Simple UV-based Soft-lithography Process for Fabrication of Low-Loss Polymer PSQ-L-based Waveguides

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Abstract

We propose a simple UV based soft-lithography process for fabrication of low-loss polymer PSQ-L waveguides. The fabrication process consists of two steps: the imprint step for structuring is done first on the cladding PSQ-LL layer and is followed by a spin-coating step to fill the imprinted features with core PSQ-LH layer material. Even with non-polishing waveguide facets, the extracted scattering loss of straight waveguides by a Fabry-Perot resonance method is less than 0.8dB/cm for the TE mode. The fully transferred pattern and low scattering loss proves it to be an effective way to replicate low-loss polymer PSQ-L-based waveguides.

1. Introduction

Polymers are emerging as an important material in the field of integrated optics. The low cost of the material itself and the simple fabrication process promise it to be a good alternative to silica for integrated optical devices[1].

Apart from conventional lithography and etching processes, many fabrication methods for polymer waveguides have been extensively studied in the past few years [2-5]. Nanoimprint Technology and Soft-lithography [2, 3] have attracted a lot of attention for the simple fabrication of polymer waveguides. The imprint process parameters highly depend on the properties of the polymer. Low-viscous UV-curable polymer is more desirable for the imprint process since it allows for low pressure in the UV-based imprint process. The UV transparent mold can be a soft PDMS mold or a hard silica glass mold. PDMS molds have more advantages than UV-transparent silica glass molds for fabrication of submicron structures: once a master mold is made and it can be used many times. Furthermore, the soft PDMS mold can be easily peeled off from the substrate.

In this paper, we introduce a novel polymer PSQ-L and propose a simple process for fabrication of low-loss PSQ-L polymer waveguides. Taking advantage of the low viscous UV-curable polymer PSQ-LL, waveguide trenches are imprinted on the lower index PSQ-LL layer by a soft PDMS mold. No pressure is applied in the imprint process. This approach smartly avoids the accurate control of the thickness of the core residual layer. The fully transferred pattern and smooth sidewall proves it to be an effective way to replicate polymer PSQ-L-based waveguides. The evaluated scattering loss of straight waveguides is less than 0.8dB/cm for the TE mode.

2. Materials

A silicate-based inorganic-organic hybrid Polymer PSQ-L is introduced recently [6, 7]. The polymer PSQ-L exists in two forms: PSQ-LH with a high index (n=1.515@1550nm) is used as a core material and PSQ-LL with a low index (n=1.454@1550nm) is used as a cladding material for the waveguides. The best aspect of using polymer PSQ-L is that it is purely liquid (solvent free) and UV curable, which makes it compatible with soft-lithography processes. PSQ-L also exhibits excellent optical properties and thermal stability (1% Td is all above 300 ^{o}C in air and 340 ^{o}C in nitrogen). The optical loss of the PSQ-LH film measured by a prism coupler (SPA-4000) is less than 0.3 dB/cm at 1310nm and less than 0.9 dB/cm at 1550nm.

3. Fabrication Process

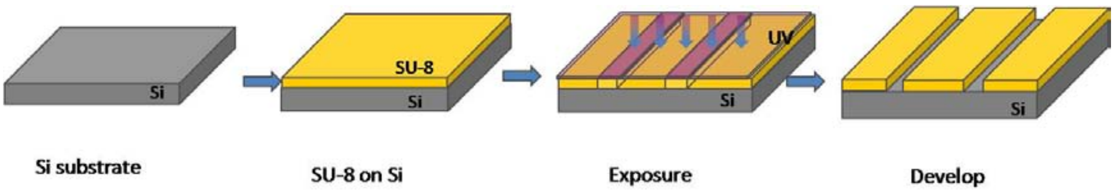
Soft-lithography has been proved an effective way to fabricate polymer waveguide circuits [3, 8] by using a soft UV-transparent PDMS mold. An important aspect in the fabrication of polymer waveguides is to minimize the residual layer thickness. A thick residual layer should be avoided because of extra bending loss and cross-talk between adjacent waveguides. Conventionally, RIE etching is carried out after the imprint to etch through the residual layer. However, RIE etching is not an ideal solution as it causes sidewall roughness and may even destroy the optical properties of the polymers.

Unlike in conventional imprint processes, the imprint step for structuring in this paper is done first on the cladding layer rather than on the core layer and is followed by a spin-coating step to fill the imprinted features with core layer material. This approach smartly avoids controlling the thickness of the residual core layer.

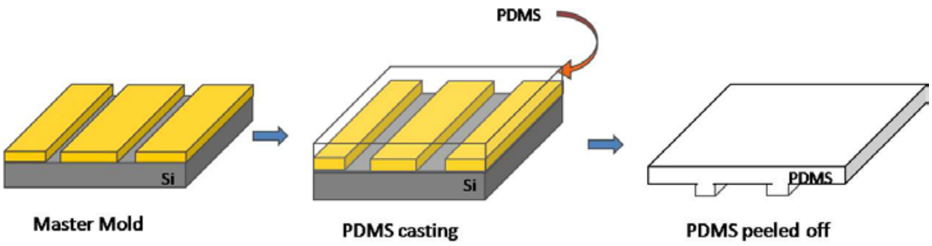
The waveguides circuits are replicated by a soft-lithography process (Fig.1). First, a master mold is fabricated by a conventional lithography from negative photo-definable resist SU-8(MICRO CHEM). Then PDMS is casted on top of the master mold. After thermal curing (150°C, 10min), the PDMS mold is peeled off from the master mold. The PDMS mold is used to replicate polymer waveguides.

The imprint process is carried out as follows. First, a drop of pure PSQ-LL is deposited on the silicon wafer, and then the PDMS mold is put on top. After 20 minutes imprint time, it is exposed to the UV lamp for 3 minutes. After that, the PDMS mold is peeled off and the polymer is baked for 1h at 180^{o}C to allow for solidification after UV exposure. To improve the adhesion to the second layer, 5 minutes of oxygen plasma etching is done on the first layer. Then the core layer PSQ-LH is spin-coated on the first layer with high speed (9500rpm). Finally, the sample is post baked at 180^{o}C for 2h and at 200^{o}C for another 2h to allow for full polymerization.

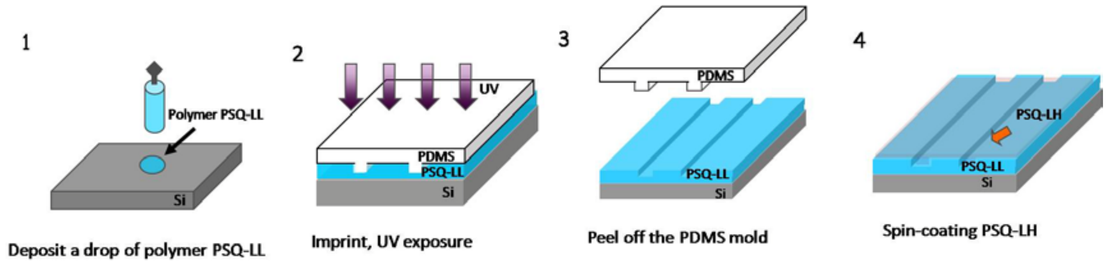
Since the residual cladding layer thickness does not need to be controlled accurately as long as it is thick enough to eliminate the substrate leakage loss, this process smartly avoids the difficulties related to controlling the thickness of the residual core layer. This method also has the advantage of being compatible with other core material.



(a)



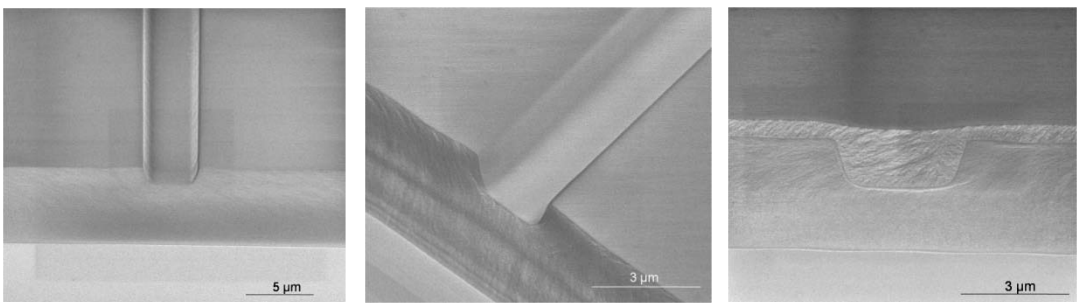
(b)



(c)

Fig.1 Fabrication Process for polymer PSQ-L waveguides

(a) Master mold fabrication process (b) Soft PDMS mold fabrication (c) UV-based soft-lithography process for fabrication of PSQ-L waveguides



(a) (b) (c)

Fig.2 (a) (b) SEM picture of the imprinted low index PSQ-LL layer

(b) SEM picture of waveguide cross-section (after spin-coating the high index PSQ-LH layer)

SEM pictures of the imprinted waveguide trench on the low index layer PSQ-LL are shown in Fig.2 (a),(b). The cross section of the waveguide (after spin-coating the high index layer PSQ-LH) is shown in Fig.2(c). The width and the height of the buried waveguide are designed as 3μm and 2μm. The slab height of the ridge waveguide is minimized by spin coating with a high speed to about 800nm. The smooth sidewall of the waveguide trench promises the low scattering loss caused by fabrication.

4. Measurement Results

The optical loss of the waveguides is an important factor for optical devices. The cut-back method is most commonly used for evaluating the loss of the straight waveguides [9, 10]. However, this method is not so accurate since the coupling loss between the lensed fiber and the waveguides is not repeatable each time.

Fabry-Perot resonance method is a simple and accurate way to evaluate the loss of the straight waveguides. One important aspect of using this method is that the facets of the waveguides have to be good enough to provide efficient reflection to the waveguides. Otherwise, imperfect reflection leads to larger evaluated loss value than the true value.

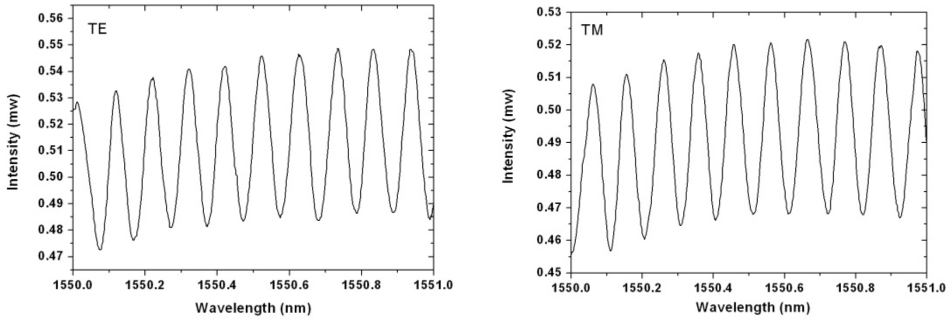
For polymer waveguides, the facet reflection between the core and air is quite low, which results in low extinction ratio of the transmission spectrum. Considering a perfect reflection condition, the reflection of the facet between the core and air is only 4% (given the index of polymer is 1.5 and the index of air is 1). Imperfect facets may easily lead to failured measurement of the resonant phenomenon. To our knowledge, we are the first one to use this method to measure the loss of polymer waveguides.

The polymer PSQ-L waveguides are cut with the cleavage of silicon wafer. No polishing is done on the facet of the polymer waveguides. Light from a tunable laser is launched into the polymer waveguides via a lensed fiber and collected by a lens to a power meter. A polarizer is inserted in front of the detector to control TE and TM mode of the waveguides. Fig.3 shows the transmission spectrum of the straight waveguides with a length of 6.8mm.

The optical loss of the straight waveguides can be extracted by using the following equation [11],

$$\alpha = -\frac{1}{L} \cdot 10 \cdot \log \frac{K}{2R} \tag{1}$$

Where α is the loss of the waveguides given in dB/cm; L is the length of the waveguides; K is the contrast factor of the Fabry-Perot resonance spectrum, defined as $K = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$; R is the perfect reflectivity of the facet between the core and air, defined as $R = (\frac{n_{eff} - 1}{n_{eff} + 1})^2$. In actual situation, the waveguide facet is never perfect and thus the real R value is always smaller than the perfect facet reflectivity. Therefore the extracted value α is an upper limit of the waveguide loss.



(a) (b)

Fig.3 Fabry-Perot resonance spectrum for measuring the loss of polymer PSQ-LH waveguides (a) TE polarization (b) TM polarization

The extracted loss of the straight waveguides is 1.7dB/cm for TE mode and 2.2dB/cm for TM mode. Assuming the substrate leakage loss can be neglected and subtracting the material absorption loss of 0.9 dB/cm @1550nm, the scattering loss of the straight waveguide is less than 0.8 dB/cm for TE mode and 1.3dB/cm for TM mode. The real value of the scattering loss should be much lower than this value since the facet is below perfect facet reflectivity.

The scattering loss extracted from the transmission spectrum of the PSQ-L ring resonators is also low. The extracted scattering loss of 400μm bending waveguides is about 1.6 dB/cm for both TE and TM polarization[12].

The low scattering loss of PSQ-L waveguides proves it to be a good fabrication process for the fabrication of polymer waveguides.

Conclusion

A simple UV-based soft-lithography process for fabrication of low-loss polymer PSQ-L waveguides is proposed. The fully transferred pattern and smooth sidewall proves it to be an effective way to replicate polymer PSQ-L waveguides. Even with non-polishing waveguide facets, the extracted scattering loss of straight waveguides by a Fabry-Perot resonance method is less than 0.8dB/cm for TE mode. The low scattering loss of PSQ-L waveguides promises it to be a good fabrication process for the fabrication of polymer PSQ-L waveguides.

Reference

[1] H. Ma, A. K. Y. Jen, and L. R. Dalton, "Polymer-based optical waveguides: Materials, processing, and devices," *Advanced Materials*, vol. 14, pp. 1339-1365, 2002.

[2] C. Y. Chao and L. J. Guo, "Polymer microring resonators fabricated by nanoimprint technique," *Journal of Vacuum Science & Technology B*, vol. 20, pp. 2862-2866, 2002.

[3] J. K. S. Poon, Y. Y. Huang, G. T. Paloczi, and A. Yariv, "Soft lithography replica molding of critically coupled polymer microring resonators," *IEEE Photonics Technology Letters*, vol. 16, pp. 2496-2498, 2004.

[4] C. Wei-Ching, H. Chi-Ting, and C. Wen-Chung, "Fabrication of polymer waveguides by a replication method," *Applied Optics*, vol. 45, pp. 8304-7, 2006.

[5] W. C. Chuang, C. K. Chao, and C. T. Ho, "Fabrication of high-resolution periodical structures on polymer waveguides using a replication process," *Optics Express*, vol. 15, pp. 8649-8659, 2007.

[6] H. B. Zhang, J. Y. Wang, L. K. Li, Y. Song, M. S. Zhao, and X. G. Jian, "A study on liquid hybrid material for waveguides - Synthesis and property of PSQ-Ls for waveguides," *Journal of Macromolecular Science Part a-Pure and Applied Chemistry*, vol. 45, pp. 232-237, 2008.

[7] H. B. Zhang, J. Y. Wang, L. K. Li, Y. Song, M. S. Zhao, and X. G. Jian, "Synthesis of liquid polysilisiquioxane resins and properties of cured films," *Thin Solid Films*, vol. 517, pp. 857-862, 2008.

[8] W. S. Kim, J. H. Lee, S. Y. Shin, B. S. Bae, and Y. C. Kim, "Fabrication of ridge waveguides by UV embossing and stamping of sol-gel hybrid materials," *Ieee Photonics Technology Letters*, vol. 16, pp. 1888-1890, 2004.

[9] K. Mune, R. Naito, T. Fukuoka, A. Mochizuki, and K. Matsumoto, "Fabrication of low loss optical waveguides using a novel photosensitive polyimide," *Photonics Packaging and Integration Iii*, vol. 4997, pp. 103-108, 2003.

[10] J. J. Chiu and T. P. Perng, "The passive optical properties of a silicon nanoparticle-embedded benzocyclobutene polymer waveguide," *Nanotechnology*, vol. 19, 2008.

[11] R. Regener and W. Sohler, "Loss in Low-Finesse Ti-Linbo3 Optical Wave-Guide Resonators," *Applied Physics B-Photophysics and Laser Chemistry*, vol. 36, pp. 143-147, 1985.

[12] J. Teng, S. Stijn, H. Zhang, X. Jian, M. Morthier, R. Beats, X. Han, and M. Zhao, "A PSQ-L Polymer Microring Resonator Fabricated by a simple UV-based Soft-lithography Process," *IEEE Photonics Technology Letters*, vol. 21, pp. 1323-1325, 2009.