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Input and output grating couplers with a grating period of 1.3 μm were fabricated in an azobenzene liquid-crystalline polymer film by holography. When a He-Ne laser beam at 633 nm was incident to the input grating, the beam was coupled, propagated in the polymer film, and then was taken out from the output grating. The coupling efficiency of the input and output coupler was estimated as about 1.1% in TE mode. Upon irradiation of the film with UV light to cause trans-cis photoisomerization of the azobenzene moiety, the intensity of the output beam was repeatedly changed.

Keywords: azobenzene; grating coupler; holographic; optical switch; waveguide

INTRODUCTION

Nowadays, diffraction gratings have been important elements in integrated optical devices such as optical waveguides, spectral filters, three dimensional information storage devices, since the amount of optical communication and information processing increased with the recent internet systems [1]. The gratings in which light is coupled from the surface of the substrate allows simpler optical setups and facile coupling of light into the integrated multi-layer system

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compared with the conventional end-fire coupling method in which light can be coupled at the edge of the substrate [2–6].

Polymer materials have been investigated for high speed, broadband, multi-function optical integrated devices, and formation of gratings. The gratings can be fabricated by lithographic and reactive ion etching (RIE) techniques [7], or direct methods such as UV laser ablation [8]. Recently several groups have reported that surface relief gratings (SRG_s) were optically produced in azobenzene-containing polymer films in a single process at room temperature [9–25]. Compared to the lithographic and RIE methods, the SRG technique which involves creation of deeply modulated dynamic holographic gratings using a visible CW laser beam, is inexpensive, and enables the formation of efficient optical couplings. This technique also provides gratings with short periods with good controllability. Grating couplers were directly fabricated with azo materials for a guiding layer or a cladding layer [9–11]. In this case, the grating coupler was formed in a waveguide to couple an incident free-space wave into the guiding layer (input coupler) or to couple a guided wave into the air (output coupler) on the same substrate. Efficient optical couplers are a key component in constructing integrated optical devices [26,27].

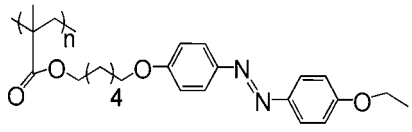
We have studied a series of azobenzene-containing liquid-crystalline polymers and applied them to photonic devices for optical switching, optical data storage, and holography [14–25].

In this paper, we fabricated input and output couplers using SRGs on the azobenzene liquid-crystalline polymer films. Incident light was coupled into the SRG with a slab waveguide and then coupled out from the other output SRG toward the air direction. Furthermore, we investigated an optical switching behavior by irradiation of the film with actinic light.

EXPERIMENTAL

The azobenzene liquid-crystalline polymer, poly {6-[4-(4-ethoxyphenylazo)phenoxy]hexyl methacrylate} (**PM6AB2**) was synthesized as reported previously [28,29]. Figure 1 shows the chemical structure of **PM6AB2** used as a photoresponsive grating coupler. A glass substrate was cleaned with water, acetone, and isopropanol, and put in an ultrasonic bath for 30 min. Polyimide (PI) solution was spin-coated on the glass slide and baked in a convection oven (2 h, 120°C) to yield the 70 nm $\sim$ 80 nm thick film. Before casting a **PM6AB2** solution, the PI film was rubbed in a unidirectional way with a clean cloth.

An optically transparent and homogeneously aligned film was obtained after annealing the film just below the nematic (N)-isotropic



PM6AB2
G 69 N 143 I
M_n = 40,000; M_w/M_n = 4.0

FIGURE 1 The chemical structure and physical properties of **PM6AB2**: G, glassy; N, nematic; I, isotropic; M_n, number-average molecular weight; M_w/M_n, molecular weight distribution.

(I) phase transition temperature (T_{NI}) of **PM6AB2**. Polarized UV-Vis spectra (JASCO, V-550) of the spin-coated **PM6AB2** film were measured to confirm the alignment of the azobenzene moieties in the polymer films and evaluate an order parameter. The order parameter was estimated as 0.24 at room temperature.

The thickness of the films was measured as 1.2 μm with a surface profiler (Dektak 3ST, Veeco instrument Inc.). To record a sinusoidal modulation on the initially flat surface of the **PM6AB2** film, we used the following experimental setup shown in Figure 2. Two coherent laser beams at 488 nm with an equal intensity were obtained with a beam splitter, Glan-Thomson prisms, and two polarizers. Polarization

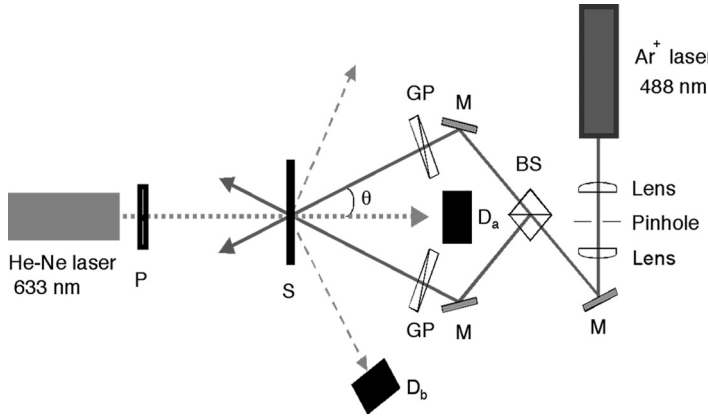


FIGURE 2 Schematic illustration of the experimental setup: M, mirror; BS, beam splitter; GP, Glan-Thomson prisms; QWP, quarter-wave plate; S, sample; P, polarizer; D, detector.

states of the writing beams were set to s-s polarization parallel to the rubbing direction of the film. The formation of such a relief pattern has been found to depend on such parameters as the state of polarization of the intersecting beams, the molecular weight and molecular weight distribution of the materials used for storage. The requirements of additional free volumes between the trans and cis-isomers of the chromophore by the isomerization process cause pressure gradients. These pressure gradients in the polymer film induce mass transportation of the polymer from the regions of high activity [9].

The fringe spacing (Λ) of interference patterns was calculated by the following equation:

$$\Lambda = \lambda_w / 2 \sin \theta$$

where, θ and λ_w are the incident angle and the wavelength of the writing beams, respectively. When the condition of $\lambda_w = 488\,\text{nm}$ and $\theta = 10.8^\circ$ was used, the fringe spacing was estimated as 1.3 μm. The formation of the gratings was monitored by measured the intensity of the transmitted beam and the first order diffraction beam with a photodiode. The ratio of the intensity of the first order diffraction beam to that of the transmitted beam was defined as diffraction efficiency. The formation of the grating was performed at room temperature with the total intensity of writing beams at $400\,\text{mW/cm}^2$. The diffraction beams were immediately observed when the writing beams were turned on. Two grating couplers corresponding to input and output couplers were fabricated with different distance: 7.5 mm and 12.5 mm as shown in Figure 3.

RESULTS AND DISCUSSION

The prepared SRGs were evaluated on a polarizing optical microscope (POM; Olympus, BX50) and the surface structure of the **PM6AB2** films was investigated with an AFM (Shimadzu Corp., Scanning Probe Microscope SPM-9500 J2) after the grating formation. Figure 4 shows the photographs of the recorded interference pattern observed with a polarizing optical microscope between two crossed polarizers. It was found that SRG couplers have a spacing period of 1.3 μm which is coincident with the estimated value by the equation.

The grating structure in the film was clearly observed as shown in Figure 4(a) at 45° and 135° with respect to the polarizer and analyzer. On the other hand, the grating structure was not observed at 0° and 90° as shown in Figure 4(b). This means that a periodic change in the molecular alignment was induced by photoirradiation. Figure 4(c)

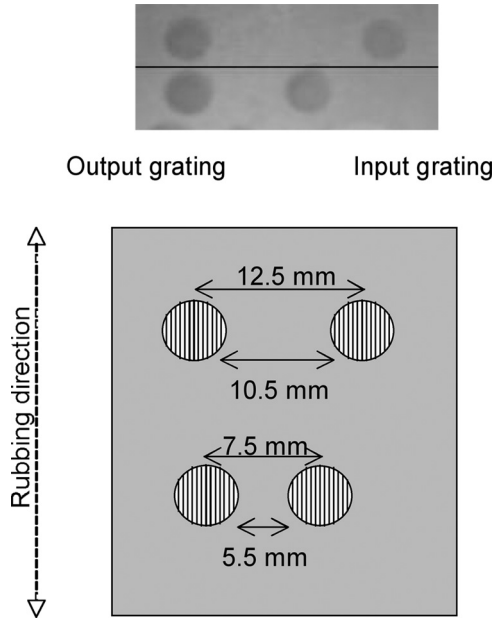


FIGURE 3 The photograph (a) and schematic diagram (b) of input and output grating couplers with the distance of 12.5 mm and 7.5 mm.

shows the AFM image of the holographic grating of **PM6AB2** measured by a tapping mode. The surface modulation with the depth of 50 nm $\sim$ 70 nm was clearly observed.

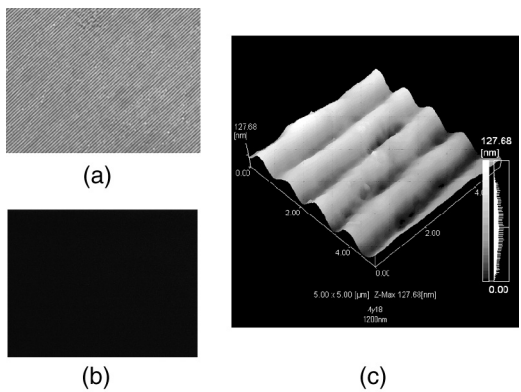


FIGURE 4 Grating structure of **PM6AB2** observed with a polarizing optical microscope (a and b) and AFM image of the film with a 1.3-μm grating period measured by a tapping mode (c).

Figure 5 shows the experimental setup to investigate the coupling behavior of the SRG coupler. The film thickness and grating depth were carefully chosen to allow the coupling of the TE-mode light at 633 nm. When a probe beam was incident to the input grating, the input beam [I_i] was propagated between two gratings as a guided mode by the propagation constant. The propagated wave was coupled from the neighboring grating (output grating) toward different diffraction orders of the air direction [O_A] and the substrate direction [O_S] as shown in Figure 5. A He-Ne laser beam at 633 nm was incident to the grating on the film at an angle of ϕ. The intensity of the output beam from the output grating was measured with a photodiode.

Figure 6(a) shows the angle dependence of the input beam on the intensity of the output beam. It was found that the intensity discontinuously changed at the angles. When the incident angle increased, the intensity of the output beam slightly increased at 6° and steeply rose up at 33°. These increases of the output intensity mean that the coupling conditions are met at these angles and the probe beam is propagated in the **PM6AB2** film. To investigate what happens at coupling

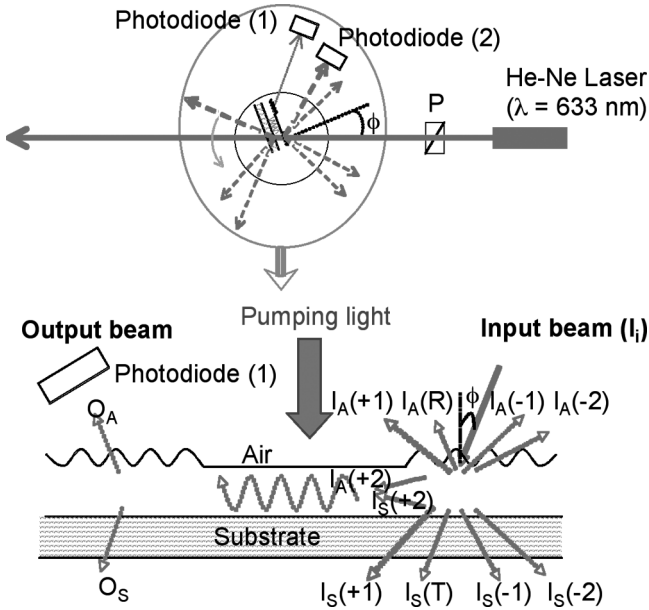


FIGURE 5 Schematic diagram of optical setup and beam configuration of the optical grating coupler. ϕ, incident angle; O_A, output beam from the grating toward the air; O_S, output beam from the grating toward the substrate.

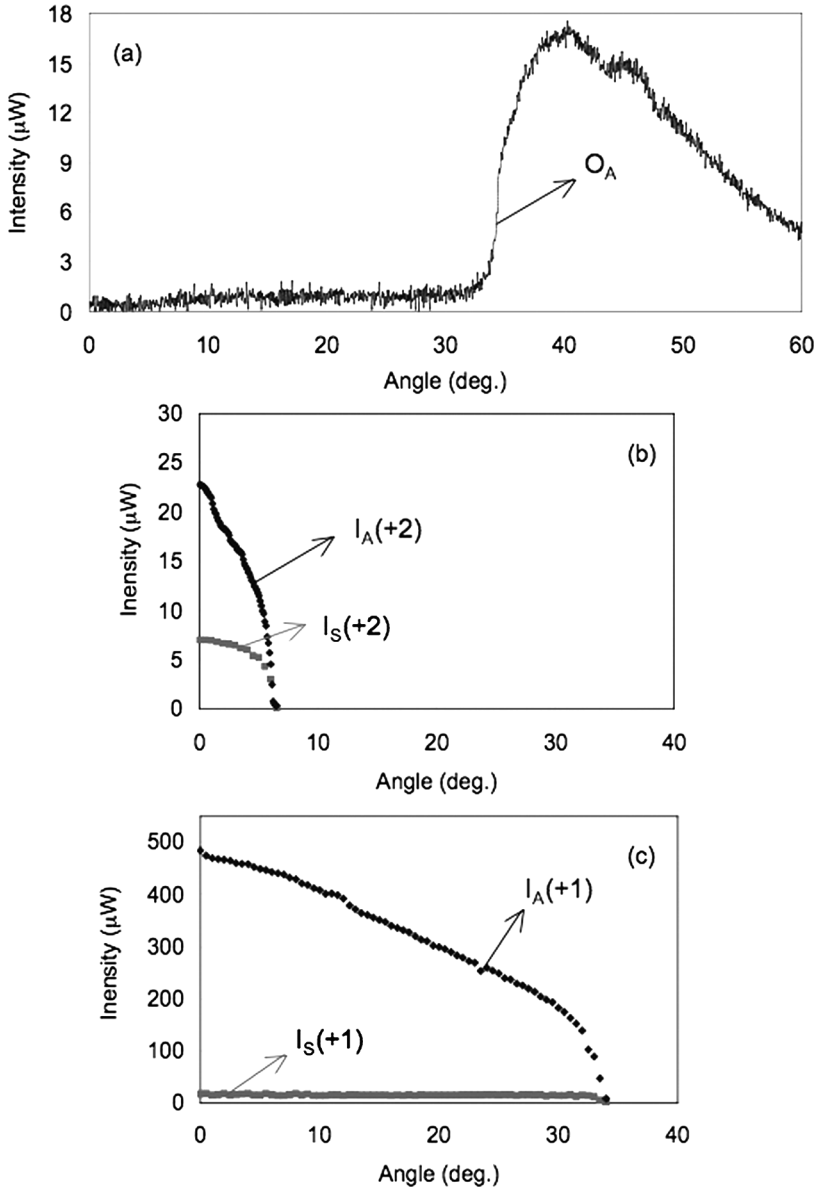


FIGURE 6 Intensity of a He-Ne laser beam from the output grating coupler in the **PM6AB2** film as a function of incident angle. (a) Intensity of $[O_A]$ in the output grating; (b) intensity of the forward second order diffraction $[I_A(+2)$ and $I_S(+2)]$; (c) intensity of the forward first order diffraction $[I_A(+1)$ and $I_S(+1)]$, in the input grating. The distance between the input and output coupler: 7.5 mm.

angles, we also measured the change in intensity of the first and second diffraction beams from the input grating at various incident angles.

No output beam was observed in the output grating, even though the first and second diffraction beams appeared at 0° as shown in Figure 6. As the sample was rotated, the intensity of the second order diffraction beam decreased at 6°, at which the diffraction angle of the beam becomes parallel to the plane of the film as shown Figure 6(b). Furthermore, when the incident angle reached 33°, the first order diffraction decreased markedly as shown Figure 6(c). These results indicate that the diffraction beams are coupled into the film at their coupling angles, and successfully propagated, followed by the decreases in the intensity of the diffracted beams.

Next, we evaluated the coupling efficiency of the SRG coupler with a 1.3-μm grating period. The throughput efficiency was defined as the ratio of the intensity of the light decoupled in one (air) direction to that of the incoming light (I_i) [30,31]. This throughput ratio includes all optical losses regarding input coupling, propagation in the waveguide, scattering, and output coupling. The calculated throughput coupling efficiency of the **PM6AB2** grating coupler was 1.1% at TE mode in one (air) direction [31]. The input efficiency of a grating coupler that allows several diffraction orders, is generally lower than 34% due to the multiple diffraction. The input efficiency of the grating should be less than that of the first order diffraction efficiency. Therefore, the higher coupling efficiency might also be expected if the grating period is shortened until only the first order is allowed.

The optical switching behavior of the SRG was explored when the film was exposed to UV light from a high-pressure mercury lamp, which was isolated with glass filters (Asahi Technoglass, UV-D36B + UV-35 + IRA-25S at 366 nm or Y-43 + V-40 + IRA-25S at 436 nm). The probe beam from a He-Ne laser at 633 nm in TE mode was incident to the film at $\Phi = 40^\circ$ to obtain the highest intensity from the output grating.

Figure 7 shows the change in the intensity of the output beam when the guided region between the input and output gratings was irradiated alternately at 366 nm (10.8 mW/cm^2) and at 436 nm (40.6 mW/cm^2) at room temperature.

Upon photoirradiation at 366 nm, the output intensity increased, then decreased gradually on irradiation of 436-nm light. It was found that the alternating irradiation at 366 nm and 436 nm induced reversible changes in the probe beam. Azobenzenes undergo trans-cis and cis-trans photoisomerization by exposure to UV light and visible light, respectively. As a result, the change in molecular alignment and a

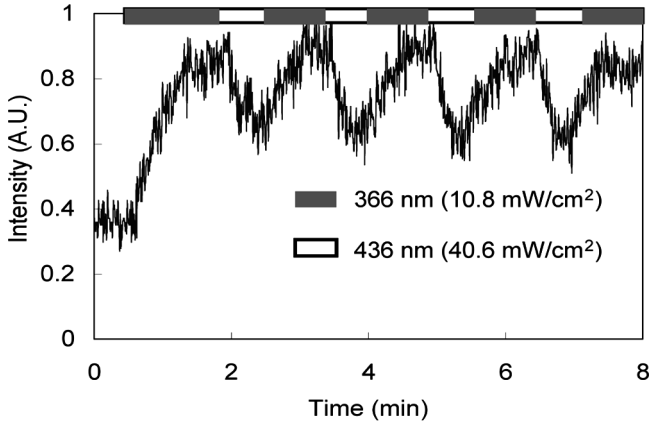


FIGURE 7 Optical switching behavior of the output intensity by pumping light. The distance between the input and output coupler: 7.5 mm.

photochemical phase transition is cooperatively induced, which leads to the change in refractive index of the film. Therefore, we consider that the photoinduced change in refractive index caused the reversible change in propagation efficiency. The large change observed with the first irradiation may be due to an alignment change from an order to a disorder state, which results in a large charge in refractive index. After the second irradiation, small changes are induced mainly by trans-cis and cis-trans isomerization of the azobenzene moiety since the molecular alignment is random and the large change due to the alignment change does not take place.

The initial ordered state provided the high scattering loss and low output intensity. The cis-rich disordered state by the trans-cis photoisomerization of liquid-crystalline polymer containing azobenzene moieties decreased the scattering loss to the TE mode light after irradiation at 366 nm. Even though the azobenzene molecules undergo cis-trans back-isomerization by irradiation at 436 nm, the initial ordered state does not recover, which explains the small change in the output intensity well.

CONCLUSION

In summary, we fabricated the input and output couplers by recording holographic SRGs with a spacing period of 1.3 μm on the liquid-crystalline polymer films containing the azobenzene moiety. The incident probe beam was coupled into the input SRG, propagated in the slab

waveguide, and was coupled out from the output SRG. The coupling efficiency of the input and output couplers was estimated as 1.1% at TE mode in the air direction. Upon irradiation of the film with UV and Vis light, the output beam could be switched repeatedly.

REFERENCES

[1] Delaire, J. A. & Nakatani, K. (1999). *Chem. Rev.*, *82*, 423.
[2] Strasser, T. A. & Gupta, M. C. (1993). *Appl. Opt.*, *32*, 7454.
[3] Strasser, T. A., Hsu, W. Y., & Gupta, M. C. (1993). *Appl. Opt.*, *32*, 6006.
[4] Xing, Q., Ura, S., Suhara, T., & Nishihara, H. (1999). *Electron. Comm. Jpn. 2*, *82*, 423.
[5] Xing, Q., Ura, S., Suhara, T., & Nishihara, H. (1999). *Electron. Comm. Jpn. 2*, *82*, 461.
[6] Hatakoshi, G., Fujima, H., & Goto, K. (1984). *Appl. Opt.*, *23*, 1749.
[7] Johnson, L. F., Kammlott, G. W., & Ingersoll, A. (1978). *Appl. Opt.*, *17*, 1165.
[8] Philips, H., Callahan, D., Sauerberey, R., Szabo, G., & Bor, Z. (1991). *Appl. Phys. Lett.*, *58*, 2761.
[9] Barrett, C., Natansohn, A., & Rochon, P. (1996). *J. Phys. Chem.*, *100*, 8836.
[10] Rochon, P., Natansohn, A., Callender, C. L., & Robitaille, L. (1997). *Appl. Phys. Lett.*, *71*, 1008.
[11] Hirose, T., Omatsu, T., Kato, R., Hoshino, K., Harada, K., Watanabe, T., & Fujii, M. (2003). *Opt. Commun.*, *228*, 279.
[12] Perschke, A. & Fuhrmann, T. (2002). *Adv. Mater.*, *14*, 841.
[13] Rocha, L., Dumarcher, V., Denis, C., Raimond, P., Fiorini, C., & Nunzi, J. M. (2001). *J. Appl. Phys.*, *89*, 3067.
[14] Ikeda, T. (2003). *J. Mater. Chem.*, *13*, 2037.
[15] Natansohn, A. & Rochon, P. (2002). *Chem. Rev.*, *102*, 4139.
[16] Kim, D. Y., Li, L., Kumar, J., & Tripathy, S. K. (1995). *Appl. Phys. Lett.*, *66*, 1166.
[17] Yamamoto, T., Hasagawa, M., Kanazawa, A., Shiono, T., & Ikeda, T. (1999). *J. Phys. Chem. B*, *103*, 9873.
[18] Yamamoto, T., Hasagawa, M., Kanazawa, A., Shiono, T., & Ikeda, T. (2000). *J. Mater. Chem.*, *10*, 337.
[19] Yamamoto, T., Yoneyama, S., Tsutsumi, O., Kanazawa, A., Shiono, T., & Ikeda, T. (2000). *J. Appl. Phys.*, *88*, 2215.
[20] Yamamoto, T., Ohashi, A., Yoneyama, S., Hasegawa, M., Tsutsumi, O., Kanazawa, A., Shiono, T., & Ikeda, T. (2001). *J. Phys. Chem. B*, *105*, 2308.
[21] Yoneyama, S., Yamamoto, T., Hasegawa, M., Tsutsumi, O., Kanazawa, A., Shiono, T., & Ikeda, T. (2001). *J. Mater. Chem.*, *11*, 3008.
[22] Yoneyama, S., Yamamoto, T., Tsutsumi, O., Kanazawa, A., Shiono, T., & Ikeda, T. (2005). *Macromolecules*, *35*, 8751.
[23] Ikeda, T. & Tsutsumi, O. (1995). *Science*, *268*, 1873.
[24] Kurihara, H., Shishido, A., Tsutsumi, O., Shiono, T., & Ikeda, T. (2005). *Mol. Cryst. Liq. Cryst.*, *441*, 173.
[25] Kurihara, H., Shishido, A., & Ikeda, T. (2005). *J. Appl. Phys.*, *98*, 083510.
[26] Donval, A., Toussaere, E., Zyss, J., Levy-Yurista, G., Jonsson, E., & Friesem, A. A. (2001). *Synth. Met.*, *124*, 19.
[27] Pascal, D., Orobtchouk, R., Layadi, A., Koster, A., & Laval, S. (1997). *Appl. Opt.*, *36*, 2443.

[28] Angeloni, A. S., Caretti, D., Carlini, C., Chiellini, G., Galli, G., & Altomare, A. (1989). *Liq. Cryst.*, *4*, 513.
[29] Ringsdorf, H. & Shmidt, H. W. (1984). *Makromol. Chem.*, *185*, 1327.
[30] Waldhausl, R., Schnabel, B., Dannberg, P., Kley, E.-B., Brauer, A., & Karthe, W. (1997). *Appl. Opt.*, *36*, 9383.
[31] Gong, Q., Assanto, G., Zanoni, R., Stegeman, G. I., Burzynski, R., & Prasad, R. N. (1990). *Appl. Opt.*, *29*, 3887.