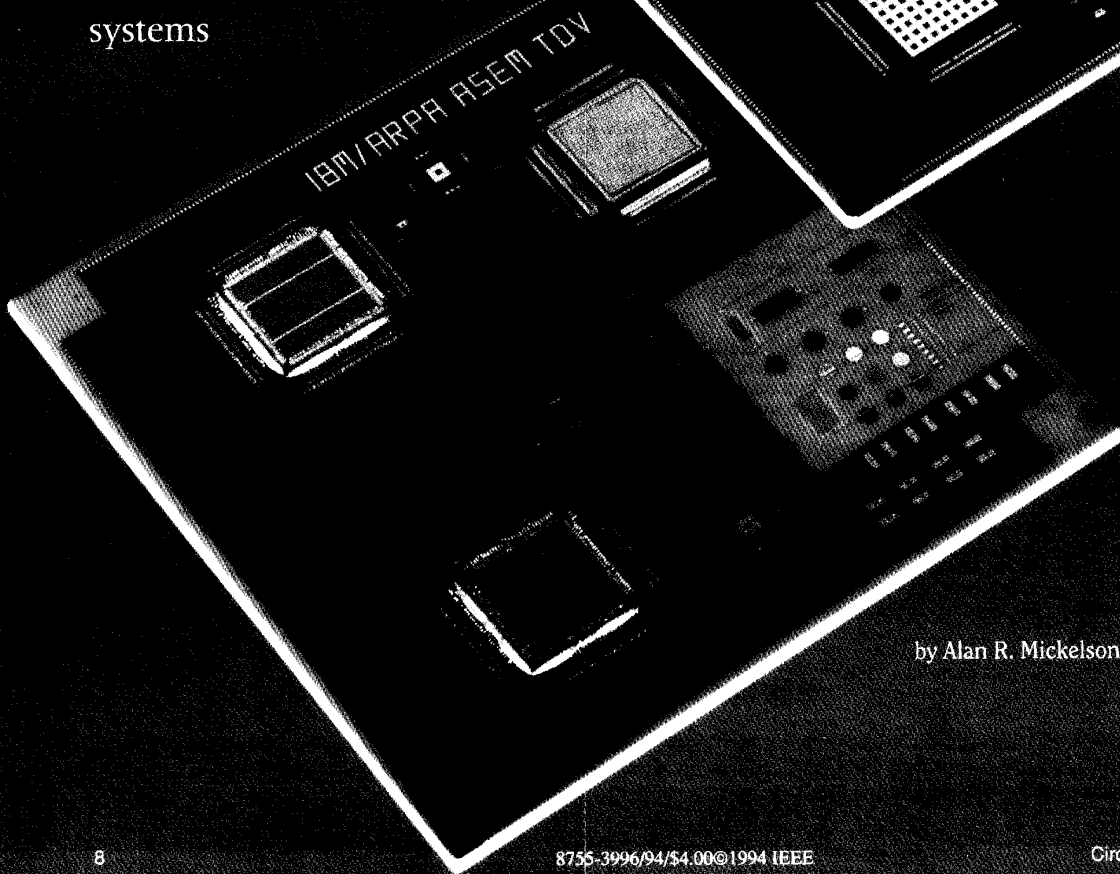
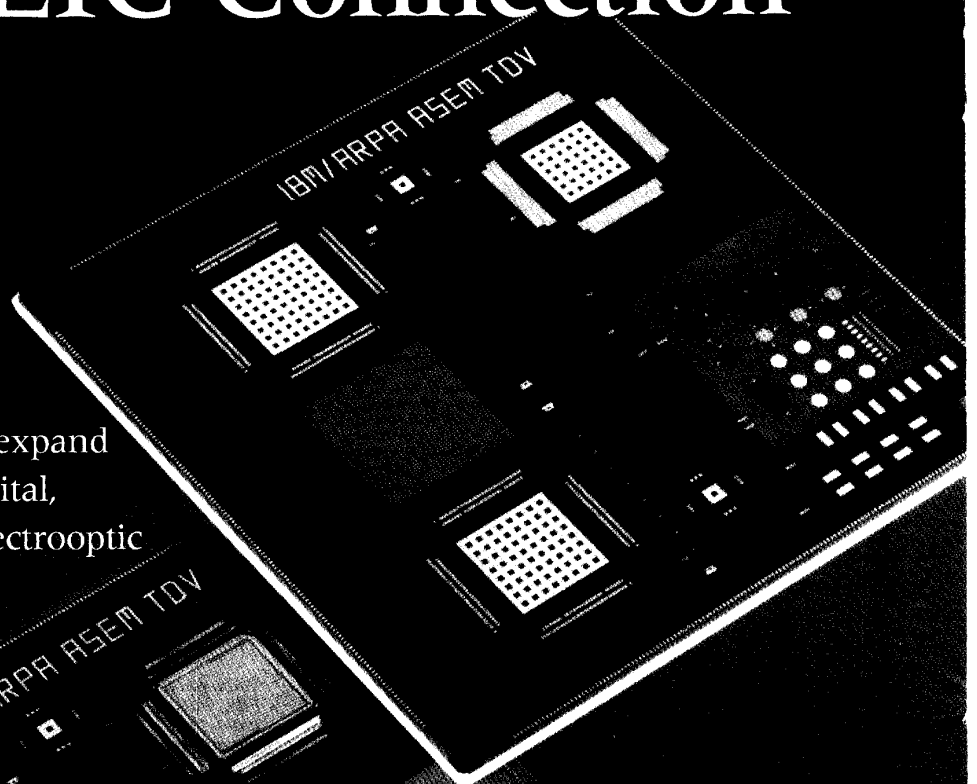


Polymers Make the OEIC Connection

Improving plastics expand
their domain in digital,
microwave, and electrooptic
systems



by Alan R. Mickelson

In an opening scene from the 1967 film *The Graduate*, Mr. McGuire takes Ben, the graduate (played by Dustin Hoffman) aside and says, "Plastics." "What exactly do you mean, Mr. McGuire?" asks Ben. "There is a great future in plastics," comes the response. Plastics are one phase of a condensed state of the long-chain hydrocarbon (organic) molecules that we call polymers. The plastic phase of polymers, indeed, is the one which we are most interested in for high-technology electronics and optoelectronics, applications that I doubt Mr. McGuire had in mind during his dialogue with Ben.

Indeed, polymers have long found extensive application in today's electronics packaging. Printed circuit boards (PCB's) and printed wiring boards (PWB's) are polymer based. The most ubiquitous present day PCB is an epoxy laminate (thin layers stuck together) known as FR4. High-frequency analog (microwave) electronics often use costly ceramic boards, but in many of today's low-cost commercial applications, teflon- and laminate-based boards are also becoming increasingly popular. Chips need to be mechanically protected and are therefore often potted in other types of polymers such as epoxies. Likewise, interconnections need protection and tend to be placed into yet other polymers, especially polyimides. As pin counts and digital clock speeds increase, these interconnect structures become more intricate and massive and begin to become an ever more integral part of the electronics systems function. Multilayer interconnects are another topological necessity in all but the simplest of digital systems. These multilayered interconnects show up at all levels of the electronic packaging hierarchy digital and analog, from the chip carrier to the multichip module (MCM), to the PCB or the PWB and on to the motherboard (Fig. 1).

Polymers are also rapidly expanding into high technology areas such as fiber optics, which is the transmission technology of choice for communication extending over more than a few meters. Thus far, fibers have been used primarily as a direct substitute for electrical wires. However, integrated optics

Mixed interconnect MCD-D built by IBM under the Advanced Research Project Agency's Application Specific Electrical Modules (ASEM) program.

technology is advancing to the point where optical interconnections can be extended down to shorter and shorter interconnection lengths and, thereby, allow the synergistic union of optics and electronics. In that context, polymers promise to be useable both as low cost waveguides and as active electrooptic devices, and open the prospect for widespread use of integrated optics even in miniaturized systems. In short, polymers are expanding everywhere in digital, microwave, and light-based systems.

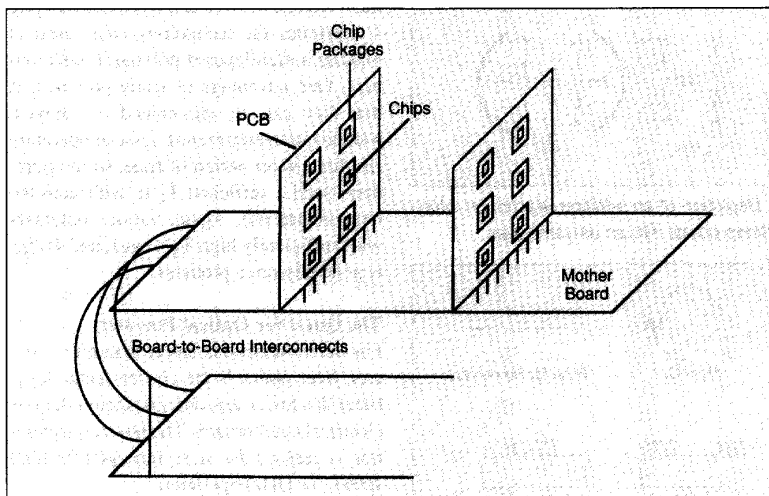
What is a Polymer?

The Greek work "poly" means many, and so a polymer is literally many "mers." A mer is a functional unit derived from a monomer. To gain a little insight into the polymer world, let's draw some pictures of some of these entities.

Organic chemistry refers to the chemistry that goes on in compounds containing carbon and hydrogen and perhaps something else. A carbon atom has a half-filled outer shell consisting of four electrons. To be stable, each carbon atom needs to bond with other atoms to share four more elec-

pairs would be somewhat superfluous and, indeed, this is the case. The second electron pair of the double bond is delocalized, i.e., each electron spins near its own atom with an elongated orbital sticking out of the paper. Indeed, if one were to take a quantity of the ethylene of Fig. 2c and process it properly, one could form polyethylene through the so-called additional process (Fig. 3). The double bond of Fig. 3a can be enticed to form single bonds with other entities, as indicated by Fig. 3b, which is a mer. It is just such addition reactions that are used to form acrylates, which are reasonably low temperature polymers that are used extensively for electrical isolation layers.

The next most simple method of polymer formation is that of the condensation reaction, one in which mer formation requires a water molecule to come off in order to free the bonds. Such a reaction is the second step in synthesis of the polyimides, perhaps the most important of the electronic (electrooptic) polymers. More complex reactions are necessary to form the polyethers, better known as epoxies, which are the most important of potting materials. For one inter-



1. An electronic system, showing the packaging hierarchy.

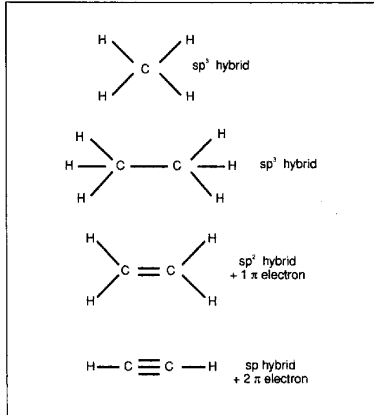
trons to fill the outer shell. The four simplest hydrocarbons that can be formed are shown in Fig. 2. The bonds, i.e., shared electrons, can assume several forms. In some cases, all of the bonds (lines between atoms indicating coupled electronics) are single (Figs. 2a, b). Physically, such a bond consists of two long electron orbitals in the plane of the paper, lying side by side. It stands to reason that in a double bond (Fig. 2c), additional electron

ested in further polymer discussion, see [1] and [2].

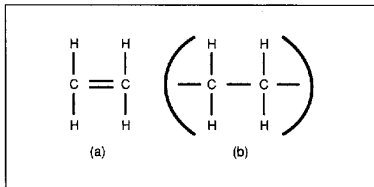
Desirable Electrical Properties

One could come up with a long list of desirable properties for electrical polymers. Here we wish to concentrate on a few salient ones. These include lifetime, temperature stability, high breakdown voltage, and processibility.

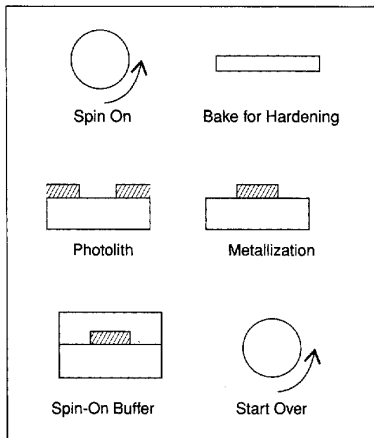
Lifetime and temperature stability are closely linked. Central to these characteristics is the glass transition temperature, above which the polymer enters a rubber like state in which the long strands can rotate relative to each other. Below this temperature, the



2. Some depictions of the bonding schemes for the simplest hydrocarbon compounds; (a) methane; (b) ethane; (c) ethene; (d) ethyne.



3. Depiction of an addition reaction in which ethene opens into an ethylene mer.



4. Processing steps necessary to form a multilayered interconnect structure to support a multichip module or board level chip-to-chip interconnect.

disorder of the structure is frozen in and the state is glasslike or plastic-like. The time for a polymer to reach disorder appears to be dependent primarily on the difference between the glass transition temperature (T_g), and the operating temperature. Epoxies can exhibit T_g 's greater than 200°C , and polyimides can exhibit significantly higher T_g 's.

If one creates a dense structure of electrical interconnects, high breakdown voltage will be desirable, as this voltage may determine the ultimate chip density. For example, a polymer layer in a multichip module may have a thickness of less than 2 mm. If six volts are applied across the 2 mm layer, the breakdown quotient will be 3 volts/mm. In practical applications, there would be both a real risk of failure and impaired lifetime in substrate material exposed to this stress. Fortunately, polyimide has a breakdown consistently exceeding 50 V/mm, which exceeds the breakdown of many materials.

Processibility is another characteristic which seems to be becoming ever more important. Establishing mass markets, such as the commercial microwave links of the future, demand low-cost electronics, and polymers are one answer to the problem. Figure 4 illustrates the technology steps used in making a multilayered polymeric interconnect. One advantage of using polymers is that they can be spin-coated or sprayed. Metallization may require some temperature rise for a short period of time, so the polymers need a sufficient T_g to withstand the temperature rise. Again, various polymers with sufficiently high T_g 's exist, and so this is generally not a problem.

The Quest for Optical Polymers

For interconnections larger than a few meters, fiber optics is the chosen technology. Fiber has lower loss and dispersion than its electrical counterparts. The latter consideration is perhaps the most important for high speed (>1 GHz) operation.

Optics, however, has significant overhead; electronic signals need to be converted to optical signals, transmitted, and then detected and reconverted back. On the other hand, as clock rates increase and optical technology improves, however, the interconnect length is likely to shrink. How small it might go is a matter of debate, but estimates as low as $100 \mu\text{m}$ have appeared in the literature. Polymers thus offer a viable medium through which optical signals can be generated and transmitted.

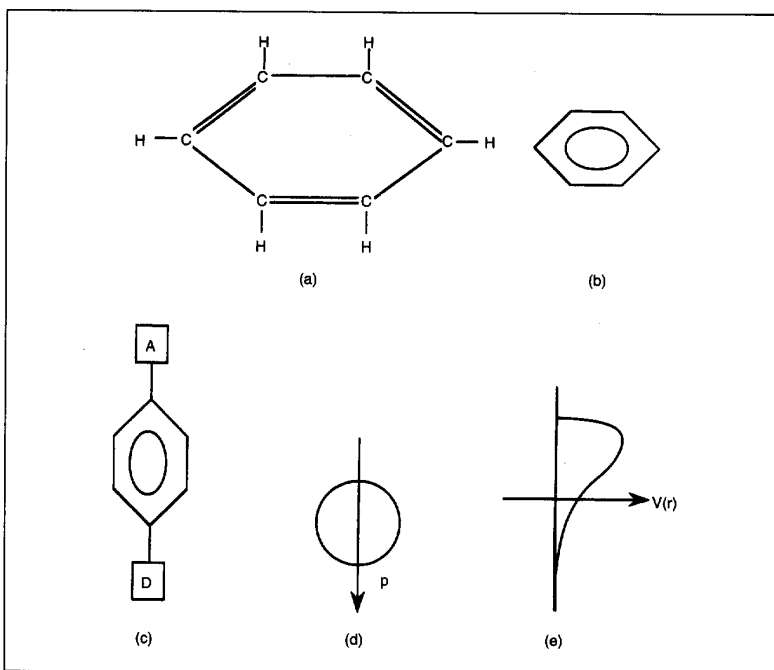
Desirable Optical Properties

As discussed previously, polymers are used at all levels of the packaging hierarchy. Most of the electrical interconnect structures are for fixed routing, and the switching is located at the peripheries of the interconnect structure. Therefore, we require first and foremost that an optical polymer support low loss waveguides for signal routing. The material, therefore, should be transparent at wavelengths of interest and have a high enough optical damage threshold that allows us to operate at reasonable optical power levels.

The next question concerns the insertion and read-out of the electrical information stream. Generally, detection is an easier process to implement than light generation. Depending on the density of the interconnect structure, therefore, it might well be desirable that the optical polymer be sufficiently electrooptic. Then, modulating structures to convert the electrical data to optical data streams could be placed on top of the waveguide structures, with the optical sources placed some distance away and guided to the modulators by the waveguides. In addition to these qualities of transparency, optical damage thresholds, and electrooptic activity, the polymer would ideally have all of the electrical polymer qualities mentioned above, i.e., long lifetime, high temperature stability, high voltage breakdown, and processibility.

Relating some of these properties to atomic structure, we first consider the benzene ring of Fig. 5a and 5b. From Fig. 5a, we see that every other bond on the ring is a double bond. Recalling the earlier bonding discussion associated with Fig. 2c, recall that the second bond places an electron on each of the bonded carbons, with their orbitals sticking out of the plane of the paper. In the benzene ring, therefore, each carbon has an electron orbital sticking out of it. As each orbital is identical, we can interchange any two without affecting the energy of the configuration.

Figure 5b shows the symbolic depiction of the benzene ring. The ring in the center indicates the six shared electrons. The hydrogens are suppressed in the depiction. In essence, each of these six electrons is free to roam about the ring. This is primarily due to the fact the hydrogens are reasonably easy to substitute with other entities requiring one more bond, a so called substitution reaction. This allows for a myriad of structures to be formed with this simple and basic structure.



5. (a) Depiction of a benzene ring indicating where all of the hydrogen bonds are located, where (b) gives the general symbol for the ring, and (c) is a depiction of a typical azo dye molecule with (d) its effective electrical equivalent and (e) the effective potential that an electron on the ring would see due to other electrons.

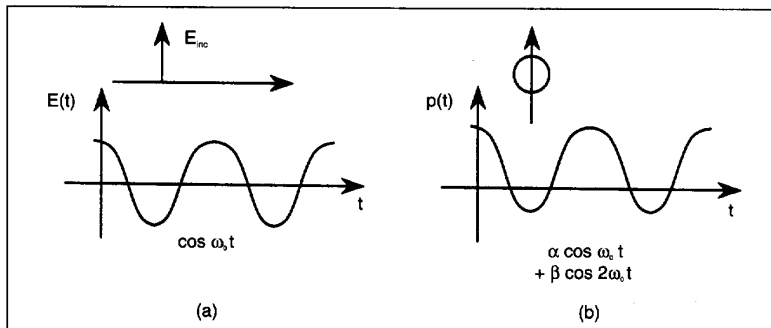
In particular, substitutions on diametrically opposed hydrogens could allow one to form monomers, and connection of the monomers could allow one to form polymer chains. This ability to incorporate dopants facilitated the making of many important semiconductor devices. These dopants are either donors, which have one electron too many to bond; or acceptors, which have one valence electron too few to bond.

Bonding dopants to the ends of our benzene ring is illustrated in Fig. 5c. The electrons in the ring free to move around will need to rearrange themselves to minimize the energy of their configuration. As the acceptor wants to take on an electron and the donor would like to push one into the ring, the negative charge will tend to move up toward the acceptor. This molecule will exhibit a residual electric field, known as a dipole moment.

Figure 5d depicts the permanent microscopic dipole moment. Figure 5e also exhibits the effective potential that an electron within the ring would see. Clearly, this potential is non-centrosymmetric. How would

our dye molecule react to the application of an electric field?

Figure 6 illustrates such a response. An incident electric field in Fig. 6a will cause a change in the dye molecular orientation at the same frequency ω_0 . This is known as the linear electrooptic effect, and is exactly the effect we need to transfer electrical signals onto optical carriers. But Fig. 6 was for a single dye molecule and would be a small effect. We need to have a macroscopic quantity of these molecules. How could we incorporate them into a stable polymer?



6. Electric field (a) excites the electronic dipole moment (b), as seen for a dye in Fig. 5.

There are two ways (Fig. 7). In the guest host arrangement (Fig. 7a), the dye molecules are simply added to the solution with the polymer, previous to processing. In Fig. 7b, the dye molecules are attached to the polymer backbones in a so-called side chained system.

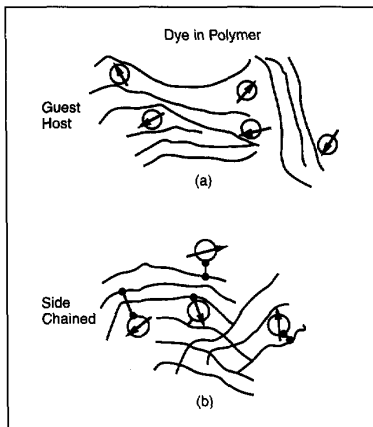
There is a problem, however. The molecules are randomly oriented and, therefore, the electrooptic effect of one will cancel the electrooptic effect from the next. This is a problem with essentially all electrooptic materials, including the commonly used ferroelectric crystals of LiNbO_3 , LiTaO_3 , BaTiO_3 , and so on. The material needs to be ordered, or poled, so that each molecule lacks a center of symmetry along a common direction. The process of "poling" is achieved through raising the material to its glass transition temperature (for crystals it is called the Curie temperature) and then applying an electric field. As the molecules have a permanent dipole moment, they interact with the field through a $\mathbf{p} \cdot \mathbf{E}$ potential. The dipoles, therefore, find it energetically favorable to align as well as they can, given their mobility, with the applied electric field.

We have previously discussed polymer lifetime. A sensitive measure of the aging of the polymer is the degree of poling that they retain as a function of time after the poling. Extensive measurements on different polymer dye systems have led to the results in Fig. 8. Here, the lifetime t , given in seconds, is defined as the time at which the electrooptic coefficient would fall to its $1/e$ point. The data is plotted versus the inverse of $T_g + 50 - T_0$, where T_0 is the temperature at which the polymer is stored. Researchers do not yet completely understand why it should depend on this quantity, and its exact relationship with the theory of relaxation processes [3-4]. Interestingly enough, guest host poly-

| Material | Electrooptic coefficient (pm/V) | T _g or T _c (°C) | Typical Loss dB/cm @ 1.3 μm |
|--------------------|---------------------------------|---------------------------------------|-----------------------------|
| PMMA/DR1 | 13 | 120 | <1 |
| Ultem/DEDR1 | 10 | 180 | <1 |
| LiNbO ₃ | 30 | 1250 | 0.2 |
| LiTaO ₃ | 30 | 650 | 0.2 |
| GaAs | 1 | 600 | >>1 |

mers all fall on a straight line, independent of composition, and for values of the independent variable less than about 0.09, with lifetimes measured in years. Thus, as long as guest host polymers are stored (or operated) at least 55 degrees below their glass transition temperatures, they will have sufficiently long lifetimes. The side-chained systems have roughly the same lifetime breakpoint, but have much steeper slope, indicating longer lifetime than the guest hosts in the temperature regime of interest. Even for military specifications, where operation is specified up to 125°C, glass transition temperatures need not exceed roughly 200°C. Numerous polyimides exist with such characteristics.

To date, various dyes have been doped into various acrylates and polyimides. The polymers demonstrated to date still have lower electrooptic coefficients than LiNbO₃ (30 pm/v), but there is really no fundamental



7. Depiction of how the dye molecules sit in a polymer matrix before the poling process (a) for a guest host system and (b) a side-chained system.

reason that these values cannot be greatly improved by substituting different dye/polymer systems.

Present-Day Applications

Perhaps the easiest way to talk about progress toward achieving a useful interconnect is to first present some results obtained in our laboratory, and then quote some other results from the literature.

One topic we have not yet discussed at any length is channel formation. We have chosen bleaching technology as our channel forming technology. Bleaching works much the same way as the bleaching of clothing. The little dipoles of Fig. 7 are, as previously discussed, dye molecules. Indeed, the unbleached polymers we work with appear to be quite colorful before bleaching, and reasonably clear after. In our bleaching process, we mask off the parts of the polymer that we want to be guiding, and then expose the polymer to the light of a broadband lamp with a significant portion of its energy lying in the blue/green portion of the optical spectrum. Exposure to such light through absorption excites molecular transitions.

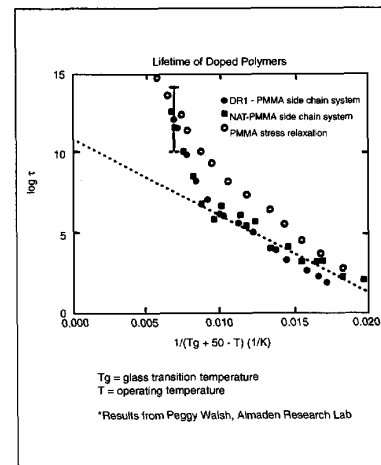
Somehow, a combination of generated heat and molecular oscillation breaks up the dye molecules. As the dye molecules have large dipole moments, their presence raises the optical index of refraction. Without them, the index is lowered and therefore the bleached regions form waveguide claddings.

Some results for losses in channel waveguides formed by bleaching are given in the Table. We have results for 2 polymer systems, one a polymethylmethacrylate (PMMA) side chained with an azo dye called DR1. This compound has a T_g of 120° and an r = 13 pm/v. The second compound is a polyimide with the trade name Ultem,

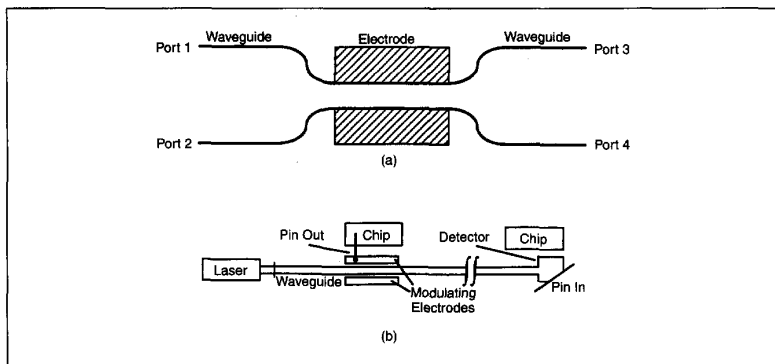
used as a host for a modified version of DR1 called DPDR1 (diphenyl disperse red 1) which has a T_g = 180 °C, and r = 10pm/v. As can be seen, either compound can be bleached to form channel waveguides with losses less than 1 dB/cm at 1.3 μm. There are many different technologies to form waveguides, but bleaching is a totally planar one, that is, one that requires no etching or redeposition and therefore one that is most amenable to the process of forming multi-layer structures.

What kind of structure do we want to use to modulate? It would be aesthetically pleasing if we could limit ourselves to one structure plus waveguides, much like VLSI circuits limit themselves to FET's and wires. Certainly, a candidate structure is the directional coupler of Fig 9. The structure is designed such that light incident at port 1 is transmitted at port 4 without applied voltage, or at port 3 with applied voltage. The structure can be used as a switch or modulator. As a modulator, it has the added advantage that it transmits both signal and complement, allowing for sensitive detection schemes when necessary. Figure 10 illustrates some results on directional couplers in our efforts to obtain so-called "passive" bias. As shown, couplers can be made with reasonably low loss and crosstalk.

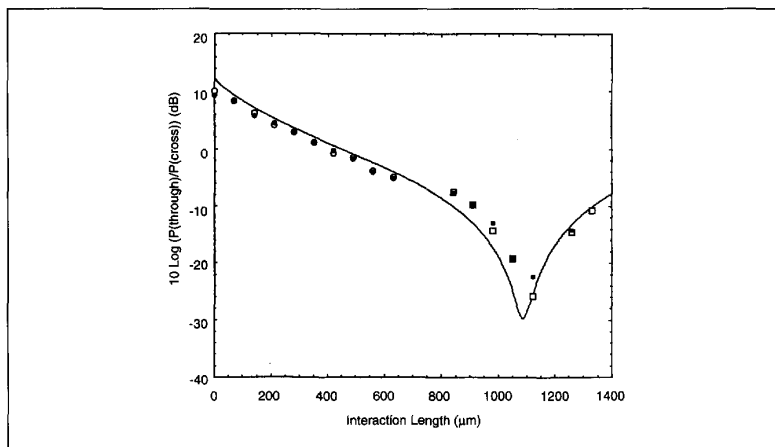
Although we have yet to perform any modulation experiments, it is clear the low index of refraction of the polymer for the electrical wave allows for high speed modulation of the optical wave. Several groups



8. Plot of log polymer lifetime as a function of $1/(T_g + 50 - T)$. Plot courtesy of IBM Almaden Research Laboratory.



9. Depiction of (a) a directional coupler switch and (b) how it would be inserted into a communications link.



10. A plot of experimental values versus a theoretical curve for crosstalk in a passively biased directional coupler.

have reported modulation at up to 40 GHz [5]. Such rates exceed anything presently necessary in electrical interconnect.

More Applications?

Integrated optics in general has been hampered by various, rather inherent problems. Although the promise is great, single device demonstrations do not necessarily indicate that the advantages will be so compelling upon system insertion, especially highly advanced digital systems where painstaking effort has allowed for the development of standard solutions which allow for bit error rates (BER's) below 10⁻¹⁵ with multi-year reliability. One does not want to radically change such a technology overnight. As soon as one mentions integrated optical technology, the digital engineer will bring up the issues of material compatibility, alignment tolerance, and system insertion loss.

As has been discussed, polymer materials similar to the electrooptic ones we are using are already in use in electronics. This is a clear indication of their compatibility with present-day electronic and electronics packaging. Perhaps a major reason for this is that polymers "give." That is, even though they do not have the same thermal expansion coefficient as their host, they will not fly off due to a temperature change, whereas a ferroelectric crystal such as LiNbO₃ might.

The issue of alignment tolerance is even more serious than material compatibility. Single mode optical waveguides tend to be well less than 20 μm in diameter; therefore, alignment tolerance is less than 1 μm. Striplines tend to be tens of micrometers in width (to achieve reasonable propagation loss), allowing for almost an order of magnitude larger alignment tolerance. In addition, manufacturing lines for electronics

tend to be big and expensive and they do not achieve any tolerances they do not have to.

We can, of course trade off loss for tolerance. By flaring the ends of waveguides and effectively increasing the spot size, we can decrease tolerance, but at the cost of a constant loss per coupling. This leads us to our next consideration.

Engineers do not want to see high loss in interconnect lines. Electronics can be dense. Amplifiers cannot be as dense due to both component count and heat dissipation. It would be ideal if optics were totally transparent to these electrical signals. Perhaps this is not so impossible. Incorporating rare earth elements into optical fibers has advanced optical amplifier technology. Rare earths, however, can be doped into most any host, if only the technique of insertion can be found. Indeed, integrated optic lasers have been demonstrated in glass, and optical amplifiers in LiNbO₃. Quite recently, optical gain has been reported in a polymer. Perhaps we are nearing the era of transparent optics.

A bright future in plastics? Only the future can tell, but I am hopeful, as ever. After reading this article, I hope you are too. **CD**

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