

# Fabrication of Three Dimensional Tapered Polymeric using Compression-Molding Technique

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## ABSTRACT

We report for the first time, three-dimensionally tapered polymeric waveguides fabricated by the compression-molding technique. The waveguides presented herein provide a feasible solution to bridge discrete optoelectronic devices having the apertures of a few microns to hundreds of microns. One-cm long tapered channel waveguides with the cross-sections of  $5\ \mu\text{m} \times 5\ \mu\text{m}$  at one end and  $100\ \mu\text{m} \times 100\ \mu\text{m}$  at the other end were fabricated. These waveguides have a propagation loss of 0.5 dB/cm when the 632.8 nm He-Ne laser light is coupled from the small end and of 1.1 dB/cm when coupled from the large end. By confining the energy to the fundamental mode, when coupling from large end to the small end, a low-loss packaging can be achieved bidirectionally.

**Keywords:** Optoelectronic Packaging, Tapered Waveguides, Optical interconnections

By now, many of the key components required to realize optical communication networks have reached an appreciable state of maturity. On the one hand, impressive performance data have been obtained for a large variety of optoelectronic active devices including lasers, amplifiers, electro-optic switches, modulators, and detectors[1-4]. Also, the transmission characteristics achieved for the optical waveguides and fibers are very close to cover various optical transmission spans from intra-wafer interconnection to global optical communication. On the other hand, the full exploitation of these achievements in data communications is hindered by the coupling-bottleneck that appears at the interfaces among all these components that are often fabricated on different substrates with different dimensions [1-4]. For example, laser diodes can be made on GaAs, detectors on silicon, and modulators on  $\text{LiNbO}_3$  [2-4]. The dimensions of these discrete devices are often pre-selected to optimize their own performance, and the size-range of these optoelectronic components varies from a few microns (single-mode waveguides and vertical cavity surface-emitting lasers) to hundreds of microns (photodetectors and multimode plastic fibers). It has been realized that achieving efficient optical couplings among these devices with sufficient alignment tolerance is difficult by using prisms, gratings, or optical lenses. Three main problems occur at the interfaces: (1) the inconveniently high coupling loss due to the optical mode mismatch [5-6], (2) the strict alignment tolerance[5-6], and (3) the separation mismatch when the array devices (such as laser diode array, smart pixel array, photodetector array and optical fiber/waveguide array) are employed [5]. Due to the planarized nature of these devices mentioned above, the most common approach based on microlens is bulky and very expensive because it requires the complicated three-dimensional spatial and angular alignments[7-8]. An effective method is needed to efficiently couple light from one device to another at a relaxed alignment tolerance.

Tapered waveguides have been proposed and demonstrated to improve the optical coupling among various optoelectronic devices[9-11]. However, there is no existing optoelectronic/microelectronic fabrication method that can make satisfactory three-dimensional (3D) tapered waveguide devices, varying from a few microns to a few hundred of microns in both horizontal and vertical directions. To grow a high-index waveguide layer with hundreds of microns of thickness is impractical using any existing waveguide fabrication methods for inorganic materials such as GaAs,  $\text{LiNbO}_3$ , and glass[12]. In this paper, we report the fabrication of the polymer-based 3D tapered waveguide couplers for cost-effective and low-loss coupling among optoelectronic components. The compression-molding technique was used which takes the

advantage of plastic characteristics of optical polymer to create a horn-shaped waveguide array having the required waveguide dynamic range three-dimensionally.

A compression-molding technique has been developed for fabricating 3D tapered polymeric waveguides couplers. We have fabricated 3D horn-shaped polymeric waveguides that have waveguide dimensions of 5  $\mu\text{m}$  at one end and that of 100  $\mu\text{m}$  at the other end. With proper design, such 3D tapered waveguides can provide an adiabatic optical transition between the optoelectronic devices that have different mode profiles and different pixel separation. Consequently, both the coupling efficiency and alignment tolerance could be significantly improved by using them to interconnect different optoelectronic devices. The compression-molded polymeric waveguides described herein present a promising solution to bridge the huge dynamic range of different optoelectronic device-depths varying from a few microns to a few hundred of microns.

A brass mold plunger was first fabricated using precision diamond turning machine (Pnemo Ultra 2000). With various gem quality diamond tools, precision microstructure can be generated with one millionth of an inch resolution and surface finishes in nanometers. Brass was selected because of its homogeneity and suitability for electroplating processing of the master die. The brass substrate was first mechanically polished and tested for its flatness. An array of 3D tapered waveguide structure (male) was then created by using the diamond turning machine. The finished master die was then transferred into mold plunger (female) by using Nickel electroforming technique. Nickel electroforming provided hard, chemically stable and high quality mold plunger, and no further polishing or machining was required after fabrication.

The process of compression-molding is depicted in Fig.1. Only one end of the molded waveguide is shown in this figure. The mold plunger provides a cavity having the shape of the desired 3D tapered

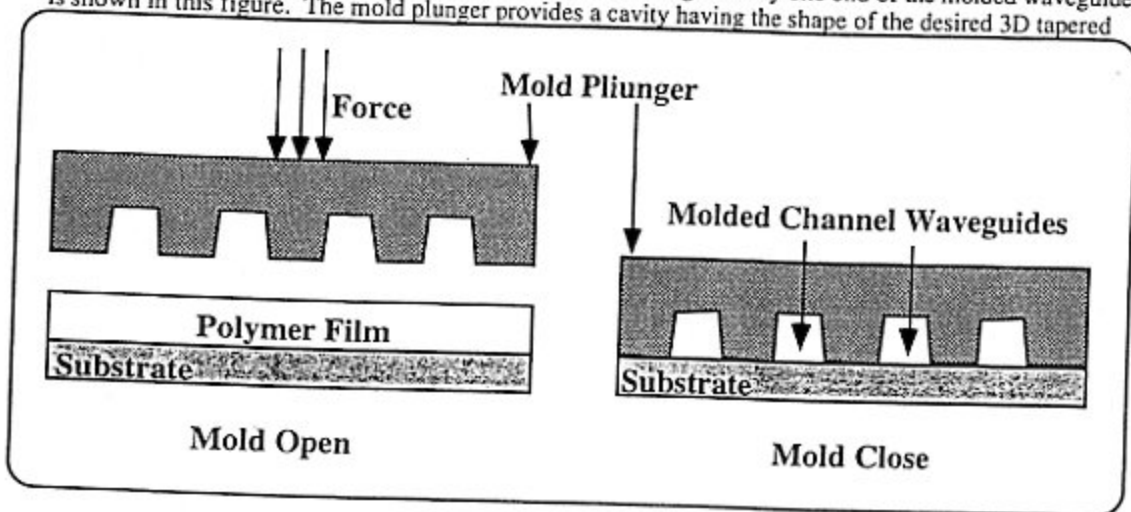


Fig. 1 Schematic of the two-piece compression-molding technique for fabricating 3D tapered waveguides.

waveguide. An appropriate amount of molding material, (polymer in this case), is spin-coated or laminated onto the substrate of interest. The film thickness must be equal to the maximum thickness of the tapered structure. Due to the nature of compression-molding, the shape of the molded waveguide is completely defined by the shape of the mold plunger. The molding process begins with heating the mold plunger and the polymer film to the glass transition temperature ( $T_g$ ) of the polymer. The polymers used in this experiment were photolime gel polymer, DuPont Surphex P-40, and polycarbonate having glass transition temperatures of 60, 110, and 148  $^{\circ}\text{C}$ , respectively [13-14]. The compression-molding is carried out by bringing the two parts of the heated-mold together under pressure. The polymer film, softened by heat, is thereby welded into the shape of the stamp. The last step is to harden and fix the molded waveguide shape. The fundamental differences in types of polymers dictate the plastic processing method to be used [13-14]. If the polymer is thermosetting, the hardening is effected by further heating under pressure in the mold. If it is a thermoplastic, the hardening is effected by chilling. For the photo polymer, this process can be carried out by UV exposure. After curing process, the mold plunger can be removed which leaves behind the 3D tapered waveguide structures on the substrate. We investigated the photolime gel polymer waveguides in details. The photolime gel polymer thin film possesses the graded index (GRIN) distribution. This exclusive characteristic of this polymer thin film allows us to fabricate the molded waveguide devices on any substrate of interest regardless of the substrate refractive index and conductivity.

Fig. 2 shows the 3D tapered waveguides fabricated by the compression-molding technique using photolime gel polymer. The molding tool that we employed was linearly tapered in height and width along the 1.0 cm of channel length. It had a waveguide width ( $t$ ) and height ( $h$ ) of  $5\ \mu\text{m}$  at the small end and that

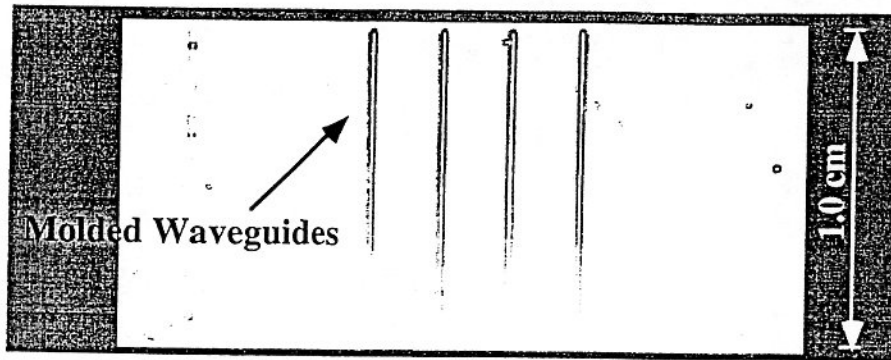


Fig. 2 Photograph of compression-molded 3D tapered waveguides using photolime gel polymer.

of  $100\ \mu\text{m}$  at the large end. A small section of the molded polymer waveguide and the images of two ends are shown in Fig.3, where the 3D tapering is clearly indicated. We observed a tapering in the vertical cross-section caused by shrinkage during the curing process. Note that the molding process shall be performed near the glass transition temperature, while the polymer film is deformable. The waveguide thus fabricated demonstrates multiple modes without a cover cladding. However, it becomes single-mode waveguide at the small end if a low-index polymeric cladding layer is further spin-coated on it.

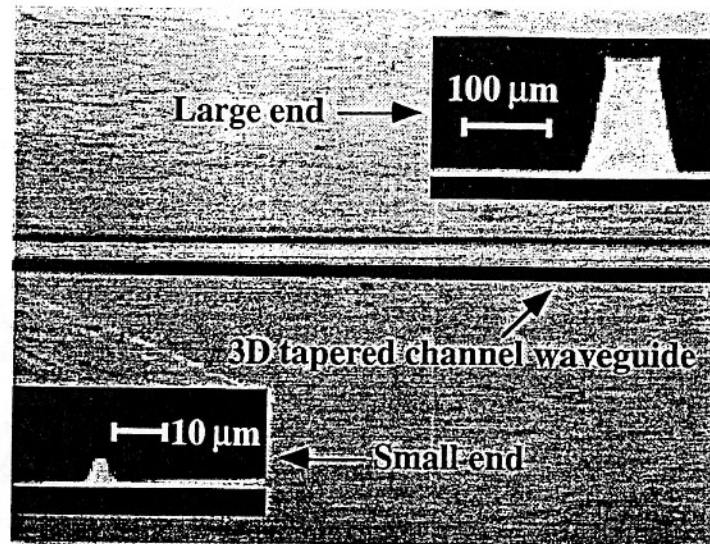


Fig. 3 Microphotographs of the molded 3D linear tapered waveguide.

A theoretical simulation using two-dimensional beam-propagation-method (2D BPM\_CAD) was carried out to evaluate the performance and the loss in the 3D tapered waveguides. For these simulations, the two ends of tapered waveguide were assumed to have square cross-section with sides measuring  $5$  and  $100\ \mu\text{m}$  at the small and large ends, respectively. The waveguide length was taken as  $10\ \text{mm}$ . At the incoming light wavelength of  $632.8\ \text{nm}$ , the refractive indices of film and substrate were taken as  $1.52$  and  $1.5$  respectively. Since, such a device has to be bi-directional in order to be useful, the two cases of light coupled-in from the small and large ends were simulated. The simulated results were in good agreement with experimental observations. For the optical signal launched from the small end, the  $99.2\%$  of the fundamental TE mode input power was coupled to the output end. For the case of optical signal launched

from the large end, the 98.3% of the input power was coupled out of the output port. Similar results were obtained for the TM mode. Simulations for TM modes of input light gave the efficiencies of power transfer as 99.9% ( from small to large end) and 97.9% ( from large to small end). The power transfer efficiencies of higher order modes launched from the large end were calculated as 85.9% for TE<sub>21</sub> mode and 71.1 % for TE<sub>31</sub> mode. Higher order modes suffer higher losses according to these simulated results.

The propagation loss can be evaluated experimentally by measuring the integrated intensity distribution of the scattered light along the direction of propagation. Fig 4 shows the measured integrated-optical scattering power distribution along the waveguide. The curve (a) represents the case when the 632.8 nm He-Ne laser beam was coupled from the large end. The measured loss was 1.1 dB/cm at 632.8 nm in the photolime gel polymer 3D tapered waveguide. The curve (b) in Fig 4 is the case when the light was coupled from the small end. The measured loss for the fundamental mode in this case is 0.5 dB/cm at 632.8 nm. The output (100 μm end) and input ( 5 μm end) mode profiles are shown in Fig.5. The experimental results match very well with the theoretical predictions for the single mode operation. The mode profile of the incoming optical signal plays a pivotal role in maintaining a low-loss coupling when light is launched from the highly multi-mode end to the single-mode region. If most of the energy could be confined to the fundamental mode, the coupling loss would be significantly reduced.

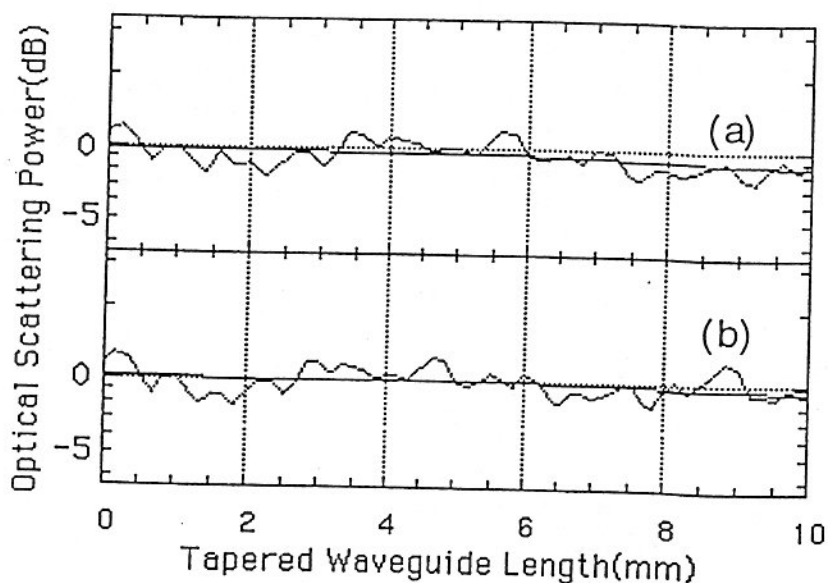


Fig.4 The measured integrated-optical scattering power distribution along the waveguide (a) the 632.8 nm He-Ne laser beam was coupled from the large end. (b) the 632.8 nm He-Ne laser beam was coupled from the small end.

In conclusion, compression-molded 3D tapered waveguides are demonstrated for the first time. Not only the vertical depth variation but also the linear dimensions of the molded waveguides are well beyond the limits that any other conventional waveguide fabrication methods can provide. The molded waveguides with a vertical depth of 100 μm at one end and 5 μm at the other end with length of 1.0 cm have been fabricated using a photolime gel polymer. Among all the thin film waveguides reported, polymer-based optical waveguides have been widely agreed to be the best candidates for 3D optical interconnects due to their cost-effectiveness, low dielectric constant and ability for multilayer coating. Propagation loss of 0.5 dB/cm when light was coupled from 5 μm x 5 μm end to 100 μm x 100 μm end



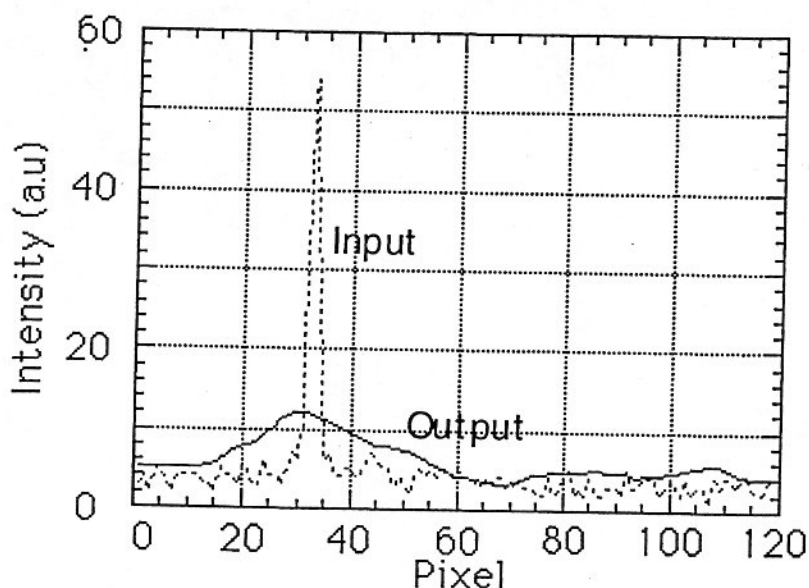


Fig.5 Measured mode profiles at the output (100  $\mu\text{m}$  end) and input (5  $\mu\text{m}$  end).

and that of 1.1 dB/cm when light was coupled from 100  $\mu\text{m}$  x 100  $\mu\text{m}$  end to 5  $\mu\text{m}$  x 5  $\mu\text{m}$  end were experimentally confirmed. By confining the energy to the fundamental mode, when coupling from large end to the small end, a low-loss packaging can be achieved bi-directionally. 3D Compression-molded polymeric waveguides present a promising solution to bridge huge dynamic range of different optoelectronic device-depths varying from a few microns to several hundred of microns. The technique presented in this paper can be used to mold 3D structures in any polymer-based thin film, that often can not be fabricated by conventional microlithographic machines.

This research is sponsored by the BMDO, U.S. Air Force Rome Lab, 3M foundation and the ATP program of the state of Te

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