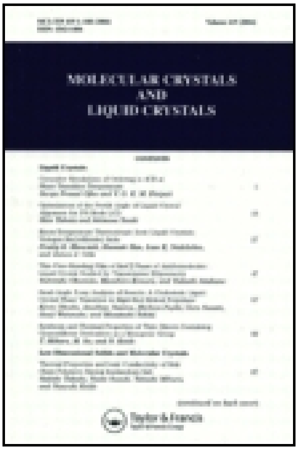

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LIQUID CRYSTALLINE DEVICE WITH REFLECTIVE WIRE GRID POLARIZER

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We studied the optical performance of reflective polarizers made of a fine grid of conducting wires. The polarizer reflects visible light polarized along the grids and transmits light polarized perpendicular to the grid with low losses. We show that the optical performance of wire-grid polarizers can be adequately described by representing the polarizer as an effective uniaxial medium with anisotropic absorption. The description facilitates the incorporation of the polarizers in modeling procedures widely used for liquid crystal device design. We present the modeling and measurement results of twisted nematic devices with wire-grid polarizers serving simultaneously as reflective polarizers, alignment layers, and back electrodes. The application of the wire-grid polarizers for reflective liquid crystal devices provides brightness enhancement, high contrast ratio at wide viewing angles, and elimination of viewing parallax.

Keywords: liquid crystal device modeling; twisted nematic displays; wire grid polarizers

1. INTRODUCTION

Remarkable progress in telecommunications stimulated development of new technologies for high performance reflective liquid crystal devices that are capable of signal attenuation and rerouting. On the other hand, there is

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a great market demand in hand-held displays that also utilize reflective polarizing components. This and many other applications call for reflective polarizers that offer viable solutions for many problems where polarizing effects contribute to performance enhancements.

Grids made of thin conducting wires have been used extensively in radar systems and far infrared applications as polarizers and beam splitters [1]. However, to be useful in visible and near infrared domains, the period of the grating should be much less than the wavelength of light. The challenge of manufacturing fine aluminum grids with periods on the order of 100 nm has been successfully overcome by Moxtek Co. [2]. The grating with that small period does not show any diffraction behavior for visible light. The absence of diffraction orders allows one to treat a wire grid polarizer as a medium with anisotropic absorption, similar to a dichroic polarizer. The polarizing effectiveness of the wire grids suggests their wide application for liquid crystal devices. The most powerful approach in a liquid crystalline device design is modeling based on exact solutions of Maxwell's equations for anisotropic media (Berreman's 4×4 matrix method [3]). In order to incorporate grid polarizers into the modeling, one should represent them as a continuos medium with anisotropic refractive and absorption coefficients.

The first considerations of the applicability of the effective medium theory to the wire grids were expressed in the works of A. Yariv and P. Yeh [4–6]. The authors showed that a layered medium with period, Λ, that consists of alternating layers behaves as a uniaxial birefringent medium with ordinary and extraordinary indices, n_o and n_e, given by [4–6]

$$n_0^2 = \frac{a}{\Lambda} n_1^2 + \frac{b}{\Lambda} n_2^2 \tag{1}$$

$$\frac{1}{n_e^2} = \frac{a}{\Lambda}\frac{1}{n_1^2} + \frac{b}{\Lambda}\frac{1}{n_2^2} \tag{2}$$

where n_1 is the complex refractive index for the metallic layers; n_2 is the refractive index of the dielectric medium, a is the wire width, and $\Lambda = a + b$ is the period of the structure. In the case when the wire grids are made of perfect conductors and the dielectric spaces are made of perfect insulators, incident radiation with the electric field vector parallel to the wire grids interacts with the medium that has a refractive index mostly determined by the metallic layers, and is reflected. For incident radiation with dielectric vector perpendicular to the wire grids, the polarizer behaves as a perfect dielectric layer, and mostly transmits.

In our work we apply this approach to estimate the absorption and refractive indices of the effective medium that adequately represents Moxtek's polarizers. We also demonstrate the application of the wire grid polarizers in a liquid crystal device modeling.

2. SAMPLES

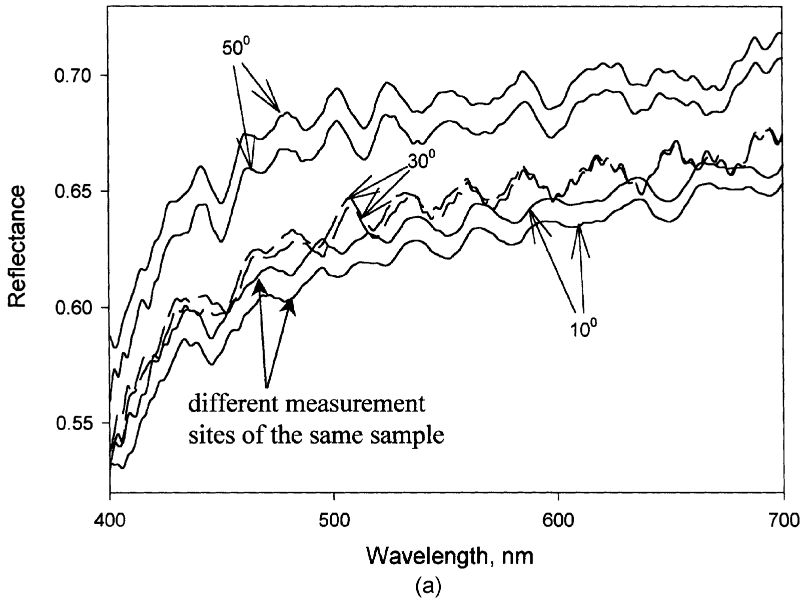
We estimated reflectivity and transmission coefficients of wire grid polarizers that consisted of fine aluminum grids with the period about 100 nm manufactured on glass substrates. In order to build a satisfactory model for wire grids, we measured transmitted and reflected luminance by stacks of crossed and parallel grids separated by an optical contacting layer (glycerin). We also studied the optical performance of liquid crystal devices with wire grids used either as reflective or transmission polarizers. The basic element of the studied devices was a liquid crystal cell with 90° twisted director configuration (TN cell). The 5.1-micron thick cells were filled with nematic fluid ZLI4792 (manufactured by Merck). A sample of a wire grid on glass substrate was used as a back substrate for the TN cell. The grid polarizer served as an internal polarizer and back electrode. By placing the polarizer inside the LC cell, we avoided parallax in the reflection device. In some cases, we used a grid as an alignment layer: the grid grooves acted similarly to a rubbed substrate providing strong enough anchoring. The dichroic polarizer used as a front polarizer had an anti-reflection coating.

3. MEASUREMENT SETUP

The measurements of the reflected luminance were performed by detecting specular reflections from either polarizer stacks or reflective displays using computerized SpectraScan PR 704 camera. We adjusted the incidence angle of the light by moving both the camera and the light source (Illuminant A with color temperature 2857°K) to obtain the desired polar angle, and then rotated the display in the azimuthal plane. The display brightness was characterized by the reflected luminance compared to the luminance of the light source. Iso-luminance transmission curves of polarizer stack and iso-contrast curves for TN devices were obtained using the same instruments, however, the luminance data were collected in transmission mode.

4. OPTICAL PERFORMANCE OF GRID POLARIZERS

We treated a wire grid polarizer as a birefringent medium with anisotropic absorption and initially estimated the refractive and absorption indices by using expressions (1) and (2). Figure 1 presents measured and modeled spectra when the incident light is polarized. The figure depicts one of four studied cases, when the light is polarized along the grids regardless



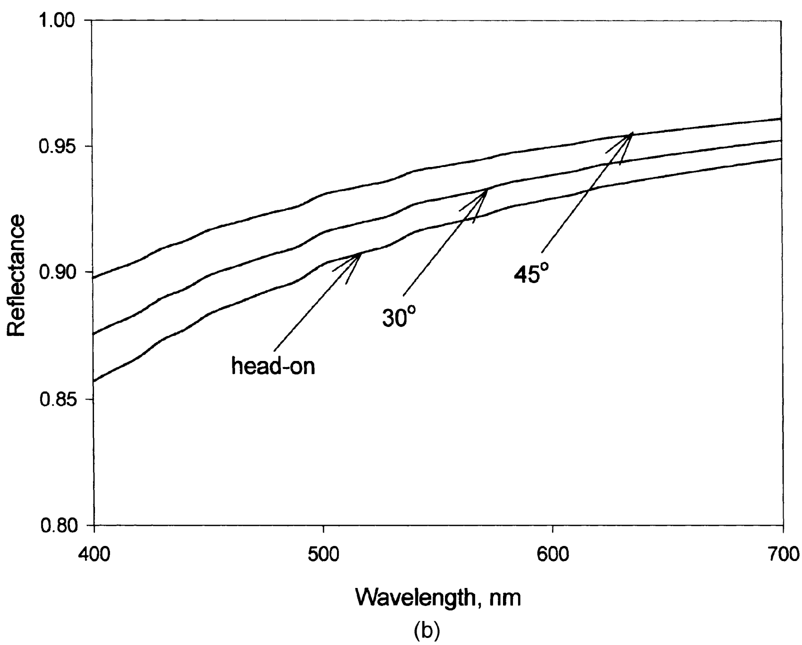


FIGURE 1 Measured (a) and modeled (b) reflectance of the wire grid polarizers when the incident light is polarized along the grids.

of the incident angle. The grid reflects light polarized along the grids (E-polarization) and transmits light polarized perpendicular to the grid direction (H-polarization) with low losses. Comparison of the model with the measured data demonstrated that the calculated indices provide only qualitative agreement with experiment. In order to get the quantitative agreement with experimental data, we measured and modeled reflected and transmitted luminance from a stack formed with two crossed grids with optical contact fluid (glycerin) in between. The iso-luminance curves measured at different wavelength are very sensitive to small changes in the absorption index for the extra-ordinary wave k_e. Thus, it is possible to adjust the calculated indices $k_e(\lambda)$ in order to get a better agreement with experimentally measured optical characteristics (reflectivity and transmission of polarized light). Two wire grids have very high reflectivity exceeding 78% that is close to the reflectivity of an aluminum mirror. Two crossed wire grid polarizers are almost as effective as conventional dichroic polarizers [7]: the transmission of two crossed grids is about 0.1% for normal direction. Two parallel grids transmit about 31% of the light. We further modeled transmission and reflectivity of the grid stacks at various viewing angles by using the calculated effective medium coefficients and applying Berreman's 4×4 matrix method. The absorption coefficient for extraordinary ray $k_e(\lambda)$ at the given λ was chosen as a fitting parameter. We found that the higher absorption coefficient k_e resulted in higher reflectivity. On the other hand, transmission of the stack increases with a decrease in the effective medium thickness, d. We found that the effective medium with thickness $d = 0.043$ microns and indices presented in Table 1 adequately described the performance of the grid in optically dense glycerin. We then used these indices in liquid crystal display modeling.

TABLE 1 Indices of Refraction and Absorption for Uniaxial Birefringent Absorptive Medium Used in Modeling of Wire Grid Polarizers

Wavelength, nm	n_o	k_o	n_e	k_e
400	1.5	0.1	1.48	4.1
450	1.5	0.1	1.48	4.45
500	1.5	0.1	1.48	4.7
550	1.5	0.1	1.48	5.0
600	1.5	0.1	1.48	5.9
650	1.5	0.1	1.48	6.4
700	1.5	0.1	1.48	6.8

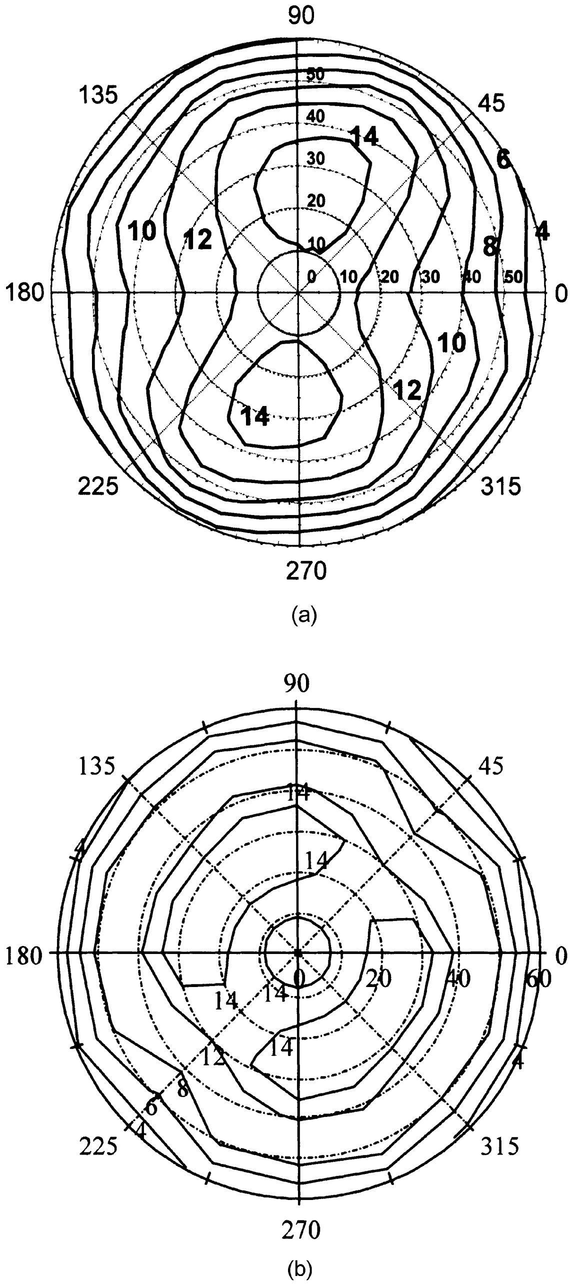


FIGURE 2 Measured (a) and modeled (b) iso-contrast curves for reflective liquid crystal device with a wire grid polarizer.

5. MEASUREMENT AND MODELING OF THE DIRECT VIEW REFLECTIVE DEVICE WITH WIRE-GRID POLARIZERS

In order to study the optical performance of the grids for the liquid crystal displays we modeled and measured the optical performance of TN reflective devices that had a wire-grid polarizer on the back and a dichroic polarizer on the front. The device was tested in reflection and transmission modes. Figure 2 shows measured and modeled iso-contrast curves for a reflective display driven between 0 and 6 V. In the figures, the circumference of the diagram corresponds to azimuthal angle and the radius corresponds to the polar angle. The center of the diagram corresponds to head-on viewing and any other pair of angles corresponds to off-normal direction. The studies show a remarkable agreement between the measured and modeled data. Comparison of the data with our previous measurements of a conventional reflective device with two dichroic polarizers and an aluminum mirror features similar iso-contrast characteristics. However, the device with wire grid polarizer is about 10% brighter.

Figure 3 shows iso-contrast curves for the display with back wire grid polarizer that operates in transmission mode. The viewing angle characteristics of this display are very similar to a conventional one that has two dichroic polarizers. However, the contrast ratio for this display is lower

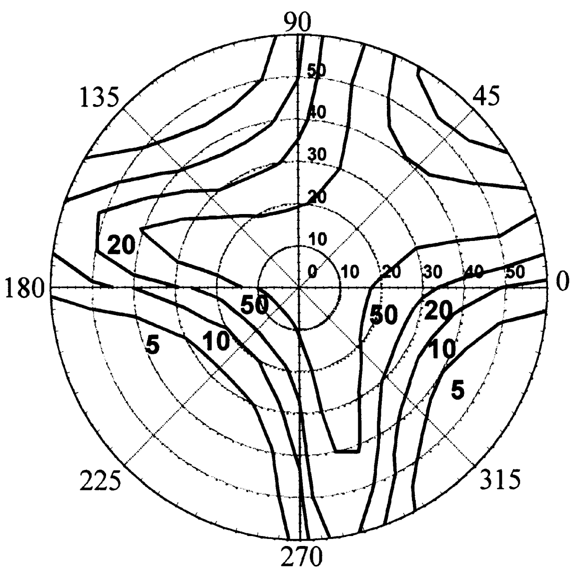


FIGURE 3 Measured iso-contrast curves for twisted nematic device with wire grid polarizer operating in transmission mode.

because of higher leakage of the rejected polarization compared to the sheet polarizer.

6. CONCLUSIONS

The conducted research shows that the optical performance of Moxtek's wire-grid polarizer can be adequately described using an effective medium with anisotropic absorption. The medium possesses high transmission for light polarized in the direction perpendicular to the wires and high reflectivity for light polarized in the direction parallel to the wires. The effective medium with the thickness of $d = 0.043$ microns and $n_o = 1.5$, $n_e = 1.48$, $k_e = 0.1$ and $k_e = 4.1 \div 6.8$ in the wavelength range $\lambda = 400 \div 700$ nm provided good agreement of measured and modeled data for reflectivity and transmission coefficients of the wire grid in an optically dense medium. The estimated parameters of the polarizer were used for modeling of a TN reflection device. The modeled data are in good agreement with the measurements of the actual device that employed one grid polarizer and one dichroic polarizer. Twisted nematic reflective devices with wire-grid polarizers provide high contrast and wide viewing angle performance, brightness enhancement and elimination of viewing parallax. Wire grids placed inside the active liquid crystal cell can serve simultaneously as polarizers, alignment layers, and back electrode.

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