Photonics polymer for fiber to-the-display

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ABSTRACT

We have started the basic researches in order to investigate and explain the relation between photonics polymers and their properties. And based on them, we have proposed and demonstrated photonics polymers with new optical functions for application in photonics fields, for example, graded-index polymer optical fibers (GI-POFs), highly scattered optical transmission polymers, zero-birefringence optical polymers, and polymer optical fiber amplifiers and lasers. We propose the concept of "Fiber to the Display" and will apply these photonics polymers for it. In this concept, the GI-POF is directly connected to a large and high-quality display with more than gigabit order data transmission. Therefore, the real-time communication by high quality motion picture will become available for the first time even at home. The gigabit technology which we propose will bring us back to "Face-to-Face Communication".

Keywords: photonics polymers, graded-index polymer optical fibers, zero-birefringence optical polymers, highly scattered optical transmission polymers, Fiber to the Display

1. INTRODUCTION

Photonics polymers have been put into practical use as pickup lenses for CD and MD players, liquid crystal display (LCD) devices, plastic optical fibers, etc. As photonics polymers have unique properties that cannot be found in inorganic glass, they are beginning to hold their own position as materials in the fields of optics and photonics. However, photonics polymers also have their own problems that prevent the upgrade of photonics polymer devices and expansion of their applications. The problems that have been noted are lower clarity, larger birefringence, larger wavelength dispersion of refractive index, lower optical uniformity, etc., compared with optical glass. These problems have been considered as unavoidable properties peculiar to photonics polymers because they are caused by complex systems of polymer solid being an aggregation of huge molecular chains. Therefore, it has been thought that photonics polymers are not suitable for applications in the next generation photonics, which require longer-distance transmission, less distorted transmission of ultra high-speed signals, more accurate control of polarized waves, sharper focusing, more amplification, etc. However, our question is "Is it really true?".

In order to investigate into this matter, it is necessary to discuss molecular structures of polymers as well as higher order structures to conformation and configuration of polymer chains. However, at present, there is still a great difference between the optical properties estimated from basic physical theories and the actual properties of photonics polymers. There has been made almost no basic research worldwide that can fully investigate and explain the relation between photonics polymers and their optical properties. In other words, there is still a huge gap between the academic fields of polymer material science and optics. It seems that photonics polymers have been evaluated with almost no fundamental debate linking these two fields, and that this evaluation has become common knowledge.

We have started our research by breaking down those academic boundaries, and studied in details about how polarized waves or photon relates to various polymer chains (angstrom), their aggregation (several hundred angstroms), higher order structures, and huge heterogeneous structures, investigating their origins. And based on those basic researches, we have proposed and demonstrated photonics polymers with new optical functions for applications in photonics fields such as optical communication and high-quality display, not as a substitute for inorganic glass which has been used in those fields exclusively so far.

With the recent practical application of polymer optical fibers, the conventional assumption that polymers are less suitable as optical materials than inorganic glass is beginning to be broken down gradually. Also, the emergence of

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graded-index polymer optical fibers (GI-POFs) suggests that polymers can be optical materials with properties that are not inferior to, and in some situations might be superior to that of inorganic glass.

Followings are the current results of our research explained on the basis of relation between polarized waves (or photon) and polymers, starting from atomic dimension to macro heterogeneous structures. Figure 1 shows the basic concept. When there are heterogeneities of refractive index on the macro order of more than several dozen microns, the wave front of light is refracted or reflected by such large sized heterogeneities of the macro refractive index within polymers. Using this phenomenon, we will realize high-speed transmission of gigabit-per-second class by constructing an appropriate refractive-index distribution radially within the fiber core[1-3]. When the size of heterogeneities of refractive index becomes that of higher order structure (approximately 1000 angstroms), no refraction is exhibited and the wave front of light becomes spherical waves and causes light scattering. We can use this scattering phenomenon positively and propose high-luminance area light sources for a LCD backlight by adding scattering function to light guide plates[4-7], which have been said to require more transparent polymers (see Fig. 1). When the size becomes that of monomer units (several to ten angstroms), no spherical waves are exhibited and no more scattering is caused. Instead of it, polarizability anisotropy is formed within polymers to cause birefringence by orientation of polymer chains. As the birefringence disturbs polarized waves, it is an undesirable phenomenon for high performance optical devices that handle polarized light. We have noted this phenomenon and proposed a method of elimination by tracing back to its development principle. This idea has led us to synthesize zero-birefringence optical polymers[8-12]. With the dimension of atomic systems, no polarization is exhibited and there are light emission and absorption concurrent with transition between energy levels caused by interaction between atomic systems and electromagnetic field. There are two types of light emission, one is spontaneous emission such as fluorescence, and the other is stimulated emission that is the basic principle of laser and optical amplification. By applying the stimulated emission to polymers, we can realize extremely and high-power optical amplification[13-17].

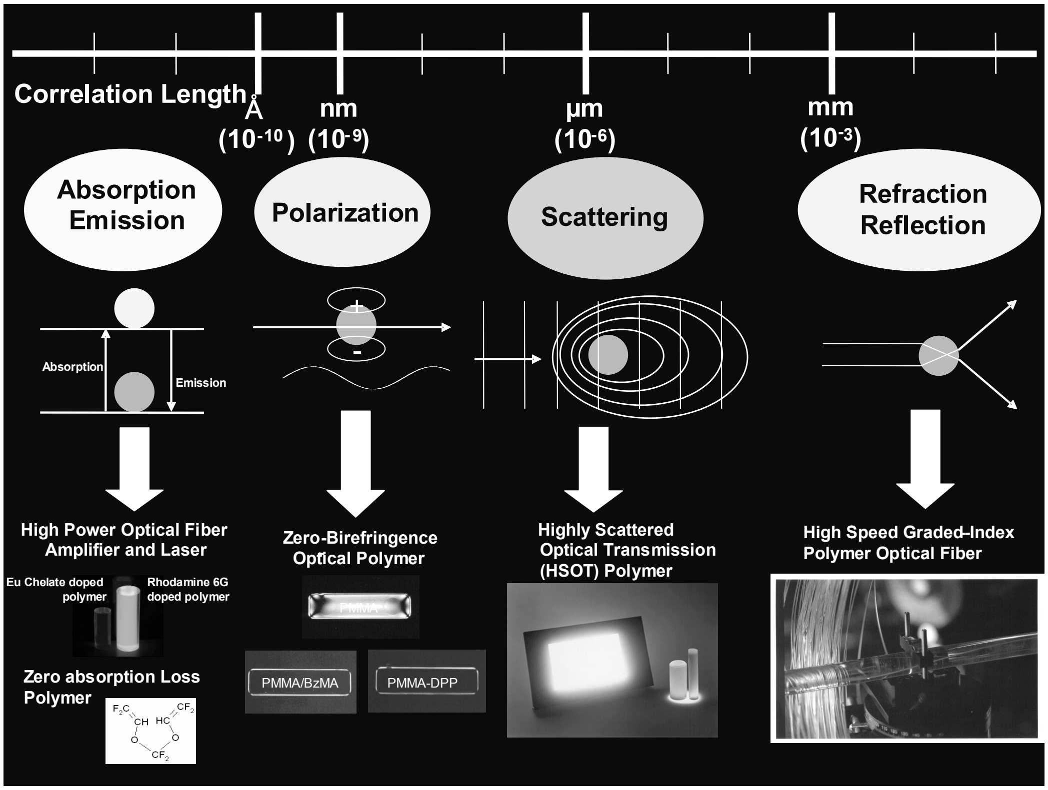


Fig. 1 Interaction between polymers and light waves.

We will apply the research and development of new photonics polymers to high-speed GI-POF networks, LCD devices, and other novel photonics technologies. Our basic philosophy is that technology should be considered as a tool, while serving the needs of people. We propose the concept of "Fiber to the Display" based on the results of photonics polymers mentioned above. This concept is not the continuous way of existing keyboard oriented IT, but is the Face-to-Face communication. Figure 2 shows the concept of the "Fiber to the Display". In this concept, the GI-POF is directly connected to a large and high-quality display with more than gigabit order data transmission. Therefore, the real-time communication by high quality motion picture will become available for the first time even at home. For example, when elderly people get sick late at night, it will be a great relief if they can consult doctors online with such real-time clear motion picture in a large-sized display without hitting keyboard. The gigabit technology which we propose will bring us back to "Face-to-Face Communication". Keio University is leading the research and development of high-speed data communication system based on the Internet at its Fujisawa Campus and optical devices at Yagami Campus. These technologies may enable us to realize our long-cherished dream of real-time video transmission and high-speed access to the Web with instant downloading of large data files. However, in order to construct this kind of gigabit-class information space within homes and offices, it will be necessary to start a future-oriented research and development project that closely coordinates hardware and software.

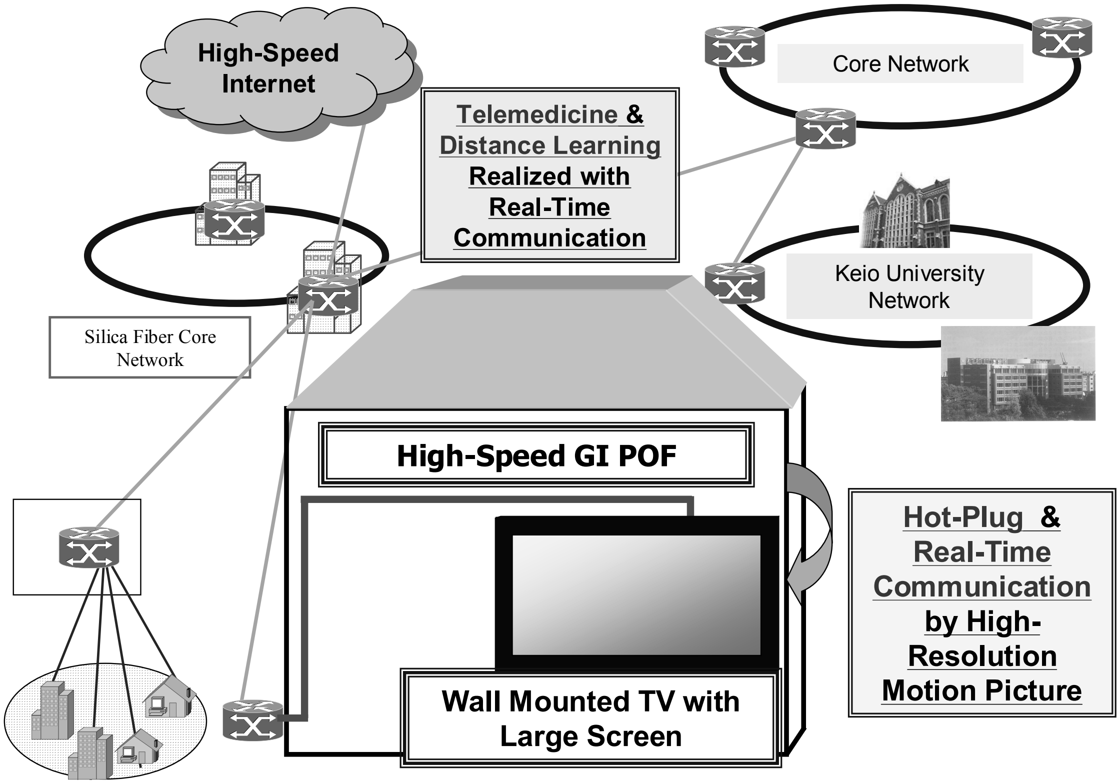


Fig. 2 Concept of "Fiber to the Display".

2. HIGH-SPEED PLASTIC OPTICAL FIBERS

The biggest challenge in IT will be how to install gigabit optical fibers to local area networks at homes and offices. The local area networks, often called as "the last one mile", are said to account for 95% of the whole network, and many connections and junctions are needed to install optical fibers. However, the silica optical fibers used in the backbone of the networks have diameter less than one tenth of a hair. Therefore, installing the silica optical fibers in "the last one mile" has not been realized, as it requires enormous amounts of cost due to the many connections and junctions.

Under these circumstances, we are pursuing the research and development of high-speed plastic optical fibers. The high-speed plastic optical fibers have a large core that they are as easy to make and easy to handle as the existing metal cables, but can achieve the high-speed data transmission comparable to that of silica optical fibers. The installation of "the last one mile" using plastic optical fiber has another advantage over silica optical fiber. Plastic fiber is so flexible that it can easily be installed in even existing buildings, which brings about various options to the construction planning. Gigabit and 10Gigabit Ethernet standards specify the use of a multimode fiber and an inexpensive VCSEL sources as a light source. However, the dispersion of the multimode fibers (MMFs) is the serious problem particularly in the 10Gigabit transmission systems. For the premises network applications, we have proposed a low-loss perfluorinated polymer based GI POF (PF-GI POF)[18]. The attenuation of the current PF-GI POF is 10 dB/km in 0.8–1.3μm wavelength range. In addition, material dispersion of the PF-GI POF is lower than that of silica. It is noted that 10 GHz bandwidth for 500 m is achieved by the PF-GI POF, which is approximately twice higher than that of silica based MMFs.

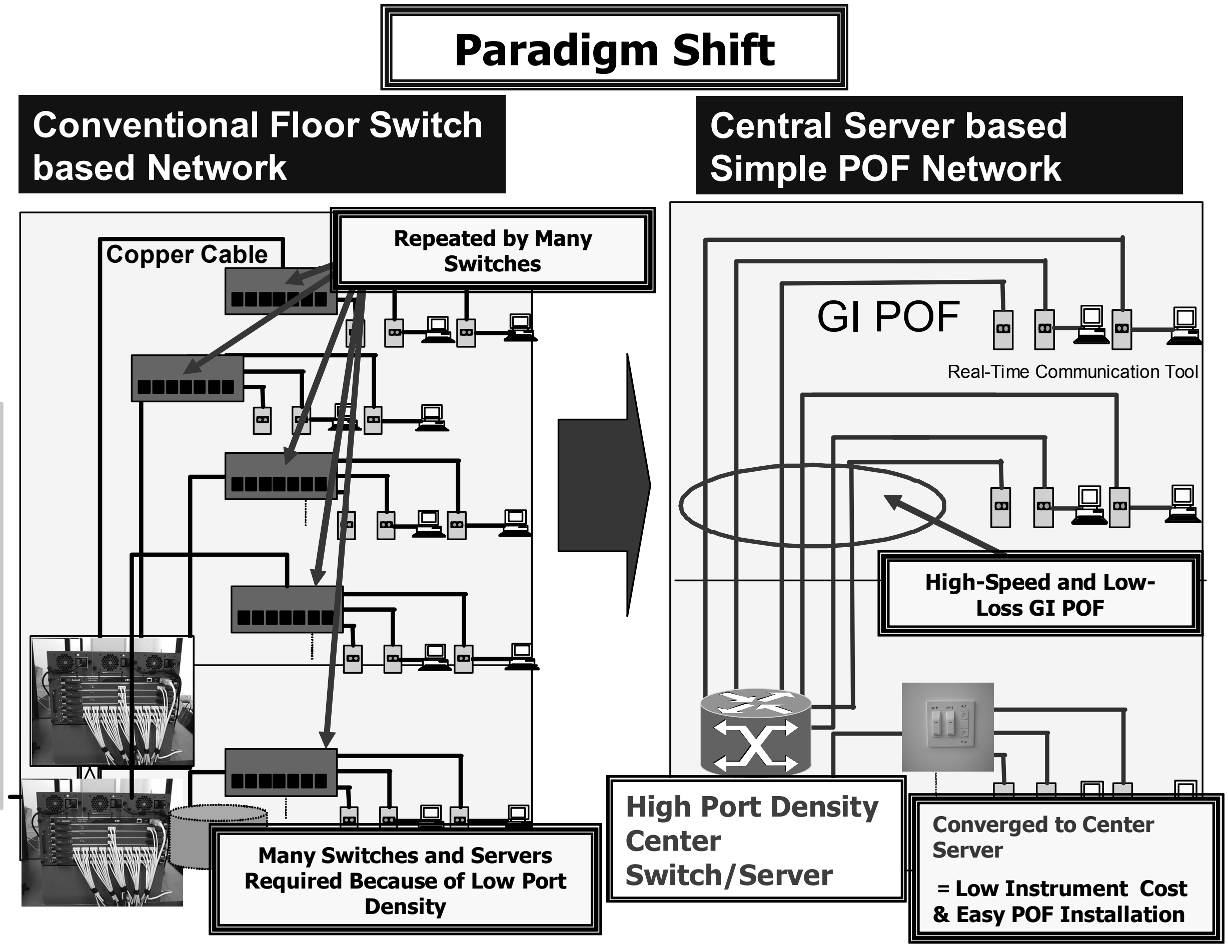


Fig. 3 Proposal of centralized GI POF network.

The typical copper cable network adopted in conventional buildings is the dispersed network system, where main- and sub- servers and switches are dispersed on each floor and those are connected by copper cables. On the other hand, with using high-speed GI-POFs mentioned above, we have proposed a quite novel "centralized network", where there is only one main server and GI-POFs are directly distributed to any outlet and terminal from one main server, without any floor switches or sub-servers in intermediate. Therefore, the security of network is very high and the maintenance fee of it is one fifth of the case of conventional dispersed network. Such a world-first gigabit hospital system with the centralized network using all GI-POF was realized in a cardiac hospital with 320 beds, which is located in Tokyo last year. The total length of GI-POF used in this hospital is 230 km, which is likened to much longer branched veins compared to main veins of human body.

Fig. 4 Main server where GI POFs are directly connected in ”Giga-bit hospital” in Tokyo.

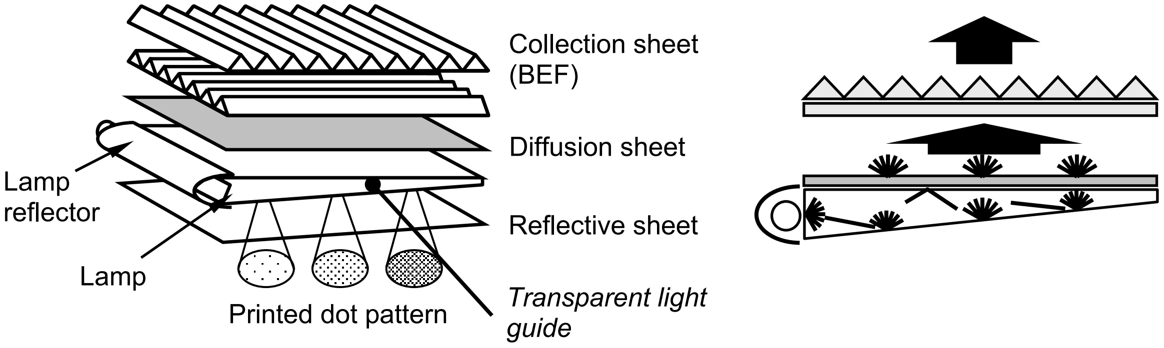
3. HIGHLY SCATTERED OPTICAL TRANSMISSION POLYMERS

We have proposed a novel photonics polymer, a highly scattered optical transmission (HSOT) polymer[4-7]. Light injected into the HSOT polymer is multiply scattered and homogenized, and then comes out as a directive illuminating light because of the microscopic heterogeneous structures formed by doping with spherical particles in the HSOT polymer. The scattering property of the HSOT polymer depends on the size and relative refractive-index of the heterogeneous structures. We applied the HSOT polymer to a light guide plate (LGP) in a backlight unit for LCDs and designed the heterogeneous structures by the multiple scattering simulators that we developed using the Monte Carlo method based on Mie scattering theory.

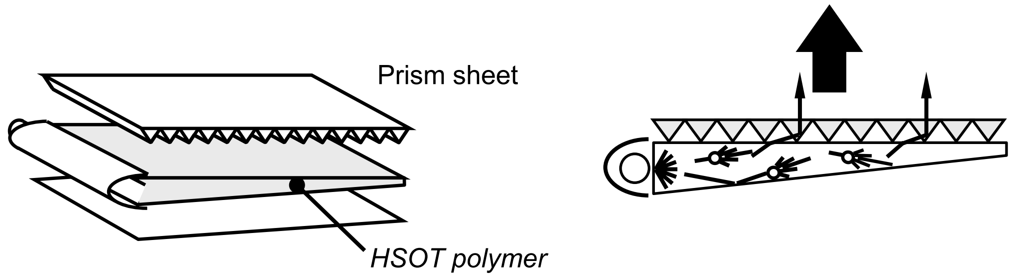
Figure 5(a) shows the conventional backlight in which the LGP was made from a transparent polymer such as an acrylic polymer. Light from a cold fluorescent lamp is injected from the edge of the LGP. Injected light is scattered by dot patterns at the bottom of the LGP and then comes out. The dot patterns are typically formed by white ink or microscopic uneven structures. The density of the printed dot patterns increases with increasing distance from the lamp in order to homogenize the luminance at the output surface. In addition, a diffuser film and two prism films are placed on the output surface in order to hide the dot patterns and to collect the scattered light. The LGP guides light from a cold fluorescent lamp and radiates light homogeneously from all over its output surface. In other words, the LGP is a device to convert a linear light source or a point light source into an area light source. Conventionally, all LGPs were made of transparent polymers, and it was thought that polymers for the LGPs must be transparent without any contaminant, because the contaminant would absorb and scatter light. Even if the contaminant is transparent, it would scatter light leading to a decrease in brightness and a degradation of color uniformity. However, we had some doubt whether the conventional transparent LGP was the brightest one. We thought that the LGPs of polymers containing a great deal of contaminant would be the brightest ones. Figure 5(b) shows the HSOT backlight using a wedge-shaped LGP made from the HSOT polymer. Only one prism film optimized for the HSOT LGP is placed on the HSOT LGP. Light injected into the HSOT LGP was multiply scattered maintaining its directivity due to the contaminant and then homogeneously came out as a directed scattered light. The HSOT backlight demonstrated twice the brightness of the conventional one with sufficient colour uniformity by optimizing the heterogeneous structures with using the multiple scattering simulators. This disproved the speculation that the LGPs must be transparent. Consequently, the HSOT backlight has become commercially used in some types of thin notebook computers because of its higher brightness based on these technologies.

Recently, we proposed a novel HSOT backlight having no films and call it a HSOT II backlight[19]. Figure 6 shows a schematic diagram of the HSOT II backlight. The HSOT II backlight has an array of microprisms at the bottom surface as shown in Fig. 6. The microprisms can reflect the light directly into the front direction, as opposed to that the previous

HSOT backlight converts the light direction by the prism film. Also, typical ray trajectories in the array of microprisms are shown in Fig. 6. We calculated a luminance distribution against the viewing angle from the HSOT II backlight by the multiple light scattering simulation program based on Mie scattering theory using the Monte Calro method. The calculated results are in good agreement with the measured results as shown in Fig. 7. The HSOT II backlight will allow us to lower the total cost of backlight and realize a thinner backlight.



(a) Conventional backlight system



(b) HSOT backlight system

Fig. 5 Schematic diagrams of the HSOT backlighting system and a conventional backlighting system.

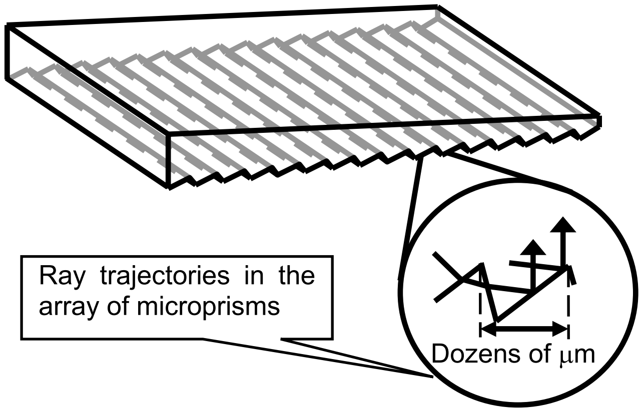


Fig. 6 A schematic diagram of the HSOT II backlight and its luminance distribution.

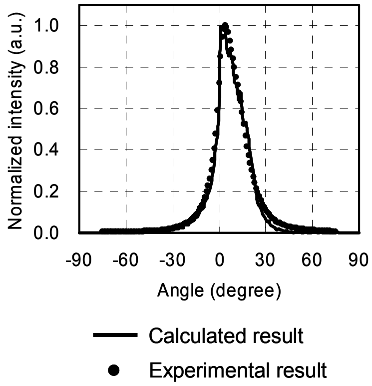


Fig. 7 Luminance distribution of the HSOT II against the viewing angle.

4. ZERO-BIREFRINGENCE OPTICAL POLYMERS AND ZERO·ZERO-BIREFRINGENCE POLYMERS

4.1 Compensation of orientational birefringence of polymers

Optical polymers have been widely used as key materials for various optical devices, for example, lenses and functional films for liquid crystal displays (LCDs), because of their easy processing, light weight, high transparency, and low cost. Optical polymers tend to exhibit birefringence caused by the orientation of the polymer chains during processing by injection-molding, extrusion and drawing thus creating an optically anisotropic material. Birefringence is the division of a ray of light into two rays when it passes through an optically anisotropic material depending on the polarization of the light. Two different refractive indices are assingned to the material for different polarizations. In the case of uniaxially drawn polymer samples, the orientational birefringence Δn is defined as $\Delta n = n_{//} - n_{\perp}$ where $n_{//}$ and $n_{\perp}$ are refractive-indices for light polarized in a parallel direction and a perpendicular direction to the drawing direction, respectively. Although most of polymer chains have intrinsic optical anisotropy derived from asymmetry of their chemical structures, a polymer material becomes macroscopically isotropic and exhibits no birefringence when polymer chains are randomly oriented because their intrinsic optical anisotropies are cancelled each other. However, a polymer material becomes birefringent when polymer chains are oriented because their intrinsic optical anisotropies are not cancelled each other. This hinders maintaining the polarization state of light or focusing by lenses and results in degradation of the performance of the optical devices. Most of the optical device manufacturers attempt to reduce birefringence by increasing annealing time and temperature, which increases both processing time and cost. In addition, almost all of low birefringent optical films for LCDs are manufactured by the solvent casting process instead of the extrusion process to reduce birefringence although the production rate of the former do not exceed a tenth part of that of the latter.

Optical polymers that exhibit no birefringence for any orientation of polymer chains are desirable to realize high performance optical devices for handling polarized light at low cost compared to conventional ones. We named such polymers as “zero-birefringence optical polymers”. Methods have been proposed to realize a zero-birefringence optical polymer. They include polymer blending[20], random copolymerization[8-9] and doping anisotropic molecules[10-11]. Polymer blending is a well-known method to obtain a zero-birefringence optical polymer, in which negative and positive birefringence homopolymers are blended. In practice, it is difficult to completely blend two polymers during injection molding or extrusion, and thus difficult to achieve the transparency and homogeneity required for use in high performance optical devices; the blends tend to phase separate into domains of corresponding homopolymers on the order of more than several hundred nanometers, leading to scattering. The random copolymerization method was proposed in order to solve this problem by creating chemical bonding between negative and positive birefringent monomers. This approach has proven to be somewhat successful for the fabrication of optical devices such as pick-up lenses for optical disks. However, the suitable monomer pairs for zero-birefringence optical copolymers are quite limited, since they have to satisfy both conditions that two monomers have positive and negative birefringence, respectively, and that two monomers are randomly copolymerized. And also, the typical optical, mechanical and thermal properties of most zero-birefringence optical polymers synthesized by these two methods were significantly different from the corresponding homopolymers, because the mixing ratio of the minority component was usually more than 10 wt%. Therefore, compensating the birefringence of conventional optical polymers such as poly(methyl methacrylate) (PMMA) is still required.

In the anisotropic molecule dopant method, molecules that have an anisotropic polarizability and a rodlike shape are chosen and doped into the polymers. When the polymer chains are oriented in processing, the molecules are also oriented because of their rodlike shape. The negative birefringence of the polymer can be compensated by doping with positive anisotropic molecules which have a higher polarizability in the direction of orientation than in the perpendicular direction. In principle, the positive birefringence of a polymer can be compensated by doping with negative anisotropic molecules. The orientational birefringence of PMMA was compensated by doping with 3.0 wt% of *trans*-stilbene based on the anisotropic molecule dopant method[10-11]. The anisotropic molecule dopant method is available for compensating the orientational birefringence of conventional polymers while preserving transparency and processability.

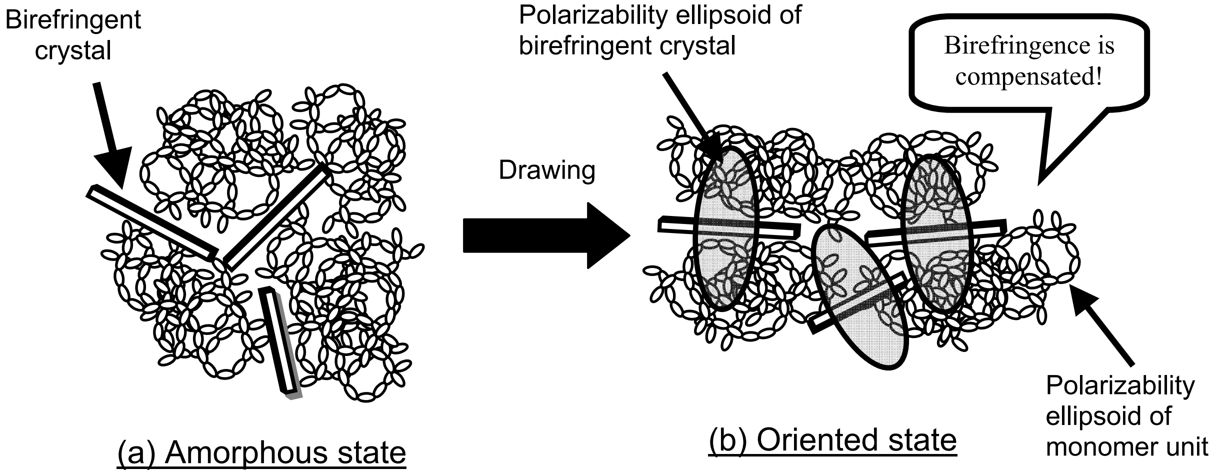


Fig. 8 Mechanism for the compensation of orientational birefringence by the birefringent crystal dopant method. (a) In the completely amorphous state, polymer chains and birefringent crystals are randomly oriented, so that the polymer containing the birefringent crystals exhibits no birefringence. (b) Polymer chains and birefringent crystals are oriented in the drawing direction. However, birefringence of the polymer is compensated by that of the crystal.

We proposed a birefringent crystal dopant method in order to realize a zero-birefringence optical polymer[12, 21]. By using a birefringent crystal dopant, we show that it is possible to compensate the orientational birefringence of conventional polymers while preserving transparency and thermostability. In the following, an inorganic birefringent crystal that has a higher refractive index for light polarized along its longer axis than that along its shorter axis is defined as a positive crystal, and the opposite one is a negative crystal. The compensation mechanism for the positive birefringence of a polymer by a negative crystal is shown in Fig. 8. The structural units of the polymer that correspond to the repeating units are illustrated by polarizability ellipsoids representing the polarizability anisotropy. The rectangular solids signify birefringent crystals, and ellipsoids overlapping with the birefringent crystals signify the polarizability anisotropy of the crystals. The polymer containing the crystals exhibits no birefringence when the repeating units are randomly oriented in the amorphous state as shown in Fig. 8(a). The crystals are oriented when the polymer chains are oriented as shown in Fig. 8(b). As a result, the birefringence of the polymer is compensated by the birefringence (strictly, polarizability anisotropy) of the crystal. The orientational birefringence of positive and negative polymers can be compensated by a small amount of negative and positive crystals, respectively, because of their relatively large birefringence (typically > 0.1).

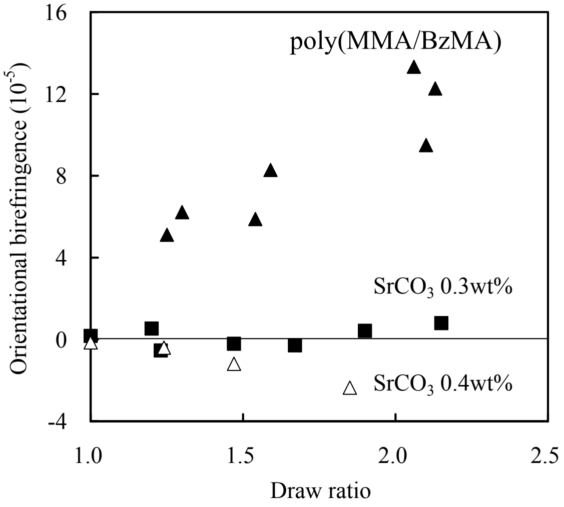


Fig. 9 Orientational birefringence of the poly(MMA/BzMA) films containing $SrCO_3$ with respect to draw ratio.

The orientational birefringence of the compensated poly(MMA/BzMA) film uniaxially heat-drawn at 130 °C is shown in Fig. 9. The poly(MMA/BzMA) film containing 0.4 wt% of 200 nm long crystals of $SrCO_3$ showed a negative orientational birefringence while the poly(MMA/BzMA) film showed a positive orientational birefringence. The negative value of the orientational birefringence increased with an increase in the crystal concentration. At a doping level of 0.3 wt% the orientational birefringence of poly(MMA/BzMA) was almost eliminated for draw ratios less than 2.0. We confirmed that the $SrCO_3$ needle-like crystal particles were statistically oriented in the drawing direction based on a micrograph of the heat-drawn poly(MMA/BzMA) film containing 1 wt% of $SrCO_3$ with a length of approximately 200 nm at a draw ratio of 2.0 obtained with a transmission electron microscope. The poly(MMA/BzMA) film containing 0.3 wt% of $SrCO_3$ showed sufficient transmittance for optical films used in LCDs in the visible region. In spite of doping with 0.3 wt% of $SrCO_3$, the transmittance of the doped film was the same as the undoped one in the visible region because $SrCO_3$ has no large absorption band in the visible region.

4.2 Compensation of the photoelastic birefringence of a polymer

Birefringence caused by elastic deformation is called “photoelastic birefringence”. Mechanism of generation of photoelastic birefringence of polymers has not been clarified in detail and is different from that of orientational birefringence. In fact, some polymers exhibit the opposite sign of birefringence in elastic deformation to that of orientational birefringence.

We compensated the negative photoelastic birefringence of PMMA at a wavelength of 633 nm by doping with 2.2 wt% of *trans*-stilbene[22]. Cylinder-shaped samples (18mmϕ ×10mm) were prepared to measure the photoelastic birefringence of PMMA doped with *trans*-stilbene. The photoelastic coefficient of the samples was determined at a wavelength of 633 nm by optical heterodyne interferometry using a birefringence measurement equipment (ABR-10A, Uniopt Corporation, Ltd.). The photoelastic birefringence Δn generated in a stressed material is defined as follows:

$$\Delta n = C\Delta\sigma , \quad (1)$$

$$\Delta\sigma = \sigma_1 - \sigma_2 , \quad (2)$$

where C is a photoelastic coefficient of the material, σ_1 and σ_2 are principal stresses as shown in Fig. 10. A positive polymer has a photoelastic coefficient $C > 0$ and a negative polymer has $C < 0$. Principal stress is tensile stress when its sign is positive, and it is compression stress when its sign is negative. $\Delta\sigma$ is a principal stress difference between the two principal stresses. The samples were compressed between two parallel plates, and the photoelastic birefringence at the center of the samples was measured (Fig. 10). Figure 11 shows the photoelastic birefringence of the samples against the principal stress difference. We found that *trans*-stilbene exhibited positive photoelastic birefringence in the PMMA bulk. Photoelastic birefringence of the sample became almost zero with any stress at a concentration of 2.2 wt%. Photoelastic coefficients of PMMA doped with *trans*-stilbene are listed in Table 1.

We prepared PMMA films doped with *trans*-stilbene for the measurement of the infrared dichroic ratio in order to investigate the motion of molecules. The dichroic ratio was measured while the films were elastically deformed with less than 1% strain by tensile stress. The symmetric bending of C-αCH_3 at 1388 cm^{-1} was selected as the characteristic band of PMMA, and the out-of-plane deformation of the benzene ring at 696 cm^{-1} was selected as the characteristic band of *trans*-stilbene. We used the α-value of 90 degrees for C-αCH_3 bending band which was determined by Zhao et al.[23] and also used the α-value of 90 degrees for the vertical bending of a phenyl group band because *trans*-stilbene was planar rodlike molecules. The results of the infrared dichroic ratio indicated that the main chain of PMMA was hardly moved but the side chain of PMMA and *trans*-stilbene were oriented. We therefore conclude that photoelastic birefringence of PMMA in elastic deformation with less than 1% strain was mainly caused by the orientation of the side chain and it was compensated by the orientation of *trans*-stilbene. The detail motions of the side chain and *trans*-stilbene have not been clarified.

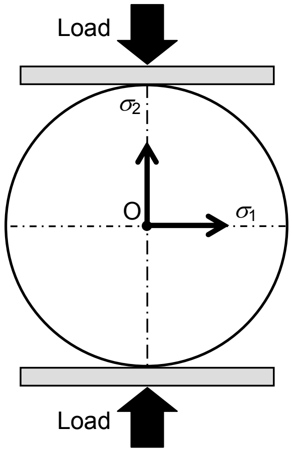


Fig. 10 Experimental set-up of the photoelastic birefringence measurement. Photoelastic birefringence is measured at the center of cylinder-shaped samples under a compression load.

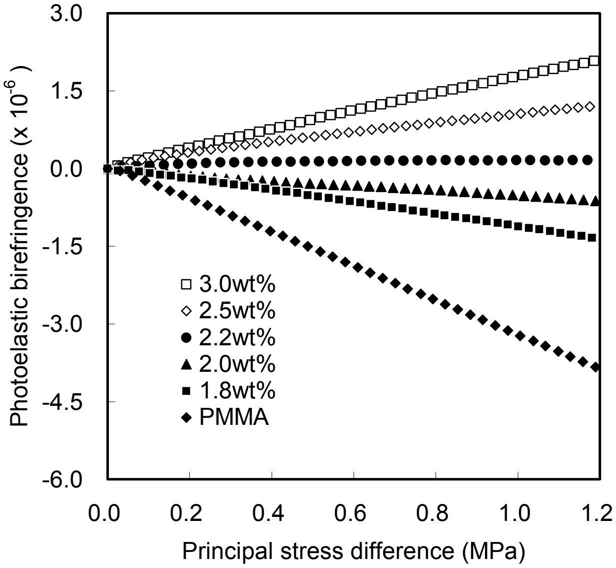


Fig. 11 Photoelastic birefringence of PMMA samples doped with *trans*-stilbene against the principal stress difference at a wavelength of 633 nm.

Table 1 Photoelastic coefficient of PMMA doped with *trans*-stilbene at a wavelength of 633 nm.

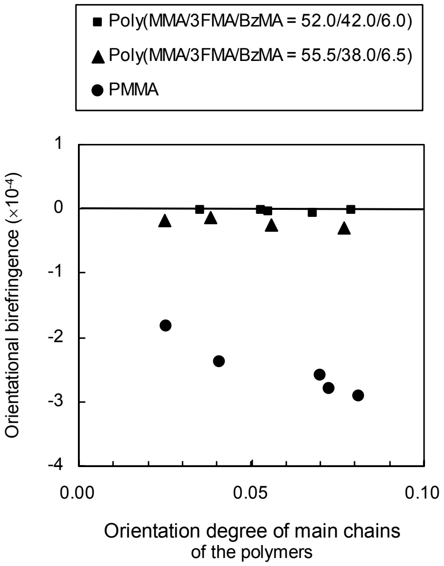
trans-stilbene (wt %)	Photoelastic coefficient C ($\times 10^{-12}$ Pa^{-1})
0.0	-3.321
1.8	-1.153
2.0	-0.471
2.2	0.057
2.5	0.937
3.0	1.729

4.3 Zero·zero-birefringence polymer

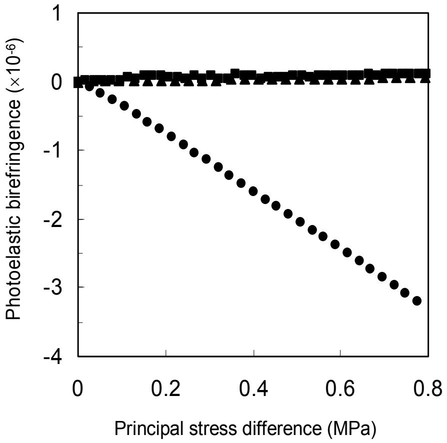
In the case of the random copolymerization method, it should be pointed out that the composition of the copolymer for eliminating orientational birefringence is different from that for eliminating photoelastic birefringence. For example, in the case of poly(MMA/BzMA), the composition for eliminating orientational birefringence is MMA/BzMA=82/18(w/w) and the composition for eliminating photoelastic birefringence is MMA/BzMA=92/8(w/w). Therefore, simultaneous compensation of the orientational birefringence and the photoelastic birefringence by means of the random copolymerization method has not been demonstrated. Similarly, in the case of the anisotropic molecule dopant method, the concentration of the anisotropic molecule for eliminating orientational birefringence is different from that for eliminating photoelastic birefringence. For example, the concentration of *trans*-stilbene is 3.0 wt % for eliminating the orientational birefringence of PMMA and that for eliminating the photoelastic birefringence of PMMA is 2.2 wt %. Therefore, simultaneous compensation of the orientational birefringence and the photoelastic birefringence by the anisotropic molecule dopant method has not been demonstrated either.

We define polymers as zero·zero-birefringence polymers that exhibit no birefringence with any orientation of the polymer main chains and in elastic deformation (i.e., both the orientational birefringence and the photoelastic birefringence are zero). The zero·zero-birefringence polymers are ideal for realizing high performance and low cost optical devices for handling polarized light or fine focusing.

We demonstrated, for the first time, that it is possible to synthesize a polymer that exhibits no orientational birefringence and no photoelastic birefringence using two methods[24]. In these methods, the contributions of monomers and an anisotropic dopant to orientational birefringence and photoelastic birefringence are analyzed experimentally, after which the composition of a ternary copolymer or a binary copolymer including the dopant is adjusted, based on the results, to compensate for both types of birefringence. By the methods and fine adjustment of the composition, we synthesized poly(MMA/2,2,2-trifluoroethylmethacrylate (3FMA)/BzMA =52.0/42.0/6.0(w/w/w)) and poly(MMA/3FMA=85.0/15.0(w/w)) containing 2.8 wt % of *trans*-stilbene that exhibited close to zero birefringence. We confirmed that these polymers exhibited close to zero birefringence in the oriented state and in elastic deformation as shown in Figs. 12 and 13, respectively. Clearly, these methods are applicable to other polymers composed of other monomers and anisotropic dopants, opening the way to synthesizing novel zero-birefringence optical polymers.

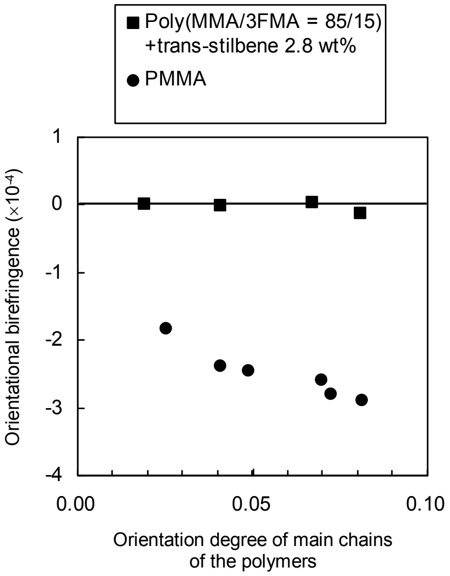


(a) Orientational birefringence

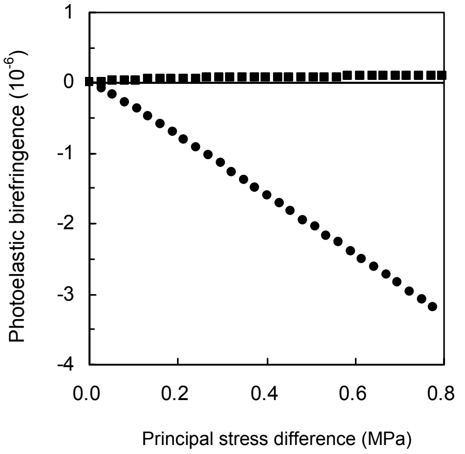


(b) Photoelastic birefringence

Fig. 12 Orientational birefringence and photoelastic birefringence of poly(MMA/3FMA/BzMA).



(a) Orientational birefringence



(b) Photoelastic birefringence

Fig. 13 Orientational birefringence and photoelastic birefringence of poly(MMA/3FMA) containing *trans*-stilbene.

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