We propose a concept of fabricating a liquid-crystal (LC) polarization beamsplitter based on binary phase gratings. The binary grating phenomenon in the LC layer physically originates from two different interfacial interactions at periodically alternating domain boundaries. The periodic LC domains are produced by employing a single-step photoalignment technique which precisely controls the surface orientation of the LC molecules in an alternating homeotropic and hybrid aligned geometry. In this binary configuration, the polarization-separating phase modulation of an input beam is achieved in a wide range of the wavelengths under an applied voltage. The experimental data are consistent with our linearly graded binary model. © 2003 American Institute of Physics. [DOI: 10.1063/1.1609042]
\[
\eta_k = \frac{1}{\Lambda^2} \int_{-\Lambda/2}^{\Lambda/2} e^{i\phi} e^{-i(2\pi k x/\Lambda)} dx^2,
\]

where \( \phi \) is the phase shift dependent on \( x \) in one grating period of \( \Lambda \). In our binary phase grating system as shown in Fig. 1, the resulting diffraction efficiency of the \( k \)th order is calculated as

\[
\eta_k = \begin{cases} 
\cos^2((\Delta \phi/2) & \text{if } k = 0, \\
\left[ (2/k\pi) \sin(k\pi/2) \right]^2 \sin^2(\Delta \phi/2) & \text{if } k \neq 0,
\end{cases}
\]

where \( \Delta \phi \) is the relative phase difference between two adjacent homeotropic and hybrid domains in the binary grating system. For the case that off-diagonal elements do not vanish in the Jones matrix, any linearly polarized beam can be decomposed into two linearly polarized states that are orthogonal to each other. In our case, the diffracted beam of a linearly polarized input is decomposed into the \( x \) and \( y \) components. As shown in Fig. 1(a), only the input beam polarized along the \( y \) direction experiences the phase difference of \( \Delta \phi = 2\pi(n_{\text{eff}} - n_{\text{e}})dx/\lambda \), where \( \lambda \) is the wavelength of the input beam. Note that at \( \Delta \phi = (2n + 1)\pi \) (\( n \) integer), the diffractional efficiencies of odd orders \( (k = \pm 1, \pm 3, \pm 5, \ldots) \) have the maxima while the zeroth order or the nondiffracted beam has the minima of zero. For the case that \( \Delta \phi = (2n + 1)\pi \), all of the odd orders of the diffracted beam are polarized along the \( y \) direction and the zeroth order is polarized along the \( x \) direction. As for an ideal case, it is obtained from Eq. (3) that the diffraction efficiency of the first order \( \eta_{\pm 1} = 40.5% \) is nine times larger than that of the third order \( \eta_{\pm 3} = 4.5% \). Therefore, it is not unreasonable to deal with only the zeroth and the first orders of the diffracted beam.

In the light of the aforementioned idea of the LC PBS, we fabricated an alternating homeotropic and hybrid aligned LC cell with binary phase gratings using a single-step photoalignment technique. The periodicity of the grating was chosen as 20 \( \mu \)m as predicted in a linearly graded binary model for observing the binary phase grating phenomenon. The curvature distortions of the LC were assumed to be linear in the interfacial region in our graded binary model. The photosensitive polymer should be capable of aligning the LC molecules homogeneously by the polarized ultraviolet (UV) exposure and homeotropically without the UV treatment. The photopolymer material used was LGC-M1 of LG Cable, Ltd. (Anyang, Korea) It has cinnamoyl containing photosensitive side-chain groups attached to polymethacrylate backbone. The photopolymer dissolved in cyclohexane was coated onto transparent indium-tin-oxide glass substrates and baked at 150°C for 30 min. An array of one-dimensional binary phase gratings was then produced on the substrate by a single-step exposure of a polarized UV beam through an amplitude photomask at 2.0 mW for 2 min. Under the polarized UV exposure, the photosensitive side chains induce the anisotropic photoreaction along the polarization direction of the UV beam which is perpendicular to the LC molecular director. It should be noted that the magnitude of the pretilt angle with respect to the substrate plane depends on both the intensity and the incident angle of the UV light. In our case, the pretilt angle was about 3° in the UV exposed region while it was about 89° in the unexposed region. The gap of the LC cell was maintained using glass spacers of 8.8 \( \mu \)m thick. A commercially available nematic LC, MLC-6012 of E. Merck, was filled into the cell at 95°C in the isotropic state. The ordinary and extraordinary refractive indices of MLC-6012 are \( n_o = 1.4620 \pm 5682/\lambda^2 \) and \( n_e = 1.5525 + 9523/\lambda^2 \), respectively, where \( \lambda \) is the wavelength of light in nm. The dielectric anisotropy and the elastic constants are \( \epsilon_{a} = 8.2 \), \( K_1 = 11.6 \times 10^{-12} \text{ N} \), \( K_2 = 5.5 \times 10^{-12} \text{ N} \), and \( K_3 = 16.1 \times 10^{-12} \text{ N} \), respectively.

The microscopic textures of our LC cell with binary phase gratings in an alternating homeotropic and hybrid geometry are shown in Figs. 2(a) and 2(b). The two photographs showing two alternating stripes were taken with a polarizing optical microscope (Nikon, Optiphoto Pol II) under crossed polarizers when the grating vector makes angles of 0° and 45° with respect to one of the crossed polarizers. Although an ideal binary grating device has no grating effect, our LC device exhibits some degree of the grating effect in the absence of an applied voltage as shown in Fig. 2(a). This results from the initial curvature distortions of the LC at two different domain boundaries in the periodically alternating homeotropic and hybrid geometry. However, the observed nonzero grating effect does not limit the applicability of our LC device for use as a PBS. Basically, this binary nature of the LC grating structure will be capable of spatially controlling the phase modulation and the polarization separation of the diffracted beam by adjusting an applied voltage. In other words, the polarization of the diffracted beam will be separated into two well-defined components, the \( x \) and \( y \) components, that are mutually orthogonal. One point is that the phase retardation will vary with the applied voltage only in the UV exposed regions when the grating vector makes a nonzero angle with respect to the polarizer. In the boundaries of the alternating gratings, there exist curvature distortions of the LC director due to the elasticity of the LC.

Three laser sources of 488 nm, 544 nm, and 632.8 nm in wavelength were used to examine the effect of the input wavelength on the polarization separation of the diffracted beam. The angle between the \( x \) direction and the polarizer was fixed to be 45° so that the \( x \) and \( y \) components of the input beam are identical. The two components of the diffracted beam passed through the LC cell were simultaneously measured using a commercial beamsplitter. All of the measurements were performed using a square wave voltage of 1 kHz at room temperature.

Figure 3 shows the \( x \) and \( y \) components of the zeroth and the first orders of the diffracted beam as a function of the
applied voltage for fixed input wavelength of 632.8 nm. The solid lines in Fig. 3 represent theoretical results predicted in the linearly graded binary model for the binary grating phenomenon. The two $x$ components are quite insensitive to the applied voltage $V_a$ while the $y$ components show a strong dependence on $V_a$. Note that the $x$ component of a higher order, i.e., the first order, and the $y$ component of the zeroth order are essentially zero at $V_a=1$ V, which corresponds exactly to the case of $\Delta \phi = \pi$ in Eq. (3). This means that at such a voltage, the LC cell behaves as an ideal PBS which separates the polarization of the diffracted beam into a pair of beams, one of which is polarized along the $x$ direction and the other along the $y$ direction. In fact, only the $y$ component, polarized perpendicular to the grating vector, of an input beam always experience the phase modulation and the polarization separation on passing through the LC cell with binary phase gratings. As already discussed in Fig. 2(a), there exists the difference between the experimental and theoretical results in the low-voltage limit. Generally, the curvature distortions of the LCs at different domain boundaries depend on the grating periodicity and the applied voltage.

In Fig. 4, the input wavelength selection and the tuning capabilities of our LC PBS cells with different cell gaps were shown as a function of the applied voltage under the condition that both the $x$ component of the first order and the $y$ component of the zeroth order of diffraction vanish. For example, the input wavelength of 632.8 nm and $V_a=1.0$ V for the LC cell of 8.8 $\mu$m thick corresponds to the case of $\Delta \phi = \pi$. Generally speaking, a relatively thick LC cell is desirable to obtain the tuning capability as well as the polarization separation of the diffracted beam. For given cell gap, a rather high voltage is required for a short wavelength of an input beam. The measured extinction ratio of the LC cell was found to be about 100:1 for three different input wavelengths of 488 nm, 544 nm, and 632.8 nm. It is clear that the experimental data agree well with theoretical predictions shown in Fig. 4. Note that in the absence of the applied voltage, the LC cell of 6.75 $\mu$m thick behaves as a PBS for fixed input wavelength of 632.8 nm. It may be concluded that a thick LC cell provides a wider selection of the input wavelength but it is more sensitive to variations of the applied voltage than a thin LC cell.

In summary, we have demonstrated that the LC cell with binary phase gratings in an alternating homeotropic and hybrid aligned geometry provides the polarization-separating phase modulation and diffraction together with the wavelength tunability as a function of an applied voltage. Details of our linearly graded binary model for the binary grating phenomenon will be published elsewhere. The fabrication process of our LC PBS is simple and powerful for tailoring the device characteristics since only one step UV exposure through an amplitude photomask was employed to produce an array of alternating homeotropic and hybrid domains on the photosensitive polymer. The LC PBS presented here is expected to have a significant impact on various optical systems for optical signal processing and optical data storage.

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15 Data provided by E. Merck Company.