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Electro-optic Polymers for Optical Interconnects

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ABSTRACT

Glassy nonlinear optical polymers can be processed into channel waveguides. When poled, the channels become electro-optic, and can switch and modulate light. Using lithographic and machining techniques familiar to the chip industry, it should be possible to integrate large numbers of electro-optic switches into a board-level package or module, and thus provide the additional benefits of active switching and reconfiguration to passive hybrid optical interconnect modules. We describe some of the properties of the materials, some process methods, and potential applications in optical interconnection.

1. INTRODUCTION

The synthesis of glassy polymer films containing molecular units with large nonlinear polarizabilities has led to the rapid implementation of polymer integrated optics[1-4]. These polymers may be guest-host systems[5], in which nonlinear optical molecular units are dissolved into a polymer "host", side chain polymers[6] with the active group covalently bound to the backbone of the polymer, or even crosslinked systems[7], where the nonlinear optical molecule is linked into the polymer chains. Films of nonlinear optical polymers, formed by either spinning, spraying, or dipping, are amorphous as produced, and can be processed to achieve a macroscopic alignment for the generation of second-order nonlinear optical effects by electric-field poling[8]. Typically, the films are poled by forming an electrode-polymer-electrode sandwich, and applying an electric field to the heated sandwich, normal to the film surface. Films can also be corona-poled. Either way, the films are ideally suited for guided wave applications.

With the availability of certain classes of research formulations, many efforts are now underway to understand the design capabilities of devices based upon active polymers, and to attempt to develop suitable processes for fabricating prototype devices to evaluate both material and device performance. To date, many 'test structures' have been fabricated in E-O polymers, including Y-branch interferometers, directional couplers, novel evanescent switches, and travelling-wave modulators. With few exceptions, most of the structures represent a first attempt to make something that 'wiggles' on an oscilloscope. Recently, more advanced work in single-mode polymer channel waveguides has produced demonstration devices exhibiting some of the potential of the materials. In concert with this work, there has been a significant effort to understand the true requirements of polymer materials for integrated optical devices and packages. Much work remains, especially to produce stable, uniform, and reliable materials before practical, cost-effective products can be realized.

2. THE MATERIALS

Organic electro-optic (E-O) materials offer potentially significant advantages over conventional inorganic electro-optic crystals, such as $LiNbO_3$ and GaAs, in several key areas of integrated optics technology, as summarized in Table 1, including materials parameters, processing technology and fabrication technology. The most striking advantage, and the reason for the intense interest in these materials, is due to the intrinsic difference in the electro-optic mechanism. Unlike inorganic ferroelectric crystals, where the electro-optic response is dominated by phonon contributions, the electro-optic effect in certain organic materials arises in the electronic structure of the individual molecules, yielding extremely large E-O coefficients with little dispersion from dc to optical frequencies (second harmonic generation) and low dielectric constants[9-11]. Poled polymer organic materials have been demonstrated which exhibit electro-optic coefficients significantly larger than that of $LiNbO_3$ coupled with a dielectric constant nearly an order of magnitude smaller. The low dielectric constant is essential to the success of high bandwidth modulators due to the resulting lower velocity mismatch between the RF and optical waves, and could lead to an improvement of more than a factor of 10 in the bandwidth-length product over current $LiNbO_3$ devices. The microscopic molecular origin of the second order nonlinear susceptibility, $\chi^{(2)}$, and linear electro-optic coefficient, r, in organic NLO materials is now well understood theoretically and experimentally, and the materials are ready for exploitation.

Table 1. Comparison of Current $LiNbO_3$ and Projected Organics Integrated Optics Technologies

PHYSICAL & DEVICE PROPERTIES	Ti:Lithium Niobate	Organic Polymers
Electro-optic coefficient (pm/V)	32	10-50*
Dielectric constant	28	4
Loss (dB/cm @ λ=1.3 mm)	0.1	0.2-0.5
Space-bandwidth product (GHz-cm)	10	120
Crystal Growth Temperature, °C	1000	NA
Waveguide Processing Temperature, °C	1000	150-200
Waveguide Processing Time	10 hr.	10 min.
Multiple Layers Possible	No	Yes
Fabrication & processing	difficult	simple
Packaging	expensive	UNKNOWN
Maturity	30 years	10 years

* poling-field and wavelength-dependent

The materials research effort in recent years has centered on the inclusion of the nonlinear optical moiety in a guest/host or polymer system with appropriate linear optical, mechanical and processing properties and the artificial creation of the desired symmetry through electric field poling. These materials can then be simply and rapidly coated into high quality thin films, processed with standard photolithographic techniques and poled quickly and efficiently. A table of the materials and measured electro-optic coefficients from various groups is presented in Table 2. Figure 1 presents our own measurements of the electro-optic coefficients of two of the polymers as a function of the poling field applied to the film at its glass transition temperature. Slab losses at the indicated wavelength were about 1-2 dB/cm. Losses are much lower at 1.3 μm, with a corresponding decrease of about 10-20% in the E-O coefficient. Channel waveguides and integrated optic circuits can be defined by the poling process itself or by a variety of well understood micro-machining techniques. These processes represent a considerable increase in fabrication flexibility and processing simplicity over current titanium indiffused $LiNbO_3$ waveguide technology, which requires processing at temperatures approaching 1000 °C after expensive and difficult crystal growth.

Table 2. Some Reported Electro-Optic Coefficients in Poled Polymers

- AT&T BELL LABS. (K. Singer et. al, Appl. Phys. Lett. 53, 1800 (1988))
- DCV-MMA, r = 15 pm/V, λ = 0.8 μm, corona poled

- AKZO RESEARCH (G. Mohlmann, IGWO/OFC '89, Feb. 89)
- DANS , r = 28 pm/V, λ = 1.3 μm (random copolymer)
- MONS, r = 18 pm/V, λ = 1.3 μm (random copolymer)

- HOECHST CELANESE (D. Haas, SPIE, San Diego, 1989)
- r = 40 pm/V; λ = 1.3 μm

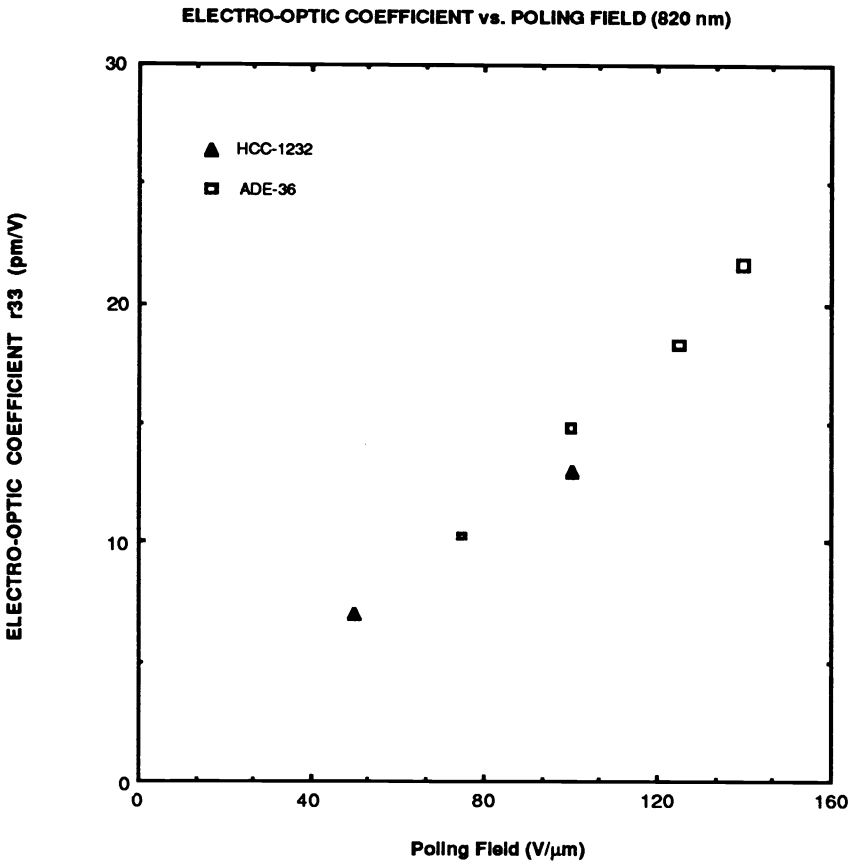

Figure 1. Measured Electro-optic Coefficient r_{33} of Two Electro-optic Polymer Materials

The key potential advantages of these materials for device applications are summarized in Table 3. For example, the chief limitation of $LiNbO_3$ modulators is the velocity mismatch between the electrical wave traveling down the electrodes and the optical wave traveling down the optical waveguide. The RF field from the electrodes extends into the dielectric material and thus travels with a velocity $v = c/\sqrt{\varepsilon_{eff}}$ where c is the free space velocity of light and ε_{eff} is the effective dielectric constant of the waveguide structure, and depends on the details of the electrode structure itself. The effective dielectric constant is generally a linear function of ε_S, where ε_S is the dielectric constant of the E-O material. For $LiNbO_3$, $\varepsilon_S = 38$, while for the poled polymer films $\varepsilon_S = 3.5$. The light , however, travels down the waveguide with a velocity $v = c/n$, where n is the index of refraction of the waveguide material, which for $LiNbO_3$ is $n = 2.2$ and for the poled polymer films $n = 1.57$. Thus, the optical and electrical waves traveling down the device structure gradually get out of phase with each other, and for a given device interaction length there is a maximum frequency, f_c at which the device can be driven. The high speed modulation limit of the material can be estimated by the bandwidth-length product f_cL. For $LiNbO_3$, $f_cL = 9.6$ GHz-cm for a standard Mach Zehnder configuration, while for the organic poled polymer films proposed here $f_cL = 120$ GHz-cm. Thus for this new class of materials the primary limitation of $LiNbO_3$ for high speed modulation in the 20 - 40 GHz range is effectively removed. The limiting factor for the poled polymer films will probably be RF loss in the electrodes, which is increasing as the square root of the drive frequency.

Table 3. Potential Advantages of Polymer Electro-optic Materials

- *Large, broadband electro-optic coefficients*
- Current materials exhibit $r \leq 40$ pm/V @ $\lambda = 830$ nm
- New materials may exhibit $r \sim 100\text{-}200$ pm/V

- *Low DC and microwave dielectric constants*
- $\varepsilon \sim 3\text{-}4$
- high time-bandwidth products (~ 120 GHz-cm)
- resonances located well above 20 GHz

- *Ultrafast response times*
- Materials have $\tau \sim$ fsec for electronic response
- Waveguide switches have $\tau_{RC} \sim 50$ psec, and are capacitative

- *Low optical loss*
- $\alpha \leq 0.5$ dB/cm @ diode laser wavelengths, depending on material
- Low loss channels producible by RIE, laser ablation, selective poling, other methods

- *High levels of integration into optical packages*
- Small single-mode waveguide dimensions (~ 3-5 μm)
- High waveguide packing density (20 μm centers for < 30 dB crosstalk over 10 cm)

- *Potential for novel hybrid optoelectronic packages*
- Multilevel polymer/metal interconnect packages
- Hybrid optical multichip modules
- Hybrid packaging and connection of sources, detectors, and electronic components
- Integrated Si substrates containing detectors, amplifiers, and other circuitry

The application of electro-optic polymer materials to practical devices will require some significant advances in the development of the materials. These required advances arise mainly from the required thermal stability of the polymer poled state and the stability and tolerances required to minimize or control device or package performance variations when operating over a desired environmental range. They also arise from the additional variations in device performance that arise from an uncontrolled, or only partially understood manufacturing process, and in uncontrolled variations in materials parameters, such as refractive index variations from batch to batch. Systems users will require performance/cost ratios that rival alternate approaches to solving their problems, and will not be favorably disposed to solving materials problems by the use of cooled packages with extra wires and power requirements, and reduced reliability. Moreover, such users, and component manufacturers and assemblers, will require that they be capable of using standard manufacturing and assembly equipment to build devices. The full assembly of a device, be it a fiber-pigtailed modulator or an integrated module, will require such processes as die attachment using established, standard industry processes, module packaging, and final systems assembly (wave soldering, etc.), that is compatible with military end use requirements (125 °C continuous, 200 °C storage). This requires materials with good long-term thermal and environmental stability, large temperature operating ranges, and the existence of a significant reliability base, including failure (FIT) rates.

Current research formulations probably cannot meet these requirements. For example, most of the current research E-O polymers, whether guest-host or side chain, are based on thermoplastic acrylate chemistry (i.e. PMMA) and, as a result, exhibit glass transition temperatures between 100 - 125 °C. This low T_g results in high polymer chain diffusion rates, of the order of 10^{-12} to 10^{-15}, and a calculable variation of at least 10% in the optical properties of the poled state over 5 years operation at ambient temperature. This rapid change is the natural consequence of the dynamic processes by which glassy polymers, operating close to their T_g's, undergo physical aging and relaxation to minimize free volume. When higher operating temperatures are considered (125 °C), the stability of the optical properties becomes even worse. The performance limitations of these materials is due to the fact that they have not yet been formulated for field use, and is not a result of any

intrinsic scientific limitations. For example, recent work has shown that crosslinked systems may exhibit much better stability than guest-host or side-chain systems, and it is obvious that many higher temperature host materials could exhibit much better thermal stability, if properly formulated.

As an example, consider the sensitivity of the basic engineering performance parameters of an optical waveguide due to variations in poled optical properties that result from both thermal effects and processing variations over their expected temperature operating range of -40 to 125 °C. Specifically, consider the variation in half-wave voltage (V_π) for a polymer channel waveguide such as that shown in Figure 2. Assuming that the polymers adhere to the substrate, the fractional change in V_π is given by $\delta V_\pi/V_\pi = \delta\lambda/\lambda - 3\delta n_0/n_0 - \delta r/r + \delta\Delta/\Delta - \delta L/L$. The variables in the individual parameters that yield $\delta V_\pi/V_\pi$ are tabulated below for two different polymers, one with a high T_g (>400 °C) and the other with a low T_g (~125 °C), over a temperature range of -40 to 125 °C. The total variation in half-wave voltage over these conditions is then summarized below. As can be seen, the low temperature polymer, which is representative of all of the research materials currently under evaluation, affords a substantial performance variation in this key poled optical property that is clearly dominated by material thermal effects. The large changes in the thermal coefficient of expansion (TCE) that characterize the thermoplastic acrylates make them impractical for any application, other than device research, that involves a wide range of temperature environments or operation close to their T_g's.

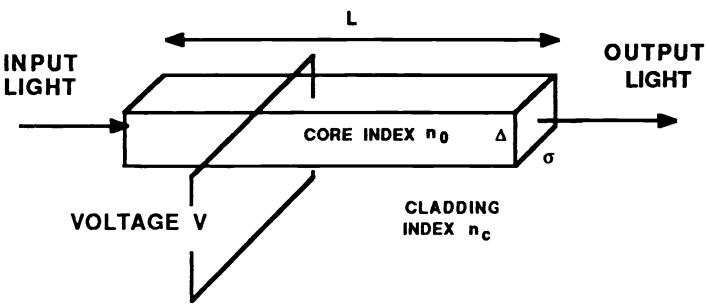

Figure 2. Parameters for a Polymer Channel Waveguide

Table 4. Parameters and Their Variation over Operating Ranges

VARIABLE	THERMAL		FABRICATION[1]
	LOW T_g (125 °C)[2]	High T_g (>400 °C)[3]	
$\delta\lambda/\lambda$	0	0	0
$\delta n_o/n_o$	1.5%	0.6%	2%
$\delta r/r$	10-50%	<1%	0.6%
$\delta\Delta/\Delta$	1.5%	0.6%	4%
$\delta L/L$	0.04%	0.04%	0%

TOTAL $\delta V_\pi/V_\pi$ FOR LOW T_g POLYMER: 15 - 55%
TOTAL $\delta V_\pi/V_\pi$ FOR HIGH T_g POLYMER: 5%
[1] 0.2 μm precision, Substrate TCE = 3 ppm/°C; [2] TCE = 100 ppm/°C;[3] TCE = 30 ppm/°C

The simple analysis presented above confirms that new formulations are required to produce stable, reliable products for field use. Practical system requirements, as defined by Mil Spec conformity and the use of standard fabrication and assembly processes, definitely requires that a electro-optic polymer system with better thermal properties than thermoplastic acrylates be developed. That this is true for optical interconnection modules is not surprising because of their complexity. It is perhaps remarkable that it remains true for even simple devices, such as a packaged, pigtailed traveling-wave modulator. The ultimate

success of electro-optic polymers will be their use in cost-effective products that are used by systems designers. It seems likely that continued development of the materials and concurrent fabrication processes should provide such products.

3. THE DEVICES

Device research with poled polymer materials is still in its infancy. For the most part, this is due to the requirement that the material must be poled to produce a nonzero electro-optic coefficient. However, it is also due to the evolution of the materials themselves, and the significant batch-batch variations that exist in formulations that are new today and obsolete tomorrow. The maturation process is rapid, and, consequently, device designs and processes mustbe continually updated for each improved generation of material. For example, it is possible to purchase large quantities of passive polymers (acrylates, polyimides, and others) with essentially the same uniformity and quality control as is available from the photoresist industry. With such materials, the precise measurement and control of the refractive index, stress and strain tensors, uniformity, and loss is possible, and, consequently, the design and fabrication of precise waveguide units is possible. With active polymers, the materials are evolving rapidly, and variations in all optical and electrical properties are expected and observed from one batch to another. Moreover, the requirement to pole a waveguide can add many mask steps to the process, and introduces the need to be concerned with the electrical properties of the core and cladding materials, and their compatibility with electrode materials. Consequently, essentially all reported device structures exhibit 'wiggles' on an oscilloscope and exhibit desired effects, but do not yet achieve the performance expected from these potentially important materials.

As the materials mature, it is expected that practical fabrication problems will be solved, and that eventually various grades of E-O polymers will be available, like photoresist is today, for a variety of different applications and needs. For this reason, polymers represent a unique, potentially powerful addition to the library of materials comprising optoelectronic components, and polymer devices provide new and novel approaches to optical interconnection, electronic packaging, and integrated optics. In what follows, we provide a summary of our device work with current research materials, and a discussion of potential applications to optical interconnection modules and packages.

3.1 Poled Polymer Waveguides

Integrated optic devices have been fabricated at Lockheed based on organic polymers by spinning the material into high quality thin films on optical substrates. As spun, the films are isotropic and thus exhibit no linear electro-optic effect, r. In addition to inducing a non-centrosymmetric structure to achieve a macroscopic electro-optic effect, a second major transformation must be engineered in the material to enable the fabrication of integrated optic circuits. Channel waveguides must be formed to confine and guide the light from one active element of the integrated optic circuit to another. Electric field poling has been extensively studied as a means to partially align nonlinear optical molecules in an inert polymer matrix to induce a macroscopic r. Figure 2 illustrates a novel method, developed by Lockheed, by which channel waveguides can be fabricated by the poling process itself[12,13]. An electrode pattern, defining the channel waveguides, is deposited on an optical substrate and covered with a buffer layer, to isolate the active waveguide layer from the electrode. The buffer material must be chosen to have an index lower than the guiding layer and to be compatible with the required processing. The electro-optic polymer is spun directly onto the lower buffer layer, and different buffer layers must often be used with different nonlinear polymers. A metal ground plane is then deposited directly onto the nonlinear polymer for poling using standard photolithographic techniques. The nonlinear layer is then poled by applying an electric field above the polymer glass transition temperature and cooling the sample to room temperature under the influence of the field. The degree of alignment induced and the resultant electro-optic coefficient can be calculated based on a statistical average of the molecular susceptibilities. In this case only those regions of the material defined by the electrode pattern on the electro-optic material are poled.

Since most organic nonlinear optical molecules also possess an anisotropic microscopic linear polarizability, the poled region becomes birefringent. The poled regions are uniaxial, with n_e oriented along the direction of the poling field. Consequently, TM waves propagating along the device structure will experience a greater refractive index in the poled regions than in the unpoled regions, and so can be confined in the lateral dimension. Thus, by applying the poling fields using electrodes patterned to define the waveguide network, including both active and passive sections, no further patterning of the nonlinear optical organic layer is required to form the channel E-O waveguide structures. The devices are then completed by etching off the poling electrode, applying an upper buffer layer and depositing the patterned switching electrodes, as shown in Figure 3. The switching electrodes are positioned to address only the sections of the guide desired to be active. A photograph

of a section of poled waveguide is shown in Figure 4. The region on the left is unpoled and the light fans out and is clearly unguided. The region on the right has been poled and the light is clearly guided and confined to the waveguide region. Using this technique, Lockheed has fabricated poled polymer channel waveguides, and has demonstrated modulators, couplers, and bends in electro-optic polymer materials[12-14].

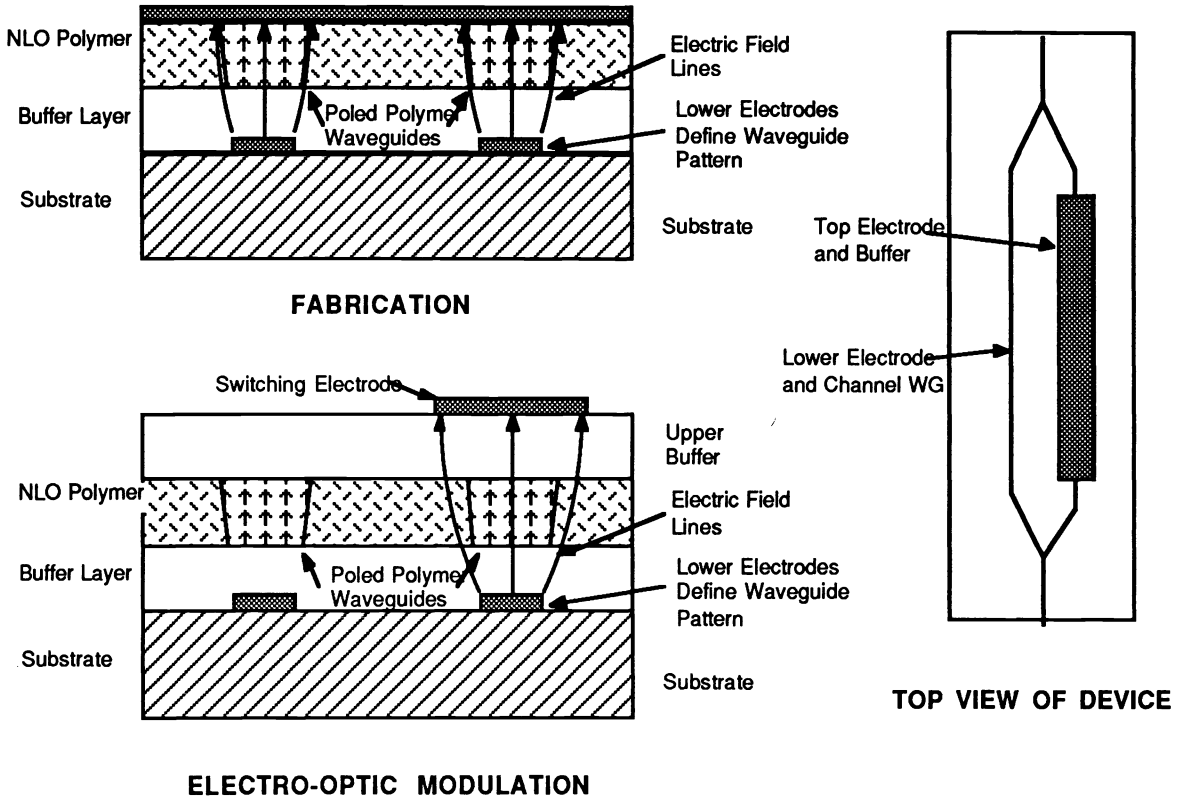

Figure 3. Fabrication of Channel Waveguide by Electric Field Poling

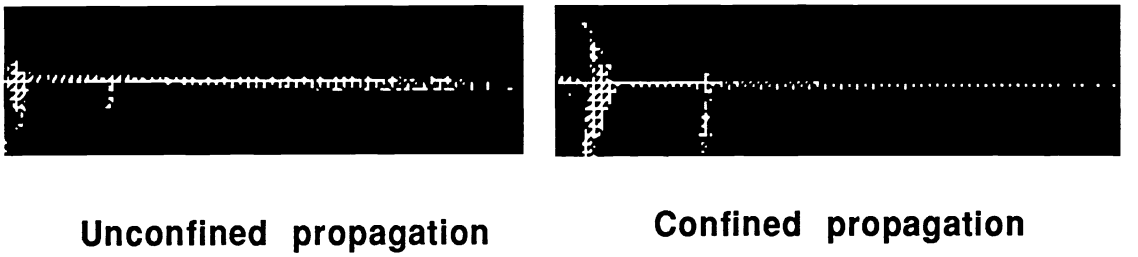

Figure 4. Photograph of a Poled Polymer Waveguide.

Figure 5 illustrates a schematic and photograph of a new switching device, the Lockheed psi switch[14]. This device is an evanescent, triple-coupler, providing in principle complete switching of light from a center guide to either of two outer guides. A prototype was fabricated in an oxynitrostilbene polymer material to demonstrate both single-mode operation and switching at moderate frequencies. Figure 5b shows both the confinement of light in the poled channels and the appearance of much scattered light from the center guide, due to improper coupling lengths. This type of device has great potential for optical interconnection networks, but requires extraordinary control of the material properties to achieve both precise waveguide dimensions and effective indices.

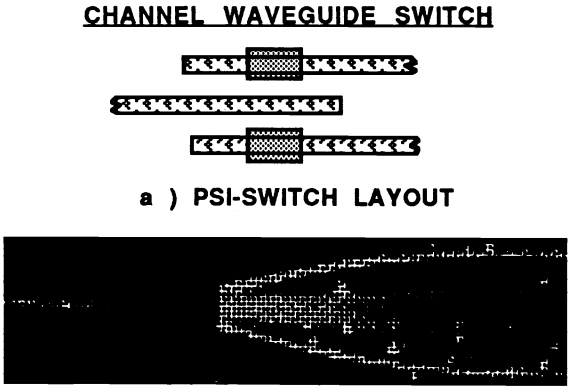

Figure 5. Schematic and Photographic of an Evanescent Waveguide Switch

Electro-optic polymer device research has proved many of the potential advantages of the materials. However, the device research is still maturing due to the rapid maturation of the materials. The fabrication techniques exist to produce very high-quality devices, including high-performance single-function components, such as modulators, switches, and active splitters. Good device performance demands both the use of high precision equipment and highly stable, consistent materials with predictable optical properties, such as refractive indices and E-O coefficients. Such materials will be formulated as research continues. Because of their switching properties, polymer E-O guides may find their most beneficial application to highly integrated packages, rather than single-function, pigtailed devices. These would include optical interconnection nodes and switches, and distribution networks.

3.2 Applications to Optical Interconnects

Optical signals can carry information at very high bandwidths with much lower loss, power dissipation and crosstalk than electrical signals in metallic conductors[15,16]. In order for these benefits to be realized, however, the improved transmission capability of optical signals must make up for the added difficulty of converting the information from electrical to optical form at the output pin of one chip and back to electrical form at the input pin of the receiving chip. This conversion process has been the strongest impediment to achieving optical interconnects because it requires an active function in the interconnection network. The most common solution suggested for this problem is to place an individual laser diode, either a discrete or monolithically integrated device, at each output line. In a typical multichip package or board with several hundred to several thousand output lines, the complexity of assembling discrete components becomes prohibitive. Monolithic integration of laser diodes onto high speed, high performance integrated circuits is a complex and difficult process. The chip real estate required for integrated laser diodes could probably be better used for logic gates.

Passive optical waveguides solve many of the problems confronting system designers attempting to interconnect electrical signals at speeds above 1 GHz. Optical waveguides reduce crosstalk, signal attenuation and the power necessary to drive the signals. There is a frequency (bandwidth) distance product where optical signal transmission offers advantages over electrical. However, the system design trade off analysis of optical and electrical comes up against the problem of the electrical to optical back to electrical conversion since the logic operations currently must be performed by electronic

integrated circuits. An electronic system will have hundreds to thousands of signal lines interconnecting the integrated circuits. The conversion of each of these chip I/O's to optical lines is difficult and expensive with discrete sources and detectors. Additional factors hindering the use of passive optical interconnections are listed in Table 5.

Table 5. Limitations on Passive Optical Interconnects

Electrical to Optical Conversion
Separate Laser for Each Line
Laser Drive Circuitry
Separate Detectors for Each Line
Amplification for Detectors
Assembly
Optical Alignment of Lasers
Optical Alignment of Detectors
System Density
Electrical and Optical in Same Board
Multilevel Optical Interconnects
Material
Thermally Stable Optical Materials Required
Low Loss Waveguides
Reliability
Discrete Laser: 50 - 100 FIT's
Discrete Detector: 1 FIT's
Many More Separate Components
Cost
More Components
More Assembly Steps
More Complex Assembly

The alignment and assembly of individual sources increases the complexity of the interconnect system, reduces the reliability of the finished board, and significantly increases its cost. For high data rates the source lasers must be environmentally protected and temperature controlled, requiring individual packages or packaged laser arrays, and possible direct cooling. High speed laser packages are particularly real-estate inefficient, with the active device occupying less than 1% of the area of the package. This wasted space can lead to timing problems and data errors since the electrical signals from the control IC are thus forced to travel relatively long distances that may be several fractions of a wavelength (15 cm for 1 GHz). Multiplexing of multiple data lines is now used for optical interconnections between boards and may be appropriate as a way of reducing the number of lasers required for some applications. However, the electrical complexity of sending and receiving the signal at two or more times the data rate makes multiplexing impractical above a few hundred megahertz, and thus it may not be useful at high speeds where optical interconnects are the most appropriate.

The alignment of discrete detectors for each input is no less a difficult task than the source assembly problem. The extra traces associated with connecting discrete FET's, PIN's, or APD's leads to degradation of signal, lower reliability, and greater cost. The integration of photo FET's onto the IC does provide a way to simplify the detector side of the problem, unfortunately at the expense of wavelength flexibility (850 nm). Integrated photo FET's are currently possible only in GaAs technology.

The optical assembly tolerances for single mode E-O polymer waveguides are much tighter than those found in electronics assembly, requiring device to waveguide alignment of $\pm$ 0.5 μm versus $\pm$ 10 to 25 μm for an electrical die

assembly with pad pitch of 5 to 8 mils. The use of larger, multimode waveguides reduces the problem somewhat, requiring ± 5.0 μm accuracy, but this may still more difficult than electronic assembly. A modest size board with 10 IC's and 1,000 internal I/O's would require approximately 1,000 lasers and detectors. The assembly and alignment of all of these optical devices, even incorporating arrays and subassemblies, is a formidable undertaking. The total system complexity becomes greater because alignments must be made between two separate planar structures, with as many as six degrees of alignment required in assembly to very tight tolerances.

The direct modulation of laser diodes by each chip I/O requires additional electrical circuitry plus other elements to dissipate the power and noise associated with these high speed switching lines. The integration of lasers onto the IC solves many of these problems, and is thus a goal of the programs on monolithic integrated optics. This integration has been achieved in the laboratory, using the drive circuits on the chip to directly modulate the lasers. SRI has recently produced such a device that incorporates 100 lasers. However, complex IC's can have hundreds of outputs on the chip. Even on an IC, hundreds of direct drive lasers operating at multi GHz frequencies will produce more problems, such as crosstalk and power dissipation. Putting high power lasers on hot IC's that are close to their heat dissipation limit will certainly push the device over its thermal threshold, and thus force either a reduction in the number of on chip logic elements or an increase in chip size. The former is more likely since there is a practical limit to the size of a chip, dictated by fabrication and yield considerations.

The use of active polymer waveguides may simplify the signal drive and modulation problems in optical chip interconnections by providing external modulation of laser light and by using switched waveguides. With appropriate design, a single CW laser can service 100 I/O pins, reducing the number of lasers, and associated alignment processed during assembly, dramatically. This approach is comparable to an electrical hybrid and allows the integration on a module of various technologies of integrated optics and electronics without limiting optical interconnections to monolithic optical integration type devices. This would be accomplished by using the active nature of the switches to redistribute light within a package at high-speeds. It is worth noting, for example, that a typical E-O polymer waveguide switch would have an RC time constant of under 50 psec, and would provide very fast creation and distribution of optical signals within a package. This is particularly useful for active interconnection of high-speed GaAs IC's, but even more important for solving interconnection problems with Si CMOS at frequencies as low as 100 MHz. This latter fact, practically unstated in the literature, is the result of the much lower output buffer power dissipation when CMOS is driving an E-O capacitative switch, as opposed to an electrical interconnect line. The design of such packages is in its infancy at Lockheed, and will be reported at a later date.

4. ACKNOWLEDGEMENTS

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