COMPRESSION-MOLDED POLYMER BASED OPTICAL BUS

Ray T. Chen And Sunning Tang
Microelectronics Research Center
Department Of Electrical And Computer Engineering
University Of Texas, Austin
Austin, Tx 78759

and

Gajendra Savant and Tomasz Jannson
Physical Optics Corporation
2545W 237 Street
Torrance, CA 90505

ABSTRACT

In this paper, we report an optical bus fabrication technology using compression-molding technique. The linear dimension of such a waveguide is well beyond that of a microlithographically defined waveguide. The interconnection patterns such as fan-ins and fan-outs can be easily defined by the mold plunger. The resolution of compression molding can be as high as $2\ \mu m$. Therefore, optical bus density as high as $\sim 10^4$ channels/cm is producible while the linear dimension of the waveguide can be much larger than that made through conventional microlithography. Employment of optically transparent electronic packaging polymers (OTEPPs) as the system buses automatically provides process compatibility with silicon IC fabrication. All the polymer microstructure waveguide materials are either thermosets or thermoplastics. Both can be molded to a specific shape as desired.

1.0 INTRODUCTION

The intrinsic limitations of the current generation of computers have lead 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, RC time constants (for intra-chip 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

0-8194-1075-6/93/$6.00

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 settling time are not solved by 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. Given the RC parameters of VLSI, the signals will be communicated at approximately 0.5% the speed of light.

The current status of the major features of electrical and optical interconnections are further summarized in Table 1. It is clear that optical interconnection has a clear advantage over electrical interconnection which is based on metallic wiring. Waveguide based optical buses are produced by either laser beam direct writing or projection lithography which are inevitably small in size (up to 8 inches) and low volume. Specifically, large-scale (system-wide) interconnection may involve an optical motherboard with a linear dimension up to ~1 meter; laser writing and projection lithography will not be able to provide such a large field size. Innovative ideas are needed to produce a large field size optical bus system while maintaining cost effectiveness.

Table 1 Demonstrated Features of Electrical and Optical Interconnects

Characteristics	Metal	Optical
Maximum practical frequency	1.5 GHz	1000 GHz
Minimum number of layers needed for high-performance interconnection	4	1
Interconnect density/layer	500 lines/inch	1600 lines/inch
Problems of Electro-migration	Serious	Immune
Module cost	Comparable	Comparable
Crosstalk	Yes	No
RFI immunity	Poor	Excellent
Availability	Now	Two years

2.0 COMPRESSION-MOLDED WAVEGUIDE

Two elements empolyed for guided wave optical interconncets are optical fibers and thin film waveguides. 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. Thin film waveguide has the advantage of providing cascaded fanout in optical domain where the interconnect pattern can be easily defined using conventional lithographic tool. Therefore, thin film guided wave optical device has the advantage in distributed massive fanout systems such as optical backplane bus. However, the problem associated with current microlithographic technology is the limits of the wafer size which is up to 8 inches. No microlithographic patterning tool is available beyond this dimension.

In this paper, we report a thin film waveguide fabrication technology using compression-molding technique. The linear dimension of such a waveguide is well beyond that of microlitnographically defined waveguide. The interconnection patterns such as fan-ins and fan-outs can be easily defined by the mold plunger. The resolution of compression molding can be as high as 2 μm [3]. Therefore, optical bus density as high as $\sim 10^4$ channels/cm is producible.

An optical bus thus fabricated is depicted in Figure 3 where a number of daughter boards containing multichip module (MCM)-based processing elements (PEs) and memory chips are incorporated. Employment of optically transparent electronic packaging polymers (OTEPPs) as the system buses automatically provides process compatibility with silicon IC fabrication. All the polymer microstructure waveguide materials are either thermosets [4] or thermoplastics [5]. Both can be molded to a specific shape as desired. It is a high pay-off technology.

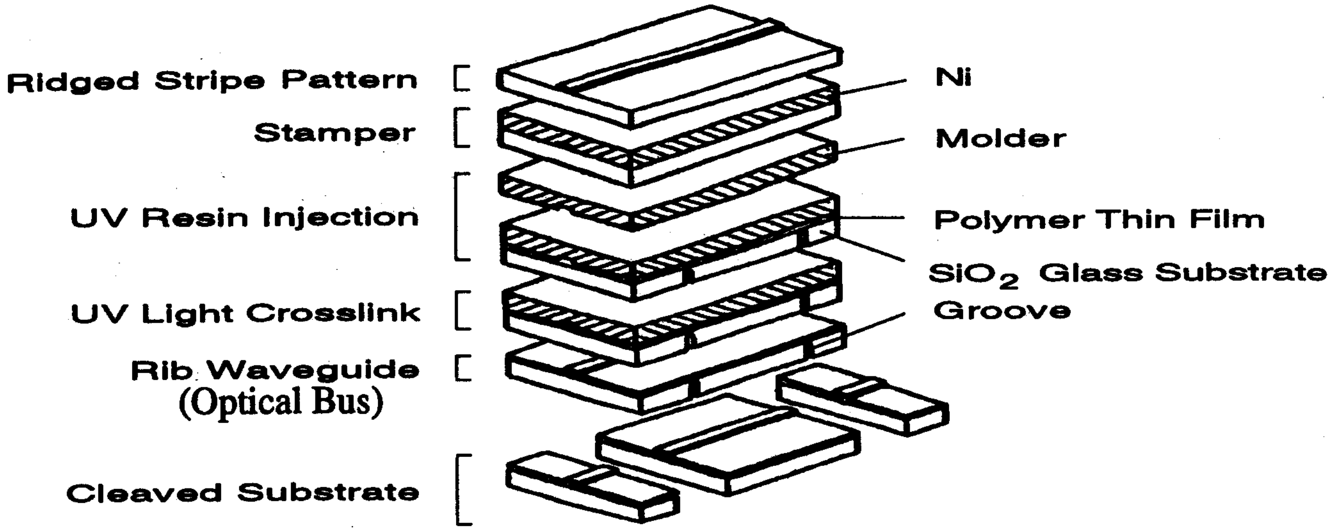


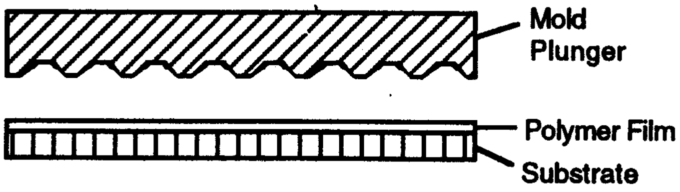
Figure 1
An Optical Bus Fabricated by the Molding Technique (Only a Small Section of the Optical Bus is Shown)

Replacement of electrical interconnects by optical interconnects requires an optical medium through which optical signals, in either digital or analog format can be routed from transmitters to receivers. If guided waves are chosen over free space routing for this purpose, the two available media are optical fibers and thin film waveguides. For machine to machine (or platform to platform) optical interconnects, optical fibers are the medium of choice. For interconnection scenarios such as backplanes, intermodule and intra module, thin film waveguides are under intensive investigation. Especially for high density highly parallel interconnections, such as fine grained computing systems, thin film channel waveguides are the only guided wave interconnection devices which are lithographically mass-producible.

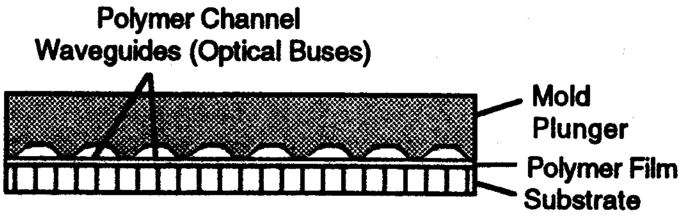
Among all the thin film waveguides reported, polymer-based optical waveguides have been widely agreed to be the best candidates due to their cost-effectiveness, low dielectric constant for multilayer coating and feasibility of conducting 3-D optical interconnects. Basically, all polymers are formed by the creation of chemical linkages between relatively small molecules, i.e. monomers, to form very large molecules or polymers. Such a procedure can be realized by either a condensation process or an addition process [6]. As a result, there are infinite number of polymers that can be synthesized, only a few hundred of which are being used for electronic packages [7]. Since silicon IC fabrication is a well-developed industry and the optically transparent electronic-packaging polymers (OTEPPs) (including thermosetting and thermoplastic) are compatible with IC fabrication process, it will be useful to make a thorough investigation of these existing polymers. It is to be noted that all the OTEPPs can be formed in molding processes such as compression and transfer molding, injection molding, casting, embedding, encapsulation, impregnation and potting.

There are many molding processes, and often the designer has some freedom in selecting how an electronic component 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 is so high that considerable pressure is required to force it into its final configuration[8,9]. 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 processing method to be used.

The optical bus shown in Figure 1 is made by a typical compression molding process. Both thermosetting and thermoplastic polymers can be processed with the compression method. The process of compression molding may be described by reference to Figure 2. A two-piece mold provides a cavity having the shape of the desired polymer-based channel waveguide array. The mold is heated. An appropriate amount of molding material, polymer waveguide film in this case, is loaded into 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 optically transparent electronic packaging polymer (OTEPP) 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.



(a) Mold Open



(b) Mold Closed

Figure 2
Basics of a Two-Piece Compression Mold

3.0 DESIGN CONSIDERATION

To provide the required high packaging density, the optical bus has to employ channel waveguides where both the lateral and transverse confinements of the optical signal is provided. Due to space limitations, only the transverse-electric (TE) mode is considered in this section.

The electric field distribution of the TE_{11} mode profile within the five regions shown in Figure 3 can be written as follows:

$$\left.\begin{array}{ll}
\text{Region 1:} & \psi_1 = A_1 \cdot \cos(k_{x1} \cdot X + \beta) \cdot \cos(k_{y1} \cdot Y + \alpha) \\
\text{Region 2:} & \psi_2 = A_2 \cdot \cos(k_{y2} \cdot Y + \alpha) \cdot e^{-}|k_{x2}| \cdot (x - a) \\
\text{Region 3:} & \psi_3 = A_3 \cdot \cos(k_{x3} \cdot X + \beta) \cdot e^{-}|k_{y3}| \cdot (y - b) \\
\text{Region 4:} & \Psi_4 = A_4 \cos(k_{y4} \cdot Y + \alpha) \cdot e^{+}|k_{x4}| \cdot (x + a) \\
\text{Region 5:} & \Psi_5 = A_5 \cos(k_{x5} \cdot X + \beta) \cdot e^{+}|k_{y5}| \cdot (y + b)
\end{array}\right\} \cdot e^{i(k_z z - \omega t)} \tag{1}$$

where k_z is the wave number in the propagation direction, k_{xi} and k_{yi} are the wave numbers of the two transverse directions in the ith region, A_i is the amplitude in the ith region, α and β are two phase constants, and a and b are the half waveguide dimensions in the horizontal and vertical directions, respectively. All the wave numbers can be determined by the effective index method (EIM) [10]. Figure 3 shows the EIM calculation procedure.

The channel waveguide is treated as a combination of two planar waveguides. The effective index of the first planar guide is used as the guiding layer index of the second planar guide. The k_{xi} and k_{yi} values are given in the following four equations,

$$k_{yi} = \left(N_i^2 \cdot k^2 - N_{ep}^2 \cdot k^2\right)^{1/2}, \quad i = 1, 3, 5 \tag{2}$$

$$k_{xi} = \left(N_i^2 \cdot k^2 - N_{1eff}^2 \cdot k^2\right)^{1/2}, \quad i = 1, 2, 4 \tag{3}$$

and

$$k_{y1} = k_{y2} = k_{y4}$$
$$k_{x1} = k_{x3} = k_{x5}$$

where k is the wave number in free space, N_{1eff} is the effective index of the first planar waveguide (Figure 3(b)), N_{ep} is the effective index of the channel waveguide which is also treated as the effective index of the second planar waveguide in the effective index method. From Maxwell's equation for a source-free boundary, we have

$$\nabla \cdot E = 0 \tag{4}$$

and

$$\nabla \times E_1 \Big|_{y=b} = \nabla \times E_3 \Big|_{y=b} \tag{5}$$

where E_1 and E_3 are the electric fields in regions 1 and 3, respectively. The amplitudes determined by Eqs. (4) and (5) are

$$A_2 = A_1 \bullet \cos(k_{x1} \bullet a + \beta) \tag{6}$$

$$A_3 = A_1 \bullet \cos(k_{y1} \bullet b + \alpha) \tag{7}$$

$$A_3 = A_1 \bullet \cos(k_{x1} \bullet a - \beta) \tag{8}$$

$$A_5 = A_1 \bullet \cos(-k_{y1} \bullet b + \alpha) \tag{9}$$

where A_1 is an arbitrary constant depending upon the intensity of the input laser light. Two more values that need to be determined are α and β. Since the cladding index in region 2 is equal to that in region 4 (Figure 3), we have

$$\beta = 0 \tag{10}$$

The phase constant α can be determined through boundary condition Eq. (5). After some trivial calculations, we have

$$k_{y1} \bullet \sin(k_{y1} \bullet b + \alpha) = k_{y3} \bullet \cos(k_{y1} \bullet b + \alpha). \tag{11}$$

Therefore,

$$\alpha = -k_{y1} \bullet b + \arctan(k_{y3}/k_{y1}). \tag{12}$$

The waveguide dimensions needed to form a TE single-mode channel waveguide are shown in Figure 4, with $\Delta n \equiv n_{1eff} - n_{2eff}$ (Figure 3(b)) as a parameter. Note that the numerical values of n_{1eff} and n_{2eff} are dependent on the final molding shape of a rib waveguide.

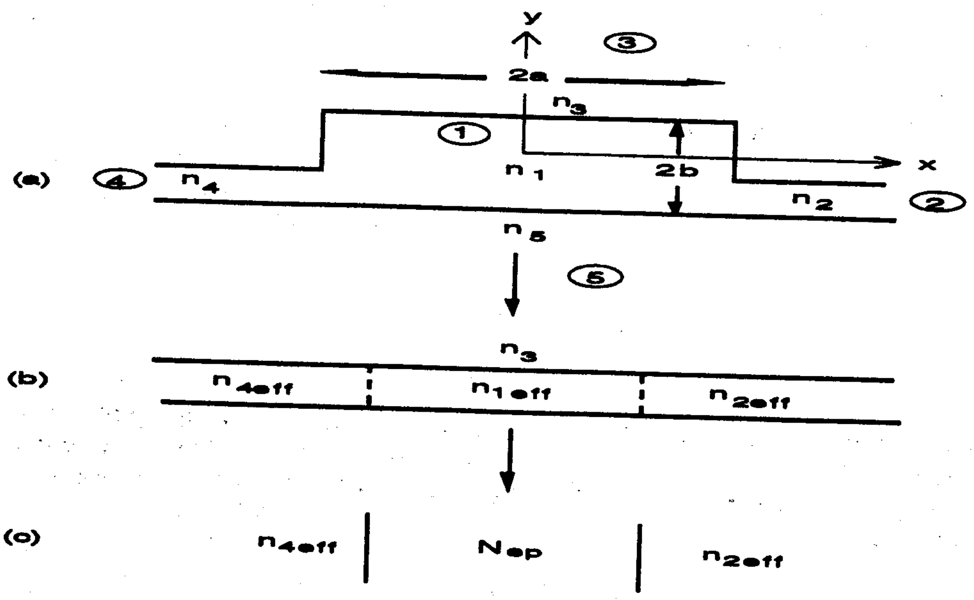


Figure 3
Schematic Representation of the Effective Index Method. N_{ieff} is the effective index of the ith zone.

4.0 PRELIMINARY EXPERIMENTAL RESULT

A Polymer-based Optical Bus using Photolime Gel[11,12] has been fabricated and then evaluated. The design rule described in previous section provides us with the limit of waveguide dimension below which there is no waveguiding effect. The molding tool we empolyed has a 100µm rib width and a 10µm groove depth. Channel to Channel Separation was set at 200 µm (center to center). The waveguide thus fabricated demonstrated multiple modes. It is to be noted that the molding process shall be performed during the phase transition period within which the polymer thin film is deformable.

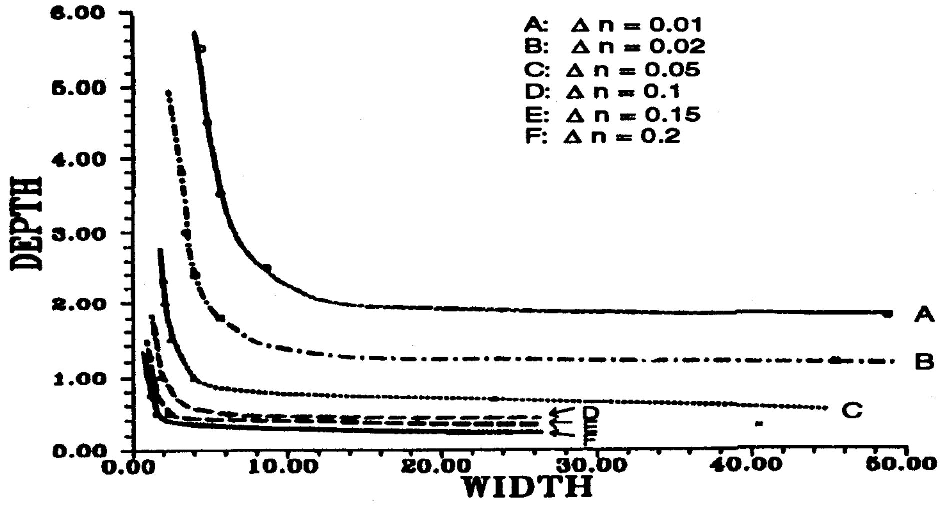


Figure 4
Theoretical Results for a Single-Mode Waveguide Dimension with Δn ($n_{1eff} - n_{2eff}$) as a Parameter

Fig. 5 is a compression-molded optical bus with a linear dimension of 1.5 feet working at 1.31μm. Such a large linear dimension will be useful for backplane optical interconnects[13]. The near field profile of the optical throughput of the bus array taken at the imaging plane is further illustrated in Fig.6. Note that the optical wave was coupled into the bus array using a cylindrical lens. The nature of a multimode waveguide is not clearly shown in this figure. This is because of the overlap with higher order modes in the endfire coupling.

Fig.5 Compression-molded Optical Bus Working at 1.31μm with Linear Dimension of 1.5 feet

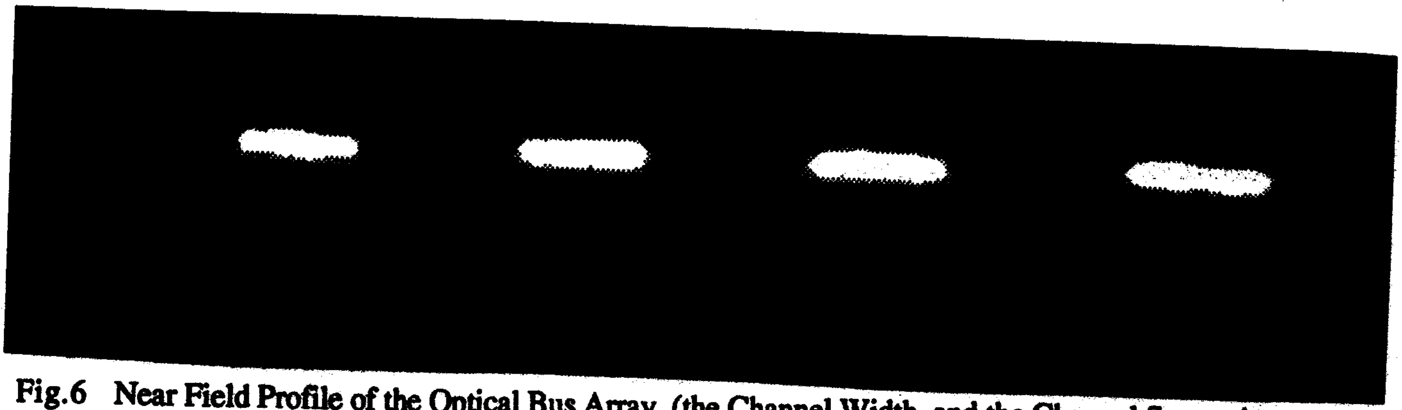


Fig.6 Near Field Profile of the Optical Bus Array (the Channel Width and the Channel Separation are both 100μm)

5.0 CONCLUSIONS

We report the first compression-molded optical bus with a linear dimension of 1.5 feet using a photolime gel polymer thin film. The molding tool we employed has a 100μm channel width and a 10μm groove depth. Channel to channel separation was set at 200μm. Preliminary experimental data were reported in this paper.

Among all the thin film waveguides reported, polymer-based optical waveguides have been widely agreed to be the best candidates due to their cost-effectiveness, low dielectric constant for multilayer coating and feasibility of conducting 3-D optical interconnects. Basically, all polymers are formed by the creation of chemical linkages between relatively small molecules, i.e., monomers, to form very large molecules or polymers. Such a procedure can be realized by either a condensation process or an addition process. As a result, there are infinite number of polymers that can be synthesized, only a few hundred of which are being used for electronic packages. Implementation of OTEPP-based optical bus using the molding technology is a promising approach. Since silicon IC fabrication is a well-developed industry and the optically transparent electronic-packaging polymers (OTEPPs) (including thermosetting and thermoplastic) are compatible with IC fabrication process. Implementation of optical layers in the electronic systems will be feasible in a cost-effective manner.

This research is currently sponsored by Cray Research, Physical Optics Corporation and the School of Engineering of the University of Texas at Austin.

6.0 REFERENCES

1. D. Z. Tsang, "Optical Interconnections in Digital Systems Status and Prospects," Optics and Photonics News, 23-29 (1990).
2. Ray T. Chen, "Optical Interconnccects: A Solution to very High Speed Integrated Circuits and Systems," Proc. SPIE, Vol.1374, 20(1990).
3. Chapter 24 of the Plastic Engineering Handbook, editor Frados, fourth edition.
4. Thermosetting polymers are partially polymerized at the time of manufacture, forming a resing, full polymerization is accomplished by the person who forms the final shape. The polymerization process is called crosslinking, curing, hardening, or vulcanization.
5. Thermoplastic polymers are deformable in glass-transition temperature. Its polymerization does not involve chemical reactions as thermosets do. Therefore, thermoplastics are reusable.

6. Joel Frados, Plastic Engineering Handbook (Van Nostrand Reinhold Company).

7. Charles A. Harper, ed., Electronic Packaging and Interconnection Handbook (McGraw-Hill, Inc., 1991).

8. C. A. Harper, Handbook of Plastics and Elastomers (McGraw-Hill Book Company, 1976).

9. R. Juran (ed.), Modern Plastics Encyclopedia, McGraw-Hill, New York, 1985.

10. B. Hocker and W. K. Burns, "Mode Dispersion in Diffused Channel Waveguides by Effective Index Method," Appl. Opt., 16, 113 (1977).

11. R. T. Chen et al., "60 GHz Board to Board Optical Interconnects," to appear in Appl. Phys. Lett., February 1992.

12. Ray T. Chen, "Polymer-based Guided wave Devices and Their Applications," Critical Review on Integrated Optics and Optoelectronics, 1993

13. J. P. G. Bristow, "Polymer Waveguide-Based Optical Backplane for Fine-Grained Computing," Proc. SPIE on Optical Interconnects in the Computer Environment, 1178, 103 (1989).