UNCLASSIFIED

1999

Unclassified

Electro-optical Polymer Technology

By

Charles Lee, AFOSR

William Steier and Larry Dalton, University of Southern California

Harold Fetterman

University of California, Los Angeles

Unclassified

Abstract

Because of ease of processing and low dielectric constant, electrooptical polymer is considered as a technology that is capable of fabricating low cost, complex structure high speed electrooptic devices. Over 100GHz modulation has been demonstrated. With the continuing improvement in electrooptical coefficient, EO modulators with drive voltage below 1V can be achieved in the near future. Using spincoating and photolithography techniques, complex electrooptic device structures have been demonstrated.

UNCLASSIFIED

-Example of Device Quality EO Polymer-
FTC Molecule Attached to a Thermo-set Polyurethane
Di-link System (TS-PU-FTC)

FTC Chromophore

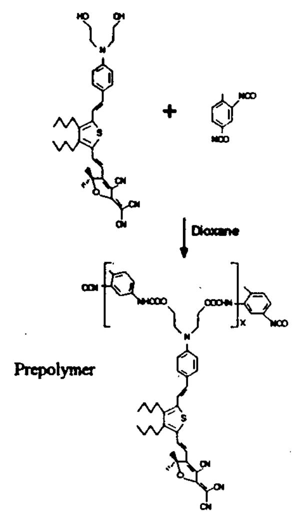
$\mu\beta$ = 17,000 X 10^{-48}esu@1900nm
r_{33} = 55 pm/V @ 1060 nm in PMMA guest host system(20 wt%).
Chromophore T_d >300°C

TS-PU-FTC

FTC + TEA $\xrightarrow[\text{Dioxane}]{}$ TS-PU-FTC

r_{33} = 40 pm/V @ 1060 nm

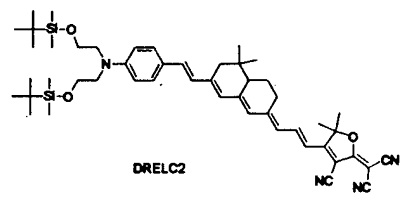
r_{33} = 25 pm/V @ 1300 nm in devices



Polymers with electro-optic (EO) properties have been under development for several years. EO polymers require highly optically nonlinear chromphores which can be incorporated into a polymer host, aligned by a poling electric field, and finally hardened to maintain the alignment. One of the most promising of the new electro-optic polymers developed in Dalton's laboratory uses a high $\mu\beta$ chromophore based on a novel tricyanobutadiene acceptor incorporating a furan-derivative ring, FTC (2-dicyanomethylen-3-cyano-4-{2-[*trans*-(4-N,N-diacetoxyethyl amino)phenylene-3,4-dibutylthien-5]vinyl}-5,5-dimethyl-2,5 dihydrofuran). The furan ring plays an important role in keeping the conjugation planar and stabilizing the acceptor end of the chromophore. Also, the two methyl groups on the heterocyclic (oxygen) ring and the two butyl groups on the thiophene ring should prevent the large dipolar chromophores from aggregating which is caused by strong electrostatic interactions in most of the high mb chromophores. The interaction between the chromophores may reduce the achievable EO coefficients. The FTC chromophore when doped into a PMMA host has an r_{33} " 55 pm/V @ 1060 nm. To produce a device quality material with good thermal stability the FTC was incorporated into a thermal-set polyurethane system. The FTC chromophore is mixed with toluene diisocyanate (TDI) in a solvent and heated to attach the NCO groups to the OH groups. Next, the crosslinker, triethanolamine (TEA), is added which acts to form a three dimensional network during the precuring and final hardening during poling. Excess TDI and TEA can be added to control the density of chromophores

Recent Advances in EO Polymer Synthesis
-Record High High r_{33}-

- **The DRELC2 Chromophore**



DRELC2

λ_{max}(dioxane) 664 nm
λ_{max}(chloroform) 719 nm
T_d 267°C

- **EO Coefficient, r_{33} (PMMA host polymer @ 20 wt%)**
  90 pm/V @ 1060 nm (measured)
  63 pm/V @ 1300 nm (extrapolated)
  54 pm/V @ 1550 nm (extrapolated)

HIGHEST YET REPORTED

- **Now being incorporated into hardened fluorinated host polymer for device applications**

This is an example of a new class of promising electro-optic chromophores being developed by Dalton. The electro-optic coefficient has been measured for the chromophores doped into a PMMA host polymer. The r_{33} coefficient measured at 1060nm of 90 pm/V is one of the highest numbers yet reported for an EO polymer. From the known wavelength of the absorption maxima of the chromophore, this EO coefficient can be extrapolated to other wavelengths of interest using a simple two level model. This extrapolation gives 63 pm/V @ 1300nm and 54 pm/V @ 1550nm; two important tele-communication wavelengths.

The important next step is to co-valently incorporate the chormophore into a stable and hardened polymer host. Fluorinated host polymer are now under development.

The EO coefficients for these newest polymers are now larger than $LiNbO_3$ and come close to making possible an optical modulator with V_π under 1V.

OPTO-ELECTRONIC APPLICATIONS WHERE POLYMERS HAVE INHERENT ADVANTAGE

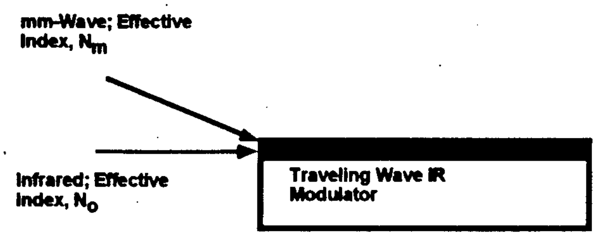
- **Wideband, traveling wave infrared modulators operating at 100 GHz and above;[n(opt.) - n(mmwave)] is relatively small**
- **Heterogeneous integration with pre-processed VLSI to achieve wideband, high speed opto-electronics**
- **Heterogeneous integration of passive and active (electro-optic, amplifiying, etc.) polymer materials for multi-functional intghregrated optics.**
- **In-situ trimming of photonic components to meet specific specifications (wavelength, balance, etc.)**
- **Potential for low cost.**

Polymers offer some unique advantages over other materials for opto-electyronic applications. The interest stems from their possible large electro-optic coefficients, their relatively low dispersion in the index of refraction in going from infrared to millimeter-wave frequencies, their potential ability to integrate easily with other materials, and their potential for low cost.

The first advantage listed will be discussed in the following slide. The second advantage of polymers as electrooptic materials is that they can be deposited onto and will adhere to many substrates including semiconductors. This makes possible a significant step forward in opto-electronic integration. A material with large EO effects and good optical quality can be integrated on the same substrate with the high speed drive and signal processing electronics. The third advantage is the ability to integrate the active polymer materials into an optical circuit which includes other optical materials. The key technology lies in the ability to fabricate low loss vertical waveguiding structures in the polymers, which can interconnect multiple layers in optical integration.

Finally, we have demonstrated that polymer integrated optical components can be in situ trimmed by photo-bleaching to achieve specific design specifications. For example, waveguide couplers or Y junctions can be trimmed to specs and the bandpass wavelength of WDM filters can be tuned.

Bandwidth limitations in high speed traveling wave electro -optic modulators due to velocity mismatch in the material



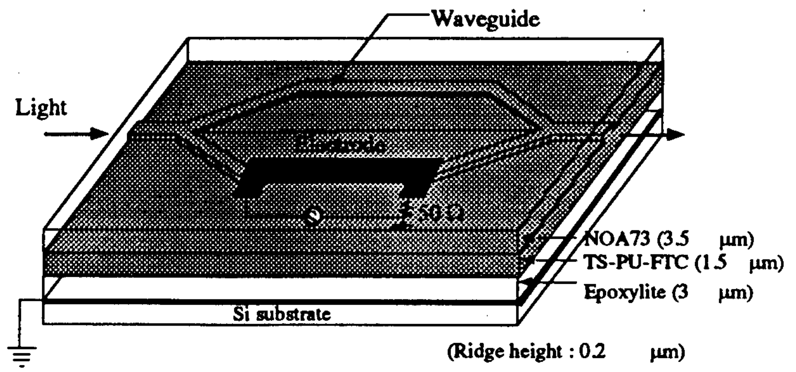
Because of velocity mismatch, the mm-waves and the IR slip out of phase

$$\Delta f_{3dB}L = 1.4c/\pi[N_o - N_m]$$

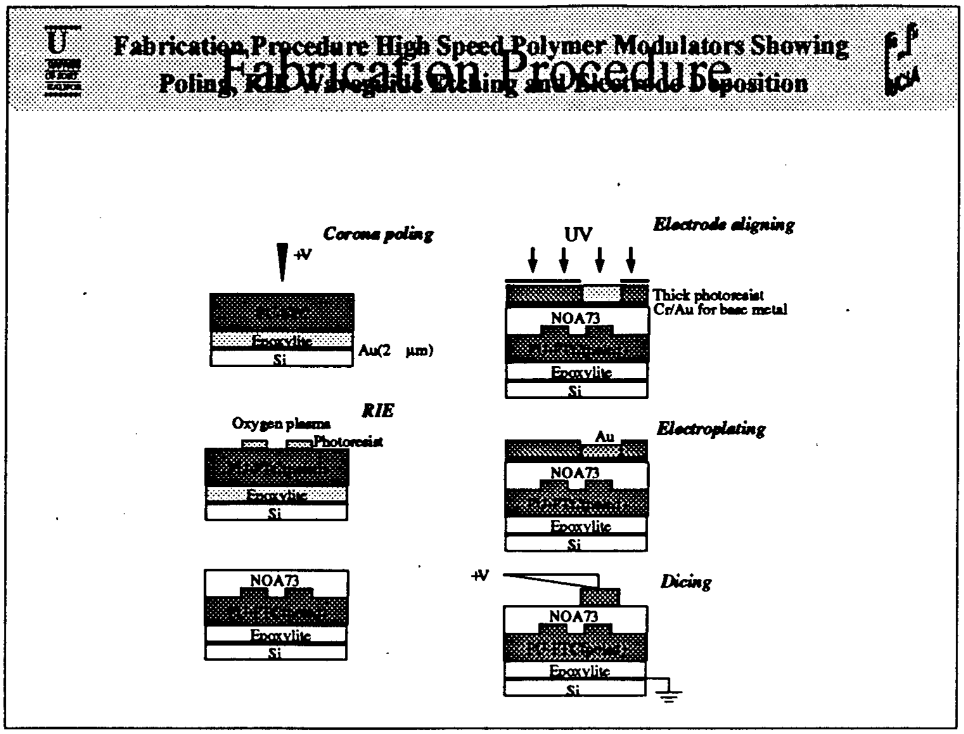
LiNbO$_3$	**EO Polymer**
$n_{dc} = 5.29$	$n_{dc} = 1.82$
$n(1.3\mu m) = 2.2$	$n(1.3\mu m) = 1.75$
$\Delta fL = 4.5$ GHz-cm	$\Delta fL = 190$ GHz-cm

For very wide band, high frequency operation the EO modulators must be traveling wave devices and therefore the issue of maintaining a velocity match between the optical wave and the mm-wave becomes important. The maximum interaction length is set when the two waves slip π out of phase. Since the dielectric properties of the polymers are all electronic in nature, n(opt) ~ n(mmwave) and a phase match can be maintained over a reasonable length in a simple structure For example at 100 GHz the polymer modulator can still be ~2 cm long while the $LiNbO_3$ device is limited to ~1mm. Successful LiNbO3 modulators have been demonstrated at over 70 GHz using clever velocity matched structures to increase the interaction length. Using standard strip line and optical waveguide technology we have demonstrated a polymer modulator over 1 cm long with high overlap integral operating to 113 GHz. The close phase match comes about essentially because of the relatively low dielectric constant of polymers as compared to crystalline ferroelectrics. The low dielectric constant may make it possible to locate several individual high speed modulators close to one another without causing degrading rf crosstalk between the modulators.

Polymer High Speed EO Modulator Structure



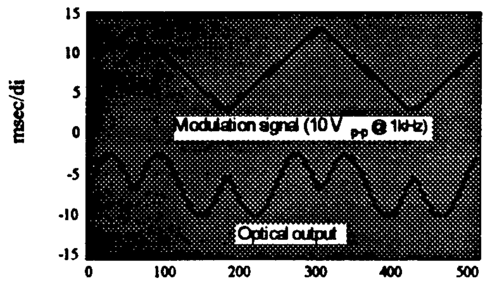
High speed modulators combine a traveling wave optical Mach Zehnder interferometer and a high speed traveling wave microstrip line circuit. For vertical confinement in the optical waveguides, a triple stack structure composed of the lower cladding, core EO polymer, and upper cladding is used. Lateral optical confinement is achieved by a rib structure etched by RIE on the core layer. Epoxylite 9653 (n=1.54 @ 1300 nm) was used for the lower cladding and a UV curable epoxy, NOA73[13] (n=1.54 @ 1300 nm), was chosen for the upper cladding. NOA73 has good adhesion to the metals used for the upper electrode (Cr and Au) and it can be rapidly UV cured. In the typical device, the waveguide rib width is 6 μm, the core layer thickness is 1.5 μm, and the rib height is 0.3 μm. The thickness of the lower and upper claddings were set at 3 μm and 3.5 μm, respectively, to keep the optical loss due to the electrodes small. The length of the arms of the interferometer where the modulation interaction occurs is 20 mm. and the length of the linear Y-branch transition is 3 mm at each side.



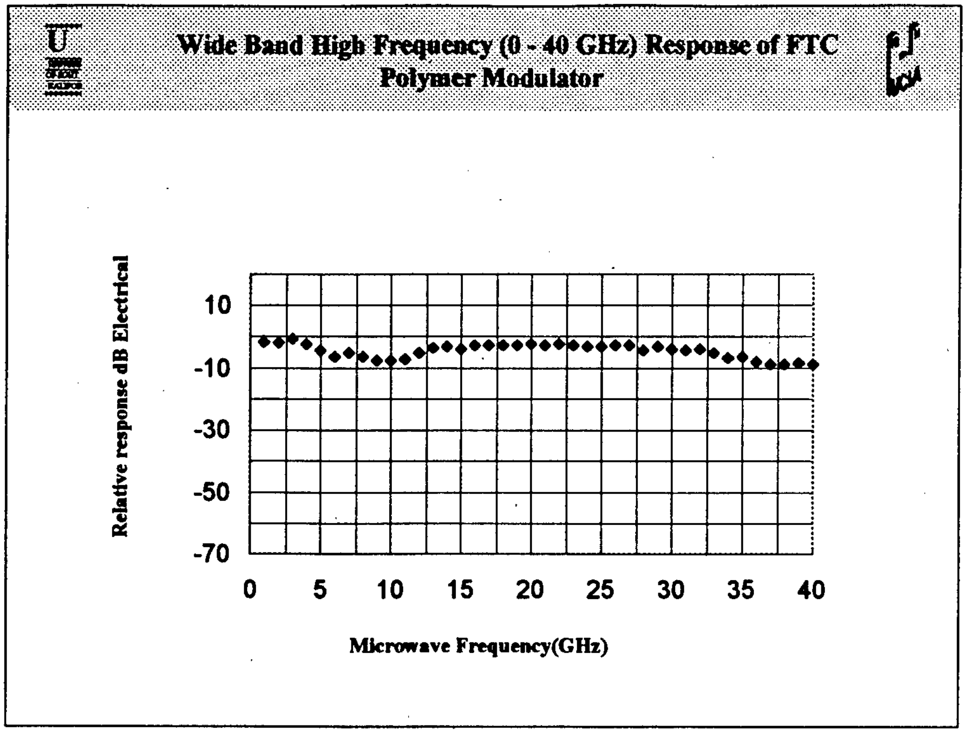
The steps for the fabrication of a typical polymer modulator are shown. This includes corona poling of the EO layer to achieve the required alignment of the chromophores. The material is hardened by the thermo-set process as the poling is in progress. The ridge waveguide structures are fabricated by RIE in an oxygen atmosphere. Thick upper electrodes for the micro-strip line structure are required to keep the mm-wave losses low. As the final fabrication step, the end faces were prepared for butt coupling to a fiber by dicing with a nickel blade.

Measured Low Frequency Response of TS-PU-FTC Mach Zehnder Amplitude Modulator at 1300 nm

- $V_\pi = 4.5$ V at 1.3 µm $r_{33} => 25$ pm/V
  - V_π ranges from 4.5 V to 5.5 V across wafer



To measure the performance of the modulator, TM-polarized light at 1310 nm was butt-coupled into the device through a single mode fiber and the output light was collected by a microscope objective lens and focused onto a photodetector. The figure shows the response of the modulator to a low frequency sawtooth wave electrical signal to measure, V_π, the voltage required to turn the modulator from full on to full off. The measured V_π was 4.5 volts, which corresponds to an r_{33} of approximately 25 pm/V with an effective field-overlap integral factor of one. This is consistent with the r_{33} value measured at 1060 nm on test samples. Eight modulators are fabricated on a single substrate and the V_π ranged from 5.5V to 4.5V. The extinction ratio, the ratio of the light power out during the on state to that of the off state, was measured to be 18 dB.



The variation of the modulator response from very low frequency out to 40 GHz is shown in the figure. The modulator should remain velocity matched to frequencies greater than 100 GHz as we have demonstrated in our earlier work. The increased rf loss due to the upper electrode may become a factor at 60 GHz or greater. We believe the ripples in the response shown are due to impedance mismatches at the input and the output.

These modulators using the TS-FTC polymer demonstrate some of the advantages that EO polymers have long been promising. The V_π is low enough for systems interest and the frequency response is well into the millimeter wave range.

Photograph of the packaged FTC modulator

Packaging done by Y. Shi, TACAN, Inc.

The packaged polymer modulator is shown with fiber connectors and rf input and output. This packaging was done by Y. Shi at TACAN, Inc.

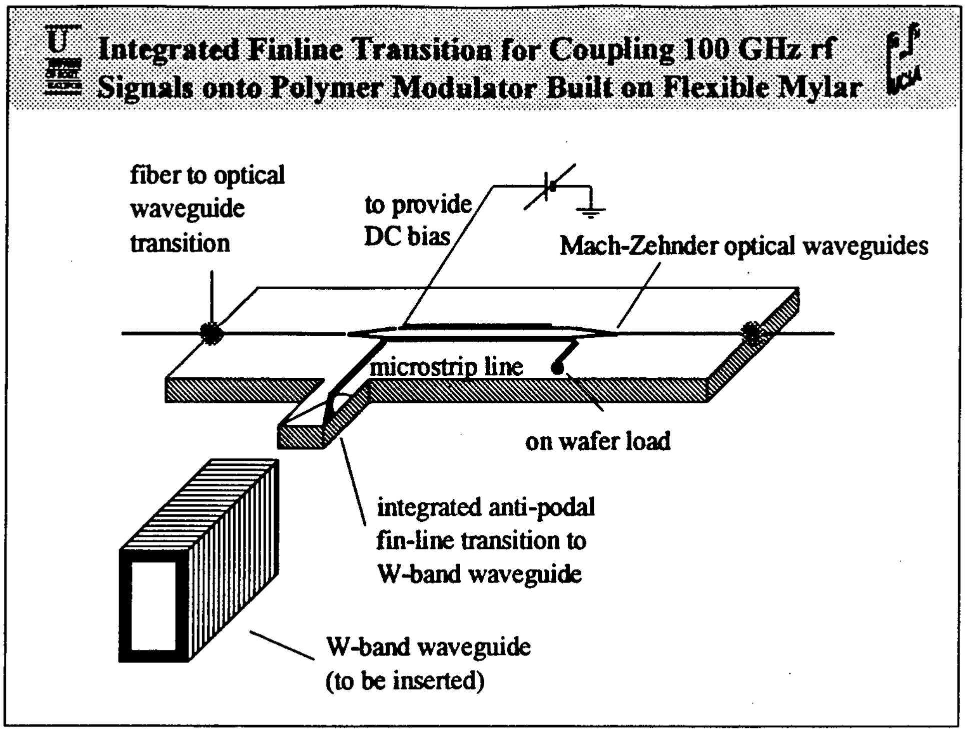
NEXT GENERATION OPTO-ELECTRONIC POLYMER DEVICES AND INTEGRATION

★ Next generation of opto-electronic polymer devices
- 100 GHz modulator
- Opto-electronics on flexible substrates
- Polymer RF photonic phase shifter.

★ Higher levels of integration in opto-electronic using polymers
- Integration with Si electronics and laser sources
- New approach for the integration of passive and active polymers in integrated photonic circuits.

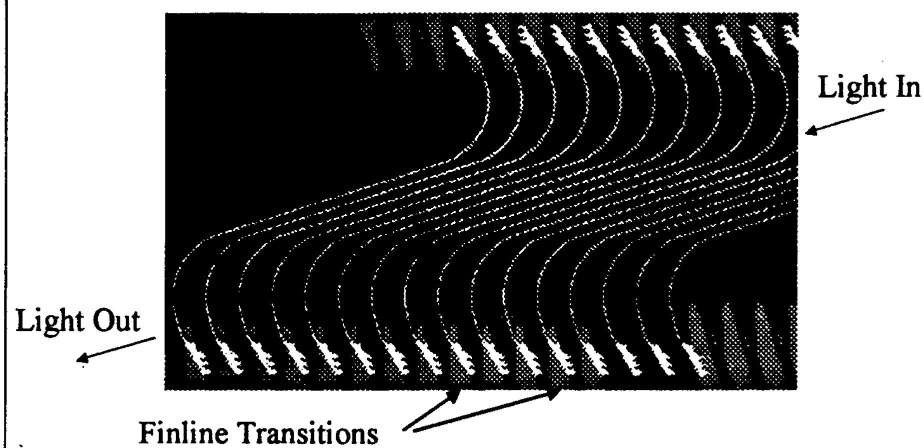
The next generation of opto-electronic devices must take advantage of the inherent material advantages offered by the polymers. We discuss in the next slides the polymer modulator with the integrated finline coupling structure between the millimeter waveguide and the modulator micro strip-line. This device operates up to 100 GHz. It is fabricated on a flexible mylar substrate which opens up new and interesting applications for opto-electronics on flexible substrates which can conform to specified shapes. A more complex polymer opto-electronic device, the photonic phase shifter, is also described.

The potential of integrating several photonic components in the same optical circuit by heterogeneous integration is a very promising advantage of the polymer materials. This is discussed in the following slides.



At modulation frequencies greater than ~70 GHz, the packaging of polymer high speed modulators requires novel approaches. Millimeter wave transmission lines from sources or from antennas at these frequencies are typically rectangular hollow metal waveguides whose cross sectional dimensions are on the order of a few millimeters. In contrast the millimeter wave transmission line in the polymer modulator is a microstrip line. To couple between the two very different types of transmission lines requires novel integrated anti-podal finline transition structure as shown. aThe transition gradually transforms the electric field profile of the rectangular metallic waveguide to that of the microstrip line electrode on the device and effectively couples the microwave driving power into the modulator. This structure must be inserted into the small W-band rectangular waveguide (1.25 mm X 2.5 mm) and therefore the thickness of the substrate must be kept as low as possible. For lower frequency modulators the substrate thickness is not an issue since coaxial rf connectors are used and we therefore typically fabricate the modulators on relatively thick silicon substrates. For the high frequency modulator using the anti-podal finline coupler, the substrate must be a thin dielectric with low microwave loss as well as good electrical, chemical, thermal and mechanical properties.

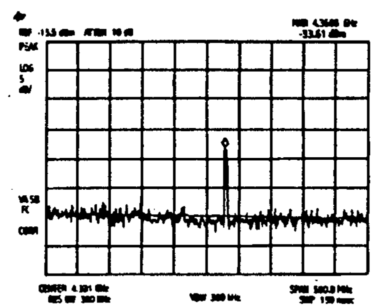
Array of Integrated Finline Polymer Phase Modulators On Mylar Substrate



This figure shows the array of phase modulators. The particular finline transition region to be inserted into the rectangular waveguide was separated from the array and the polymer layers on the lower finline transition pattern removed using a solvent that was locally applied. The transition was then inserted into the waveguide. The ridge waveguides cannot be seen in this photograph.

In this modulator we used an amino phenylene isophorone isoxazolone (APII) chromophore developed in Dalton laboratory. The chromophores are incorporated into a crosslinked polyurethane thermosetting network similar to that used with the FTC chromophore. The optimum loading density of the APII chromophore in polyurethane thermoset is 40 wt. %, which is much larger than corresponding values for other high $\mu\beta$ chromophores.

95 GHz Response of Finline Polymer Modulator



The performance of these integrated finline coupled modulators was measured using an optical heterodyne technique. This technique involves mixing of the modulated output of our device and the output of a tunable laser that is set at a fixed frequency away from the center frequency of the modulated laser beam. This effectively down converts the millimeterwave modulation frequency by the difference frequency between the two lasers. The frequency measured by the detector is therefore much lower and thus alleviates the need for a detector which can respond to millimeterwave frequencies. The figure is the spectrum analyzer trace of the down converted signal at 95 GHz. These modulators were configured as birefringence modulators and had a V_π of 16V. Since birefringence modulators rely on the difference in the EO coefficients (r_{33} - r_{13}), if we assume the usual condition that $r_{33} = 3r_{13}$ this material should have a V_π of ~10 V in a Mach Zehnder configuration.

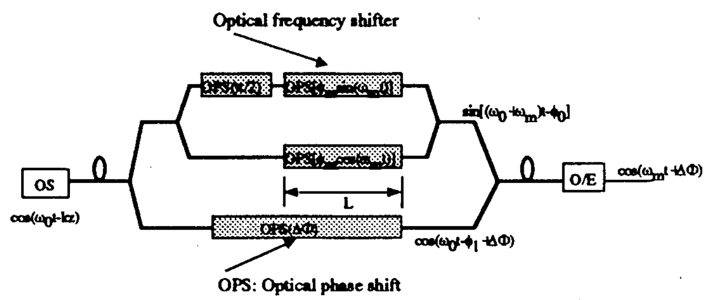
Potential for Polymer Integrated Optics on Flexible Conformable Substrates

- Passive and Active Polymer Integrated Optics on Flexible Mylar Substrates
- Applications:
  - Polymer opto-electronic circuits attached directly to rf antenna - conform to antenna shape
  - Conform integrated optical circuits to shape of collecting optics
- Issues
  - Waveguide bending loss
  - Micro-cracking due to bending
  - effects of bending on EO poling

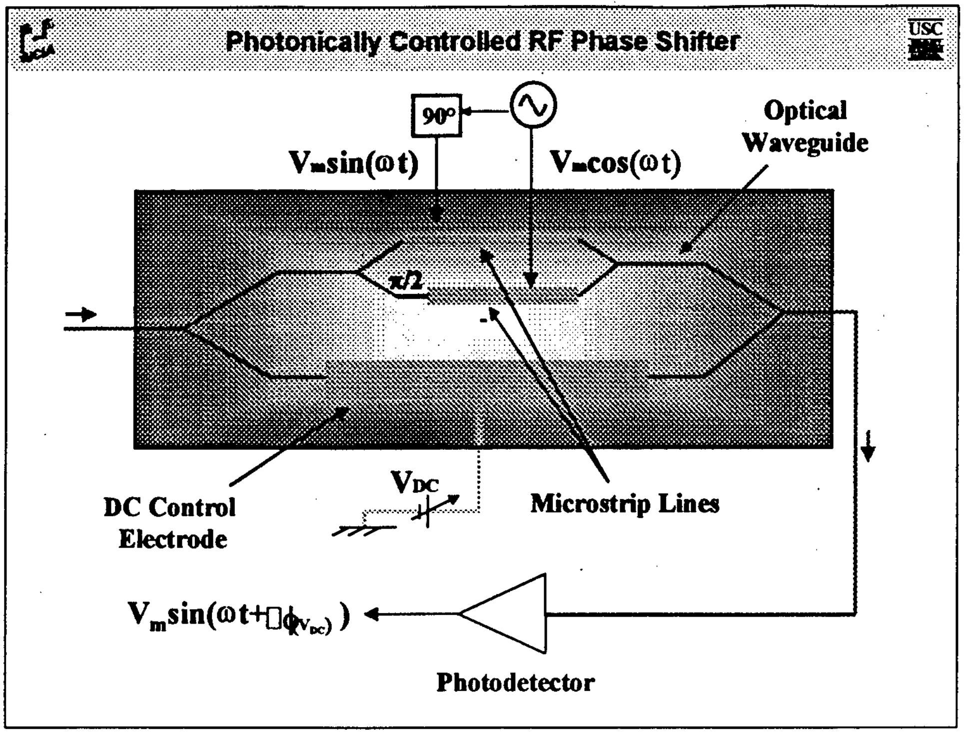
The fabrication of polymer EO modulators on thin flexible substrates such as Mylar means that the modulator to some extent can be molded to fit a curvilinear surface. This opens some new possibilities for polymer modulators and polymer integrated optics in applications where the optical circuit might be molded to fit some specified contour such as that of a receiving antenna.

Polymer Photonic RF Phase Shifter

- Simultaneously modulates rf signal at ω_m onto infrared carrier at ω_o and controls the phase of the modulation with a control voltage on the phase shift electrode.
- Phase of rf signal at ω_m is shifted by the optical phase shifter.
- Applications optically controlled rf systems - phased array antennas



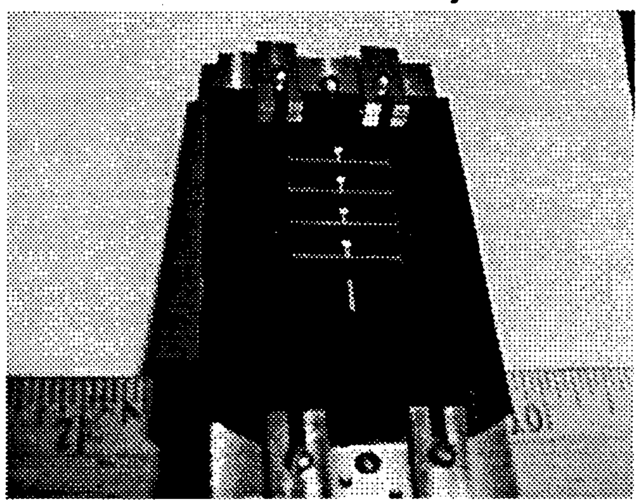
The fabrication of polymer integrated optics devices is a spin technology which can cover large areas and uses relative inexpensive substrates, typically silicon. This means that relatively large area and complex integrated optical circuits and devices can be built with relatively low cost using the polymer technology. As an example of a complex active waveguide device using polymers we have recently demonstrated a wide band millimeterwave photonic phase shifter. Photonic millimeterwave phase shifters will play a key role in large phased array antennas. Phased array antennas are composed of a large number of radiating elements with the phase and amplitude of the radiation from each element under independent control. By varying the phase and amplitude, the pattern of the array can be electronically scanned or its radiation patterned modified to avoid unwanted signals. The ideal phase shifter should be voltage controlled, broadband, and lightweight. A very promising approach to delivering these controlled signals to each antenna is the use of low loss optical fibers. The millimeterwave signal is modulated onto an infrared carrier and transmitted by fiber to the antenna where an optical detector recovers the millimeterwave signal, which is then radiated by the antenna. The fibers have the advantage of very low loss, very low weight, and possible use of low noise optical amplifiers. The photonic phase shifter that we have demonstrated in the EO polymer combines into one unit the modulator and the millimeterwave phase shifter.



The figure is a schematic of the photonic phase shifter which is composed of a Mach Zehnder interferometer within a Mach Zehnder interferometer. The millimeterwave signal is applied to each arm of the upper interferometer but with a 90° phase shift between the signals. If the amplitude of the drive signals is small, the frequency of the output of this interferometer is the infrared carrier frequency shifted by the rf frequency. A dc phase control voltage is applied to other arm of the complex interferometer. The phase of the rf modulation on the infrared carrier at the output is now controlled by the magnitude of the dc voltage. This device performs two functions; it modulates the rf on to the infrared beam and it controls the phase of that modulation.

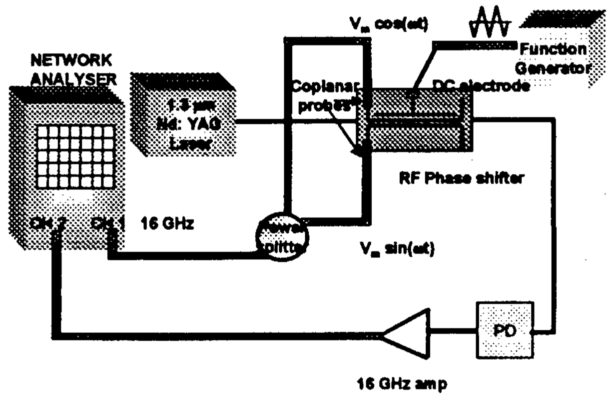
Photonic RF Phase Shifter Fabricated using New EO Polymers on Si Substrate

Four devices in array



The figure is a photograph of the phase shifter; four devices were fabricated on each silicon substrate. We fabricated a polymer phase shifter using the same rib waveguide technology used to fabricate the Mach Zehnder amplitude modulator discussed earlier. The EO polymer contained the CLD2 chromophore synthesized in Dalton's laboratory. This high $\mu\beta$ chromophore is similar to FTC except the thiophene moiety is replaced with a diene moiety. When covalently incorporated into a crosslinked polyurethane network the measured EO coefficient was 45 pm/V @ 1060 nm. The length of the electrodes was 16 mm and the V_π was 7V. The total length of the device was 45 mm.

Experiment to Demonstrate Polymer RF Phase Shifter at 16 GHz and 1300 nm



Input to the DC electrode :-
- **50 Hz triangular wave**
- **Peak to peak voltage :-7.8 Volts**

Phase of the microwave signal at the output of the phase shifter:-
- **Near linear dependence with voltage on DC electrode**
- **Peak to peak phase change :- 108.1°**

The properties of the phase shifter were measured at a wavelength of 1310 nm and a rf frequency of 16 GHz. A low frequency sawtooth waveform was applied to the control electrode and the rf phase measured by a network analyzer. The figure shows the results. In the ideal phase shifter the phase is linearly related to the control voltage. The results shows that the phase is close to linear with some deviation at higher voltages. With an applied voltage of 7.8V, the phase of the 16 GHz modulation could be shifted by 108°.

Higher Levels of Integration in Opto-Electronics Using Polymers

A. Integration with Si Electronics
   - Demonstrated hybrid integration of low speed driver integrated electronic driver circuit with array of polymer modulators.
   - Now extending the technology to 2.5 GHz integrated circuits

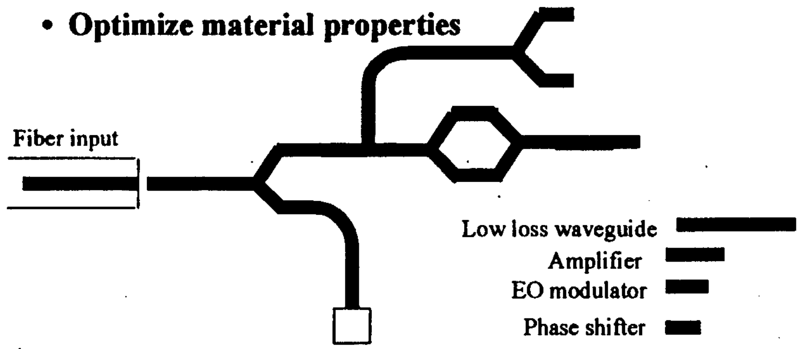
B. Integration with Diode Laser Sources
   - Demonstrated hybrid integration of 980 nm laser with polymer photonic circuits.
   - Critical issue is optical mode matching for low loss coupling.

C. Integration of active and passive polymer photonic circuits.
   - Work reviewed on next slides

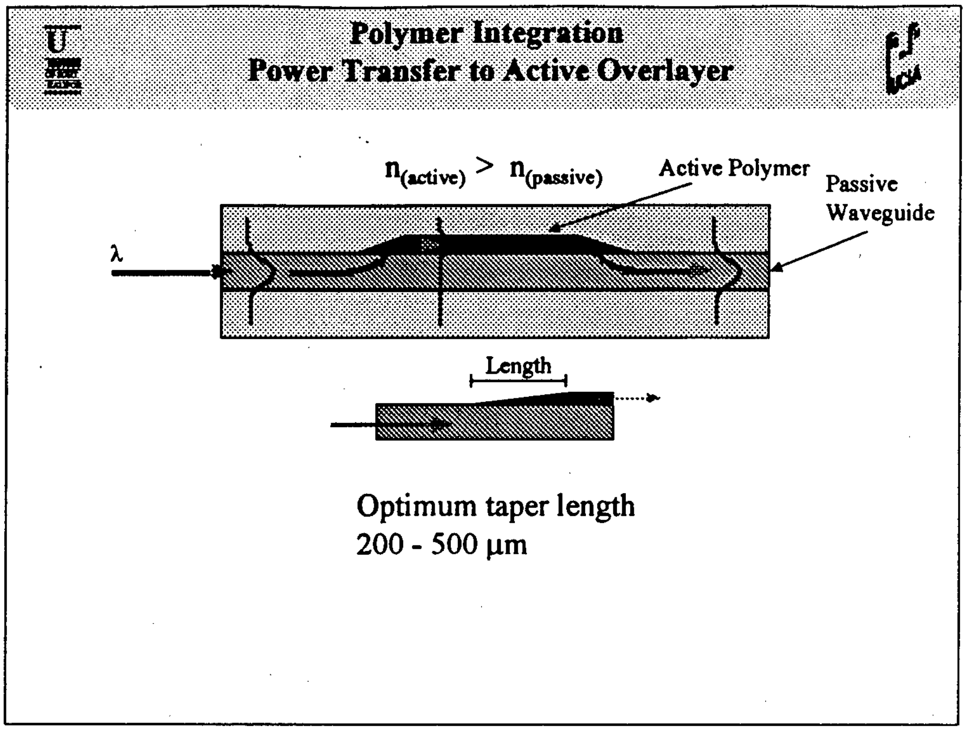
There are well established and highly developed VLSI semiconductor foundries from which one can have fabricated state of the art high speed integrated semiconductor electronic circuits built to your design. This technology could now become available for high speed optoelectronic circuits by developing the techniques of fabricating the polymer optical switch/modulators and other polymer integrated optical devices onto the Si or GaAs substrate which already contains the control, drive, and interface integrated electronics. The final steps of interconnecting the polymer optical devices with the electronics, attaching fiber inputs, and final packaging must be done using fabrication techniques compatible with the polymer and the semiconductor devices. The integration of the well developed existing semiconductor foundry technology with the high potential of the polymer optical devices opens up a promising new approach to high speed optoelectronics. We have demonstrated heterogeneous integration of a low speed (1 MHz) electronic clocking circuit with an array of polymer switches. We are now expanding that work to demonstrate an integrated a 2.5 GHz electronic VCO and a polymer modulator. In earlier work we have shown that high speed electronics can be protected during the polymer poling process and that low loss waveguides can be fabricated on top of pre-processed electronics. We have also done an initial demonstration of the integration of a laser diode with polymer waveguides. In this case the critical issue is the mode matching between the laser and the waveguide.

Integration of Active Waveguide Devices with Low Loss Passive Waveguides Using Polymers

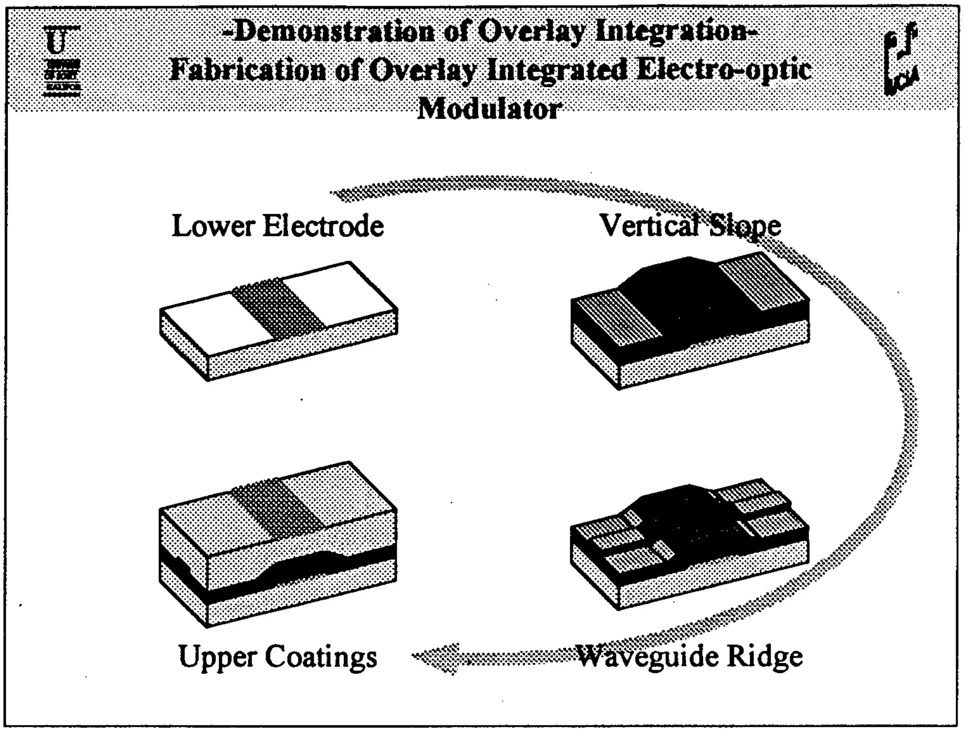
- **Place active material (amplifiers, modulators, phase shifters) where needed in complex low loss waveguide circuit**
- **Solving the mode match and reflection problem**
- **Solving the fiber match problem**
- **Optimize material properties**



One of the advantages of the optical polymer technology is the ability to use different types of polymers within the same integrated optical circuit to perform specific functions. For example electro-optic polymers or light amplifying polymers could be integrated with low loss passive polymers which provide the low loss interconnections. Polymers which have been specifically designed for very low optical loss have been demonstrated in waveguides with losses as low as 0.1 dB/cm @ 1310nm. On the other hand, polymers specifically designed for high electro-optic coefficients inevitably have higher loss. It is very difficult or impossible to achieve both very low loss and very high EO coefficients in the same material. In complex or large integrated optical circuits it would be advantageous to place the active polymer only in the portions of the circuit where it is required and thus minimize the transmission loss.



While the adhesion and patterning problems in achieving the wedding of different polymers can sometimes be difficult, the greatest difficulty is often in achieving an optical mode match between the waveguides made from the different polymers. The optimum optical mode pattern in the passive waveguides is typically nearly circular while that in a modulator is a relatively flat ellipse. This mismatch in shape and the difference in the index of refraction of the two polymers means the two waveguides cannot be simply butted together without suffering significant reflection and radiation loss at the junction. The use of the third vertical dimension provides a promising method to integrate different polymers while easily solving the mode match problem. In this approach, the interconnect waveguide pattern is first fabricated in a low loss passive polymer system. The active polymer is then placed on top of this layer and patterned into the area where needed. Vertical coupling structures are then fabricated to channel the light up into the active polymer and then back down again into the passive waveguides. We have developed fabrication techniques to provide three dimensional routing to transfer the beam between the passive and active polymer layers. The optimum taper length is a compromise between keeping the radiation loss in the taper low and at the same time minimizing the length of the taper because of the higher absorption loss of the upper waveguide

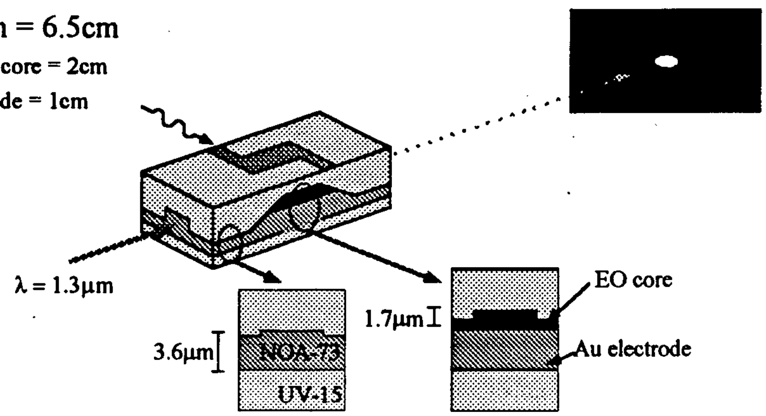


To demonstrate the feasibility of the approach, we have integrated a poled polymer modulator with passive polymer waveguides. The design of the polymer modulator integrated on top of a passive waveguide is shown in the figure. The passive waveguide was designed to provide a close mode match to the standard 9 μm core fiber for fiber coupling. The critical fabrication technology is the etching of the vertical taper that was designed to adiabatically couple light to the higher index upper core layer which is made of a poled electro-optic polymer. Vertical tapers can be reactive ion etched in O_2 and CF_4 either directly by shadow masks or through intermediate patterned photoresist layers. These techniques can create vertical slopes whose height can be accurately controlled from 1 - 15 μm and whose length can be set from 100 - 2000 μm.

Experimental Results: Integrated Modulator Performance

Total length = 6.5cm

- Active core = 2cm
- Electrode = 1cm



- $r_{33} \approx$ 12pm/V @ λ = 1.3μm observed phase modulation
- Taper transition loss ~ 1dB scattering loss

The figure shows the final device dimensions and scaled cross-sections of the passive and active waveguide segments. The passive core and cladding layers consisted of NOA-73 and UV15LV, respectively. Thermoset polyurethane containing a DR 19 chromophore composed the active upper core. The 6.5cm long devices were fabricated on 3" Si wafers as a substrate. The integrated modulator was operated as a birefringence modulator. The modulation measured corresponded to an electro-optic coefficient of r_{33}=12 pm/V. Both the contrast observed in the modulation and the insertion loss of the device indicated that essentially all of the transmitted light coupled up into the modulator and back down again. Any light that remained in the lower waveguide is highly attenuated by the lower metal electrode. We also measured the insertion loss of several samples with different lengths of passive and active waveguide regions. From the known propagation losses in the two materials, we were again able to confirm that the light couples almost entirely up into the EO polymer and down again. Also from the known propagation losses in the passive and active materials, we were able to estimate the loss in the transition region to be ~1dB. From beam propagation studies we expect the radiation losses in the tapers to be small and therefore believe the loss is due to scattering from the surface roughness of the etch. Better fabrication techniques should reduce this loss significantly.