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Switchable Zero-Order Diffraction Filters Using Fine-Pitch Phase Gratings Filled with Liquid Crystals

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Zero-order transmission efficiency is controlled using electrically switchable liquid crystals confined in periodic fine grooves. Trapezoidal grating profiles are designed in order to improve the extinction ratio. Using the index matching and mismatching conditions of liquid crystals with the grating grooves, we achieve a transparent window for the entire visible range in the matching state, and a dark color filter in the mismatching state. Spectral transmittance is changed through the frequency-dependent anisotropic permittivity of the liquid crystal. Polarization-insensitive operation is performed using a two-stack device with crossed grating directions.

KEYWORDS: diffraction grating, liquid crystal, zero-order diffraction, optical filter, light valve

1. Introduction

Electrically switchable optical filters have a variety of possible uses such as light valves, tunable color filters, displays, and optical switches. Several types of switchable filters based on liquid crystals exhibit advantages such as two-dimensional formability and low power consumption, however, their light utilization is still too low to make the filters optically clear.[1–3] Most of the liquid crystal filters using Fabry-Perot etalons or variable birefringence systems require at least one fixed linear polarizer, implying that at least 50% of the incident light is wasted. The guest-host mode liquid crystals are fixed in color and reveal some absorptive loss even in the open state. A compromise between the optical efficiency and the extinction ratio needs to be considered.

Diffraction gratings are generally used with diffracted light other than that of the zero order, even though the zero-order light, which is generated by subtraction of the other diffractive orders, has valuable features, *e.g.*, high efficiency and color representation with no dispersion. Surface-relief gratings have been used to reproduce color and black-and-white images for the zero-order diffraction.[4,5] In order to fabricate a switchable filter, the diffraction grating must have voltage-addressable optical properties. Micromechanical structures realize zero-order diffraction light valves; however, they often require a high driving voltage.[6] Liquid crystals are an obvious choice for use in switchable layers as they exhibit large changes in refractive indices which can be driven with low voltages. Knop and Kane first described a tunable subtractive filter composed of a phase grating layer and a liquid crystal layer in their patent.[7] Electrical modulation of the zero-order beam was experimentally demonstrated by filling the diffraction gratings with liquid crystals, showing the efficient use of light with a high extinction ratio.[8] Recently, liquid-crystal-filled gratings with very fine pitches were investigated for their ability to switch the beam from the zero order to the first order.[9] In this study, we examined light modulation over the visible range with optimally designed tunable phase gratings based on liquid crystals.

2. Principles and Designs

The experimental model, shown in Fig. 1, basically consists of two glass substrates with transparent electrodes that are separated by periodic grooves filled with liquid crystals. In the absence of applied voltage, the liquid crystal molecules orient themselves along the narrow tubes constructed by the grooves and the cover. Thus when the electric field of the incident light is polarized in the direction of the groove lines (TE polarization), the incident light detects the extraordinary refractive index (n_e) of the liquid crystal in the off-state. Under an electrical bias, the liquid crystal undergoes a deformation, tilting out of the plane of the substrate. On application of a full voltage to the electrodes in the on-state, the molecules reorient perpendicular to the substrate, in which case the incident light detects the ordinary index (n_o) of the liquid crystal. The effective refractive index n_{eff} for TE-polarized light can be described as

$$n_{\mathrm{eff}} = \frac{n_{\mathrm{o}} \cdot n_{\mathrm{e}}}{(n_{\mathrm{o}}^2 \cos^2 \varphi + n_{\mathrm{e}}^2 \sin^2 \varphi)^{1/2}}, \qquad (1)$$

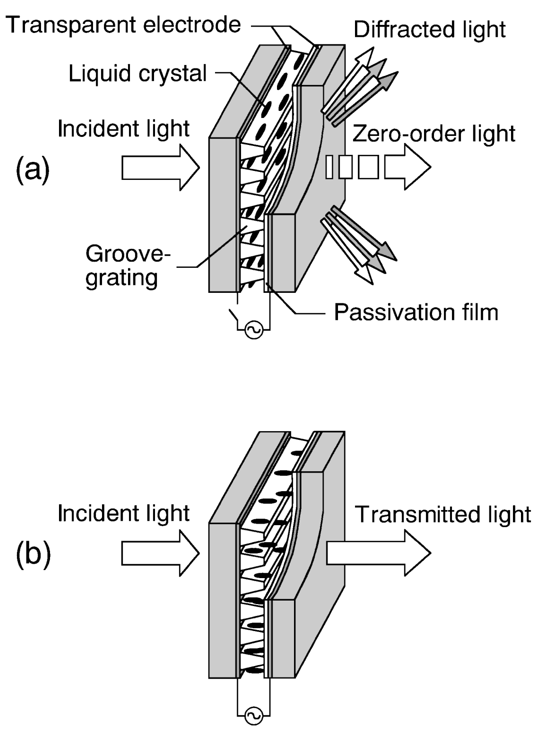

Fig. 1. Schematic diagram of a switchable filter constructed by a liquid-crystal-filled grating: (a) the device works as a dark color filter when the voltage is off, (b) the device works as a transparent window when the voltage is on.

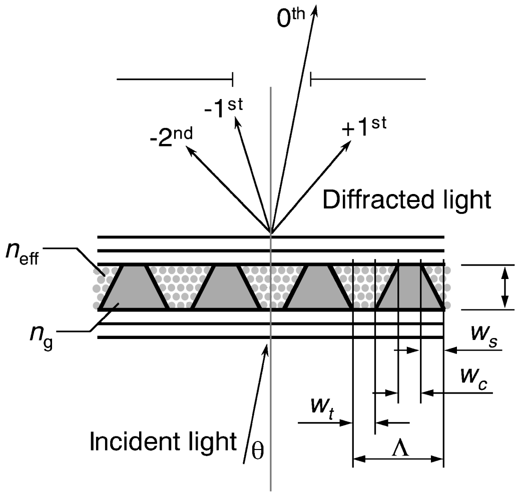

Fig. 2. Analysis model consisting of a trapezoidal-shaped diffraction grating filled with liquid crystals.

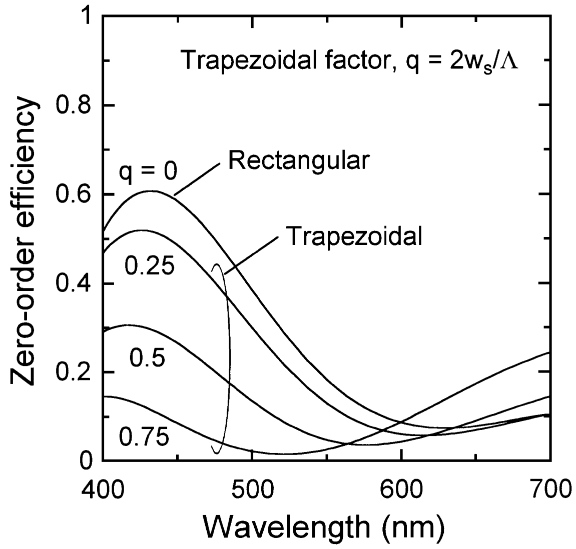

Fig. 3. Calculated results of zero-order diffraction efficiency as a function of wavelength for different trapezoidal profiles. The grating period and depth are both 1.5 μm.

where φ represents the tilting angle of the liquid crystal molecules out of the plane of the substrate. Hence, the depth of the modulated phase can be unambiguously controlled by the cell voltage.

As shown in Fig. 2, the phase grating is modeled as a trapezoidal refractive index structure involving the refractive indices n_g and n_{eff} sandwiched between thin layers of the substrates, where n_g is the refractive index of the grating ridge. The trapezoidal grating profile is characterized by the depth d, the period Λ, the dutyratio p, and the trapezoidal factor q. The grating dutyratio is the most effective factor for further suppressing the off-state zero-order transmittance when the grating depth is already optimized. The trapezoidal factor denotes the percentage contribution of the crest-to-trough slopes to the grating period as a whole. These parameters are described as

$$\Lambda = w_c + w_t + 2w_s, \tag{2}$$

$$p = (w_c + w_s)/\Lambda, \tag{3}$$

$$q = 2w_s/\Lambda, \tag{4}$$

where w_s is the horizontal width of the slope, w_c is the crest width, and w_t is the trough width. The incident light is diffracted by the phase grating when n_{eff} is detuned from n_g. The diffraction orders are distributed in one plane, where the zero-order light is transmitted, while that of higher orders is blocked by an aperture, such as a lens, a louver, or a baffle. A smaller period is required to deflect the light at a larger diffraction angle. Because the fine-pitch grating has a thickness approximately equal to its period, the calculations are carried out using a rigorous differential grating theory. The calculation model is divided into uniform thin layers fulfilling the boundary conditions at the interfaces, except for the grating layer. In the grating layer region, we integrate a set of coupled differential equations from the bottom to the top of the grooves.[10)]

Figure 3 shows the calculated zero-order transmission efficiencies for the different trapezoidal profiles. The transmission peak and valley in the zero-order curves correspond to the effective phase shift of 2π (minimum diffraction) and π (maximum diffraction), respectively. The grating groove depth used for the curves was optimized in order to yield a transmission valley close to the middle of the visible range. Refractive indices were taken from the measured results of the extraordinary index of the liquid crystal and the index of the groove material, as descried below (see Fig. 6). The calculation results confirm that the zero-order transmission efficiency is wavelength dependent, with the transmission color being darker for larger trapezoidal factors, indicating that the transmittance can be suppressed for a wide range of wavelengths. Under the index matching condition of the groove material with the ordinary index of the liquid crystal, the phase grating disappears resulting in total light transmission. Such calculations with trapezoidal, rather than rectangular, profiles imply a high extinction ratio over the visible range. The design of the extinction ratio does not limit the intrinsic transmittance in the on-state.

In order to increase the usable light flux in the on-state, the entrance pupil for the device should be enlarged, creating a wider angle of incidence. If the diffracted beams are not strewn sufficiently in the off-state, the outgoing light may not be purely zero-order light when the angle of incidence increases. Our device, in which Λ/λ ranges typically from 2 to 4, allows five to eight diffraction orders to survive. The -1-order light comes into the aperture first. Figure 4 expresses the relationship between the numerical aperture of the input/output optical system and the grating period normalized by the wavelength. The dark-shaded area shows the case when only zero-order light passes through the aperture. The light-shaded area shows the case when -1-order light is added to the output light. If we make the -1-order and zero-order diffraction efficiency low, the maximum numerical aperture doubles.

Figure 5 shows the transmission behavior of the zero, first and second diffraction orders as a function of the trapezoidal factor. The grating parameters are $\Lambda = 1.5\,\mu$m, $p = 0.5$, and $d = 1.4\,\mu$m. The refractive indices are $n_g = 1.53$ and $n_{eff} = 1.78$ at a wavelength of 540 nm. The incidence of light is examined for two directions; one from the top (top-incidence) and another from the bottom (bottom-incidence) of the grating grooves. The angle of incidence, θ, represents the angle normal to the grating plane and perpendicular to the grating direction. As shown in Fig. 5, the trapezoidal-shaped grating can bias the diffraction efficiency of either positive or negative orders for the θ of interest. The first-order diffraction efficiency with bottom-incidence is greater than that with top-incidence at normal incidence. At larger angles of incidence, the -1-order efficiency with bottom-incidence decreases, while that with top-incidence increases. Thus, even if the oblique-incidence flux includes the -1-order beam in the output light as the angular aperture widens, it would apparently not degrade the quality of the off-state extinction with a bottom-incidence setup.

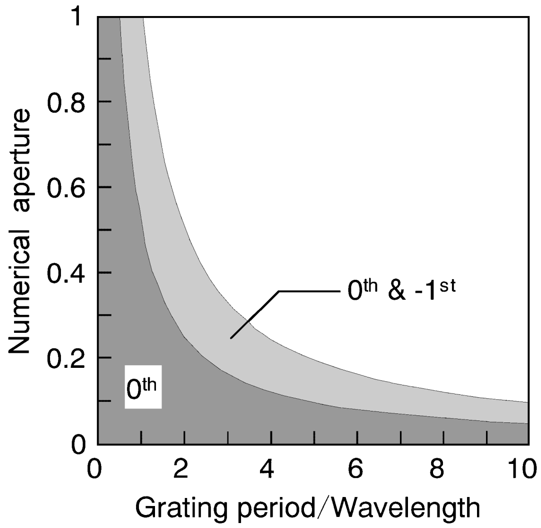

Fig. 4. The relationship between the numerical aperture of the optical system and the grating period normalized by the wavelength. The shaded areas show which diffraction orders can pass through the aperture.

3. Experimental Results

We studied the switchable properties of basic devices in which liquid crystals were confined inbetween a corrugated substrate and a flat one; each substrate had a 100-nm-thick transparent indium tin oxide (ITO) coating. Grating ridges with a dutyratio of 0.5 and trapezoidal factors of 0.4–0.5 were made of photoresist (ODUR1013) that was spin-coated onto one ITO surface. To avoid a short between the two electrodes, a SiO_2 passivation film was sputtered onto the other ITO surface. After surface treatment ensuring liquid crystal homogeneous alignment, we sealed the cell and inserted the nematic liquid crystals (RO-TN403) into the narrow gaps. Once filled, the cell was clamped tightly without spacers to give thickness to the grating layer. The small period gratings, $\Lambda \leq 2\,\mu$m, homogeneously align the liquid crystal. The grating grooves thus serve as both the spacers and the orientation-assist layer. The liquid crystal chosen has a large optical anisotropy so

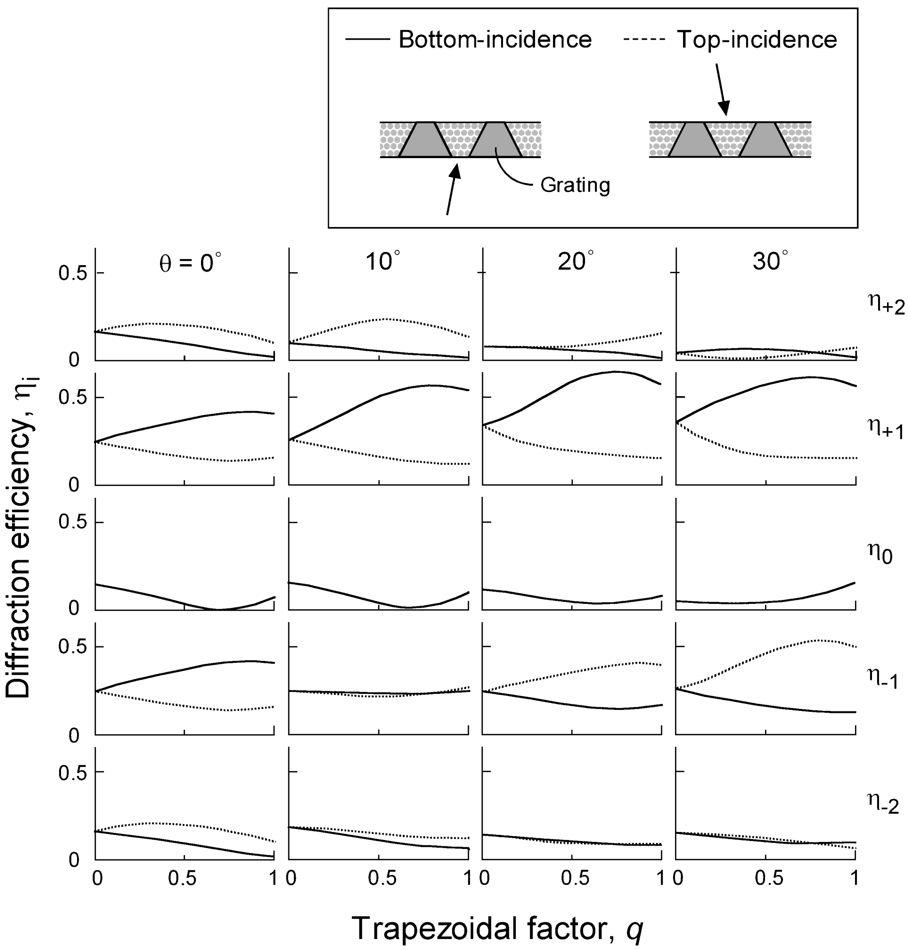

Fig. 5. Calculated diffraction efficiencies, η_i, as a function of trapezoidal factor, where the subscript i denotes the diffraction order. The angle, θ, refers to the angle of incidence in air. The solid curves represent the incident light from the bottom of the grooves, and the dotted curves represent the incidence from the top of the grooves.

the groove can be shallow. Using an Abbe refractometer, the birefringence Δn of the liquid crystal was measured to be from 0.33 to 0.24 for the 420 to 650 nm wavelength region, as shown in Fig. 6. The grating material was chosen to match the ordinary index of the liquid crystal throughout the entire visible range.

We measured the zero-order transmittance as a function of wavelength using TE-polarized light. As shown in Fig. 7, strong diffraction occurs when no voltage is applied, resulting in little power left in the transmitted zero-order light. The valley wavelength shifts to a higher value as the groove depth is increased from 1.1 μm to 1.3 μm. When a square-wave voltage is applied with an alternating frequency of 5 kHz, the phase grating is erased and most of the incident light is transmitted by the switchable filter. The extinction ratio calculated from the data for spectrally weighted intensities exceeds 10 : 1. At the valley wavelength, the zero-order light is expected to be less than 1% of the incident light with optimized grating dutyratio. The overall reflection loss throughout the layers is estimated to be ∼13% including the loss at the glass-air, glass-ITO, and grating-ITO interfaces. An intrinsic transmittance of 90–99% over the visible wavelengths must be achieved in the see-through grating layer. We measured the zero-order transmittance as a function of the applied voltage with the grating periods ranging from 1 to 4 μm. A 4-μm-period grating produced switching even at voltages under 5 V, while a 1.5-μm-period grating required 15 V. For a 1-μm-period grating, transparency was hardly attained under our conditions, owing to the difficulty in reorienting the liquid crystal molecules.

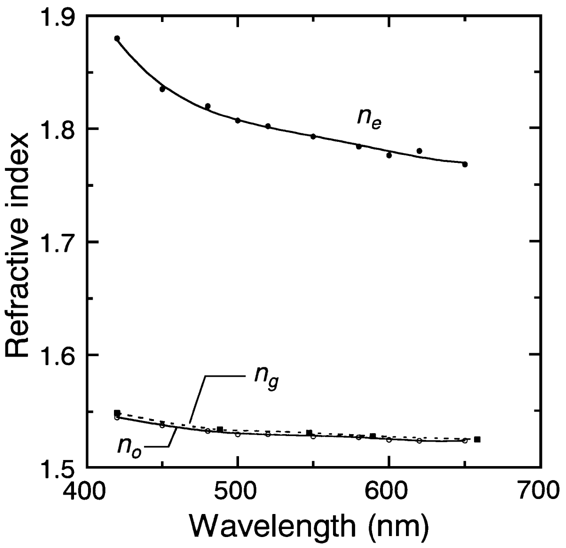

Fig. 6. Measured results of the refractive indices for the liquid crystal (solid curves) and the grating material (dotted curve).

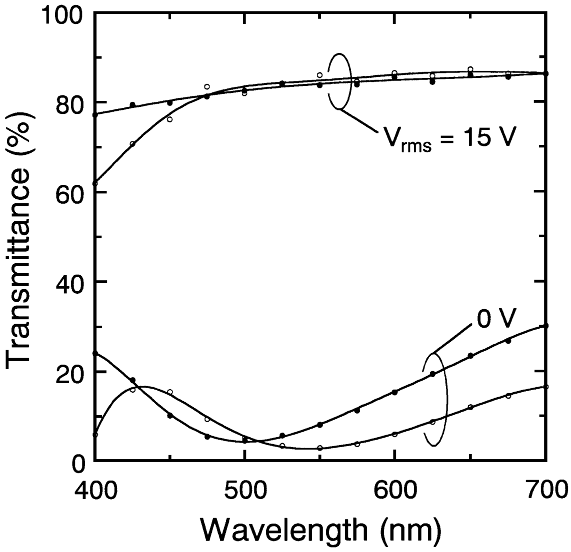

Fig. 7. Zero-order transmissive spectra of the switchable filters under polarized illumination. Turn-on voltage of 15 V_{rms} is applied to 1.5-μm-period gratings with depths of 1.1 μm (black circles) and 1.3 μm (white circles).

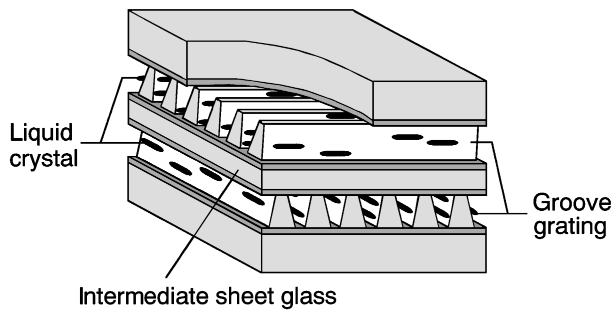

Fig. 8. Schematic diagram of the two-stack device with crossed grating directions.

The TM-polarized light, that is light polarized perpendicular to the groove lines, is not affected by the diffraction grating due to index matching between n_g and n_o. Thus, by turning the grating on and off, the device works alternately as a high-transmittance window or a linear polarizer; it acts as a switchable polarizer itself. We were able to achieve polarization-insensitive operation with a two-stack formation in which the groove directions were perpendicular to each other. As shown in Fig. 8, we constructed a three-sheet device in which the sheet glass in the middle was coated on both surfaces with an ITO film. The sheet glass comprised of the upper grating ridges was piled on the top of the lower grating ridges. This arrangement, in which the two grating layers experience the same bottom-incidence, is preferred because the device exhibits a good extinction ratio. The zero-order transmittance of the two-stack device, in which each grating has the same groove depth of 1.5 μm, is shown in Fig. 9. Under unpolarized illumination, the off-state produces a dark bluish color. The on-state produces an almost flat spectrum over most of the visible range. Because of the accumulative Fresnel reflection loss at the interfaces and the residual absorption in the ITO electrodes, the transmittance reaches only ∼70%. The transmittance can, nevertheless, be improved to 90% or more if an optimized layer design and a proper antireflection coating are used. Hence, the device we fabricated behaves like a plain plate with unnoticeable diffraction.

Figure 10 shows the spectral change in zero-order transmittance with applied voltage. The grating was designed to have a 4 μm period and 3 μm depth using SiO_2 grooves filled with the liquid crystal RO-TN407. The transmittance valley wavelength becomes shorter as the voltage increases. The valley wavelength changes from ∼650 nm to ∼400 nm as the voltage varies from 0 V to 14 V. Even if the full volt-

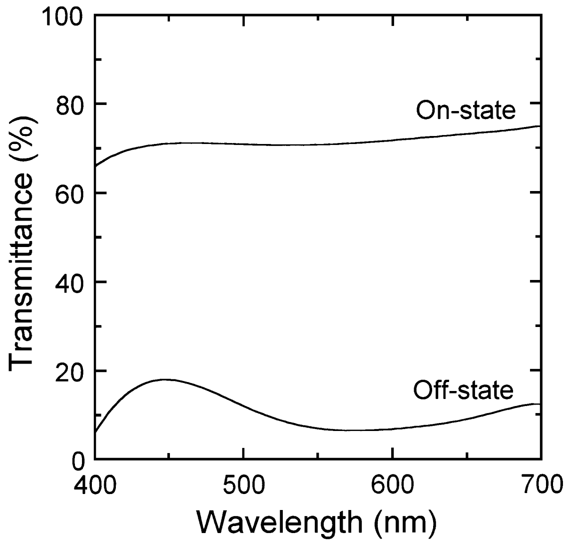

Fig. 9. Measured transmittance of the two-stack switchable filter. This result was obtained using unpolarized light.

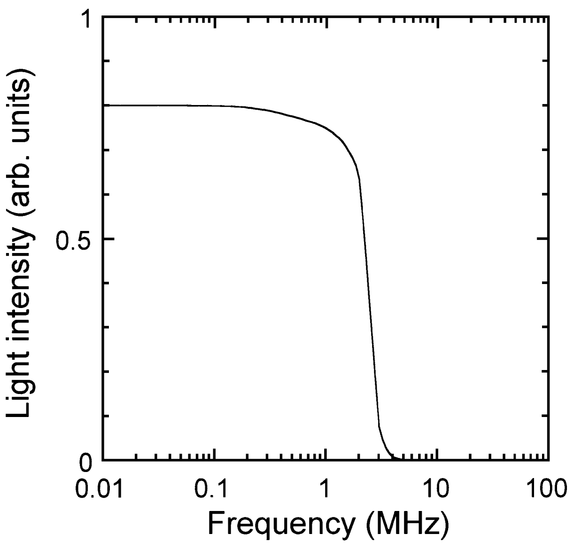

Fig. 11. Light intensity through the liquid-crystal-filled grating as a function of frequency.

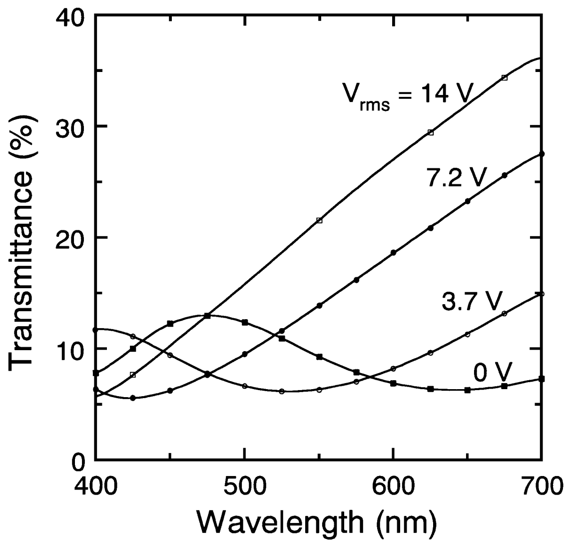

Fig. 10. Spectral change of the zero-order transmittance with varying signal voltage.

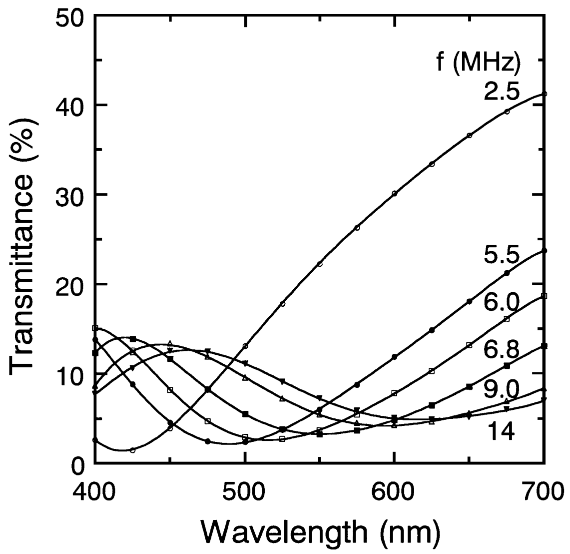

Fig. 12. Spectral change of the zero-order transmittance by varying the signal frequency.

age of 14 V is applied, the tunable phase grating does not become transparent because of index mismatching between n_g and n_o. As well as being controlled by the voltage tuning, the liquid crystal molecules are controlled by a signal frequency. The long axis of each liquid crystal molecule aligns itself along the applied field under low frequency operation. As for a frequency higher than the boundary frequency, the long axis turns perpendicular to the applied field owing to the frequency-dependent anisotropic permittivity of the liquid crystal. That means that the index difference between the grooves and the liquid crystals increases as the frequency is increased. Figure 11 depicts the frequency-dependent transmission of the device at $\lambda = 633$ nm for an applied voltage of 14 V. We verified the boundary frequency of ~2 MHz. Figure 12 shows the change in the zero-order spectral transmittance. As the signal frequency is increased to 14 MHz, crossing the boundary frequency, the valley wavelength shifts resulting in the change of the transmitted light color from brown to magenta, to blue and finally to cyan. The grating material and profile have to be designed properly in order to yield the optimum color performance.

Results for the switching response are shown in Fig. 13. The liquid crystal cell is switched from $\lambda/2$ phase retardation to zero phase retardation in less than 1 ms, and vice versa in ~10 ms with a grating period of 4 μm. As the grating period is reduced, the rise time becomes longer and the fall time becomes shorter. This phenomenon is related to the increasing role of the grating surface effect anchoring the liquid crystal molecules.[11] As the switching voltage is increased, the rise time shortens being inversely proportional to the square of the voltage, while the fall time gradually lengthens. Thus, the relaxation of the molecules is slower than their field induced reorientation at higher voltages. The rise time as low as 60 μs is due to the higher voltage gradient of the thinner liquid crystal layer compared to that of the ordinary twisted nematic mode. The fall times increase almost linearly with voltage which is

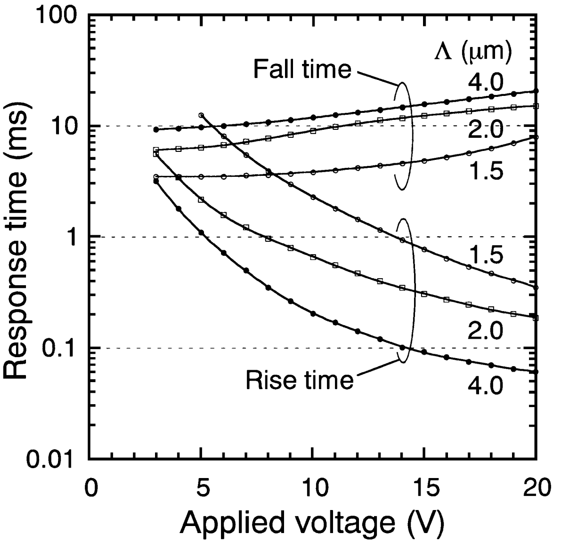

Fig. 13. Response times as a function of the applied voltage, in which the parameter Λ denotes the grating period. The materials used are the same as those in Fig. 7 and the grating depth is 1.5 μm.

due solely to charging effects in the cell. In order to lay down the liquid crystal molecules quickly, we fabricated an interdigital electrode across the grating grooves.[12] As a result, we succeeded in reducing the fall time to about 2 ms at a voltage of 15 V for a 4-μm-period grating with no change in the turn-on speed. Such a vertical-to-horizontal swing in the applied electric field is effective for shortening the fall time.

4. Discussion

In our experiments we found that a small period grating does not necessarily require an additional alignment process over the substrate. Although we did not examine the dependence of birefringence on the groove period, it is known that the refractive index of the liquid crystal is determined from the orientational order parameter due to the fine-pitch grooves.[11] A finer pitch produces a higher extraordinary index in the liquid crystal cell, contributing to a thinner grating layer.

The refractive index of the liquid crystal is also sensitive to temperature. According to our measurements, the temperature coefficient is higher for the extraordinary index than for the ordinary index that is almost equal to the coefficient of the groove material. Thus the phase retardation is also likely to change in the grating, resulting in spectral transmittance variation with the operation temperature. Although the color of the transmitted light would be somewhat altered, the trapezoidal profile would suppress the fluctuation in the total extinction because of its low saturated spectrum.

The time response experiments show that thin nematic cells can take full advantage of the d^2 switch time dependence with a turn-on time of less than 100 μs. However, with a very small period grating, the liquid crystals lying close to the grooves are anchored so heavily that they cannot respond to the applied electric field. Nevertheless, the turn-on reaction can be improved by using interfacial control, such as surface smoothing lithography or a surface-active agent.

5. Conclusions

Voltage induced reorientation of the liquid crystal in the diffraction grating was shown to induce a large change in the zero-order transmittance. We succeeded in erasing the phase grating by broad-band index matching, and in modulating the transmitted light by electrically controllable index mismatching. The transmissive spectra between white and various dark colors were controlled using the signal frequency as well as the voltage. No polarizer was needed, and much improved on-state transparency was achieved. The switching response was strongly influenced by the liquid crystal characteristics in the narrow grooves. A shorter grating period enhanced the anchoring effect on the liquid crystals, resulting in faster turn-off and slower turn-on times.

Acknowledgments

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