

Large Bidirectional Refractive Index Change in Silicon-rich Nitride via Visible Light Trimming

Dmitrii Belogolovskii,* Md Masudur Rahman, Karl Johnson, Vladimir Fedorov, Andrew Grieco, Nikola Alic, Abdoulaye Ndao, Paul K. L. Yu, and Yeshaiah Fainman

Phase-sensitive integrated photonic devices are highly susceptible to minor manufacturing deviations, resulting in significant performance inconsistencies. This variability has limited the scalability and widespread adoption of these devices. Here, a major advancement is achieved through continuous-wave (CW) visible light (405 and 520 nm) trimming of plasma-enhanced chemical vapor deposition (PECVD) silicon-rich nitride (SRN) waveguides. The demonstrated method achieves precise, bidirectional refractive index tuning with a single laser source in CMOS-compatible SRN samples with refractive indices of 2.4 and 2.9 (measured at 1550 nm). By utilizing a cost-effective setup for real-time resonance tracking in micro-ring resonators, the resonant wavelength shifts as fine as 10 pm are attained. Additionally, a record red shift of 49.1 nm and a substantial blue shift of 10.6 nm are demonstrated, corresponding to refractive index changes of approximately 0.11 and -2×10^{-2} . The blue and red shifts are both conclusively attributed to thermal annealing. These results highlight SRN's exceptional capability for permanent optical tuning, establishing a foundation for stable, precisely controlled performance in phase-sensitive integrated photonic devices.

measured at 1550 nm) ranging from 2.0 (lower Si content: Si_3N_4) to 3.2 (higher Si content: Si_7N_3).^[1,2] Furthermore, other linear and nonlinear optical properties of SRN are also altered remarkably with the change of silicon content, including linear optical losses and transparency window,^[2] nonlinear optical losses,^[1,3] thermo-optic coefficient,^[4] and third-order susceptibility (χ_3).^[1,5] Consequently, control of these properties enables SRN films to be optimized for various applications. For example, a wide variety of nonlinear effects have been demonstrated in SRN devices, such as the DC Kerr effect,^[6] nonlinear Kerr switching,^[7] second harmonic generation,^[8] intermodal frequency generation,^[9] four-wave mixing,^[5] and supercontinuum generation.^[10] Additionally, SRN's relatively high thermo-optic coefficient (especially for higher Si-content films) enables implementation of efficient thermally driven phase shifters and switches.^[11,12] Finally, SRN is substantially more compatible with traditional

CMOS mass-manufacturing process than other materials, such as low pressure chemical vapor deposition (LPCVD) Si_xN_y , since the relatively low temperature of PECVD SRN deposition (350 °C) does not exceed the thermal budget of front-end-of-the-line semiconductor processes.^[2]

On the other hand, fabrication variability continues to represent a persistent challenge in integrated photonics, including SRN integrated platform. In particular, phase-sensitive devices, such as micro-ring resonators (MRRs), are highly sensitive to variations in the fabrication process even on the scale of 1 nm, which can lead to significant performance inconsistencies, ultimately precluding these devices from commercial and widespread use.^[13,14] These random variations typically require optical devices to be biased to operating specifications using power-demanding heaters.^[15] Alternatively, optical trimming, which is fine tuning of the optical properties of photonic devices post-fabrication, has been employed to compensate for such variations. However, most presented trimming methods either induce unidirectional refractive index change only, or suffer from strong relaxation, or require CMOS-incompatible materials as cladding, limiting their effectiveness.

It has been well-known for nearly half a century that optical materials exposure to high-intensity visible or UV light

1. Introduction

Silicon-rich nitride (SRN) grown using plasma-enhanced chemical vapor deposition (PECVD) has numerous qualities that are outstanding for a versatile complementary metal-oxide semiconductor (CMOS) compatible integrated photonics platform. As the Si content (and with it – the refractive index) of SRN films vary with the choice of PECVD deposition and post-processing parameters, films can be grown with a refractive index (as

D. Belogolovskii, M. M. Rahman, K. Johnson, V. Fedorov, A. Grieco, N. Alic, A. Ndao, P. K. L. Yu, Y. Fainman
University of California
San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA
E-mail: dbelogol@ucsd.edu

The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adom.202403420>

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can alter their optical properties.^[16] As such, some of the first approaches to trimming integrated photonic devices used UV exposure to silane-based waveguide cladding—and soon after, Si_xN_y waveguide cores—to substantially shift the center wavelengths of filters and ring resonators.^[17,18] In the time since, a wide variety of methods and optical materials have been proposed to trim optical properties of integrated components, including further developments of continuous wave (CW) UV and visible light exposure,^[19–22] pulsed laser irradiation,^[23] electron beam exposure,^[24,25] and localized annealing of regions exposed to ion implantation.^[26–31] These methods can introduce waveguide effective index changes on the order of 10^{−3} to 10^{−2}, which is sufficient for many applications.^[26,30] However, several of these methods require exotic non-CMOS-compatible materials to sensitize the optical structure to the applied stimulus, such as chalcogenides, phase change materials, tunable polymers, and liquid crystals.^[17,19,21,32] Other methods require trimming to be performed on waveguides prior to the application of the final cladding, necessitating the use of temporary cladding and adding complexity to the trimming process.^[33] Recently, simple CMOS-compatible post-fabrication trimming of structures has been demonstrated using localized annealing from on-chip heaters included in the chip design.^[26–31] While this method is simple and effective, it requires Ge implantation of the waveguide and is capable only of decreasing the refractive index of the optical material. In fact, most of those mentioned above techniques are not capable of post-fabrication trimming in both directions.

Exploring the feasibility of trimming SRN via laser annealing is of significant interest. It is widely recognized that rapid thermal annealing (RTA) of SRN at high temperatures (typically > 600 °C) leads to the dissociation of Si–H bonds, significant hydrogen (H) desorption, reduced nitrogen (N) content, and an increased concentration of Si–Si bonds.^[34–36] Conversely, studies have shown that RTA at lower temperatures (<600 °C) causes bond redistribution (such as Si–Si, Si–N, Si–H, N–H), leading to an increase in Si–H and Si–N bond concentration at the expense of N–H and Si–Si bond concentration.^[34,35] Such structural changes should inevitably result in permanent refractive index change necessary for trimming. At the same time, a relatively low thermal conductivity of PECVD SRN thin film was reported, in the range of 0.45 to 4.5 W m^{−1} K^{−1},^[37] much lower than that of c-Si, which is 148 W m^{−1} K^{−1}.^[38] This suggests that SRN can efficiently localize heat, which is favorable for localized laser annealing where high temperatures are required. When a thin film absorbs laser radiation, the resulting temperature increase can be approximately estimated using the equation $T_{max} = T_0 + P/(w_0 k \sqrt{\pi})$, where T_{max} is the maximum temperature, T_0 is the room temperature, w_0 is the mode diameter of the Gaussian beam, k is the thermal conductivity, and P is the optical power.^[39] Assuming that SRN's thermal conductivity is roughly in the middle, for example, $k = 1.7$ W m^{−1} K^{−1}, and $P = 40$ mW, $w_0 = 10$ μm, we estimate $T_{max} = 1350$ °C, large enough to activate both mechanisms that are responsible for thermal annealing,^[34–36] making SRN an excellent candidate for trimming studies.

In this manuscript, we present extensive and novel results on visible CW radiation (405 and 520 nm) induced bidirectional trimming of PECVD SRN with refractive indices of 2.4 and 2.9 (at 1550 nm). Refractive index tuning is accomplished in a sim-

ple and cost-effective setup that allows rapid fine trimming via real-time position tracking of a resonance in an MRR. Remarkably, both 405 and 520 nm radiation can induce blue and red wavelength resonance shifts in an SRN MRR. The latter implies that a refractive index of SRN can be both decreased and increased by using a single laser-source, which is undoubtedly a highly advantageous feature for the trimming of SRN devices. Furthermore, the blue and red shifts can be easily separated in a fully controllable way simply by changing the trimming laser power or the exposure duration. Moreover, a strong blue shift of 10.6 nm and a largest ever reported red (to date) shift of 49.1 nm are achieved in trimmed SRN MRRs. In addition, the refractive index can be decreased by -2×10^{-2} and increased by a large value of 0.11. We demonstrate that both blue and red shifts originate from thermal annealing, with blue shifts occurring at lower annealing temperatures (400–500 °C) and red shifts emerging at temperatures above 500–600 °C. Intriguingly, the magnitude and direction of the shifts vary significantly with the refractive index of SRN, which makes the material an excellent choice for coating. Additionally, it is established that the presence of both red and blue shifts mitigates the resonance backshifting by pushing the resonance in opposite directions. Finally, we demonstrate the effectiveness of the novel technique employing it for trimming of an SRN-based optical demultiplexer with MRRs to an accuracy of approximately 10 pm. Overall, our results suggest that SRN is a highly reconfigurable CMOS-compatible platform, which offers a pathway toward significantly improving the precision and manufacturability of SRN (or Si if SRN is used as coating) photonic devices, particularly for phase-sensitive applications where sub-nanometer tuning accuracy is required.

2. Results

2.1. Experimental Setup

To investigate the effects of visible light exposure on SRN waveguides, we deposited SRN films with refractive indices of 2.4 and 2.9 (measured at 1550 nm) using PECVD. For the waveguide with a refractive index of 2.4, the width and thickness were 600 and 385 nm, respectively; for the waveguide with an index of 2.9, they were 450 and 340 nm. The fabricated MRRs had a radius of 25 μm, with a coupler length of 6.5 μm, yielding a total length of approximately 170 μm. The gap between a bus waveguide and a coupler was 400 nm. **Figure 1a** demonstrates a microscope image of the fabricated device used for trimming experiments.

Figure 1b,c demonstrates the setup used for the trimming experiments. The goal was to achieve a strong MRR resonance shift and fine-tuning in real time as the visible laser exposure was applied, while maintaining a simple and cost-effective setup. For this, we used inexpensive fiber-coupled multimode (MM) 405 and 520 nm laser diodes (Laser Tree LT-FCLD-M405075 and LT-FCLD-M520065) coupled to SMF-28 patch cables. The bare fiber tip, cleaned and cleaved, was angled at 10 degrees relative to the sample to minimize back reflections. The fiber was attached to the grating coupler stage which had six degrees of freedom, enabling precise alignment, with an accuracy of 500 nm (more details on how high accuracy alignment was achieved can be found in Supporting Information, Section S1). The trimming

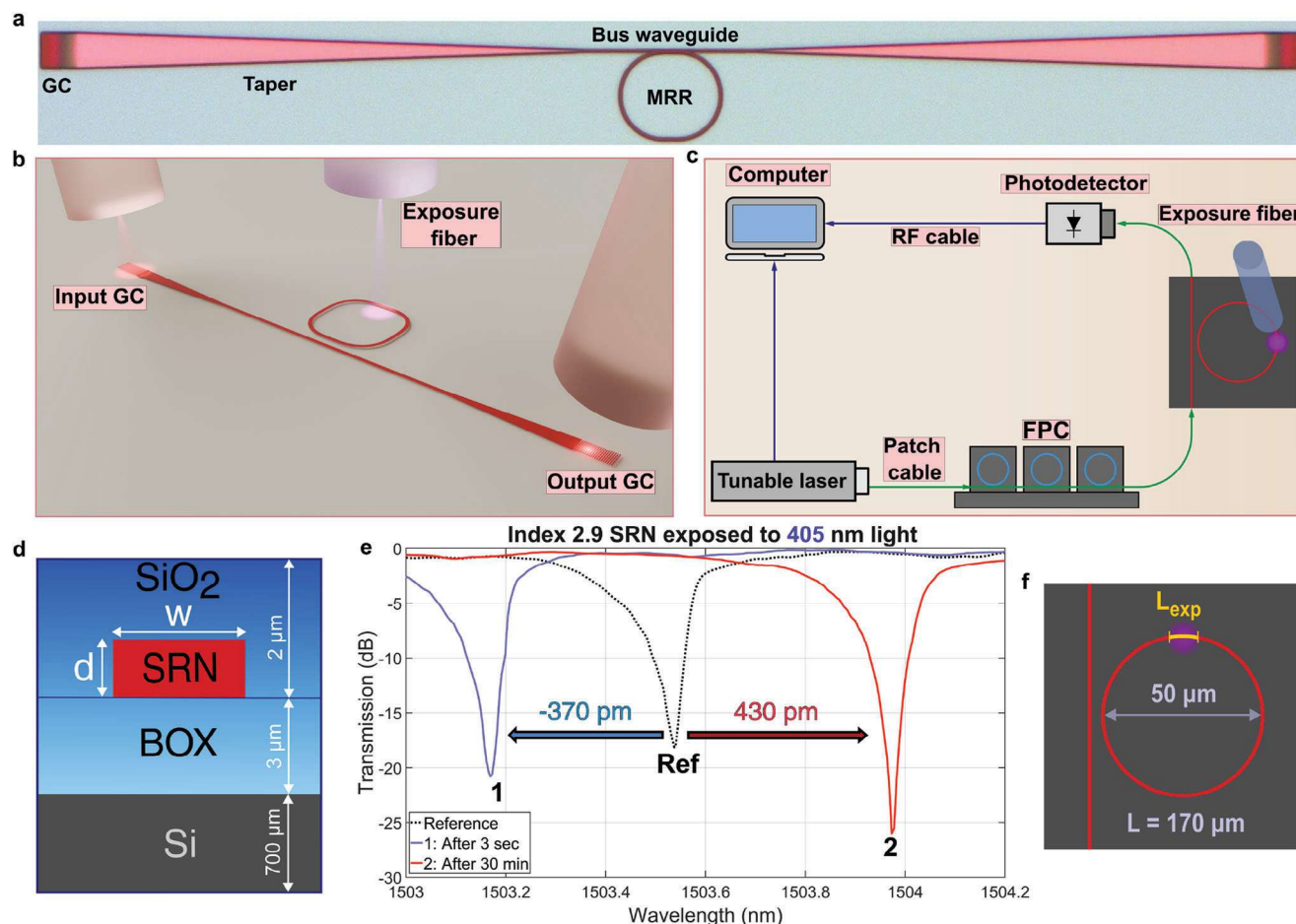


Figure 1. a) Microscope image of a device to be trimmed showing an MRR, bus waveguide, grating couplers (GC), tapers. b) 3D illustration of the configuration of 3 fibers used for trimming and real-time measurement. Laser light couples in and out via grating couplers. The exposure fiber is centered over a section of an MRR. c) Block-diagram of the setup showing the equipment used in experiments. Here FPC is fiber polarization controllers used to set transverse electric (TE) polarization. Blue arrows denote RF cables, while the green ones—fiber patch cables. d) Cross-section of a waveguide used in experiments. Here BOX is buried oxide. The parameters w and d are 600 and 385 nm for the index 2.4 SRN, respectively, while they are 450 nm and 340 nm for the index 2.9 SRN, respectively. e) Transmission spectra of the probing signal in SRN MRRs after exposure to 405 nm light. The dotted black curve indicates the initial position of resonance (reference). The numbers (and “Ref”) next to the resonances indicate the order in which the spectra were measured (starting with “Ref”). The labels describe exposure time. f) Image of MRR showing how its section is exposed (violet circle), MRR diameter is 50 μm , and ring length (L) is 170 μm . The length of one exposed section is L_{exp} .

resolution (that is the minimum feature size that can be exposed) in this setup was 10 μm , primarily limited by the beam size of the trimming light. While the SMF-28 patch cable was not optimized for 405 nm or 520 nm light, we found it suitable, with transmission losses of only 0.7 dB. No degradation in cable or laser performance was observed, even at maximum power of 16.4 dBm used in the experiments. It is worth noting that one way to improve the trimming resolution is to use a single-mode (SM) fiber specifically designed for 405 nm, such as the S405-XP, which has an MFD of 3.3 μm and is sufficient for many applications. Additionally, using a lensed 405 nm SM fiber could further reduce the size of the trimming beam.

Figure 1c demonstrates a block-diagram of the setup used in the experiments. To monitor the trimming-induced resonance shift in real time, light from an Agilent 81980A tunable

continuous-wave laser (1465–1575 nm) was coupled into the SRN samples (cross-section is shown in Figure 1d) using grating couplers. Polarization controllers were used to set polarization to transverse electromagnetic (TE) mode, and the output light was measured by a photodetector.

Figure 1e exemplifies the measured transmission spectra of the probing signal in SRN MRRs when a section of an MRR was exposed to 405 nm (as illustrated in Figure 1f; also see Supporting Information, Section S2, for more results). The results confirm that it is indeed possible to achieve both red and blue resonance shifts using a single laser source. A blue shift was observed within a few seconds of exposure while the red shift took up to 30 minutes to saturate. These results demonstrate the ability to clearly separate blue and red shifts by varying the duration of exposure, a crucial property for trimming applications.

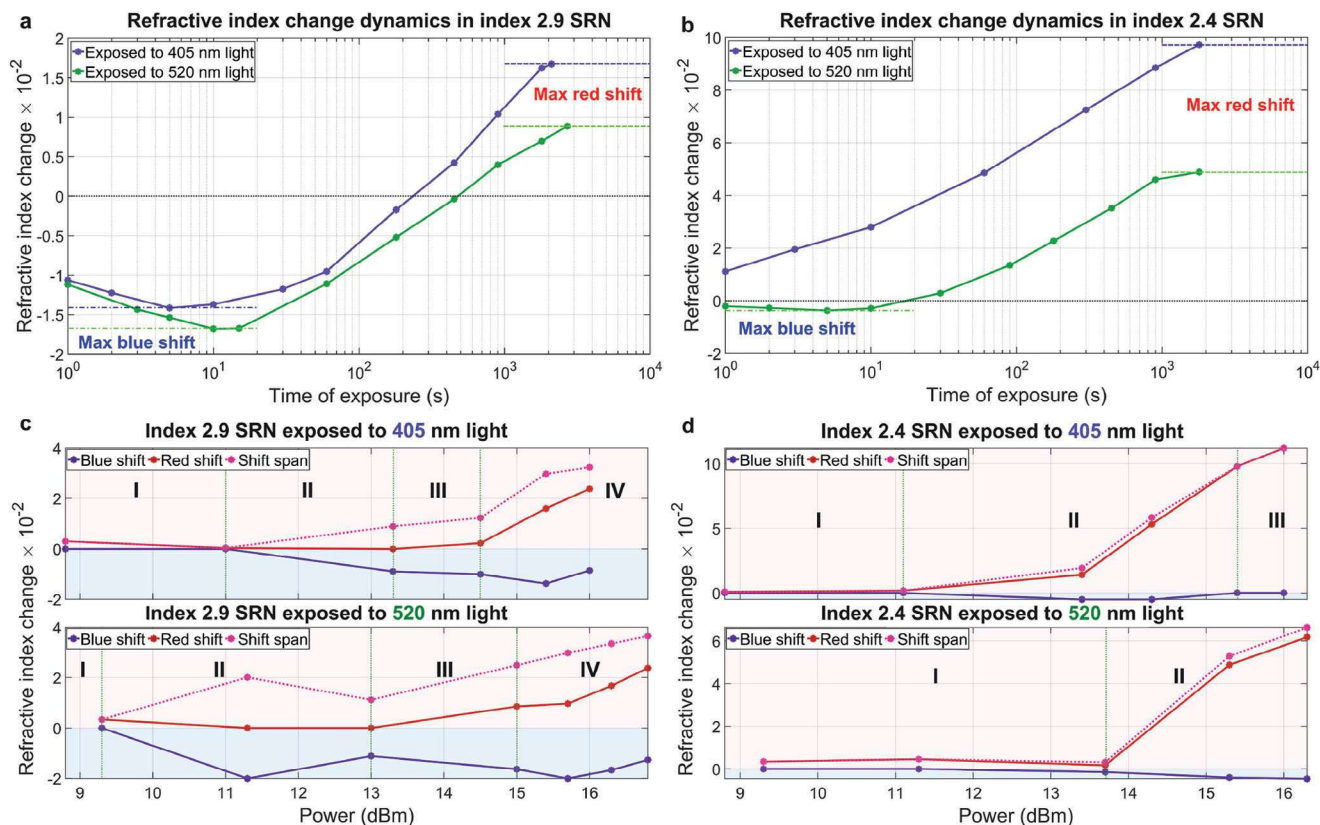


Figure 2. Dynamics of resonance shift in an SRN MRR when a) $n_{srn} = 2.9$, and b) $n_{srn} = 2.4$. The exposure power $P_{exp} \approx 15.5$ dBm; the violet curve represents exposure to 405 nm light, and the green – to 520 nm light; the dotted black line indicates no refractive index change. Refractive index change of SRN as a function of exposure power when c) $n_{srn} = 2.9$ and d) $n_{srn} = 2.4$; the upper plots represent the case when the exposure was done with the 405 nm laser, and the bottom ones – with the 520 nm laser; red and blue areas mark positive and negative refractive index changes, respectively.

2.2. Dynamics and Power Dependence of SRN Refractive Index Change

This section systematically analyzes how key parameters—such as a refractive index of (n_{srn}), exposure wavelength (λ_{exp}), optical power of exposure (P_{exp}), exposure duration (t_{exp}) – affect the trimming process. Specifically, we exposed SRN MRRs with refractive indices n_{srn} of 2.4 and 2.9 to visible radiation wavelengths of 405 nm (violet) and 520 nm (green).

The presence of both blue and red resonance shifts in MRRs demonstrates that the effective index of SRN waveguides n_{eff} can be both decreased and increased using either 405 or 520 nm lasers. The refractive index change is proportional to the resonance wavelength shift, as shown in Equations (1–3):^[39,40]

$$\Delta n_{eff} = n_g \frac{\Delta \lambda_{res}}{\lambda_{res}} \frac{L}{L_{exp}} \quad (1)$$

$$n_g = \frac{\lambda_{res}^2}{FSR \cdot L} \quad (2)$$

$$L_{exp} = \frac{\Delta \lambda_{sec}}{\Delta \lambda_{ring}} L \quad (3)$$

Here Δn_{eff} is the change of the effective index n_{eff} in an SRN waveguide, n_g is the group index, λ_{res} is the resonance wavelength of an MRR, $\Delta \lambda_{eff}$ is the resonance wavelength shift in an MRR, FSR is a free spectral range of an MRR, $\Delta \lambda_{ring}$ is the resonance wavelength shift when the whole MRR is exposed, $\Delta \lambda_{sec}$ is the resonance wavelength shift when only one section of the MRR is exposed, L_{exp} is the length of the single exposed section (see Figure 1f), L is the length of the MRR. Additionally, to estimate a refractive index change Δn_{srn} , we performed simulations in Lumerical to calculate what refractive index change Δn_{srn} is required to cause the corresponding effective index change Δn_{eff} . Based on Equations (1–3), and the resonance shift from MRRs transmission spectra (like in Figure 1e, also see Figure S2, Supporting Information), we estimated the refractive index changes. It is worth noting that L_{exp} of 10 μm was estimated experimentally (see next section) and used in Equations (1–3).

First, we investigate the SRN refractive index change dynamics measured in MRRs exposed to 405 and 520 nm light (Figure 2a,b). Only one section of an MRR was exposed in each experiment, as shown in Figure 1f. In Figure 2a, we observe the refractive index change in an SRN MRR with $n_{srn} = 2.9$ as a function of exposure time for 405 and 520 nm light. Focusing on the 405 nm case, the blue shift (due to refractive index decrease) saturates in approximately 5 s, while the red shift (due to refractive index increase) fully compensates for the blue shift in about

200 s when exposed to 405 nm light. In contrast, the red shift takes approximately 30 min to saturate. Meanwhile, both the blue and red shifts induced by the 520 nm laser follow a similar pattern, though they take slightly longer to saturate compared to the 405 nm laser. Also, stronger blue shift can be observed when induced by 520 nm laser, while strong red shift can be observed when induced by 405 nm laser (for the same power of exposure).

Similarly, Figure 2b illustrates the refractive index change in an SRN MRR with $n_{\text{SRN}} = 2.4$ as a function of exposure time for 405 and 520 nm light. This time, the difference in dynamics between the two lasers is more evident. Notably, no blue shift is observed within the first second of exposure to 405 nm light, unlike with the 520 nm laser. Additionally, a stronger red shift can be seen when an SRN MRR is exposed to 405 nm light.

The complex behavior of SRN trimming originates from the thermal annealing mechanism driving the refractive index change. We found that lower temperature annealing (400–500 °C) leads to a decrease in refractive index, while annealing at temperatures above 500–600 °C results in an increase. Notably, the refractive index reduction is significantly smaller in SRN with an index of 2.4 compared to SRN with an index of 2.9, and that agrees well with the results shown in Figure 2c,d, where it is evident that the blue shift is noticeably weaker in index 2.4 SRN. Greater details and discussion are provided in the Supporting Information, Section S3. Also, in Supporting Information, Section S6, we demonstrate that neither PECVD SiO₂ nor residual HSQ contribute to the permanent shifts observed in SRN MRRs.

It was also of great interest to investigate how exposure power affects direction of the shifts (or refractive index change) and their magnitude. Figure 2c,d shows the refractive index change in SRN measured in MRRs exposed to 405 and 520 nm light as a function of exposure power.

Based on Figure 2c, overall, we indicate 4 different sections with distinct dynamics (I – IV). In Section I, at the lowest exposure powers, we observe only weak red shift, and no blue shift. As power increases, in section II, no red shift can be observed, although noticeable blue shift can be visible. It takes 10–30 min for the blue shift to saturate. As the exposure power continues to increase, in section III, aside from a strong blue shift, the onset of the red shift can be seen. The red shift takes over only after the blue shift saturates (after about 5–15 min), and it takes the red shift about 30 min to saturate. Therefore, it is possible to separate the directions of the shifts by time of exposure, although the red shift is much weaker since both red and blue shifts partially compensate each other. Finally, section IV reveals that both strong blue and red shifts are possible. In noticeable contrast to Section III, the red shift is much stronger, although it still takes around 30 min to saturate. The blue shift, however, dominates first and takes a few seconds only to saturate, which can also be seen from Figure 2a. Therefore, it can easily be separated from the slower red shift, which results in both strong red and blue shifts, which is favorable for bidirectional trimming. Overall, a maximum refractive index increase of 2.4×10^{-2} was observed with exposure to either the 405 or 520 nm laser, while the greatest decrease, -2×10^{-2} , occurred with 520 nm laser exposure.

Figure 2d shows a different trimming behavior for $n_{sm} = 2.4$. This time up to three different sections can be highlighted. The

first section I, which corresponds to the lowest exposure powers, indicates only weak red shifts. With the increase of exposure power, in Section II, we can first observe a weak blue shift which takes a few seconds to saturate, followed by a strong red shift, which in turn takes around 30 min to saturate. In case of exposure to 405 nm light, we also indicate Section III where no blue shift could be observed, although a much stronger red shift can be seen. Remarkably, the maximum refractive index increase was 0.11, the largest ever reported, which indicates a great potential of this material for trimming. Meanwhile, the largest refractive index decrease was only -0.5×10^{-3} for both wavelengths of exposure.

We discuss the observed trend in greater detail in Supporting Information, Section S4, where we conclude that thermal annealing explains the observed behavior. Specifically, a laser beam has a non-uniform distribution of power, which results in a temperature gradient within a section of an MRR. The sections of the ring heated to 350–550 °C induce the blue shifts, while the sections heated above 550 °C – the red shifts. Here we also briefly report that in case of index 2.9, 520 nm light is favored for bidirectional trimming since it causes lower temperature gradient in a SRN waveguide, which results in a stronger blue shift (see Supporting Information, Section S4), while a stronger red shift can be achieved by simply increasing exposure power. Meanwhile, 405 nm is preferred when trimming $n_{\text{SRN}} = 2.4$ SRN MRRs since it causes a stronger red shift due to larger absorption and heating.

In summary, this complex behavior offers significant advantages for trimming. Both the direction and magnitude of the shifts, as well as the shift rates, can be finely tuned by adjusting the laser power, allowing higher power for coarse trimming and lower power for fine-tuning. This offers significant flexibility for trimming applications, depending on the specific requirements from a photonic device.

2.3. Maximizing Resonance Shift

In the previous section we established that significant refractive index changes in both directions are possible. Therefore, in this section we aim to maximize the resonance shifts, and so we exposed the whole length of SRN MRRs to both 405 and 520 nm lasers. **Figure 3a,b** exemplify the measured resonance shifts in SRN MRRs during exposure. Figure 3c demonstrates how resonances shift in the case of blue shift from Figure 3a. Meanwhile, Figure 3d,e provide illustrations which demonstrate that the whole ring was exposed by steps. Specifically, the ring was split into even sections separated by the arc length L_{step} . Another parameter, L_{exp} , is the length of the exposed section of the ring, limited by a beam size. Given that the length of the ring was 170 μm , and the number of exposed sections was 18 – 30, based on Figure 3a,b, L_{step} was in a range of 5.5 μm – 9.5 μm .

From Figure 3a, we observe a large blue shift of 10.6 nm and a red shift of 9.3 nm in index 2.9 SRN when exposed to 520 nm light. Meanwhile, from Figure 3b, a lower blue shift of 2.8 nm and the largest ever reported red shift of 49.1 nm were achieved in index 2.4 SRN when exposed to 405 nm light. Notably, blue shifts were saturated while the red shifts were not since each section of the MRR was exposed only for 10 min to expedite trimming

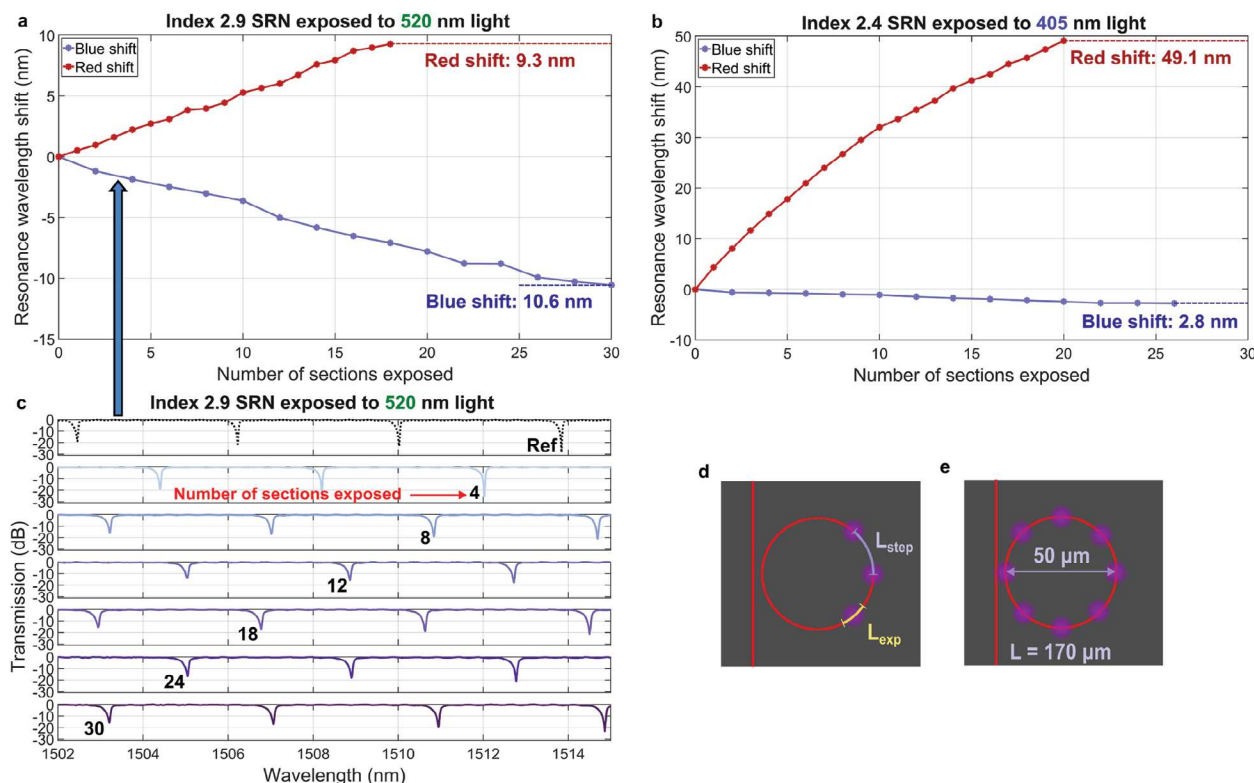


Figure 3. Resonance wavelength shifts in SRN MRRs exposed to a) 16.7 dBm of 520 nm light when $n_{srn} = 2.9$ and b) 16.0 dBm of 405 nm light when $n_{srn} = 2.4$. c) Transmission spectra of the probing signal in SRN MRR for the case of blue shift from Figure 3a. The dotted black curve indicates the initial position of a resonance (reference). The numbers next to the resonances indicate the number of sections exposed. d) Illustration of how L_{exp} and L_{step} are defined. e) Illustration of how the whole ring was exposed, where L_{step} varied in a range of 5.5–9.5 μm based on number of sections exposed.

process (it takes around 30 min for the red shift to saturate). Therefore, we conclude that the red shift can be even stronger.

It is worth noting that depth of resonances changes after exposure, as apparent from Figure 3c. It is caused by change in transmission coefficient of a coupler section of a ring and increase in optical losses. The latter is due to scattering losses stemming from non-uniform refractive index profile caused by stepped exposures (Figure 3e). We demonstrated that a significant reduction in losses is possible if the ring is exposed more uniformly, and provided greater details in Supporting Information, Section S5.

We can estimate the maximum resonance shift possible to achieve by using Equations (1–3) when the whole ring is exposed to saturation. First, we need to determine L_{exp} from Equation 3, and for that we need to measure the resonance shift $\Delta\lambda_{sec}$ when only one section is exposed (Figure 1f), and $\Delta\lambda_{ring}$ when the whole ring is exposed (Figure 3d). Since the maximum blue shift of $\Delta\lambda_{ring} = 10.6$ nm was measured in the case when $n_{srn} = 2.9$, $\lambda_{exp} = 520$ nm (Figure 3a), and $\Delta\lambda_{sec} = 540$ pm blue shift was observed when only one section of the ring was exposed (Figure S2b, Supporting Information), it was possible to estimate the exposure length: $L_{exp} \approx 10$ μm . Now it is possible to estimate $\Delta\lambda_{ring}$ since $\Delta\lambda_{sec}$ is known. For example, when $n_{srn} = 2.4$, $\lambda_{exp} = 405$ nm, we determined that $\Delta\lambda_{sec} = 3900$ pm (Figure S2c, Supporting Information), and so $\Delta\lambda_{ring} = 66.3$ nm. Both demonstrated $\Delta\lambda_{ring} = 49.1$ nm and estimated $\Delta\lambda_{ring} = 66.3$ nm are the largest among all known trimming

methods to date, proving that SRN can be trimmed in a very high range.

Table 1 summarizes the estimated maximum resonance shifts possible when the whole ring is exposed to saturation. We used the best results from Figure 2c,d, where we measured refractive index changes for different exposure powers. The shift span is achieved by subtracting $\Delta\lambda_{ring}$ for blue shift from $\Delta\lambda_{ring}$ for red shift.

As can be seen in Table 1, overall, $n_{srn} = 2.4$ SRN yields a much larger range of trimming than $n_{srn} = 2.9$ SRN, although the blue shift is much weaker. In contrast, in case of $n_{srn} = 2.9$ SRN, the blue shift can be as strong as 10.6 nm when SRN is trimmed by the 520 nm laser, which favors bidirectional trimming. Therefore, there is a tradeoff between these two cases.

We also provide Table 2, which summarizes our results and compares them with those of other research groups. We focus on the best results achieved in our work and demonstrated elsewhere for any trimming method.

While some groups have successfully achieved strong blue shifts, inducing a substantial red shift has proven particularly challenging. The largest red shift reported so far, 6.7 nm, required a CMOS-incompatible chalcogenide cladding.^[19] In contrast, our work demonstrates nearly an order of magnitude improvement in refractive index using SRN with a refractive index of 2.4. Furthermore, most studies report only unidirectional resonance shifts, with few exceptions. For instance, a bidirectional shift was achieved using HSQ cladding;^[26]

	$n_{sm} = 2.4$, $\lambda_{exp} = 405$ nm	$n_{sm} = 2.4$, $\lambda_{exp} = 520$ nm	$n_{sm} = 2.9$, $\lambda_{exp} = 405$ nm	$n_{sm} = 2.9$, $\lambda_{exp} = 520$ nm
$\Delta\lambda_{ring}$ [nm], red shift	66.3	36.6	10.9	
$\Delta\lambda_{ring}$ [nm], blue shift	3.1	2.7	6.1 ^{a)}	10.6 ^{a)}
$\Delta\lambda_{ring}$ [nm], shift span	69.4	39.3	17	21.5

however, this approach suffered from significant backshifting due to moisture absorption.^[26] Alternatively, bidirectional shifts in crystalline silicon (c-Si) have been demonstrated via ablation and amorphization using a 400 nm femtosecond laser (second harmonic of a Ti:Sa laser).^[23] This method, however, entails considerably higher trimming costs, limits precision, and was only demonstrated in uncladded samples,^[23] raising concerns about its compatibility with cladded devices. To clarify, trimming an uncladded device introduces uncertainty because the final resonance position after cladding is unpredictable. This undermines one of the primary advantages of trimming: achieving controlled and precise resonance adjustment. In summary, the bidirectional tuning capability, record-breaking red shift, CMOS-compatibility, and precise, cost-effective trimming achieved in SRN clearly underscore its exceptional performance.

It is known that the resonance shift induced by trimming may drift over time.^[26] Therefore, it was important to assess the sta-

In Figure 4a, a backshift (red shift in this case) of 240 pm was observed 35 days after exposure of the MRR where an initial blue shift of 5.5 nm was induced. This result aligns with previous reports, where long-term backshifting is commonly observed after trimming.^[26] However, the backshift is considerably smaller than the initial 5.5 nm shift, making wide-range trimming approach suitable for applications where accuracy within approximately 200 pm is acceptable.

Additionally, in one case where an initial 80 pm red shift was followed by an 800 pm blue shift, a forward shift was observed within the first 10 days instead of the expected backshift. This suggests that the red shift dominated the early back-shifting process immediately after exposure. Over time, however, the blue shift prevailed, causing the resonance to shift in the opposite

Refs.	$\Delta\lambda$ [nm], span	$\Delta\lambda$ [nm], blue and red shift	$\Delta n_{\text{srn}} \times 10^{-2}$ blue and red shift	CMOS-comp.?	Material	Method
[25]	2.5	−2.5	−	No	Chromophore-doped polymer cladding	Exposure to e-beam
[26]	3	−1 and 2	−0.4 and 0.8	No ^{a)}	HSQ cladding	Laser annealing
[24]	4.9	4.9	−	Yes	SiO ₂ cladding	Exposure to e-beam
[19]	6.7	6.7	4.8	No	As ₂ S ₃ cladding	Illumination with halogen lamp
[41]	7	−7	−	Yes	Si core implanted with Ge ions	Laser annealing
[42]	7	−7	−0.7	Yes	Nitrogen-rich SiN core	Exposure to 244 nm light
[39]	8	−8	−	Yes	a-Si core	Exposure to 405 nm light
[22]	8.7	−8.7	−	Yes	c-Si core	Oxidizing by 532 nm CW laser
[17]	9.7	−9.7	−7.5	No	Polysilane cladding	Exposure to 370 nm light
[18]	12.1	−12.1	−1.3	Yes	SiN core	Exposure to 244 nm light
[23]	16	−10.5 and 5.5	−	Yes	c-Si core	Amorphization and ablation by 400 nm femtosecond laser
This work	19.9	−10.6 and 9.3	−2 and 2.4	Yes	Index 2.9 SRN core	Annealing by 405 nm and 520 nm light
This work	51.9	−2.8 and 49.1	−0.5 and 11.2	Yes	Index 2.4 SRN core	Annealing by 405 nm and 520 nm light

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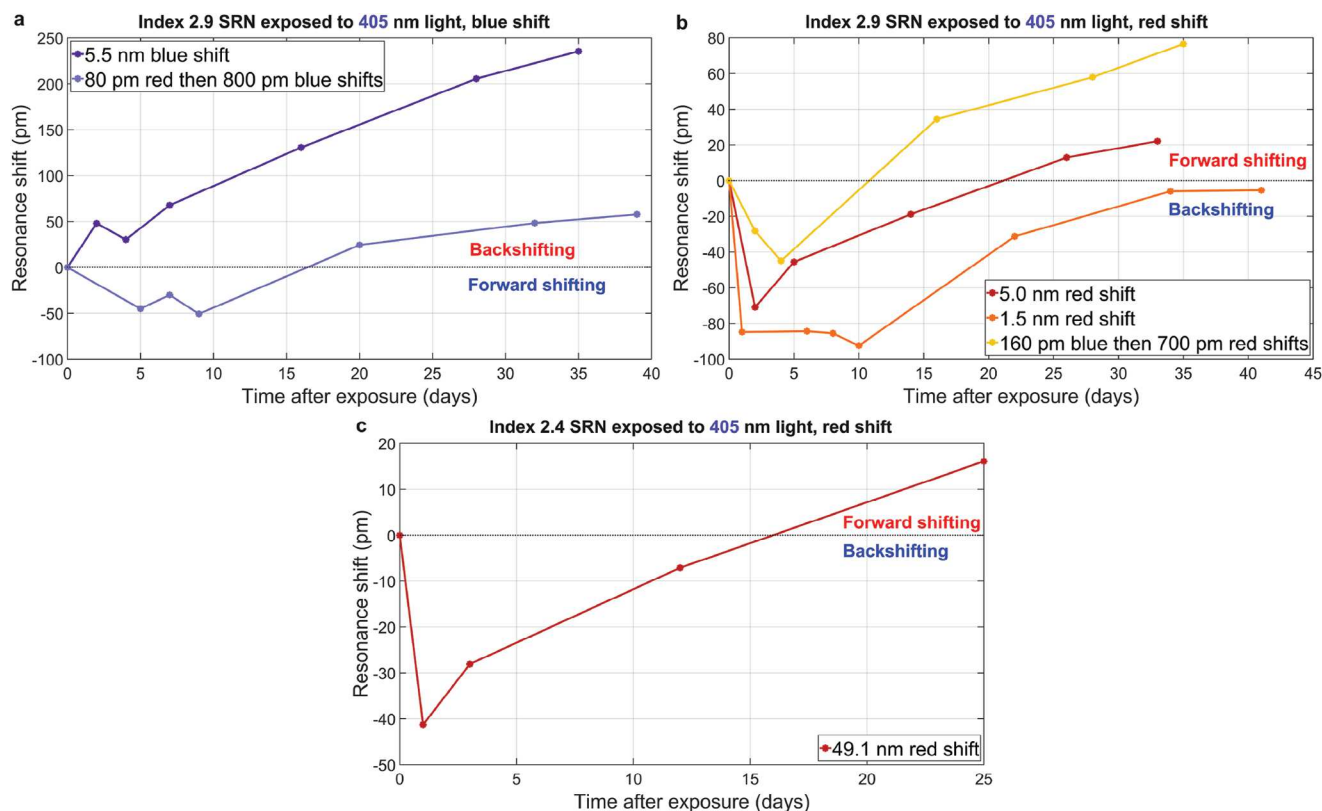


Figure 4. Resonant wavelength shift as a function of time after exposure when MRRs are exposed to 405 nm light in case of a) a blue shift, $n_{sm} = 2.9$, b) a red shift, $n_{sm} = 2.9$, c) a red shift, $n_{sm} = 2.4$. The dotted black line separates the areas of forward shifting and backshifting.

direction. This behavior suggests that red shifts tend to dominate shortly after exposure, while blue shifts have a more pronounced long-term influence.

To further support this, in another example, shown in Figure 4b, where a 1.5 nm red shift was initially induced, the resonance first back-shifted within the first 10 days, after which it reversed the direction of shifting, and gradually returned close to its original position over 41 days. Similar dynamics was observed when the initial shift was 5.0 nm, where resonance returned close to its initial position after 33 days. This demonstrates that, under certain conditions, resonance backshifting can be almost fully mitigated when a balance between red and blue shifts is achieved.

In addition, we also provide an example where a resonance was first blue-shifted by 160 pm, followed by a 700 pm red shift. In this case, the blue shift eventually prevailed, forward shifting the resonance by 80 pm without signs of saturation. This suggests that excessive blue shift may still cause significant (forward) shifts even after a red shift is induced post-exposure.

Finally, Figure 4c demonstrates that resonance relaxation dynamics at $n_{\text{SRN}} = 2.4$ is similar to that at $n_{\text{SRN}} = 2.9$. Notably, the observed instability was under 100 pm, despite an initial large red shift of 49.1 nm—highlighting the exceptional stability and suitability of SRN for trimming applications.

In conclusion, red and blue shifts coexist and drive resonance shifts in opposite directions, but they follow distinct dynamic patterns. Red shifts dominate within the first 3–10 days, while blue shifts tend to take over afterward. The stronger backshifting ef-

fects caused by blue shifts suggest that large blue shifts may be less desirable for long-term stability. However, a balanced combination of red and blue shifts can lead to resonance stabilization post-exposure.

3. Application Demonstration: Fine Trimming of a Demultiplexer

In this section, we demonstrate the benefits of bidirectional refractive index trimming. We adjust the passbands of a wavelength-division multiplexing (WDM) demultiplexer fabricated using SRN with a refractive index of $n_{srn} = 2.9$ (at 1550 nm). This example illustrates that a passband can be trimmed with the accuracy of about 10 pm, proving the effectiveness of the approach.

Figure 5a presents a microscopic image of the WDM demultiplexer used in practical trimming experiments. In addition, **Figure 5b** shows a magnified image of an MRR that was trimmed. The ring was made of four straight sections connected by four arcs with the radius of $25\text{ }\mu\text{m}$. The straight sections at the couplers' sides had the length of $16\text{ }\mu\text{m}$, while the length of the other two straight sections was $10\text{ }\mu\text{m}$. In total, the length of the ring was about $209\text{ }\mu\text{m}$.

Figure 5c,d shows the transfer characteristics of the WDM demultiplexer at a through port and one of drop ports, respectively, before and after trimming with a 405 nm laser. The objective of the trimming process was to set the passbands of the

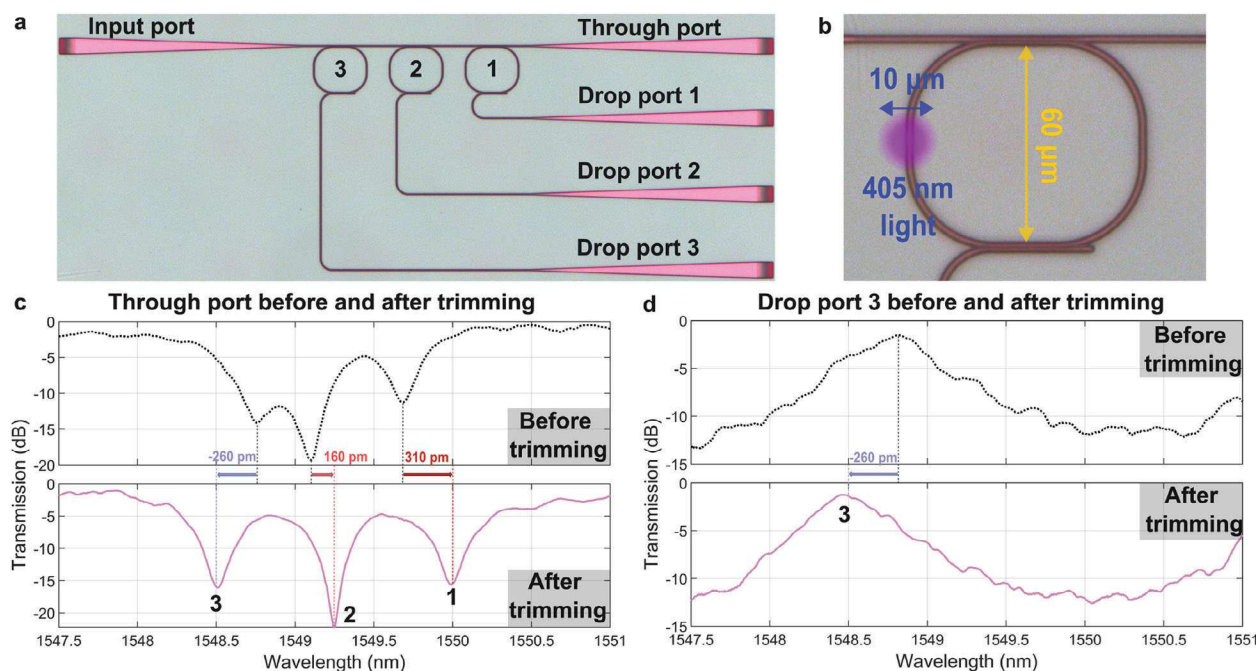


Figure 5. a) Microscope image of a fabricated demultiplexer. b) Magnified microscope image of an MRR. Transmission of the probing signal in SRN MRRs as a function of the wavelength for c) through port and d) drop port 3. The values above the arrows represent resonance shifts necessary for trimming to achieve the target. The numbers 1,2,3 represent each ring from Figure 5a.

demultiplexer at 1550, 1549.25, and 1548.5 nm such that they are separated by 750 pm. Based on Figure 5c,d, we achieved the trimming accuracy of about 10 pm. Indeed, the final resonances' positions were 1548.508, 1549.248, and 1549.988 nm, which means they were away from the targets by 8, 2, and 12 pm, respectively. Notably, the trimming technique enabled both red and blue shifts of resonances, providing a versatile method for fine-tuning the device's filtering properties. The switching of the direction and the rate of resonance shifting was enabled by changing the laser's power.

Here we highlight the importance of bidirectional shifting. Indeed, the initial position of the resonance "3" (from Figure 5c) needed to be blue-shifted by 260 pm, while the position of the resonance "2" – red-shifted by only 160 pm, and finally, a stronger red shift of 310 pm was needed for the resonance "1." If only blue shift was available, the resonances "1" and "2" would need to be blue-shifted by $\text{FSR} - \Delta\lambda_{\text{red}}$, where $\Delta\lambda_{\text{red}}$ is the resonance red shift needed. Given that typical FSR is in a range between 1 nm and 5 nm, that would require a much stronger blue shift from 850 to 4850 pm for the resonance "1." A large shift is undesirable since it will lead to stronger backshifting and increased losses.

Thus, the results confirm that the trimming approach is suitable for sophisticated photonic devices, providing the necessary precision for fine-tuning passbands in WDM applications. By leveraging the bidirectional trimming method, we can achieve enhanced performance in SRN-based integrated photonic systems.

4. Discussion

Our study demonstrates the remarkable potential of SRN as a re-configurable photonics platform, offering unprecedented control

over the refractive index through visible light trimming. The ability to achieve bidirectional resonance shifts, both blue and red, with a single laser source represents a significant advancement over most existing trimming methods, which are largely limited to unidirectional index changes. This capability opens new possibilities for dynamic tuning of phase-sensitive devices.

The observed resonance shifts, reaching up to 10.6 nm for blue shifts and a record-setting 49.1 nm for red shifts, underscore SRN's scalability and versatility across diverse photonic applications. These shifts correspond to refractive index changes of approximately -2×10^{-2} and 0.11, respectively, which are not only substantial but also finely tunable through adjustments in laser power and exposure duration. This tunability addresses a critical limitation in photonic device manufacturing by providing a means to precisely control device performance post-fabrication, effectively compensating for inherent variations.

Moreover, the coexistence of red and blue shifts provides an additional benefit: significantly reduced trimming backshifting over time, thus contributing to the long-term stability of the trimmed devices. This stabilization is particularly valuable for photonic devices where phase accuracy is critical, such as in WDM systems and other high-performance optical networks.

Our results also highlight the cost-effectiveness of this trimming approach. Unlike alternative methods that often require CMOS-incompatible materials, or expensive trimming methods, our approach uses widely available equipment and CMOS-compatible materials, positioning it as a practical solution for scaled up and industrial applications.

Additionally, the bidirectional shifting in SRN arises from its thermal annealing properties. We established that at lower annealing temperatures (400–500 °C), the refractive index decreases, while above 500–600 °C, it increases. This behavior

aligns with trimming trends, where lower power induces blue shifts and higher power causes red shifts. Also, refractive index reduction is more pronounced in higher-index SRN during rapid thermal annealing, matching observations in trimming, where higher-index SRN undergoes larger blue shifts. Furthermore, thermal simulations revealed that SRN can be heated to temperatures exceeding 1000 °C using only 16 dBm of CW 405 nm laser radiation. This is attributed to its exceptionally low thermal conductivity, which facilitates effective heat localization during laser trimming. Therefore, the simulation results confirm that it is possible to induce both red and blue shifts during trimming. Overall, these findings suggest that trimming behavior can be effectively predicted by thermal simulation and annealing SRN thin films at different temperatures and measuring refractive index changes, which is a much faster and cheaper alternative to fabricating SRN waveguides.

As it has been discussed previously, subjecting SRN to rapid thermal annealing (RTA) at elevated temperatures (typically above 600 °C) results in the dissociation of Si–H bonds, substantial hydrogen (H) desorption, a reduction in nitrogen (N) content, and an increase in the concentration of Si–Si.^[34–36] On the other hand, studies indicate that RTA at lower temperatures (below 600 °C) promotes bond redistribution (Si–Si, Si–N, Si–H, N–H), leading to a rise in Si–H and Si–N bond concentrations while decreasing N–H and Si–Si bond concentrations.^[34,35] In our study, we also observed a noticeable change in behavior when RTA temperatures exceeded 600 °C. Based on these findings, we hypothesize that the refractive index reduction at <600 °C is due to bond redistribution which results in increased Si–H and Si–N bond formation, while the refractive index increase at >600 °C results from significant H desorption due to Si–H bond dissociation, and nitrogen reduction.

While both 405 and 520 nm lasers enable bidirectional trimming as both wavelengths are absorbed by SRN, generating heat, it is important to acknowledge that 520 nm light is preferred for index 2.9 SRN bidirectional trimming since it causes a stronger blue shift. It was demonstrated that this is due to lower absorption resulting in lower temperature gradient, which was proven to favor blue shift. Meanwhile, in SRN with a refractive index of 2.4, red shifts are noticeably smaller under 520 nm exposure due to its much lower absorption (extinction coefficients are 0.44 for 405 nm and 0.08 for 520 nm), resulting in less heating, so 405 nm light trimming is preferred.

We also would like to compare our trimming approach to widely used heaters. First, the primary advantage of fiber-based laser trimming is cost efficiency. The one-time cost of setting up the trimming process—including fiber and diode lasers—is minimal compared to the recurring fabrication costs of heaters. Furthermore, heaters require continuous energy input to maintain resonance tuning, whereas laser trimming is a one-time adjustment (e.g., to set the resonance wavelength of a microring resonator), after which no further energy is needed. Another key benefit of laser trimming is its bidirectional tuning capability, unlike heaters, which are generally limited to red-shifting. Additionally, packaging of trimming fibers is not required since trimming is performed only once (e.g., by scanning the trimming fiber's position), and the fibers can be removed afterward.

On the other hand, heaters excel in scenarios requiring large-scale integration due to their scalability. They allow for

real-time tuning of resonance positions, enabling dynamic modulation or switching. Moreover, heater technology is well-established and widely adopted in CMOS foundries, making it a reliable and standardized solution for integrated photonics.

Ultimately, both approaches have their practical uses and complement each other rather than compete. In fact, combining the two methods can provide an optimal solution. For instance, laser trimming can be employed to permanently adjust the resonance position close to its target value, while heaters can be used for fine-tuning, modulation, or switching. This combination significantly reduces the power required for heaters, as they only need to compensate for small perturbations caused by environmental factors, such as temperature fluctuations. Thus, integrating both methods enhances the overall functionality and efficiency of photonic devices.

Finally, we identify new applications for SRN in integrated photonics. For example, SRN shows promise as a CMOS-compatible coating for silicon-on-insulator (SOI) platforms, enabling bidirectional tuning through visible light exposure. Its capacity for a significant refractive index increase also suggests potential for creating etch-free SRN waveguides using visible light, which could reduce fabrication costs and minimize scattering losses due to the absence of etched sidewalls.

In conclusion, this work establishes visible light trimming of SRN as a powerful, flexible tool for photonic device optimization. The demonstrated bidirectional tuning capability, coupled with its precision, cost-effectiveness, and stability, positions SRN as a key material for the next generation of integrated photonics. Future research should explore extending this technique to other photonic architectures, potentially broadening the range of applications and further refining the precision and scalability of SRN-based devices.

5. Materials and Fabrication Process

The fabrication process of PECVD SRN MRRs began with the removal of the silicon device layer from silicon-on-insulator (SOI) substrates using tetramethylammonium hydroxide (TMAH) wet etching, leaving only a 3 µm buried oxide (BOX) layer on top of a 700 µm Si substrate (note that this step can be skipped if Si samples with only SiO₂ layer on top are available). Next, PECVD SRN films were deposited in an Oxford Plasmalab PECVD system at a temperature of 350 °C and a pressure of 650 mTorr. The SiH₄ and N₂ precursor gases were introduced at flow rates of 80 and 800 sccm, respectively, for the 2.4 refractive index film, and 450 and 200 sccm for the 2.9 refractive index film. Following deposition, hydrogen silsesquioxane (HSQ) e-beam resist was spun onto the SRN films, and electron-beam lithography was used to define the waveguide patterns. After developing the HSQ resist, the SRN films were etched in a Plasma-Therm ICP-RIE system, and the HSQ was subsequently removed using a 6:1 buffered oxide etch (BOE) diluted with deionized water in ratio 1:20. Complete removal of the HSQ resist was confirmed by measuring the remaining waveguide thickness with a stylus profilometer. The samples were then clad with a 2 µm PECVD SiO₂ layer, also deposited using the Oxford Plasmalab PECVD system.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

D.B. assembled a setup, performed most experiments, processed data, determined the direction of research. M.D. fabricated samples and assisted with experiments. K.J. assisted with experiments, manuscript preparation, exchanged ideas. V.F. and A.G. assisted with manuscript preparation, discussed ideas. N.A., A.N., P.K.L.Y., and Y.F. assisted with manuscript preparation, exchanged ideas, provided funds and equipment.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Keywords

integrated photonics, laser annealing, optical trimming, silicon nitride, tunable optical material

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