Polymer Microstructure Waveguides on Various Substrates for Optical Interconnection and Communication

Ray T. Chen, Michael R. Wang*, G. J. Sonek* and Tomasz Jannson

Physical Optics Corporation
2545 W. 237th Street
Torrance, CA 90505

ABSTRACT

The feasibility of constructing graded-index (GRIN) Polymer Microstructure Waveguides (PMSWs) on various substrate surfaces, including semiconductors, conductors, insulators, and ceramics, has been consistently proven. The PMSW formed by Physical Optics Corporation (POC) is at least one to two orders of magnitude larger than those constructed by the state-of-the-art microstructure formation systems such as MOCVD and MBE. The polymer material used possess a large dynamic range of temperature stability (from -180°C to +200°C) and wide transmission bandwidth (from 0.3 μm to 2.7 μm wavelengths). Local sensitization technique applied to PMSW has also been introduced to facilitate the formation of planar multiplexed holographic gratings for single wavelength 1-to-many fanouts and wavelength division (de)multiplexing (WD(D)M). Realization of such technology is useful for optical interconnection, signal processing and communication.

2. INTRODUCTION

The necessary advances in optoelectronics for the many Strategic Defense applications will require advances in materials that can modulate, focus, transmit, multiplex, demultiplex, receive and demodulate optical signals. These advancements are crucial to realizing an advanced optoelectronic system to fully employ the wide potential bandwidth (~THz) of optical signal processing and computing. To date, the related materials mainly focus on Lithium Niobate ($LiNbO_3$) and III-V compounds such as Gallium Arsenide (GaAs). $LiNbO_3$ is for hybrid integration and GaAs is for monolithic integration. From systematic and economic points of view, quite a few limitations exist on both materials. First, $LiNbO_3$ and GaAs can not produce the high index modulation needed for the implementation of multiplexed phase gratings, which is one of the most important building blocks for VLSI optical interconnection and optical computing. Second, the facilities needed to fabricate microstructure waveguides are not cost effective. Third, only very few materials can be grown on top of III-V compounds because of the strict requirement for lattice matching. Fourth, the yield rate of such devices is relatively low. Therefore, their cost is high. Development of new materials that can function as microstructural waveguides but do not have the problems mentioned above are extremely important for building economical and reliable optical signal processing and computing systems.

We introduce a new polymeric material with tunable profile of guiding layer index that will be able to solve all the complicated issues associated with conventional thin-film microstructural waveguide fabrication mentioned above. This polymer waveguide will be a low cost building block for optical signal processing. The polymer microstructure waveguides (PMSWs) on Si, GaAs, glass, $LiNbO_3$,

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* Also with Department of Electrical and Computer Engineering, University of California Irvine, Irvine, CA 92717

Quartz, Fused Silica, PC Board, Aluminum, Chromium, Gold, Copper, Kovar, Al_2O_3, BeO and AlN were formed with excellent optical quality (loss <1dB/cm). A guiding layer as large as 4" x 8" was further constructed with this new material. The polymer waveguide structure is able to be grown on any kind of substrate including insulators, semiconductors, conductors and ceramics regardless of their indices of refraction (guiding effect), and conductivity (loss effect), with low propagation loss (< 1dB/cm). Furthermore, the local sensitization technique is introduced to facilitate the formation of multiplexed hologram. Many plausible applications using PMSWs should, therefore, be possible.

3. FORMATION OF POLYMER MICROSTRUCTURE WAVEGUIDES

A good quality thin film (loss<1dB/cm) can be formed by using pure polymer gelatin. A pure photo-lime polymer gelatin solution with various water and gelatin ratios is spun on top of the substrates. When the gelatin is first formed, it is in an aqueous solution and the molecules exist as single chains surrounded by water molecules. After standing at temperatures below 30°C, solutions with more than 1% gelatin become rigid and exhibit rubber-like mechanical properties[1]. An optical thin film is thus formed. The film thickness can be varied from submicron to ~100 μm by changing either the ratio of water and photo-lime gelatin or the spin speed of film coating. It was proven that the gelatin film prepared in such a way shows a step index[2]. When the film is formed on absorptive, or conductive, or higher index substrate materials, the excessive loss or leaky wave behavior makes the waveguiding in such thin film impractical. In order to achieve good waveguiding in the gelatin film, index tuning from step index into graded index profile with a higher surface index is necessary. The low-index portion of the polymer film functions as a clading layer for the formation of the waveguide.

A guiding layer refractive index tuning mathod was developed to meet this purpose. A combination of wet and dry processing was used to perturb the mass density of the polymer thin film. According to the Lorentz-Lorentz equation[3], the index of refraction n of a material is given by

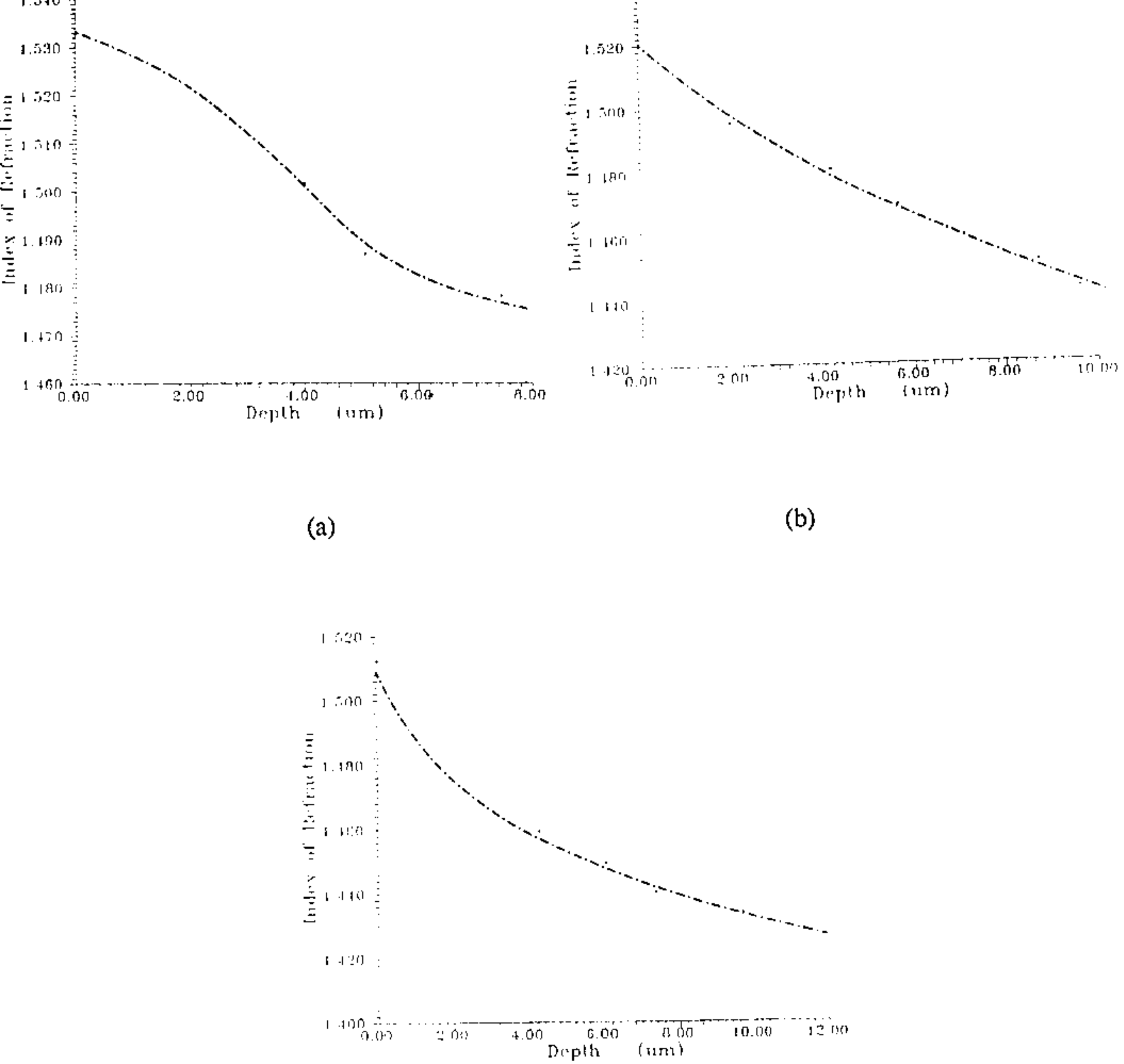
$$n = \left(1 + 4\pi \frac{Ni \cdot ri}{1 - 4\pi \cdot Ni \cdot ri/3}\right)^{1/2} \qquad (1)$$

where ri is a constant which characterizes the response of the i^{th} type molecules to an applied field, and Ni is the average number of i^{th} type molecules per unit volume. This is proportional to the density of the substance. Summation over i is assumed in Equation (1).

The wet and dry processing changed the mass density of the polymer thin film. As a result, the refractive index of the polymer thin film was disturbed. The prism coupling method is employed to examine its waveguiding property. various guiding layer refractive index profiles of multimode PMSWs are determined by the Inverse Wentzel-Kramers-Brillouin (IWKB) method[4,5]. The WKB approximation reduces the solution of the eigen value problem, by application of boundary conditions at the waveguide surface, to the solution of the equation

$$\int_0^{h_m} \left(N^2(h) - N_{eff\,m}^{\;2}\right)^{1/2} dh = \frac{4m-1}{8} \qquad m = 1, 2, \ldots \qquad (2)$$

where h_m is defined by $N(h_m) = Neff_m$. The integration is along the depth direction (h) of the polymer film. We also let h = 0 and Neff = N_0. This treatment is good because the effective index of the 0^{th} order mode of a waveguide with many modes is very close to the surface index[6]. The polymer refractive index profiles ranging from approximately linear ones to approximately Gaussian ones can be produced



(a)

(b)

(c)

Fig. 1 Refractive Index Profile on (a) Al_2O_3, (b) Al, and (c) GaAs substrates.

by choosing different wet and dry processing procedures. Fig. 1 shows the index profiles on some substrates after tuning. Similar results hold for other substrates. With a guiding layer profile like this, the overlap between the evanescent waves and the substrates is drastically reduced. Excellent waveguidings for fundamental mode with low propagation loss (<1dB/cm) are thus formed. Fig. 2 shows the excellent waveguiding in PMSWs on GaAs, Quartz, glass, Gold, and Al_2O_3. Similar results had been observed on Si, $LiNbO_3$, Fused Silica, Al, Cu, Cr, Kovar, BeO, AlN and PC Board.

4. FORMATION OF MULTIPLEXED HOLOGRAM BY LOCAL SENSITIZATION FOR WDM AND OPTICAL INTERCONNECTS

The formation of PMSWs through index tuning technique provides us a mean to transport optical signals on various substrate materials. Additional advantages of using PMSWs for various applications would rely on the possibility of building optical devices on PMSWs.

The implementation of multiplexed holograms is crucial to make truly useful microstructure waveguides for various optical interconnect and signal processing applications. A typical microlithography process is used to accomplish this goal. The local sensitization process was achieved by dipping the sample into an ammonium dichromate solution at room temperature. The masking material was then removed, and within two hours after drying and stabilization of the sensitized region, the sample was ready for dichromated gelatin (DCG) holographic recording and processing.

A four-channel wavelength division demultiplexer, with center wavelength $\lambda = 632.8$ nm (red), 611.9 nm (orange), 594.1 nm (yellow), and 543.0 nm (green), was successfully demonstrated (Fig. 3) on a locally sensitized single-mode PMSW on Soda-Lime glass substrate. Notice that the PMSWs can be built on various substrates. Hence, using Soda-Lime glass as substrate is not a necessary mean to achieve WD(D)M. TE_0 guided mode for all wavelengths is used in the present device. In order to form the multiplexed waveguide holographic gratings, to be used in demultiplexing the signal carriers of different wavelengths, a two-beam interference recording method was employed. Each individual holographic grating, having a sinusoidal phase modulation profile, is recorded such that

$$K_i = 2k_{\lambda_i} \sin\left(\frac{\theta_i}{2}\right) \tag{3}$$

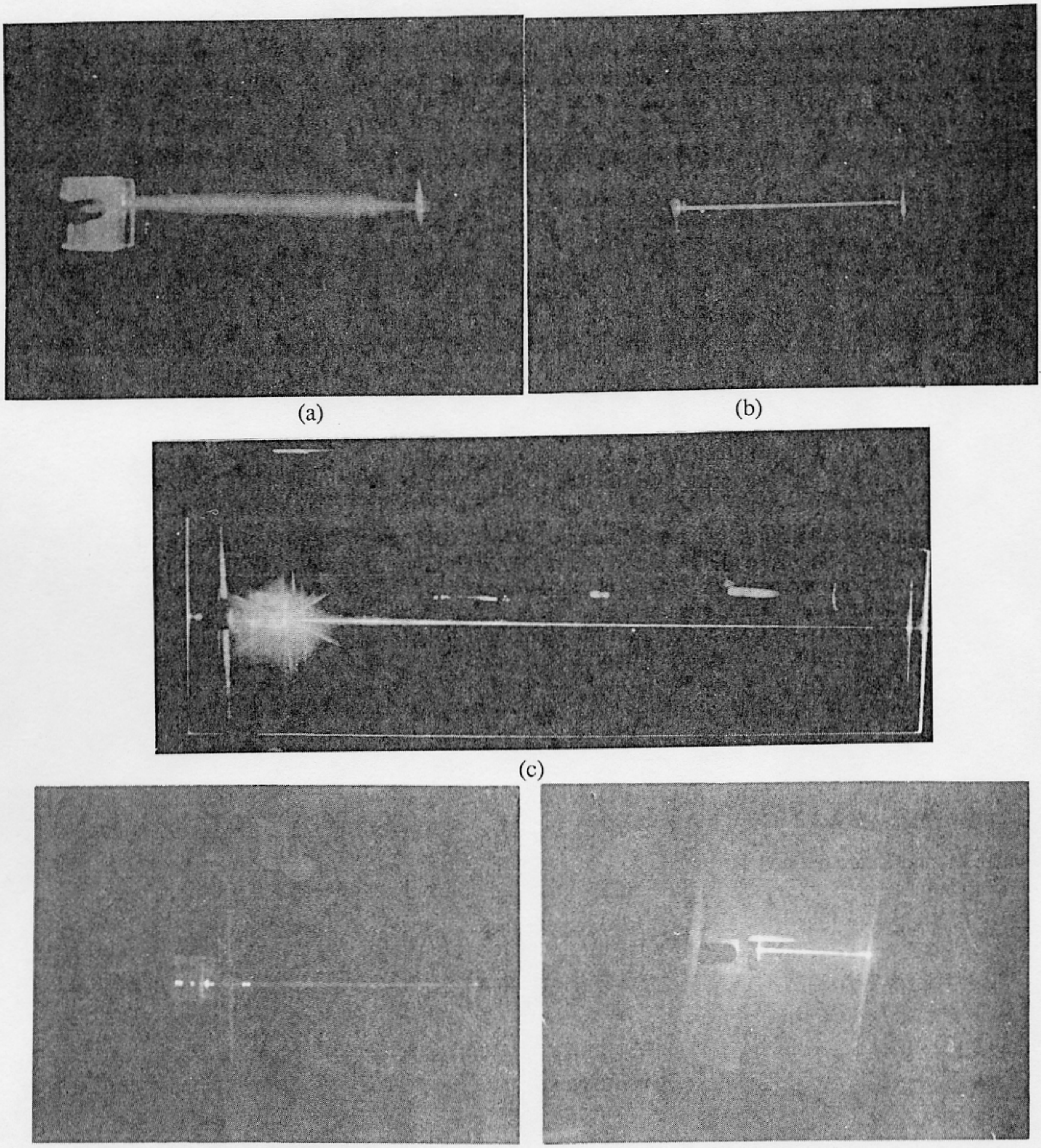
where k_{λ_i} and K_i are defined as

$$k_{\lambda i} = N_{\mathrm{eff}_{\lambda_i}} \cdot \frac{2\pi}{\lambda i} \tag{4}$$

and

$$K_i = \frac{2\pi}{\Lambda_i} \tag{5}$$

Here, θ_i is the angle of Bragg Diffraction, Λ_i is the holographic grating period, K_i is the i^{th} grating wave vector, and $N_{\mathrm{eff}\lambda i}$ is the waveguide mode effective index at λ_i. Since the effective index N_{eff} of the PMSW is a function of wavelength, different recording angles were selected for each wavelength. Exposure parameters were adjusted during successive holographic recordings in an attempt to optimize



(a)

(b)

(c)

(d)

(e)

Fig. 2 PMSW on (a) GaAs, (b) Quartz, (c) 8" glass, (d) Gold, and (e) Al_2O_3 substrates.

diffraction efficiencies. Each grating is, therefore, designed to be capable of deflecting only one wavelength within a 4 - 10 nm spectral bandwidth. The crosstalk of each individual channel was measured to be ~-40 dB, while the diffraction efficiency at each wavelength was found to be higher than 50%. It should be possible to achieve much higher diffraction efficiencies, for each individual grating, if the grating index modulation profile and the grating interaction length are optimized. While excellent crosstalk figures were obtained, it is conceivable that the presence of substrate radiation modes from each signal carrier, generated by the interaction with other existing gratings, or from random fluctuations in grating modulation index and waveguide thickness, will limit the overall WD(D)M device efficiency for closely spaced channels. The angular and spectral sensitivities for the present device were determined to be within 0.2 - 0.4° and ~4 - 10 nm, respectively.

The technology succeeded on WD(D)M is transferable to 1-to-many fanouts for optical interconnection. For the interconnects, single wavelength will be used. The multiplexed holographic gratings are designed and patterned on the locally sensitized PMSW to deflect the incoming signal into many directions. Hence, the local sensitization enables the use of PMSWs for optical interconnection.

5. OPTICAL FANOUT DENSITY

Optical interconnections with massive fan-out require high efficiency and low cross talk. The high efficiency can always be achieved by carefully controlling some grating parameters. The low cross talk for massive fan-out requires minimal angular overlap between each fan-out direction. Thus, the angular sensitivity of the Bragg hologram is the key to determine the theoretical massive fan-out capability.

By using coupled mode theory, as it is applied to a lossless step-index waveguide medium containing slanted phase gratings[7], depicted in Fig.4, the TE mode (p-light) diffraction efficiency verse the grating interaction length, d, at some diffraction angles are calculated. For the calculation, it was assumed that there is complete overlap between the guided mode and the index perturbation, and that the modulation index has a value of $\Delta n \sim 0.01$. We note that the effects of a finite beam width and a graded index profile were not accounted for in the present analysis. The diffraction efficiency is periodically modulated, undergoing a transition between a maximum and a minimum value as the diffraction angle is changed. The diffraction efficiency at all angles can be improved upon by tuning the modulation index during the fabrication process.

The dependence of angular width and fanout channel density on the grating interaction length, d, and diffraction angle is shown in Fig.5. A decrease in angular bandwidth can be achieved, but requires either an increase in the grating interaction length or an increase in Bragg angle. Hence, as the angular bandwidth decreases, the greater number of fanout channels can be accommodated within the waveguide. In comparison, the smaller interaction lengths (~<60 μm) often utilized in 3-D holographic 1-to-many fanouts or WD(D)M devices limit the overall channel density that can be achieved.

6. DISCUSSION AND APPLICATION

Many far-reaching applications can be realized based on the PMSW technology. Basically, the PMSW we proposed and then developed in this program shall find its suitability in all the optical and electrooptic systems that involve microstructure waveguides. The capability of locally sensitizing the PMSWs provides us with a new way to develop optical device systems. Some of the more highly plausible applications are further described in this section.

When the speed and fan-out number increase, there is a need to employ optical interconnects on the back plane to perform board-to-board interconnection. We have already concluded that a PMSW can be constructed on any smooth surface including insulators, semiconductors, conductors, and ceramics. As

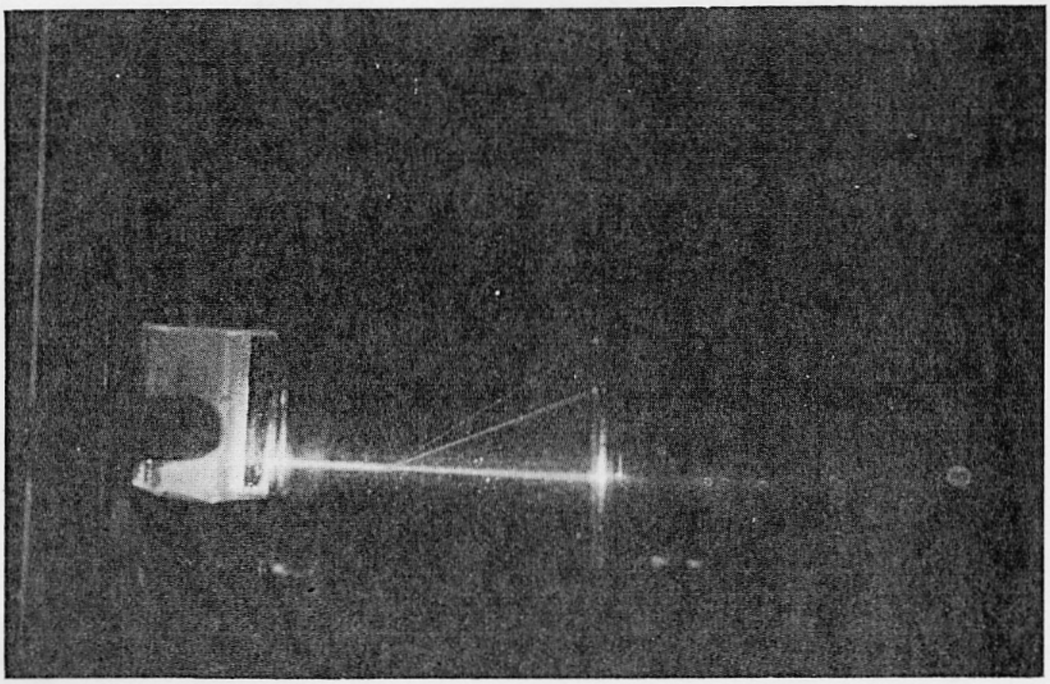


Fig. 3 A 4-channel wavelength division demultiplexer on locally sensitized PMSW

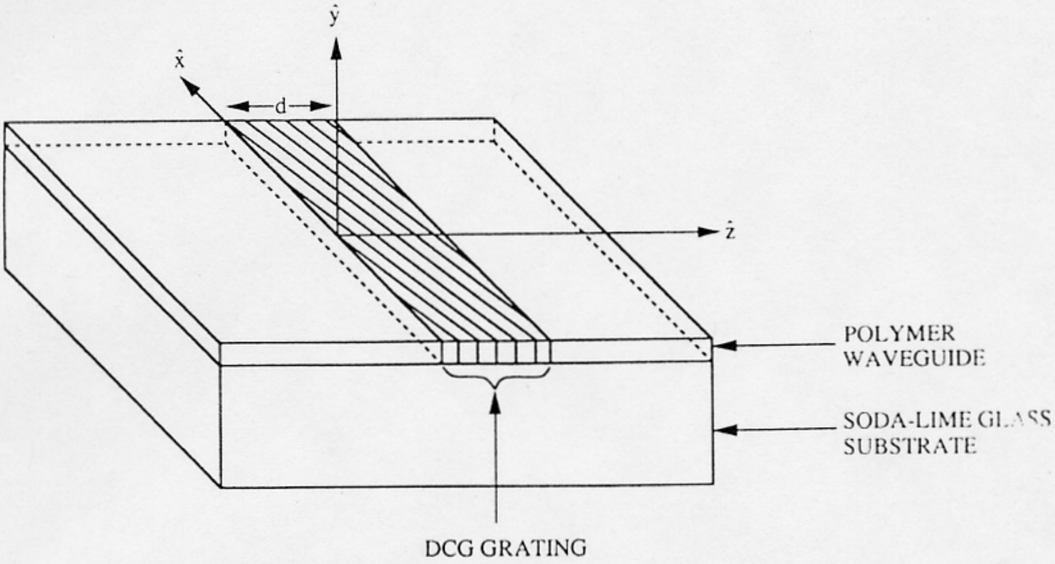


Fig. 4 Schematic of Locally sensitized Polymer Waveguide, containing a DCG holographic phase grating

a result, PMSW is an attractive alternative to realize the back plane interconnection. The PMSW is deposited on the back plane which holds the layers of IC boards. If the interconnectability and parallelity need to be further increased, several integrated PMSW back planes can be added on the same board. Optical components such as laser diodes, photodetectors, and multiplexed holograms can be integrated on to the same PMSW back plane to transmit, route, and receive the optical signals.

PMSW itself is transparent over a wide range of the optical spectrum. Accordingly, the PMSW itself functions as a good optical path to route optical waves with various wavelengths (~0.3 μm to ~2.7 μm) (Fig. 6). A high density wavelength division multiplexing and demultiplexing device based on PMSW technology and multiplexed holograms is feasible. Integration of holographic lenses and highly multiplexed Bragg holograms into PMSWs is doable in both the transmitter and the receiver. Since the refractive index modulation of DCG can be as high as 0.1, a large number of gratings can be multiplexed on the same holographic emulsion[8]. Local area networks, highly parallel computer interconnections and long distance, wide band communications are some of the areas in which the PMSW based WD(D)M will find its use.

Recently, fiber optics sensors that are based upon wavelength division multiplexing (WDM) techniques[9] have been a major area of interest. By using WDM techniques, rotary and linear position sensing, rotary speed sensing, and pressure and temperature sensing information is provided. The working principle is to use WD(D)M devices to create a chromatically dispersed strip of light, which can be either an LED or a laser diode array. The dispersed light is then focused onto the code tracks which contain binary information (i.e., transmission, 0; reflection, 1). Different binary codes correspond to different sensed parameters. The detected optical signal is coupled back into a fiber through the same WDM device. The topology of this sensor system is shown in Figure 7. The PMSW based WD(D)M we propose herein is an outstanding device for this application. For example, the four-channel WD(D)M we demonstrated can be used as a linear or rotary position sensor for 16 different positions[9]. Each individual position is identified by four different binary codes. Figure 8 (a) and (b) represents (1,1,0,1) and (1,0,1,1), respectively. Currently we are developing a 15-channel WD(D)M which will give us a 15-bit binary code sensing capability ($2^{15}>10^6$). This will upgrade the resolution of present fiber sensors by more than 30 dB. Further results of this application will be presented in future publications.

7. CONCLUSION

The feasibility of constructing graded-index (GRIN) Polymer Microstructure Waveguides (PMSW) on any surface, including semiconductors, conductors, insulators, and ceramics, has been consistently proven. A 4" x 8" PMSW on a glass substrate was demonstrated. The PMSW which Physical Optics Corporation (POC) can form is at least one to two orders of magnitude larger than those formed by the state-of-the-art microstructure formation systems such as MOCVD and MBE. The first 4-channel wavelength division demultiplexer on locally sensitized single-mode PMSW has been successfully demonstrated. A high transmission bandwidth (from 0.3 μm to 2.7 μm wavelengths) was observed. The PMSW structure which POC invented will be an invaluable means to implement microstructure waveguides for any optical computing and/or signal processing scheme which requires microstructure waveguides. Also, the polymer material used has a large dynamic range of temperature stability from -180°C to +200°C. Further theoretical calculations were made to confirm the ability to perform high density WD(D)M and to make single wavelength massive fan-out optical interconnects based on the technology reported.

The technology we developed in this program is a cost-effective and universal method to provide excellent quality optical waveguides which is not achievable through any other known waveguide fabrication technologies. Tunability of the guiding layer index of refraction provides us the feasibility of constructing good quality PMSW on any smooth surface. We employed a newly developed wet and dry processing method to tune the index of the guiding layer. Such processes mainly perturb the mass

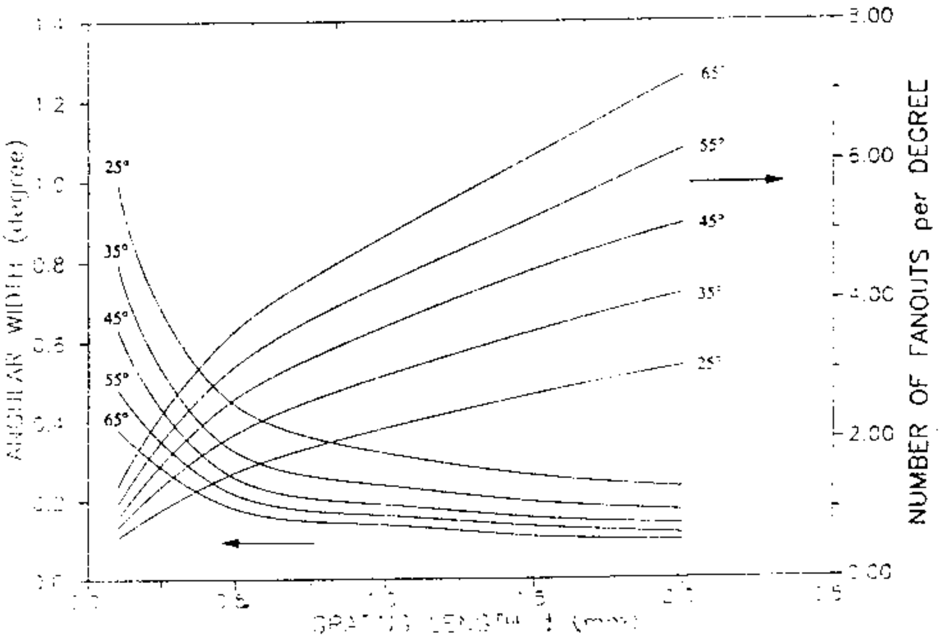


Fig. 5 Angular bandwidth, and fanout density, plotted as a function of grating interaction length d. A mode effective index $N_{eff} = 1.5172$, center wavelength λ =632.8 nm and waveguide thickness of 3 μm were used in the calculation.

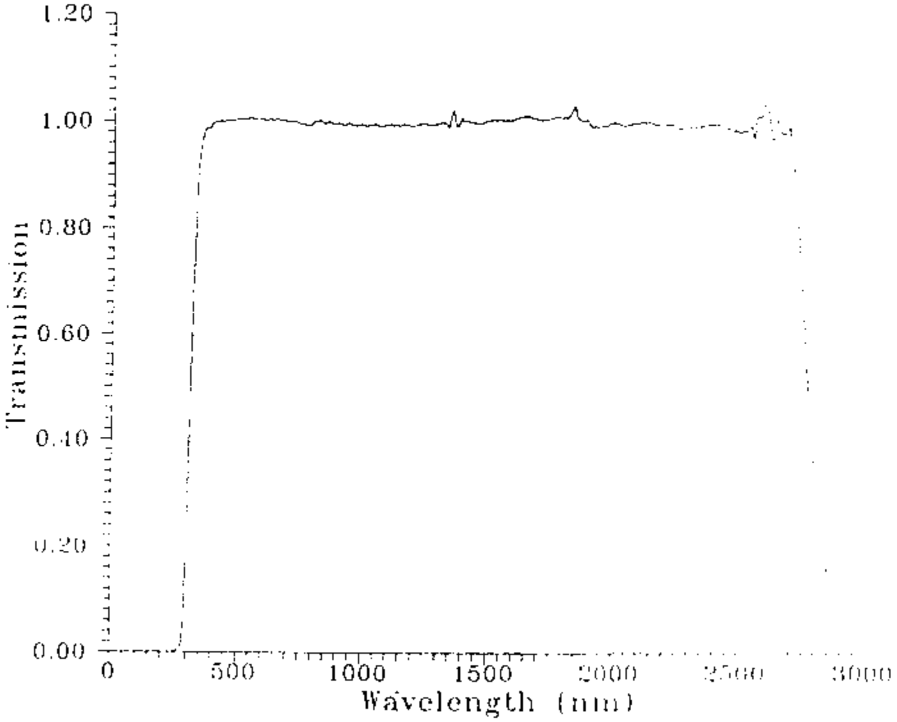


Fig. 6 Optical Transparency of Polymer Gelatin Thin Film (10 μm)

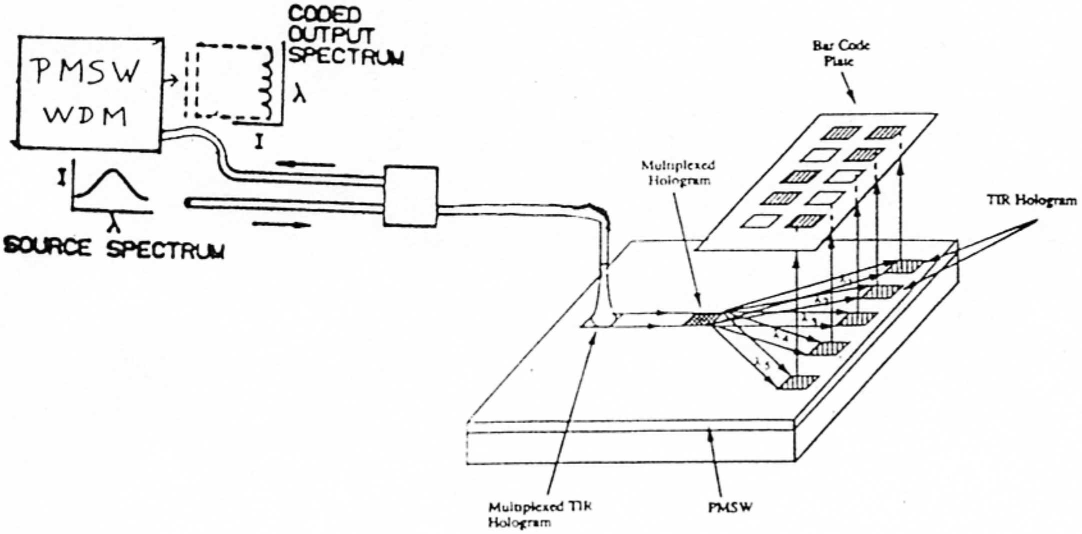
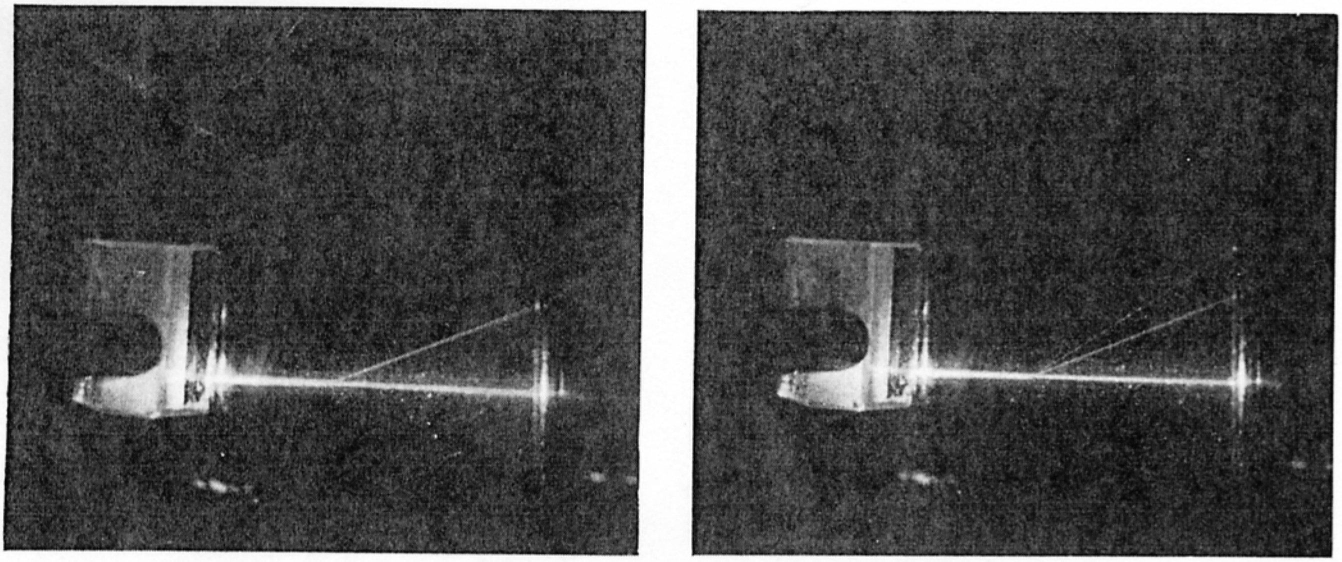


Fig. 7 Schematic Illustration of Broadband Energy being Transmitted Through a WDM System to a Fiber Sensor



(a) (b)

Fig. 8 Four-bit Position Sersor (a) (1101) (b) (1011) density of the polymer film. Since the index of refraction n of a material is a function of the density of the substance, the combination of the wet and dry processing results in the graded index profile observed. High quality PMSW has been consistently observed on a myriad of substrates including Si, GaAs, glass, $LiNbO_3$, Quartz, Fused Silica, PC board, Al, Cr, Au, Cu, Kovar, Al_2O_3, BeO and AlN. The survivability of such PMSW on harsh environments including nuclear radiation, electromagnetic interaction, and high power microwave was tested. The PMSW material is immune to these influences.

Many far reaching applications can be realized based on the PMSW technology. Basically, the PMSW we proposed and then developed in the program shall find its suitability in all the optical and optoelectronic systems that involve microstructure waveguides. The capabilities of locally sensitizing the PMSW provide us with a new way to develop passive and active optoelectronic systems. It is anticipated that this optical research and development program will result in a reliable and cost effective optoelectronic system which will cover the visible and IR regions. The research will positively impact future military optoelectronic systems. In a like manner, commercial applications of this new technology could include VLSI optical interconnects, signal processing and computing.

8. ACKNOWLEDGEMENT

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