Electrically controllable in-line-type polarizer using polymer-dispersed liquid-crystal spliced optical fibers

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The polarization-dependent transmission of light through an electrically controllable in-line-type polarizer that is made from polymer-dispersed liquid-crystal spliced optical fibers is discussed experimentally and theoretically. This in-line-type optical splicing method has the advantage of low transmission loss when it is applied in optical fiber communication systems. An anomalous diffraction approach is used to compute the scattering cross section of polymer-dispersed liquid-crystal droplets. The experimental results are supported by a theoretical analysis. This device can be employed in electrically controllable in-line-type polarizers and has the potential to yield electrically controllable polarization-dependent loss compensators. © 2003 Optical Society of America

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1. Introduction

Polymeric dispersion of liquid crystals (LCs) was recently demonstrated in optical and optoelectronic devices. The interest in polymer-dispersed liquid crystals (PDLCs) comes from their applications, such as light modulators used in displays and in switching devices. In this paper we describe and study the feasibility of a new in-line-type polarizer that uses PDLCs.

A schematic diagram of our in-line-type polarizer with PDLC spliced optical fibers is shown in Fig. 1. PDLCs, which are randomly oriented initially, are placed between optical fibers. An external electric field is applied by means of a low-frequency voltage source and metallic electrodes. The fibers are aligned with a glass tube for maximum coupling efficiency. PDLCs have randomly distributed micro-sized LC droplets immersed in a polymer matrix. The spherical droplets are usually uniform in size throughout the dispersion but can vary from 0.1 to 10 µm, depending on the properties of the polymers and the LCs, on their concentrations, and on environmental conditions such as temperature. The nematic director configuration within droplets depends on surface anchoring, elastic constants, and external fields. Droplets are optically anisotropic materials whose optic axis directions vary in space as determined by local nematic directors. PDLCs are commonly used as optoelectronic films that switch between opaque and transparent states for display purposes. In the communications wavelength region PDLCs also become opaque through the process of UV curing and can be transparent with an external field. Therefore the transmission of light can be electrically controllable. Moreover, as droplets are randomly oriented, the optical refractive indices of PDLCs are effectively identical regardless of the polarization state of the incident light in the absence of an external field. As a result, an incident light experiences an identical refractive index, and its scattering loss is unchanged regardless of the polarization state. When an external field is applied, the nematic directors within the droplets become reoriented in accordance with the direction of an external field. Therefore in this case the incident light experiences a different refractive index, depending on the polarization state. As a result, PDLCs have electrically controllable polarization-dependent scattering loss. The scattering characteristics of polarized light have been studied in film- and cell-type PDLCs. However, devices that use PDLC films or cells have a critical disadvantage when they are employed in optical fiber communication systems. Light guided by optical fibers has to be launched from one fiber and recoupled to another fiber in these bulk devices. Thus the alignment of these two fibers with a bulk device is mandatory but difficult. As a result, additional loss could occur, which limits the practical use of such devices. Therefore the optical fiber splicing method with in-line-type PDLCs has the important advantage of easy alignment and low transmission loss.

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There are no exact theoretical solutions for light scattering from small and optically anisotropic materials. In general, approximations that are appropriate for specific conditions must be used. The Rayleigh–Gans approximation is valid for small (when the object’s diameter is much smaller than the wavelength of light) and optically soft (weakly refracting) objects. For large and optically soft objects the anomalous diffraction formula must be used. The ADA approximation is valid for small diameter is much smaller than the wave.

2. Theory

Assuming that the number of droplets per unit volume between two fibers is not high, a single-scattering regime may prevail. The transmission intensity is

\[ I = I_0 \exp(-Nd\sigma), \]

where \( N \) is the number of droplets per unit volume, \( d \) is the distance between two fibers, and \( \sigma \) is the total scattering cross section, that is, the droplet scattering cross section averaged over the whole PDLC area. The reference frame is shown in Fig. 2. In this figure \( \mathbf{k} \) is the wave vector, \( \mathbf{N}_d \) is the director of the droplet, \( \mathbf{E}_{\text{opt}} \) is the optical wave incident upon the PDLCs, and \( \mathbf{E}_{\text{ext}} \) is the externally applied electric field. \( \gamma_d \) is the incident angle between a wave vector and a director of droplets, \( \theta \) is the angle between the droplet director and the applied electric field, and \( \phi \) is the angle between \( \mathbf{N}_d \) and the wave vector. We assume that a monochromatic wave is traveling through the PDLC orthogonally to the section of the fibers and that a low-frequency transverse electric field is applied in a direction orthogonal to the wave vector. Inasmuch as the wave vector is parallel to the \( x \) axis, we can write \( \mathbf{k} = (1, 0, 0) \) and \( \mathbf{N}_d = (\cos \phi, \sin \theta \sin \phi, \cos \theta) \). Thus \( \gamma_d \) is expressed as

\[ \gamma_d = \cos^{-1}(\sin \theta \cos \phi). \]
The droplet’s refractive indices can be expressed as\textsuperscript{11}

\[ n_{do} = \frac{2}{\pi} \frac{n_e}{n_o} \left( \frac{\pi}{2} \cdot \frac{1}{n_e} \left[ \frac{2}{3} (n_e^2 - n_o^2)(1 - S_d) \right]^{1/2} \right), \quad (10) \]

\[ n_{de} = \frac{n_e n_o}{n_e^2 - \frac{1}{3} (n_e^2 - n_o^2)(1 + 2S_d)}^{1/2}, \quad (11) \]

\[ S_d = 1 - (1 - S_{d0}) \exp(-E_{cos}/E_d), \quad (12) \]

where \( n_o \) and \( n_e \) are the ordinary and extraordinary refractive indices of the LC, respectively, and \( F(\pi/2, m) \) is a complete elliptical integral of the first kind. Droplet order parameter \( S_d \) is related to the orientation of the molecules inside the droplet, and \( S_{d0} \) is the value assumed by \( S_d \) when no external field is applied. For \( E_d \) the reorientation of the LC’s molecules inside each droplet is taken into account.

Without an external electric field the incident light has a refractive index that remains the same regardless of the polarization states of the incident light because of the random orientation of droplets even if a PDLC droplet is an anisotropic sphere. When an external field is applied, however, the PDLC droplets become aligned in the direction of the external field. Thus the various transmission characteristics can be related to the polarization states of the incident light. So we have to distinguish two different polarization states, ordinary and extraordinary. If incident light is unpolarized and if there is no external field, the scattering characteristics of the incident light through the device are similar to those of polarized light owing to the random orientation of droplets. When PDLC droplets are realigned with an external electric field, the transmittance of unpolarized light varies randomly from 0 to 1 with time because the polarization state of unpolarized light varies with time. Hence the average transmission can be thought of as a time average for all kinds of polarization states of incident light. Therefore for unpolarized light we assume that the incident light has an effective electric vector that forms an angle of 45° with respect to the \( z \) axis. Inasmuch as an external electric field is applied along the \( z \) axis, the distribution function of an external field is uniform with respect to \( \phi \). Thus it is possible to get the average of \( \phi \) just by carrying out the integration of \( \phi \):

\[ \langle \sigma_d^{\text{unp}} \rangle_\phi = \frac{1}{2\pi} \int_0^{2\pi} \sigma_d^{\text{unp}} d\phi. \quad (15) \]

This integration has an analytical solution, which is

\[ \langle \sigma_d^{\text{unp}} \rangle_b = \frac{1}{2} \sigma_d(2kR)^2 \left( \frac{3}{16} \cos^4 \theta + \frac{1}{8} \cos^2 \theta \right. \]

\[ + \frac{3}{16} \frac{3}{16} n_{do}^2 + \frac{3}{16} \cos^4 \theta - \frac{3}{8} \cos^2 \theta \]

\[ + \frac{11}{16} n_{do}^2 + n_{do}^2 - \frac{3}{8} \cos^4 \theta - \frac{1}{4} \cos^2 \theta \]

\[ - \frac{1}{8} n_{do} n_d - \frac{1}{2} (1 + \cos^2 \theta) n_{do} n_p \]

\[ - \frac{1}{2} \left( - \frac{1}{2} (3 - \cos^2 \theta) n_{do} n_p \right). \quad (16) \]

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After some manipulation we can obtain the expression that shows the droplet’s scattering cross section:

\[
\langle \sigma_d^{\text{unp}} \rangle_\theta = \frac{1}{2} \sigma_d(2kR)^2 [C_0^{\text{unp}} + C_2^{\text{unp}} P_2(\cos \theta) + C_4^{\text{unp}} P_4(\cos \theta)], \tag{17}
\]

where \(P_2(\cos \theta)\) and \(P_4(\cos \theta)\) are the second- and fourth-order Legendre polynomials, respectively, and their coefficients are

\[
C_0^{\text{unp}} = \frac{95}{336} n_{de}^2 + \frac{69}{112} n_{do}^2 + \frac{2}{3} n_{de} n_p - \frac{2}{3} n_{do} n_p - \frac{4}{3} n_{de} n_p + \frac{5}{168} n_{do} n_{de},
\]

\[
C_2^{\text{unp}} = \frac{\Delta n_d (4n_{de} + 3n_{do} - 7n_p)}{21n_p^2},
\]

\[
C_4^{\text{unp}} = \frac{3\Delta n_d^2}{70n_p^2},
\]

where

\[
\Delta n_d = n_{de} - n_{do}.
\tag{21}
\]

The dependence of Eq. (17) on \(\theta\) is limited to only Legendre polynomials. Hence we can obtain the total scattering cross section by averaging the Legendre polynomials with respect to \(\theta\):

\[
\langle \sigma_d^{\text{unp}} \rangle_\theta = \frac{1}{2} \sigma_d(2kR)^2 [C_0^{\text{unp}} + C_2^{\text{unp}} \langle P_2(\cos \theta) \rangle_\theta + C_4^{\text{unp}} \langle P_4(\cos \theta) \rangle_\theta].
\tag{22}
\]

The average of Legendre polynomials is given by

\[
\langle P_2(\cos \theta) \rangle_\theta = S_D,
\tag{23}
\]

\[
\langle P_4(\cos \theta) \rangle_\theta = \frac{7}{12} + \frac{5}{12} S_D - \frac{35}{32e_r} \left[ \frac{2}{3} + \frac{(e_r^2 - 1)^2}{4e_r^2} \right. \\
- \frac{(e_r^2 + 1)^2(e_r^2 - 1)}{8e_r^3} \left. \tan^{-1} \left( \frac{2e_r}{e_r^2 - 1} \right) \right],
\tag{24}
\]

where \(S_D\) and \(e_r\) are the device order parameter and the dimensionless reduced electric field, respectively.

The device order parameter and the dimensionless electric field are related by

\[
S_D = \frac{1}{4} + \frac{3(e_r^2 + 1)}{16e_r^2} + \frac{3(3e_r^2 + 1)(e_r^2 - 1)}{32e_r^3} \ln \left| \frac{e_r + 1}{e_r - 1} \right|,
\tag{25}
\]

\[
e_r = E_{\text{ext}} \left[ \frac{3\epsilon_p \nu_{\text{LC}}}{\epsilon_{\text{LC}} + 2\epsilon_p - \nu_{\text{LC}}(\epsilon_{\text{LC}} - \epsilon_p)} \right]^{1/2},
\tag{26}
\]

\[
\epsilon_{\text{LC}} = \epsilon_\perp + \frac{1}{3} (1 + 2S_D S_D)(\epsilon_\parallel - \epsilon_\perp),
\tag{27}
\]

where \(\nu_{\text{LC}}\) is the volume fraction of LCs in the device; \(\epsilon_p\) is the dielectric constant of the polymer; \(\epsilon_{\text{LC}, \perp}\), in response to the external field, is the dielectric constant of LCs, averaged over the device; and \(K\) is an elastic constant per unit volume for which the relaxation of the droplets to their original orientation after the applied field has been removed is taken into consideration.

B. Ordinary Polarized Light

In Fig. 2 the ordinary polarized light can be expressed by \(\mathbf{E}_{\text{opt}} = (0, 1, 0)\) and polarization angle \(\alpha_d^{\text{opt}}\), so the droplet scattering cross section \(\sigma_d^{\text{opt}}\) for a single droplet is given by

\[
\sigma_d^{\text{opt}} = \frac{1}{2} \sigma_d(2kR)^2 (C_0^{\text{opt}} \cos^2 \alpha_d^{\text{opt}} + C_2^{\text{opt}} \sin^2 \alpha_d^{\text{opt}}),
\tag{28}
\]

where

\[
\alpha_d^{\text{opt}} = \sin^{-1} \left( \frac{\cos \theta}{\sin \gamma_d} \right).
\tag{29}
\]

Using a procedure similar to that for unpolarized light, we can obtain the total scattering cross section:

\[
\sigma_d^{\text{opt}} = \frac{1}{2} \sigma_d(2kR)^2 [C_0^{\text{opt}} + C_2^{\text{opt}} \langle P_2(\cos \theta) \rangle_\theta + C_4^{\text{opt}} \langle P_4(\cos \theta) \rangle_\theta],
\tag{30}
\]

\[
C_0^{\text{opt}} = \frac{4n_{de}^2 + 9n_{do}^2 + 15n_p^2 - 10n_{de}n_p - 2n_{do}n_p + 2n_{do}n_{de}}{15n_p^2},
\tag{31}
\]

\[
C_2^{\text{opt}} = -\frac{\Delta n_d (5n_{de} + 9n_{do} - 14n_p)}{21n_p^2},
\tag{32}
\]

\[
C_4^{\text{opt}} = -\frac{\Delta n_d^2}{35n_p^2},
\tag{33}
\]
where $\Delta n_d$ is given by Eq. (21) and the averages of the Legendre polynomials over $\theta$ are the same as those in Subsection 2.A.

C. Extraordinary Polarized Light

We can also get the total cross section for the extraordinary polarized light through a process similar to that described in Subsection 2.B. The incident light that is in a state of extraordinary polarization can be described by $E_{\text{opt}}^e = (0, 0, 1)$ (Fig. 2), so the polarization angle and the total scattering cross section are expressed by

$$\alpha_d^e = \cos^{-1}\left(\frac{\cos \theta}{\sin \gamma_d}\right),$$

$$\sigma_z^e = \frac{1}{2} \sigma_0 (2kR)^2 [C_0^e + C_4^e (P_2(\cos \theta))_0 + C_4^e (P_4(\cos \theta))_0],$$

$$C_0^e = \frac{4n_{de}^2 + 9n_{do}^2 + 15n_p^2 - 10n_{de}n_p - 20n_{do}n_p + 2n_{de}n_{do}}{15n_p^2},$$

$$C_2^e = \Delta n_d (13n_{de} + 15n_{do} - 28n_p),$$

$$C_4^e = \frac{4\Delta n_d^2}{35n_p^2}.$$

3. Experiment

A schematic diagram of our experimental setup is shown in Fig. 3. In the experiment with unpolarized incident light, the polarizer located after the light source is not needed, so it is removed. However, a polarizer is necessary for detection of the polarization-dependent characteristics of the device because the amplified spontaneous emission of an erbium-doped fiber amplifier (EDFA), which is used as the broadband light source, is an unpolarized light source. An optical spectrum analyzer is used for detection of transmitted light. An external electric field is applied by means of a low-frequency voltage source and metallic electrodes. The PDLC-filled glass tube can be seen clearly in Fig. 1. For our experiments, curing of PDLCs with a UV gun is needed. The PDLC used in our experiments is mixture of a LC, E48 (from Merck, Korea), and UV-curable polymer, NoA65 (from Norland), at a 50:50 ratio by weight. Before UV curing the PDLC is transparent to light from the EDFA, but it becomes opaque through UV curing, as shown in Fig. 4. In addition, the spliced optical fibers are fixed by the polymer inside the PDLCs because the polymer becomes adhesive through UV curing. This is a practically important characteristic that can distinguish PDLCs from other LC optical fiber devices.14–16

In the absence of an external field the PDLC droplets are randomly oriented such that unpolarized incident light experiences scattering loss as a result of refractive-index mismatch. When an external field is applied, droplets are realigned in accordance with the direction of the external field, so the scattering loss becomes small. The theoretical and experimental results of the unpolarized light case are shown in Fig. 5. The solid curve and the squares represent theoretical and experimental results, respectively. The values of the parameters of droplets used for the theoretical simulation are $N = 7.07 \times 10^{19}$, $R = 150$ mm, $K_d = 4.00 \text{ N/m}^2$, $E_d = 2.57 \times 10^3$ V/m, $S_{do} = 0.7$, and $v_{LC} = 0.6$. The distances between electrodes, $D$, and fibers, $d$, are $D = 3$ cm and $d = 60$ $\mu$m. The
principal ordinary and extraordinary refractive indices of the LC are \( n_o = 1.5143 \) and \( n_e = 1.6802 \) at 1550 nm and, in addition, the dielectric constants of the LC are \( \varepsilon_\perp = 5.4 \) and \( \varepsilon_\parallel = 20.5 \), respectively, at 1 kHz. The principal refractive index and dielectric constant of polymer are \( n_p = 1.4883 \) and \( \varepsilon_p = 4.5854 \), respectively; they are the values at the same wavelength and frequency as those of a LC. The scattering cross section discussed in Section 2 was based on a far-field approximation. Because we are assuming that the single-scattering regime is valid, and considering that LC molecules are dispersed within the two fibers at a distance \( d = 60 \ \mu m \), we can assume that the distance between the scattering molecule and the second optical fiber is generally much larger than the wavelength of light \( (~1.55 \ \mu m) \). Hence the far-field approximation is valid. Even though the theoretical model is somewhat limited, the simulation result is in agreement with the experimental result. In addition, the dotted curve in Fig. 5 represents the ensemble average of the theoretical results for ordinary and extraordinary polarization states of the incident light derived from the analysis described in Subsections 2.B and 2.C. Figure 5 shows that the assumption described in Section 2 (solid curve) is in more reasonable agreement with experiments than the dotted-curve case.

We obtained the experimental results shown in Fig. 6 by using the experimental setup shown in Fig. 3. A polarizer was used in this experiment. The solid and dashed curves in Fig. 6 represent the simulation results for ordinary and extraordinary polarization states, respectively, of the incident light, and the filled and open squares also represent the experimental results for ordinary and extraordinary polarization. In addition, the dotted curve in Fig. 6 represents the theoretical results (of Subsection 2.A) for unpolarized incident light. The values of the parameters used for the simulation of polarized incident light are similar to those for unpolarized incident light, except for \( d = 125 \ \mu m \). In the ordinary polarization state of incident light the extent of the index mismatch becomes to be small because of the external field, so the scattering loss becomes smaller and the transmitted power becomes larger. In the extraordinary polarization state of incident light, however, the extent of index mismatching gets larger; as a result the transmitted power becomes smaller with an increase of the external field. For unpolarized incident light it can be also seen that the transmission is greater than the ensemble average of the ordinary and extraordinary polarized light, but its variation based on applied voltage is similar to that of Fig. 5.

4. Conclusions

Electrically controllable transmission of an in-line-type polarizer that uses PDLC spliced optical fibers has been demonstrated. The proposed device has superior coupling efficiency because of the advantage of easy fiber alignment. The transmission variations in unpolarized light and the transmission difference between two orthogonal polarizations of light are \( -3.5 \) and \( -10 \ dB \), respectively, at 100 V. The experimental results are supported by the theoretical analysis. This scheme should be useful for an in-line-type polarizer and also has the potential for application to electrically controllable switching and to polarization-dependent loss compensation.

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