UV trimming of Polarization-independent Microring Resonator by Internal Stress and Temperature Control

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Abstract: The temperature dependence of the resonant wavelength of vertically coupled microring resonator can be controlled via internal stress caused by the thermo-optic and photo-elastic effects. In the case of strong internal stress, a polarization-independent microring resonator can be realized by controlling the device surface temperature using a heater module; the temperature dependence of TE and TM polarizations are different due to the internal stress and thus manipulating temperatures, the resonant wavelengths for TE and TM can be equalized at a specific temperature. In this study, the UV trimming of polarization-independent wavelength was demonstrated using UV-sensitive SiON as a core material. The temperature dependence of TE polarization was almost athermalized and that of TM was made negative by controlling internal stress. As a result, the simultaneous realization of the UV trimming and the polarization-independent microring was made possible more easily than before; the UV trimming can be done at room temperature due to the athermalized resonant wavelength for TE polarization.

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References and links
1. S. T. Chu, B. E. Little, W. Pan, T. Kaneko, S. Sato, and Y. Kokubun, “An eight-channel Add/Drop filter using vertically coupled microring resonators over a cross grid,” IEEE Photon. Technol. Lett. 11, 691–693 (1999).
2. D. V. Tishinin, P. D. Dapkus, A. E. Bond, I. Kim, C. K. Lin, and J. O’Brien, “Vertical resonant couplers with precise coupling efficiency control fabricated by wafer bonding,” IEEE Photon. Technol. Lett. 11, 1003–1005 (1999).
3. H. Takahashi, Y. Hibino, and I. Nishi, “Polarization-insensitive arrayed-waveguide grating wavelength multiplexer on silicon,” Opt. Lett. 17, 499–501 (1992).
4. N. Kobayashi, N. Zaizen, and Y. Kokubun, “Athermal and polarization independent microring resonator filter by stress control,” Jpn. J. Appl. Phys. 46, 5465–5469 (2007).
5. Y. Kokubun, H. Haeiwa, and H. Tanaka, “Precise center wavelength trimming of vertically coupled microring resonator filter by direct UV irradiation to ring core,” in proceedings of IEEE/LEOS Annual Meeting (IEEE/LEOS, Glasgow, U.K., 2002), pp.746–747.
6. H. Takahashi, K. Oda, H. Toba, and Y. Inoue, “Transmission characteristics of arrayed waveguide N N wavelength multiplexer,” J. Lightwave Technol. 13, 447–455 (1995).
7. Y. Kokubun, N. Funato, and M. Takizawa, “Athermal waveguides for temperature independent lightwave devices,” IEEE Photon. Technol. Lett., 5, 1297–1300 (1993).
8. Y. Namihira, M. Kudo, and Y. Mushiake, “Effect of Mechanical Stress on the Transmission Characteristics of Optical Fiber,” IEICE Trans. Electron. J60-C, 391–398 (1977) [in Japanese].
9. A. J. Moses, Handbook of Electrical Materials, Vol.1, (New York, IFI/Prenum, 1971), p.68.

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1. Introduction

We have proposed and demonstrated a vertically coupled microring resonator (VCMRR) as a wavelength add/drop multiplexer in the next generation dense WDM networks, which has many desirable features such as functionality, compactness and potential for dense integration using a cross-grid configuration [1, 2]. However, there remained two problems: polarization dependence and the fabrication error when achieving resonant wavelength.

For optical waveguide filters, there are two methods to solve the first problem. One is a method using half-wave plate inserted in the midpoint of the optical path of the device, which was adopted for the arrayed waveguide grating (AWG) filter [3]. However, this method is difficult to apply to ultra compact photonic devices such as microring resonators of several tens microns in radius, because the thickness of \( \lambda/2 \) plate is as large as ten microns. Another method is to control the aspect ratio of waveguide cross section. However, this method is also difficult to apply to high index contrast waveguide devices such as microring resonators allowing only small tolerance. In addition, the second problem still remains, i.e. compensating for the discrepancies between the designed and fabricated values of the polarization independent resonant wavelengths. In order to solve the second problem, we proposed and demonstrated a UV trimming technique using a UV-sensitive SiON film as a core.

In our previous report [4], we demonstrated a novel method to realize polarization-independent microring resonator controlling internal stress and temperature. When the microring resonator involves strong internal stress inside the core, the temperature dependence of resonant wavelength can be controlled by the combination of the thermo-optic and photo-elastic effects[4]. Utilizing the differences of the temperature dependence of resonant wavelengths for TE and TM polarizations, both TE and TM resonant wavelengths can be equalized by controlling surface temperatures of the device. However, the UV trimming technique was difficult to apply to this polarization independent microring resonator, because a sputter deposited Ta2O5-SiO2 (n=1.785 @ \( \lambda=1550\text{nm} \)) core was used – the UV sensitivity of Ta2O5-SiO2 is very small[5]. To solve this problem, a polarization-independent microring resonator is fabricated using a UV-sensitive SiON core. However, the control method of the temperature dependence of resonant wavelength has not been developed, since the SiON film is deposited by a plasma-enhanced chemical vapor deposition (PECVD) which makes the internal stress of films much smaller than that of films deposited by RF sputtering.

In this report, we describe the experimental study of the relationship between the temperature dependence of resonant wavelength and the initial internal stress, and demonstrate the realization of UV trimming of polarization-independent SiON microring resonator by controlling internal stresses and temperatures. The device is athermalized for TE mode. This method is effective to realize the polarization independent filter using high index contrast optical waveguide and can compensate for fabrication-originated error for achieving the designed value of polarization-independent wavelength.

2. Modeling of non-linear photo-elastic effect

When the internal stress is negligibly small, the photo-elastic effect can be ignored. The temperature coefficient of resonant wavelength \( \frac{d\lambda_0}{dT} \) of silica-based waveguide filter is around
0.01 nm/K [6], which is determined by the temperature coefficients of refractive index of core and cladding materials and the thermal expansion coefficient of substrate [7]. For SiON core device, the temperature dependence is almost the same as that of the silica-based devices.

However, when the internal stress is too strong to be ignored, the refractive index of core layer is affected by both thermo-optic and photo-elastic effects. If the photo-elastic effect of silica-based materials with strong internal stress exceeds the thermo-optic effect, the temperature dependence of resonant wavelength can be tuned by controlling internal stress [4].

The photo-elastic constant of most silica-based glass materials is negative [8]. Furthermore, the thermal expansion coefficient of silica glass is $0.55 \times 10^{-6}$ [1/K] [9], which is smaller than that of Si substrate ($2.63 \times 10^{-5}$ [1/K] [10]). Therefore, if the intrinsic internal stress in the core layer is compressive, the stress increases with temperature due to the thermal expansion difference between the core and the substrate - the direction of stress is opposite to that induced in the substrate at the boundary between the bottom of core layer and the top of substrate.

According to our preliminary experiment, the photo-elastic effect was found to be controlled by the internal stress inside the waveguide core [4]. To explain this phenomenon, we assumed non-linear Young’s modulus, which is known as the stress stiffening effect.

![Fig. 1. Modeling structure of photo-elastic effect.](image)

First, let us define the coordinate system as shown in Fig. 1. According to the experimental results, the temperature dependence of resonant wavelength for TM mode was strongly affected by the internal stress. To explain this experimental result, we assume that the Young’s modulus in the $x$ direction be largely affected by the internal stress induced in the direction parallel to the film as expressed in Eqs. (1) and (2).

$$E_x = (1 + k_x \sigma_x)E$$  \hspace{1cm} (1)

$$E_y = (1 + k_y \sigma_y)E$$  \hspace{1cm} (2)

where $E_x$ and $E_y$ are the Young’s modulus for $x$ and $y$ directions, $k_x$ and $k_y$ are the non-linear coefficient, $\sigma_x$ and $\sigma_y$ are the internal stress and $E$ stands for original Young’s modulus ($= 72$ GPa for silica glass [11]). These equations indicate an intuitive condition that when the initial
stress in parallel direction is unusually strong, the stress in the perpendicular direction needs to be changed to much greater extent than in the parallel one.

The relationship between the change in refractive index $\Delta n$ and the stress is expressed by the following equation known as the photo-elastic effect\[8\].

$$\Delta n = C_1 \sigma_{//} + C_2 \sigma_{\perp}$$

(3)

where $\sigma_{//}$ and $\sigma_{\perp}$ are the stresses in the parallel (horizontal) and perpendicular (vertical) directions to the substrate, respectively, and $C_1$ and $C_2$ stand for the photo-elastic coefficients for horizontal and vertical axes, respectively. $C_1$ and $C_2$ for SiO$_2$ are $-5.00 \times 10^{-13}[1/Pa]$ and $-3.00 \times 10^{-13}[1/Pa]$, respectively\[8\].

The relationship between Young’s modulus and the stress $\sigma$ is expressed by,

$$\sigma = \varepsilon E \cdot \delta T = (\alpha_{\text{sub}} - \alpha_{\text{core}})E \cdot \delta T$$

(4)

where $\varepsilon$ is the strain per degree, $\delta T$ is the temperature change, $\alpha_{\text{sub}}$ and $\alpha_{\text{core}}$ are the coefficients of thermal expansions of the substrate and the core, respectively.

In our assumption, $\sigma_x$ is negligibly small ($\sigma_x = 0$) because the surface of the film is open to the air cladding. This assumption is usually appropriate for such a device. Then, we obtain the following equations by introducing the non-linear Young’s modulus Eqs.(1) and (2) into the above equation of photo-elastic effect Eq.(3).

$$\Delta n_x = C_1 \sigma_x + C_2 \sigma_y$$

(5)

$$\Delta n_y = C_2 \sigma_x + C_1 \sigma_y$$

(6)

We can roughly estimate the nonlinear Young’s modulus considering the fact that when the temperature dependence of resonant wavelength is almost zero, the internal stress is around 1 GPa\[4\]. Therefore, estimating the value of nonlinear coefficient from experimental values ($k_y = 2.31 \times 10^{-8}$), we can obtain the experimental relationship between the initial stress and the change of refractive index as shown Fig. 2 using Eqs.(4), (5) and (6).

In Fig. 2, the horizontal axis shows initial stresses, the left vertical axis the stress changes, and the right vertical axis the changes of refractive index. This figure indicates that stress change increases with internal stress and the change of refractive index gets sharper as the stress change does. When the initial stress is smaller than $10^8$ Pa, the change of refractive index is smaller than that of thermo-optic effect. However, when the initial stress is in the order of $10^9$ Pa of magnitude, the change of refractive index is greater than that of thermo-optic effect. In fact, in our experimental results, the devices with strong internal stress showed the negative temperature dependence of resonant wavelength as shown in Fig. 3. The device was the same as described in section 3 (Fig.5). The width and thickness of busline waveguide were 1.5 $\mu$m and 0.8 $\mu$m, respectively, and those of ring waveguides were 1.5 $\mu$m and 0.8 $\mu$m, respectively. The ring radius was 50 $\mu$m. However, after annealing at 1160 °C, the temperature dependence of resonant wavelength of the same devices turned positive. This phenomenon is considered to be an evidence of the model, i.e., the internal stress disappears by annealing and the temperature dependence of resonant wavelength is controlled by the thermo-optic effect only.

3. Fabrication of vertically coupled microring resonator

The fabrication process is shown in Fig.4. A 76.2mm (3 inch) φ Si wafer was used as a substrate and a 4 $\mu$m thick thermally grown SiO$_2$ (n=1.445 at $\lambda=1550$nm) was used as a lower
Fig. 2. Experimental relation between initial stress and photo-elastic effect.

Fig. 3. Temperature dependences of SiON core microring resonator before and after annealing.
cladding under the busline waveguide. Both ring and busline waveguide cores were made of SiON (n=1.780 at λ=1550nm) using plasma-enhanced chemical vapor deposition (PECVD) method, the lower cladding of upper microring resonator was sputter deposition SiO2 (n=1.452 at λ=1550nm) and the upper cladding air. The target size was 152.4mm (6 inch) φ and the RF power was 1.0kW. In order to bury the busline waveguide with flat top surface, we used the lift-off process by SOG (Spin-on Glass)[12]. The waveguide pattern was formed by a conventional photo-lithography technique and reactive ion etching (RIE) using C2F6 gas (pressure: 0.5Pa, RF power: 20W). The internal stress is mainly induced in the deposition process of the waveguides core.

![Fabrication processes of vertically coupled microring resonator.](image)

Fig. 4. Fabrication processes of vertically coupled microring resonator.

The structure of vertically coupled microring resonator is shown in Fig. 5. The width and thickness of busline waveguide were 1.2μm and 0.8μm, respectively, and those of ring waveguides were 1.2μm and 1.0μm, respectively. The ring radius was 30μm. The bending loss of 30 μm ring radius was calculated to be less than 0.01dB/round, which corresponds to the propagation loss per one round-trip length of microring resonator. The buffer layer thickness tsep between busline and ring waveguides was 0.4 μm, and the over etching depth toe to the buffer layer was 0.2 μm.
4. UV trimming of polarization-independent microring resonator via temperature control

4.1. Principle of UV trimming of polarization independent wavelength

The temperature dependence of the resonant wavelengths for TE and TM polarizations before UV trimming are shown by the upper curves in Fig. 6. The temperature dependence of the resonant wavelength was successfully athermalized for TE polarization, while that for TM polarization remained negative before UV trimming. Although the internal stress of films deposited by PECVD was considered much smaller than that of films deposited by an RF sputtering, the possibility of the controlling temperature dependence via internal stress was demonstrated by this experimental result. The resonant wavelength of TM mode is longer than that of TE mode and the temperature dependence of TE and TM polarizations are different due to the internal stress. Therefore, the resonant wavelengths for both polarizations can be equalized at a certain temperature. However, the polarization-independent resonant wavelength is generally different from the designed value due to the fabrication error.

Thus, we tried the UV trimming of the polarization-independent wavelength. Since the temperature dependence of TE mode is athermalized in this device, it only requires adjusting the resonant wavelength of TE polarization to a designed value at room temperature. After the UV trimming of resonant wavelength for TE mode, the polarization-independent microring resonator can be realized again at the designed wavelength by controlling device temperatures. In this process, since the UV trimmed resonant wavelength for TE mode is athermalized, the polarization-independent resonant wavelength can be obtained at the same wavelength as the UV trimmed wavelength.

4.2. UV trimming of polarization-independent wavelength via temperature control

The temperature dependences of resonant wavelengths for TE and TM polarizations after UV trimming are also shown by the lower curves in Fig. 6. Before the UV trimming, the wavelength of TM mode at room temperature was longer than that of TE mode and the temperature dependence of TE mode was almost athermalized. The polarization-independent wavelength is approximately 1551 nm at around 60 °C. Then after 5 minute UV trimming, the resonant wavelengths for both polarizations at room temperature were shifted to a shorter wavelength by 1nm. The wavelength of UV lamp was 254 nm and the power density was 42.6 mW/cm². Although a small difference was observed between the temperature dependences for TE and TM polarizations before and after the UV trimming, the difference is within the measurement error. The temperature dependence for TE mode is also athermalized after the UV trimming and the polarization-independent wavelength is evaluated to be approximately 1550 nm at around 60 °C after UV trimming.
The spectrum responses of TE mode before and after UV trimming are shown in Fig. 7. By the precise temperature control, the wavelengths for both polarizations were equalized at 64°C as shown in Fig. 8. Thus we successfully realized the UV trimming of polarization independent microring resonator by controlling internal stress and temperature. The difference between the 3dB bandwidths of the filter responses of TE and TM polarizations is caused by the difference of the propagation loss in the microring resonator for TE and TM polarizations.

4.3. Enhancement of Thermo-optic coefficient by controlling geometrical parameter

We fabricated a vertically double series coupled microring resonator, in which two ring resonators were stacked on the busline waveguide as shown in Fig. 9. In the coupling region
between ring resonators, the spacing between ring waveguide is limited to 1.0\(\mu\)m due to fabrication limit of photo-lithography. However, since the refractive index of air gap is too small for appreciable coupling with the 1.0\(\mu\)m gap, it was difficult to achieve coupling efficiency of 0.03-0.06 required for the box-like filter response. Therefore, we adopted a ridge channel core as shown in the inset of Fig. 10. The coupling efficiency was analyzed using a Finite-Difference mode solver (APSS by Apolo Optics inc.) for various ridge heights. The calculated results are shown in Fig. 10. It is seen from this figure that the coupling efficiency can be controlled by thickness of ridge height.

Using this design data, we fabricated a double series coupled microring resonator. The width and thickness of busline waveguide were 1.2\(\mu\)m and 0.8\(\mu\)m, respectively, and those of ring waveguide were 1.2\(\mu\)m and 0.8\(\mu\)m, respectively. The distance between ring resonators was 1.0\(\mu\)m and the ridge height of the ring resonator was 0.2\(\mu\)m to realize a desirable coupling efficiency. The ring radius was 30\(\mu\)m and the length of straight waveguide was 100\(\mu\)m. The
bending loss of 30 μm ring radius was calculated to be less than 0.01dB/round. The free spectral range was evaluated to be about 4nm. The temperature dependences of resonant wavelengths of channel core and ridge core microring resonators are shown in Fig. 11. The channel core microring resonator is the same device described in the previous section. The temperature dependence of resonant wavelength of ridge core is about six times greater than that of channel microring resonator due to a strong residual internal stress resulted from the remaining thin (0.2μm) layer of core material. The difference of the temperature dependence of resonant wavelength between TE and TM modes is much smaller than that of stress-induced conventional microring resonator. The control of the temperature dependence of resonant wavelength for both polarizations can be realized by varying the ridge height of waveguide.

Fig. 10. Coupling efficiency of ridge core.

Fig. 11. Resonant wavelength shift of channel core and ridge core microring resonator.
5. Conclusion

We described the theoretical consideration of relationship between the temperature dependence of resonant wavelength and the initial internal stress by introducing the nonlinear Young’s modulus, and demonstrated the UV trimming of polarization-independent SiON microring resonator by the internal stress and the temperature control. The device was athermalized for TE mode. This method is effective to realize the polarization-independent filter using high index contrast optical waveguide and can compensate for the fabrication error so as to attain the designed value of polarization independent wavelength. By adopting the ridge core into microring resonator, the control of temperature dependence of resonant wavelength of both polarizations can be realized by varying the ridge widths of waveguide core.

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