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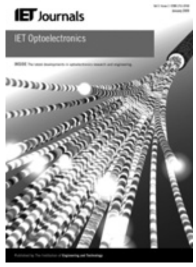

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Simple ultraviolet-based soft-lithography process for fabrication of low-loss polymer polysiloxanes-based waveguides

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Abstract: A simple ultraviolet (UV)-based soft-lithography process is used for fabrication of polymer polysiloxanes (PSQ-L) waveguides. The imprint process is first done 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. The optical loss of the straight PSQ-L waveguides is characterised by the Fabry–Perot method for the first time. Even with non-polished facet of the waveguide, the Fabry–Perot resonance spectrum is obtained. An upper limit scattering loss of the waveguide is extracted to be less than 0.8 ± 0.2 dB/cm for TE mode and 1.3 ± 0.2 dB/cm for TM mode at 1550 nm. 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. In [6], we have proposed a simple ultraviolet (UV)-based soft-lithography process for fabrication of polymer polysiloxanes (PSQ-L) microring resonators. The optical loss of the bend waveguides is extracted from the transmission spectrum of the ring resonators. The optical loss of the straight waveguides has not yet been characterised.

The cut-back method is commonly used to evaluate the loss of the straight waveguides. However, this method suffers from the disadvantage of coupling dependence, especially when the waveguide size is significantly reduced. The Fabry–Perot method is an accurate method for measuring 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. The difficulty to use this method for evaluating the loss of polymer waveguides is that the intrinsic reflectivity of the waveguide facets is low (which leads to low contrast of the transmission spectrum). Imperfect waveguide facets or large waveguide propagation loss can easily lead to failure measurement of the resonance spectrum. To our knowledge, we are the first one to use this method to measure the loss of the polymer waveguides.

In this paper, a simple UV-based soft-lithography process is used for fabrication of polymer PSQ-L waveguides. The imprint process is first done 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. After fabrication, the loss of the straight waveguide is evaluated by the Fabry–Perot method. Even with non-polished facet of the waveguide, the Fabry–Perot resonance spectrum is obtained. An upper-limit scattering loss of the waveguide is extracted to be less than 0.8 ± 0.2 dB/cm for TE mode and 1.3 ± 0.2 dB/cm for TM mode at 1550 nm.

2 Materials

A silicate-based inorganic–organic hybrid polymer PSQ-L is introduced recently [7, 8]. The polymer PSQ-L exists in two forms: PSQ-LH with a high index ($n = 1.515$@1550 nm) is used as a core material and PSQ-LL with a low index

($n = 1.454$@1550 nm) 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% degradation temperature (Td) is all above 300°C in air and 340°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 1310 nm and less than 0.9 dB/cm at 1550 nm.

3 Fabrication process

Soft-lithography has been proved an effective way to fabricate polymer waveguide circuits [3, 9] by using a soft UV-transparent polydimethylsiloxane (PDMS) mold. 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. 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, unlike in conventional imprint processes, the imprint step for structuring 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 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, 10 min), 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 min imprint time, it is exposed to the UV lamp (about 2000 mJ/cm^2) for 3 min. After that, the PDMS mold is peeled off and the polymer is baked for 1 h at 180°C to allow for solidification after UV exposure. In order to improve the adhesion to the second layer, 5 min 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 (9500 rpm). Finally, the sample is post-baked at 180°C for 2 h and at 200°C for another 2 h to allow for full polymerisation.

Since the thickness of the residual cladding layer does not need to be controlled accurately as long as it is thick enough to eliminate the substrate leakage loss. The width and the height of the buried waveguide are designed as 3 and 2 μm. The slab height of the ridge waveguide is minimised by spin-coating with a high speed to about 800 nm. This fabrication process is also compatible with other core material.

4 Measurement results

4.1 Theory

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 [10, 11]. However, this method suffers from the disadvantage of coupling dependence, especially when the waveguide size is significantly reduced.

Fabry–Perot resonance method is a simple and accurate way to evaluate the loss of the straight waveguides. By

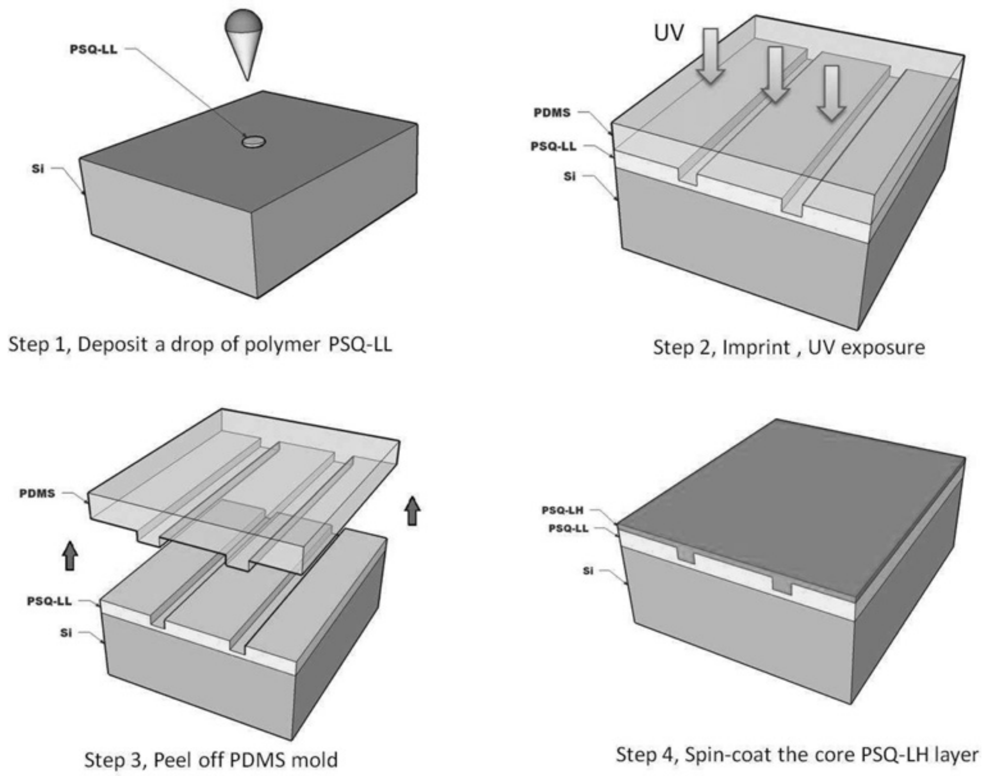

Fig. 1 *Fabrication process for polymer PSQ-L waveguides*

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measuring the transmitted intensity of the monomode Fabry–Perot resonator, the attenuation coefficient of the waveguide can be evaluated [12]. A convenient way to evaluate the attenuation coefficient of the waveguide is to determine the contrast factor of the transmitted spectrum

$$K = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{1}$$

where $I_{\max}$, $I_{\min}$ are the maximum and minimum intensity values on the transmitted spectrum. The contrast factor K is independent of the input power and the coupling efficiency of the lensed fibre (or single-mode fibre) and the waveguide. It is only as a function of the combined loss-reflection factor $\tilde{R}$ [12]

$$K = \frac{2\tilde{R}}{1 + \tilde{R}^2} \tag{2}$$

$$\tilde{R} = R\,\mathrm{e}^{-\alpha L} \tag{3}$$

where R is the end-face reflectivity of the Fabry–Perot resonator, α is the attenuation coefficient of the waveguides, L is the length of the Fabry–Perot resonator. From (2), for small value of reflectivity R, the combined loss-reflection factor $\tilde{R}$ can be expressed as

$$\tilde{R} = \frac{K}{2} = R\,\mathrm{e}^{-\alpha L} \tag{4}$$

Therefore if the end-face reflectivity R is known, the attenuation coefficient factor α can be evaluated

$$\alpha = -10 \times \frac{1}{L} \times \log \frac{K}{2R} = -4.34 \ln \frac{K}{2R} \tag{5}$$

where α is given in dB/cm.

From (4), the contrast factor K depends on the reflectivity R and the attenuation coefficient α. For small K, the maximum value of the contrast factor K equals $2R$, and the contrast factor K is decreasing dramatically with the loss of the cavity.

By deviation of (5), the absolute error of the attenuation coefficient α is as

$$|\Delta\alpha| = \frac{4.34}{L} \frac{|\Delta K|}{K} \tag{6}$$

From (6), the deviation $|\Delta\alpha|$ will be large for small K value.

4.2 Experimental results

For polymer waveguides, the facet reflectivity between the core and air is quite low, which results in low contrast in the transmission spectrum. Considering a perfect reflection condition, the reflection of the end face between the core and air is only 4% [assuming a perfect reflection: calculated from Fresnel reflection formula $R = ((n-1)/(n+1))^2$, given the index of polymer is 1.5 and the index of air is 1.0]. The maximum value of the contrast factor K can only be 0.08 for a lossless polymer waveguide. Therefore imperfect facet (low reflectivity R) or large waveguide loss (large attenuation coefficient factor α) may easily lead to

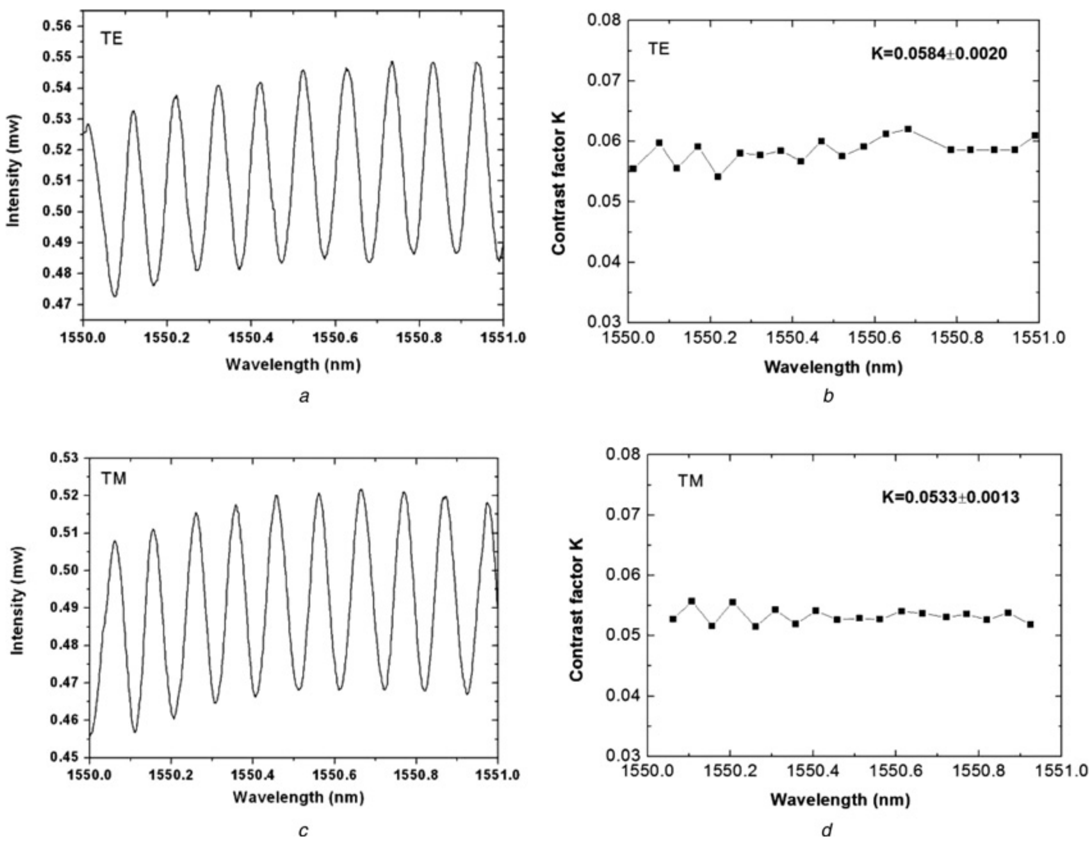

Fig. 2 *Measured Fabry–Perot resonance spectrum for polymer PSQ-L straight waveguides*

a TE mode
c TM mode
b and *d* Corresponding to calculated contrast factor K

failure measurement of the resonant phenomenon (low contrast K). To our knowledge, we are the first one to use this method to measure the loss of polymer waveguides.

The polymer PSQ-L waveguide facets are obtained by cleavage of the silicon substrates. No polishing is done on the facets of the polymer waveguides. Light from a tunable laser is launched into the polymer waveguides via a lensed fiber and collected by a lens (Newport: MV-40X) to a power meter. An infra-red camera and a TV monitor are used for alignment at the output port of the waveguide. A polariser is inserted in front of the detector to select TE or TM mode of the waveguides. The total insertion loss is about 6 dB. From theoretical calculation, the waveguide supports two modes, the first-order mode is slightly guided in the waveguide, but will be exhausted in the waveguide. The near-field image showed on the TV monitor also proves single mode guided in the waveguide.

Fig. 2 shows the transmission spectrum of the straight waveguides with a length of 6.8 mm. Fig. 2*a* shows the corresponding calculated K value. Assuming the facet between the core and the air is a perfect reflective facet, the reflectivity of the facet is calculated to be 0.038 $[R = ((n_{\text{eff}} - 1)/(n_{\text{eff}} + 1))^2$, the calculated effective index of the polymer waveguide is 1.484]. Thus, the optical loss of the straight waveguides can be extracted by using (5). The extracted loss of the straight waveguides @1550 nm is 1.7 ± 0.2 dB/cm for TE mode and 2.2 ± 0.2 dB/cm for TM mode. Assuming the substrate leakage loss can be neglected and subtracting the material absorption loss of 0.9 dB/cm @1550 nm, the scattering loss of the straight waveguide is less than 0.8 ± 0.2 dB/cm for TE mode and 1.3 ± 0.2 dB/cm for TM mode.

In actual situation, the waveguide facet is never perfect. Cleavage can cause imperfect facet with extra scattering loss (Fig. 3*b*). The reflected power in radiation mode also causes scattering loss at the end face of the waveguide [13]. Misalignment of the waveguide and the wafer orientation during fabrication or measurement process can cause a tilted facet of the waveguides (Fig. 3*c*), which also lead to a reduction in reflectivity of the end face of the waveguide [14]. Therefore the extracted attenuation coefficient of the waveguides includes the reflectivity loss at the cleaved facet. The real reflectivity value of the end face is always below the perfect reflectivity. The extracted attenuation coefficient α is an upper limit of the waveguide loss.

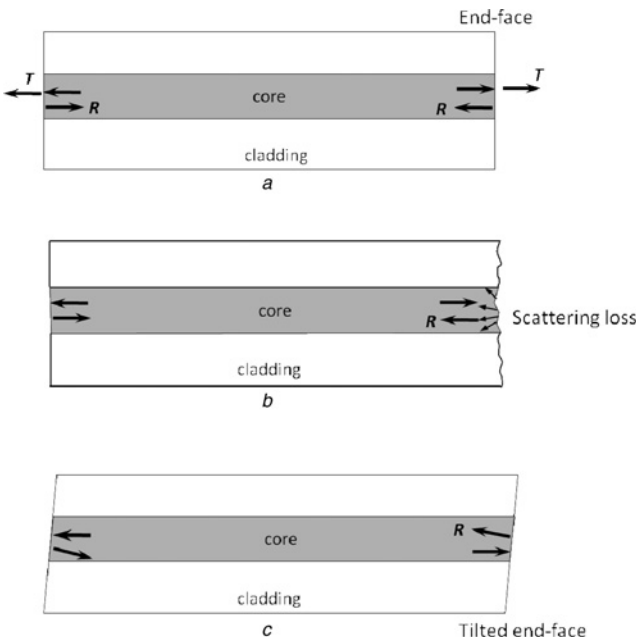

Fig. 3 *Fabry–Perot resonator formed by cleaved waveguides*

a Ideal condition: end face with perfect reflectivity
b Imperfect facet: scattering loss at the end face
c Imperfect facet: insufficient reflectivity at the tilt end face

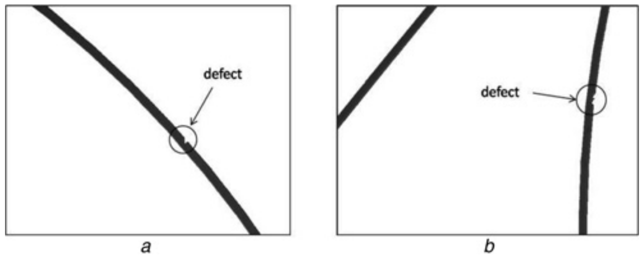

Fig. 4 *Defects on the contact mask (microscope pictures)*

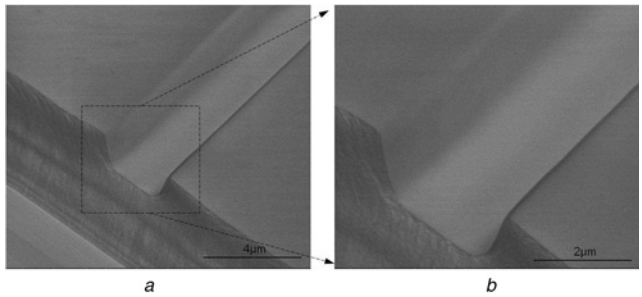

Fig. 5 *SEM pictures of the imprinted waveguide trench*

a Wide view
b Zoomed view

5 Discussion

As reported before, the scattering loss extracted from the transmission spectrum of the PSQ-L ring resonators is also low. The extracted scattering loss of 400 μm bend waveguides is about 1.6 dB/cm for both TE and TM polarisation [6]. Later we found that there are some defects on the mask of the bend waveguides (Fig. 4). We suspect the scattering loss is mainly from the defects on the bend waveguides, and not mainly from the roughness of the sidewall caused by fabrication process. Fig. 5*b* shows a close look at the waveguide trench from SEM. Smooth sidewall of the trench can be seen from Fig. 5*b*. The success to observe Fabry–Perot resonance spectrum and the extracted attenuation coefficient value also confirms the low loss of the polymer waveguides. We believed that the scattering loss of the polymer PSQ-L waveguides should be much lower than the extracted value from Fabry–Perot resonance experiments.

6 Conclusion

A simple UV-based soft-lithography process is used for fabrication of polymer PSQ-L waveguides. Even with non-polishing waveguide facets, the extracted scattering loss of the straight waveguides by a Fabry–Perot resonance method is less than 0.8 ± 0.2 dB/cm for TE mode and 1.3 ± 0.2 dB/cm for TM mode at 1550 nm. The fully transferred pattern and low scattering loss promises it to be a good fabrication process for polymer PSQ-L waveguides.

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