

45 Degree Polymer Micromirror Integration for Board-Level Three-Dimensional Optical Interconnects

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Abstract: We introduce here a simple method of integrating 45° total internal reflection micro-mirrors with polymer optical waveguides by an improved tilted beam photolithography on printed circuit boards to provide surface normal light coupling between waveguides and optoelectronic devices for optical interconnects. De-ionized water is used to couple ultraviolet beam through the waveguide core polymer layer at 45° angle during the photo exposure process. This technique is compatible with PCB manufacturing facility and suitable to large panel board-level manufacturing. The mirror slope is controlled accurately (within $\pm 1^\circ$) with high repeatability. The insertion loss of an uncoated micro-mirror is measured to be 1.6 dB.

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References and links

1. A. V. Krishnamoorthy, and D. A. B. Miller, "Scaling optoelectronic-VLSI circuits into the 21st century: A technology roadmap," *IEEE J. Sel. Top. Quantum Electron.* **2**(1), 55–76 (2006).
2. J. W. Goodman, F. J. Leonberger, S.-Y. Kung, and R. A. Athale, "Optical interconnects for VLSI systems," *Proc. IEEE* **72**(7), 850–866 (1984).
3. M. Li, and S. J. Sheard, "Waveguide couplers using parallelogramic-shaped blazed gratings," *Opt. Commun.* **109**(3–4), 239–245 (1994).
4. J. T. Kim, B. C. Kim, M. Jeong, and M. Lee, "Fabrication of a micro-optical coupling structure by laser ablation," *J. Mater. Process. Technol.* **146**(2), 163–166 (2004).
5. L. Schares, J. A. Kash, F. E. Doany, C. L. Schow, C. Schuster, D. M. Kuchta, P. K. Pepeljugoski, J. M. Trehwella, C. W. Baks, R. A. John, L. Shan, Y. H. Kwark, R. A. Budd, P. Chiniwalla, F. R. Libsch, J. Rosner, C. K. Tsang, C. S. Patel, J. D. Schaub, R. Dangel, F. Horst, B. J. Offrein, D. Kucharski, D. Guckenberger, S. Hegde, H. Nyikal, C. Lin, A. Tandon, G. R. Trott, M. Nystrom, D. P. Bour, M. R. T. Tan, and D. W. Dolfi, "Terabus: terabit/second-class card-level optical interconnect technologies," *IEEE J. Sel. Top. Quantum Electron.* **12**(5), 1032–1044 (2006).
6. N. Herdrickx, J. V. Erps, G. V. Steenberge, H. Thienpont, and P. V. Daele, "Laser ablated micromirrors for printed circuit board integrated optical interconnections," *IEEE Photon. Technol. Lett.* **19**(11), 822–824 (2007).
7. S. Garner, S.-S. Lee, V. Chuyanov, A. Chen, A. Yacoubian, W. Steier, and L. Dalton, "Three-dimensional integrated optics using polymers," *IEEE J. Quantum Electron.* **35**(8), 1146–1155 (1999).
8. S. Lehmacher, and A. Neyer, "Integration of polymer optical waveguides into printed circuit boards," *Electron. Lett.* **36**(12), 1052–1053 (2000).
9. L. Wang, X. Wang, W. Jiang, J. Choi, H. Bi, and R. T. Chen, "45° polymer-based total internal reflection coupling mirrors for fully embedded intraboard guided wave optical interconnects," *Appl. Phys. Lett.* **87**(14), 141110 (2005).
10. M. Kagami, A. Kawasaki, and H. Ito, "A polymer optical waveguide with out-of-plane branching mirrors for surface-normal optical interconnections," *J. Lightwave Technol.* **19**(12), 1949–1955 (2001).
11. A. L. Glebov, J. Roman, M. G. Lee, and K. Yokouchi, "Optical interconnect modules with fully integrated reflector mirrors," *IEEE Photon. Technol. Lett.* **17**(7), 1540–1542 (2005).
12. S. Han, I. Cho, S. Hwang, W. Lee, and S. Ahn, "A high-density two-dimensional parallel optical interconnection module," *IEEE Photon. Technol. Lett.* **17**(11), 2448–2450 (2005).
13. N. Hendrickx, J. Van Erps, E. Bosman, C. Debaes, H. Thienpont, and P. Van Daele, "Embedded micromirror inserts for optical printed circuit boards," *IEEE Photon. Technol. Lett.* **20**(20), 1727–1729 (2008).

14. M. Moynihan, B. Sicard, and T. Ho, "etc., "Progress toward board-level Optical Interconnect technology," Proc. SPIE **5731**, 50–62 (2005).
 15. T. Yoshimura, M. Miyazaki, Y. Miyamoto, N. Shimoda, A. Hori, and K. Asama, "Three-dimensional optical circuits consisting of waveguide films and optical z-connections," J. Lightwave Technol. **24**(11), 4345–4352 (2006).
 16. K. Y. Hung, H. T. Hu, and F. G. Tseng, "A novel fabrication technology for smooth 3D inclined polymer microstructures with adjustable angles," Proceedings of the International Conference on Solid State Sensors, Actuators and Microsystems, USA, 821–824 (2003).
 17. F. Wang, F. Liu, A. Adibi, and R. Tummala, "A Simple Method to Fabricate 45° Polymer Micro-Mirrors for Three-Dimensional Board-Level Optical Interconnects", The 90th OSA Annual meeting, Laser Science XXI, Optical Society of America, 8–12 (2006).
 18. F. Wang, F. Liu, G. K. Chang, and A. Adibi, "Precision Measurements for Propagation Properties of High Definition Polymer Waveguides by Imaging of Scattered Light," Opt. Eng. **47**(2), 024602 (2008).
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1. Introduction

The ever-increasing need for higher bandwidth and density is one of the motivations for extensive research on planar optoelectronic structures on printed circuit boards (PCBs) substrate [1]. Among many applications, optical interconnects [2] have gotten considerable attention in the last decade. In all planar optoelectronic systems, optical waveguides are crucial elements that facilitate signal routing. As an example, integration of optical waveguides and polymer passive devices on high density PCB substrate is a major area of research in optoelectronics. Low propagation loss, high optical quality, and manufacturability are among the requirements of polymer optical waveguides and polymer passive devices on PCB substrates for practical applications. In three-dimensional fully embedded board-level optical interconnects, another key challenge is to realize efficient optical coupling between in-plane waveguides and laser/detector devices. 45° total internal reflection (TIR) micro-mirrors and grating devices [3] integrated on waveguides have been studied as surface normal couplers. 45° TIR mirror couplers are more widely employed as waveguide couplers compared with the grating couplers, because they are coupling-efficient, easy to fabricate, and relatively insensitive to wavelength variations.

Various techniques can be used to construct such 45° TIR micro-mirrors, such as laser ablation [4–6], grayscale lithography [7], hard molding [8], soft molding [9], reactive ion etching (RIE) [10], micro-dicing [11], the X-ray lithography technique [12], deep proton writing [13]. Among these technologies, Photolithography is commonly used in printed circuits, semiconductor fabrication, MEMs, bio samples and optical polymer devices, because it has excellent ability to define smooth and high definition microstructures. Devices with precise structure profile and optical smooth surface required for optical application can be achieved by photolithography technology. Photolithography is the least disruptive technology to implement optical interconnects on PCBs, because it is easy, cost-effective, and compatible with present-day printed circuit board processing. Other techniques might yield better quality micro-mirrors, but may be more "exotic" and therefore less compatible with high-volume and large-scale PCBs production.

2. Discussion on tilted beam lithography

In most cases, the device structures are defined by utilizing ultraviolet (UV) beam normally incident into the polymer so that the structures have vertical side walls. The titled beam lithography can make tapered structure when UV beam is traveling inside the polymer material at an inclined angle. It can be used to make polymer waveguides with tapered micro-mirrors integrated at the ends. The principle of titled beam photolithography is shown in Fig. 1. Two different types of tapered micro-mirrors (with positive slope and with the negative slope) will be defined at the different ends of the optical polymer waveguide core layer in one photo exposure step.

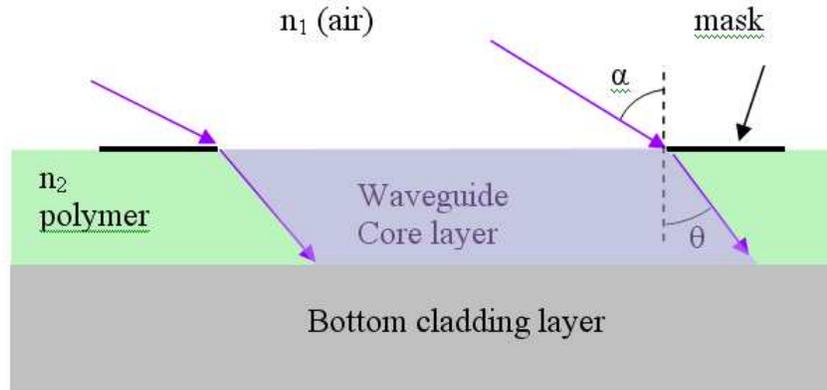


Fig. 1. Schematic of tilted beam photolithography. (α and θ being the incident angles in air and in the polymer respectively)

In most cases of the photolithography, the UV beam is incident from air to the polymer. The UV beam propagation at the interface between air and polymer obeys the Snell Law:

$$n_1 \sin \alpha = n_2 \sin \theta \quad (1)$$

with n_1 and n_2 being the refractive index of air (media 1) and the optical polymer (media 2) respectively, and α and θ being the incident angles in media 1 and media 2 respectively.

The refractive index n_2 of most photo polymers at the wavelength of the UV exposure beam (i.e., 365nm, i-line of the mercury lamp), is above 1.5, depending on the type of polymer material chosen. Taken the refractive index of photo polymer as 1.5, according to the Snell's Law the maximum slope angle θ that can be formed in photo polymer by using the tilted photolithography is 41.8° , which is smaller than 45° . And to achieve this maximum angle, the UV exposure beam has to be tilted at the angle α close to 90° in the air, which suffers from the huge reflection loss on the air-polymer interface. Thus it is impossible to fabricate micro-mirrors with 45° by simply tilting the UV exposure beam. A polymer optical waveguide channel with a 31.5° negative tapered mirror facet integrated at the end is demonstrated on a silicon substrate by simply tilting the UV exposure beam at 52.7° in the air, as shown in Fig. 2. A waveguide ($50 \mu\text{m}$ in height and $200 \mu\text{m}$ in width) is carefully cleaved along the waveguide propagation direction to show the mirror facet in details at the waveguide end. The imperfections (as circled in Fig. 2) near the mirror facet and inside the waveguide are introduced by the cleaving damage. A pair of optical polymers with low optical loss, LightLinkTM, provided by Rohm & Haas Electronic Materials is used to fabricate optical waveguides and micro-mirrors. The LightLinkTM is a negative acting photoimaging polymeric system that is based on an inorganic-organic hybrid platform [14]. It consists of two parts with refractive indices of 1.5196 and 1.4908 for the waveguide core layer and cladding layer.

In order to have the UV exposure beam traveling inside the polymer waveguide core layer at an angle greater than 41° , i.e., with 45° , a prism can be used on top of the polymer core layer to couple light [15]. However, there are some practical issues in using prism for the micro-mirror integration on polymer waveguides on PCB substrates. Firstly, the desired waveguide circuit length can usually reach more than 10cm. Thus multiple prisms have to be placed at the different mirror locations on the waveguide core layer. Furthermore, the edge of the prism will cause the UV beam distortion during the exposure. At last, because the substrate or optical board is not ideally smooth and flat, there will be air gaps at the interface between the prism and the photo mask, as well as the interface between the polymer core layer and photo mask. Usually these air gaps have to be filled with index matching glue during the UV exposure process and then be cleaned out thereafter. In order to reduce the mismatch of

the, glycerol was employed to achieve compensation for the refraction effect. Another solution of reducing the mismatch of the refractive index between air and photo resist was reported in 3D inclined polymer microstructures fabrications, as Glycerol was employed as an index matching material between the photo mask and photo resist Su-8 during tilted beam exposure to compensate the refractive index difference, thus extended the possible inclined angles in the resist [16].

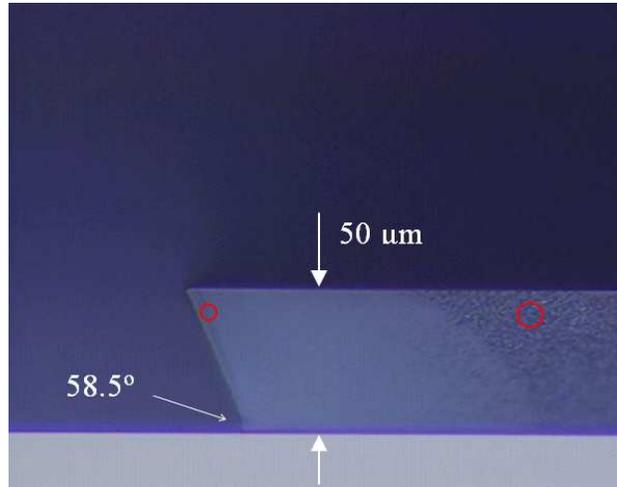


Fig. 2. Microscope image of a cleaved 50 μm thick polymeric waveguide core layer with a 31.5° negative tapered mirror integrated at the end on silicon substrate by using the air-polymer tilted beam (52.7°) contact photolithography.

3. Design of improved tilted beam lithography

Here we introduce a simple method to fabricate the polymer optical waveguides with precisely integrated 45° TIR micro-mirrors at waveguide ends on PCB substrate with an improved titled-beam photolithography method, and the preliminary results were reported by us in conference [17]. The key task here is to find an alternative solution of the prism coupler during the UV exposure. This solution should be cost-efficient, convenient, compatible to PCB manufacturing technology, and practical to large area processing on large size panel board-level optical polymer waveguide circuits. We notice the refractive index of de-ionized (D.I.) water at the wavelength of 365 nm (i-line of mercury lamp) is 1.35. With some straightforward setup, it can be used to replace the prism to match the refractive index difference between optical polymer and air during UV exposure. At the interface of polymer and water, in order to have the UV beam to propagate inside the waveguide core polymer layer at 45° angle, the beam incident angle in D.I. water should be close to 52.7° , which is practical.

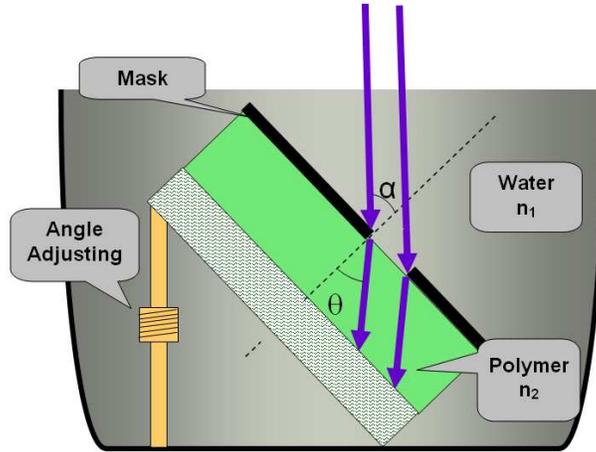


Fig. 3. Schematic of improved UV photolithography on PCB substrate. (α and θ being the incident angles in water and polymer respectively)

Figure 3. shows the schematic of the improved tilted beam photolithography. In this improved system, the whole PCB substrate along with polymer waveguide core layer and photo mask aligned above is tilted at 52.7° and immersed in a tank filled with D.I. water. The UV exposure beam is normal to the water surface in the water tank so that the reflection of UV exposure beam at the air-water surface is negligible. Because the PCB substrate is tilted, UV beam at different location of polymer core layer has different propagation length in water, thus the absorption loss of D.I. water is different. Fortunately, the absorption coefficient of D.I. water at 365nm is very low and the absorption loss of 10 cm water is less than 0.1%. Thus the different propagation path in water will not affect the UV exposure process. This method allows fabricating the 45° micro-mirrors for large panel manufacturing for the optoelectronics industry with almost no extra cost. Thus a tank of D.I. water provides a cost-effective solution to match the refractive index difference between air and polymer material. By this method, the tapered angle can reach up to 60° for most photo resist material, and people in MEMS may find application in fabrication of large slope structures, i.e., V-groove holders.

4. Fabrication and measurements

In this study, a $10\text{cm} \times 10\text{cm}$ FR4 substrate is employed to build planar optical waveguide circuits. A pair of optical polymers, LighLinkTM, is used. The sequential fabrication steps of the integration of 45° tapered TIR micro-mirrors at the ends of waveguides are as follows: 1) spin-coat the bottom cladding layer on the FR4 board and cure it, 2) coat the core layer and soft-bake it, 3) immerse the FR4 board at a tilted angle in the D.I. water tank, and expose the core layer to an appropriate dose of UV radiation through a mask, as illustrated in Fig. 3. Special attention is needed to remove any air bubbles between the interface of photo mask and photo resist. Any air bubbles will block UV beam from propagation during the exposure, thus there will be no patterns defined inside the resist under the air bubbles. Additionally, the photo mask should be aligned with the photo resist inside the water tank to avoid any air bubbles between the photo mask and photo resist, and the air bubbles can be easily removed by a soft tissue inside the water tank. 4) develop the pattern using a wet process. The developer used for patterning of LighLinkTM is an aqueous solution (2% Alkaline). Developments are carried out at room temperature for about 3 minutes. Unexposed areas are dissolved and washed away and the exposed areas remain. In this process, the 45° TIR micro-mirrors are defined simultaneously with the waveguide core at the end of the waveguides.

Figure 4 shows the microscope images of a $50\mu\text{m} \times 50\mu\text{m}$ polymer waveguide integrated with 45° positive or negative tapered mirror facets on FR4 substrate. It is critical to maintain an accurate 45° tapered mirror angle for the optimum light coupling between waveguides and out of plane optoelectronic devices. The tapered angle of the micro-mirrors is measured by the contact surface profiler (DekTek 303). The surface profile measurement of the positive tapered mirror (as shown in Fig. 4(a)) confirms an exact 45° mirror angle, as shown in Fig. 5, compared with the fact that the mirror sample fabricated under the same condition can only achieve 31.5° (as shown in Fig. 2). The surface profile measurement of the micro-mirrors on different waveguide channels, as well as on different FR4 substrates, demonstrates an angle accuracy of $\pm 1^\circ$ and a high repeatability.

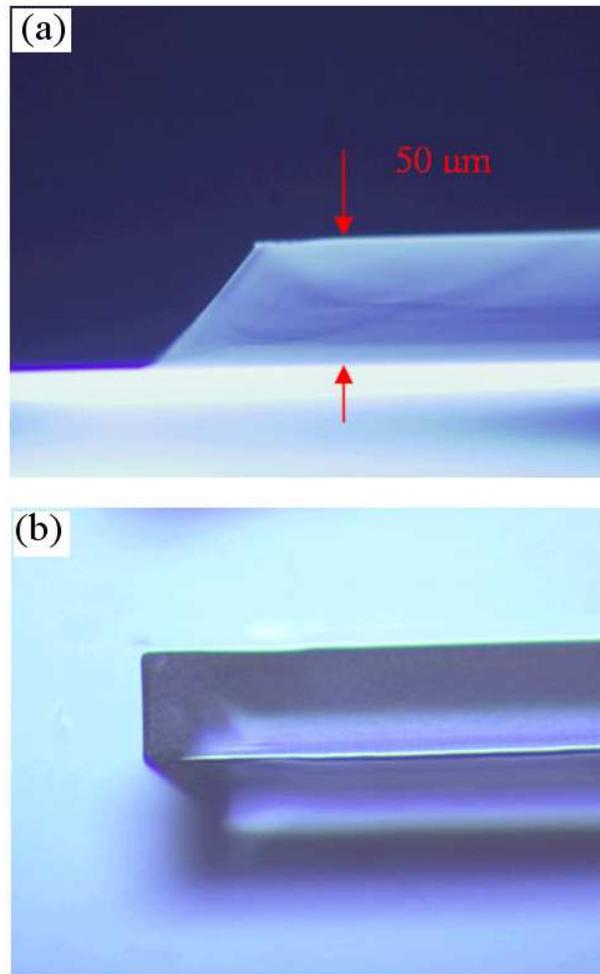


Fig. 4. Microscope images of a $50\mu\text{m} \times 50\mu\text{m}$ polymer waveguide with a 45° (a) positive and (b) negative tapered mirror facet at the end on FR4 substrate.

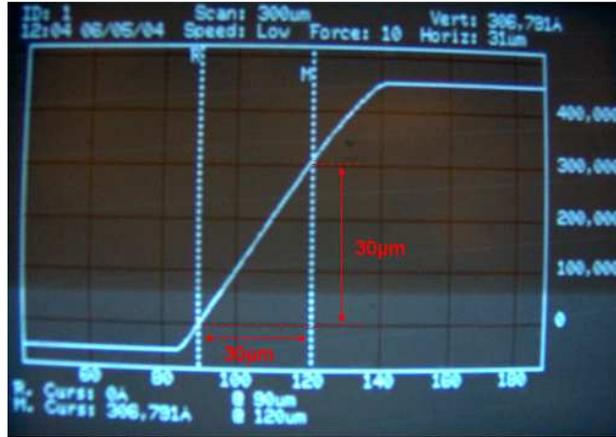


Fig. 5. Surface profile of the positive tapered mirror (as in Fig. 4(a)) at the waveguide end measured by the contact surface profiler (DekTek 303).

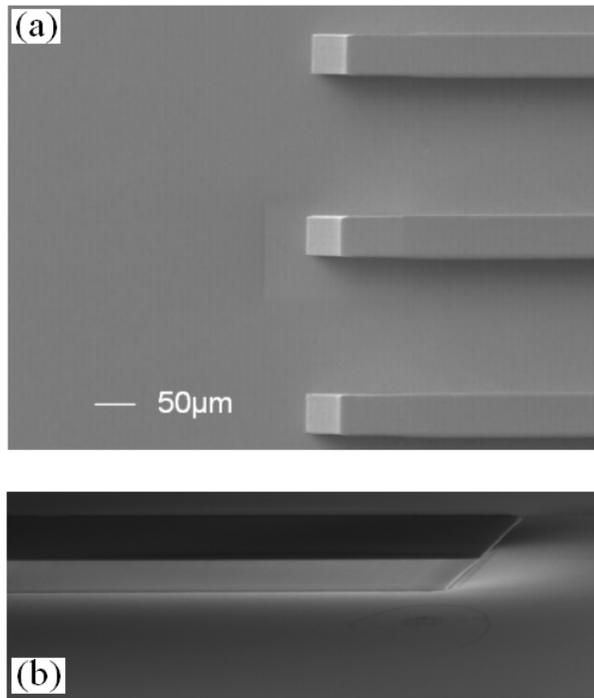


Fig. 6. SEM images showing the top views of (a) positive tapered and (b) negative tapered 45° micro-mirrors at the ends of $50 \times 50\mu\text{m}$ multimode waveguides on PCB substrate.

Scanning electron microscope (SEM) images confirm the smooth surface of the tapered mirror that is essential for a low scattering loss, as shown in Fig. 6. Clear and smooth rectilinear mirror planes are achieved for both positive and negative tapered mirrors. The surface root-mean-square (rms) roughness of the positive tapered 45° mirror facet is measured by atomic force microscope (AFM). The average surface roughness measured for different positive tapered mirror samples is 40 nm rms with small variation, as measured over an area of $10\mu\text{m} \times 10\mu\text{m}$. A similar surface roughness is expected on the negative tapered mirror facets. This small surface roughness guarantees that the tapered facets can be used as high quality 45° TIR mirrors.

Optical waveguides fabricated on FR4 substrates in this study have very low propagation loss at the wavelength range of 850-1000 nm, which is rather tedious to measure by using the conventional destructive cutback method due to the difficulty to cleave the FR4 board. We have developed a reliable, non-destructive, and real time technique for characterization of propagation properties of planar optical waveguides based on accurate imaging the scattered light from the waveguide using a sensitive CCD camera with built-in integration functionality [18]. Using this characterization tool, the optical waveguides show loss coefficients of 0.085 dB/cm at $\lambda = 850\text{ nm}$ with great accuracy.

To characterize the surface normal coupling efficiency of the integrated micro-mirrors, the negative tapered facet (as shown in Fig. 4(b)) is tested. The probe laser beam is coupled into the waveguide through a $9\mu\text{m}$ single mode fiber from air. The numerical aperture is 0.29 for the waveguide and 0.14 for the single mode fiber. Then the coupled beam propagating inside the waveguides is reflected out of the waveguide circuit plane by the micro-mirror at the end. And the reflected light is collected by a $62.5\mu\text{m}$ multimode fiber (with an NA of 0.275) above the negative tapered 45 degree TIR mirror. By comparing the insertion loss measurement from the waveguides of the same length with and without the micro-mirror, the excess loss of the mirror is obtained as 1.6 dB, corresponding to a coupling efficiency of 69%. We have tested 3 FR4 substrates with 5 micro-mirrors on each substrate, and less than 10% variation of the mirror insertion loss was observed in all measurements. The performance of the air-polymer interface based TIR 45 degree micro-mirrors can be further improved by metal coating on the surface, which is under further study.

5. Conclusion

In summary, we introduce here a simple method to fabricate polymer optical waveguides with integrated 45° TIR micro-mirrors on printed circuit boards by improved tilted beam contact photolithography for fully embedded optical interconnects. The 45° TIR coupling mirrors are shaped at the ends of the waveguides in one exposure step to provide surface normal light coupling between waveguides and optoelectronic devices by using the low cost PCB facility in a class-1000 substrate laboratory. The optical polymer waveguides on PCB substrate show propagation loss of 0.085 dB/cm at $\lambda = 850\text{ nm}$. The slope of the 45° TIR mirrors can be accurately controlled within $\pm 1^\circ$ and has a high reproducibility. The average insertion loss of the 45° TIR uncoated mirrors is around 1.6 dB with less than 10% variation. Given the length of such a waveguide channel integrated with 45° mirrors to be 10cm, the total power penalty required will be less than 2.4 dB, which is practical in the real optoelectronic system. This technique is compatible with PCB manufacturing technology, and offers a low-cost solution to large panel board-level manufacturing for optical interconnects. Metal coating of the mirror surface to improve the reflection and polarization-independent performance is under further study.

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