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. Compression-molded polymeric waveguides presented herein provide a feasible solution to bridge discrete optoelectronic devices having the apertures of a few microns to hundreds of microns in both horizontal and vertical directions. One-cm long tapered channel waveguides with the cross-sections of 5 μm x 5 μm at one end and 100 μm x 100 μm at the other end were fabricated. These polymeric channel waveguides have a propogation loss of 0.5 dB/cm when the 632.8 nm He-Ne laser light is coupled from the small end to the large end and of 1.1 dB/cm when coupled from the large end to the small 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.

1. INTRODUCTION

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 $LiNbO_3$ [2-4]. The dimensions of these discrete devices are often pre-selected to optimize thier 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 few microns to hundreds 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, $LiNbO_3$ 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 μm at one end and that of 100 μm 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 few microns to few hundreds of microns.

2. FABRICATION OF POLYMER-BASED 3D TAPERED WAVEGUIDE COUPLERS USING COMPRESSION-MOLDING TECHNIQUE

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 transfered into mold plunger(female) by using Nickle electroforming technique. Nickel electroforming was selected based on its hardness and chemical stability. High quality surfaces can be generated without the need for further polishing or machining after fabrication. Fig. 1(a) shows the picture of the 3D mold plunger fabricated.

The process of compression-molding is depicted in Fig.1(b). 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 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, 110, 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 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 we employed, 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 invetigated 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. We have also demonstrated an array of integrated photonic devices using this polymeric material. These include planar waveguide, linear and curved channel waveguide arrays, traveling wave electro-optic waveguide modulator, multiplexed waveguide hologram, Nd^{3+}-doped waveguide amplifier[15].

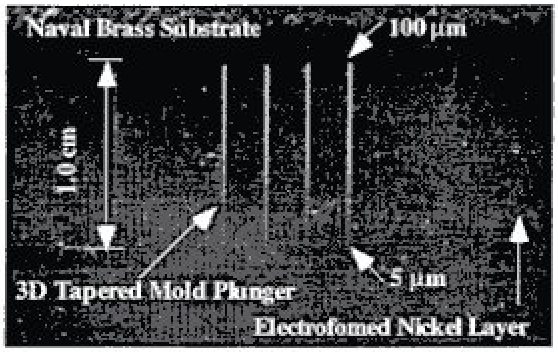

Fig. 1 (a) Photograph of the 3D linear tapered waveguide mold plunger.

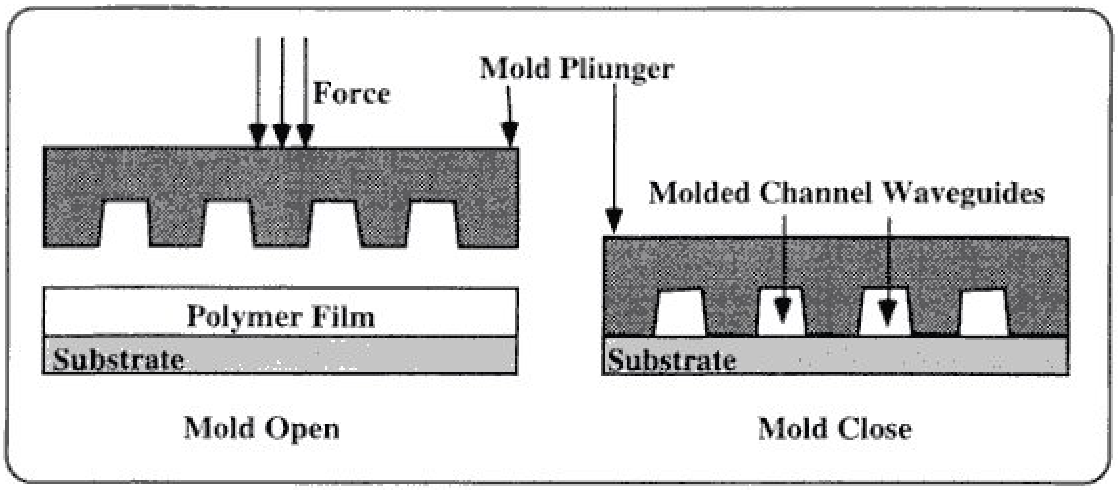

Fig. 1 (b) Schematic of the two-piece compression-molding technique for fabricating 3D tapered waveguides.

Fig. 2(a) shows the 3D tapered waveguides fabricated by thecompression-molding technique using photolime gel polymer. The molding tool that we have employed is linearly tapered in height and width along the 1.0 cm of channel length. It has 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 sectionof the molded polymer waveguide and the images of two ends are shown in Fig. 2(b), 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 transitiontemperature, while the polymer film is deformable. The waveguide thus fabricated demonstrates multiple modes withouta 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.

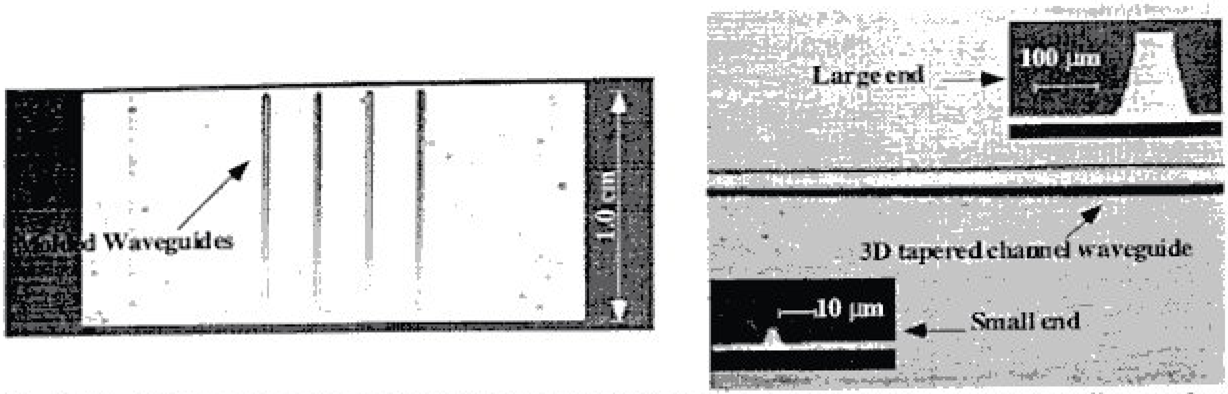

Fig. 2(a) Photograph of compression-molded 3D tapered waveguides using photolime gel polymer. (b) Microphotographes of the molded 3D linear tapered waveguide

3. CHARACTERIZATION OF COMPRESSION-MOLDED 3D TAPERED WAVEGUIDES

A theoretical simulation using two-dimensional beam-propagation-method (2D BPM_CAD) was carried out to evaluate the performanceand the loss in the 3D tapered waveguides. For these simulations, the two the ends of tapered waveguidewere assumed to have square cross-section with sides measuring 5 and 100 μm at the small and large ends, respectively. Thewaveguide length was taken as 10 mm. At the incoming light wavelength of 632.8 nm, the refractive indices offilm and substrate were taken as 1.52 and 1.5 respectively. Since, such a device has to be bi-directionalin order to be useful. The two cases of light coupled-in from the small and large ends were simulated. The simulated results are in good agreement with experimental observations. Fig.3 (a) shows the mode profiles at the small and large ends for the case of optical signal launched from the small end. The 99.2% of the input power is coupled to the output end. Fig. 3(b) shows the mode profiles at both the ends for the case of optical signal launched from the large end. The 98.3% of the input power is coming out of the output port. The results shownin the Figures 3(a) and 3(b) are for the fundamental TE mode of input light. Similar results are obtained for the TM mode.

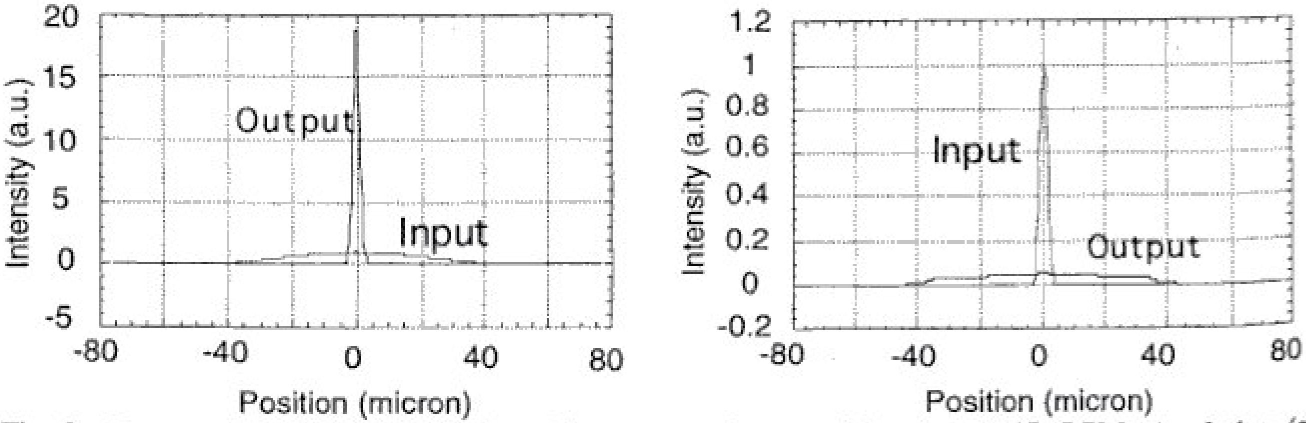

Fig. 3. Input and output mode profiles of linear tapered waveguide using 2D-BPM simulation (a) coupling from the large end to the small end with efficiency of 98.3% (b) coupling from small end to the large end with couplingefficiency of 99.2%. Wavelength = 632.8 nm, Width of the large end = 100 μm, width of the small end = 5 μm, waveguide length = 10 mm, Substrate refractive index = 1.5 and film refracive index = 1.52.

Simulations for TM modes of input light give 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 launching from the large end are 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.

The propagation loss can be evaluated experimentally by measuring the integrated intensity distribution of the scattered light along the direction of propagation. Fig. 4(a) shows the scattered light intensity from a 3D-tapered waveguide when the 632.8 nm He-Ne laser beam is coupled from the large end. The measured integrated-opticalscattering power distribution along the waveguide is shown by the dotted curve in Fig 4(b). The measured loss is 1.1 dB/cm at 632.8 nm in the photolime gel polymer 3D tapered waveguide.

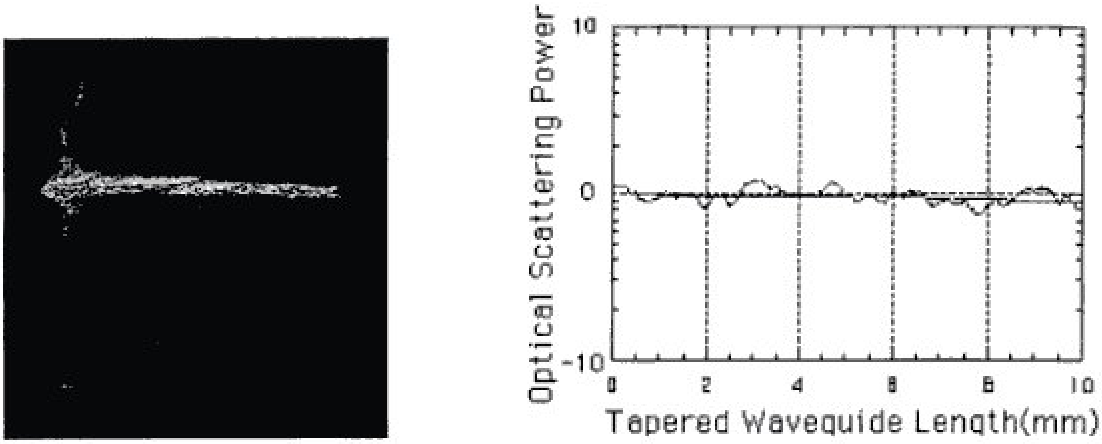

Fig.4 (a) The intensity profile of a 3D-tapered waveguide when the 632.8 nm He-Ne laser beam is coupled from the large end. (b) The measured integrated-optical scattering power distribution along the waveguide.

The Fig. 5 (a) shows the integrated optical power distribution along the waveguide when the light is coupled from 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(b). The experimental results match very well with the theoretical predictions for the single mode case. 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 confined to the fundamental mode, the coupling loss would be significantly reduced.

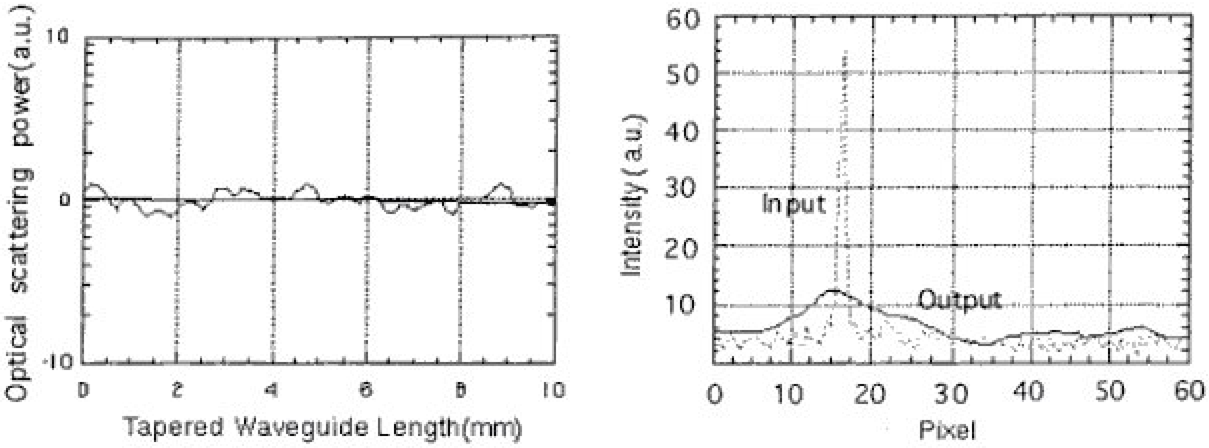

Fig. 5. (a) The measured integrated-optical scattering power distribution along the waveguide when the 632.8 nm He-Ne laser beam is coupled from the small end. (b) Measured mode profiles at the output (100 µm end) and input (5 µm end).

4. CONCLUDING REMARKS

In conclusion, compression-molded 3D tapered waveguides are demonstrated for the first time. Not only the vertical depthvariation 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 dielectricconstant and ability for multilayer coating. Propogation loss of 0.5 dB/cm when light was coupled from 5 µm x 5 µm end to 100 µm x 100 µm end and that of 1.1 dB/cm when light was coupled from 100 µm x 100 µm end to 5 µm x 5 µm end were experimentally confirmed. By confining the energy to thefundamental 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 few microns to several hundreds 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.

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