Soft Lithography Replica Molding of Critically Coupled Polymer Microring Resonators

Joyce K. S. Poon, *Student Member, IEEE*, Yanyi Huang, George T. Paloczi, *Student Member, IEEE*, and Amnon Yariv, *Life Fellow, IEEE*

***Abstract*—We use soft lithography replica molding to fabricate unclad polystyrene (PS) and clad SU-8 microring resonator filters. The PS resonator has an intrinsic quality factor of 1.0×10^4 at $\lambda = 1.55$ μm, while that of the SU-8 resonator is 7100. The extinction ratios of the PS and SU-8 microring filters are -12 and -20 dB, respectively, with net insertion losses of 6.7 and 9.9 dB. The good quality factors and high extinction ratios of the microring resonator filters show the practicality of soft-lithography replica molding for the fabrication of integrated optical devices.**

***Index Terms*—Optical device fabrication, optical polymers, optical resonators.**

I. Introduction

As FABRICATION technologies mature, microring resonators have garnered significant interest in recent years since they may open new avenues toward compact integrated optical devices such as filters and delay elements [1]–[4]. Polymers provide an attractive material platform for the microring resonators, and more generally integrated optics, since their material and production costs may be substantially lower than other material systems. A fabrication technique that is important for polymeric integrated optical circuits is replica molding. In replica molding, a mold of the original master device is subsequently used to cast nearly exact copies of the master. This technique is powerful because it allows for high-throughput replication of the master device, and unlike other wet-etch or chemical processes, it does not chemically or physically alter any dopant molecules that may be in the polymer.

Soft lithography replica molding is a particular technique where the mold is flexible [5]. We have previously shown that very high fidelity between the master and molded devices can be achieved using soft lithography molding [6]. Moreover, we have recently used this technique to fabricate a high performance Mach–Zehnder modulator in a polymer doped with electrooptic chromophores [7]. Recently, Martin *et al.* have used this technique to fabricate polymeric toroid resonators with Q factors of 10^6 [8]. In this work, we further address the important issues of loss and device performance in polymeric integrated optics by demonstrating, using soft lithography replica molding, high-Q polymeric microring resonator notch filters in two material systems with excellent extinction ratios.

Manuscript received May 20, 2004; revised July 8, 2004. This work was supported by the National Science Foundation (NSF), Defense Advanced Research Projects Agency (DARPA), and Hughes Research Laboratories (HRL). The work of J. Poon was supported by an NSERC-Julie Payette scholarship.

The authors are with the Departments of Electrical Engineering and Applied Physics, California Institute of Technology, Pasadena, CA 91125 USA (e-mail: poon@caltech.edu).

Digital Object Identifier 10.1109/LPT.2004.835610

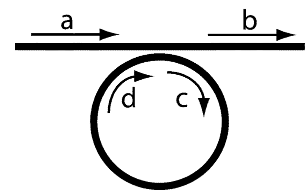

Fig. 1. Microring resonator coupled to a waveguide. The field amplitudes are denoted by a, b, c, and d.

II. Theory

The microring resonator notch filter consists of a single resonator coupled to a waveguide, as shown in Fig. 1. Using the notation in Fig. 1, the coupling between the microring and the waveguide can be described by the matrix equation [3], [9], [10]

$$\begin{bmatrix} b \\ c \end{bmatrix} = \begin{bmatrix} t & \kappa \\ -\kappa^* & t^* \end{bmatrix} \begin{bmatrix} a \\ d \end{bmatrix} \tag{1}$$

where κ is the dimensionless length-integrated coupling coefficient and $|\kappa|^2 + |t|^2 = 1$. As the field propagates in the ring, it accumulates a phase shift and may be attenuated, so $d = \alpha c \exp(-i2\pi\beta R)$, where α is the field attenuation constant, R is the ring radius, and β is the propagation constant in the ring. Hence, the transfer function of the filter is described by [11], [12]

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

An important parameter that describes the losses in resonators is the quality or Q factor. The loaded quality factor (Q_L) of a resonator is given by [10], [13]

$$\frac{1}{Q_L} = \frac{1}{Q_i} + \frac{1}{Q_{\text{ext}}} \tag{3}$$

where Q_i is the intrinsic Q factor and Q_{ext} is the external Q factor from the resonator-waveguide coupling. In general, since α and $|t|$ in (2) are interchangeable, Q_i and Q_{ext} cannot be uniquely determined from the spectral response of the device. However, when the special condition $\alpha = |t|$ is satisfied, or alternatively, when the internal power loss is equal to the coupling $(1-\alpha^2 = |\kappa|^2)$, $Q_i = Q_{\text{ext}} = 2Q_L$. This condition is known as critical coupling [12]. At critical coupling, the transfer function

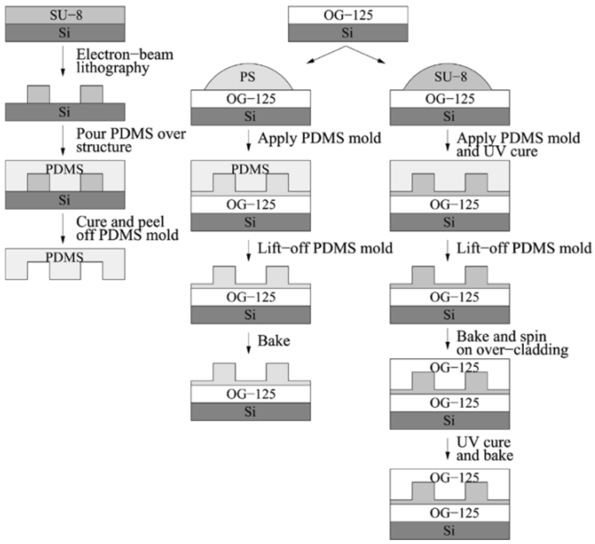

Fig. 2. Fabrication process for the microring resonators. The leftmost column shows the fabrication of the soft PDMS mold. The center column shows the fabrication of the PS microring resonators. The rightmost column shows the fabrication of the SU-8 microring resonators.

completely vanishes at the resonance frequencies of the ring resonator. Therefore, not only do critically coupled ring resonators allow us to unambiguously determine the intrinsic losses of a resonator through a single measurement of the spectral response of the geometry in Fig. 1, they also enable optical notch filters with high extinction ratios.

III. Fabrication

With the aim of demonstrating the applicability of soft lithography replica molding to integrated optical devices, we fabricate critically coupled microring resonators. We fabricate both unclad and clad devices in polystyrene (PS, $n \simeq 1.56$) and SU-8 (Microchem, $n \simeq 1.56$), respectively. Fig. 2 shows the schematic flowchart of the fabrication process. The fabrication of the mold is described in greater detail in [6] and [14]. Briefly, we create a poly(di-methylsiloxane) (PDMS) (General Electric) mold from the master devices which are defined using electron-beam writing of SU-8. The waveguides in the master devices have a height of $\sim$1.5 μm and a width of $\sim$1.9 μm. The resonator-waveguide gap size is about 350 nm. The PDMS molds are highly robust, and the same molds are used repeatedly in this experiment for the different materials without any noticeable physical difference in the molded device characteristics.

We begin the fabrication of the molded devices by spinning a 3-μm-thick layer of OG-125 (Epotek, $n \simeq 1.456$), an ultraviolet (UV) curable epoxy, as the under-cladding on a silicon wafer. The chip is then cured with UV light and baked at 80 °C for 2 min. For the unclad microrings, we deposit 10 μL of PS solution (4 wt% in toluene) on the chip and press the mold against the chip with a force of 25 N for about 20 min. The toluene evaporates through the PDMS mold during this time. Even though our molding process leaves behind a thin ($\sim$200 nm) residue film over the chip, this film should not be detrimental on the loss of the devices if it is sufficiently thin [14]. After the mold

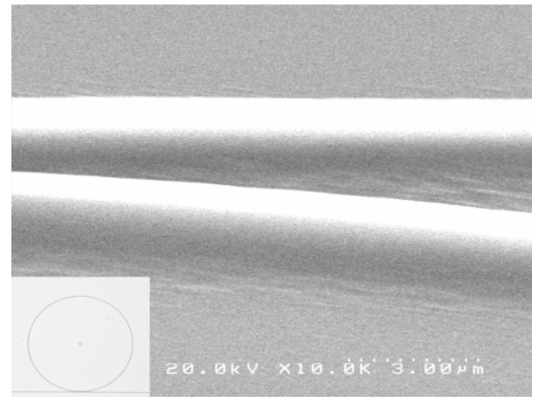

Fig. 3. SEM image of the resonator-waveguide coupling region in PS. Smooth side-walls are achieved using the soft lithography fabrication process. Inset: An optical micrograph of the microring resonator filter.

is lifted away, the chip is baked at 80 °C for 3–5 min. Finally, the chip is cleaved to separate the devices. The deviation in the radius of the molded and master devices is about 2%. The radius of the master is 200 μm, and the radius of the molded resonator is about 204 μm. The deviation can be reduced by decreasing the force applied to the mold.

Fig. 3 shows a scanning electron microscope (SEM) image of the PS microring resonator. The slight unevenness at the base of the waveguides is replicated from the master device and is caused by the electron-beam lithography fabrication process.

The fabrication process of the clad SU-8 resonator filters is similar to that of the PS microrings. The only differences are that the SU-8 must be UV-cured to harden and an over-cladding is applied. After the SU-8 is UV-cured, the chip is baked at 80 °C for about 3 min. An extra 3-μm layer of OG-125 is subsequently applied as the over-cladding. After the second application of OG-125, the chip is UV-cured again and finally baked at 80 °C for 3–5 min.

IV. Measurement

We measure the spectral response of the fabricated devices by coupling light from a tunable laser to the waveguide via a tapered fiber and collecting the transmitted light through a lens. Fig. 4 shows the transmission spectra for the PS and SU-8 microring resonator filters for transverse electric (TE) polarized light. The PS and SU-8 devices have maximum extinction ratios of -12 and -20 dB, respectively, illustrating that the critical coupling condition is essentially satisfied. The PS resonators have a free spectral range (FSR) of 1.15 nm and a 3-dB bandwidth of 0.3 nm, and hence, a finesse of 3.8. The SU-8 microrings have an FSR of 1.2 nm, a 3-dB bandwidth of 0.436 nm, and a finesse of 2.75. By taking the ratio between the resonance wavelength and the full-width at half-maximum linewidth of the resonance, Q_L factors are found to be approximately 5200 and 3555 for the PS and SU-8 microrings, respectively. These quality factors imply that the resonators have Q_i values of 1.0×10^4 and 7.1×10^3. These intrinsic Q factors are comparable to the highest reported values to date at the optical wavelength of 1.55 μm for integrated polymeric microring resonators fabricated with reactive ion etching ($\sim$2–4 $\times$ 10^4 in [4]).

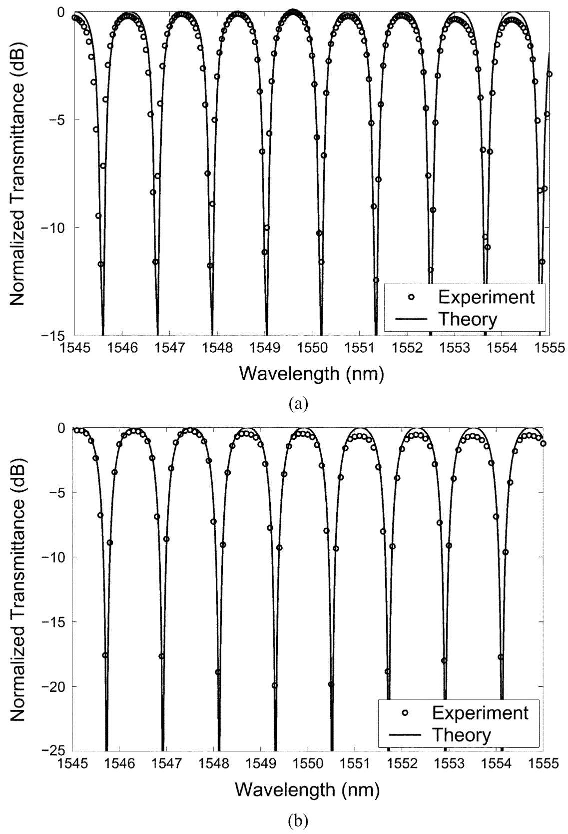

Fig. 4. Transmission spectra for TE polarized light of (a) the air-clad PS microring resonator and (b) the OG-125-clad SU-8 microring resonator.

We also fit the experimental data with the theoretical response described by (2) to find excellent agreement between them. The fit parameters for the PS microring are $\alpha(\text{or } t) = 0.689, t(\text{or } \alpha) = 0.620$, and the group index n_g is 1.624. The fit parameters for the SU-8 microrings are $\alpha = t = 0.536$ and $n_g = 1.562$. Extrapolating the Q factors from the attenuation in the microring resonator, we find that $Q_i = 1.1 \times 10^4$ for the PS microring and $Q_i = 6.5 \times 10^3$ for the SU-8 microring. These values imply a distributed loss of about 25 dB/cm in the resonator. The Q factors are in excellent agreement with the direct measurements of the resonance linewidths.

For the microring radius and refractive index contrast in this experiment, we expect that the resonator loss will be dominated by the side-wall scattering ($\sim$15–20 dB/cm) and material losses ($\sim$5 dB/cm) rather than the bend loss [4], [15], [16]. Therefore, resonators with larger FSRs and similar Q factors can be achieved by reducing the radius.

To determine the total insertion loss of the devices, we measure the difference between the transmitted powers with and without the microring resonator devices in our experimental setup. The total off-resonance insertion losses are found to be 6.7 and 9.9 dB for the PS and SU-8 microring resonator filters, respectively. These values indicate fairly low losses at the cleaved end facets and good mode-matching between the fiber taper and the waveguide. The coupling efficiency can be improved by designing a suitable mode-converter between the fiber and our device.

V. Conclusion

We have used soft lithography replica molding to fabricate critically coupled high-Q microring resonator notch filters at the telecommunications wavelength of 1.55 μm using PS and SU-8 with OG-125 as the cladding material. We expect that the insertion losses of the devices can be further reduced by improving the input–output coupling, reducing the side-wall scattering, and reducing the material losses of the optical polymers. This demonstration of low-loss, high-extinction integrated optical microring resonator filters illustrates the potential of the soft lithography replica molding technique for integrated optical circuits.

Acknowledgment

The authors thank W. Green and Dr. J. Scheuer for helpful discussions.

References

[1] B. E. Little, S. T. Chu, H. A. Haus, J. Foresi, and J.-P. Laine, "Microring resonator channel dropping filter," *J. Lightwave Technol.*, vol. 15, pp. 998–1005, June 1997.

[2] P. P. Absil, S. T. Chu, D. Gill, J. V. Hryniewicz, F. Johnson, O. King, B. E. Little, F. Seiferth, and V. Van. Very high order integrated optical filters. presented at *Optical Fiber Communication Conf.* [CD-ROM]Paper TuL3

[3] C. K. Madsen and J. H. Zhao, *Optical Filter Design and Analysis: A Signal Processing Approach*. New York: Wiley, 1999.

[4] P. Rabiei, W. H. Steier, C. Zhang, and L. R. Dalton, "Polymer micro-ring filters and modulators," *J. Lightwave Technol.*, vol. 20, pp. 1968–1975, Nov. 2002.

[5] Y. N. Xia and G. M. Whitesides, "Soft lithography," *Annu. Rev. Mater. Sci.*, vol. 28, pp. 153–184, 1998.

[6] Y. Huang, G. T. Paloczi, J. Scheuer, and A. Yariv, "Soft lithography replication of polymeric microring optical resonators," *Opt. Express*, vol. 11, no. 20, pp. 2452–2248, 2003.

[7] G. T. Paloczi, Y. Huang, A. Yariv, J. Luo, and A. K.-Y. Jen, "Replica molded electrooptic polymer Mach-Zehnder modulator," *Appl. Phys. Lett.*, vol. 85, no. 10, pp. 1662–1664, Sept. 2004.

[8] A. L. Martin, D. K. Armani, L. Yang, and K. J. Vahala, "Replica-molded high-Q polymer microresonators," *Opt. Lett.*, vol. 29, no. 6, pp. 533–535, 2004.

[9] A. Yariv, "Universal relations for coupling of optical power between microresonators and dielectric waveguides," *Electron. Lett.*, vol. 36, no. 4, pp. 321–322, 2000.

[10] H. A. Haus, *Waves and Fields in Optoelectronics*. Englewood Cliffs, NJ: Prentice-Hall, 1984.

[11] P. P. Absil, J. V. Hryniewicz, B. E. Little, R. A. Wilson, L. G. Joneckis, and P.-T. Ho, "Compact microring notch filters," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 398–400, Apr. 2000.

[12] A. Yariv, "Critical coupling and its control in optical waveguide-ring resonator systems," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 483–485, Apr. 2002.

[13] O. Schwelb, "Transmission, group delay, and dispersion in single-ring optical resonators and add/drop filters—A tutorial overview," *J. Lightwave Technol.*, vol. 22, pp. 1380–1394, May 2004.

[14] G. T. Paloczi, Y. Huang, J. Scheuer, and A. Yariv, "Soft lithography molding of polymer integrated optical devices: Reduction of the background residue," *J. Vac. Sci. Tech. B*, vol. 22, no. 4, pp. 1764–1769, 2004.

[15] V. Van, P. P. Absil, J. V. Hryniewicz, and P.-T. Ho, "Propagation loss in a single-mode GaAs-AlGaAs microring resonators: Measurement and model," *J. Lightwave Technol.*, vol. 19, pp. 1734–1739, Nov. 2001.

[16] C.-Y. Chao and L. J. Guo, "Reduction of surface scattering loss in polymer microrings using thermal-reflow technique," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 1498–1500, June 2004.