45-cm long compression-molded polymer-based optical bus

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We report the formation of an optical bus using compression-molding technique. The linear dimension of such a waveguide is well beyond that of a microlithographically defined waveguide. Theoretical calculation based on the effective index method was used to determine the optimal dimension of the molding tool design for single- and multimode waveguides. A molded photolime gel-based polymer optical bus with a linear dimension of 45 cm was fabricated and then tested at 0.6328-μm wavelength. Waveguide propagation loss from 0.5 to 2 dB/cm was determined using the two prism method. As a result of this long interconnection distance, board-to-board optical interconnects through backplane can be realized using the technology.

The intrinsic limitations of the current generation of computers have led researchers to seriously consider new computing architectures based on optoelectronic interconnects.[1,2] The basic limitations of electronic interconnects include interconnection time bandwidths, clock skew, settling time, resistance-capcitance (RC) time constants (for intrachip interconnects) and even the distributed line RLC time constant (for chip-to-chip interconnects and higher level architectures). In particular, when the time bandwidths provided by electrical interconnects are too wide they are very difficult to manage. As cycle time and pulse widths shrink, the bandwidth needed to preserve the rising and falling edges of the signals increases. This makes using bulky, expensive, terminated coaxial interconnections a necessity. Clock skew is the next most important performance limitation of conventional computers, especially on the board-to-board interconnect level. It slows the signal processing and occurs when signals from different parts of a circuit arrive at a gate at slightly different times, a difference of nanoseconds. This input skew causes a gate to generate an erroneous output. The push for higher speed forces shorter cycle times and this, in turn, limits the maximum differences in processor interconnection lengths.

The fear of clock skew precludes the use of logic in a pulsed mode. The accepted approach is to wait for the inputs to settle before utilizing the output of a gate. This input settling time is dependent on the amount of time it takes to fully charge the input connection and is quite different from the time it takes for a pulse to propagate down the interconnection. This charging time is a function of the resistance, capacitance, and inductance of the interconnection and the input of the gate. Presently, the RC time constant is already slower than the time it takes for a transistor to switch. As a result, it is very difficult to exploit the performance of ultrafast logic gates in a circuit with traditional interconnects.

The difficulties associated with this RC or RLC-dominated (R=resistance, L=inductance, and C=capacitance) settling time are not solved by very large scale intergration (VLSI). As the length of a wire shrinks by a factor of S and the cross-sectional area of the wire is reduced by a factor of S^2, the capacitance of the wire decreases by a factor of S while the resistance increases by a factor of S. The RC time constant and thus the input charging time remain the same, independent of scaling. Accordingly, given the RC parameters of VLSI, the signals will be communicated only at approximately $\sim 1\%$ the speed of light.

Guided wave optical interconnects based on optical fibers and thin-film waveguides can significantly reduce all the aforementioned bottlenecks. This is because of their larger base band coverage, zero settling time, immunity to electromagnetic interference (EMI) effect, faster propagation speed and much smaller impedance mismatch for massive fan-in and fan-out interconnects. Optical fibers are implemented for point-to-point interconnects where the massive fanout was realized using time division multiplexing/demultiplexing technique in the electrical domain.[3] A thin-film waveguide has the advantage of providing cascaded fanout in the optical domain, using either holographic gratings[4] or microprisms,[2] where the interconnect pattern can be easily defined using conventional lithographic tools. Therefore, a thin-film guided wave optical device has an advantage in distributed massive fan-out systems. However, the problem associated with current microlithographic technology is the limit of the field size which is well below the linear dimension of some of the most important interconnect scenarious such as backplane[3,4] and module-to-module interconnects.[5]

In this letter, we report the first compression-molded optical bus using photolime gel which is thermosetting material and can be transformed to thermoplastics after laser beam induced crosslinking.[6–7] Compression molding is conducted at the glass-transition temperature where thermoplastic polymers, i.e., photolime gel in this case, are deformable.

There are many molding processes, and often the designer has some freedom in selecting how a device may be made. Some processes, such as embedding, may be done at ambient conditions, but in general, both high temperatures and high pressures are a part of the processes. This is because most processes consist of melting the polymer, causing it to flow, and then freezing the polymer in its desired form. Generally, the viscosity of the liquid polymer

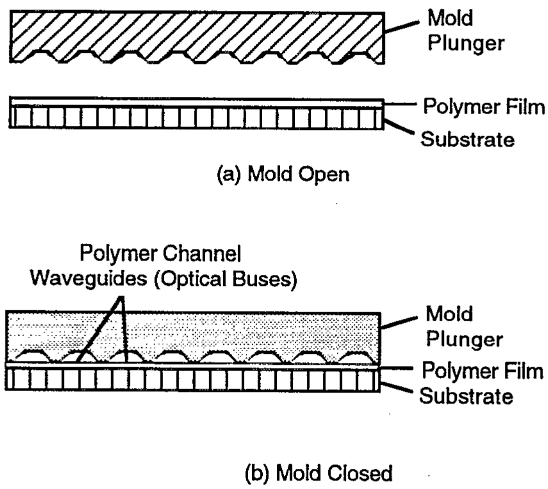

FIG. 1. Basics of a two-piece compression mold.

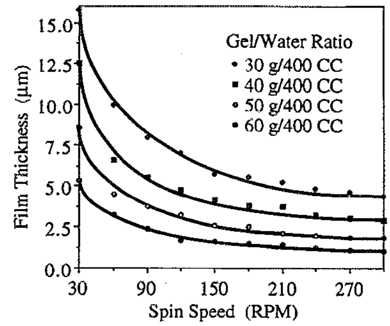

FIG. 2. Film thickness as a function of the spin speed with different gel/water ratios as a parameter.

is so high that considerable pressure is required to force it into its final configuration.[9,10] Thermosetting polymers freeze by a chemical reaction converting the liquid to a solid, while thermoplastic polymers truly freeze by a phase change from liquid to solid. These fundamental differences in polymers dictate the plastic molding method to be used.[7,8]

The process of compression molding is described by reference to Fig. 1. A two-piece mold provides a cavity having the shape of the desired polymer-based channel waveguide array. The mold is heated to the glass-transition temperature and the molding process is performed during the phase-transition period within which the polymer thin film is deformable. The glass-transition temperature for dehydrated photolime gel is ranging from 80 to 180 °C depending on the degree of material crosslinking.[5] An appropriate amount of molding material, photolime gel solution in this case, is loaded onto the substrate. The molding process is carried out by bringing two parts of the mold together under pressure. The polymer film, softened by heat, is thereby welded into the shape of the stamp. 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, under pressure, in the mold.

Unlike most of the polymeric materials used for nonlinear optics applications, which are synthesized in the laboratories, the polymer we employed in this experiment is photolime gel extracted from animal tissues. We have demonstrated an array of integrated photonic devices using the polymeric material reported herein. These include planar waveguide,[11] linear and curved channel waveguide arrays,[12] traveling wave electro-optic waveguide modulator,[13] multiplexed waveguide holograms,[14,15] multilayer optical interconnects,[16] and Nd^{+++}-doped waveguide amplifier working at 1.06 μm.[17] Furthermore, the graded index characteristic[11] of the waveguide allows the formation of high-quality waveguide devices on any substrate of interest. Therefore, this integrated photonic device technology can be transferred to any substrate of interest. The interconnect distance of previously reported devices was limited by the field size of microlithographic tools. The success of our previous research encourages us to develop a larger linear dimension molded waveguide employing the same material system. The polymeric solutions with various photolime gel and water ratios were prepared and then spin coated on glass substrates. Film thickness as a function of spin speed with photolime gel/water ratios as a parameter is shown in Fig. 2. Together with the cutoff dimension determined through the three-layer waveguide geometry,[18] the appropriate spin speed can be determined.

The compression-molded optical bus has a waveguide cross section very similar to that of GaAs/GaAlAs rib waveguide. The effective index method[19] used for determining GaAs/GaAlAs rib waveguide[20] is employed to determine the dimension of the compression-molded waveguide. The result of the computer simulation is shown in Fig. 3 where a three-dimensional (3D) plot with waveguide effective index (z axis) as a function of rib width (x axis) and rib depth (y axis) are clearly shown. The value of T_1 (see the inset of Fig. 3) is fixed at 2 μm which provides a single-mode planar waveguide to both TE (transverse electric) and TM (transverse magnetic) modes. The result shown in Fig. 3 is the numerical value of the effective index of the rib waveguide. By fixing $T_1=2$ μm, $n_{\text{substrate}}=1.5$, $n_{\text{guide}}=1.52$, and $\lambda=0.6328$ μm, it is a function of W and T_2. The cutoff dimensions for E^x_{11}, E^x_{12}, and E^x_{13} are clearly indicated in Fig. 3(b). This result provides the optimum waveguide dimension for single- and multimode waveguides and therefore serves as the molder design tool.

A compression-molded optical bus using photolime gel[5] has been fabricated and then evaluated. The design rule described in Fig. 3 provides us with the waveguide dimensions of single- and multimode waveguides. The molding tool we employed has a rib width (W) of 110 μm and a groove depth (T_1) of 10 μm. The film thickness was measured to be 8 μm. A small section of the molded polymer waveguide is shown in Fig. 4 where the 110-μm waveguide rib width is clearly indicated. Channel-to-channel separation was set at 200 μm (center-to-center). The waveguide thus fabricated demonstrated multiple modes. The thickness of the guiding layer is determined by the pressure between the molding stamper and glass substrate. A 45-

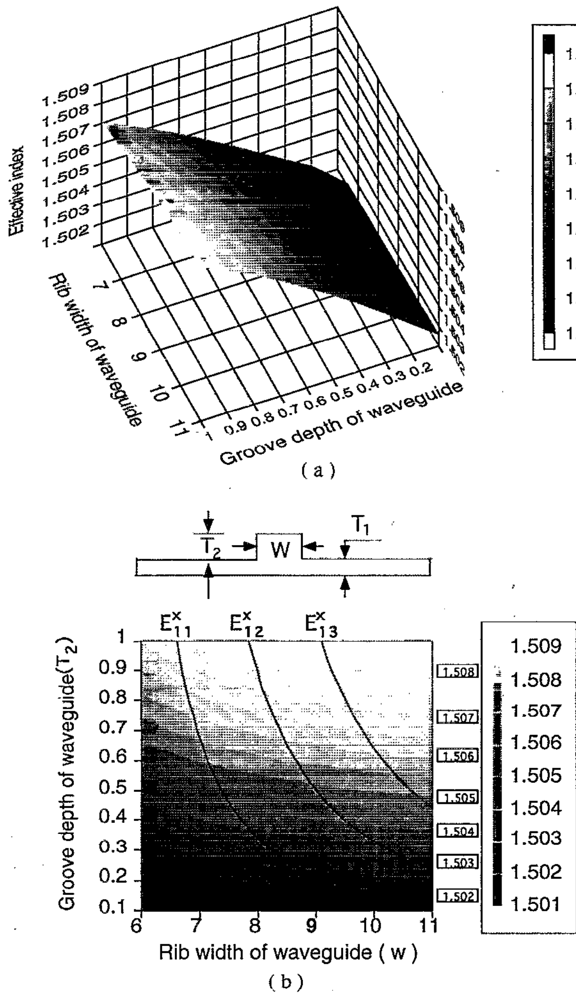

FIG. 3. (a) Value of effective index of the rib waveguide as a function of rib width and rib depth [see the inset of (a)], (b) equal effective index topology lines based on (a). The cutoff dimensions for E_{11}^x, E_{12}^x, and E_{13}^x are also indicated.

cm-long compression-molded channel waveguide made on a glass substrate is illustrated in Fig. 5 where a micro-prism[21] is employed to coupled 0.6328-μm HeNe laser beam into the guiding medium. The phase matching angle was set at the E_{11}^x mode. The ambient light displayed along

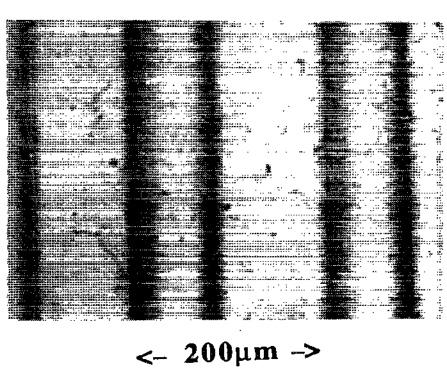

FIG. 4. A small section of the compression-molded photolime gel-based polymer waveguide.

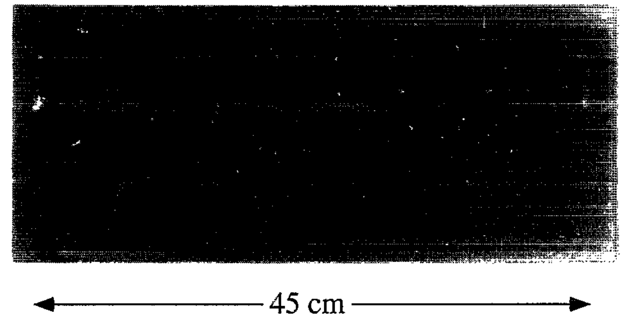

FIG. 5. A compression-molded optical bus with a linear dimension of 45 cm working at 0.6328 μm.

the rib waveguide (see Fig. 5) is the planar waveguide region T_2 shown in the inset of Fig. 3. Waveguide propagation losses of different samples were measured using the two prism method. Loss figures from 0.5 to 2 dB/cm were experimentally confirmed at 0.6328 μm.

A 2500-nm-wide transmission window (300–2800 nm) was reported on this material.[11] No overtone vibration was observed at 1.3 μm. As far as the effect of residual absorption is concerned, the molding process was performed at the phase transition temperature at which the polymer is in a liquid form. As a result, highly uniform waveguide structure was produced. Variation of the molded microstructure is mainly due to the fluctuation of pressure rather than the large linear dimension of the polymer thin film which is 45 cm in this demonstration.

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