Low loss, flexible single-mode polymer photonics

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Abstract: Single-mode polymer photonics is of significant interest to short-reach data communications, photonic packaging, sensing, and biophotonic light delivery. We report here experimental demonstration of mechanically flexible waveguides fabricated by using commercial off-the-shelf biocompatible polymers that claim a record low propagation loss of 0.11 dB/cm near 850 nm wavelength. We also show the excellent flexibility of the free-standing waveguides which can withstand repeated deformation cycles at millimeter bending radius without compromising their low-loss characteristics. High-performance passive optical components, such as waveguide Y-branches, multi-mode interferometers (MMIs), and waveguide crossings are also realized using the polymer photonics platform.

1. Introduction

Polymers are important materials for integrated photonics. They boast high transparency at communication wavelengths, vast compositional and processing versatility, mechanical flexibility, and low refractive indices matching that of silica fibers, attractive attributes that complement those of inorganic optical materials such as silicon and silicon nitride. Polymer waveguides are readily amenable to both on-chip and on-board integration and they also claim low propagation losses below 1 dB/cm, making them a promising optical interconnect platform [1–8]. In addition, unlike traditional photonic devices which are almost exclusively made on rigid substrates, polymer waveguides can be made highly flexible, capable of sustaining bending, twisting, and even stretching [9–13], emerging as potential alternatives to replace fiber bundles in space-constrained applications with significantly enhanced channel density and minimized form factors. This feature leads to a new photonic assembly scheme leveraging mechanically compliant polymer waveguides to interface photonic chips and fiber package [14], where low effective indices of the polymer waveguides also decrease Fresnel reflection in fiber coupling and facilitates mode conversion. When it comes to biophotonic applications, the mechanical flexibility of polymers minimizes the elastic mismatch between biological tissues and photonic components, enabling conformal integration for optical sensors on curvilinear tissue surfaces (e.g. human skin) and reduced tissue damage caused by implanted devices [15,16]. Finally, the ability to sculpt 3-D sub-wavelength structures in polymers using two-photon lithography offers unprecedented design degrees of freedom for agile light coupling and manipulation [17–20].

For many of the aforementioned applications of polymer photonics, realizing single-mode transmission is essential. Single-mode waveguides circumvent intermodal dispersion and also permit dense photonic integration commensurate with the ever-increasing bandwidth density demands for photonic I/O [21,22]. They are also necessary for interfacing on-chip waveguides with standard single-mode optical fibers in photonic packaging with intermediate mode sizes and lithographically-defined waveguide arrays [23]. In biophotonic sensing, meeting the single-mode condition avoids ambiguity in data interpretation due to the co-existence of multiple modes with different overlap factors in the sensing medium [24].
Despite these advantages, single-mode polymer waveguides generally exhibit much higher propagation losses compared to their multi-mode counterparts. While propagation losses as low as 0.03 dB/cm have been demonstrated in multi-mode waveguides [25–33], the minimal loss figures in single-mode waveguides remain at 0.14 dB/cm (at 808 nm wavelength [33]) mainly due to increased modal overlap with roughness and defects at the core/cladding interfaces.

In this paper, we describe fabrication and measurement of flexible waveguides and photonic components in commercially available polymers. The devices are prepared using a standard UV lithography and etching process optimized for low-loss single-mode waveguiding. Mechanical durability of the flexible waveguides was also characterized, indicating high flexibility and robustness of the photonic devices.

2. Device fabrication

Here we use Ormocer polymers (Micro Resist Technology GmbH) to fabricate the devices. These UV-curable organic-inorganic hybrid polymers exhibit low intrinsic absorption loss (~0.03 dB/cm at 850 nm wavelength), tailorable refractive indices (between 1.523 and 1.542), excellent adhesion to various substrates, high environmental stability, and validated biocompatibility [34]. These appealing features qualify Ormocer as an ideal material candidate for polymer photonic device processing. To obtain low-loss single-mode waveguides, we choose to use standard i-line lithography and etching over direct UV or laser writing [35], as we have experimentally compared both techniques and found that the former approach offers improved dimensional accuracy (without volume shrinkage due to photo-curing) and reduced propagation loss (the i-line projection lithography tool with 5x magnification offers lower line edge roughness compared to the laser direct write tool). As shown in Fig. 1(a) in steps 1-6, the fabrication process started with RCA-cleaned thermal oxide coated wafers as the substrates. A polyimide support layer (PI2574, HD MicroSystems) and a bottom cladding layer (OrmoClad, $n = 1.523$ at 850 nm), both of which are 10 μm in thickness, were sequentially spin-coated on the substrate. A 2.3-μm-thick core layer (OrmoCore, $n = 1.542$ at 850 nm) was subsequently spin-coated and UV cured in a nitrogen environment. The wafer was then treated with vapor phase hexamethyldisilizane (HMDS) in an oven to promote adhesion between photoresist (SPR220 3.0) and the core layer. Next, the photoresist was patterned on an i-line stepper (GCA AutoStep 200). Subsequent through etch patterning was performed using an oxygen-fluorine chemistry in an inductively coupled plasma (ICP) etcher (Oxford PlasmaPro 100 Cobra 300) to define the strip waveguide geometry, followed by a short oxygen plasma cleaning step to remove residual surface C-F (Teflon) contamination. The optimized waveguide etching parameters are summarized in Table 1. The etched waveguide has a smooth sidewall with low roughness as shown in the scanning electron microscope (SEM) image (Fig. 1(b)). Once the etch was complete, the sample was rinsed in acetone and isopropanol to remove the resist. Finally, an OrmoClad top cladding layer of 8 μm thickness was spin-coated and UV cured to encapsulate the devices.

The etching recipe shown in Table 1 is optimized for organic-inorganic hybrid polymer etching. O$_2$ ashes the organic side chains of the polymer, whereas CF$_4$ is introduced to produce F radicals to chemically remove the Si-O backbones of the hybrid polymer. The substrate temperature is a critical parameter and should be kept constant during etching: due to the prolonged etching process (~25 min), the photoresist mask can reflow if the substrate temperature is not stabilized, resulting in waveguide dimensional deviations; in addition, high substrate temperature gives rise to excessive formation of C-F polymers, and micro-masking results. In our process, the substrate is attached to a temperature-controlled helium-cooled wafer carrier with thermal paste to prevent temperature rise.

To create freestanding, flexible devices, the Si substrate is partially removed using deep reactive ion etching (DRIE) on an Omega LPX Rapier etch system (SPTS Technologies). In this process (Fig. 1(a), in steps 7-8), the polyimide layer underneath the bottom cladding
provides adequate mechanical support to the flexible devices and also acts as an etch stop for DRIE. The DRIE process can be masked using Kapton, for instance to protect the substrate at the two ends of the flexible waveguide ribbon to facilitate sample handling (Fig. 1(c)). Our measurements assure that the substrate removal process does not impact the device optical characteristics.

Table 1. Optimized OrmoCore polymer etching conditions

<table>
<thead>
<tr>
<th>Gas flow</th>
<th>O₂ / 10 sccm</th>
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<tbody>
<tr>
<td></td>
<td>CF₄ / 30 sccm</td>
</tr>
<tr>
<td>Plasma power</td>
<td>ICP / 900 W</td>
</tr>
<tr>
<td></td>
<td>RF / 50 W</td>
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<tr>
<td>Pressure</td>
<td>50 mTorr</td>
</tr>
<tr>
<td>Temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Etch rate</td>
<td>~100 nm/min</td>
</tr>
</tbody>
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3. Flexible waveguide characterizations

To ensure single-mode operation, the waveguides are designed to have a core dimension of 2.3 µm × 2.3 µm. The waveguide cross-sectional structure is illustrated in the inset of Fig. 2. The devices were characterized using a fiber end fire coupling configuration. A superluminescent diode (QFLD-850-100S-PM, QPhotonics LLC) was used as a light source. Light was coupled into/out of the devices through lensed fiber tapers (OZ Optics), and the output was monitored using an optical spectrum analyzer (Yokogawa AQ-6315A OSA).

Figure 2 shows the waveguide loss across the superluminescent diode spectrum (830 nm – 900 nm) measured using a cut-back method using a series of spiral structures with lengths up to 29.6 cm. A minimal propagation loss of (0.11 ± 0.004) dB/cm was obtained at 840 nm wavelength with negligible polarization dependent loss (PDL) between the transverse electric (TE) and transverse magnetic (TM) modes. The negligible PDL is consistent with the low sidewall roughness observed in our etched waveguides [36]. The loss peak at 875 nm is attributed to the 4th order overtone absorption resulting from asymmetric stretching of C-H bonds present in the organic side chains of Ormocer polymer [37,38]. Cross talk between parallel waveguides was also characterized, and waveguide arrays with a pitch of 25 µm and a
length of 1.3 cm exhibits cross talk below −30 dB, enabling dense photonic links at the chip edges.

Performance of the flexible waveguide ribbon under repeated mechanical deformation was also quantified. An experimental setup (shown in Fig. 3(a)) similar to our previous reports [39–41] was used for the waveguide transmission measurement. Transmittance of the flexible waveguides after 1,000 bending cycles at a radius of 2 mm was compared to its as-fabricated state before the bending test (Fig. 3(b)). The data show that the optical attenuation variation is mostly within the error bar of the loss measurement. The results therefore indicate excellent mechanical flexibility and durability of the flexible waveguide ribbon compared to prior reports [6].

![Fig. 2. Measured waveguide propagation loss; inset shows the cross-sectional structure of the waveguide with simulated mode profile.](image)

![Fig. 3. (a) Experiment setup for flexible polymer waveguide ribbon measurement; (b) transmittance variation of the flexible waveguides after 1,000 bending cycles at 2 mm bending. Here positive numbers correspond to a drop in transmission and negative numbers imply an increase of measured transmittance compared to that of as-fabricated waveguides.](image)

### 4. Passive photonic components

Using the same fabrication protocols described herein, we further demonstrated an array of passive polymer photonic components including 1 × 2 MMIs (Fig. 4(a)), waveguide Y-branches (Fig. 4(b)), crossings (Fig. 4(c)), and 90° bends, which are essential to optical signal/power routing and distribution. The MMIs were first designed analytically following the self-imaging principle [42], and then optimized for operation at 850 nm wavelength using a full-vectorial finite-difference time-domain (FDTD) solver (Lumerical FDTD Solutions). The optimal length and width of the 1 × 2 MMI were 358 µm and 18.6 µm, respectively with a simulated insertion loss (IL) of 0.12 dB at 850 nm wavelength. The 1 × 3 MMI design has a negligible excess loss of 0.06 dB at 850 nm and splitting uniformity of less than 0.3 dB. The Y-branch layout comprises two identical S-bends with 2 mm bending radius emanating from
a common single-mode input waveguide. FDTD modeling predicts a low insertion loss of 0.004 dB at 850 nm.

In our experiment, three devices were characterized for each type of device. Figures 5(a)-5(b) plot the average measured wavelength-dependent IL and uniformity of the 1 × 2 MMI and the Y-branch, respectively. Here IL is taken as the excess loss of the device measured against a reference waveguide of the same length, and uniformity is defined as $IL_{avg} = 10 \times \log(P_1 / P_2)$, where $P_1$ and $P_2$ are the measured power of each MMI or Y branch output port. The MMI exhibits a moderate IL of approximately 0.25 dB between 840 – 860 nm wavelengths and an excellent uniformity below 0.1 dB. In contrast, the Y-branch has a low IL (~0.1 dB) around 850 nm, but its uniformity is more wavelength dependent, indicating the Y-branch structure’s higher sensitivity to wavelength variation and fabrication errors. The optical properties of both devices show only minor differences between TE/TM polarizations, consistent with our simulation results.

![Image](https://example.com/image1)

**Fig. 4.** SEM image of (a) 1 × 2 MMI, (b) Y-branch, and (c) 45° waveguide crossing. Insets show detailed structure at high magnification.

![Image](https://example.com/image2)

**Fig. 5.** Measured insertion loss (IL) and uniformity of (a) 1 × 2 MMI and (b) waveguide Y-branch; (c) insertion loss spectrum of waveguide crossings with 45° and 90° crossing angles; (d) simulated and measured waveguide bending loss as a function of bending radius.

Waveguides with different bending radii and crossing angles were also fabricated and characterized. Figure 5(c) shows the insertion loss spectra of waveguides with 90° and 45°
crossings. The 45° crossings exhibit higher IL than the 90° crossings, as the mode is more likely to leak into the other waveguide for smaller crossing angles [43,44]. Cross talk between the crossing waveguides is below the noise floor of our measurement system (< −40 dB). Again, no obvious polarization-dependent loss was observed in the crossings. The waveguide bending loss (loss due to modal mismatch at the straight/curved junctions is also included) was measured for the TE polarization using test structures illustrated in Fig. 5(d) inset. The measurement data agree very well with simulation results (Fig. 5(d)), suggesting that waveguide bends with > 1.5 mm bending radii exhibit negligible bending loss.

5. Conclusions

We demonstrated single-mode flexible polymer waveguides with a record low propagation loss of 0.11 dB/cm at 840 nm wavelength using standard UV lithography and etching. In addition to their low optical loss, the waveguides also exhibit excellent mechanical flexibility and ruggedness, capable of withstanding over 1,000 bending cycles at 2 mm bending radius. Passive photonic components including MMIs, Y-branches, and waveguide crossings were also realized in the polymer photonics platform. The waveguide materials used in our work are also environmentally stable and biocompatible, making the polymer photonics technology a viable solution for applications such as data communications and biophotonics.

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References


