Wide-range tuning of polymer microring resonators by the photobleaching of CLD-1 chromophores

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Received July 6, 2004

We present a simple and effective method for the postfabrication trimming of optical microresonators. We photobleach CLD-1 chromophores to tune the resonance wavelengths of polymer microring resonator optical notch filters. A maximum wavelength shift of -8.73 nm is observed. The resonators are fabricated with a soft-lithography molding technique and have an intrinsic Q value of 2.6×10^4 and a finesse of 9.3. The maximum extinction ratio of the resonator filters is -34 dB, indicating that the critical coupling condition has been satisfied.

OCIS codes: 230.5750, 160.5470, 130.2790.

Microring resonators are becoming an important technology as they find applications in the realization of highly compact optical devices, such as filters, modulators, and multiplexers and demultiplexers.[1–5] A central issue with microring resonators, as well as with other microresonators, is the need for strict fabrication tolerances for several reasons. First, the resonance wavelengths are highly sensitive to the optical path lengths in the resonators. Second, the evanescent field coupling between a resonator and another resonator or a waveguide is strongly dependent on the spatial separation between the two structures. In the absence of any means to modify the resonators, fabrication resolution in the tens of nanometers range is required. Therefore, for many practical applications, postfabrication trimming or tuning of the resonators would be desired or even required to shift the resonance frequencies or to adjust the coupling ratios to the operational values.

In recent years, polymeric integrated optical devices, including microring resonators, have attracted much attention due to potentially low material and production costs. Furthermore, the development of low-loss and optically nonlinear polymers allows for the realization of both passive and active high-performance polymeric optical devices.[6,7] In particular, polymers provide a promising material platform for the fabrication of microring resonators since many tuning mechanisms are available. For example, electro-optic and thermo-optic tuning of microring resonators was recently demonstrated.[3,8] UV trimming of ring resonators using polymers was also demonstrated through changing the refractive index of polymer cladding layers.[9,10]

In this Letter we use a simple and fast method to trim high-Q, critically coupled polymer microring resonators. Using a soft-lithography replica-molding method,[11–13] we fabricated high-performance microring notch filters in a polymer doped with a nonlinear electro-optic chromophore, CLD-1.[6,14] The trimming is accomplished by photobleaching the CLD-1 chromophores. Photobleaching of electro-optic chromophores was previously used to tune the splitting ratio of a Y junction and to fabricate polymer waveguides.[15–17] However, photobleach trimming of high-Q microring resonators, which is a highly sensitive process and is also of crucial importance in microresonator technology, has not been previously demonstrated.

The microring notch filter consists of a ring resonator coupled to a waveguide as shown in Fig. 1. As described in Ref. 18, at the resonances the transmitted

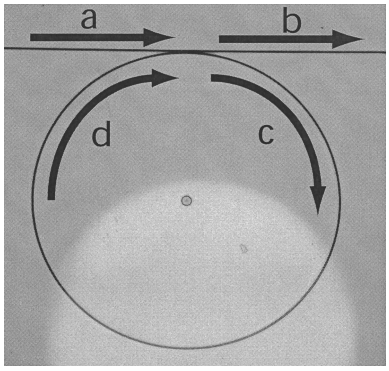

Fig. 1. Optical micrograph of a photobleached resonator filter. The ring resonator notch filter consists of a waveguide coupled to the microring. The electric fields are labeled. The photobleached spot is the lighter region in the figure. The unphotobleached polymer is green and is the darker region in the figure.

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light is attenuated. With the notation in Fig. 1 the transfer function of the filter is described by[18]

$$\left|\frac{b}{a}\right|^2 = \frac{|t|^2 - 2\alpha|t|\cos(2\beta\pi R) + \alpha^2}{1 - 2\alpha|t|\cos(2\beta\pi R) + \alpha^2|t|^2}, \quad (1)$$

where κ is the dimensionless length-integrated coupling coefficient, $|\kappa|^2 + |t|^2 = 1$, α is the field attenuation constant in the ring, β is the propagation constant, and R is the ring radius. If the critical coupling condition is satisfied, wherein $\alpha = t$, the transmitted light will be completely extinguished at the resonance wavelengths.[18,19] Therefore critically coupled ring resonators are ideal for compact notch filters with high extinction ratios.

We fabricate microring resonators in polymer using a soft-lithography replica-molding technique. The details of the fabrication process are described elsewhere.[12,13] Soft-lithography replica molding is a powerful technique since it does not affect the dopant molecules in the polymer, allowing for a wide variety of dopants to be introduced into the polymer matrix. In this experiment the polymer solution from which we mold the devices consists of 5.5 wt.% of CLD-1/amorphous polycarbonate (APC) in trichloroethylene/dibromomethane. The CLD-1:APC ratio is 1:4 by weight, and the solvent consists of trichloroethylene and dibromomethane in a 50% ratio by volume. The resonators are molded directly on a silica-on-silicon substrate. The thickness of the thermally grown silica is 5 μm. The fabricated ring resonator has a radius of approximately 207 μm, and the thickness and width of the waveguides are approximately 1.6 and 1.4 μm, respectively. The residue layer thickness from the molding is approximately 130 nm. The waveguide–resonator gap is 430 nm.

To trim the resonator, we focus broadband visible light onto a section in the lower half of the ring resonator in ambient conditions. The illumination intensity can be varied, and the exposure area can be changed by the use of different objective lenses. The transfer characteristics of the resonator are recorded after exposure at fixed time intervals with a tunable laser. The input laser power is set to 0.1 μW to prevent additional photobleaching from the laser source during the measurement. The photobleached ring resonator is shown in Fig. 1. The photobleached region is transparent, whereas the original polymer film is green.

Figure 2 shows the total shift of the resonance wavelength as a function of exposure time for an exposure intensity of 26 mW/cm^2 over a 0.12-mm^2 area. The experimental data are curve fitted with an exponential model with excellent agreement. At the initial stages of photobleaching, the fractional index change ($\Delta n/n$) and resonance wavelength shift vary approximately linearly with exposure time at a rate of -2.3×10^{-6}/s and -3.6×10^{-3} nm/s, respectively. We observe a shift of -8.73 nm after approximately 1.75 h of exposure, although the exponential fit suggests a maximum wavelength shift of -9.8 nm or a fractional index change of -6.3×10^{-3} should be possible. At long exposure times, the filter 3-dB bandwidth can be broader than that at $t = 0$ by approximately 20%. The decrease in the loaded Q factor, Q_L, can be caused by a slight decrease in the index at the coupling region over time and also a slight change in the loss of the resonator induced by the photobleaching of the chromophores.

Figure 3 shows the transfer characteristics after different exposure times for an illumination intensity of approximately 34 mW/cm^2 over an area of 0.28 mm^2. The resonance peaks were shifted by approximately 0.2 nm from each other. The width of the notch is essentially maintained as the resonance is shifted. For the device the loss and refractive index vary with the photobleaching such that the extinction ratio increases from -15 to approximately -35 dB, indicating that the critical coupling condition is more closely satisfied. The device has a 3-dB bandwidth of 0.12 nm, a free spectral range of 1.11 nm, and hence a loaded quality factor Q_L of approximately 1.3×10^4 and a finesse

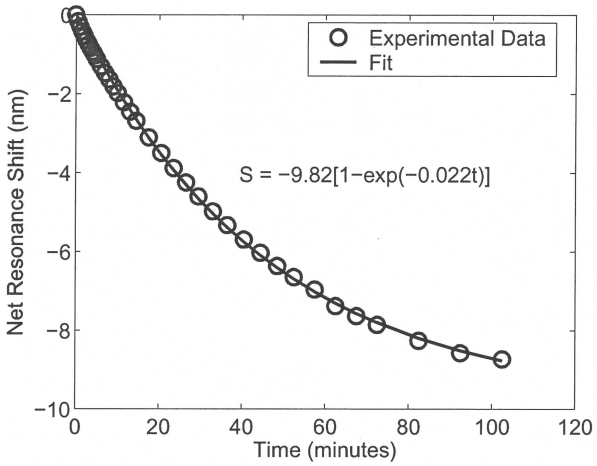

Fig. 2. Net resonance wavelength shift as a function of exposure time. The exposure intensity is approximately 25 mW/cm^2 over a 0.12-mm^2 area. The experimental data are fitted with an exponential function as indicated. S is the shift in wavelength in nanometers; t is the exposure time in minutes.

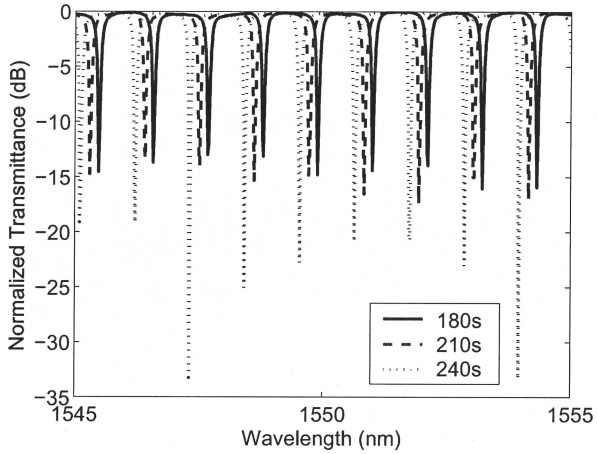

Fig. 3. Tuning of the microring resonances. The transmission spectra are for TE-polarized light after certain exposure times. The resonances shift by approximately -0.2 nm after each 30-s exposure with a light source intensity of approximately 35 mW/cm^2 over a 0.28-mm^2 area.

of 9.3. For critically coupled resonators, $Q_i = 2Q_L$, where Q_i is the intrinsic Q factor.[20] Hence Q_i for the ring resonator is approximately 2.6×10^4 at 1550 nm, which is among the highest reported for CLD-1-doped microrings.[3]

The change in refractive index due to photobleaching is most likely caused by photochemical degradation of the chromophores.[15,17,21] Previous studies on CLD-1/APC show that the composite has an absorption peak centered at approximately 670 nm.[6,14] In ambient conditions the photoexcited chromophores can react with oxygen and subsequently become damaged.[6,14,17] As confirmed by our experiment, the photodecomposition of chromophores leads to the decrease in the refractive index of CLD-1/APC. However, it is well established that the photochemical stability of CLD-1/APC can be significantly improved in an environment void of oxygen and purged with an inert gas such as argon.[6,14] Therefore, for practical applications, after the device is trimmed, it should be hermetically packaged to ensure long-term stability.

In summary, we have fabricated, using soft-lithography replica molding, high-Q polymer microring resonators in APC doped with CLD-1, and we subsequently trimmed them by photobleaching the chromophores with visible light. A very wide tuning range is achievable with this method. The trimming rate and range can be controlled by the concentration of chromophores, the size of the exposure area, and the optical intensity. The chromophores that have not been photobleached can still be poled to render the polymer electro-optic.[17,22] The soft-lithography fabrication method and the postfabrication trimming are applicable to other types of integrated optical device.

J. Poon (poon@caltech.edu) thanks J. Scheuer and L. Zhu for fruitful discussions. She is grateful for the support of the Natural Sciences and Engineering Research Council of Canada. The financial support of the National Science Foundation, the Defense Advanced Research Projects Agency, and Hughes Research Laboratories is gratefully acknowledged.

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