Polymer Waveguides for Co-Packaged Optics

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This paper demonstrates a low-loss photopatternable polymer waveguide material platform based on benzocyclobutene (BCB) that works in both liquid resins and dry film formats. By precise control of molecule design and refractive index between the core and clad layers, we minimized material absorption at target wavelengths, achieving a propagation loss value of <0.1 dB/cm at 850 nm and <0.3 dB/cm at 1310 nm at the system level based on cutback measurements. We patterned these waveguides on silicon and PCB substrates with laser direct imaging (LDI) or mask aligner, with sub-10 µm accuracy. Moreover, our patterned waveguides maintain thermal stability, with <±5% change in optical loss after multiple reflow processes and 1000 h at 85 °C and 85% humidity (HAST) tests. Lastly, we introduce our modeling framework, predicting transmission, mode profile, and optimal performance of waveguides while considering varying geometries, coupling designs, bend radii, and pitch sizes.

Keywords—Polymer waveguide, on-board optics, single mode, multimode, photopatternable, low loss

I. Introduction

The exponential growth of data traffic in both data centers and high-performance computing has created a need for new, efficient technologies. Advanced optical design, such as Co-Packaged Optics (CPO) or embedded optics at the board level, presents an opportunity for the industry to lower energy consumption while providing high-speed data communication at a desirable cost, latency, and bandwidth. Optical fibers are widely used in CPO assembly, but polymer waveguide has emerged as a new alternative. One notable difference is the pitch size, where polymer waveguide has a smaller pitch size, allowing for higher density and bandwidth. Additionally, polymer waveguide is easier to assemble, which can help reduce manufacturing costs compared to optical fiber [1].

Benzocyclobutene (BCB) based material has been widely used for waveguides in academic literature due to its great material properties including low moisture absorption, low optical loss, high chemical resistance, and high thermal stability. For example, L-Y Chen et al. fabricated single mode BCB optical waveguides fabricated by the UV pulsed-laser illumination method with ~0.6 dB/cm propagation loss at 1548nm. More recently, R. Zhang et al prepared single mode waveguides using BCB based DuPont CYCLOTENE 6505 on glass substrates and observed ~0.6 dB/cm loss at 1310 nm.

In this report, we introduce a new class of BCB based materials with low optical absorption. The refractive index (RI) delta between core and clad can be precisely controlled for single mode (SM) and multimode (MM) applications. Depending on the fabrication requirements, we can prepare different sample formats (liquid resins or dry films) that can be patterned by preferred exposure tools (mask aligner or laser directly imaging (LDI)) on both Si wafers and PCB substrates. The loss of patterned waveguides is <0.1 dB/cm at 850 nm and <0.3 dB/cm at 1310 nm through the cutback method with excellent thermal and moisture stability. Together with the modeling framework, we demonstrated a commercially viable pathway to introduce polymer waveguides for various co-packaged optics applications.

II. Materials and process development

A. Materials

We developed various BCB based formulations targeting for both SM and MM applications on wafers and PCBs. See the summary in Table 1. Depending on different target applications, we can precisely control the RI delta between the core and the clad of the waveguide (numerical aperture) ranging from 0.003 to 0.02. Due to the nature of the BCB crosslinking chemistry, all the developed formulations have low birefringence, which is preferred for optical communications. In addition, we design the formulation to ensure the core and clad materials have similar dn/dT values, which allow the waveguide to maintain the NA at different working temperatures. In this report, we fixed the RI delta at 0.004 for single mode applications and 0.015 for multimode. The RI values are measured by Metricon at different wavelengths, while the dn/dT is measured by a J.A. Woollam spectroscopic ellipsometer.

Table 1: Summary of the developed BCB waveguide material properties. The loss results are the propagation loss of the patterned waveguides measured by the cutback method.

Products	Sample format	patterning	Loss at 1310nm	Loss at 850nm
CYCLOTENE 6505	Liquid resin	Mask aligner	0.5 dB/cm	--
Type A	Liquid resin&dry film	Mask aligner/LDI	0.39 dB/cm	0.088 dB/cm
Type B	Liquid resin&dry film	Mask aligner/LDI	0.3 dB/cm	--
Type C	Liquid resin	Dry etching	0.2 dB/cm	--

B. *Process Development*

The patterned waveguide has a buried channel structure. The CYCLOTENE™ 6505 RDL and Type C materials are liquid resins only, while Type A and Type B materials offer both liquid resin and dry film formats. Other than the type C material, all the other formulations, both core and clad, can be patterned with i-line exposure tools. For the liquid resins, the film is cast by spin-coating; and the dry film samples can be laminated by either hot roll or vacuum lamination. The developer used in this study is Tetramethylammonium hydroxide (TMAH), while metal ion carbonate developer study is ongoing. The films are cured under N_2 or vacuum at 220 °C for 1 hour. We then diced the full-stack waveguides on either wafers or PCB boards for the metrology study and loss measurements without any additional polishing steps.

III. WAVEGUIDE PATTERNING

CYCLOTENE 6505 RDL is a positive-tone photo dielectric material known for achieving sub-5 µm resolution and >1:1 aspect ratio. To match the core size of the SMF-28 Corning fibers, we targeted a feature size close to 8.2 µm. As shown in Fig 1. (A) and (B), the patterned waveguides have trapezoidal shapes, and we were able to pattern smooth curves around bends.

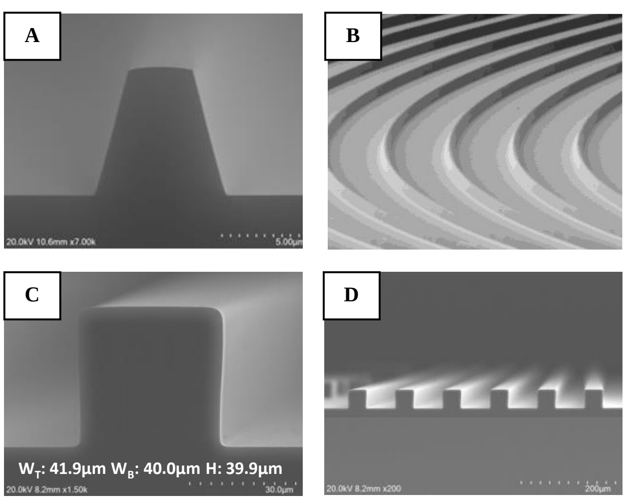

Fig. 1: SEM images of the patterned waveguides on Si wafers. The films were spin coated and exposed by the i-line mask aligner. (A) and (B): CYCLOTENE 6505 on Si wafer; (C) and (D): Type A core on clad on Si wafer.

The Type A and Type B developed materials are negative-tone materials available in both liquid resin and dry film formats. This class of material can achieve >1:1 aspect ratio resolution at film thickness ranging from 5 to 80 µm. Here, we primarily demonstrate the patterning resolution of the Type A material, which is specifically designed to support MM applications, with a target feature size of 40 µm. As shown in Fig. 1 (C) and (D), we coated a 40 µm core on top of a 20 µm clad and then patterned the core layer through a mask aligner. The sidewall angle of the patterned waveguides is closer to 90°, with a low surface roughness. We applied an adhesion promoter between the clad and the wafer, but no adhesion promoter was used between the core and clad layers, and there are no signs of delamination.

We further evaluated the patterning resolution of the Type A dry films. Here, the substrate is a regular multilayer FR4 PCB boards. We first laminated the 20 µm clad and 40 µm core layers

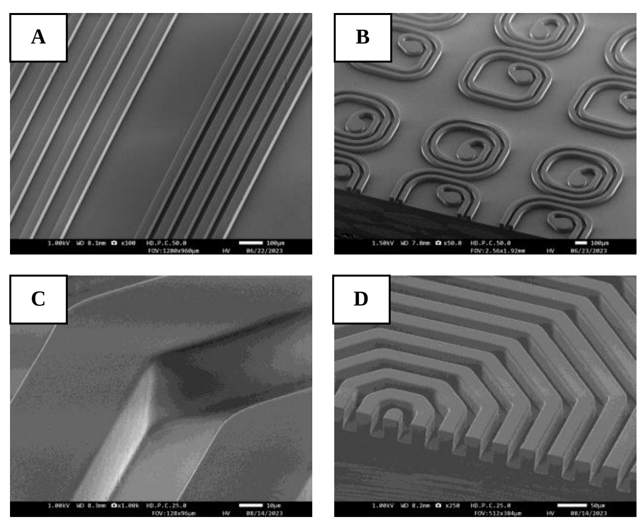

Fig. 2: SEM images of the patterned waveguides on PCB substrates. The films were laminated by the vacuum laminator and exposed by a 375 nm LDI tool from Orbotech. (A) to (D): Type A materials.

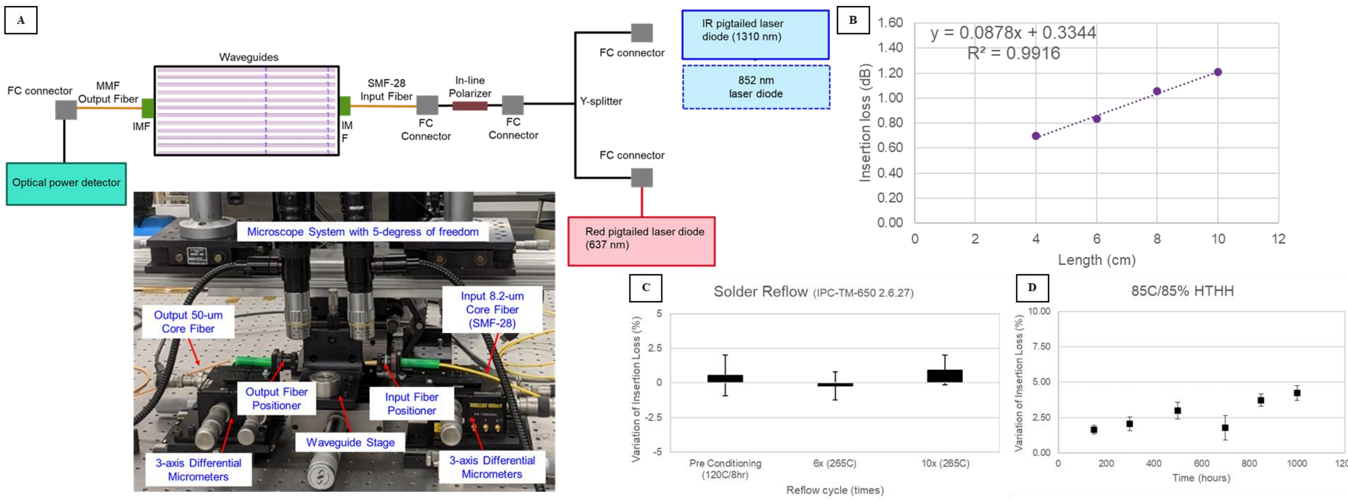

Fig. 3: Loss measurement and reliability testing of the waveguides. (A) the block diagram and the picture of the waveguide measurement setup. (B) the cutback measurements of 40 µm Type A multimode waveguides on wafer. The wavelength is 850 nm; (C) & (D) reliability testing (reflow and HAST) of single mode CYCLOTENE 6505 waveguide. The wavelength is 1310 nm.

and then imaged through 375 nm LDI. No adhesion promoter was required between any lamination steps. As shown in Fig. 2, we achieved high resolution patterning in various design shapes with a smooth sidewall. This result confirms that Type A material is suitable for both wafer-level packaging as a liquid resin and board-level packaging in the dry film format.

IV. Waveguide Loss Measurement and Reliability

The patterned waveguides, whether on a wafer or a board, were cut to a specific length for loss measurements. We used the cutback method to decouple the propagation loss and the coupling loss. Plotting the loss value at different lengths allows us to determine the propagation loss from the slope and the sum of the coupling loss at both ends from the intercept.

The measurement setup is shown in Fig. 3A. We have two laser sources at 850 nm and 1310 nm, targeting multimode and single mode light loss measurements. An 8.2 µm SMF28 fiber and a 50 µm multimode fiber are used as the input and output fiber, respectively, for all insertion loss measurements. To decrease the coupling loss, we add index matching fluid between waveguides and fibers.

Fig. 3B is a representative plot of the cutback loss measurement. We measured the loss at 850 nm of Type A 40 µm waveguides at 4, 6, 8 and 10 cm, and each data point was an average of 8 to 12 waveguide samples. As shown in the graph, the propagation loss of the waveguide is 0.088 dB/cm, and the coupling loss is 0.33 dB.

We further studied the reliability of the waveguide samples. Fig. 3(C) and 3(D) show the reflow and high temperature, high humidity testing results of single mode CYCLOTENE 6505 waveguides. The insertion loss changes at 1310 nm were less than 5% after 10X reflow (following the temperature ramping profile in the IPC-TM-650 2.6.27 standard) or 1000 hours at 85 °C and 85% humidity. The reliability testing of Type A waveguide for multimode application is still ongoing. The good reliability performance of the BCB based waveguide material is critical for market adoption.

V. Modeling

Our material development/design effort has been supported by a complementary device simulation capability. This overall capability includes passive component simulation using Fimmwave and Fimmprop (PhotonDesign), active thin film design using Setfos/Laoss (Fluxim), and classical microoptics using OpticStudio (Zemax/Ansys).

We have modeled the waveguide mode profile (single mode/multimode cutoff for different geometries), pitch size requirements (avoiding the crosstalk), radius of curvature tolerance (minimizing the loss around the bends) and lens design

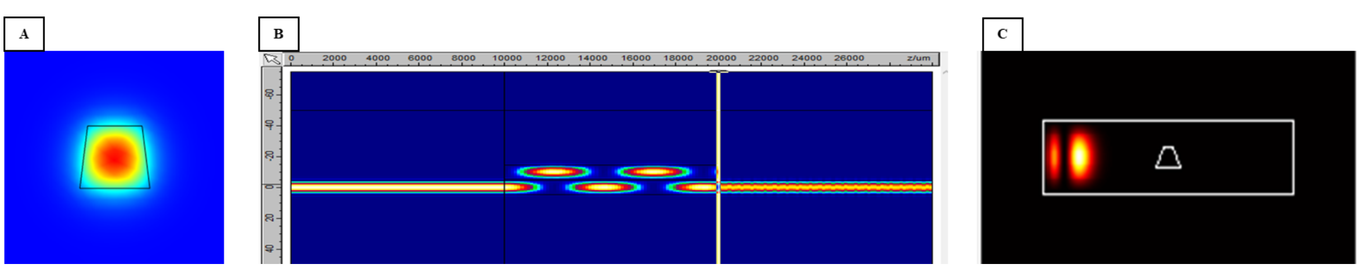

Fig. 4: Representative modeling results of (A) mode profile of a single mode waveguide; (B) crosstalk between two waveguides; and (C) the super-mode profile of the waveguide around 90° bend.

(light coupling between waveguide and photonic engine). Fig 4. presents a few representative pictures from the modeling study.

VI. Conclusion

In this paper, we have demonstrated the successful fabrication of single mode and multimode waveguides using various BCB-based formulations. Our experiments show low loss at both 850 nm and 1310 nm, making our approach highly promising for use in co-packaged optics. The processing techniques we've developed are compatible with existing wafer and board packaging infrastructure, making the adoption of this technology straightforward. Our results highlight the potential for BCB-based materials in optical interconnects and pave the way for further research in this field.

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