_{odd}$). Based on these values, a wavelength offset of $-0.36$ nm per each 20 µm removal step is expected. An average offset of $-0.39$ nm per step was observed in the measurements (Fig. 7), in general agreement with expectations. (Note that the offset in $\lambda$, following each step is close to the free spectral range of the device transfer function). Small-scale variations in the offsets following successive steps could be due to inconsistencies in step size or angular misalignments [27]. Specific values of $\lambda_i$ can be restored by local illumination of short segments within the resonator loop [17,27], if necessary.

The transfer function of a different device was monitored over more than 3 months following the tuning of the directional coupler (Fig. 8). The coupler was 200 µm long, with a section of 100 µm length initially uncovered by chalcogenide cladding (red curve). The cladding was then removed from an additional 35 µm-long section (blue curve). The loaded $Q$ of the device was 18,000. Photo-removal changed the extinction ratios of the resonances near 1565 nm from 10 dB ($r = 0.3$) to 35 dB ($r = 0.532$), and down-shifted the resonance wavelengths by 0.61 nm (or more than a free spectral range, see discussion of $\partial \lambda_i/\partial x$ above).
The tuning of $r$ corresponds to $\Delta \kappa$ of 0.0054 $\mu$m$^{-1}$, in agreement with expectations. No significant changes in extinction ratios or resonance wavelengths were found over two weeks of monitoring. Following 95 days of storage, extinction ratios were reduced to 32 dB (corresponding to $r = 0.527$). This variation in extinction ratio corresponds to a reduction of $\Delta \kappa$ by 3% of its initial tuning. The resonant wavelengths were down-shifted after 95 days by 0.04 nm, or 6% of the initial offsets. The drift in $\lambda_r$ is attributed to the structural relaxation of the chalcogenide layer after exposure to light above the band gap [17]. The wavelength drift was three times larger than that observed in [17] using a different chalcogenide composition (As$_2$S$_3$). All measurements were taken at 25 ± 0.1 °C, with the device mounted on a temperature-controlled stage working in closed-loop. The residual uncertainty in the measurement temperature corresponds to variations of ± 0.01 nm in the resonance wavelengths. The device was stored in the dark between measurements.

4. Conclusions

In conclusion, the one-time, rapid and stable tuning of silicon-photonic directional couplers over a broad range of coupling ratios, using the selective photo-removal of a chalcogenide glass upper cladding, has been proposed, analyzed and demonstrated. Simulations suggest that the coupling coefficient per unit length between two partially-etched waveguides can be modified by 10%. The calculations are supported by the experimental characterization of race-track resonators, following several steps of tuning. The extinction ratios of specific resonances were adjusted between 4 and 40 dB. Although the principle could be demonstrated using a stand-alone coupler, the tuning of resonators represents a problem of interest.

While the relatively long couplers used in experiments are strongly wavelength-dependent, this restriction is not fundamental. Analysis shows that the photo-removal of the upper cladding may modify the coupling coefficient per unit length between standard, fully-etched waveguides by 45%. The power coupling ratio of such devices may be adjusted between 0 and 100%, with residual wavelength dependence that is much weaker. The length of a coupler of this type can be 50 µm only. It may be further reduced if a smaller tuning range is sufficient: The modification of the coupling ratio by few percent would be sufficient to change the coupling into a high-Q, micro-ring resonator from weak to critical.

The trimming of smaller, high-Q resonators would require high accuracy in the removal process. The resolution step of the photo-removal setup is about 1 µm, determined by the illumination spot size and the step-size of the linear stage. A coupler such as that of Fig. 3, for example, may be tuned in about 50 resolution steps of complete cladding removal. Finer tuning resolution can be achieved with partial removal of the upper layer, to nonzero residual thickness. Tuning precision is improved further with closed-loop monitoring of the device transfer function during photo-removal. A closed-loop setup is already in use in our measurements. The applicability of the method to the trimming of point or ultra-short couplers, however, requires further experimental investigation.

Although the thermo-optic coefficient of arsenic-selenide glasses is six times larger than that of silica [31], it is about four times smaller than that of silicon. The chalcogenide cladding helps push a larger fraction of the modal profile out of the thermally-sensitive silicon core. Altogether, numerical calculations show that the variation of the effective index with temperature in a chalcogenide-on-SOI waveguide is practically the same as that of a waveguide with a silica upper cladding.

Selective photo-removal of a chalcogenide upper cladding is also suitable for the tuning of the differential phases within balanced MZI couplers [3]. Ongoing work is being dedicated to the employment of the principle in the tuning of fully-etched waveguides, and in cascaded silicon-photonic filters.
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