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UTILITY POTENTIAL OF NONLINEAR OPTICAL POLYMERS FOR OPTICAL TELECOMMUNICATION AND SWITCHING APPLICATIONS

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ABSTRACT This paper attempts to examine the utility potential of polymeric electro-optic devices for applications in optical telecommunication, switching and signal processing. A preliminary study reveals that there exists a great deal of potential in the polymeric devices for applications that require high bandwidth, low loss and integration possibility. Yet further investigations are needed for practical applications: improving thermal stabilities, increasing the electro-optic coefficient to decrease the half wave voltage below 2V, and reducing the optical loss at the wavelength of 1.55μm. It is shown that the modulation bandwidth of polymer electro-optic devices is limited by microwave power loss.

INTRODUCTION

Lightwave transmission systems in the past have employed direct modulation of injection lasers and the time division multiplexing (TDM) scheme. At modulation rates higher than 10Gbps, however, the spectral control of the laser becomes more difficult and power penalties caused by dispersion becomes more important. An alternative approach therefore is to use continuous wave (CW) laser sourses and external modulators instead of direct modulation of lasers.

In future broadband integrated service networks, services like video conferencing, and high quality distributed and on-demand HDTV transmission are likely to be integrated to telecommunication networks. In such cases it might be essential to extend the use of optical fibers in the long haul telecommunication systems to the local area networks including homes and offices. Tens of Gbps switching speed may then be required for these services and the direct modulation TDM scheme may be no longer applicable. Instead, wavelength division multiplexing (WDM) or frequency division multiplexing (FDM) techniques may be required to play a major role.

In Fig.1, for the purpose of illustration, a wavelength division multiplexing scheme having external modulators is shown. Lights emitted from the CW lasers at

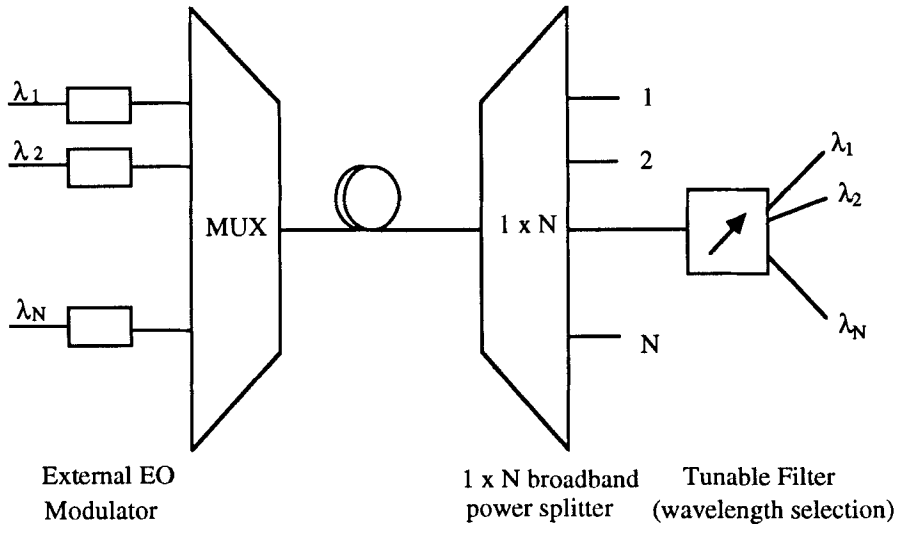

FIGURE 1 A schematic diagram of wavelength division multiplexing scheme with external modulators

slightly different wavelength (~ 10nm spacing) are modulated with the external modultors, and subsequently multiplexed and transmitted through the optical fiber. At the receiving end different wavelengths are demultiplexed and detected by the photodiode.

The required main signal processing functions in the system are as follows: broadband external modulation, power splitting, combining, and wavelength selection. The discret devices can be realized using $LiNbO_3$, III-V semiconductors, or linear and nonlinear optical polymers, and it might be appropriate to examine the competitive characteristics thereof from the system's point of view.

TABLE I Some required specs of the electro-optic modulator for telecommunication

modulation bandwidth	the higher the better
loss	<10 dB
half wave voltage	<2V
extinction ratio	>25-30 dB
life time	30 years

We first consider an electro-optic (EO) modulator. The requirements of the device for the system applications include half wave modulation voltage, modulation bandwidth, loss, extinction ratio, and reliability, and are summarized in Table I. Half wave modulation voltages are required to be lower than 5V, or hopefully 2V, for the compatibility with the existing driving circuit. Total loss of 10dB was deduced from CCITT spec which reguires optical power higher than -3dBm at the transmitting end. CW laser power of 5mW was assumed in the considerations.

STATUS OF POLYMER EO DEVICES FOR TELECOMMUNICATIONS

Many waveguide test devices have been fabricated and their performances have been reported. These include Mach-Zender interferometers[1], directional couplers[2], x-switch[3], thermo-optic digital switches[3], and optical tap for optical interconnections[4]. In principle most of the devices developed for $LiNbO_3$ can be fabricated using electro-optic polymers.

Current status of the device research of the polymer EO modulators are compared with the performances of the current $LiNbO_3$ and GaAs devices in Table II. Development of the $LiNbO_3$ EO modulator is so mature now that the device performance has almost arrived to the theoretical limits. For example, the modulation bandwidth of about 16 GHz with half wave voltage of ±2.25 V and interaction length of 4mm was obtained for the conventional traveling wave type electrode[21]. The $LiNbO_3$ EO modulator with about 10GHz bandwidth and 5V driving voltage is commercially available. Higher bandwidth can be obtained with aperiodic phase reversal electrode[5].

Compound semiconductor multiquantum well waveguides have been actively

TABLE II. Performance comparison of traveling wave EO modulators for different materials

	$LiNbO_3$		Semiconductor	Polymer[1]
	conventional[21]	phase reversal[5]	MQW[6]	
Switching voltage (V)	± 2.25	7.5	2.0	9
Active length (mm)	4	20	0.1	17
Bandwidth (GHz)	16	40	16	20
Extinction ratio (dB)	22	-	20	10
Loss (dB)	-	3.5	6	-

researched recently and high bandwidth about 20 GHz has been achieved[6]. Semiconductor waveguide can be monolithically integrated with another optoelectronic and electronic devices like laser diodes, photodetectors and transistors. However the fabrication of the devices need complicated and expensive processes.

Device research of the polymer EO devics is still in infancy. Yet despite short research period, progress in device research has been impressive. Already 20GHz bandwidth has been achieved[1]. With the optimization of the device dimensions and the fabrication processes the performance of the devices will be further improved. Half wave voltages as low as 4.4V and the extinction ratio of -23dB[7] have also been reported. All of these results indicate strong potential of the polymer waveguide devices for practical uses.

POTENTIALS OF POLYMER EO DEVICES

Since the maturity of the device research is different for different materials, the plain comparison of the device performance at the present status has limited meanings. It would be more informative to compare the potentials and limitations of devices deduced from the basic material properties. In table 3 are shown the material properties affecting the device performance and the device figure of merits.

TABLE III Comparison of some properties of electro-optic materials for wave guide applications

	$LiNbO_3$	GaAs	NLO polymer
ε	16.5	13.1	3.2
n	2.2	3.4	1.62
γ (pm/V)	30.8	1.6	34
tanδ	0.0005	0.002	0.007
CTE(ppm/K)	9.4	5.7	250
(dn/n)/dT (ppm/K)			110
Δf-L (GHz-cm)	10	10	40
	(10)	(80)	(120)
V_π-L (V-cm)	5.6	13	5.4
loss at 1.3μm (dB/cm)	0.3	0.2	0.1
stability	fair	good	?

Modulation Bandwidth Limit

The most significant advantage of the polymeric EO devices over $LiNbO_3$ is the potentially large bandwidth-length product. This large handwidth-length product originates from the low dielectric constant which results in the small velocity mismatch between microwave and optical signals in traveling wave type devices.

If the velocites are different each other the voltage seen at any point along the electrode by a photon that enters the waveguide will change with position and so does the phase shift because the electro-optically induced phase shift is proportional to voltage. In general the velocity of the microwave pulse traveling along the electrode and the velocity of the light in the the waveguide are inversely proportional to the effective dielectric constant and the refractive index of the waveguide, respectively. From this consideration, the bandwidth-length product can be expressed as follows

$$\Delta f\, L = \frac{2c}{\pi\,(\sqrt{\varepsilon_{eff}} - n_{eff})}$$

The resulting potential bandwidth-length product due to the velocity mismatch of the polymer modulator is over 100 GHz-cm which is more than one order of magnitude higher than $LiNbO_3$ modulators. That of GaAs is close to polymer, but the speed of GaAs is severely limited by the high freguency microwave loss described below.

High frequency microwave loss reduces the effective phase shift along the modulator length, which results in the reduction of frequency bandwidth. RF microwave power losses in microstrip line come from three main factors: conductor losses α_ρ, dielectric losses α_ε and leakage losses α_κ[8].

The conductor losses are due to the finite specific resistance of the strip electrode and the ground plan metallization. Dielectric losses are due to the ohmic losses in the substrates (in this case waveguiding materials), and can be described by a dielection loss factor tanδ. Leakage losses are due to the limited conductivity of the waveguiding materials which can be neglected for electro-optic polymer materials. For given electrode dimensions, the total high frequency microwave losses can be described as follows[8].

$$\alpha\ (\mathrm{dB/cm}) = \alpha_\rho + \alpha_\varepsilon + \alpha_\kappa \cong \alpha_\rho^{*} f^{1/2} + \alpha_\varepsilon^{*} \tan\delta\, f$$

where f is the modulation frequency and α_ρ^{*} and α_ε^{*} the frequency independent constants depending upon electrode dimensions and material properties. With typical

values for EO waveguide devices (ε_{eff} =3.2, tanδ=0.007, gold electrode material, w/h=2, t/h=1 in Fig.2), α_p* and α_ε* are 0.4 and 0.8, respectively, with f in GHz. Bandwidth-space product due to the RF losses, which is defined as the frequency for which integrated phase shift is reduced by 50 percent relative to low frequency, is about 40 GHz cm .

In III-V semiconductors, major contribution to the microwave loss is the leakage loss which depends upon doping concentration in the semicontuctor. The p-i-n type microstrip modulators on n^+-GaAs substrate suffer from high microwave loss and dispersion, limiting its -3dB bandwidth to 10 GHz-cm. By adopting the schottky barrier symmetric coplanar modulators on semi-insulating substrates, bandwidth in excess of 20 GHz was obtained. However, electrode length is still short with 4mm so that high half wave voltage of 38V was required to get the bandwidth. The bandwidth-space product of $LiNbO_3$ due to the microwave power loss is about 10 GHz-cm which is about same order restricted by the velocity mismatch.

The above analysis shows that the modulation bandwidth of polymer EO device is limited not by the mismatch between optical and microwave velocities, but by microwave power loss. This suggests that waveguide electrode design is critical to capitalize the large space-bandwidth product of the polymer devices. Even with electric power loss considerations the polymer EO devices have potentials to have 4 times higher bandwidth-length product and to be used in the systems requiring the very high modulation speed.

Optical Losses

Optical loss is one of the major concern in the passive/active waveguide. The propagation losses in polymer waveguide have decreased rapidly during the last 5 years. The most commonly used materials for passive waveguides are PMMA, polystylens, polycarbonates and polyimide. Most of the Active materials are also based on PMMA and polyimide backbones. Optical losses of 0.1, 0.3 and 1.2 dB/cm have been reported at the wavelength of 830nm, 1.3 and 1.55μm, respectively[10]. Higher losses at 1.3 and 1.55μm are due to the higher harmonics of C-H vibrational absorptions[11]. By substituting the hydrogen by deuterium and fluorine, the loss at 1.3μm had been reduced to lower than 0.1dB/cm[12]. However that was not very successful at the wavelength of 1.55μm (1.5dB/cm) since the absorption peak due to the 3rd harmonic overtone of the C-D vibrational mode shifts to the wavelength range.

Low refractive indices of the polymers offer natural advantages in fiber coupling over inorganic materials like $LiNbO_3$ and InP. Fiber coulping losses are reported to be as low as 0.12dB/cm[10].

The absorption data mentioned above are based on the passive waveguides. Fewer reports are available for active devices. Typical propagation losses of the active waveguide devices at 1.3μm are reported to be 1 ~ 3dB/cm[13]. NLO moieties are incorporated into the basically same polymer materials as passive ones in the active waveguide. However the NLO moieties are not expected to significantly increase the losses at the 1.3 & 1.55μm because they are not related to the absorption mechanism mentioned above and it was indeed demonstrated by the experiment[14]. Since the same fabrication techniques can be applied and the same base polymer matrix are used, the similar loss value, in principle, can be obtained in active waveguides. Birefringence in the poled waveguide may increase the loss a little.

Low loss of polymer waveguide gives flexibilities for the device design and system architecture. For instance, in combination with the large bandwidth-length product, long electrode can be used for modulators or switches which in turn reduce the half wave voltage of the devices. Low losses also offer the integration possibility of many active and passive devices on single chip without any ampifications.

Still there are areas to be improved with respect to the loss. For instance, propagation losses due to the absorption at 1.55μm should be further reduced. This may be achievable by replacing the hydrogen not by fluorine and deuterium but by just fluorine so that the 3rd overtone of the C-D vibration at 1.55μm region can be removed.

To minimize the scattering loss, waveguide must be made with smooth (better than 0.1μm) walls, which requires excellent process control. The multilayers should be free from dusts, voids, cracks, crystallites, grains due to phase separation, etc. and the interface between the layers be smooth. Thermal expansion mismatch between guides and the subtrates must be controlled to minimize the stress-induced scattering and undesired guide birefringence. Thermoset polymers such as polyimide-based materials will be better suited on this matter.

Modulation / Switching voltage

Driving circuit design for the microwave power supplier may need special effort if the modulation voltage is too high. Driving voltages for wideband laser diode and ECL used in telecommunications are about 2-3V and 1V, respectiviely. 5V is used in low speed devices. Therefore devices with switching/modulation voltage lower than 5V, hopefully 2V, are preferred.

The modulation voltage (half wave voltage) of the EO modulator is related to the operating wavelength λ, the refractive index n and the electro-optic coefficient γ of the waveguide material, the electrode gap h, the electrode length L and the overlap factor between optical beam and electric field Γ, and is given by[15]

$$V_\pi L = \frac{\lambda h}{n^3 \gamma \Gamma}$$

Overlap factors of coplanar ($LiNbO_3$)and ridge (polymer) waveguides are typically about 0.4 and 1, respectively.

Half wave voltage-length products with typical electrode dimensions are compared for different materials in Table III. Half wave voltage-length product of the poled polymer EO modulator is already comparable with the $LiNbO_3$. Here material parameters of DANS based polymer were employed for the calculation. Modulation voltage of 4.4V with the DANS polymer was already obtained at 1.3μm with the 14mm electrode length[7].

Half wave voltage can be decreased by increasing the interaction length. However increasing the length of the waveguide cost the higher optical loss and the decrease of the available modulation/switching bandwidth. This is espicially true at the wavelength of 1.55μm where the propagation loss is still high. The better solution is to improve the electro-optic coefficient of the polymer. Simple calculation reveals that the E.O. coefficient of the poled polymer should be higher than 70pm/V in order for the E.O. modulatior to have 2V with the electrode length of 1cm at 1.3μm. There is potential to reduce it further by molecular engineering. Much work remains to be done to achieve this goal.

Integration

In the future information processing systems many discret devices will be integrated on single substrate to generate new functions. Monolithic integration of the semiconductor devices has been persued over a decade with limited success. Up to now the devices required for optical information processing cannot be made using a single material. An alternative way is the hybrid integration where the devices made of various materials are integrated afterward. For instance the hybrid integration concept was described for an optical crossconnect element[16]. The semiconductor devices which are not easy to realize by polymers such as the optic-optical frequency converter and an optical amplifier are integrated with polymer waveguides and polymer components such as broadband power splitters and combiners, optical space switches and channel branching filteres or as polarization control units. By integration, the advantages that the various materials possess can be fully utilized and optimized.

Polymeric materials are best suited for the integration because of its good processability. The basic structure of polymer waveguides consists of multilayer

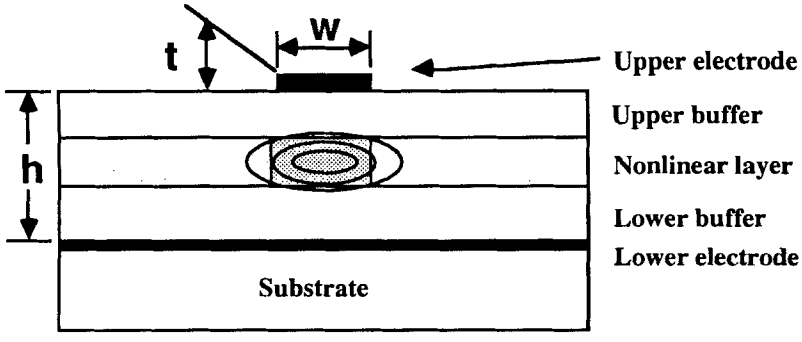

FIGURE 2 A basic structure of polymer active waveguide

structures as shown in Fig 2. The thin film multilayers are formed by spin coating or dipping, etc and the macroscopic alignment of the NLO moieties in the active layer can be achieved by electic field poling. Either electrode poling or corona discharge poling can be applied for the the poling processes. Channel waveguide can be formed by poling itself[17], photobleaching[18], photolocking[19], etching[20], etc.

Most of the fabrication techniques of polymer waveguide formation are common in the semiconductor processing technique and do not require high temperature processing. These flexible, low temperature processing offer considerable advantages over current titanium diffused $LiNbO_3$ waveguide technology in the hybrid integration point of view for example in optical interconnections[22], distribution networks, transmitters, etc.

REQUIRED IMPROVEMENT

Materials

Recent interests of NLO organic/polymeric materials originate from the discovery of the extremely large nonlinearty, especially 2nd order molecular hyper polarizability[23]. To capitalize the molecular hyper polarizability to the macroscopic 2nd order susceptibility, the non-linear molecules should be aligned non-centrosymmetrically. There are three main methods to achieve the non-centrosymmetric alignment; (1) crystal growing, (2) Langmuir-Blodgett technique and (3) electric field poling. Poled polymers show better processing properties for integrations with electronic and optoelectronic devices than other forms of non-linear optical materials.

The first poled polymers are the guest-host systems, in which NLO molucules units (guest) such as disperse Red 1 are dissolved into polymer matrix (host) such as

PMMA to form solid solutions[24]. The systems, however, suffer from low solubility of NLO moieties and low thermal and temporal stabilities. The $\chi^{(2)}$ values of the system decays to zero even at room temperature because of the randomization of the aligned molecules[25].

Side chain polymers have been proposed to overcome the problems, where, instead of doping, NLO moieties are covalently bound to the backbone of the polymers using a spacer[25]. The molecular density of the NLO moieties can be increased, so does the electro-optic coefficient. DANS attached to PMMA backbone which is one of the most widely used material for the device researches belongs to this system[26]. The electro-optic cofficients as high as 40pm/V have been obtained with the system[27].

Thermal stability of the systems were improved significantly compared to the guest-host systems[28], but is still limited to 60-70°C. The limited thermal stability of the polymer are due to the low glass transition temperatures of the polymer backbones. Most of the NLO side chain polymes are based on PMMA or polystyrene whose glass transition temperatures are below about 150°C.

A number of approaches have been tried to improve the thermal stability. One approach is crosslinking the NLO polymers during the poling in order to reduce the mobility at elevated temperature[29,30]. The other approach is to use highly stable polymer matrixes. One example of the such kind materials is polyimide which is stable up to 400°C and has been widely used in semiconductor processing. Themal stability up to 300°C has been demonstrated using the DR1 doped polyimide guest-host system[31].

The former epoxy type polymeric materials have limited thermal stability to near 100°C due to the low glass transition temperature[29] and it may not be stable enough for practical applications. The devices should survive during the short term excursions at the temperatures as high as 300°C[22]. The thermal stability of the guest/polyimide system is good enough for the practical applications. However coplanar electrode structure should be used for the poling and the solubility of the NLO molecules may be limited because of the phase separation. Side chain polymers based on polyimide backbone may be a solution.

There are also many research areas to be improved to fulfill the system requirements mentioned already: increasing the electro-optic coefficient to decrease the switching voltages below 2V, reducing the optical loss at the wavelength of 1.55μm, etc.

When one develops electro-optic materials for device applications, materials for the buffer layers and solvents for each layer should be considered at the same time. The differences of the refractive indices between the waveguiding and the buffer layers for the single mode operations depend on the wavelength of the light, the refractive indices

of the guiding layers and so on and the typical values are on the order of 0.005[32]. Solvent of the upper layer must be selected not to disturb the bottom layers significantly during the successive spin coating.

Life Time and Reliabilities

For a device to be used in telecommunication systems, 30 years of life time is required for reliable and stable functions under various environment and operating conditions. The device should survive during the final system assembly processes in which high temperature as high as 300°C is sometimes required for short time excursion.

The stability and reliability are one of the weakest point of the polymer based devices. Thermal stability problems related to the randomization of the poled NLO moieties were described already. The reliability under various operating conditions can also be a serious problems. Lytel has analyzed the sensitivity of the half wave voltage of a polymer channel waveguide[22] resulting from both thermal effects and processing variations over the operating temperature range of -40 to 125°C. As high as 15-55% variations were anticipated in low temperature polymers (Tg ~ 150°C). High glass transition polymers (Tg ~ 400°C) such as polyimide performs much better with ~5% variations suggesting an approach for the material development. The operating temperature of the devices can be controled in telecommunication systems by thermo electric cooler but at the expense of price and complications.

Environmertal stability is also one of the major concern. Water uptake in humid environment is just an example of it. Long term reliabities of the polymer devices has not been actively examined up to now. Polymeric materials are often degraded upon extensive use. There are so many things to be tested before the polymeric devices find their practical use in real telecommunication systems.

Devices

The potential of the polymeric EO materials should be demonstrated by the real devices for system designers to seriously consider the devices for their use. The 'real devices' mean the packaged and reliablity-proven devices through the field test. One of the main difficulties device researchers confront with this polymeric devices is the lack of the good available materials. Many materials introduced in public domain are produced in laboratory scale. Laboratory research produces them only in small amount, and their quality fluctuates from batch to batch. Large amount, good quality, and high purity materials are essential in obtaining the reproducible results.

Device researchers should try to find the most possible and practical application area(s) and concentrate on realizing it however small it is. Once the devices are implemented for routine use in real systems, the system designer would appreciate the

polymeric devices. The device researchers need to be aware of the specs required by the system and of the progresses of the competitive technologies and maximize the advantages of the materials to the devices of the purposes. Interdisciplinary cooperation between chemists, device researchers and system designers are essential for the polymeric devices to succeed in the near future.

SUMMARY

The utility potential of polymeric electro-optic devices has been examined for applications in optical telecommunications and optical signal processing. There exists a great deal of potential for the polymeric devices that can be utilized for applications, including high bandwidth, low loss and integration possibility. Yet further improvements are needed for practical applications: improving thermal stabilities, increasing the electro-optic coefficient to decrease the half wave voltage below 2V, and reducing the optical loss at the wavelength of 1.55μm. Reliable operation of the devices for up to 30 years remaines to be proven through the field test. While the major breakthrough is required in the materials research, interdisciplinary cooperations between chemists, device researchers and system designers are essential for the development of the devices to be successful in the near future.

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