First Demonstration of Single-mode Polymer Optical Waveguides with Circular Cores for Fiber-to-waveguide Coupling in 3D Glass Photonic Interposers

Rui Zhang^, Fuhan Liu, Venky Sundaram, and Rao Tummala
3D System Packaging Research Center
Georgia Institute of Technology
Atlanta, GA
rzhang@gatech.edu

***Abstract*—A simple and low-cost fabrication method for single-mode polymer optical waveguides with circular cores was demonstrated for fiber-to-waveguide coupling. The waveguide structure consists of trenches with semicircular cross sections, fabricated with dry film benzocyclobutene (BCB) as the bottom cladding layer, circular cores embedded inside the trenches, and another layer of dry film BCB as the top cladding layer. Simple photolithography is used to pattern both trenches in the bottom cladding layer and cores, and only one mask is used for both lithography steps. The advantages of single-mode circular waveguides on ultra-thin 3D glass interposers are discussed by comparing optical properties of those with conventional polymer waveguides with trapezoidal cross sections. To the best of the author's knowledge, this is the first demonstration of single-mode polymer waveguides with circular cross sections. Fabrication of circular-core waveguides are discussed and geometry characterization and analysis are performed.**

Keywords-polymer optical waveguide; circular core waveguide; BCB; 3D glass interposer

I. INTRODUCTION

As global IP traffic continue to rise, low-cost low-loss and high-capacity interconnections are needed to meet the increasing demands [1]. Optical interconnect technologies have been the best choice for telecommunications due to its unmatched propagation loss and high capacity. However, it has not been exploited in shorter-distance communications due to its high cost and overall loss. With increasing demands for processing speed and bandwidth for chip-to-chip communications in high performance computers and servers, optical interconnection technologies are considered a promising candidate to address the challenges. There are two main reasons that contribute to high cost. One is the tight requirement for single mode fiber alignment, and the other is the complicated structure build on the substrate to compensate coupling loss.

Several approaches are investigated as a solution to address the fabrication challenges and associated cost. Silicon photonics has been widely investigated as the future of optical communications because of its on-chip integration of photonics and electronics [2]. However, currently, silicon photonics is considered a high-cost approach. Waveguides in silicon photonics are extremely low loss (~0.1 dB/cm) [3], but direct coupling from a single-mode fiber to a waveguide in silicon photonic chip have a high loss (~20 dB) due to the large-mode mismatch between the fiber core (~ 55 µm2) and the on-chip waveguide core (~ 0.2 µm2). Brusberg et al., at Fraunhofer IZM built electro-optical circuit boards on glass substrates [4], and fabricated waveguides in the glass using a two-step thermal silver ion-exchange process. This leads to low-loss single-mode waveguides on glass substrates. This approach also needs high-cost active alignment for fiber assembly. Soma et al., at Keio University fabricated graded-index multimode circular polymer waveguides by mosquito method [5]. Waveguides were fabricated by using a moving needle to dispense core monomer into the viscous cladding layer, followed by curing and cladding under UV exposure. This method is good for multimode waveguides, but it is not applicable on single-mode waveguides due to the small core cross section area and the viscosity of the polymer.

Optical communications through single-mode fiber and single-mode waveguides draw a lot of attentions these days due to the high bandwidth demand. Glass interposers, developed at Georgia Tech Packaging Research Center, have emerged as a superior candidate compared to traditional silicon and organic interposers [6]. Glass has low optical absorptions at telecommunication wavelength, a refractive index matching optical fibers, low electrical loss, low electrical loss and panel level processing technology. For increasing power efficiency and capacity for the optical link, circular-core single-mode polymer waveguides on glass substrates are investigated. Polymer as a waveguide material has refractive index close to optical fiber, relatively large dimension for fiber coupling compared to silicon-based waveguides, and simple fabrication process. Several kinds of polymers such as poly(methylmethacrylate) (PMMA) [7], polystyrene (PS) [8], siloxane [9], etc. have been investigated. Benzocyclobutene (BCB) was chosen as the waveguide material because of its low loss at telecommunication wavelength, high glass-transition temperature, low dissipation loss and high breakdown voltage [10] [11]. In this paper, both circular-core single-mode BCB waveguides and traditional trapezoidal single-mode waveguides were fabricated on glass substrates. Geometry characterization of the fabricated waveguides are discussed.

TABLE I. PROPERTIES OF CHOSEN MATERIALS

Material	**CYCLOTENE 6505**	**14-P005**	**SGW3**
RI @ 1550 nm	1.5575	1.543	1.4935
T_g/ °C	300	300	670
Thickness/µm	6	10	150
CTE (ppm/°C)	45	63	3.2

II. MODELING AND DESIGN

CYCLOTENE™ 6505 (liquid BCB) is used as the core material. It is a positive-toned, photo-definable and aqueous developable BCB-based polymer developed by Dow Electronic Materials. BCB in dry film form 14-P005 (dry film BCB) by Dow Electronic Materials was chosen the cladding layer. The glass substrates (SGW3) were provided by Corning Inc. The basic properties of these three materials are listed in Table 1.

Geometry of the cross-section of the waveguide core influences the effective refractive index of the propagating beam. Mode calculation for circular waveguides is simple due to the similarity between circular waveguides and optical fibers. In the current approach, liquid BCB as core material is embedded in the dry-film BCB as the cladding material. Liquid BCB has a refractive index of 1.5575 at 1550 nm, while dry film BCB has a refractive index of 1.543 at 1550 nm, and such a material system has a numerical aperture of 0.21. V is the parameter that determines the mode of a material system, and is defined as follows:

$$V = \frac{2\pi \times a \times NA}{\lambda}. \quad (1)$$

where a is the radius of the core, NA is the numerical aperture and λ is the wavelength of the light. The single-mode condition requires that the V of the system is less than 2.405. Therefore, for the wavelength of 1550 nm, the maximum diameter of the core is 5.6 µm.

For trapezoidal-core waveguides, maximum height is desired to relax the alignment requirement in y direction while measuring the loss of the waveguide. The maximum height achieved with liquid BCB was 6 µm, with a 77° sidewall angle [12]. The schematic of the cross-section of such a system is shown in Fig. 1(a), as the glass is the bottom cladding layer and the dry-film BCB is the top cladding layer.

In order to reduce the alignment requirement in x direction during characterization, the maximum waveguide width as single-mode waveguides need to be calculated. For trapezoidal waveguides, COMSOL Beam Envelope Method is used to calculate the effective refractive index of lower-order modes and determine the critical geometry parameter to achieve the single-mode condition. Glass with a refractive index of 1.4935 is the bottom cladding layer for trapezoidal

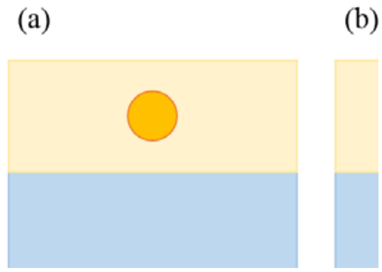

Figure 1. Schematic cross sections of (a) circular waveguide and (b) trapezoidal waveguide.

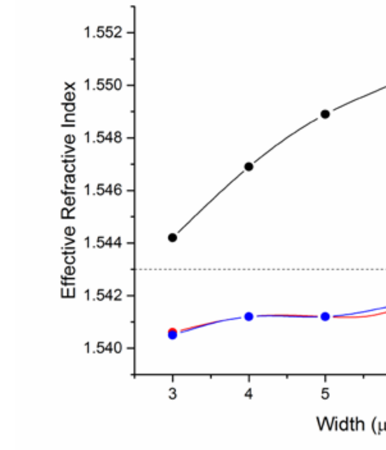

Figure 2. Mode simulation of trapezoidal waveguide with 6 µm height by COMSOL beam-envelope method for 1.550 µm wavelength.

waveguides, and dry-film BCB with a refractive index of 1.543 is the top cladding layer. Simulation shows that the maximum of the long base for the wavelength of 1550 nm is 6.8 µm. The simulation results are shown in Fig. 2. When the long base of the cross section is smaller than 6.8 µm, only TEM00 mode is supported in this waveguide for 1550 nm light.

III. FABRICATION

A. Circular Waveguides

The fabrication of circular waveguides is shown in Fig. 3. Circular waveguides were fabricated in two steps. The first step involves the fabrication of semicircular trenches in the bottom cladding layer. Because the widths of designed patterns are less than 10 µm, when they are transferred onto

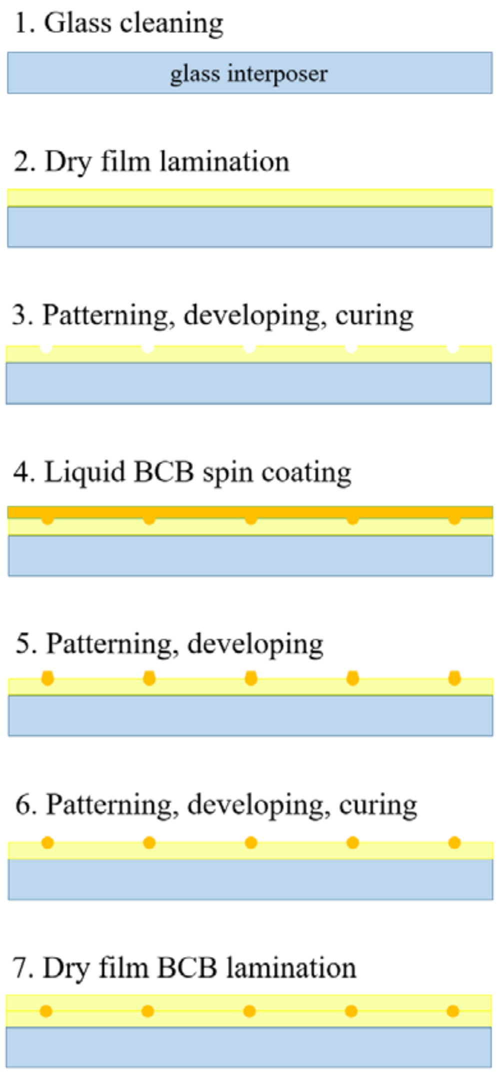

Figure 3. Fabrication of circular core wacveguides.

the dry film, such small features could not completely shield the underneath material from exposure, so that the etching chemical would not be able to penetrate the whole layer down to the substrate and stop at partially exposed material. After development, semicircular trenches were formed. Second step deals with the fabrication of the waveguide core using simple photolithography. After spin coating and developing liquid BCB, cores with a trapezoidal shape cross section were formed. During the curing process, cores would reflow at elevated temperature, lose trapezoidal cross sections, and finally form semicircular tops. The circular cores were fabricated after these two steps, and the same mask was used in both the trench fabrication and the core formation process.

B. Sample fabrication

Trapezoidal core waveguides were also fabricated in order to make comparison with circular core waveguides. These two kinds of waveguides were fabricated on different sides of one glass substrate, as shown in Fig. 4(a). Fig. 4(b) shows the top view of one diced sample with waveguides on it. The process steps were as follows:

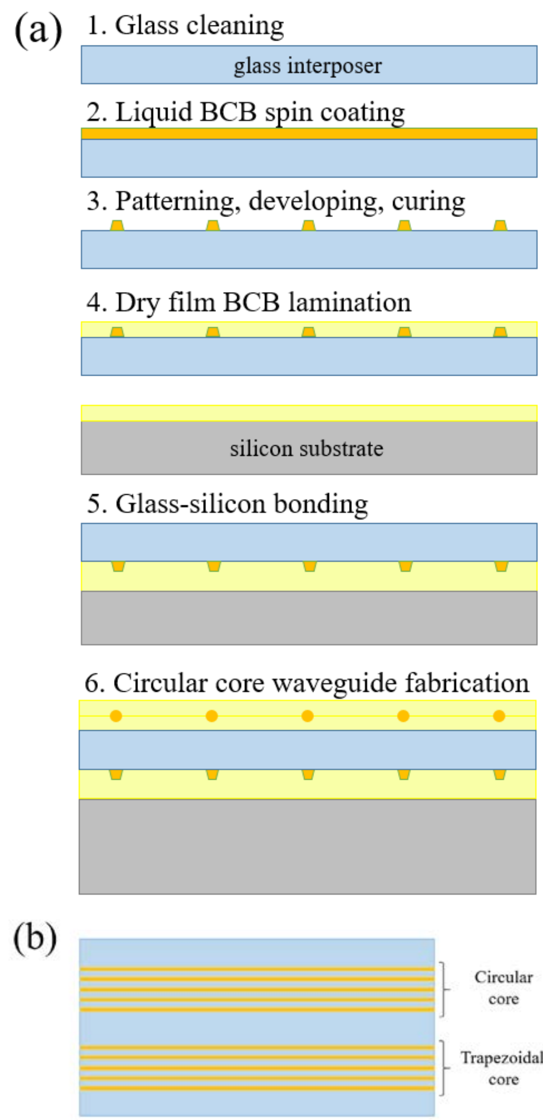

Figure 4. (a) Fabrication process of the complete sample and (b) schematic of the top view of a diced sample with waveguides of both cross sections.

1) The glass surface was cleaned by solvents and plasma etching.
2) Adhesion promotor was spin coated onto the glass, and heated to activate it.
3) Liquid BCB was spin-coated, soft-baked to remove solvents.
4) The liquid BCB film was patterned, developed by Tetramethylammonium hydroxide (TMAH), and cured to form a trapezoidal shaped core.
5) Dry-film BCB was laminated onto glass as both upper cladding layer and an adhesive. Dry-film was also laminated onto a silicon wafer.

6) Glass was flipped over and bonded to the silicon wafer by lamination tool and then cured.
7) The glass surface was cleaned by solvents and plasma etching.
8) Adhesion promotor was spin coated onto the glass, and heated to activate it.
9) Dry-film BCB was laminated onto the glass, patterned, developed by DS3000 from Dow Electronic Materials, and cured.
10) Adhesion promoter was spin-coated, and heated to activate it.
11) Liquid BCB was spin-coated onto the dry film, patterned by Ushio projection aligner, developed and cured.
12) Dry-film BCB was laminated and cured as top cladding layer.

For pure circular-core waveguide fabrication, only Steps 7 to 12 are needed. To cure trapezoidal core waveguides, the sample was kept in a nitrogen oven (Blue M Electronics) at room temperature, heated up to 130℃ and kept for 15 minutes to remove excessive solvent in the core material, so that the waveguides retain their shape in the following process. The sample was then heated to 230℃ for 1 hour, and cooled down in nitrogen atmosphere to avoid oxidation at high temperature. To fabricate semicircular tops of the cores, the sample was inserted into the oven at 150℃, heated up to 230℃, kept for 1h and then cooled down. A vacuum laminator MEIKI MVLP300 was used to laminate the dry-film BCB as the top cladding layer and protection layer, and another layer of dry-film BCB onto a silicon substrate as adhesive. Glass and silicon wafers were bonded to each other with dry-film BCB adhesive. Silicon wafers were used in the fabrication process because they served as the back-bone for the structure and helped protect the glass-interposer from cracking during the dicing process later. Circular waveguides were fabricated on the other side of the glass by the method mentioned at the beginning of this section. During the semicircular trench fabrication process, alignment marks were also patterned onto the dry-film to achieve sub-micron alignment with the core layer. Finally, the top cladding layer was cured and laminated. The samples were diced into long slices to prepare them for cross-section observation and the propagation loss measurements.

IV. CHARACTERIZATION AND DISCUSSION

The fabricated wafers were cleaned and diced into several waveguide samples using Disco dicing tool DAD3360. MBT-A161 SD1500L25MT101 diamond blade with 80 µm thickness was used for the dicing step. Each sample has both circular-core waveguides and trapezoidal-core waveguides on it, as shown in Fig. 4. Feed-speed of the dicing saw is set to as low as 0.5 mm/s in order to avoid glass cracking and blade damage. The edges of each sample were then polished in order to observe the geometry of the cross section.

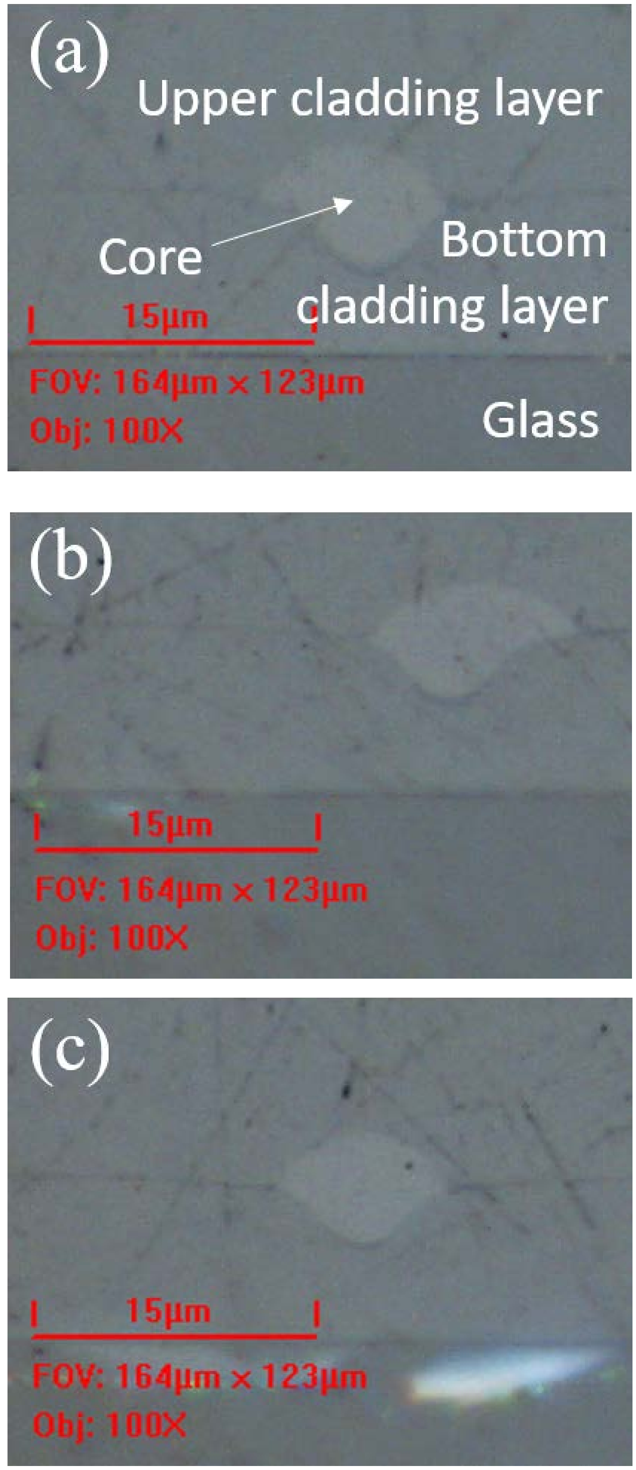

Figure 5. Cross section images of (a) a waveguide core with left-shift on top, (b) a waveguide core with right-shift on top, and (c) a waveguide core without shift.

Cross-section images of circular-core waveguides at different locations along waveguides on the wafers are shown in Fig. 5. Fig 5(a), (b), (c) are on the cutting lines located at 0 cm, 2 cm, and 4 cm from one end of the waveguides. Fig. 5(a) shows that there is about 1 µm left-shift from the top-half of the core to the bottom part. Fig. 5(b) shows the shift in the opposite direction. This is because there was a ~0.003° misalignment in the stage-turning angle when alignment was performed. Fig. 5(c) shows one waveguide core with top-half and bottom-half aligned to each other with no shift. The depth of the trench in the bottom cladding layer is 2.8 µm, and the height of the top semicircular core is 2.8 µm. The total height of the core is 5.6 µm as shown in Fig. 6(a), which meets the single-mode condition of 5.6 µm. Widths of the cores are larger than the designed geometries. This deviation occurs because of two reasons. First, the development on the bottom cladding dry-film layer makes the trench have tails on both sides in the horizontal direction. Second reason is that the cores (formed from liquid BCB) are under-developed. Trenches in dry-film have radius of curvature of around 2 µm, and the radius of curvature of the top of the core is about 7.5 µm.

Trapezoidal-core waveguides were also measured from different cross-sections, an example of which is shown in Fig. 6(b). The length of the long base is around 6.6 µm, which is well-within the maximum length for single-mode condition. The height is about 4.4 µm, which is shorter than the designed height. This height difference is presumably from the fact that exposure intensity is lower than what was targeted.

These results show that, even though the top-half of the core is strictly aligned with the bottom half, the geometry of the core is still not perfectly circular. Several approaches might be pursued to achieve the circular shape. When fabricating the trenches in the dry-film BCB, increasing the exposure dose and reducing the developing time can create trenches with larger radius of curvature. After trenches are fabricated and the bottom cladding layer is cured, increasing the exposure intensity on the core layer, and extending the developing time in order to eliminate the filling of tails can also enable the formation of a round top shape with a smaller radius of curvature.

V. CONCLUSION

Concept demonstration of circular-core single-mode polymer waveguides on 3D glass photonic interposers was demonstrated for fiber-to-waveguide alignment. Circular-cores were fabricated by etching the bottom dry-film cladding layer to form semicircular trenches, followed by curing and reflowing the core material inside the trench to form circular tops. Height of the circular core is 5.6 µm, which is within the limit of single-mode condition, but the width of the core is larger than the designed parameters due to the long tails on both sides of the trenches, and the underdevelopment of the core layer. Circular-core waveguides with 5.6 µm is large enough to enable manual adjustment for optical loss measurement and passive alignment for fiber-to-waveguide coupling.

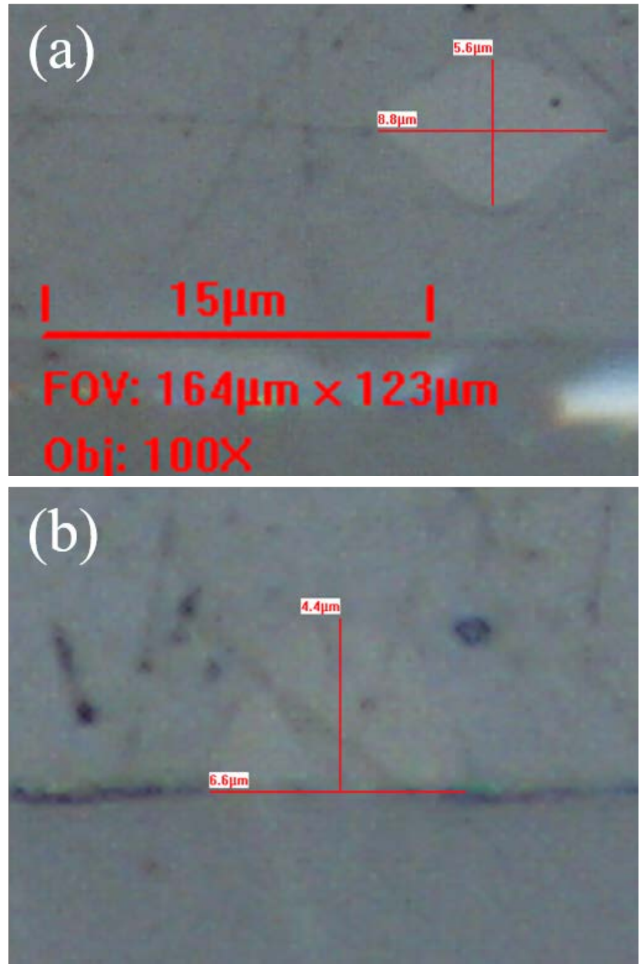

Figure 6. Height and width measurements: (a) Circular core and (b) trapezoidal core.

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