CROSS-LINK INDUCED LINEAR AND CURVED POLYMER CHANNEL WAVEGUIDE ARRAYS FOR MASSIVELY PARALLEL OPTICAL INTERCONNECTS

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ABSTRACT

A single-mode polymer-based channel waveguide array with 1250 channels/cm packaging density on a cross-link induced photopolymeric thin film is reported. This array works at 1.31μm and 0.63μm. Curved waveguides with radii of curvature (ROC) from 1mm to 40mm were demonstrated. Waveguide propagation loss in the neighborhood of 0.1db/cm was demonstrated for both linear and curved waveguides. Interconnectivity for various interconnection architectures including cross bar, hypercube, daisy chain and star are further considered. Multiple layers of optical interconnects may be required for an optical backplane involving massively parallel highly distributed computing systems.

1.0 INTRODUCTION

Replacement of electrical interconnects requires an optical medium through which optical signals in either digital or analog format can be routed from transmitters to receivers. If guided wave rather than free space routing is chosen for this purpose, two available choices are optical fibers and thin film waveguides. For machine-to-machine optical interconnects, optical fibers are the medium of choice. For interconnection scenarios such as backplane, intermodule and intramodule, thin film waveguides are the major tools under intensive investigation[1,2]. A thin film channel waveguide is the only guided wave interconnection device that is lithographically mass-producible. This is especially important for applications requiring high density highly parallel interconnections, as do fine grained computing systems.

Among all the thin film waveguides reported in the literature, polymer-based optical waveguides are widely agreed to be the medium of choice due to their substrate transferability, cost-effectiveness, availability for multilayer coating and potential to serve as 3-D optical interconnects.

2.0 FORMATION OF HIGH DENSITY CHANNEL WAVEGUIDE ARRAY

In this paper, we report the first cross-link induced linear and curved channel waveguide and waveguide array on graded index (GRIN) photo-lime gelatin[3]. The GRIN characteristic of the polymer thin film allows us to implement such a channel waveguide on any substrate of interest. After the polymer film was spin-coated on a substrate, it was dipped into ammonia dichromate solution for sensitization. Formation of a channel waveguide was realized by cross-linking the polymer film

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through UV exposure. It was observed that the cross-linked area has a higher index of refraction than the unexposed area. The index modulation due to the photo-induced cross-link can be as high as 0.2[4]. Consequently, the channel waveguide confinement and thus the packaging density (number of channels/cm) can be extremely high. Implementation of the waveguide pattern was realized either by laser beam direct writing or through a conventional lithographic process. The graph in Fig.1 was produced by computer simulation based on the effective index method[5]. It shows the optimal single-mode channel waveguide dimensions for an optical wavelength of 1.31μm. The cutoff dimension is shown with index modulation as a parameter. Note that the cutoff boundary defined here is for E_{12}, above which the channel waveguide becomes multimode. Marcatili's five-region method[6] was also used for this purpose. The result (not shown) is very close to that of Fig.1. However, the cutoff dimension for E_{11}[5,6] determined by the effective index method is quite different from that determined by Marcatili's method. In any case, the waveguide cutoff dimension for E_{12} is well above the cutoff condition for E_{11}. The discrepancy between these two methods for E_{12} is negligible[7].

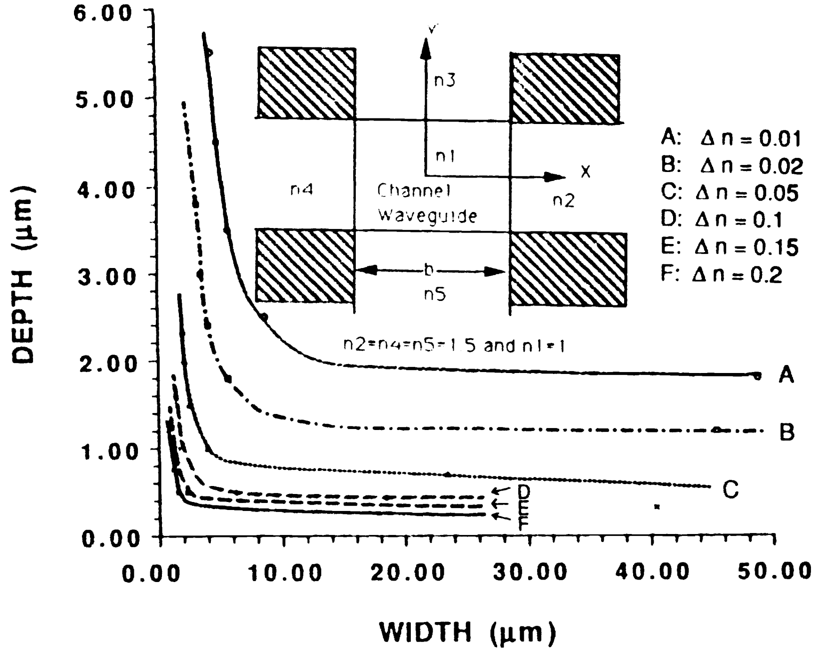


Fig.1 Single mode polymer waveguide dimensions based on the effective index method with index modulation as a parameter

3.0 EXPERIMENTAL RESULTS

The experimental results of a linear polymer channel waveguide array working at 0.63μm and 1.31μm were experimentally verified using the setup shown in Fig.2(a). A microprism was employed[3] to provide simultaneous coupling for multiple channels. The observed near field patterns for 0.63 and 1.31μm, using the setup shown in Fig.2(a), are displayed in Figs. 2(b) and 2(c), respectively. A single-mode waveguide at 0.63μm was further confirmed(Fig.3) by employing a Si charge coupled photodetector (CCPD) array to image the mode profile in both horizontal and vertical directions. The packaging density of the waveguide device shown in Figs. 2 and 3 is

1250 channels/cm, which is approximately two orders of magnitude higher than that of electrical board to board interconnections[8]. Confirmation of single mode guiding at 0.63μm assures that the waveguide mode for 1.31μm shown in Fig.2(c) is also single mode[9].

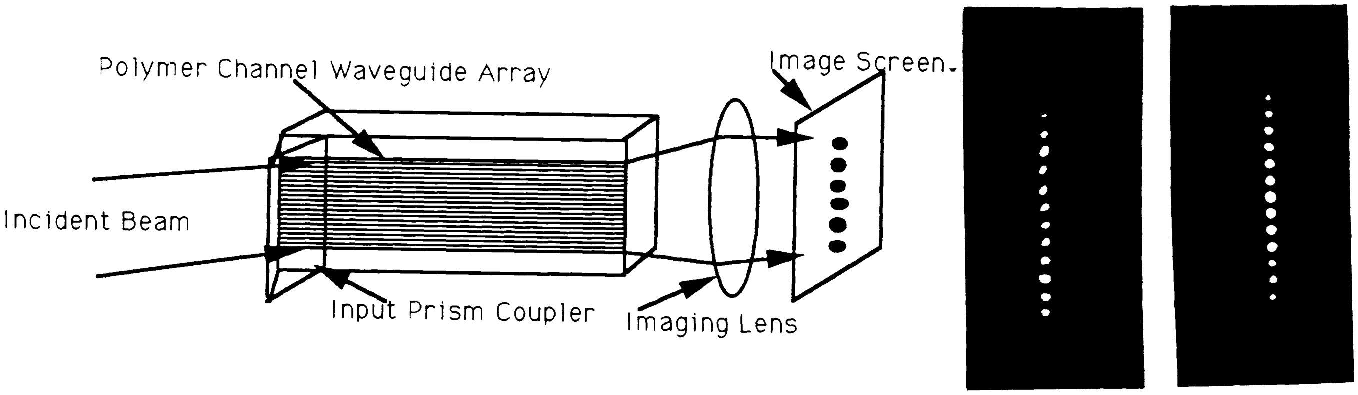
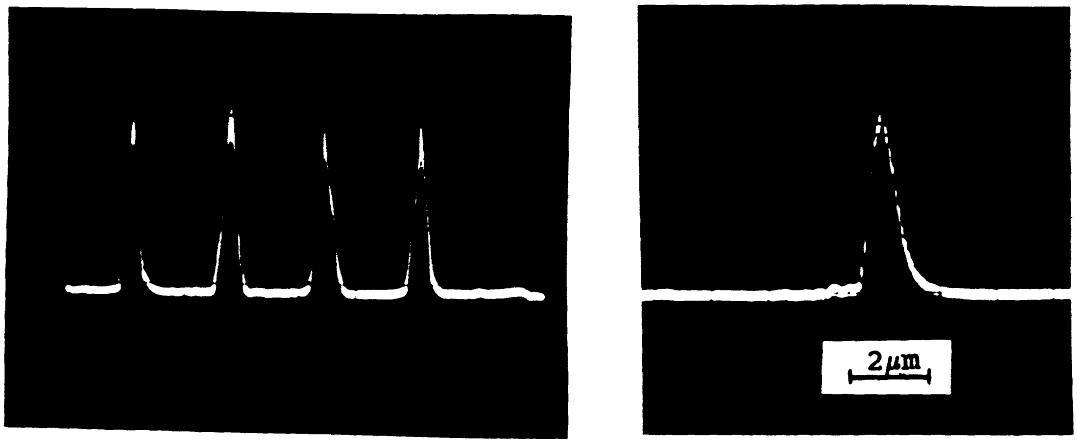


Fig.2 (a) Experimental setup for the observation of polymer channel waveguide array (channel width=2μm), and near field patterns of the channel waveguide array for wavelengths at (b) 0.63μm and (c) 1.31μm, respectively. Channel separation is 8μm.



(A) (B)

Fig.3 Mode profiles of the single-mode channel waveguide array in the (a) horizontal (peak to peak separation is 8μm) and (b) vertical directions.

To provide optical interconnects on the intraMCM (multichip module), interMCM and backplane levels, an optical bus may need to be curved in order to transmit optical signals to the addressed location (e.g., memory). To evaluate the feasibility of generating a curved polymer waveguide, channel waveguides with radii of curvature

(ROC) of from 1 mm to 40 mm were made. Table 1 summarizes the parameters of the curved waveguides fabricated. Large index modulation caused by photo-induced cross-linking provides a better waveguide confinement factor and thus a smaller ROC. Theoretically, the loss due to waveguide bending can be negligibly small if [7]

$$ROC > \frac{3N_{eff}^2 . \lambda}{\pi[N_{eff}^2 - N_c^2 + (\lambda/2b)^2]^{3/2}} \quad (1)$$

where N_{eff} is the guided wave effective index, N_c is the cladding layer index and λ and b are the optical wavelength and the width of the channel waveguide. Note that in deriving Eq.(1), the wave number of the guided wave along the x direction (the inset of Fig.1) is assumed

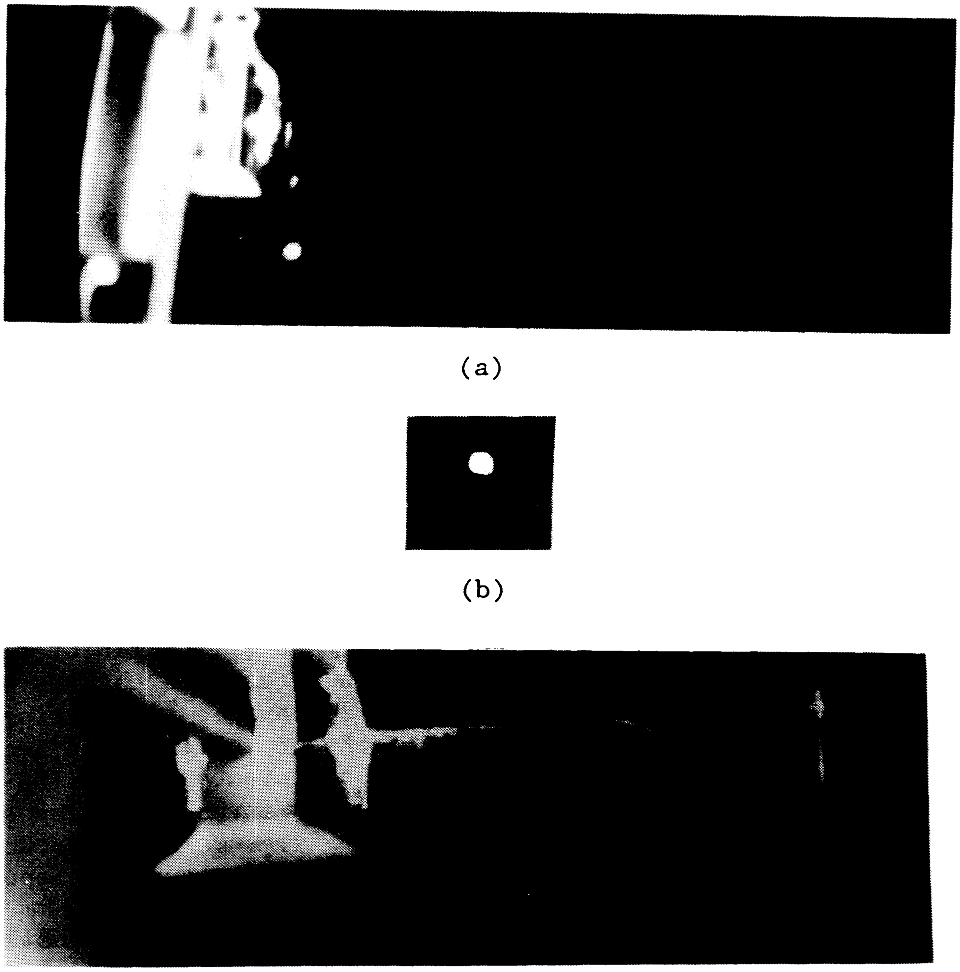
Channel Width (um)	Radius of Curvature (mm)	Degrees of Rotation
10	1	90, 180
10	2	90, 180
10	3	90, 180
10	4	90, 180
10	4.5	90, 180
10	40	90, 180

Table.1 Curved waveguide parameters under investigation

to be equal to $\lambda/2b$. Figs.4(a), 4(b) and 4(c) show the experimental results of a curved polymer channel waveguide. The coupling angle of the input prism was set at the phase matching angle for E_{11}. No surface scattering can be observed from the image taken by a vidicon camera. The confirmation of curved waveguiding was made by scribing the curved channel waveguide surface (Fig.4(a)). A bright spot was observed. The bright streak on the waveguide surface, which can be an indicator of loss[10], disappeared (Fig. 4(a)) in our linear and curved channel waveguide devices. The photograph shown in Fig.4(b) is the near field mode patterns at the output end of the curved waveguide through end-fire coupling. Special surface treatment is needed to increase the loss and thus to make surface scattering visible. Fig. 4(c) shows a curved waveguide with same pattern of Fig.4(a) after surface treatment.

The value of the index modulation plays an important role in minimizing the propagation loss for the curved region. The larger the index modulation, the better the waveguide confinement factor. The evanescent field decays drastically in the cladding region. The radiation loss due to velocity mismatch[11,12] is thus minimized. As far as the waveguide propagation loss is concerned, the measured loss for a single mode linear waveguide using the two prism method is shown in Fig.5. Purification of the polymer thin film significantly reduced the volume scattering centers within the guiding medium and thus reduced the waveguide loss previously reported[10]. The losses for various curved waveguides (dB/rad) were determined by comparing linear and curved waveguides which have the same propagation length. Within the error shown in Fig.5, there is no extra loss due to waveguide curving.

The advancement in high-speed computers requires an interconnection technology capable of routing high-speed signals, especially clock distribution for a synchronous bus such NUbus[7] and high speed data for a compelled asynchronous bus such as VMEbus and Futurebus[7]. Electrical interconnects using either thin metal films or transmission lines are not efficient enough to provide highly parallel, high-speed (~>1GHz [13]) connection. Optical interconnections based on polymer waveguides have been reported[14] to provide two-dimensional(2-D) and three-dimensional (3-D) optical interconnects with 60 GHz modulation bandwidth and 22dB signal to noise ratio[14]. The results presented herein give us a packaging density as high as 1250 channels/cm with propagation loss as low as 0.1dB/cm.



(a)

(b)

(c)

Fig.4 Experimental results of curved channel waveguides, (a) observation of a curved channel waveguide (ROC=3mm) at the scribed waveguide surface (no surface scattering can be observed from the vidicon camera); (b) near field pattern of the curved channel waveguide with the same ROC of (a) (observed through end-fire imaging); (c) observation of the curved channel waveguide with a ROC equivalent to that of Fig.4(a) after surface treatment.

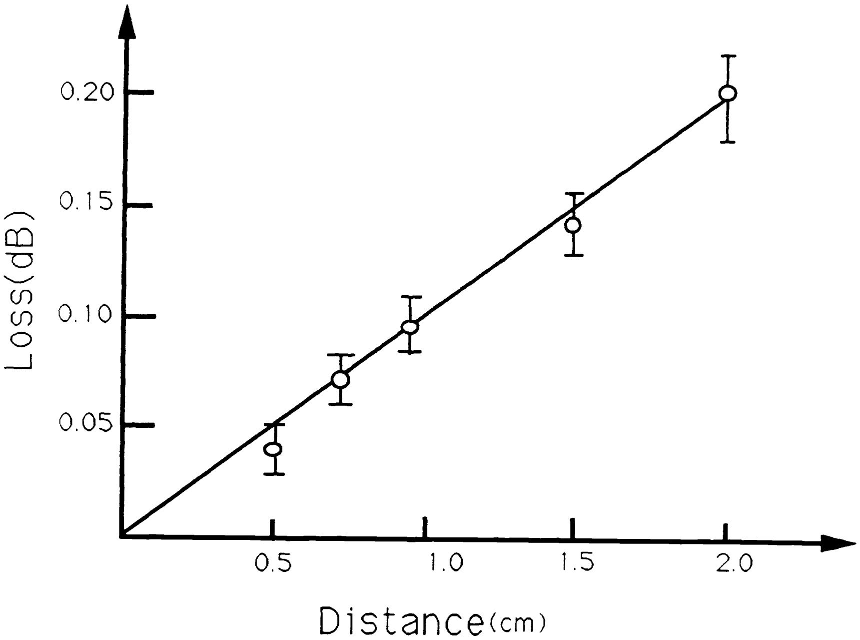


Fig.5 Measured loss of a single-mode polymer-based channel waveguide at 1.31μm optical wavelength. The same result holds for the curved waveguide shown in Table 1.

The fullest connectivity is provided by a crossbar architecture where each processing element (PE) is fully interconnected with other PEs within the system. Assuming a massively parallel, fine-grained computing system with message widths of 64 bits, the total number of channel waveguides needed for a bidirectional optical bus is $N=128 \cdot 128 \cdot 64 \cdot 2 \sim 2 \cdot 10^6$ channels. This corresponds to a backplane linear dimension of ~10 meters (assuming that the 128 PEs are located on 16 daughter boards and have a packaging density of 1250 channels/cm. The factor 2 provides bidirectionality). It is clear that either multilayer optical interconnects or multiplexing techniques such as time division multiplexing (TDM) and wavelength division multiplexing (WDM) are needed in such a massively parallel, highly distributed interconnection system. For computing systems with relatively low interconnectivity, such as hypercube, daisy chain and star architectures, the single layer optical interconnects reported herein are sufficient to provide the required interconnectivity.

Implementing of fiber arrays for current backplane buses such as VMEbus[15] and Futurebus[16] is not practical since these bus architectures connect all processors and memory cardboards in parallel, along a set of common communication lines which can in general be driven by any machine and listened to simultaneously by all machines (eg., using low efficiency coupling holograms[17]). Thus, any machine on a bus can communicate directly with any other (subject to bus ownership protocols). As a result, implementation of a practical optical backplane bus requires microlithographic process which is not applicable for fiber arrays. Furthermore, the GRIN property of the polymer waveguide facilitates the implementation of optical integrated circuits on any optoelectronic substrate. Finally, we have recently demonstrated[18] a linear electrooptic effect with r_{33} equivalent to that of $LiNbO_3$ on photolime polymer film. Therefore, both polymer-based passive and active guided wave devices can be monolithically integrated on a single substrate.

4.0 CONCLUSIONS

In summary, we report the first cross-link induced linear and curved polymer channel waveguide arrays on photolime gelatin with packaging density as high as 1250 channels/cm. Waveguide propagation loss of 0.1 dB/cm was confirmed by eliminating the volume scattering centers within the guiding medium. Computer simulation based on the effective index method and Marcatili's method were conducted to predict the criterion for single-mode operation at 1.31μm. For interMCM and intraMCM optical interconnects, polymer channel waveguides, which function as the physical layer of optical buses, may need to be curved. Curved waveguides with ROC from 1 mm to 40 mm were fabricated and then evaluated. No extra waveguide loss due to the waveguide bending was observed. Finally, a highly parallel fully interconnected crossbar architecture with 128 processors, 64 bit message width, located in a fine grained computing system with 16 daughter boards, is considered. Either multilayer interconnects or multiplexing techniques may be required on the backplane for such an architecture. Interconnection networks with lower connectivity, such as hypercube, daisy-chain and star single-layer optical waveguides, will be sufficient to provide the required interconnectivity.

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