Compression-Molded Three-Dimensional Tapered Polymeric Waveguides for Low-Loss Optoelectronic Packaging

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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 micrometers to hundreds of microns. 1-cm-long tapered channel waveguides with the end cross sections of 5 μm × 5 μm and 100 μm × 100 μm 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.**

Index Terms—**Optical interconnections, optoelectronic packaging, tapered waveguides.**

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 variety of optoelectronic devices including lasers, amplifiers, electrooptic 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, which 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 $LiNbO_3$ [2]–[4]. The dimensions of these discrete devices are often pre-selected to optimize performance, and the size-range of these optoelectronic components varies from a few micrometers [single-mode waveguides and vertical-cavity surface-emitting lasers (VCSEL's)] to hundreds of micrometers (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 (3-D) tapered waveguide devices, varying from a few micrometers to a few hundred of micrometers in both horizontal and vertical directions. To grow a high-index waveguide layer with hundreds of micrometers of thickness is impractical using any existing waveguide fabrication methods for inorganic materials such as GaAs, LiNbO3, and glass [12]. In this letter, we report the fabrication of the polymer-based 3-D 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 dynamic range three dimensionally.

A compression-molding technique has been developed for fabricating 3-D tapered polymeric waveguide couplers. We have fabricated 3-D horn-shaped polymeric waveguides that have waveguide dimensions of 5 μm at one end and that of 100 μm at the other end. With proper design, such 3-D tapered waveguides can provide an adiabatic optical transition between the optoelectronic devices that have different mode profiles and pixel separation. Consequently, both the coupling efficiency and alignment tolerance could be significantly improved.

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

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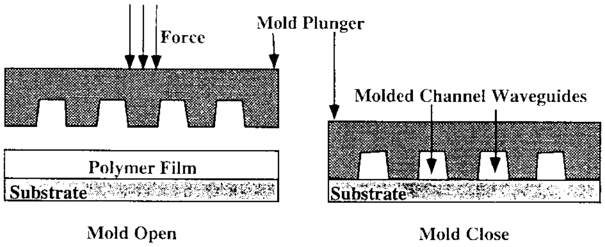

Fig. 1. Schematic of the two-piece compression-molding technique for fabricating 3-D tapered waveguides.

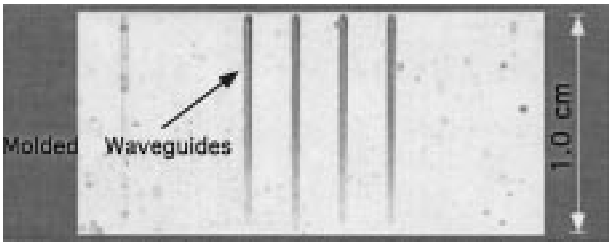

Fig. 2. Photograph of compression-molded 3-D tapered waveguides using photolime gel polymer.

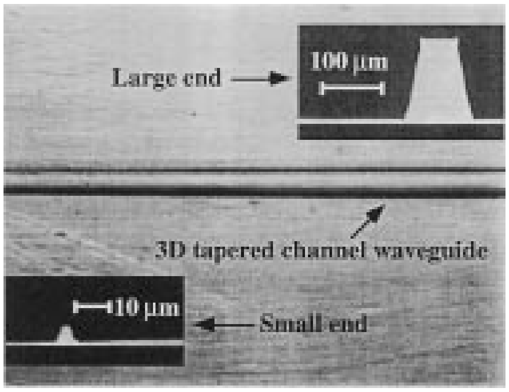

Fig. 3. Microphotographs of the molded 3-D linear tapered waveguide.

and tested for its flatness. An array of 3-D tapered waveguide structure (male) was then created using the diamond turning machine. The finished master die was then transferred into mold plunger (female) using Nickel electroforming technique. Nickel electroforming provided hard, chemically stable and high-quality mold plunger, and no further polishing or machining was required.

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 3-D tapered 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 (Tg) of the polymer. The polymers used in this experiment were photolime gel polymer, DuPont Surphex P-40, and polycorbonate having glass transition temperatures of 60 °C, 110 °C, and 148 °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 3-D 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 3-D 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 μm at the small end and that of 100 μm 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 3-D tapering is clearly indicated. We observed a tapering in the vertical cross section caused by shrinkage during the curing process.

A theoretical simulation using two-dimensional beam-propagation-method (2-D BPM_CAD) was carried out to evaluate the performance and the loss in the 3-D tapered waveguides. For these simulations, the two ends of tapered waveguide were assumed to have square cross section with sides measuring 5 and 100 μm at the small and large ends, respectively. The waveguide length was taken as 10 mm. At the incoming light wavelength of 632.8 nm, the refractive indices of film and substrate were taken as 1.52 and 1.5, respectively. Since, such a device has to be bidirectional 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_{21} mode and 71.1% for TE_{31} mode. Higher order modes suffer higher losses according to these simulated results. A change of approximately 5.9% in the numerical aperture (NA) of this waveguide structure was estimated.

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

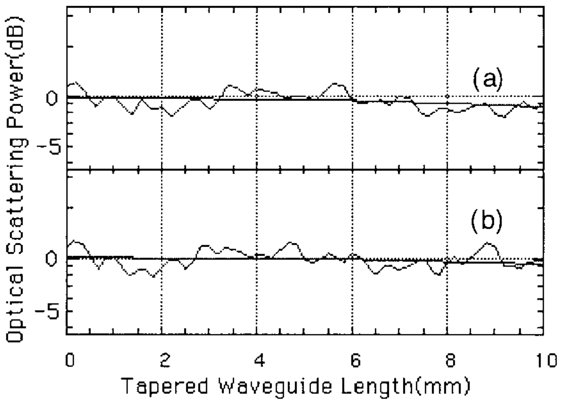

Fig. 4. The measured integrated-optical scattering power distribution along the waveguide (a) the 632.8-nm He–Ne laser beam was coupled from the large end. (b) The 632.8-nm He–Ne laser beam was coupled from the small end.

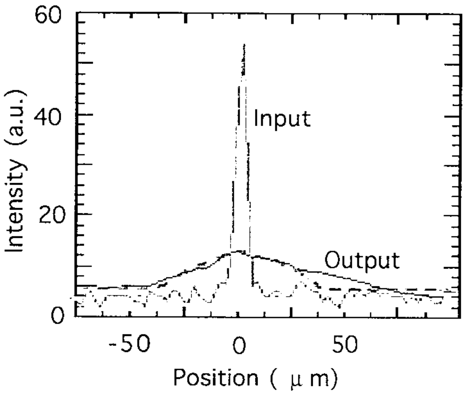

Fig. 5. Measured mode profiles at the output (100-mm end) and input (5-μm end). The simulated fundamental mode profile at the output end is shown with dotted line.

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. 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 was 0.5 dB/cm at 632.8 nm. The experimental output (100 mm end) and input (5-μm end) mode profiles are shown in Fig. 5. For comparison the simulated fundamental mode profile at the output end is also shown by the dotted line. Fundamental mode remains dominant while a little power transfer occurs to higher order modes. 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 multimode 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.

In conclusion, compression-molded 3-D tapered waveguides are demonstrated for the first time. The molded waveguides with a vertical depth of 100 mm at one end and 5 μm at the other end with length of 1.0 cm have been fabricated using a photolime gel polymer. Propagation losses of 0.5 dB/cm when light was coupled from 5 μm × 5 μm end to 100 μm × 100 μm end and that of 1.1 dB/cm when light was coupled from 100 μm × 100 μm end to 5 μm × 5 μm 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 bidirectionally. 3-D Compression-molded polymeric waveguides present a promising solution to bridge huge dynamic range of different optoelectronic device-depths varying from a few micrometers to several hundred of micrometers. The technique presented in this letter can be used to mold 3-D structures in any polymer-based thin film, that often can not be fabricated by conventional microlithographic machines.

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