

# Rapid Optical Switching by Means of Photoinduced Change in Refractive Index of Azobenzene Liquid Crystals Detected by Reflection-Mode Analysis

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**Abstract:** Optical switching behavior of low-molecular-weight and polymer azobenzene liquid crystals (LCs) was explored by means of reflection-mode analysis. Reflectivity changed on pulse irradiation under various conditions of orientations of LC molecules with respect to incident probe light, either s-polarization or p-polarization. For the low-molecular-weight LCs, we obtained a response time of 100  $\mu$ s, which was very similar to that observed in the transmission-mode analysis, while we observed a decay time of 1 ms, which was significantly shorter than that observed in the transmission-mode analysis. The fast decay may be due to diffusion and reorientation processes which are characteristic of the reflection-mode analysis. For the polymer LCs, we observed a much slower decay than those for the low-molecular-weight LCs.

## Introduction

Much attention has been paid to photonics in which light can be controlled by light as a stimulus as future technology for high-speed information processing.<sup>1</sup> Information dealt with has become so large that it is necessary to process more information more quickly; for instance, moving picture contains much information. Light has a lot of properties such as intensity, polarization, and wavelength, and these properties are quite useful for information processing. Therefore, by photonics, it may be possible to process much information quickly. In photonics, switching devices play an important role in the control of light, changing their own physical properties with the stimulus light.

Liquid crystals (LCs) are convenient to control the light because LCs have large optical anisotropy due to the anisotropy in molecule shape and show the responsiveness to electric field. Therefore, many studies have been reported to construct the optical switching devices by the use of LCs.<sup>2</sup> At present, LCs are used only as active media in display devices with the response time of several milliseconds because the response of LCs to electric field is slow. However, if the response becomes fast enough with light as a stimulus, we will be able to use LCs not only in display devices but for various photonics applications such as optical switching, optical image storage, optical display, and optical computing. In fact, this is a rapidly developing field in which photochemical switching of LC phases has been a key process.<sup>3–15</sup>

To drive LCs by light, we have used a phenomenon of photochemical phase transition of LCs containing photochromic molecules which change their molecular shape on photo-irradiation.<sup>16–26</sup> For instance, the *trans* form of azobenzene derivatives is a rod and tends to stabilize the phase structure of nematic LCs (NLCs) while the *cis* form of the azobenzenes is bent and tends to destabilize the phase structure. Therefore, *trans*–*cis* photoisomerization of the azobenzene in the N phase

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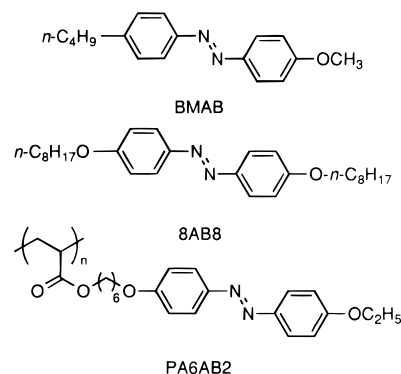
can disorganize the phase structure of NLCs, resulting in a nematic–isotropic (N–I) isothermal phase transition (photochemical phase transition). Recently it was found that the low-molecular-weight and polymer LCs possessing the azobenzene moiety in each mesogen showed the photochemical phase transition in 200  $\mu$ s on pulse irradiation.<sup>27,28</sup>

The photochemical phase transition of LCs has been analyzed most conveniently by transmission-mode analysis.<sup>21–28</sup> Since LCs show birefringence, the N–I phase transition can be monitored easily by measurement of transmittance of a He–Ne laser through a pair of crossed polarizers, with the LC sample between them. When the LC sample is in the N phase, the transmittance is high while no transmitted light is detected when the sample is in the I phase. Although the transmission-mode analysis is a very convenient method, there is a drawback; the phase transition can be detected only after the LC sample becomes an I state completely across the sample. This is in some sense not convenient, especially for the investigation of the photochemical phase transition behavior of thick samples. If photons are absorbed entirely in surface region because of a high extinction coefficient of the sample, the N–I phase transition is induced only in the surface region with the rest of the sample remaining in the N phase. Under these circumstances, it is very difficult to analyze the phase transition behavior precisely in the transmission-mode analysis. Contrary to the transmission-mode analysis, events occurring only in the surface region can precisely be explored by reflection-mode analysis.<sup>29–32</sup> In this mode of analysis, probe light incident upon the interface between the sample and substrate can penetrate only the surface region of the sample, depending on incident angle, and provides information on the surface of the sample if the reflected probe light is monitored carefully. In this study, therefore, we explored the optical switching behavior of the azobenzene LCs, especially with reference to responsiveness and the recovery of the initial state. Furthermore, we investigated the phase transition behavior of the low-molecular-weight and the polymer azobenzene LCs in detail to confirm the switching mechanism.

## Experimental Section

**Materials.** Structures of the low-molecular-weight and polymer LCs used in this study are given in Figure 1. 4-Butyl-4'-methoxyazobenzene (BMAB) and 4,4'-bis(octyloxy)azobenzene (8AB8) were synthesized and purified as reported previously.<sup>33</sup> Poly[6-[4-[(4-ethoxyphenyl)diazenyl]phenoxy]hexyl acrylate] (PA6AB2) was prepared by the method reported by Angeloni et al.<sup>34</sup> Polymerization was conducted in *N,N*-dimethylformamide (DMF) by the use of 2,2'-azobis(isobutyronitrile) (AIBN) as an initiator.

**Characterization.** The molecular weight of the polymer was determined by gel permeation chromatography (GPC; Toyo Soda HLC-802; column, GMH6  $\times$  2 + G4000H8; eluent, chloroform) calibrated with standard polystyrenes. Liquid-crystalline behavior and phase transition behavior were examined on an Olympus Model BH-2 polarizing microscope equipped with Mettler hot-stage models FP-90 and FP-82. Thermodynamic properties of the LCs were determined with a differential scanning calorimeter (Seiko I&E SSC-5200 and

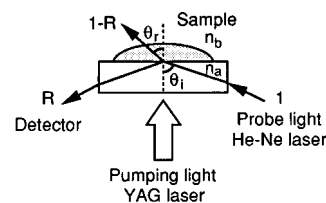


**Figure 1.** Structures of low-molecular-weight and polymer LCs used in this study.

**Table 1.** Thermodynamic Properties of LCs and Molecular Weight of Polymer Used in This Study

$M_n^a$	$M_w/M_n^b$	phase transition temperature, °C <sup>c</sup>	$\Delta H_{NI}$ , kJ/mol	$\Delta S_{NI}$ , J/(mol·K)
BMAB		K 30 N 45 I (heating) K 8 N 45 I (cooling)	0.46	1.42
8AB8		K 98 N 111 I (heating) K 92 S 94 N 110 I (cooling)	1.7	4.4
PA6AB2	9100 1.3	G 45 N 155 I	0.84	2.0

<sup>a</sup>  $M_n$ , number-average molecular weight. <sup>b</sup>  $M_w$ , weight-average molecular weight;  $M_w/M_n$ , molecular weight distribution. <sup>c</sup> K, crystal; N, nematic; I, isotropic; S, smectic; G, glass.



**Figure 2.** Schematic illustration of principle of reflection-mode analysis and optical setup for the measurement:  $n_a$ ,  $n_b$ , refractive indices of two materials;  $\theta_i$ , incident angle;  $\theta_r$ , refractive angle;  $R$ , reflectivity which is a fraction of reflected light at the interface. In this study,  $n_a$  and  $n_b$  correspond to the refractive indices of the quartz substrate and the sample, respectively.

DSC220C) at a heating rate of 0.5 °C/min for the low-molecular-weight LCs and 10 °C/min for the polymer, respectively. The thermodynamic properties of the LCs and the molecular weight of the polymer are listed in Table 1.

**Principle of Reflection-Mode Analysis.** In the reflection-mode analysis, we measured the intensity of the reflected light from the interface between the sample and the glass substrate as shown in Figure 2. Reflectivity, which is a fraction of light reflected at the interface, changes as the change in the refractive index of the sample, and their relation can be given by eq 1 and eq 2,<sup>35</sup>

$$R_s = \left( \frac{n_a \cos \theta_i - n_b \cos \theta_r}{n_a \cos \theta_i + n_b \cos \theta_r} \right)^2 \quad (1)$$

$$R_p = \left( \frac{n_b \cos \theta_i - n_a \cos \theta_r}{n_b \cos \theta_i + n_a \cos \theta_r} \right)^2 \quad (2)$$

where  $R_s$  and  $R_p$  represent reflectivities of light in s-polarization and p-polarization,  $n_a$  and  $n_b$  are refractive indices of two materials,  $\theta_i$  and  $\theta_r$  denote the incident angle and the refractive angle. Reflectivity depends on refractive indices of two materials, incident angle, refractive angle, and the polarization. In this study, we measured the reflectivity at a fixed incident angle, 71°, at which the reflectivity and its change on the phase transition were significantly large.

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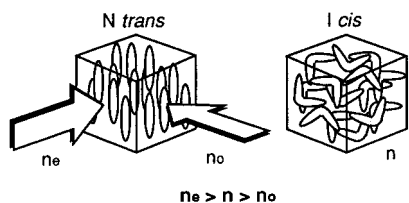
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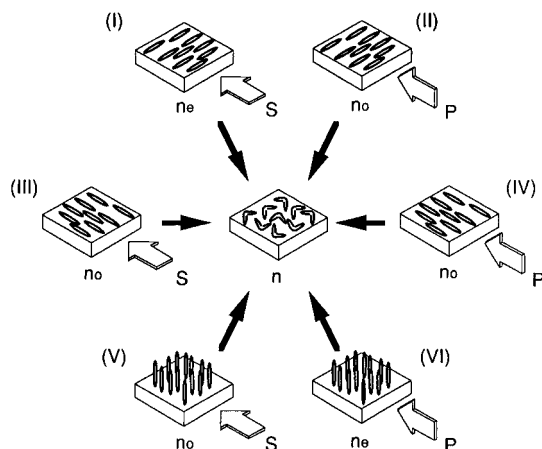
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**Figure 3.** Birefringence of azobenzene LCs: N *trans*, nematic phase in the *trans* form of the azobenzene moiety; I *cis*, isotropic phase in the *cis* form. Birefringence was observed for N *trans* whereas no birefringence in I *cis*:  $n_o$ , ordinary refractive index in the N *trans*;  $n_e$ , extraordinary refractive index in the N *trans*;  $n$ , refractive index in the I *cis*.

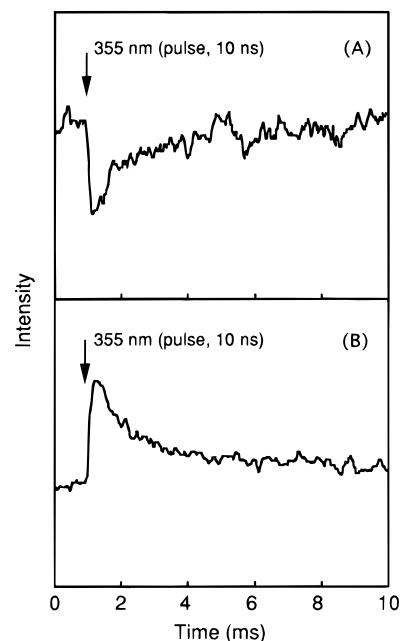


**Figure 4.** Schematic illustration of various conditions for orientations of LC molecules with respect to the incident probe light, either s-polarization or p-polarization: I and II, alignment of LC molecules in homogeneous manner perpendicular to the probe light; III and IV, alignment of LC molecules in homogeneous manner parallel to the probe light; V and VI, alignment of LC molecules in homeotropic manner. The s-polarization in I, III, and V and the p-polarization in II, IV, and VI are used for the probe light, respectively. The refractive indices equal  $n_e$  under the conditions of I and VI, while  $n_o$  under the conditions of II, III, IV, and V in the initial state. After pulse irradiation, the refractive indices change to  $n$  with the N-I phase transition under all conditions.

In the *trans* form, the azobenzene LC molecules show the birefringence in an N phase (N *trans*), which arises from the molecular shape itself (Figure 3). The refractive index parallel to the long axis of molecule,  $n_e$ , is different from that perpendicular to the short axis of molecule,  $n_o$ . On the other hand, the LC molecules in the *cis* form show only an I phase (I *cis*); birefringence has never been observed in this phase. The following relation is in general obtained:  $n_e > n > n_o$ .

**Measurements in Reflection-Mode Analysis.** The sample was irradiated with a single pulse of a Nd:YAG laser (Spectron, SL805 laser system; the third harmonic, 355 nm; 10 ns, FWHM) as shown in Figure 2. The intensity of probe light (NEC, GLC5370 He-Ne laser; 633 nm; 1 mW) reflected from the interface between the sample and the substrate was measured with a Hamamatsu R-928 photomultiplier as a function of time and recorded with a storage scope (Iwatsu, DS-8631). The probe light was passed through a polarizer and was incident upon the quartz block. Detailed optical setup was reported previously.<sup>31</sup>

To investigate the optical switching behavior of the low-molecular-weight azobenzene LCs, change in the reflectivity on pulse irradiation was measured under various conditions of orientation of the azobenzene LCs with respect to the incident probe light, either s-polarization or p-polarization. As shown in Figure 4, the low-molecular-weight LCs were aligned in three manners: first, the homogeneous alignment perpendicular to the incident probe light (I and II); second, the homogeneous alignment parallel to the incident probe light (III and IV); and third, the homeotropic alignment (V and VI). Since s-polarization and p-polarization were used for the probe light under each condition of the orientation of LCs, the reflectivities were measured

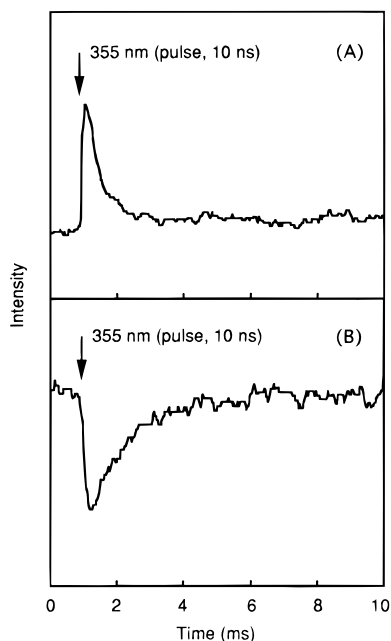


**Figure 5.** Time-resolved measurements of change in the reflectivity for BMAB on pulse irradiation (355 nm, 10 ns fwhm, 20 mJ/cm<sup>2</sup>) at 35 °C: (A) the s-polarized probe light; (B) the p-polarized probe light. The measurement conditions for A and B correspond to those of I and II shown in Figure 4, respectively.

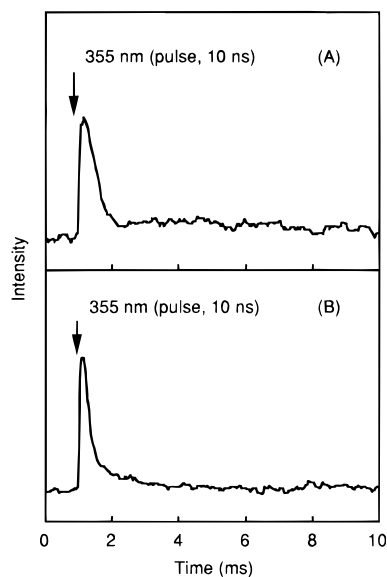
under these six conditions. For the polymer system, the measurement was performed under the condition of III. The quartz block had been rubbed into one direction to align mesogens in a homogeneous manner, and a small portion of lecithin solution in ethanol (1 wt %) had been cast on the quartz block to align mesogens in homeotropic manner. The sample was thermostated to show an N phase.

## Results and Discussion

**Change in Reflectivity.** It was found that the reflectivity changed on pulse irradiation at 355 nm under all conditions (I~VI). Parts A and B of Figure 5 show the results of the time-resolved measurements for BMAB under the conditions of I and II shown in Figure 4, respectively. The measurements were performed at 35 °C for both conditions. On pulse irradiation at 20 mJ/cm<sup>2</sup>, the reflectivity decreased in I, while it increased in II. Parts A and B of Figure 6 show the results for 8AB8 under the conditions of V and VI measured at 94 °C for A and at 90 °C for B, respectively. In these cases, the pulse irradiation brought about an increase in the reflectivity in V, but a decrease in the reflectivity in VI. In III and IV, however, we observed an increase in the reflectivity on pulse irradiation under both conditions. We observed no difference in the change of the reflectivity between BMAB and 8AB8 under each condition. In the reflection-mode analysis, the reflectivity depends on the refractive index of the sample as described above. Therefore, the different behavior of the reflectivity on pulse irradiation is due to a change in refractive index of the sample proved with specific polarization of the probe light. For instance, the refractive index of the sample in I corresponds to  $n_e$  in the initial state for the s-polarization of the probe light as shown in Figure 4 (I). If the sample is irradiated with the laser pulse, the N-I phase transition is induced and the refractive index of the sample decreases to  $n$ . This decrease of the refractive index caused the decrease of the reflectivity in I. On the other hand, the refractive index of the sample is equal to  $n_o$  in the initial state under the condition of II. The refractive index of the sample increases to  $n$  when the N-I phase transition is induced by the laser pulse. This increase of the refractive index was experi-



**Figure 6.** Time-resolved measurements of change in the reflectivity for 8AB8 on pulse irradiation (355 nm, 10 ns fwhm, 20 mJ/cm<sup>2</sup>): (A) 94 °C (nematic phase in super cooled state); (B) 90 °C (nematic phase in super cooled state). The measurements of A and B were performed under the conditions of V and VI in Figure 4, respectively.

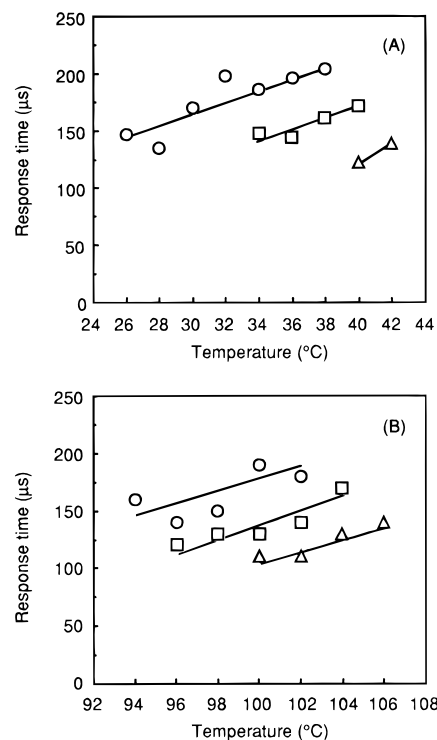


**Figure 7.** Time-resolved measurements for the low-molecular-weight LCs, BMAB and 8AB8, under the condition of III shown in Figure 4. The measurements were performed at 39 °C for BMAB (A) and at 104 °C for 8AB8 (B). Each sample was irradiated with a laser pulse at 355 nm (10 ns fwhm, 3 mJ/cm<sup>2</sup>).

mentally verified by the increase of the reflectivity as shown in Figure 5B. We found that the change in the reflectivity corresponded to the change in the refractive index of the sample under all conditions. Different rise and decay behavior was observed in the time-resolved measurements, depending on the conditions. These differences mainly depended on temperature and laser power.

**Optical Switching Behavior.** To discuss the optical switching behavior quantitatively, we defined the response time ( $\tau_r$ ) as the time required to raise the intensity of the reflected light to 90% of the maximum value.

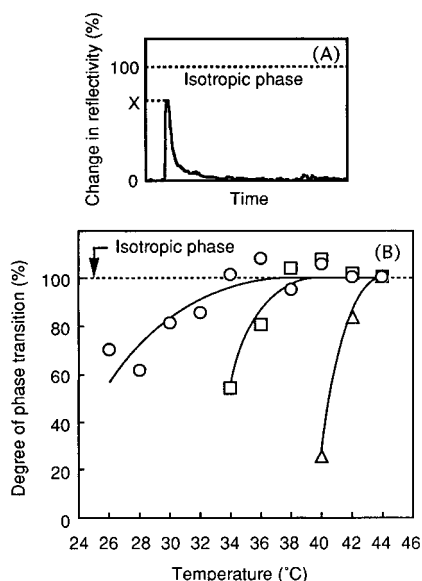
Figure 7 shows the results of the time-resolved measurements for the low-molecular-weight LCs, BMAB and 8AB8, under



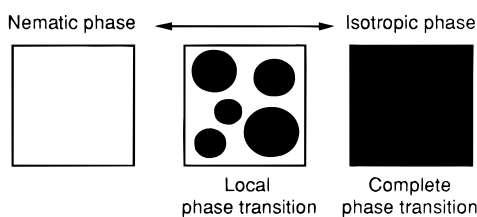
**Figure 8.** Temperature dependence of  $\tau_r$  for BMAB (A) and 8AB8 (B) at various laser powers: ( $\Delta$ ) 3 mJ/cm<sup>2</sup>; ( $\square$ ) 5 mJ/cm<sup>2</sup>; ( $\circ$ ) 10 mJ/cm<sup>2</sup>.

the condition of III. The measurements were performed at 39 °C for BMAB and at 104 °C for 8AB8. It was found that the intensity of the reflected light at the interface between the sample and the substrate rose up in 100  $\mu$ s on pulse irradiation at 355 nm and decayed immediately in both samples. These rises of the reflectivities result from the change in the refractive index of the sample induced by the N-I phase transition on pulse irradiation. Under this condition of the orientation of the LC molecules, whose direction of the long axis is parallel to the incident probe light (s-polarization), the refractive indices of both samples are equal to  $n_o$  in the initial state and increase to  $n$  due to the N-I phase transition induced by the laser pulse (Figure 4 (III)). The values of  $\tau_r$  in these measurements are smaller by 1~2 orders of magnitude than those of NLCs to the change in the electric field. Such an advantageous feature is quite favorable for application to the optical devices.

We explored the temperature dependence of  $\tau_r$  in BMAB and 8AB8 at various laser powers (Figure 8). It was found that  $\tau_r$  was in the range of 100~200  $\mu$ s and decreased gradually as the temperature was lowered in both samples at any laser power. Although the difference in the chemical structure and the N-I phase transition temperature ( $T_{NI}$ ) is large between these two samples, no difference was observed in the response time. This implies that the response time does not depend on the absolute temperature ( $T$ ) but on the reduced temperature, which is defined as  $T/T_{NI}$ , because the property of LCs is significantly influenced by the reduced temperature rather than the absolute temperature in general. The decrease of  $\tau_r$  at lower temperatures has been observed only in the reflection-mode analysis and has never been observed in the transmission-mode analysis. The mechanism of the N-I phase transition consists of (i) production of the *cis* form on photoirradiation and (ii) disorganization of the LC phase by the *cis* form, whose molecular shape is bent. This perturbation of the *cis* form propagates effectively at high temperatures, while the *cis* form disorganizes the LC phase to a much lower extent at lower temperatures. We can expect,



**Figure 9.** Temperature dependence of degree of the N–I phase transition for BMAB at various laser powers under the condition of III shown in Figure 4. As shown in A, we defined the degree of the N–I phase transition by the ratio of the maximum reflectivity after pulse irradiation to the reflectivity at the I phase. Panel B shows the degree of the N–I phase transition at various laser powers: ( $\Delta$ ) 3 mJ/cm<sup>2</sup>; ( $\square$ ) 5 mJ/cm<sup>2</sup>; ( $\circ$ ) 10 mJ/cm<sup>2</sup>.

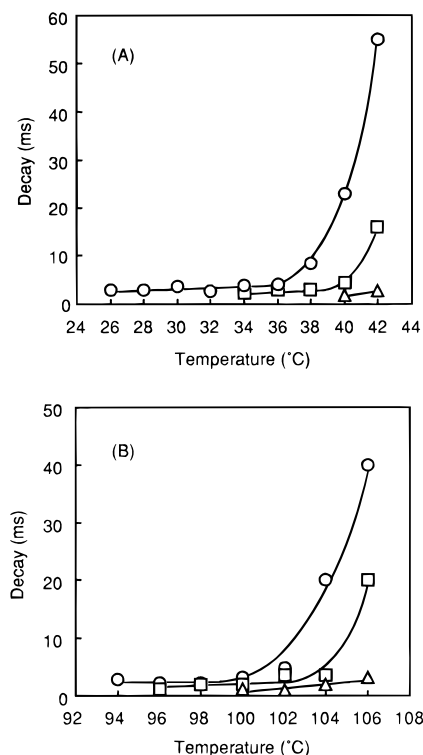


**Figure 10.** Schematic illustration for the state of the local N–I phase transition: filled area, I phase; unfilled area, N phase. In the state of the local phase transition, we obtain the refractive index between the N phase and the I phase.

therefore, that the N–I phase transition occurs ineffectively at lower temperatures.

To investigate the N–I phase transition behavior with temperature and laser power in detail, we explored the temperature dependence of degree of the N–I phase transition for BMAB at various laser powers (Figure 9). We estimated the degree of the N–I phase transition by the ratio of the maximum reflectivity observed on pulse irradiation to the reflectivity measured when the sample was isotropic, where reflectivity before pulse irradiation was taken as 0% as shown in A. It is clearly shown in B that the degree of the N–I phase transition is equal to 100% at high temperatures, while it decreases with a decrease in temperature at any laser power. This behavior indicates that the N–I phase transition is induced incompletely at low temperatures. We suggest a “local N–I phase transition” at low temperatures. As illustrated in Figure 10, the N–I phase transition is induced only in some domains with the rest of the sample remaining in the N phase. The probe light detects a macroscopic phenomenon, and we can observe an averaged state of the sample. The decrease in the degree of the N–I phase transition may be due to a decrease in the domains in which the N–I phase transition was induced. It is considered that, in this state of the local phase transition, change in the refractive index is small, and the apparent decrease of  $\tau_r$  was observed as shown in Figure 8.

Smaller values of  $\tau_r$  were obtained at lower laser powers at the same temperature. The quickest response was observed at

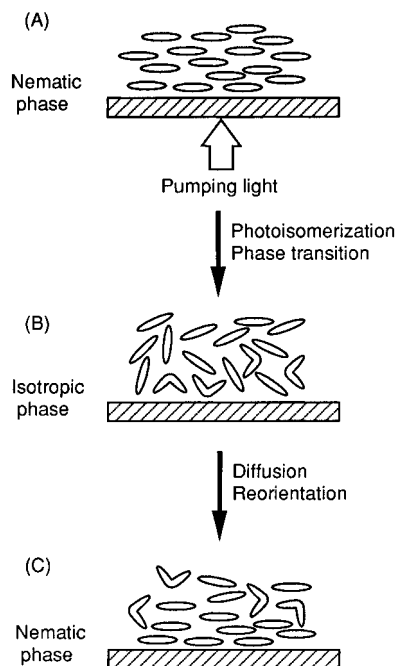


**Figure 11.** Temperature dependence of  $\tau_d$  in BMAB (A) and 8AB8 (B) at various laser powers: ( $\Delta$ ) 3 mJ/cm<sup>2</sup>; ( $\square$ ) 5 mJ/cm<sup>2</sup>; ( $\circ$ ) 10 mJ/cm<sup>2</sup>.

the lowest laser power (3 mJ/cm<sup>2</sup>) as shown in Figure 8. We can also explain the decrease in  $\tau_r$  with a decrease in the laser power at the same temperature in terms of the local phase transition. When less *cis* forms are produced at lower laser powers, only the local N–I phase transition is induced.

**Decay in Optical Switching.** To discuss the optical switching behavior, it is necessary to evaluate not only the response time, which means the N–I phase transition, but also the decay time, which corresponds to I–N phase transition. Therefore, we also defined the decay time ( $\tau_d$ ) as the time required to decrease the intensity to 10% of the maximum value.

It was found that the I–N phase transition, namely the recovery of the initial N phase, completed in only 1 ms in BMAB and 8AB8 as shown in Figure 7. This value is smaller by 6 orders of magnitude than that obtained in the transmission-mode analysis. The value of  $\tau_d$  is much different between the reflection-mode measurement and the transmission-mode measurement, while no difference in  $\tau_r$  has been observed between these two methods. We investigated the temperature dependence of  $\tau_d$  in BMAB and 8AB8 at various laser powers as shown in Figure 11 and observed the increase of  $\tau_d$  with temperature, especially the steep rise near the phase transition temperatures at any laser power. It is reported that the recovery process in the transmission-mode analysis depends mainly on the *cis*–*trans* thermal back-isomerization of the azobenzene moiety and becomes quicker with temperature.<sup>27,28</sup> This thermal back-isomerization of the azobenzene moiety is very slow at low temperatures; for instance, it takes several hours at room temperature for BMAB. However, in the reflection-mode analysis, the significantly small value of  $\tau_d$  (1 ms) was observed in both BMAB and 8AB8, although these samples show the N phase at different temperatures. Furthermore, the increase of  $\tau_d$  with temperature was obtained in both samples. This temperature dependence of  $\tau_d$  in the reflection-mode analysis is quite different from that in the transmission-mode analysis.

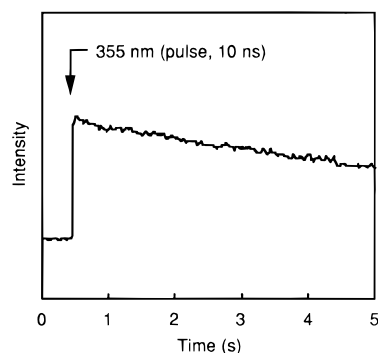


**Figure 12.** Schematic illustration of switching mechanism in the reflection-mode analysis: (A) an initial N phase before pulse irradiation; (B) an induction of the N–I phase transition by the laser pulse; (C) recovery of the initial N phase only in the surface region through the diffusion and reorientation processes.

These results indicate that the recovery mechanism is different in the reflection-mode measurements.

**Switching Mechanism.** The molar extinction coefficients of the azobenzene moieties at 355 nm are so large ( $\sim 10^4$ ) that the pumping light at 355 nm is absorbed entirely in the surface. Consequently, the *trans*–*cis* photoisomerization also is induced near the surface and the N–I phase transition occurs only in the surface, leaving the bulk area intact as an N phase. In the reflection-mode analysis, the probe light can penetrate only in the surface region. Therefore, the switching mechanism in the reflection-mode analysis is interpreted as illustrated in Figure 12. At first, the LC molecules orient on the glass substrate (A). A pulse irradiation at 355 nm brings about the N–I phase transition only in the surface with the rest of the sample remaining in the N phase. The molecules of the *cis* form produced in the surface instantly diffuse into the bulk region due to concentration gradient of the molecules of the *cis* form between the surface region and the bulk region (C). Similarly the molecules of the *trans* form in the bulk region diffuse into the surface region and reorient on the substrate in the initial manner (C). Since the diffusion and the reorientation processes are much quicker than the *cis*–*trans* back-isomerization process, which is the rate-determining step in the transmission-mode analysis, the rapid optical switching has been achieved successfully in the reflection-mode measurements.

The increase in  $\tau_d$  with temperature for both samples (Figure 11) is characteristic of the reflection-mode analysis and has not been observed in the transmission-mode analysis. This behavior may be interpreted in terms of the recovery processes described above. In the diffusion and reorientation processes, it is considered that the diffusion of the LC molecules becomes faster with temperature. Hara et al. measured diffusion constants of methyl red in NLCs by forced Rayleigh scattering and found that the diffusion constants increased with temperature except near the phase transition temperature.<sup>36</sup> On the other hand, with



**Figure 13.** Time-resolved measurement for PA6AB2 on pulse irradiation (355 nm, 10 ns fwhm, 40 mJ/cm<sup>2</sup>) at 100 °C.

an increase in the temperature in the N phase, the order parameter of LCs decreases and hence the stability of the LC phase also decreases. Therefore, the reorientation of the LC molecules becomes slower with temperature. In fact, Moriyama et al. reported that decay was much slower just below the phase transition temperature than at middle of temperatures in LC phase by the measurement using the forced Rayleigh scattering.<sup>37</sup> Consequently, near the N–I phase transition temperature, the reorientation of the LC molecules affects more strongly the recovery process than the diffusion of the LC molecules and the recovery becomes slow.

**Optical Switching in Polymer System.** If the fast decay becomes possible through the diffusion and reorientation processes, what result do we expect for the polymer system? We can expect the slower decay for the polymer because the photoresponsive moiety is linked to the main chain through a chemical bond in the polymer and the mobility of the mesogen is suppressed. Figure 13 shows the result of the time-resolved measurement for the polymer azobenzene liquid crystal, PA6AB2. We observed an instantaneous rise on pulse irradiation which was the same behavior as observed in the low-molecular-weight system. On the other hand, the decay was much slower than that in the low-molecular-weight system. This result strongly supports the decay mechanism which is composed of the diffusion and reorientation processes.

## Conclusions

The optical switching behavior of the low-molecular-weight and polymer azobenzene LCs was investigated by means of reflection-mode analysis. It was found that the reflectivity varied on pulse irradiation under various conditions for orientation of the azobenzene LCs with respect to the incident probe light, either s-polarization or p-polarization. The time-resolved measurements have shown that the reflectivity changed in 100  $\mu$ s and the initial N phase recovered in 1 ms, which was faster by 6 orders of magnitude than those in the transmission-mode measurements. It was confirmed that the fast recovery was characteristic of the reflection-mode analysis and due to the diffusion and reorientation processes of the LC molecules by the detailed measurements in the low-molecular-weight and polymer systems; we obtained the fast recovery for the low-molecular-weight LCs, but a much slower one for the polymer. The rapid optical switching has been achieved successfully by means of the reflection-mode analysis, which may be applicable to optical switching devices.

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