Fabrication of high-Q polymer microring resonators

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A novel inorganic-organic hybrid polymer polysiloxane-liquid (PSQ-L) is introduced for defining waveguides. The PSQ-L polymer film shows good optical properties and high thermal stability. The all polymer microring resonator is fabricated by conventional lithography and ICP etching process. About 3-dB extinction ratio from the through port and 23-dB extinction ratio from the drop port are obtained. A high Q value of 5.7×10^4 is obtained. The optical loss of the bending waveguides is estimated to be 1.6 dB/cm. The high Q polymer ring resonators show potential in sensing applications.

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Polymers are playing an important role in the field of integrated optics. The low cost of the material, easy processibility and compatibility with different substrates promise it to be a good alternative to silica material for fabrication of optical devices. Apart from telecommunication applications, polymer devices also have some sensing applications in biomedical engineering to achieve low cost and disposable circuits[1].

There are a lot of methods for fabrication of polymer waveguides. The waveguides can be fabricated by conventional lithography and etching processes as well as nanoimprint technology[2,3]. The fabrication method being adopted partly depends on the properties of the polymer. Fabrication process should be optimized to achieve better performance of the device. On the other hand, the optical properties and thermal stability of the polymer also play an important role in the performance of the devices.

Ring resonators are fundamental components for various applications[1,4,5]. Simple ring resonators are often chosen as a test device for new material and new fabrication technology[3,6,7]. However, large losses often exist in the reported polymer ring resonators[3,7,8]. Post treatments sometimes have to be performed to reduce the extra loss caused by fabrication process[9].

In this letter, we fabricated simple ring resonators by using a novel organic-inorganic hybrid polymer polysiloxane-liquid (PSQ-L). This polymer film shows good optical properties and high thermal stability. A lateral coupled microring resonator is fabricated by conventional lithography and ICP dry etching. About 3-dB extinction ratio from the through port and 23-dB extinction ratio from the drop port are obtained. A high Q value of 5.7×10^4 is obtained. The optical loss of the bending waveguides is estimated to be 1.6 dB/cm.

The waveguides are made from a novel silicate-based inorganic-organic hybrid polymer PSQ-L[10,11]. PSQ-L was synthesized by a sol-gel process from monomer phenyl trimethoxysilane (PhTMS), methyl trimethoxysilane (MTMS), and 3-(methacryloxy) propyl trimethoxysilane (MAPTMS).

By changing the synthesis ratio of the different monomers, polymer PSQ-LH with a high index (n=1.515 @1 550 nm) and polymer PSQ-LL with a low index (n=1.454@1 550 nm) are synthesized. The index between the PSQ-LL and PSQ-LH can be finely controlled by blending PSQ-LL and PSQ-LH with corresponding ratio. This polymer film shows good optical properties (Table 1) and high thermal stability (1% degradation temperature is above 300 °C in air and above 340 °C in nitrogen). The optical loss of the film is less than 0.3 dB/cm at 1 310 nm and less than 0.9 dB/cm at 1 550 nm.

The optical properties of PSQ-L films are characterized by prism coupling (SPA-4000). The optical loss of the film (slab waveguide) is measured by immersion oil technology[12], which is a good approximation for the absorption loss of the material itself.

Polymer PSQ-LH is used as a core material and polymer PSQ-LL is used as a cladding material for the waveguides. The waveguide cross-section is designed as a buried channel waveguide. The width and height of the core are designed as 3 and 1.8 μm. The thickness of the core layer can be controlled by the spin-coating speed.

The ring resonator is designed as a laterally coupled ring resonator. Due to the small index contrast between the core and cladding (about 0.061), the radius of the ring is chosen as 400 μm to eliminate the bending loss. The gap between the straight waveguide and the ring is designed as 1–1.8 μm. The extinction ratio of the through port and the drop port depends on both the loss of the ring waveguides and the coupling ratio between the ring and the straight waveguide. To ensure enough coupling between the ring and the straight waveguide, the ring is designed as a racetrack ring resonator with a coupling length of 150 μm.

The polymer PSQ-L ring resonators are fabricated by a conventional lithography and ICP etching process as shown in Fig. 1. First, a PSQ-LL is spin-coated on the silicon substrate. After oxygen plasma etching for 5 min (to improve the adhesion to the second layer), a PSQ-LH is spin-coated on and cured as a core layer. In order to protect the sidewall from being destroyed during the etching process, hard metal masks have to be used. Therefore, a reverse pattern is first transferred to the negative photoresist and followed by depositing a metal

Table 1. Properties of Polymer PSQ-L

	PSQ_LL	PSQ_LH
Refractive Index @1 310 nm	1.456	1.517
Refractive Index @1 550 nm	1.454	1.515
Birefringence ($n_{\mathrm{TE}} - n_{\mathrm{TM}}$)	< 0.0005	< 0.0005
Thermo-optic Coefficient (/°C)	-2.2×10^{-4}	-2.4×10^{-4}
Propagation Loss (dB/cm) (Measured from Slab Waveguide)	/	0.7∼0.9@1 550 nm
	/	0.2∼0.3@1 310 nm
Degradation Temp. (°C, 1 wt%)	322±10 (in air)	303±10 (in air)
	370±10 (in N_2)	343±10 (in N_2)
Film Surface Roughness (nm)	< 0.5	< 0.5

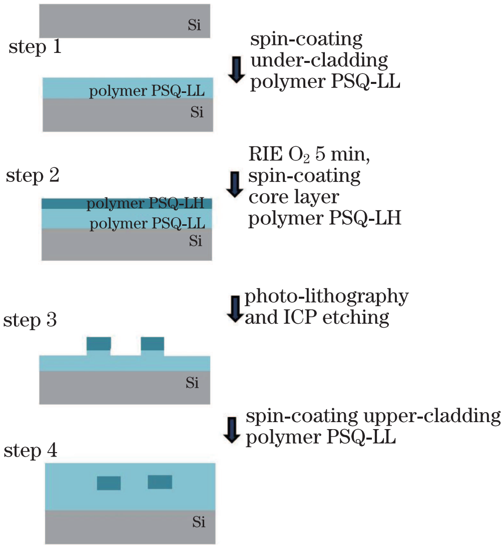

Fig. 1. Fabrication process for buried polymer PSQ-L waveguides.

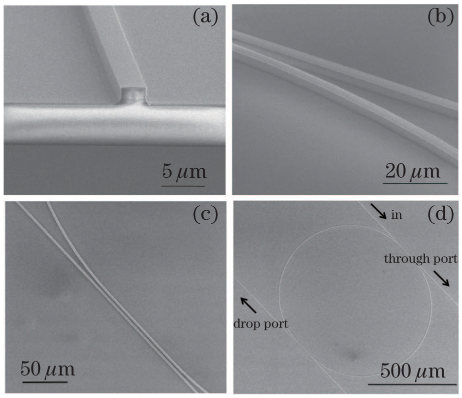

Fig. 2. SEM pictures of PSQ-L waveguide fabricated by conventional lithography and ICP etching. (a) Cross-section; (b) side view of coupling region of the ring; (c) top view of the coupling region; (d) top view of ring resonator.

mask of Ti/Au. After a metal lift-off process, the waveguides pattern is transferred to the metal mask. Then an ICP dry etching process is carried out. After that, the metal mask is removed. Finally, an upper cladding PSQ-LL is spin-coated on top of the waveguides and cured. Figure 2 shows the SEM pictures of the PSQ-L waveguides after ICP etching process. Optimization of the fabrication parameters has been carried out to achieve such rectangle waveguides and smooth sidewalls.

The ring resonators are characterized after fabrication. The transmission spectrum of the ring is measured by coupling light from a tunable laser to the waveguide via a lensed fiber. The transmitted light is collected by a single mode fiber to the power meter. A polarization controller is used at the input port to select the polarization. Figure 3 shows the measured transmission spectrum of the ring resonator for TE mode and TM mode. This ring has a radius of 400 μm, a gap of 1.8 μm, and a coupling length of 150 μm. The TM mode shows similar response to the TE mode. Taking the TE mode for example: the free spectral range (FSR) of the ring is about 0.56 nm as expected due to the large ring radius; the full-width of half-maximum (FWHM) is about 0.027 nm; by taking the ratio between the resonance wavelength and the FWHM, a Q factor of about 5.7×10^4 is calculated; the fineness is calculated about 21. About 2.5-dB extinction ratio at the through port and 23-dB extinction ratio at the drop port are obtained.

Theoretically the through port and drop port intensity should follow the expression in Ref. [13] calculated by a transfer matrix method[14,15] for symmetrical coupling ($\kappa_1 = \kappa_2$) condition. The transmission coefficient T and round trip attenuation factor A are extracted by fitting of the transmission spectrum. The per round trip power attenuation corresponds to a loss of 3.2 dB/cm of the bent waveguide. The material absorption loss is about 0.9 dB/cm (see Table 1) and the loss due to mode mismatch between the straight waveguide and the bent ring waveguide is about 0.7 dB/cm, which follows from theoretical calculations. Assuming the bending loss and substrate leakage loss can be neglected, a scattering loss of the ring waveguide of 1.6 dB/cm is estimated for both TE and TM modes, which is quite low compared with other polymer ring resonators[3,6,8]. The Q value of the ring resonator is 2–10 times higher than other polymer ring resonator[3,6,8]. This is partly because the low loss waveguide and the week coupling coefficient between the ring and the straight waveguide. The high-Q and low loss polymer ring resonator shows potential in sensing applications.

In conclusion, a novel inorganic-organic hybrid polymer PSQ-L is introduced recently. This polymer film shows

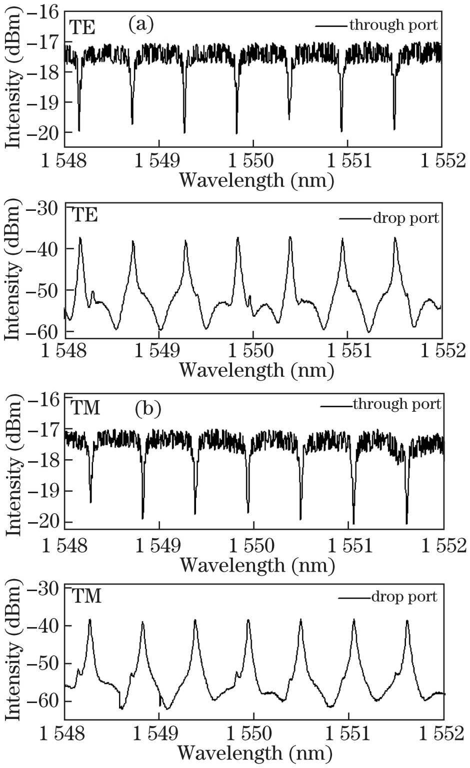

Fig. 3. Measured transmission spectrum of microring resonator. (a) TE and (b) TM polarized lights.

good optical properties and high thermal stability. The all polymer microring resonator is fabricated by using PSQ-LH as a core layer and PSQ-LL as a cladding layer. The waveguides are fabricated by conventional lithography and ICP etching process. The fabricated microring resonator has low scattering loss and a high Q factor of 5.7×10^4 is obtained. The high Q polymer microring resonators show potential in sensing applications.

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