

Localized *In-Situ* Cladding Annealing for Post-Fabrication Trimming of Silicon Photonic Integrated Circuits

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Abstract:

A significant challenge in the utilization of silicon photonics is the need to accurately control the optical path length in devices such as ring resonator filters beyond what can be achieved via the fabrication process alone. In this work, we report the use of localized annealing via *in situ* heaters to induce a permanent change in the refractive index of the cladding of an optical waveguide. This change in the cladding index induces a change in the waveguide's effective index, and thereby its effective optical path length. This method has the advantage that it enables the optical path length to be adjusted ("trimmed") once during a post-fabrication calibration process rather than adjusting it continuously by applying power to a heater during operation of the circuit. When compared to other methods for post-fabrication trimming, this method has the advantage of simplicity. Because the heaters are built into each device, no additional equipment, other than a supply of electrical power, is necessary to cause the index change. Using hydrogen silsesquioxane (HSQ) as a cladding material, the resonant wavelength of a ring resonator was adjusted by as much as 3.0 nm, when annealing the entire substrate. Adjusting the resonant wavelength by as much as 1.7 nm was demonstrated using PECVD oxide as a cladding material and *in-situ* heaters for annealing. The trimming of a 5 channel, single ring filter bank, and a single channel double ring filter is demonstrated.

Introduction:

Silicon photonics is a promising technology because of its potential to greatly reduce the size, weight, and power for many electronic and optical systems. The use of silicon fabrication technology is especially well suited to the low-cost integration of large numbers of optical components. One great challenge to fully realizing this potential is the need for extremely precise optical phase control in components such as filters and interferometers. Manufacturing tolerances make it generally impossible to achieve such phase control by fabrication alone. Typically, the effective optical path length in a device is adjusted by varying the optical index using integrated heaters. This solution has several disadvantages, including the amount of power that is consumed and the need for electronics to independently adjust the power to a large number of heaters that may be necessary in a system.

An alternative solution is to permanently modify the index of refraction of the structures to achieve the desired optical path length after fabrication. This post-fabrication trimming method would provide a much simpler set-it-once-and-forget-it mechanism for tuning. Several such methods have been demonstrated such as using UV exposure to change the index of the cladding [1] [2] [3], electronic-beam

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exposure to cause stress that changes the effective mode index [4], oxidation of the waveguide using an atomic force microscope probe [5] or patterning the cladding in an extra fabrication step [6]. Each of these methods has their advantages and disadvantages, but no method offers a quick way to perform trimming without specialized or expensive equipment. The method described here can be done quickly, and only requires a way to measure the optical response of the device, and an electrical power supply to perform the adjustment.

Instead of using UV exposure to change the index of a waveguide cladding, it is possible to use high temperature to permanently change the index of a cladding [7] [8] [9]. Integrated heaters are already commonly used for thermal adjustment of the waveguide index, and can achieve temperatures several hundred degrees above the ambient temperature [10]. Such high temperatures can cause a permanent (or semi-permanent) change in the index of a cladding material in addition to a temporary one if the cladding material is chosen right. Individual heaters can be placed at each optical element so that it is easy to individually adjust each optical element. Because the heaters and optical devices are so small, the time scale for heating and cooling the devices is on the order of 10's of milliseconds. This means that the adjustments and measurements can be done in rapid succession.

Temperature Dependence of the Cladding Material Refractive Index

One essential element for this trimming method is an optical cladding material that has a significant permanent index change when annealed at an appropriate temperature. Earlier demonstrations of this technique have used a standard silica cladding, and index changes of only 0.01% were achieved [7] [8]. This material also needs to be a good waveguide cladding material, and therefore must have low optical losses at the wavelength of interest. This work focuses on the C-band, or wavelengths near 1550 nm. Four materials with known low optical loss were investigated: Hydrogen silsesquioxane (HSQ), polydimethylsiloxane (PDMS), low temperature PECVD oxide (hereafter, referred to as simply PECVD oxide), and polymethylglutarimide (PMGI).

To investigate the permanent index change of these four materials with temperature, we first deposited the materials on silicon wafers and then measured the index before and after baking the wafers. The PECVD oxide was deposited at a low temperature of 150° C, which is known to produce oxides of poor quality [11], making the material susceptible to further thermal modification. The other materials were spin coated. The refractive index of the films were measured at a wavelength of 1 μm using spectroscopic ellipsometry. The results of these measurements are presented in Table 1. The lowest temperature in the test range is the post-apply bake temperature for the materials that were spin-coated. Shown in the table is the amount of index change and over what temperatures that index change happened. The baking was done in a small furnace-like oven and the temperature was held for 5 minutes. However, it was not possible to add the samples after the oven reached temperature, so additional bake time as the oven ramped-up is not included in the table. This time was about 30 minutes for the highest temperatures

Table 1. Temperature-induced changes of refractive indices of cladding materials.

Material	Total Temperature Range (°C)	Temperature Range of Observed Changes (°C)	Induced Change in Refractive Index
Hydrogen silsesquioxane (HSQ)	150-600	200-300, 400-500	1.392→1.375, 1.375→1.415
Polydimethylsiloxane (PDMS)	70-300	-	1.396 →No change
Low Temperature PECVD Oxide (LTO)	150-600	150-600	1.455→1.432
Polymethylglutarimide (PMGI)	70-275	125-275	1.528→1.508

All of the materials except PDMS go through a significant index change when they are baked at an elevated temperature. HSQ undergoes the largest change in refractive index, however, the change is not monotonic. At lower temperatures in the range, the index decreases. This is believed to be due to de-absorption of water, as will be discussed later. At higher temperatures, the HSQ film densifies, raising the index [12]. It should be noted that this non-monotonic characteristic of the index of HSQ upon annealing has been previously reported [12].

Demonstration of Localized *In-Situ* Cladding Annealing

To demonstrate the technique on ring-resonator-based filters, devices based on a previous filter design were fabricated [13]. This ring-resonator filters were fabricated on silicon-on-insulator (SOI) wafers with waveguides having 600-nm width and 110-nm height. This waveguide thickness is thinner than the more commonly used 220 nm. In the original design the thinner waveguide offered the advantage of reduced optical scattering. In this case, the thinner waveguide puts more of the mode in the cladding, thereby allowing greater tuning from an index change in the cladding. The first device tests were done by using HSQ as the top and side claddings after the silicon waveguide was fabricated. Figure 1 shows the change in the resonant wavelength when filters with the HSQ cladding are baked. These samples were baked in a furnace in the same manner as used in the previous section, and individual adjustment of ring resonators was not possible. As anticipated, the shift in the resonant wavelength follows the same pattern as the shift in the index of the HSQ films described above. The resonant wavelength decreases as the index of the HSQ decreases as the sample is baked at temperatures below 300° C. Above 300° C, the resonant wavelength increases. The total shift in resonant wavelength from the minimum to the maximum is 3 nm, and this would be the expected trimming range possible if an HSQ cladding is used.

For demonstrations with the *in-situ* heaters, PECVD oxide was used as the cladding material. This was necessary because of process compatibility issues with our particular CMOS fabrication equipment and HSQ. In general, HSQ is considered CMOS compatible. It was important that the PECVD oxide was deposited at the end of the process, since the processing of the metals necessary for contacting the heaters required temperatures of 475° C. Toward the end of the fabrication process, the standard oxide overcladding was removed, so that it could be replaced with the PECVD oxide. This removal was done through a series of dry and wet etch steps to avoid damaging the silicon waveguides and heaters. Figure 2 shows a SEM image of a filter with two coupled rings after the removal of the first oxide overcladding. Visible are the rings, the input and output waveguides, and the heaters. The heaters are made from the same silicon material as the waveguide, except that the heaters are n-type doped to provide a controlled electrical resistance.

Figure 3 shows the resonant wavelength shifts of the ring filters after being heated. The amount of change is dependent on both the amount of heat or electrical power applied, and on the time of the application. For the mid-range powers, the shift dependence on time is roughly linear when time is plotted on a logarithmic scale (data not shown). The highest power applied, 79 mW, is where the heaters begin to be damaged, and higher heating powers are not possible.

Using this measurement as rough guide, it is possible to trim a series of ring resonator filters. The trimming of 5 channels of a single ring filter bank is shown in Figure 4. Shown is the transmission through the through port, which allows the measurement of the resonant wavelength of all 5 channels by

monitoring a single port. Before trimming, the channel spacing is nearly random. After trimming, the resonant wavelengths are much more closely aligned to the target 0.8 nm spacing.

Many filter designs require multiple small rings to be coupled together. It is therefore important to demonstrate that this technique can be used to independently tune nearby or adjacent rings. The tuning of the two ring filter (Figure 2) is shown in Figure 5. To show the independent ability to tune each ring one ring was trimmed nearly as much as possible by heating with 79 mW for 2 min. Figure 5(a) shows the drop-port transmission of the filter before and after this trimming of one ring. Notice that the resonant wavelength of the ring shifts by -1.7 nm, while no observable change is made to the resonant wavelength of the second ring. There is a slight change in the shape of the other resonance due to the difference in coupling between the two resonances as one is shifted. The two rings were then brought into co-resonance by trimming the second ring. Figure 5(b) shows the through and drop port transmission performance after both rings in the filter were trimmed. The low on-resonance transmission of the through port indicates that the two rings are well aligned. The on-chip insertion loss to the drop port when on resonance is between 1-2 dB, which is similar to previous results from this filter design with a traditional oxide cladding [13].

Long-Term Stability of Localized Cladding Annealing

Low temperature oxides such as those used here are known to absorb moisture [11]. This is believed to be the primary mechanism for the refractive index changes observed in our PECVD oxide. As the oxide is heated, moisture is forced out of the film. It is therefore expected that the changes in index produced by heating will not be stable, unless the additional flow of moisture in and out of the oxide is prevented. Samples stored for 1 day in an ambient atmosphere show significant relaxation toward the original untrimmed resonant wavelength (Figure 6). Also shown in Fig. 6 is the comparison to a sample stored for 1 day with a desiccant. There is a dramatic improvement in stability with the desiccant, however, there is still some drift (roughly 0.25 nm in wavelength) toward a longer wavelength. It is therefore clear that moisture is an important contributor to the changes in index that are being observed, but it is not clear whether moisture is the only one.

Similarly, with the HSQ coated samples, the resonant wavelengths will relax back to their original wavelengths after being baked at a temperature of 300° C. When an HSQ coated sample is baked at 475 °C, however, the resonant wavelength is much more stable, although a small shift to longer resonant wavelengths will occur over the course of a month (data not shown). This indicates that the mechanism for the index shift at low temperatures is likely moisture, as in the PECVD case. At temperatures above 300° C, the index change is likely due to the expected densification. As the HSQ film densifies, it appears the film can still absorb moisture, but the effect is not as fast or as strong.

Future efforts will be required to develop to a method to avoid moisture changes after annealing, or to use a different mechanism for the wavelength shift. The densification of an HSQ cladding at temperatures above 300° C offers one possible solution, although a moisture barrier or some other control of moisture is still needed. It should be pointed out that other post-fabrication methods may also not be stable [1], so this problem is not unique to this trimming method. The trimming method outlined here, however, can be completely done *in situ*. It is therefore feasible to periodically readjust the trimming, which would not be feasible using the other trimming techniques. This would still offer advantages over adjusting the devices in the usual way using active heaters via the thermo-optic effect. The devices would not need to be

heated all the time, reducing power consumption, and the devices can be adjusted one-by-one, perhaps reducing complexity

Conclusion

A new post-fabrication trimming method using a thermal or annealing process has been demonstrated. This method uses in-situ heaters to cause a shift of up to -1.7 nm in the resonant wavelength of a ring resonator filter when low temperature PECVD oxide is used as a cladding. Tests indicate that this shift is at least partially due to the removal of moisture that is present in these oxide films. A larger possible wavelength trimming range was shown using hydrogen silsesquioxane (HSQ) as a cladding material. With HSQ, the resonant wavelength shifted over a range of 3 nm when annealed above 300° C. This shift is likely due to densification of the HSQ, making the change more permanent than a shift relying on changes of moisture.

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