Organic Electro-Optic Polymer Devices for Ultra-High-Speed Optical Communication

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The optical modulation is an essential technology that defines the information transmission speed in the optical communication. Organic electro-optic polymers attract attention because they enable ultra-fast modulation that exceeds 100 GHz with low power consumption. In the Nano ICT Laboratory, we conduct comprehensive research and development of from electro-optic polymer materials to modulators, switches and optical integrated circuit technology towards ultra-fast and energy-saving optical communication technology. In this paper, we review the research activities in the electro-optic polymer devices that show rapid progress recently.

1 Introduction

A high-speed optical communications network is indispensable to social infrastructure today, and progress in optical communication technology has been made by research and development to increase the speed and capacity of the network. The Electro-Optic (EO) modulator is one of the key devices of fundamental optical communication technology that converts electric signals to optical signals. Inorganic dielectric $LiNbO_3$ (LN) is now widely used as the material for EO modulators. However, organic EO materials are expected to realize larger electro-optic effect and faster modulation frequency than inorganic materials. Therefore, organic EO materials were intensely studied to increase communication capacity and accelerate operational speed at the dawn of the optical commutation era from the late 1980s to the early 1990s[1][2]. However, organic materials, except some organic dielectrics such as DAST, have not been used for any application, since the realization of increased communication capacity by Wavelength Division Multiplexing (WDM) technology in the late 1990s has made the issue of high-speed modulations less urgent, and since there was little prospect in those days of finding organic materials with an electro-optic effect as large as the theoretical expectation. However, further expansion of communication capacity is also in demand due to the wide use of video streaming over the Internet and the popularization of cloud computing in recent years. Moreover, as information processing devices are being sped up and a shift from multi-core to many-core processors takes place, on-chip optical interconnection has become an essential requirement. Under these circumstances, research and development of compact and low-power-driven ultra-high-speed optical modulators using organic EO materials have been initiated again. In this paper, the advantages of organic EO materials are examined based on the principle of the electro-optic effect; recent trends of the remarkably progressing research and development, and achievements of NICT researches are introduced; and the development of applications expected in future are discussed.

2 Optical modulation using the electro-optic effect

In the basic configuration of optical communications technology, electric signals input at a terminal unit such as a mobile phone or a computer are converted into optical signals; transmitted through optical fibers to a receiver; converted from optical signals into electric signals, and output to another terminal. There are two ways to modulate light. One is direct modulation where laser light sources are turned on and off, and the other is external modulation where amplitude, phase and polarization of propagated laser light are modulated by an external modulator. Although the system configuration of direct modulation is simple, it has a limitation in modulation at around 10 GHz because of chirping where oscillation wavelength fluctuates along with changes in refractive index, which is subject to the variability of injected carriers. By contrast, as the external modulation on the basis of the electro-optic effect is free from a chirping problem and capable of high-speed modulation, it is widely used for long-distance optical communications. Moreover, in response to recent demands for increasing communication capacity a shift is taking place from a conventional system of on-off-keying modulation of light intensity to a multi-level modulation system by combining amplitude, phase and polarization of light at multiple values. In the multi-level modulation, light phase must be controlled accurately, then the modulation based on the electro-optic effect displays characteristically high linearity, which is most suitable for multi-level modulation. An electro-optic modulator changes the refractive index of a material with electric signals to alter the phase and intensity of transmitted light. Liquid crystal is one kind of organic electro-optic material. Because the molecular rotation of liquid crystal is the origin of changing refractive index, the variation in refractive index is large, but the modulation bandwidth is as low as the kHz level. Thus, liquid crystal is not suitable for high-speed data transmission.

2.1 Electro-optic effect

The electro-optic effect is a phenomenon in which the refractive index, n, of a material changes when voltage is applied to the material. The first order electro-optic effect is known as the Pockels effect, which is a kind of second order nonlinear optical effect. An electro-optic coefficient, r, of a material, which indicates the degree of change in the refractive index due to the electro-optic effect, is defined by:

$$\Delta\left(\frac{1}{n^2}\right) = rE \tag{1}$$

with E as an electric field of modulation[3]. Here, the refractive index, $n(E)$, when voltage is applied in the electric field, E, is approximately derived as:

$$n(E) = n - \frac{1}{2}n^3 rE = n - \Delta n \tag{2}$$

According to Equation (2), the actual refractive index is found to be proportional not to the electro-optic coefficient, r, of a material, but to n^3r. For this reason, n^3r is used as the figure of merit (FOM) to compare performance between materials. Here, the refractive index, n, and the electro-optic coefficient, r, for LN are 2.2 and 32 pm/V respectively in the telecommunication wavelength band, and the FOM for LN is calculated to be 340. A change in the refractive index of LN, when the electrode gap is 10 μm and 5 V are applied to it, is estimated at $\Delta n = 8.5\times10^{-5}$. This value is smaller almost by two orders of magnitude than that of liquid crystal.

2.2 Advantages of organic materials for electro-optic modulation

For high-speed optical modulation, a waveguide-type modulator is used to reduce driving voltage and capacitance. When the length of an electrode is L, the amount of phase shift of light waves transmitted is:

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta nL = \frac{\pi n^3 rV}{\lambda}\frac{L}{d} \tag{3}$$

In an optical intensity modulator, phase modulation is converted into intensity modulation through an interference device such as a Mach-Zehnder (MZ) interferometer shown in Fig. 1. In a waveguide-type MZ interferometer, after a light wave is split into two waves by a Y-branch waveguide, phase modulation is carried out while the waves are transmitted through the arm sections. Then, the waves are made to merge again and interfere with each other to be converted into intensity modulation. When a phase difference of light waves transmitted through each arm before merging is π, they interfere destructively and the output light intensity becomes zero. The voltage on this condition is called half-wave voltage, V_π, and the following equation is derived from Equation (3):

$$V_\pi = \frac{\lambda}{n^3 r}\frac{d}{L} \tag{4}$$

In Equation (4), because all parameters of the modulator

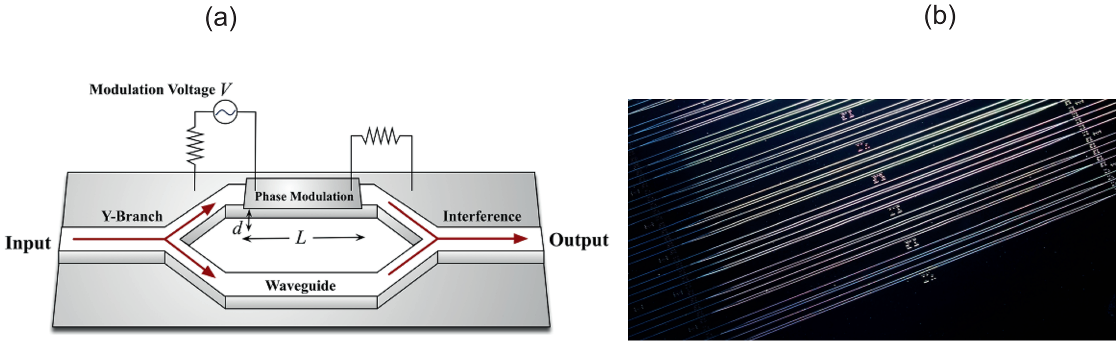


Fig. 1 (a): Schematic diagram of a MZ interferometer and (b): MZ optical waveguides fabricated on Si wafer

with the exception of the electrode length, L, are determined according to wavelength in use and both V_π and L are in the trade-off relation, the product of a half-wave voltage and an electrode length:

$$V_\pi L = \frac{\lambda d}{n^3 r} \tag{5}$$

is used as a relative index between materials in terms of FOM of the modulator, for which material performance is taken into consideration. In an actual modulator, modulation voltage can be reduced by half with a push-pull type of configuration where voltage of opposite sign for each arm is applied.

When voltage is applied to an optical modulator evenly, because a light wave spends a finite time traveling over the electrode length, the voltage needs to be applied continuously in that time span. Thus, a uniform electric field has limitations in modulation frequency, where the modulation bandwidth is only a few GHz. Since the optical communication system requires modulation at 10 GHz and higher, optical modulators in actual use are those of the traveling-wave type, in which microwave modulation signals are transmitted over an electrode. The modulation bandwidth of the traveling-wave type optical modulator is expressed by the following equation:

$$f_{3\mathrm{dB}} = \frac{1.4}{\pi \left| n_{eff} - \sqrt{\varepsilon_{eff}} \right|} \frac{c}{L} \tag{6}$$

Here, n_{eff} is the effective refractive index when light waves are transmitted through waveguides and ε_{eff} is the effective permittivity of the modulator for microwaves. In this case as well, the equation with the electrode length, L, as a multiplier:

$$f_{3\mathrm{dB}} L = \frac{1.4c}{\pi \left| n_{eff} - \sqrt{\varepsilon_{eff}} \right|} \tag{7}$$

is used to figure out a comparative index of material performance.

Table 1 shows the comparison of electro-optic coefficients and FOMs between typical electro-optic materials. As for LN, which is currently used for optical modulators, because $\left| n_{eff} - \sqrt{\varepsilon_{eff}} \right|$ is large, its modulation bandwidth is limited to somewhere around 10 GHz · cm. Figure 2(a) indicates the relation between types of dielectric polarization and resonant frequencies. In the case of inorganic dielectric crystal, because permittivity in the microwave range essentially increases under the influence of ionic polarization along with lattice vibrations, its modulation bandwidth cannot be expected to improve. Actual dispersions of the refractive index (values obtained from Reference[4]) in Fig. 2(b) show that $\left| n_{eff} - \sqrt{\varepsilon_{eff}} \right|$ of

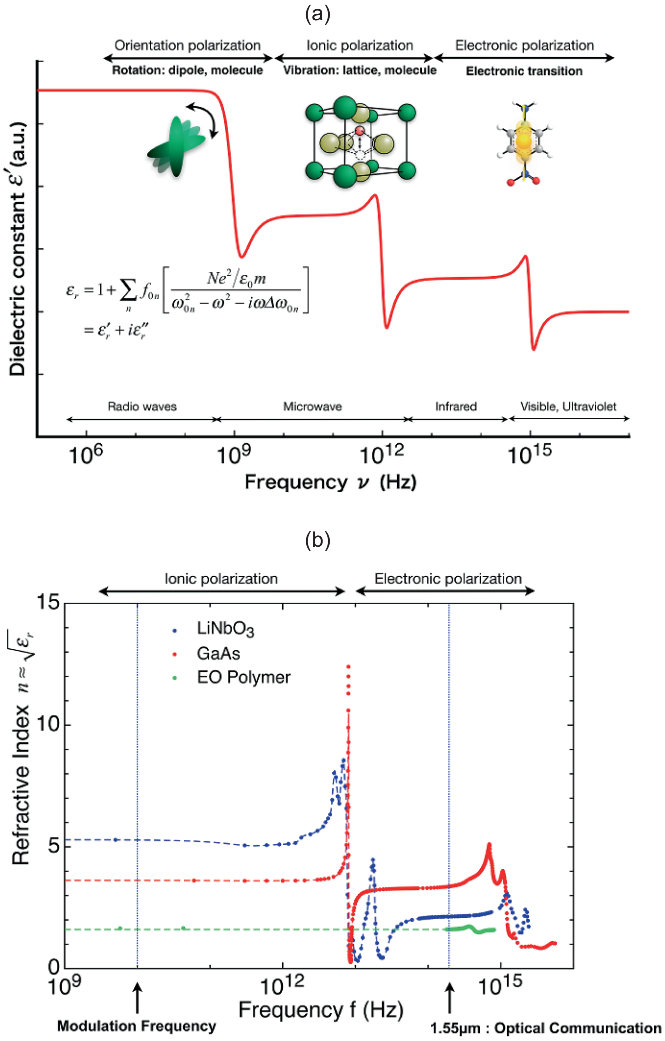


Fig. 2 (a): Types of dielectric polarization and (b): Wavelength dispersion of refractive indices of typical electro-optic materials

Table 1 Comparison of properties among typical electro-optic materials

EO materials	r (pm/V)	n	ε	n^3r	$V_\pi L$ (V · cm)	$f_{3\mathrm{dB}} L$ (GHz · cm)
EO polymer	> 100	1.6 − 1.7	2.5 − 4	> 450	< 1	> 300
DAST	50	2.17	5.2	510	3	134
GaAs	1.5	3.37	13	64	1 - 5	56
LiNbO$_3$	32	2.2	28	340	4.5	10

crystal materials is large. Under the latest device technology, waveguides are skillfully structured in such methods as an air layer inserted between electrodes. Consequently, the modulation bandwidth has increased up to 40 GHz. Yet, the high-speed LN modulator has come close to its limitation. Despite small n^3r in FOM, semiconductor materials such as GaAs have larger refractive indices, meaning that they are capable of confining light effectively. Moreover, owing to microfabrication techniques, spaces between electrodes can be narrowed, which makes it possible to materialize a relatively small $V_\pi L$. But they require a mode-matching convertor to connect a sub-micrometer size waveguide and a 10-micrometer fiber core. Even though their modulation bandwidth is greater than that of LN, they are not applicable to high-speed modulation exceeding the 100 GHz level.

In the meantime, organic materials exhibit higher values in all FOMs, possessing excellent properties to carry out ultra-high-speed modulation at 100 GHz and over with low voltage. Among all, organic dielectric crystal of DAST[5] with higher FOMs has attracted attention as a prime candidate for future implementation. It has not been applied to modulators yet because of difficulties in obtaining large crystals of high enough quality necessary for modulators, as well as processing problems. Nevertheless, some applications including THz generation take advantage of the significant nonlinear optical effect of DAST. EO polymers have exhibited great progress in recent years. Some materials are reported to have electro-optic efficiencies that exceed LN. As the future implementation of EO polymer devices has come in sight, studies with the aim of realizing far greater electro-optic efficiencies have been launched enthusiastically. In the case of organic molecules, electric polarization of π-electrons is the origin of optical response. Thus, in order to gain greater effects with a particular communication wavelength in use, it is possible to adjust the resonant frequency through molecular design. This is one of the properties possessed by organic materials but not by inorganic materials. However, all molecules do not necessarily have a non-centrosymmetric crystal structure which is associated with the appearance of electro-optic effect, and favorable crystal cannot be obtained from such molecules that show particularly large electro-optic response. These molecules can be made into electro-optic materials by being mixed with polymers or linked to them as side chains. In comparison with crystal materials, polymers have better processability. Suitable for coating over a large area of a substrate and making a hybrid with semiconductor devices, polymers are expected to facilitate new developments and applications including on-chip optical interconnection for higher-speed CPU.

3 Organic electro-optic polymers

As for organic materials, electric polarization of constituent polar molecules (EO chromophores) is responsible for the electro-optic effect. Because the influence of ionic polarization, which is a factor of increasing permittivity in the microwave range, is small, almost all organic materials are capable of modulation at 100 GHz and higher. Therefore, in developing organic EO polymers, no particular attention needs to be paid to the modulation bandwidth and researchers can focus on increasing electro-optic effect which is directly associated with low driving voltage of a modulator. The relation between the electro-optic coefficient of organic materials and the hyperpolarizability, β, of their constituent EO chromophores is expressed with:

$$r = \frac{-2}{n^4} NF \left\langle \cos^3 \theta \right\rangle \beta \tag{8}$$

Here, N is the number density of EO chromophores and F is the Lorentz-Lorenz local-field correction factor, which is a function of the refractive index, n, and the permittivity, ε. $\left\langle \cos^3 \theta \right\rangle$ is the thermodynamic average of molecular orientation order shown in Fig. 3, taking a value between 0 and 1. In short, for organic materials to gain greater electro-optic effect, molecules with a large hyperpolarizability are to be arranged with a high degree of orientation at a high level of concentration.

3.1 Development of organic EO molecules with large hyperpolarizability

When light waves are transmitted through an organic material, electric polarization is induced in the organic

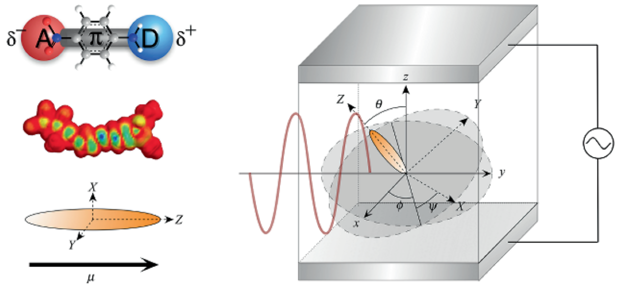


Fig. 3 Orientation of EO chromophores

molecules by the optical field, E. The second order polarization, $p^{(2)}$, at that time is expressed as follows:

$$p_I^{(2)} = \varepsilon_0 \sum_{JK} \beta_{IJK} E_J E_K \tag{9}$$

Here, the subscripts, I, J, and K correspond to any one of the molecular axes, X, Y, and Z shown in Fig. 3. When either electric field in Equation (9) is electrostatic, the outcome represents polarization which is induced by the electro-optic effect. An EO chromophore with a large hyperpolarizability, β, is rod shaped. When the long axis of a molecule is assigned to Z as Fig. 3 illustrates, $\beta_{ZZZ} \equiv \beta_{33}$ becomes a major component. In the two-level model, the molecular hyperpolarizability to electro-optic response is expressed with:

$$\beta_{33} = \frac{1}{3} \frac{\omega_{eg}^2 \left(3\omega_{eg}^2 - \omega^2\right)}{\left(\omega_{eg}^2 - \omega^2\right)^2} \beta_0 \tag{10}$$

$$\beta_0 = \frac{3}{2\varepsilon_0 \hbar^2} \frac{\Delta\mu \cdot \mu_{eg}^2}{\omega_{eg}^2} \tag{11}$$

Here, ω_{eg} and μ_{eg} are the transition resonant frequency and the transition dipole moment between the excited state and the ground state respectively, and $\Delta\mu$ is the difference in dipole moment between the excited state and the ground state. Equation (11) is offering the most fundamental guidance with the molecular structure of large polarity to obtain a large hyperpolarizability. The molecular structure with large polarity holds an electron donating group (donor) and an electron accepting group (acceptor) at both ends, which are π-conjugated and exhibiting a D-π-A structure.

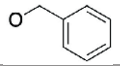
Until the early 1990s, DANS and DR1 were typical molecules and the basic structure consisted of a nitro group as an acceptor and an alkylamino group as a donor. Stilbene and azobenzene were major chemical structures for a π-conjugation bridge. Yet, the electro-optic constant of polymers with these materials barely reached 10 pm/V at most. Some attempts were made to gain good effect by extending the π-conjugation. But, simple longer chaining is not practical because it tends to take a cis form where a resonance structure is cut off. Until the mid-1990s, intensive research and development for the purpose of gaining a large hyperpolarizability had been carried out mainly in Japan, the US and Europe. With the implementation of Wavelength Division Multiplexing (WDM), large capacity transmission became available by multiplexing light waves of approximately 2.5 GHz modulated by a LN modulator. As a result, researchers suddenly lost their motivation for the study of high-speed systems and research on organic EO chromophores decreased. Most of the research projects on organic EO chromophores were terminated in Japan and Europe without gaining such a large hyperpolarizability as was expected. In the US, however, a group constituted mainly of researchers from the University of Washington has continued the research with the aim of developing superior functions for military aviation and space exploration. Consequently, they developed FTC, which is an EO chromophore with styrylthiophene as a π-conjugated frame and tricyanofuran (TCF) as an acceptor[6]. The hyperpolarizability, β_0, of FTC drastically improved, increasing 7.8 times that of DR1.

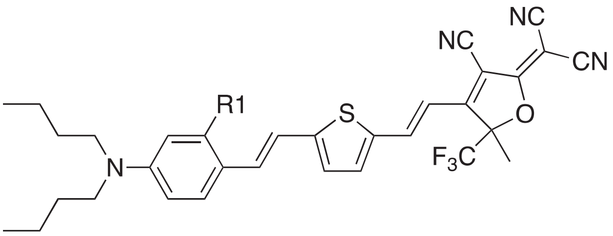
An increase in the hyperpolarizability of FTC can be attributed to the TCF acceptor. The development of acceptors, in association with a nitro group and several cyano groups including a dicyanovinyl group (DCV) and a tricyanovinyl group (TCV), has contributed to the increase in hyperpolarizability. It has been confirmed through azobenzene chromophores that TCF possesses a reinforcement effect twice that of TCV and seven times that of a nitro group. After that, variations of TCF derivatives, in which TCF was replaced partially with CF_3 or a phenyl group, were introduced[7], increasing the hyperpolarizability, β_0, to 2.7 times that of FTC and 21 times that of DR1. The resonant wavelength of these chromophores is between 700 and 800 nm. The hyperpolarizability, β_{33}, in the telecommunication wavelength band exceeded 29 times that of DR1 because of the resonance effect shown in Equation (10), which has marked a breakthrough in the development of organic EO chromophores.

As a π-conjugated frame, azobenzene, stilbene and styrylthiophene in that order increase the hyperpolarizability, β_0. According to molecular design based on quantum chemistry, a polyene frame is found to be most effective. CLD-1, in which a thiophene ring of FTC is replaced with diene, was confirmed to possess an enlargement effect on hyperpolarizability nearly twice that of FTC[8].

Meanwhile, any effective donor structure that significantly increases β has not been identified yet. In the typical donor structure, an amino derivative is linked to a para position viewed from a π-conjugated frame of a phenyl group on the donor side. Although bis-methoxyphenyl-amine has been reported recently as a donor to have an enlargement effect twice as large as that of an alkylamino group[9], there are some restrictions on molecular design in which polymerization needs to be taken into consideration because polymers are usually linked at the donor end in the process of polymerization. NICT has developed new donor structures and successfully discovered a specific donor structure that has noticeable enlargement effect on hyperpolarizability[10]. So far, replacement by donors such as an alkylamino group only at a para position of a phenyl group has been regarded as the most effective way for charge separation while an ortho position has been neglected. Nevertheless, the molecule in which the ortho position of a phenyl group on the donor side of FTC was replaced with a methoxy group exhibited noticeable enlargement effect. Table 2 shows examples of hyperpolarizability for EO molecules which were linked with substituted oxy groups, revealing that the adoption of a new donor increased hyperpolarizability 1.4 times that of the base EO molecules. When a nitro group is used as an acceptor, the replacement of a donor at an ortho position is not very effective. In the case of molecules like FTC which exhibit large charge separation due to long π-conjugation and strong acceptor, the introduction of donors even at slightly inner ortho position is considered to be effective for charge separation. Similar donor replacement was attempted on EO molecules of various π-conjugated frameworks such as stilbene and polyene. As a result, the fact that hydrogen bonding within molecules induced by a substituted group kept a π-conjugated framework stable was clarified by the ^{1}H:NMR spectrum[11]. This structural stability was also found to make the resonant frequency shift towards the low energy side and the width of the absorption spectrum narrow, particularly in the long wavelength region. This information is useful in exploiting the large electro-optic effect on the basis of resonance effect. This alkylaminobenzene donor structure is in common among many EO chromophores and the additional effect of a substituted oxy group at an ortho position is characteristically more conspicuous when EO chromophores have a larger hyperpolarizability. Its application to CLD chromophores has already manifested noticeable effect. For more details, please refer to the following paper, "Development of Organic Electro-Optic Materials and its Evaluation Techniques" in this special issue.

Table 2 Properties of EO molecules including substituted oxy donors

R1	λ_{max} (nm)	β_0 (10^{-30}esu)	$\beta_{33, 1.55\mu m}$ (10^{-30}esu)
H	776	761 (1)	1240 (1)
OCH_3	814	1010 (1.33)	1740 (1.40)
	812	1010 (1.33)	1750 (1.41)



3.2 Electro-optic properties of organic EO polymers

Aggregated polar molecules in general display the state of centrosymmetry where dipoles are counterbalanced, and they rarely turn out to be crystal of non-centrosymmetry. Because materials in the state of centrosymmetry do not produce the electro-optic effect, EO molecules with a large hyperpolarizability, β, are generally dispersed into host materials such as polymers to prevent aggregation. However, polar molecules, which are merely dispersed into polymers, take a structure of random ($\langle\cos^3\theta\rangle = 0$) orientation and eventually turn into a state of centrosymmetry. Therefore, the polling process is indispensable to EO polymers. In polling, the host polymer is heated up to its glass transition temperature, T_g, and then voltage is applied to it to promote the orientation of polar molecules ($\langle\cos^3\theta\rangle \neq 0$). As the material is cooled down to room temperature while voltage continues to be applied, their orientation is frozen. In the case of a gas model which ignores interactions between chromophores, the orientation order parameter is expressed with the Langevin function in the following equation:

$$\langle\cos^3\theta\rangle = L_3\left(\frac{\mu E_{\mathrm{dir}}}{k_B T}\right) \approx \frac{\mu E_{\mathrm{dir}}}{5k_B T} \qquad (12)$$

Here, E_{dir} is a local orientation field where voltage is applied in polling. The approximation of Equation (12) holds good up to 200 V/μm, which is close to the limit value of electric breakdown of EO polymers. In this case, as the degree of orientation is 15 to 20% at the most, orientation by polling is not very effective. Thus, further improvements have yet to be made on the orientation method to obtain larger electro-optic effect. The electro-optic effect of DAST as organic dielectric crystal is subject to the hyperpolarizability of its polar molecules. Despite the modest value of its hyperpolarizability, β, DAST crystal displays a large electro-optic coefficient, r, only because of higher degrees of number density and orientation.

Guest/host polymers in which EO molecules are doped and dispersed are EO polymers created in the simplest procedure. For the host polymer, optically transparent polymethylmethacrylate (PMMA) and amorphous polycarbonate (APC) are mostly used. But they assemble as the concentration of EO molecules increase, and turn into aggregates of centrosymmetry, which does not produce large electro-optic effect. For this reason, the concentration of EO molecules is limited up to 20 to 30 wt%. As a result, the r coefficient of FTC guest/host polymers so far remains at 40 to 50 pm/V[12]. The EO chromophores we have developed by bonding a benzyloxy group to an ortho position displayed the effect of increasing the hyperpolarizability by nearly 1.4 times. The guest/host polymers for which these chromophores were doped in the PMMA host at 20 wt% exhibited a large r coefficient of 76 pm/V, reflecting their large hyperpolarizability.

The most effective method to prevent chromophores from aggregation while increasing their concentration is to build side chain polymers, in which EO chromophores are bonded as side chains to main chain polymers. As for the side chain polymer, the donor end of an EO chromophore is usually bonded to a main chain with ester linkage. We composed side chain polymers illustrated in Fig. 4(a) by making the above mentioned oxy donor EO chromophores bonded to poly (MMA-co-MOI). In proportion to a concentration of chromophores of up to 40 wt%, the electro-optic constant of this polymer increased, exceeding 100 pm/V (Fig. 4(b)).

In an effort to obtain much larger electro-optic effect, the increase of the concentration has already reached its limitation. Thus, an issue left behind is improvement in the degree of orientation. Although the hyperpolarizability of this EO chromophore is nearly 40 times that of DR1, the electro-optic coefficient is no larger than 10 times or so. This can be attributed to such factors as that dipole moment of these EO chromophores is large, molecular interactions with the high concentration promote the state of centrosymmetry, and that an increase in conductivity checks the full function of an orientation field. To enhance the degree of orientation, a design of molecular structure which controls molecular interactions and conductivity is essential. A group from the University of Washington in the US, led by Dalton and Jen, has reported that they could obtain good orientation effect by mixing two kinds of EO chromophores and using molecular interactions between these chromophores. However, the glass transition temperature of this system is low and the method has not been practically implemented yet[13].

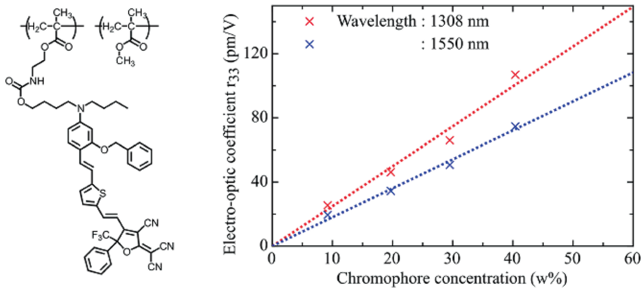


Fig. 4 (a): Structure of a side chain polymer and (b): Dependence of the electro-optic coefficient on the concentration of chromophores

3.3 Fabrication of organic EO polymer optical waveguides

The structure of the polymer electro-optic modulator is basically the same as that of the LN modulator but the former has the advantage of being turned into a parallel-plate electrode structure. In the parallel-plate electrode structure, as electrode gaps can be narrowed and the electric field is not leaky, the electric field can be effectively provided with a low voltage. To fabricate polymer optical waveguides, a multi-layered structure consisting of lower electrode, lower clad, EO polymer, upper clad, and upper electrode is built up on the substrate. Because some polymers such as PMMA and APC are soluble in organic solvent, the multi-layered structure cannot be built on combinations of these polymers. In this case, solvent-free UV curable polymers or water-soluble polymers are used as the clad polymer. However, because the conductivity of these clad polymers is higher by more than two orders of magnitude, a strong electric field is not applied in the EO layer at the time of polling and therefore large electro-optic effect cannot be produced. For this reason, it was difficult to obtain large electro-optic effect in a waveguide structure and to remarkably surpass the performance of LN modulators even in the use of EO molecules with a large hyperpolarizability. Regarding these problems, Enami et al. at the University of Arizona reported that they could materialize a polling efficiency of 100% by incorporation with relatively high conductive sol-gel silica (SOG: spin-on glass) waveguides[14]. However, because it is difficult to coat SOG over the polymer to be used as an upper clad, a special device structure is required. In addition to that, distinctive features of polymer devices, such as laminated devices, flexible devices and low-cost device fabrication based on printing technology, are not fully taken advantage of.

In producing an all-polymer EO optical waveguide device, we have adopted a method that makes the building of lamination possible by inventing insoluble polymers which are hardened through crosslinking after coating. The crosslinking reaction is known to increase propagation loss due to light scattering but we can control the increase in propagation loss by keeping the reaction at a minimum, only enough for making polymers insoluble. Since successive coating of EO polymers has become available, they can be used as a clad also, making conductivities of clads and cores adjustable at a similar level. Accordingly, large electro-optic effect is obtained in the multi-layered structure as well.

To fabricate channel waveguides, a dry processing technique of reactive ion etching (RIE) is employed. Figure 5 illustrates the fabrication process of optical waveguides with EO polymers applied to both core and clad. To the core layer and the clad layer of the optical waveguide, cross-linkable EO side-chain polymers with the EO chromophore contents of 25 wt% and 20 wt% were used, respectively. After coating the core layer on top of the lower clad layer, we coated it with photoresist and created the pattern of waveguides. Through heat treatment, cross-linkable EO polymers become insoluble. Since the cross-linked EO polymers are also resistive to photoresist solvent and developing solution, the core polymer can be directly coated with photoresist to facilitate the patterning process. In the next stage, part of the core layer where photoresist is absent is etched by RIE and the cross section is processed into a rectangular shape, as shown in Fig. 5. By coating the upper clad after the removal of photoresist, channel waveguides are formed. In addition to the above mentioned method of directly etching EO polymers, another option in the RIE technique is the fabrication of an inverse-ridge structure in which the clad layer is trench cut by making the most of the filling nature of polymers. Ambitious attempts are being carried out recently to broaden its application to silicon photonics, by filling EO polymers in gaps of silicon slot waveguides in widths of 100 nm or narrower[15]. The use of inorganic EO materials has been limited to external modulators for independent use because of difficulties in their combination with other structures. Good processability of EO polymers and their compatibility with semiconductor devices, along with huge EO effect, can be enormous advantages in expanding the application field of polymer EO modulators[16][17].

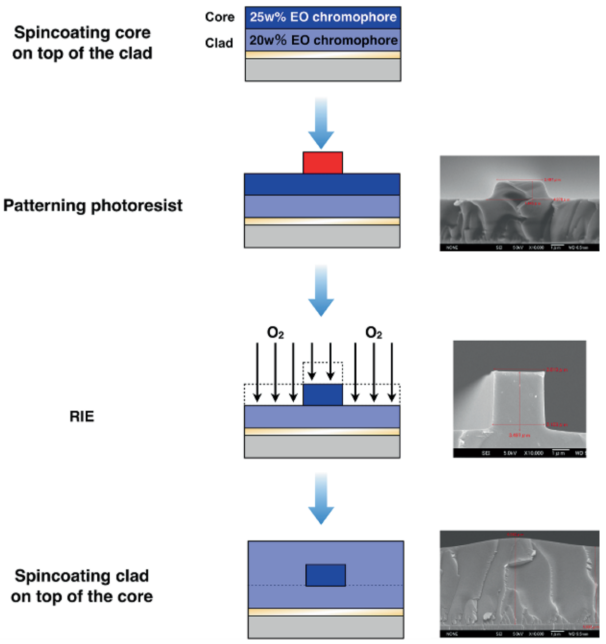


Fig. 5 Fabrication process of all EO polymer optical waveguide structure

4 Future prospects

One notable characteristic of the device production technology using cross-linkable organic EO polymers is that a device is multi-layered and then integrated. In recent optical communication, studies on space division multiplexing (SDM) communication technology using multi-core optical fibers have been promoted because of limitations of channel capacity in single-core/single-mode optical fibers. As for switching in SDM communication, the configuration of a three-dimensional cross connector which switches not only on the same layer but in the longitudinal direction has a high connectivity to multi-core fibers. Focusing on the large EO effect and multi-layer processibility of organic EO polymers, we are conducting research and development of multi-core fiber cross-connect on the basis of the multi-layer switch structure in cooperation with the Photonic Network Research Institute.

Generally, organic materials are considered to be weak in strong light exposure. In fact, many of them decompose through oxidation after absorbing light. As far as the electro-optic effect is concerned, since materials are used in the wavelengths where the light absorption coefficient is considerably low, they maintain high light stability, which is the reason why EO materials among all organic materials have received much attention in terms of practical performance. The polymer EO modulator is characterized by broadband, low driving voltage, small size, light weight, processability, low cost and little influence to electromagnetic waves and high energy radiation[18]. Its small size and light weight are advantageous properties for use in networks loaded on aircrafts and vehicles. In imaging technology as well, for high-definition and ultra-high-definition images to be transmitted, high-speed data transmission is inevitable, which is made possible by organic polymers handy in size, light in weight and low in power.

An enormous increase in electric power consumption at a data center is another problem associated with networks. A large volume of data is handled in a data center, where data transmission at a high speed with a large channel capacity is required. In order to meet these demands while reducing power consumption, on-chip optical networks for data transmission are being promoted. At present, the development of optical interconnection is advancing from inter-board to on-board inter-chip communications and studies on small-sized optical modulators have been enthusiastically carried out. The application of a small-sized optical modulator to optical communication on a CPU chip is also under examination. As a recent method for accelerating the speed of CPUs, multi-core parallel processing has become the mainstream as the increase in clock frequency has reached its limit. The time will soon come when CPUs equipped with hundreds of cores are produced. What may be a bottleneck on that occasion is signal delay caused by electric wiring. In this conjunction, studies on their replacement with optical connection are actively being conducted. For on-chip optical communication systems, a silicon-based optical circuit is being employed. But, because the EO effect of silicon is particularly small, its combination with organic EO materials is receiving much attention as one solution. In NICT, minimized optical control devices on the basis of a hybrid of organic EO polymers and silicon nanostructure are being studied. For more details, please refer to the article, “Organic and Inorganic Hybrid Devices (Photonics Technologies)” in this special issue.

Besides optical control, organic EO polymers are expected to realize highly efficient generation of THz wave and to be applied to highly sensitive electric field sensors on the basis of large electro-optic effect. In addition to the development of EO polymer materials that display far greater electro-optic effect, we will promote practical studies on durability and device processing methods with the aim of establishing the technology for producing ultra-high-speed optical modulators and inventing advanced devices which will lead the world of information and communications technology.

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