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ABSTRACT

We have observed waveguiding in thin films of polymer gelatin on GaAs, LiNbO₃, glass and aluminum substrates. A graded index profile can be induced in the gelatin layer and tuned by wet processing. This makes it possible to form waveguides on any smooth surface. Locally sensitizing the gelatin waveguide with ammonium dichromate allows us to integrate single and multiplexed gratings on the same substrate to perform various functions for optical interconnects and signal processing. A waveguide grating coupler that converts free space TEM₀₀ laser light to a two dimensional spherical guided wave with 50° angle of divergence has also demonstrated. A passive broadcasting network can be formed using this new technology. Further plausible applications such as WD(D)M local area network, optical interconnection, and optical computing are also presented.

2. INTRODUCTION

Integrated Optics (IO) is a far reaching effort to apply thin-film technology to optical circuits and devices and to accomplish better and more economical optical systems. One of the major building blocks required to fulfill the above scheme is a good quality optical waveguide that can receive and propagate optical signals with minimum loss and yet be integrated with various passive and active devices on different substrates. The difficulty in building such good quality optical waveguides on various electrooptic crystals is one of the major reasons that integrated optic devices are fabricated primarily on LiNbO₃ and III-V heterostructure (GaAs-GaAlAs, InP-GaInAsP, etc.). For example, SBN has an electrooptic coefficient r_{33} more than one order of magnitude higher than that of LiNbO₃. However, the tremendous propagation losses of SBN:60 waveguides¹ makes it impractical to build any passive or active devices on this substrate. Sputtering methods offer another means to make waveguides on different substrates. However, the complications intrinsic to multi-layer depositions, the relatively high propagation losses, and the difficulty of combining sputtered films with other integrated optic devices such as lenses, gratings etc., make it an undesirable choice. Materials that can be placed on different electrooptic substrates and form good quality waveguides and be integrated with other IO devices, are necessary to solve this problem.

In this paper we report an innovative way to form low loss optical waveguides using polymer gelatin on different substrates including insulators, semiconductors and conductors. The original motivation for building gelatin waveguides derives from our work with holographic recording emulsions such as dichromated gelatin (DCG). The importance of dichromated gelatin as a holographic material lies in its ability to record phase holograms by modulating the refractive index with values exceeding 0.1². High efficiency holographic optical elements (HOEs) based on DCG have been reported by various groups^{3,4}. Integration of such devices in the thin film format is very

useful. However, DCG itself, due to the presence of the photosensitizer ammonium dichromate, has serious in-plane scattering loss ($>10\text{db/cm}$), which makes the formation of waveguides in conjunction with other integrated optic devices impractical.

3. FORMATION OF POLYMER THIN FILM

We report good quality waveguides ($\text{loss} < 1\text{db/cm}$) formed from pure gelatin (photo limered bone gelatin), i.e., gelatin without ammonium dichromate. Pure gelatin solutions with various water to gelatin ratios were spun on top of soda-lime glass ($N=1.512$ at 632.8nm). When gelatin first goes into aqueous solution the molecules exist as single chains encircled by water molecules. Upon standing at temperatures below 30°C , solutions containing more than 1% gelatin become rigid through natural cross linking and exhibit rubber-like mechanical properties. In this work optical waveguides were thus formed.

The waveguiding properties were examined through the prism coupling method. The measured effective indices for TE and TM guided waves were the same (to 0.0001 accuracy) for each sample. This implies that no birefringence exists in the gelatin layer. The guiding layer index profiles of multi-mode gelatin waveguides were determined by the inverse Wentzel-Kramers-Brillouin (IWKB) method commonly used in integrated optics^{5,6}. The second differential equation affiliated with wave propagation in a three layer dielectric waveguide is similar to the Schrodinger equation in Quantum Physics with N_{eff} as the eigen value, index distribution $n(x)$ as the quantum well $V(x)$, and the guided wave mode as the wave function. The WKB approximation reduces the solution of the eigenvalue problem, by boundary conditions at the guide surfaces to the solution of the equation

$$\int_0^{dn} \left(n^2(x) - N_{\text{eff}}^2 \right)^{\frac{1}{2}} dx = \frac{4m-1}{8} \quad m = 1, 2, \dots \quad (1)$$

where dn is defined by $N(dn) = N_{\text{eff}n}$. We also let $dn=0$ and $N_{\text{eff}0} = N_0$. 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. The graded index profile of a multi-mode waveguide can be accurately determined by the IWKB method. Step indices can also be determined through this method with a small deviation at the turning point⁷. The calculated index profile of sample #D1, composed of 15 grams of gelatin (photo limered bone gelatin), 100 CC water and spun at 100 rpm, is given in Fig.1, curve A. The depth of the step index profile is equal to the film thickness. The measured surface refractive index of various samples with different water-gelatin ratios is shown in Fig.2. Surface refractive index variation from 1.522 to 1.543 was observed. Each data point of Fig.2 was determined by the 0^{th} order mode of the corresponding multimode waveguide (total number of modes >10).

4. TUNABILITY OF GUIDING LAYER REFRACTIVE INDEX

Since the guiding layer has a step index, the 0^{th} order mode effective index is almost equal to the surface index. The plotted index profiles of the various gelatin waveguides before wet processing, a method associated with DCG hologram

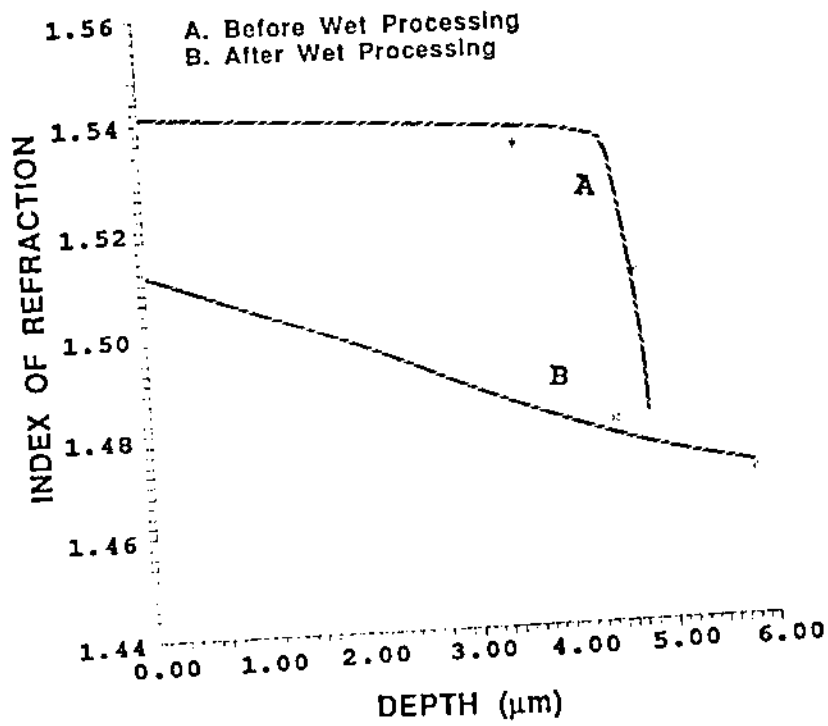


Fig. 1. Index Profile Of Gelatin Waveguide #D-1

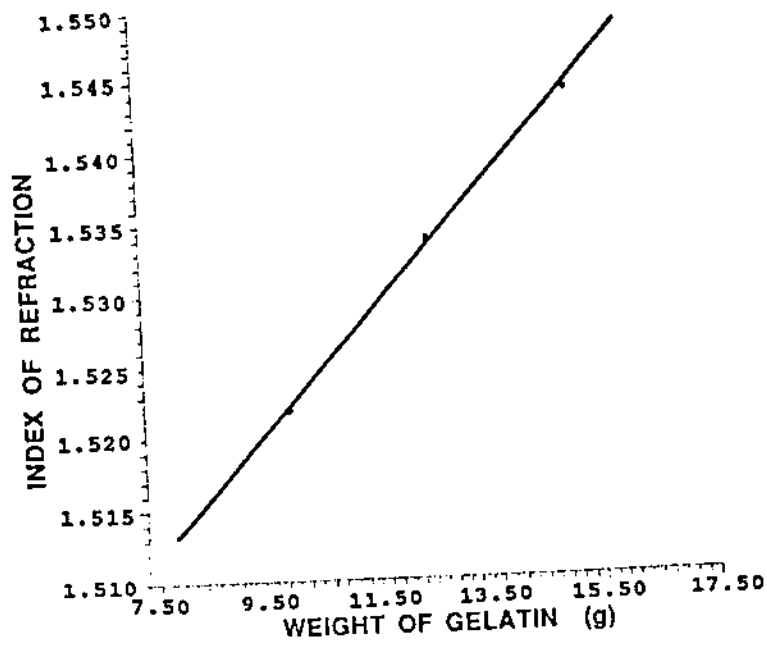


Fig. 2 Refractive Indices Of Gelatin Layer At 632.8nm as a Function Of Gelatin Weight In 100 CC Water Solution Before Wet Processing

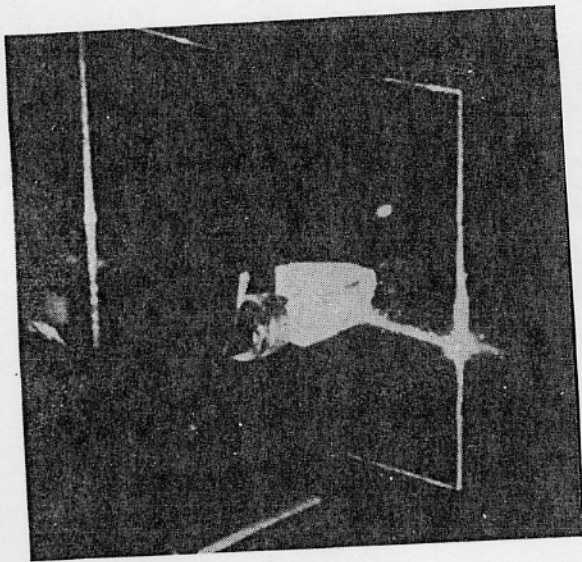
fabrication¹⁰, demonstrate that the gelatin layer forms a step index layer and the index of refraction increases as the gelatin ratio increases.

A wet processing method associated with DCG hologram fabrication was followed immediately after the above experiment. The gelatin layer was made to swell in water, and then dehydrated with isopropyl alcohol⁸. Waveguide parameters were measured again. The propagation loss measured by the two prism method⁹ gave us a propagation loss less than 1 dB/cm on various substrates. The waveguide loss remained low (<1dB/cm) after wet processing. The index profiles were shifted to a graded index with lower surface index than the initial film. Profiles ranging from approximately linear to approximately Gaussian can be produced by choosing different wet processing procedures. The result for sample #D1 after wet processing is shown in Fig.1, curve.B. The same tendency, i.e., a decrease of the surface index and a change of the index profile from a step index to a graded index distribution, has been consistently observed on all samples measured. This index distribution is similar to a graded index fiber. The lower index portion of the gelatin layer functions as a cladding layer for the formation of the waveguide. The basic material used for waveguide fabrication has extreme temperature stability. The initial results indicate that the optical parameters such as transparency and optical density will surely remain unaffected even if the temperature variation ranges from -180°C (liquid nitrogen) to +160°C for several hours and 200°C for tens of minutes¹⁰. The change of index of refraction of dichromated gelatin as a function of temperature (dn/dT) from 80° to 200°C was measured to be $2.7 \cdot 10^{-4}/^{\circ}\text{C}$ ¹⁰. This data was derived by assuming no thickness change within these temperatures. The rubber like mechanical property is relatively sensitive to moisture. Therefore, the humidity control is important to provide good quality waveguide.

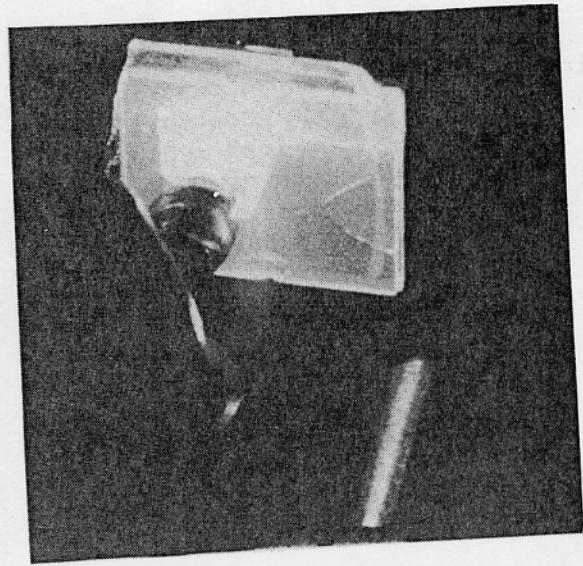
The results described above imply that waveguides with mode indices lower than the substrate index can be constructed. For example, sample #D1 has three modes with mode indices lower than the substrate index 1.512 (Fig.1). With an index profile like this, waveguide structures can be formed on any smooth surface regardless of its index of refraction and conductivity. We have spun gelatin layers on LiNbO₃, GaAs and aluminum substrates. Photographs of waveguiding in graded index waveguides made by this process are displayed in Fig.3.(a) to (d) corresponding to glass, LiNbO₃, GaAs and aluminum substrates, respectively. Graded index profiles after wet processing have also been confirmed on LiNbO₃, GaAs and aluminum substrates. The gelatin refractive index profile on LiNbO₃ after wet processing is shown in Fig.4. The general shape of the gelatin layer after wet processing is shown in Fig.5. Profiles ranging from approximately linear to approximately Gaussian can be produced by choosing different wet processing procedures.

5. INTEGRATION WITH HOLOGRAPHIC OPTICAL ELEMENTS (HOEs)

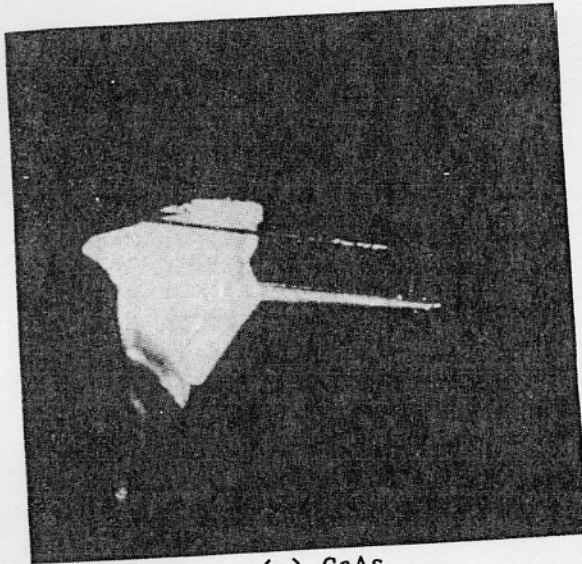
Integrated holographic optical elements (IHOE) such as lenses, grating couplers, and multiplexed gratings, etc. can be fabricated on gelatin waveguides by locally sensitizing the gelatin layer with ammonium dichromate. A grating coupler that converts free space TEM₀₀ laser light to a two dimensional spherical guided wave with 50° angle of divergence was demonstrated. Fig.6.(a) shows the side view of the device. Fig.6.(b) is a photograph of waveguide coupling. An optical clock distribution network on wafer scale integrated circuits (WSIC) is feasible with this new technology. The grating was designed at 488nm with a 45° coupling angle. We analyzed the coupling efficiency of various grating structures using coupled mode theory¹¹. Structures, including various surface relief and phase gratings which



(a) Glass



(b) LiNbO_3



(c) GaAs



(d) Aluminum

Fig. 3 Waveguiding Phenomenon in Gelatin Films On Glass, LiNbO_3 , GaAs And Al Substrates

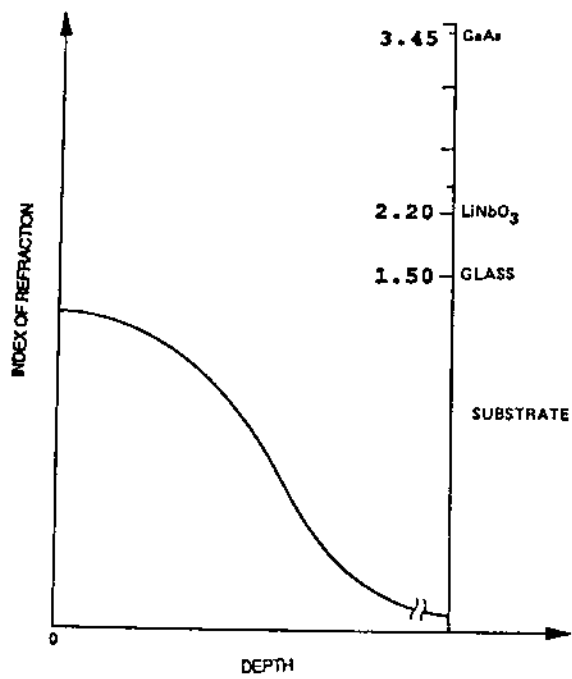


Fig.4 General Shape Of The Gelatin Index Distribution After Wet Processing

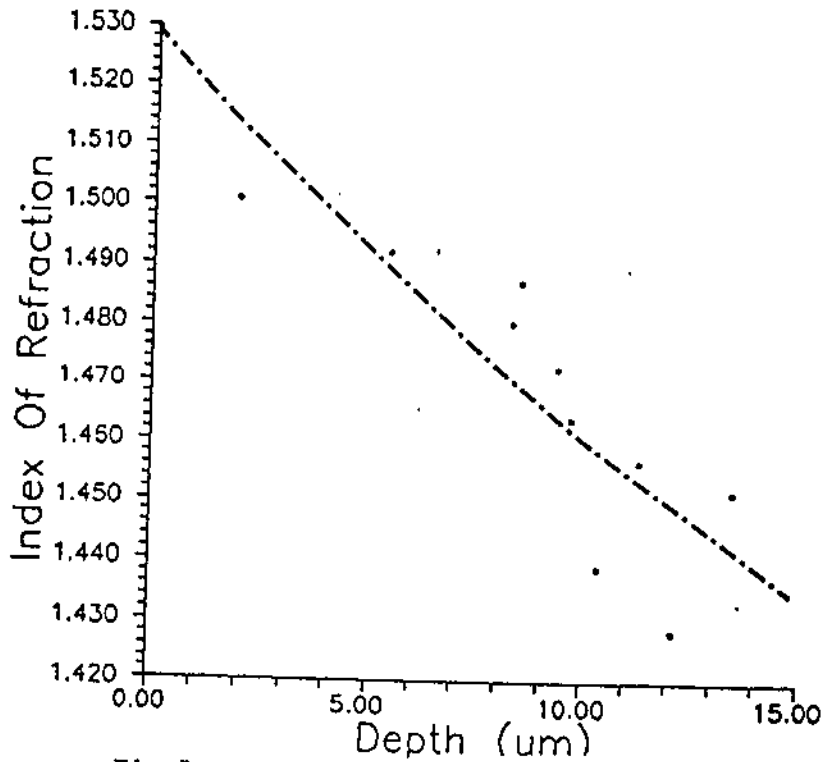


Fig.5 Refractive Index Distribution of Gelatin Layer on LiNbO3 after Wet Processing

share different portions of the waveguide cross section were analyzed. The results show that maximum coupling efficiency is obtained with the grating structure shares the same cross section as the planar waveguide. The grating couplers introduced here exactly meet this requirement. Although the experiment shown in Fig.5 was carried out with a glass substrate, this result is transferrable to any substrates such as Si or GaAs due to the exclusive characteristics of the index profile of gelatin waveguide after wet processing. Therefore, this new type of polymer gelatin waveguide, with desired locally sensitized areas for grating devices, can be integrated with various active and passive guided wave devices.

Because of the fact that only a few select materials can be grown on III-V and II-IV compounds due to the strict limitation of lattice matching, locally sensitized gelatin waveguides may provide an economical and reliable means to form high quality waveguides. In addition their ability to form various multiplexed grating structures for optical interconnects, computing and signal processing functions on different substrate materials is a very attractive side benefit. Further results of these applications will be presented in the future publications. Since DCG holograms provide large index modulation (>0.1), a large number of multiplexed gratings can be simultaneously recorded on the same locally sensitized area. A high optical fan-out capability on LiNbO_3 and GaAs is provided using this new technology while the highest grating efficiency is maintained. Furthermore, gelatin waveguides on GaAs and aluminum can also be used as active devices by employing the evanescent electrooptic effect.

6. POTENTIAL APPLICATIONS BASED UPON GELATIN WAVEGUIDES

It was proven that gelatin thin film can form good quality waveguides on any smooth surface to route optical signals. Therefore, a myriad of applications are feasible based on this new technology.

6.1 WDM and WDDM FOR LOCAL AREA NETWORK

Gelatin waveguide itself is transparent over a wide range of the optical spectrum (visible - infrared). Accordingly, the waveguide itself functions as a good optical path to route optical waves with various wavelengths. A N channel wavelength division multiplexing and demultiplexing based on gelatin waveguide and holographic optical elements is shown in Fig.7. Integration of holographic lenses and highly multiplexed Bragg holograms into gelatin waveguides is clearly shown on both transmitter and receiver. Since the refractive index modulation of DCG can be as high as 0.1. A large number of gratings can be multiplexed in the same holographic emulsion. The angular width ΔT_{Bragg} of the Bragg response between half power point is¹²

$$\Delta T_{\text{Bragg}} = \lambda/T \quad (2)$$

for transmission gratings. In equation 2, T is the thickness of the hologram and λ is optical wavelength. If $\lambda=1 \mu\text{m}$, $T=500 \mu\text{m}$, we have $\Delta T_{\text{Bragg}} = 0.002 \text{ rad}$. Therefore, a 1-to-hundreds/rad fanout is theoretically feasible with this new architecture.

6.2 VLSI Optical Interconnection

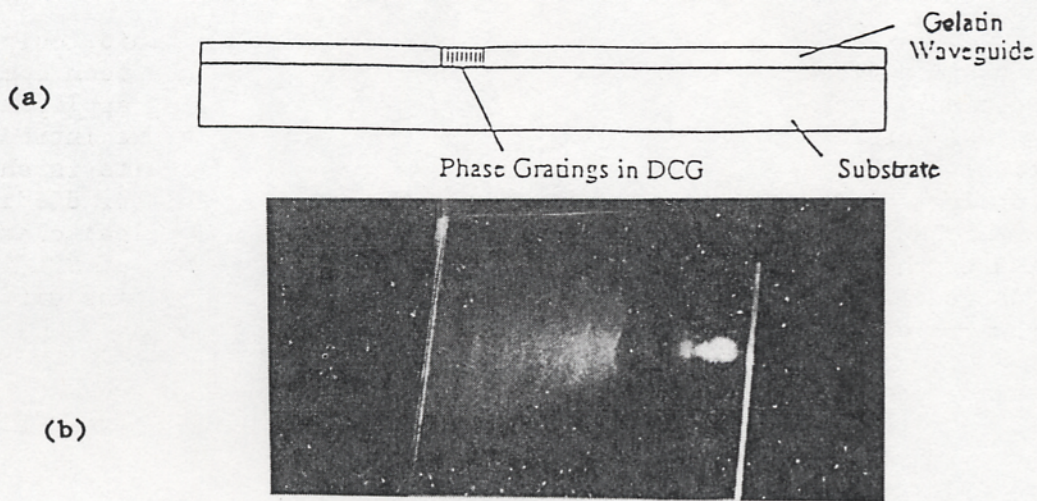


Fig.6 Coupling Of 488nm TE₁₁ Free Space Laser Radiation into a Two Dimensional Spherical Wave with a 50° Beam Divergence in a Gelatin Waveguide; (a) Cross Section of the Device, (b) Real Photograph

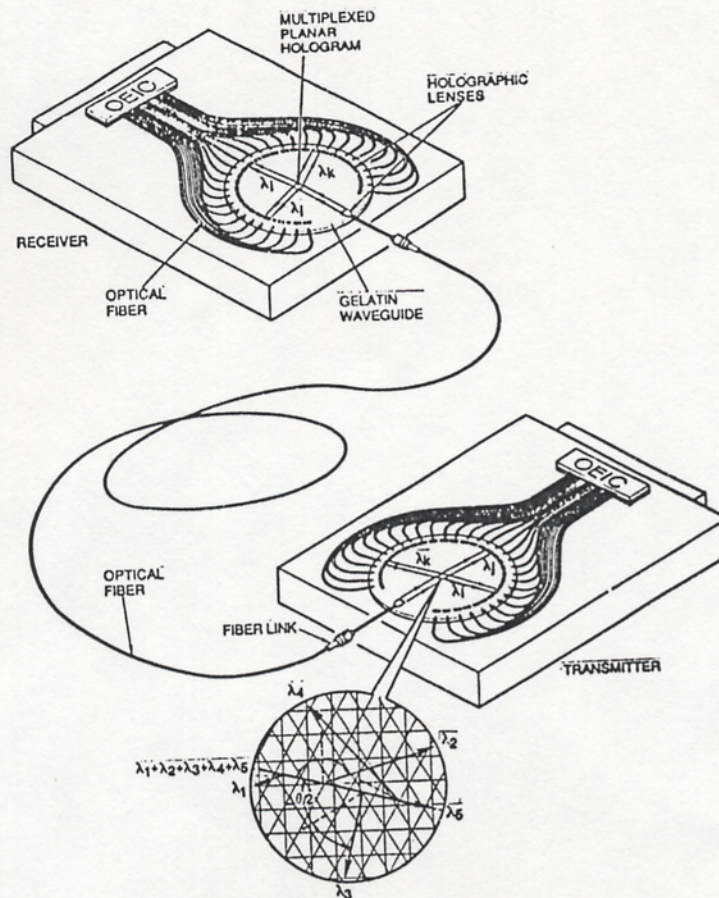


Fig.7 WD(D)M for Local Area Network Using Gelatin Waveguides and Locally Sensitized Multiplexed Hologram

Since gelatin waveguide can be formed on any smooth surface, intrachip, chip to chip and board to board optical interconnections are achievable. It has been commonly agreed that optical clock distribution is one of the most promising applications in intrachip optical interconnections¹³. Based on the new technology we introduced here, an optical clock distribution on wafer scale integrated circuits is shown in Fig.8. The optical clock signal emitted by the surface emitting laser diode is converted to guided wave through multiplexed TIR hologram. The optical clock signal is transmitted to the clock detectors shown in Fig.8. The aperture of SEL is much larger than conventional edge emitting laser diode¹⁴. Accordingly, the diffraction angle is much smaller.

A board to board interconnection is further shown in Fig.9. In this case, gelatin waveguide is deposited on the back plane which holds layers of IC boards (Fig.9(a)). If the interconnectability and parallelity need to be further increased, several integrated holoplanar elements can be added on the same board (Fig.9(b)).

6.3 OPTICAL COMPUTING

Vector and matrix multiplication can be worked out by integrating passive and active devices such as waveguides, grating lenses, Acoustooptic Bragg cell on the same substrate¹⁵. A systolic array is shown in Fig.10. All devices can be built on top of the gelatin waveguide. Acoustooptic and piezoelectric effects of polymer gelatin waveguides need to be further studied to realize such a system application. By integrating a large holographic grating array a large dimension matrix and vector multiplication can be produced.

7. CONCLUSION

In summary, we report the first polymer gelatin waveguide which is capable of being fabricated on a multitude of different kinds of substrates, including insulators, semiconductors and conductors due to the exclusive index profile introduced after wet processing. Waveguiding on GaAs, LiNbO₃, glass and aluminum were experimentally demonstrated. Further experiments showed that by locally sensitizing the waveguide with photo sensitive material (ammonium dichromate), multiplexed holographic grating (not shown in this paper) could be formed. Due to the simplicity of fabrication and the excellent optical properties, further deployment of polymer gelatin waveguides on various active and passive devices and systems appears attractive.

8. ACKNOWLEDGEMENTS

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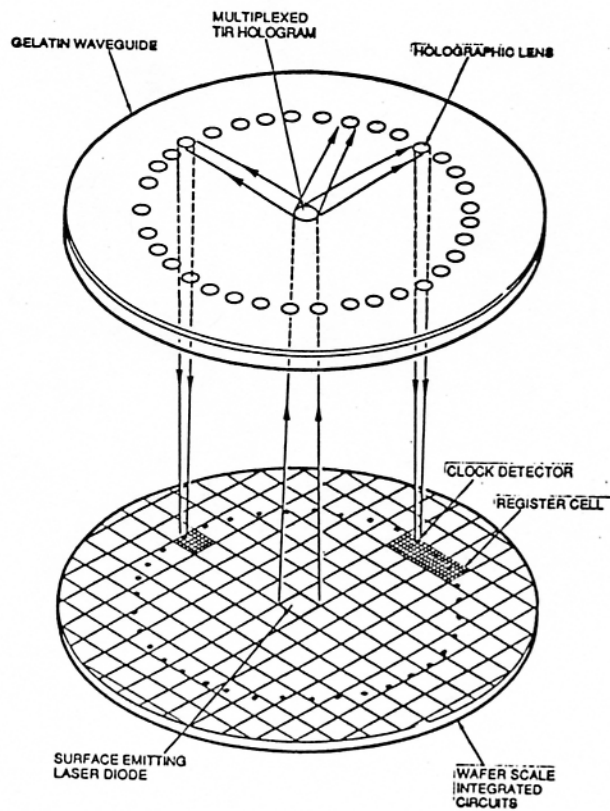


Fig. 8 Optical Clock Distribution

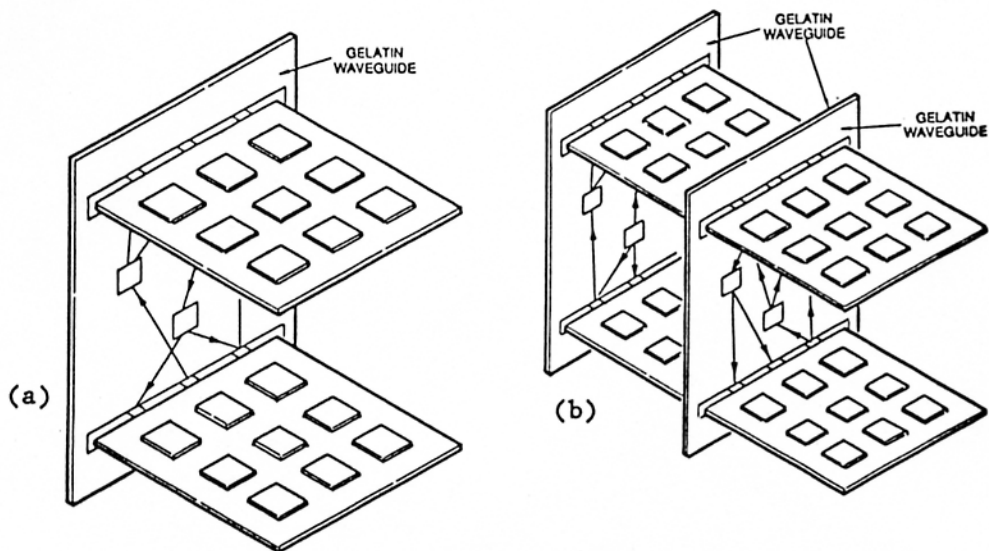


Fig. 9 Board to Board Optical Interconnection Using Gelatin Waveguide on Back Plane

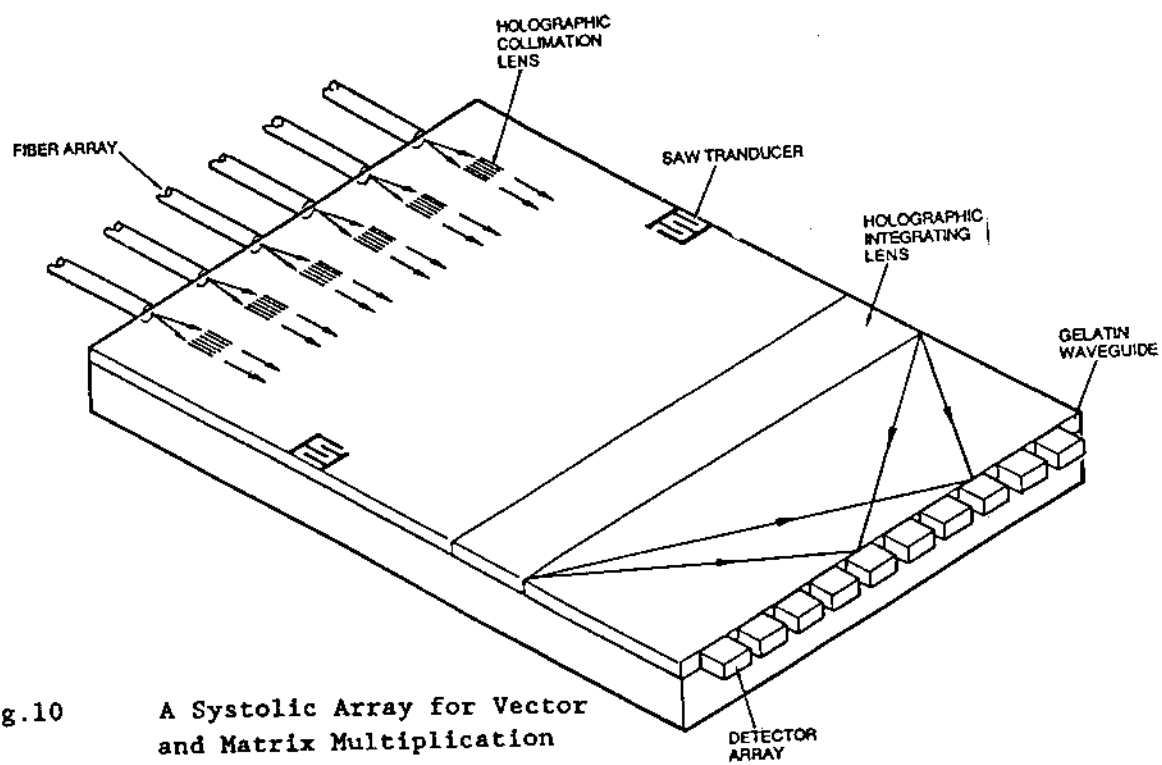


Fig.10 A Systolic Array for Vector and Matrix Multiplication

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