# TRAVELING-WAVE MODULATOR USING A GELATIN-BASED EO POLYMER WAVEGUIDE

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## ABSTRACT

An electrooptic intensity modulator using a gelatin-based EO polymer waveguide has been built and characterized. This EO modulator is constructed from a nitrophenol/gelatin guest/host poled polymer system. $V_\pi$ and $\gamma_{33}$ of 25 V and 38 pm/V are obtained, respectively. This is the first demonstration of an active EO device using electrooptic gelatin. Integration of the modulator with a traveling-wave electrode structure to increase the modulation speed is under investigation. Preliminary studies have shown electrical modulation bandwidths of up to 40 GHz.

## 1.0 INTRODUCTION

Gelatins are a class of natural polymers that exhibit many outstanding physical and optical properties. In recent years, these polymers have received increasing recognition because of their strong potential for improving the performance of integrated holographic optical elements. These elements include lenses, grating couplers, multiplexed grating, and optical interconnections [1-3]. High quality optical waveguides, which exhibit losses of less than 0.1 dB/cm have been fabricated on a variety of substrates, such as Si, GaAs, BeO, and $Al_2O_3$ [4,5]. This unique quality is due to the graded index profile of the gelatin layer, in contact with the substrate, and is induced by wet processing.

Recent efforts have produced many passive devices fabricated from gelatin. By incorporating a volume hologram into a gelatin planar waveguide, a 1-to-30 guided wave massive fanout and a wavelength division demultiplexer have been fabricated [6,7]. High density channel waveguides have also been fabricated by cross-linking the polymer films through UV exposure [8]. The formation of an integrated optical circuit, however, requires the integration of active as well as passive devices. It has been shown that gelatin can be used to build completely passive integrated optic systems. What remains to be developed are the required active devices such as waveguide modulators and switches.

In addition to its potential for use in a fully integrated optical system, the use of EO active polymers for modulation will produce significant advantages in terms of speed. In the past, high speed external electrooptic modulators were made primarily on titanium diffused $LiNbO_3$ substrates or on GaAs optical waveguides in conjunction with a traveling-wave electrode to provide frequencies of up to 20 GHz. These approaches were limited, however, because the optical signal phase velocity in $LiNbO_3$ and GaAs differs from the RF phase velocity in the electrode. This means that the magnitude of the phase shift along the modulator begins to degenerate. This results in a frequency roll-off of the modulation which has a 3 dB bandwidth given by

$$\Delta f_{3\,dB} = \frac{1.4\,c}{\pi |N_o - N_m| L}$$

where $N_o$ is the optical refractive index, $N_m$ is the RF refractive index, L is the length of the electrode, and c is the free space speed of light. Therefore, in order to maximize the modulating bandwidth, an EO material system must have a minimum dispersion between $N_o$ and $N_m$. Polymeric materials are best suited to such high frequency modulations because of their extremely low dispersion between microwave and optical waves. This allows $\Delta f_{3dB}$ to increase to 120 GHz for a 1 cm interaction length.

This paper discusses the fabrication of the first active waveguide modulator using electrooptic gelatin. The further integration of this modulator with a traveling wave electrode structure is also proposed, in order to increase modulation speeds.

## 2.0 ELECTROOPTIC MODULATOR

Gelatin is a class of biopolymer which consists of thousands of 10-20 Å long amino-acids. Gelatin has been classified as a superpolymer because of its extraordinary chemical and physical properties and its molecular structure. When a gelatin solution is subjected to temperatures below 30°C, the solution becomes a soft gel. When the gel is dried, it becomes a rigid glass film that shows very little absorption and optical scattering. The remarkable fact is that biological gelatin can be crosslinked to increase its stability. When the gelatin is sensitized with a solution of ammonium dichromate and is exposed to UV light, it behaves as a photoresist: the molecular chains in the regions of the film exposed to more light have more crosslinking, and so the physical characteristics of the film are slightly changed. Specifically, these regions swell less when immersed in water, and, if rapidly dehydrated, produce differential strains between regions of maximum and minimum swelling. These strains modify the index of refraction. It has been found that regions that have more crosslinking have a higher index of refraction. This photoinduced index modulation can be as high as 0.2. Thus, the channel waveguide confinement and packaging density can be extremely high.

A linear array of waveguides with channel widths of 10 μm and separations of 20 μm have been fabricated on a layer of Cr/Al (the ground electrode) evaporated on a glass substrate. The thickness of the gelatin waveguide array is approximately 20 μm. The graded index nature of the waveguides allow propagation of both TE and TM modes.

In order to make a modulator, the waveguides need to be electrooptic active. In this case, 4-nitrophenol (NP) from Aldrich was selected as the active dye to be doped into the gelatin matrix [8]. A solution of 3 gm of nitrophenol and 400 ml of water was prepared. The fabricated waveguides were immersed for 15 minutes in the solution so that nitrophenol could be doped by diffusion. The waveguides with nitrophenol were then baked at 50°C for one hour. The nitrophenol doped gelatin waveguides were poled to remove the centrosymmetry, by the corona poling technique, at a field strength of 100 V/μm. A layer of poly-methyl methacrylate (PMMA) of 5 μm was then coated as an upper cladding layer. A 1.5 cm long layer of Cr/Al length was deposited on top of the PMMA as the modulating electrode. A schematic of the EO device is shown in Figure 1.

In this form of modulation, a prism was used to couple the input beam at 1.3 μm from the laser diode. A polarizer is used to excite both TE and TM modes of the gelatin channel waveguides. The gelatin waveguide modulator is mounted on a rotational stage for easy prism coupling. The output is edge-coupled out from the cleaved surface and collected by a 20× microscope objective lens. The analyzer at the output is perpendicular to the input polarizer. The TE/TM mode conversion changes are detected using a high speed InGaAs photodetector placed after the analyzer. The dependence of the output intensity, as a function of the applied voltage, is illustrated in Figure 2. $V_\pi$ of 25 V is obtained from the voltage difference between the maximum and minimum intensity throughput. The half-wave voltage $V_\pi$ is defined by

$$V_\pi = \frac{3d}{L} \cdot \frac{\lambda}{2n^3 \gamma_{33}}$$

where d is the spacing between electrodes, L is the interaction length, $\lambda$ is the wavelength of the laser source, n is the index of the gelatin, and $\gamma_{33}$ is the EO coefficient of the waveguides.

By substituting $V_\pi$ in the above equation, $\gamma_{33}$ of the poled EO gelatin is roughly 38 pm/V. This value is consistent with measurements obtained from earlier work on the characterization of the EO coefficient of this material [8].

Figure 3 illustrates small signal electrooptic modulation at 3 MHz. The upper trace is the AC electrical modulating signal at 5 V peak to peak. The bottom trace is the optically modulated signal. Figure 4 shows that the 3 dB bandwidth of the fabricated EO waveguide modulator is roughly 2 MHz. The low 3 dB bandwidth of the fabricated device is due to the large RC time constant of the lumped electrode structure.

## 3.0 TRAVELING-WAVE ELECTRODE DESIGN

Maximizing the modulation bandwidth is most important when modulators are used to route optical waves over desired paths. Similarly, modulation bandwidth is a critical factor when many information channels are to be multiplexed onto the same optical beam. There are two different types of electrode structures that have been realized to date. These are the lumped electrode structure and the traveling-wave structure. The first regards the modulator as a capacitor, and usually has a 50 ohm resistance in parallel with the device. The second treats the electrode pair as a continuation of a transmission line. The 3 dB bandwidth of the second type is usually higher than that of the first. The bandwidth of the lumped electrode type is limited by the RC constant, and the bandwidth of the traveling-wave electrode type is constrained by the difference of the effective indices of the optical guided wave and the microwave.

By contrast, we propose to construct a wide bandwidth EO gelatin waveguide modulator using a traveling wave modulating electrode. A schematic of the proposed device is shown in Figure 5. In this design, coplanar microwave transmission line, with 50 ohm impedance, is fabricated on a quartz substrate. A single layer of EO gelatin is coated on the quartz substrate with the transmission line. The gelatin is locally poled in the horizontal direction using the electrodes. An optical Mach-Zehnder interferometer waveguide will then be defined by lithographic techniques with each leg of the Mach-Zehnder interferometer in between each electrode gap. A push-pull mechanism is used to increase the modulating efficiency. The advantage of the above scheme is its simplicity of processing. Due to the graded index nature of the EO gelatin, no multilayer structure (e.g., claddings) will be needed.

A test fixture including the coplanar microwave transmission line and a layer of EO gelatin has been fabricated and tested for its electrical bandwidth. The s-parameters of the device have been measured using an HP8510A network analyzer. Figure 6 shows the $S_{21}$, the transmission coefficients of the coplanar microwave transmission line with high transmission coefficient up to 40 GHz.

## 4.0 CONCLUSION

In conclusion, we have successfully fabricated the first waveguide modulator using a gelatin-based EO polymer. A half wave voltage $V_\pi$ of 25 V was obtained. The EO coefficient, $\gamma_{33}$, was calculated from $V_\pi$ to be 38 pm/V. A 50 ohm coplanar transmission line has been designed and fabricated to increase the modulating bandwidth. This success in achieving an active device using gelatin based material is an important step toward realizing a full polymer-based miniature integrated optical circuit (PBMIOC).

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## 5.0 REFERENCES

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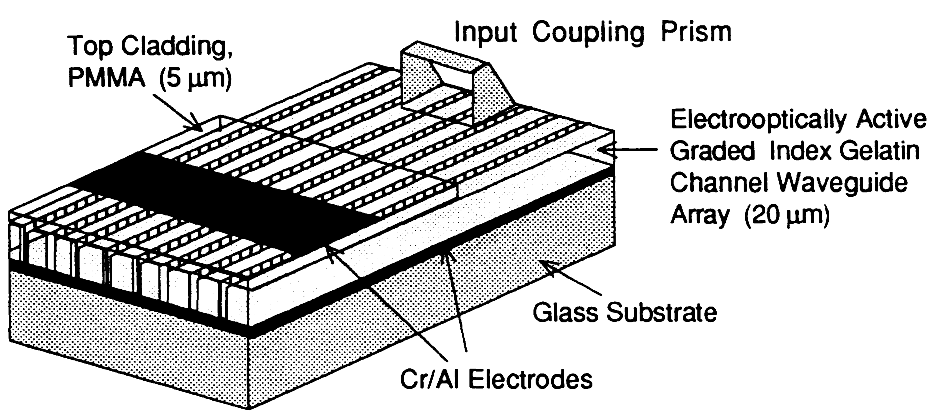



Figure 1
EO Gelatin Waveguide Modulator

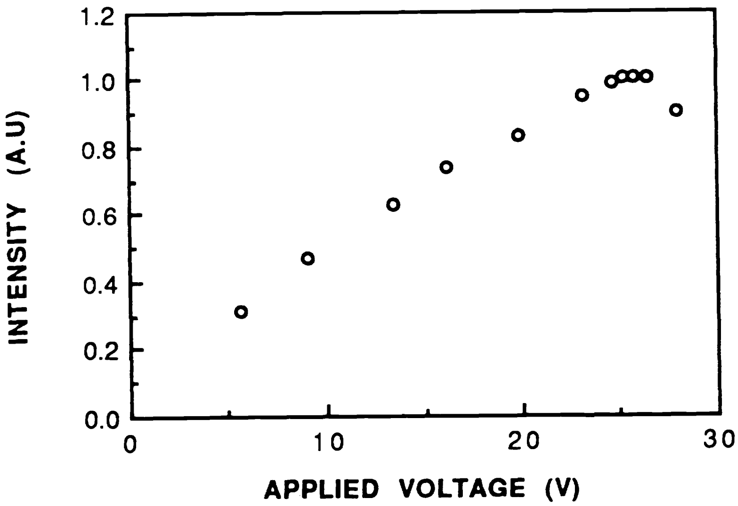



Figure 2
Output Intensity as a Function of Applied Voltage

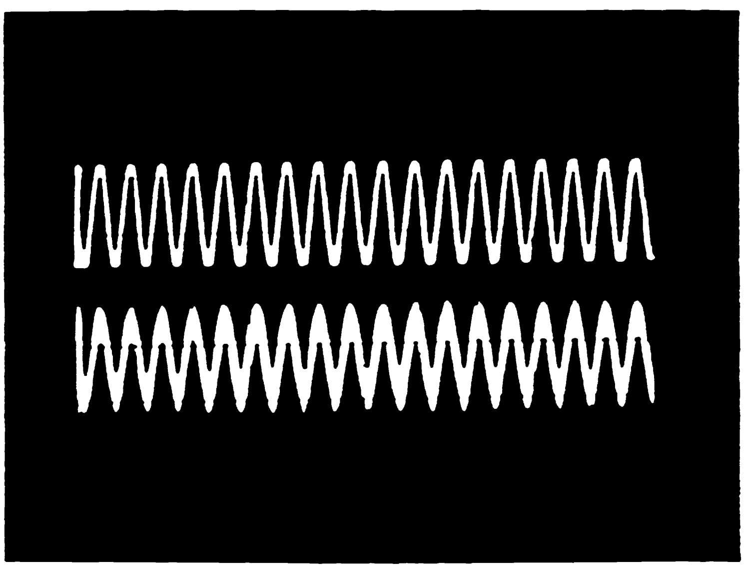



Figure 3
Modulation of the Optical Signal at 3 MHz

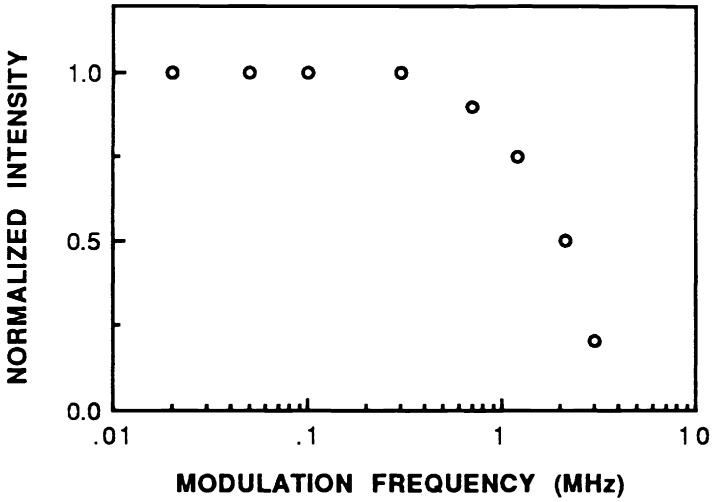



Figure 4
Modulated Intensity as a Function of Frequency. 3 dB roll-off of the response occurs at 2 MHz.

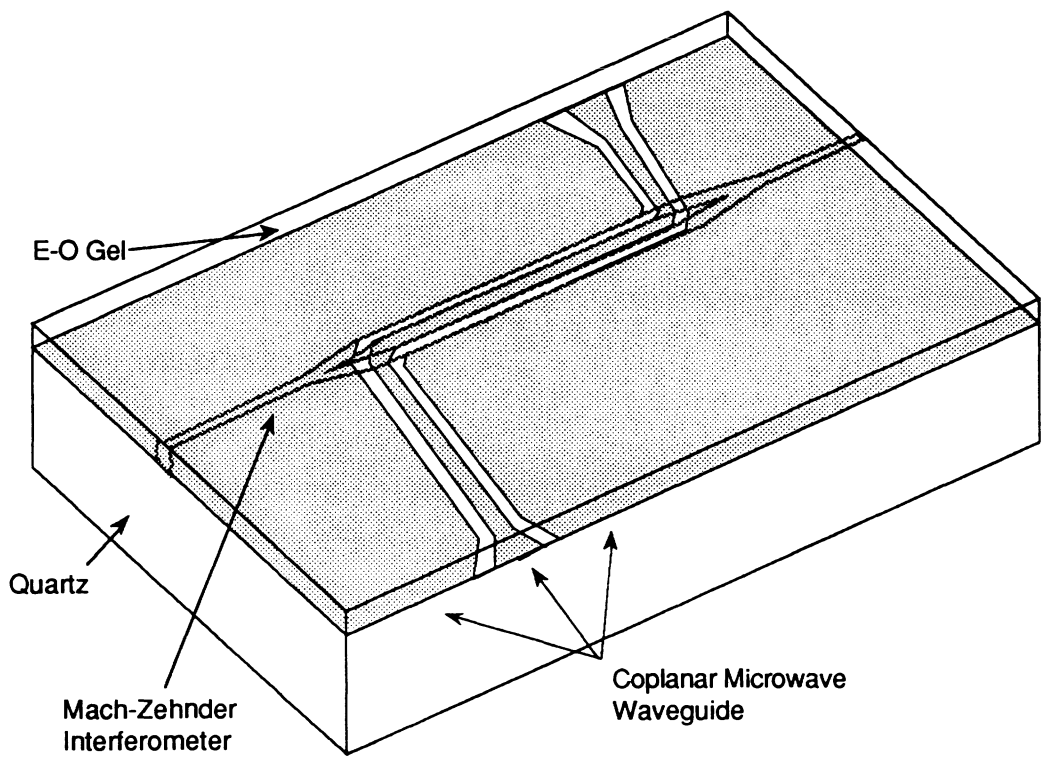
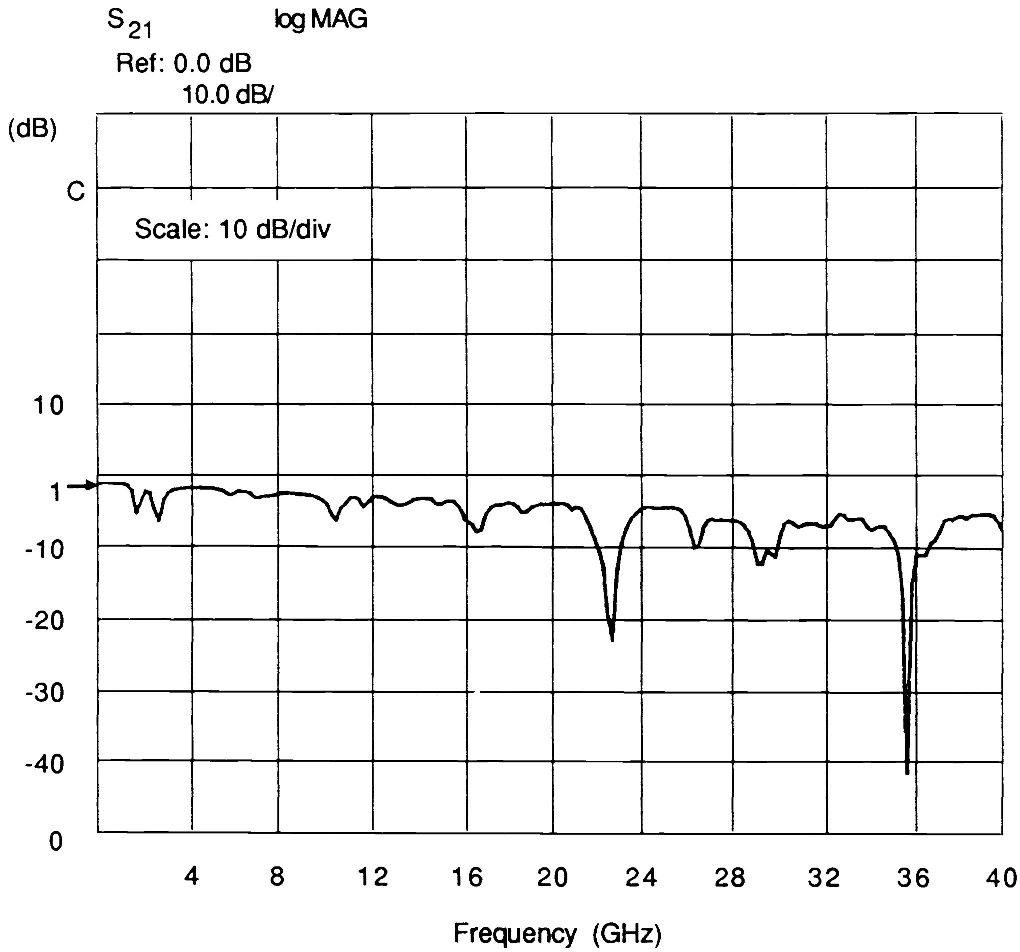



Figure 5
Traveling Wave Electrooptic Gelatin Modulator with Coplanar Microwave Transmission Line




Start 1.000000000 GHz
Stop 40.000000000 GHz

Figure 6
$S_{21}$, Transmission Coefficient, of the Travelling Wave Modulator Electrode