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R. Lytel
G. F. Lipscomb
J. Thackara
J. Altman
P. Elizondo
M. Stiller
B. Sullivan

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Invited Paper

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R. Lytel, G.F. Lipscomb, J. Thackara, J. Altman, P. Elizondo, M. Stiller, and B. Sullivan

Lockheed Research & Development Division, Lockheed Missiles & Space Company, Inc.
3251 Hanover St., 0/97-20, B/202, Palo Alto, California 94304

ABSTRACT

Organic and polymeric materials have many useful features for thin-film electro-optic devices. These include low dielectric constants, moderate-to-large electro-optic coefficients, and low optical loss. This paper presents a review of the useful features of organic materials for device applications, summarizes the current optical response levels of some organic materials, and describes the performance of several device prototypes fabricated from poled organic films.

1. INTRODUCTION

Organic and polymeric materials have emerged in recent years as promising candidates for advanced device and system applications. This interest has arisen from the promise of extraordinary optical, structural, and mechanical properties of certain organic materials, and from the fundamental success of molecular design performed to create new kinds of materials.¹ From an optical standpoint, organics offer temporal responses ranging over 15 orders of magnitude, including large nonresonant electronic nonlinearities (fs-ps), thermal and motional nonlinearities (ns- μ s), configurational and orientational nonlinearities (μ s-s), and photochemical nonlinearities (ps-s). Additionally, organic and polymeric materials can exhibit high optical damage thresholds, broad transparency ranges, and can be polished or formed to high-optical-quality surfaces. Structurally, materials can be made as thin or thick films, bulk crystals, or liquid and solid solutions, and can be formed into layered film structures, with molecular engineering providing different optical properties from layer to layer. Mechanically, the materials can be strong and resistant to radiation, shock, and heat. When coupled with low refractive indices and dc dielectric constants, the collective properties of these extraordinary materials show great promise toward improving the performance of existing electro-optic and nonlinear optical devices, as well as allowing new kinds of device architectures to be envisioned.

However, as with any new class of materials, the existence of certain promising samples does not imply that real applications will necessarily be possible. Real optical materials must exhibit some basic properties, including optical clarity (very low scattering and absorption losses), fabricability, and the potential for mass production. These secondary properties are generally not addressed by fundamental research, but it is the secondary properties which will determine whether the materials can have any practical use. For organics as a class, including pi-electron systems, conducting polymers, and other nonlinear optical polymers, a great deal of research and development remains to achieve usable, exciting new materials.

This paper provides a survey of the current research and development underway at Lockheed in organic and polymeric devices. In particular, we examine organics as a new class of nonlinear and electro-optic (E-O) materials, delineate their good and bad features, and present a discussion of certain existing organic materials, their use in devices, and their impact on device performance. Along the way, we try to provide the motivation for using an organic material rather than some other material, and point toward the specific new fabrication requirements for devices, and toward the further materials development required for optimum device performance. Our approach is a positive one, as we are firm believers that organics will have a major impact on the optoelectronic device technology of the next decade. However, we moderate our optimism with the realization that much materials research and development remains to be done before organics can even be established as an important new class of practical nonlinear optical materials.

Section 2 reviews some of the important structural and optical properties of organic materials for nonlinear optical devices, and points toward specific properties that have been demonstrated, and those that remain to be proved. Section 3 details the application of certain organic and polymeric materials to practical optical devices, including photo-addressed spatial light modulators, integrated optical devices, and gratings. We review our own work in these areas, and point toward specific performance and manufacturing advantages of organics over inorganic materials. Section 4 summarizes our conclusions regarding organic and polymeric materials for device applications, and provides some directions for future research in this exciting new area of nonlinear optical devices and applications.

2. REVIEW OF MATERIAL PROPERTIES

For the purposes of this paper, we shall refer by organics to nonresonant pi-electron organic and polymeric materials, including single crystals, thin-films, and other composite materials. As a class, organics offer a number of exciting optical structural properties for devices, summarized in Table 1. Some of these properties, such as the capability to alter linear and nonlinear optical properties in dimensions approaching visible optical wavelengths, are the result of the ability to molecularly engineer the active NLO units within a given structure.² This feature appears to be unique to organics, although molecularly tailored semiconductor multiple quantum wells offer some tunability in wavelength and response. However, the capability to engineer materials with desired linear and nonlinear properties is unique to organics, and is the major reason they are, as a class, important for device applications.

Table 1. Some Structural and Optical Properties of Organics

STRUCTURAL	OPTICAL
<ul style="list-style-type: none"> ● MOLECULAR ENGINEERING ● THIN FILMS/BULK XTAL ● ROOM TEMPERATURE ● CHEMICAL/STRUCTURAL STABILITY ● INTERNAL GRATINGS ● INTEGRATED OPTICS 	<ul style="list-style-type: none"> ● LARGE NONRESONANT NONLINEARITIES ● LOW dc DIELECTRIC CONST. ● FAST NLO RESPONSE ● HIGH OPTICAL DAMAGE THRESHOLDS ● BROADBAND ● LOW ABSORPTION

Many of the features in Table 1 have been demonstrated in a number of different organic systems. Damage thresholds as high as a GW/cm^2 have been measured in single crystal MNA³ (2-methyl-4-nitroaniline) and in urea.⁴ Large nonresonant susceptibilities have been reported in certain diacetylene polymer systems⁵ ($\chi^{(3)}$ of the order of 10^{-10} to 10^{-9} esu) and in single crystal MNA⁶ ($\chi^{(2)} = 500 \pm 100$ pm/V). Other recent measurements of large electro-optic coefficients have been reported in poled organic films,⁷ which show great promise for optical waveguides. It is noteworthy that current synthesis efforts underway are moving away from crystal growth and toward thin-film fabrication of nonlinear polymers, and that none of these systems has a $\chi^{(3)}$ or $\chi^{(2)}$ as large as the original reported susceptibilities of the diacetylenes and MNA crystals. For all of the problems of growing crystals, they yield the greatest degree of orientation, and, therefore, the largest macroscopic nonlinearities for a given NLO moiety.

It is also true that most organics fabricated to date do not yet exhibit most or all of the properties in Table 1. In particular, absorption and scattering losses are usually higher than desired, and must be minimized by building materials in cleanroom facilities or by filtering polymer solutions before using them. Many polymer films exhibit poor optical quality, and techniques for fabrication of optically flat surfaces need to be refined. Some polymer structures are inherently grainy or contain fibrous components which scatter light excessively. Finally, a few researchers are reporting new materials, such as conducting polymers, with large $\chi^{(3)}$ values, without recognizing the requirement that the material must inherently be able to transmit or guide light! These reports indicate a lack of understanding of what constitutes an optical material, as opposed to an electrical material. Nonetheless, we remain confident that the field of organics will develop into an important new area of device applications, once the materials and device scientists jointly address the problem.

In this light, it is straightforward to examine the current status of $\chi^{(2)}$ and $\chi^{(3)}$ materials,⁸ and to determine what materials parameters ought to be improved for real applications.

2.1. SHG and electro-optic materials

The largest reported SHG⁹ and E-O⁶ coefficients in an organic material exist in the organic solid MNA, in single crystal form. This result is interesting for several reasons. First, while the NLO moiety, the MNA molecule, has a large second-order molecular hyper-

polarizability β , many other molecules with larger β have been reported. However, single crystals of MNA have been grown and characterized, illustrating the effect of macroscopic orientation on the macroscopic polarizability $\chi^{(2)}$. Thus, we learn that it is critical that proper orientation be achieved to take advantage of the large β in certain molecular systems. This just illustrates the difference between a molecule and a material. Recent results in poled polymer films suggest that we are well on our way toward achieving large, usable $\chi^{(2)}$'s from partially oriented films of different polymer systems. Both AT&T and Celanese⁷ have reported new polymers exhibiting interesting $\chi^{(2)}$'s, and it is likely that materials currently unreported upon exist and have even greater $\chi^{(2)}$'s. In our view, it is only a matter of time before poled polymer films will appear regularly in real optical devices. As reported below, we have already used certain poled films to produce "proof of concept" prototypes of optical waveguide modulators with great success.

A major drawback to the current poled polymer films is that the $\chi^{(2)}$ is perpendicular to the film surface. For waveguides, this is no problem. However, for bulk E-O device applications, it is desirable to have a film with $\chi^{(2)}$ parallel to the film surface to achieve E-O modulation for two-dimensional device applications. It remains to be seen whether new orientation techniques, equivalent to surface alignment techniques for nematic liquid crystals, can be developed.

There is one major observation worthy of note when comparing organic pi-electron materials with inorganic crystals in terms of their $\chi^{(2)}$. In both materials, the contributions from $\chi^{(2)}$ to SHG arise solely from the electronic contributions, since these are the only ones capable of responding on femtosecond time scales. In organics, the same contributions also contribute to the entire E-O coefficient, while inorganics gain much of their contribution from lattice phonons. Thus, an organic material with the same $\chi^{(2)}$ as an inorganic material, as measured by SHG, will probably have a much smaller E-O coefficient than the inorganic material. This result must be borne in mind when comparing organics, as characterized by SHG, with E-O inorganic materials.

2.2. Third-order materials

The largest nonresonant $\chi^{(3)}$ yet reported⁵ for an organic material is in the diacetylene systems, and has a $\chi^{(3)}$ of the order of 10^{-9} esu. This value is large by comparison with CS_2 , but is still too small for most applications. In devices based on $\chi^{(3)}$, it is generally the product of $\chi^{(3)}$ with the light-medium interaction length and the optical intensity that determines the net nonlinear phase shift that can be obtained and exploited for device operation. Small $\chi^{(3)}$ necessarily implies large optical intensities and/or long interaction lengths. For nonresonant organics like PTS diacetylene polymers, intensities of order MW/cm^2 would be required over a length $L=1$ cm. Thus, it is likely that third-order organics will find applications in optical waveguide devices, such as bistable optical switches and optically controlled modulators and couplers. It is unlikely that thin-film applications, such as etalons, will be possible with organics unless significant advances toward achieving larger nonlinearities can be made.

Organic thin films can, however, offer some really new features for third-order devices, if the coefficients can be made larger. Through molecular engineering, it should be possible to produce anisotropic $\chi^{(3)}$ materials for optically activated birefringent film applications. It should even be possible to build layered structures with a $\chi^{(3)}$ that varies along the thickness of the layers, thus producing nonlinearly activated optical gratings for fixed and tunable filter applications.

Recent synthesis work¹⁰ includes off-resonance side and main chain polymers with reasonable nonlinearities (10^{-11} to 10^{-10} esu). Such materials could be useful in degenerate four-wave mixing¹¹ for optical phase conjugation, or as self-focusing media for optical shutters. However, it is still necessary to achieve optically good materials (clarity and optical flatness) and larger susceptibilities for most applications.

In summary, second-order poled polymer films appear to be close to achieving interesting levels of response for waveguide E-O device applications. However, third-order NLO polymers still have a way to go. In both cases, the materials must necessarily qualify as optical materials before real applications can be envisioned. In light of the recent success in producing poled polymer films, we discuss next three important device application areas for these materials.

3. DEVICE APPLICATIONS

In this section, we report recent work toward achieving useful devices based on second-order, poled polymer films. The poling process produces a material with a $\chi^{(2)}$ perpendicular to the film surface. Our major experimental results to date have been obtained in E-O waveguide devices using a polymer known to us as PC6S, and provided by the

Hoechst Celanese Research Company. This polymer is optically transparent above 0.6 μm , and has a measured value of $r_{33} = 2.8 \text{ pm/V}$. We report next on our investigations into specific devices for exploiting poled polymer films.

3.1. Spatial light modulators

Spatial light modulators (SLMs) are two-dimensional optical modulation devices.¹² Such devices are of great interest in optical processing, computing, and beam control, and are usually photo-addressed devices. A typical electro-optic SLM, operating in reflection, is illustrated in Fig. 1. This device is an E-O modulator, composed of a photoreceptor, dielectric mirror, and an E-O material. The SLM operates as follows: An incident optical field addresses the photoreceptor, creating a two-dimensional charge distribution which is proportional to the intensity of incident light. Under the influence of a bias voltage, the charge distribution $\sigma(x,y)$ migrates to the dielectric mirror-photoreceptor interface, and modulation of the E-O material due to the charge distribution can occur. If the modulation is due to the difference between σ (and the bias voltage) and the ground plane, the device is a longitudinal modulator. If the modulation is due to local differences in σ at the surface of the E-O material, the device is a transverse modulator. In the longitudinal modulator, a readout field incident from the right acquires a phase shift proportional to the induced E-O modulation due to $\sigma(x,y)$, and the device operates as an intensity to phase converter. In the transverse device, it is the local field gradient along the dielectric mirror and E-O material interface which creates the modulation field, and the device produces a phase shift upon readout proportional to the gradient of the intensity. Thus, the fundamental operation of the E-O modulator depends on the tensorial nature of the E-O medium in a fundamental way.

Electro-optic SLMs can be seen to be important optical devices because they allow the transfer of optical information from one beam to another. In particular, a longitudinal modulator can be used as an optical correlator, convolver, or optical phase conjugator, while a transverse modulator can be used as an edge detector or intensity-to-position encoder. In either case, SLM performance parameters are determined primarily by the optical properties of the photoreceptor and E-O material, and the electrical properties of the entire unit.

Photo-addressed E-O SLM technology has been under development at Lockheed for the past several years. The Lockheed photoreceptor is a high-resistivity silicon device, with very fast response times (of the order of a ns) and good lateral charge confinement. Lockheed has mated this technology to thin (100- μm) KD*P crystals to produce fast E-O modulation devices with spatial resolution approaching 10 line pairs/mm, frame grabbing times under 10 μs , and frame rates approaching a kHz.¹³ This architecture has formed the basis for all of our subsequent SLM prototypes, including a longitudinal nematic liquid crystal device,¹⁴ a transverse nematic liquid crystal edge detection device,¹⁵ and the current organic transverse SLM under development.

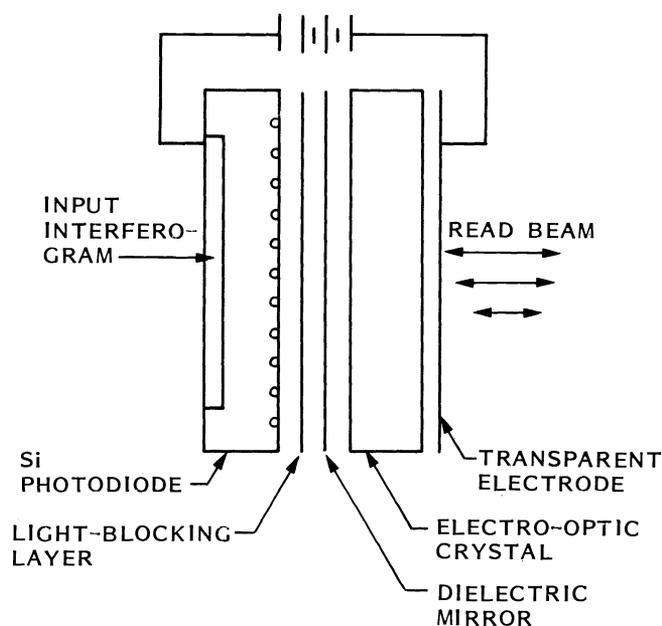


Fig. 1. Schematic diagram of an electro-optic spatial light modulator

The impact on using an organic material in the Lockheed SLM architecture is currently under experimental evaluation, and no results are available at the time of this paper. However, we have evaluated theoretical performance for an organic SLM, and it is worthwhile to explore this briefly to understand the importance of organics in SLM technology.

In the Lockheed device, response time for a single frame is determined by the integration time of the input light required to generate sufficient charge to get a desired modulation (say half-wave) on the E-O material, the RC time constant of the device, and the intrinsic response time of the E-O material. The response of the KD*P is subnanosecond, so the device frame time is determined solely by the write light intensity and the device capacitance. The KD*P is operated near its Curie temperature of -57°C , so that the enhancement in the E-O coefficient can be obtained, allowing the bias voltage to be kept below the breakdown voltage of the photoreceptor. The dielectric constant of KD*P, however, also rises dramatically near the Curie temperature and no benefit in device efficiency is achieved. Since the polarization optic coefficient is not strongly temperature dependent, the same amount of photo-generated charge (σ) is required to produce an equivalent phase modulation, and the required integration time is not reduced. Large dielectric constants are an inescapable feature of inorganic ferroelectric E-O materials, arising from the electron-phonon coupling origin of the electro-optic effect. The resultant large device capacitance adversely affects the speed and sensitivity that can be achieved in a photo-addressed device. Finally, device resolution is limited, by capacitive effects, to about 10 lp/mm. Organic thin films exhibiting a large E-O coefficient and a small dielectric constant should offer significant improvements.

A nematic liquid crystal version of the same device has been developed at Lockheed, in the hopes of achieving much more sensitivity and greater spatial resolution. This device, operated at room temperature, exploits the birefringence induced by an applied electric field. The nature of the device depends on the surface alignment of the liquid crystal. Parallel alignment produces a longitudinal modulator, while perpendicular alignment produces a transverse modulator. In both cases, a significant gain in device sensitivity is achieved, due to the much lower dielectric constant of the nematic liquid crystal relative to cooled KD*P and the larger birefringence of the nematic liquid crystal. Higher resolution is achievable because thinner films can be utilized. However, the nematic alignment must be driven off to achieve millisecond response times, and this device is never as fast as the KD*P device.

Organic E-O films can probably achieve higher resolution, higher speed, and greater sensitivity in an E-O SLM than either inorganic E-O crystals or liquid crystals. A poled organic film of the order of $10\text{-}\mu\text{m}$ thick, with an E-O coefficient comparable to KD*P, and a dielectric constant $\epsilon=4$, should produce a longitudinal SLM with sensitivity comparable to a nematic liquid crystal device, speed of a KD*P device, and resolution much better than both KD*P and nematic liquid crystals. This increased performance results from the lower film capacitance at room temperature for a given E-O coefficient. Such films, available now as poled polymer films oriented perpendicular to the surface of the film, cannot be used in normal incidence and must be read out at an angle. We expect to have the first prototype SLM of this type operating by the end of 1987.

A major drawback to the use of organics in E-O devices will arise from the poor thermal conductivity of polymers. Thus, repetition rates and optical loads will be limited by the device architecture, and careful design of heatsinks and thermal conditions will be necessary. If properly designed, the ultimate optical load of the device should be much greater than inorganic devices, due to the potentially larger optical damage threshold of organic materials.

3.2. Integrated optical devices

Organic E-O materials offer a variety of potential advantages over conventional materials for integrated optical device applications. Table 2 provides a comparison of the potential of organic materials with the current frontrunner technology, Ti-indiffused LiNbO_3 in three major areas of importance: materials parameters, processing technology, and fabrication technology. Some of these advantages have already been realized in our work on E-O modulators using poled polymer films.

The most obvious potential advantages are due to the intrinsic differences in E-O mechanisms in inorganic and organic materials. Organics should provide flat E-O response well beyond a GHz, and, indeed, measurements of the E-O coefficients and SHG coefficients of certain poled polymer films show little or no dispersion. Second, it is likely that the E-O coefficients of poled polymer films can be made nearly as large as LiNbO_3 , and it is obvious that many materials efforts underway in the U.S. and abroad are attempting to achieve exactly that. Pure MNA crystals already exhibit larger E-O coefficients than LiNbO_3 , as indicated in Table 2, but it is our sense that real device advances will be made with films, not crystals. It is also true that the dielectric constant of poled poly-

Table 2. Comparison of Integrated Optics Technologies:
Current Ti-LiNbO₃ and Projected Organics Technologies

<ul style="list-style-type: none"> ● CURRENT TECHNOLOGY: Ti:LiNbO₃ <ul style="list-style-type: none"> - MATERIALS DEVELOPMENT BEGAN IN 1930s ● $r = 32$ pm/V <ul style="list-style-type: none"> - LARGER MODULATING VOLTAGE - LITTLE IMPROVEMENT EXPECTED ● LIMITED FABRICABILITY <ul style="list-style-type: none"> - 1000°C PROCESSING - DEPTH LIMITED TO 5 μm - LOW INDEX CHANGE Δn - LOSS > 0.1 dB/cm - OPTICAL DAMAGE (PHOTOREFRACTOR) ● LARGE DIELECTRIC CONSTANT (28) <ul style="list-style-type: none"> - LONGER TIME CONSTANTS = RC - LARGE VELOCITY MISMATCH IN TRAVELING WAVE MODULATOR ● MASS PRODUCTION DIFFICULT 	<ul style="list-style-type: none"> ● POTENTIAL ADVANTAGES OF ORGANIC E-O MATERIALS <ul style="list-style-type: none"> - MATERIALS DEVELOPMENT BEGAN IN 1975 ● $r = 67 \pm 25$ pm/V (MNA) <ul style="list-style-type: none"> - LOWER MODULATING VOLTAGE - POTENTIALLY MUCH LARGER r ● FLEXIBLE FABRICATION <ul style="list-style-type: none"> - LOW TEMPERATURE PROCESSING - FLEXIBLE DIMENSIONS - CONTROLLABLE INDEX CHANGE Δn - POTENTIAL LOW LOSS - HIGH OPTICAL DAMAGE THRESHOLD ● LOW DIELECTRIC CONSTANT (4) <ul style="list-style-type: none"> - SHORTER TIME CONSTANTS = RC - SMALLER VELOCITY MISMATCH ● POTENTIAL FOR MASS PRODUCTION
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mer films is substantially lower than that of LiNbO₃, implying smaller RC time constants and wider frequency bandwidths. Finally, the processing technology for integrated optical devices based on poled polymer films is relatively straightforward and fast, requiring only moderate temperatures (100°C) for poling, and standard semiconductor fabrication equipment for fabrication of layered waveguide structures.

As with all other materials, the secondary issues will be the drivers for organic integrated optical devices. Low absorption and scattering losses need to be designed into the material and fabrication technology, and good quality films must be regularly producible. However, it seems likely that these achievements can be met with further research and development. It is worth noting that the current inorganic crystal growth technology is a very old technology, representing thousands of man-years of research. Much work remains to be done with organics!

The Lockheed organic integrated optical devices effort has recently focused on the fabrication of simple slab guided wave structures made from polymer films. These structures allow the determination of fabrication techniques for organic devices, as well as direct measurement of Kerr and E-O coefficients in the waveguide configuration. By way of example, we next discuss two guided wave structures made from organics: a Kerr effect modulator based on an unoriented MNA film and an electro-optic modulator based on the PC6S poled polymer film described earlier.

3.2.1. Kerr-effect modulator. The first organic guided wave device fabricated at Lockheed was a Kerr effect modulator based on an MNA/PMMA guest-host film.¹⁶ This structure, illustrated in Fig. 2, is a slab modulator consisting of a thin film of SiO₂ as a lower buffer layer, the MNA/PMMA film as the guide, and another thin buffer layer film composed of polysiloxane. The entire structure is built on an aluminum-coated glass substrate with an aluminum electrode at the top. Layer dimensions and composition are illustrated in Fig. 3. An HeNe laser was prism-coupled into the device, which guided both a TE and TM mode. Intermode interference was observed on output, and the frequency response of the device is illustrated in Fig. 4. The low-frequency response is exactly what one would expect from a Kerr effect in this material. The output was measured with a lock-in amplifier, set to lock to twice the modulation frequency of the applied voltage, as appropriate for a Kerr effect. A linear effect was also sought, but was not measurable, as expected for an unpoled film.

Although this device is not useful for applications, its fabrication helped define procedures for the fabrication of E-O slab waveguide devices, described next.

3.2.2. Electro-optic modulator. The next slab modulator constructed at Lockheed consisted of a layered structure similar to that in Fig. 3, with the PC6S polymer film replacing the MNA/PMMA film.¹⁶ The poling procedure consisted of first spin-coating the electrode-coated glass with the bottom buffer layer and then the PC6S, applying a top electrode, and applying a voltage of the order of 1 MV/cm to the structure. Poling was observed with a

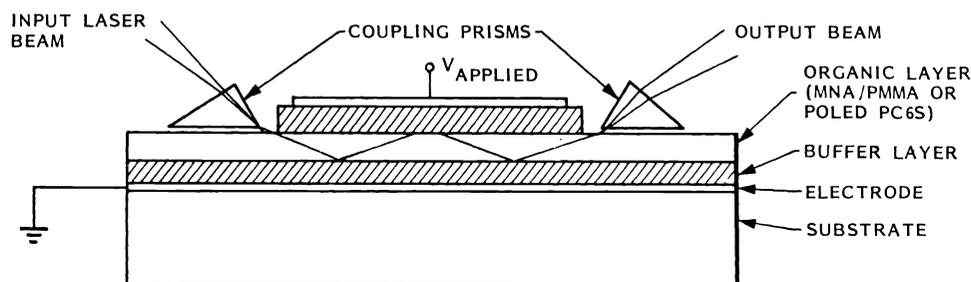


Fig. 2. Schematic of Kerr-effect waveguide modulator

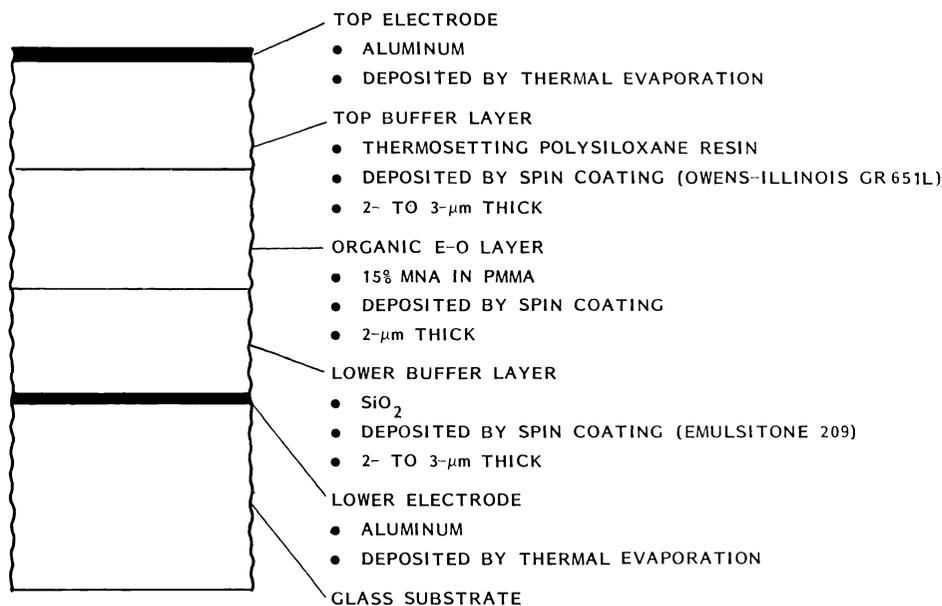


Fig. 3. Layers composing Kerr-effect modulator

polarizing microscope, and the entire procedure was monitored in realtime to optimize the poling. The top electrode was then removed, and a top buffer layer and new electrode were applied to the poled structure. Guiding of 830-nm light from a semiconductor laser over a 1.5-cm dimension with minimal loss was then achieved by locating the prism couplers directly over the ends of the poled region.

The optical response was measured interferometrically, and is illustrated in Fig. 5. The device half-wave voltage was about 23 V. Figure 6 illustrates the measured frequency response out to about 100 kHz, and shows it to be flat. The E-O coefficient of the poled PC6S film was measured to be 2.8 pm/V. Higher frequency measurements are currently underway with a new optical test system, and will be reported later in 1987.

The fabrication of such poled slab waveguide devices from spin-coated polymer films represents the first major steps toward the development of organic integrated optical devices. Many issues remain to be studied such as measurement and minimization of scattering losses, measurement of higher frequency response, development of procedures to form two-dimensional guides, and development of simple optoelectronic devices. However, the implications of this work are significant and promising. Simple fabrication techniques, requiring only standard spin-coating tools and chemical etching, can produce organic electro-optic devices from unoriented polymer films.

3.3. Fabrication of gratings for devices

Organic and polymeric materials are ideal for the fabrication of gratings as component parts of more complex electro-optic and nonlinear optical devices. Optical gratings have been fabricated in polymers by partially polymerizing monomers in crossed UV beams.¹⁷ Gratings of variable spacing can be fabricated in this manner, providing couplers for waveguide devices, Bragg mirrors for high-finesse etalon devices,¹¹ and holograms for optical memory and data storage. The unique processing of polymer structures, viz., spin-coating of films and subsequent poling of active E-O layers, can lead to the development

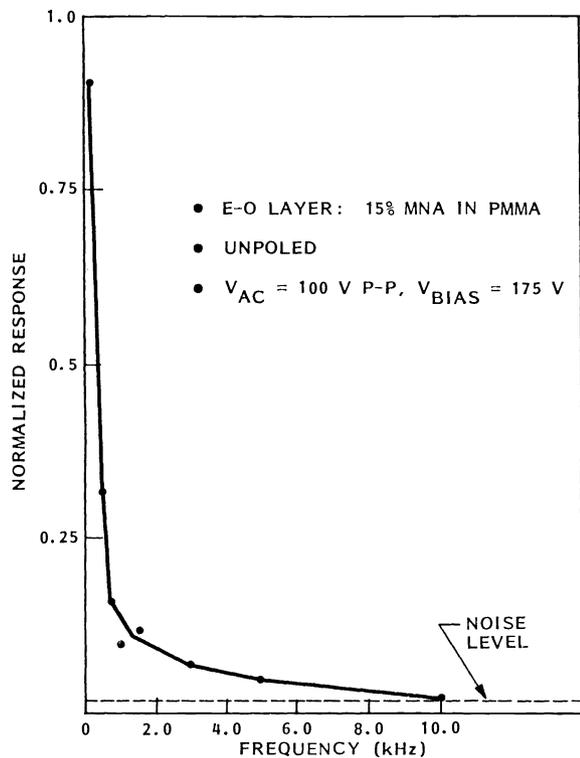


Fig. 4 Measured frequency response of Kerr-effect modulator

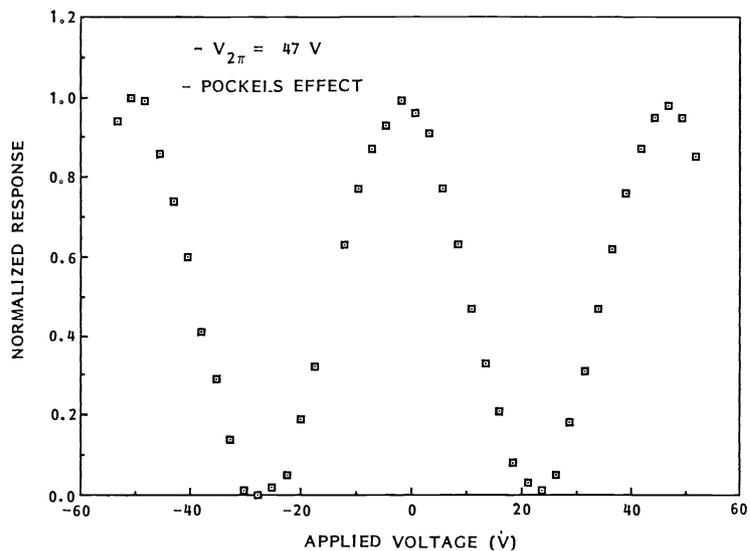


Fig. 5. Interferometric measurement of E-O modulator response

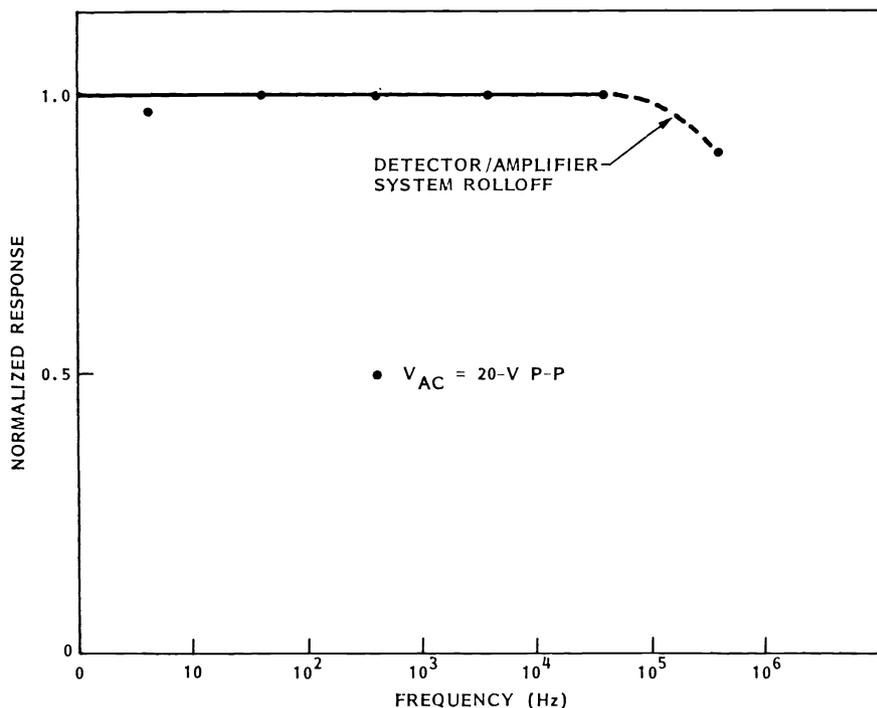


Fig. 6. Frequency response of E-O waveguide modulator

of true, integrated optic devices with couplers, guide layers, and active E-O regions integrated into a single thin-film sandwich.

We have begun preliminary work on the development of gratings for integrated optic devices. Rather than polymerizing monomer films, we have adapted a photo-active Polaroid

film, DMP-128, for use in the fabrication of gratings for Bragg mirrors and waveguide couplers. Figure 7 illustrates the fabrication procedure. The film is illuminated by a UV interferogram to provide a spatially varying, sinusoidal intensity distribution in the material. After exposure, the film is processed and fixed. The resultant structure contains a sinusoidally varying refractive index $n(z) = n_0 + n_1 \sin(2\beta_0 z)$, due to the chemical process involved in the exposure. Here, β_0 is the grating wave vector, and z is the direction normal to the film. A small refractive index modulation depth n_1/n_0 of only a few percent in a 25- μm -thick film is sufficient to produce a Bragg mirror with a reflectivity of over 90 percent for normally incident light.¹⁸ This type of processing has also been used to develop waveguide grating couplers for the devices described previously in this paper. Future research will address the fabrication of etalons using third-order, resonant films with Bragg mirrors fabricated in this manner.

- INTENSITY DEPENDENT PHOTOCHEMICAL REACTIONS RESULT IN LOCAL CHANGES IN THE INDEX OF REFRACTION OF THE MEDIUM
- ALLOWS THE ENCODING OF OPTICAL PHASE INFORMATION
- EXAMPLE: SIMPLE HOLOGRAPHIC GRATING FORMATION

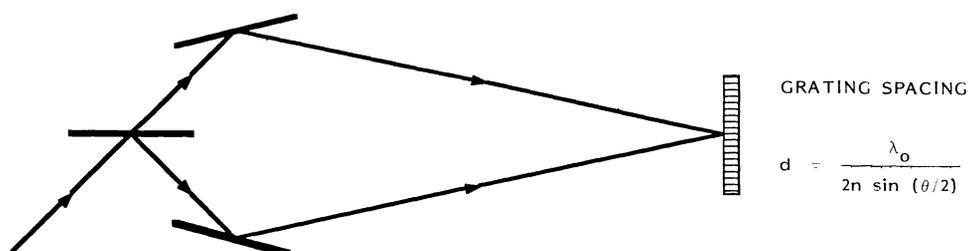


Fig. 7. Fabrication of gratings in photo-active polymer films

4. CONCLUSIONS

We have described certain features of organic and polymeric materials and their applications to nonlinear and electro-optic devices. As a class, the materials offer an important number of structural and optical properties for device applications, including flexible and straightforward fabricability, large E-O coefficients, low dc dielectric constants, and high optical damage thresholds. For second-order materials, current advances indicate that materials with performance approaching that of LiNbO_3 should soon be available, and a major impact on E-O device technology will be forthcoming. For third-order materials, it is likely that guided wave devices, with their long interaction lengths, will be the most practical for organics. At this time, it is still true that MNA (second order) and diacetylene polymers (third order) have the largest optical nonlinearities, as it was when original results were reported. However, it is clear that the fundamental material science is producing a working knowledge of how to engineer materials with larger nonlinearities, and it is only a matter of time before organics emerge as a promising class of practical nonlinear optical materials.

It is our view that future research in $\chi^{(3)}$ materials be carefully examined to ensure that claims of large nonlinearities in optically poor media do not spoil the real progress being made in the development of new materials. Nonlinearities of the order of 10^{-9} esu are not large at all. Instead, they are large for a nonresonant material, but still imply devices with large operating intensities. Nonresonant nonlinearities offer broadband response, but operating intensities must be reasonable, and should be obtainable from diode laser sources, as the latter can already be used with the large resonant response of III-V semiconductor multiple quantum well structures (10^{-1} esu). Care must be taken not to overpromote the $\chi^{(3)}$ of a new material without first carefully comparing its material parameters to other materials, and then comparing its performance in a device. As we have seen, device performance depends on materials parameters in a very complicated way, and is often determined by the device architecture or electrical properties, rather than the material.

5. ACKNOWLEDGMENTS

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