3-2000

Diffraction properties of highly birefringent liquid-crystal composite gratings

James J. Butler
Pacific University

Michelle S. Malcuit
Lehigh University

Follow this and additional works at: http://commons.pacificu.edu/casfac

Part of the Physics Commons

Recommended Citation

This Article is brought to you for free and open access by the Faculty Scholarship (CAS) at CommonKnowledge. It has been accepted for inclusion in All CAS Faculty Scholarship by an authorized administrator of CommonKnowledge. For more information, please contact CommonKnowledge@pacificu.edu.
Diffraction properties of highly birefringent liquid-crystal composite gratings

Description
We have fabricated electrically switchable holographic gratings, using Polaroid Corporation's DMP-128 photopolymer filled with the nematic liquid crystal E7. It is shown that a coupled-wave theory that includes the effects of the birefringence of the liquid crystal must be used to explain the diffraction properties of these anisotropic volume gratings. Furthermore, a detailed comparison of theory and experiment provides information about the alignment of the liquid crystal within the polymer host.

Disciplines
Physical Sciences and Mathematics | Physics

Comments
© 2000 Optical Society of America

This paper was published in Optics Letters and is made available as an electronic reprint with the permission of OSA. The paper can be found at the following URL on the OSA website: http://dx.doi.org/10.1364/OL.25.000420. Systematic or multiple reproduction or distribution to multiple locations via electronic or other means is prohibited and is subject to penalties under law.

Rights
Terms of use for work posted in CommonKnowledge.
Diffraction properties of highly birefringent liquid-crystal composite gratings

James J. Butler

Department of Physics, U.S. Naval Academy, Annapolis, Maryland 21402

Michelle S. Malcuit

Department of Physics, Lehigh University, Bethlehem, Pennsylvania 18015

Received October 14, 1999

We have fabricated electrically switchable holographic gratings, using Polaroid Corporation’s DMP-128 photopolymer filled with the nematic liquid crystal E7. It is shown that a coupled-wave theory that includes the effects of the birefringence of the liquid crystal must be used to explain the diffraction properties of these anisotropic volume gratings. Furthermore, a detailed comparison of theory and experiment provides information about the alignment of the liquid crystal within the polymer host. © 2000 Optical Society of America


Holographically recorded liquid-crystal composite gratings can be used as active beam-steering elements for applications such as time-delay networks, beam modulation, and switching. The liquid-crystal composite is an attractive material for electrically switchable holographic gratings because liquid crystal has a large field-induced birefringence change, which results in large changes in refractive-index modulation and, therefore, diffraction efficiency of the composite grating. In particular, high-contrast optical switches have been produced by use of Polaroid Corporation’s DMP-128 photopolymer. DMP-128 is a photosensitive material that is porous after it has been exposed to light and processed. After processing of the material, the pores of the grating can be filled with a nematic liquid crystal. The diffraction efficiency of these gratings is controlled by the application of an electric field. When the field is turned on, the liquid crystals rotate within the pores, thereby changing the refractive-index modulation experienced by the incident light. This change in refractive-index modulation produces a corresponding change in the diffraction efficiency of the grating.

In this Letter we present the results of a study in which we compared the measured diffractive properties of liquid-crystal composite gratings with a two-wave coupled wave analysis that includes the effects of birefringence. We show that one must include the anisotropy of the composite grating in the model to explain the observed diffraction properties. Furthermore, we show that this comparison also provides information about the alignment of the liquid crystal within the porous grating.

To analyze the unslanted volume transmission gratings used in this work, we model the DMP-128 holograms as having regions of high porosity separated by regions of low porosity. Each region has a refractive index given by

\[ n_{a,b} = f_{a,b} n_f + (1 - f_{a,b}) n_{\text{DMP}}, \quad (1) \]

where \( f_a \) is the filling fraction of the high-porosity region, \( f_b \) is the filling fraction of the low-porosity region, \( n_f \) is the refractive index of the material that is contained within the pores, and \( n_{\text{DMP}} \) is the refractive index of the processed DMP-128 photopolymer, which is equal to 1.56 ± 0.02. \(^1\) The filling fractions in this model were determined from measurements of the average refractive index and the refractive-index modulation of the unfilled grating. These parameters were found by comparison of the experimentally measured angular dependence of the diffraction efficiency for the unfilled grating with both \( s \)- and \( p \)-polarized light and the predictions of the coupled-wave theory of volume gratings. \(^8\)

After the unfilled gratings were characterized, we filled them with E7 liquid crystal (\( n_\epsilon = 1.75, n_o = 1.52 \)). The angular dependence of the diffraction efficiency was measured for both \( s \)- and \( p \)-polarized light. The diffraction efficiency for \( s \)-polarized light was small, which indicates that the liquid crystal orients in the porous grating in such a way that an \( s \)-polarized wave sees primarily the ordinary index of the liquid crystal, which is nearly index matched to the polymer host.

Figure 1 shows the angular dependence of the diffraction efficiency (filled squares) for \( p \)-polarized light at a wavelength of 0.6328 \( \mu \)m incident upon an 8-\( \mu \)m-thick liquid-crystal composite grating with unslanted grating planes and a grating spacing of 0.489 \( \mu \)m. The average refractive index and the refractive-index modulation of the unfilled grating were measured to be 1.20 and 0.045, respectively.

The coupled-wave theory of Kogelnik \(^8\) was used as an initial step to explain the diffraction properties of the liquid-crystal composite grating. Figure 1 shows a comparison of the experimentally measured angular dependence and the predictions of Kogelnik’s coupled-wave theory (solid curve). The theoretical calculation was done with the assumption that the liquid crystal aligns along the grating vector within the
 pores of the polymer host in both the high- and the low-
porosity regions. Additionally, we assumed an order
parameter of unity for the liquid crystal within the
 pores, since this assumption results in the maximum
index modulation and our experimental results indi-
cated an anomalously high diffraction efficiency. We
then calculated the liquid-crystal refractive index for
each angle. Finally, the average refractive index and
the refractive-index modulation for each angle were cal-
culated with Eq. (1), along with the filling fractions
obtained from the characterization of the unfilled grat-
ing. The discrepancy between the data and the theo-
retical prediction most likely is due to the fact that
Kogelnik’s coupled-wave theory does not include the ef-
fects of the birefringence of the grating.

In a recent paper,7 Montemezzi and Zgonik modi-
ﬁed the two-wave coupled wave theory of Kogelnik8 to
include volume gratings that are fabricated from bire-
fringent materials. In this case it is assumed that the
relative permittivity tensor of the grating can be writ-
ten in the form $\bar{\varepsilon}(x) = \bar{\varepsilon}_0 + \bar{\varepsilon}_1 \cos(2\pi x/\Lambda)$, where $\bar{\varepsilon}_0$ is the average relative permittivity tensor, $\bar{\varepsilon}_1$ is the relative permittivity modulation tensor, and $\Lambda$ is the grating spacing. The diffraction efficiency of an anisotropic volume grating for light incident at the Bragg angle is given by

$$\eta = \sin^2 \left( \frac{\pi d}{\Lambda} \frac{\hat{e}_0 \cdot \hat{e}_1}{2n_0 \cos \delta} \right), \quad (2)$$

where $d$ is the grating thickness, $\lambda_0$ is the free-
space wavelength, $\hat{e}_0$ and $\hat{e}_1$ are polarization unit
vectors for the zeroth and the first diffracted orders, respectively, $n_0$ is the average refractive index of the grating, $\theta$ is defined as the angle between the grating normal and the energy-propagation direction of a diffracted wave, and $\delta$ is the angle between the energy-
propagation direction and the wave-vector direction for the diffracted wave. It is important to remember that $n_0$ depends on $\theta$, owing to the average birefringence of the grating. Additionally, $\delta$ is small for the composite gratings considered in this work. As can be seen from Eq. (2), the predicted diffraction efficiency is highly dependent on the form of the relative permittivity
modulation tensor. In turn, the form of this tensor for the material system under consideration in this work is dependent on factors such as porosity and liquid-
crystal alignment.

The symmetry of the unslanted grating geo-
metry that we are studying, along with the fact that
we observe no coupling between $s$- and $p$-polarized
light, leads us to assume that the average relative permittivity tensor for the composite grating can be written as

$$\bar{\varepsilon}_0 = \begin{bmatrix} \varepsilon^{0}_{xx} & 0 & 0 \\ 0 & \varepsilon^{0}_{yy} & 0 \\ 0 & 0 & \varepsilon^{0}_{zz} \end{bmatrix}, \quad (3)$$

and the relative permittivity modulation tensor can be written as

$$\bar{\varepsilon}_1 = \begin{bmatrix} \varepsilon^{1}_{xx} & 0 & 0 \\ 0 & \varepsilon^{1}_{yy} & 0 \\ 0 & 0 & \varepsilon^{1}_{zz} \end{bmatrix}. \quad (4)$$

In Eqs. (3) and (4) the $x$ direction is parallel to the
grating vector and the $z$ direction is parallel to the
grating normal.

To obtain information about the components of these
tensors for the liquid-crystal composite, we measured
the diffraction efficiency as a function of angle of in-
cidence for many different wavelengths. The Bragg
condition is given by $\sin \theta_B = \lambda_0/2n_0 \Lambda$. From this re-
lation we can see that each wavelength will have its
own Bragg angle. Thus, by measuring the diffraction
efficiency at many different wavelengths, we are effec-
tively probing the composite medium at many differ-
ent Bragg angles. As we shall show, this is a sensitive
measure of the relative permittivity modulation tensor
and, therefore, of the liquid-crystal alignment.

We used a grating with a grating spacing of
0.281 $\mu$m for this set of measurements to maximize
the range of accessible Bragg angles with the wavelengths
that we had available. We fabricated the gratings in
the DMP-128 photopolymer by interfering two beams
with a wavelength of 0.6471 $\mu$m from a krypton-ion
laser. The gratings were then filled with the nematic
liquid crystal E7, and the angular dependence of the
diffraction efficiency was measured for $p$-polarized
light at several wavelengths. For this set of mea-
surements the liquid-crystal composite grating was
sandwiched between two BK7 prisms. The prism cou-
pling was necessary so that the Bragg angle for each
wavelength could be accessed. The angle within the
prism is defined to be the angle that the incident beam
makes with the grating normal at the prism–sample
interface.
we found that anisotropic grating theory assuming that solid curve is a theoretical calculation obtained with two-liquid crystal orients along the grating vector, and the experimental data points, the dashed curve is a theoretical prediction that neglects the birefringence of the grating do not agree with the experimental results. To compare the experimental results with the anisotropic coupled-wave theory, we used the relative permittivity modulation values as the fitting parameters. From fitting the experimental dependence and using \( \varepsilon_{0x} = 2.56, \varepsilon_{1x} = 0.22, \) and \( \varepsilon_{1z} = 0.07. \)

Additionally, we performed measurements of the diffraction efficiency for small detunings from the Bragg angle at each wavelength. We found that the anisotropic coupled-wave theory not only predicts the value of the diffraction efficiency at the Bragg angle but also accurately predicts the entire angular spectrum.

Information about the alignment of the liquid crystal within the pores of the grating can be extracted from the theoretical fits to the data and the filling fraction model of the grating. The unfilled average refractive index of the grating discussed above was found to be 1.24, and the unfilled refractive-index modulation was found to be 0.0625. These values yield filling fractions of the high- and low-porosity regions of \( f_a = 0.69 \) and \( f_b = 0.46, \) respectively. The effective refractive indices of the liquid crystal within each region of the filled grating were then determined to be \( n_{faz} = 1.72, \) \( n_{faz} = 1.65, \) \( n_{fbx} = 1.49, \) and \( n_{fbz} = 1.60. \) We defined \( n_{faz} \) and \( n_{faz} \) as the effective refractive indices of the liquid crystal in the high-porosity region and \( n_{fbx} \) and \( n_{fbz} \) as the effective refractive indices of the liquid crystal in the low-porosity region. Note that in region a, \( n_{fz} > n_{fz} \), whereas in region b, \( n_{fz} < n_{fz}. \) Thus it appears that the liquid crystal aligns differently in regions a and b. Currently we do not understand why the anisotropy in the refractive index in the two regions is different. In the proposed model the refractive-index profile of the grating is assumed to be sinusoidal. The effect of relaxing this assumption is currently under investigation.

In summary, we have conducted a study of composite gratings recorded by use of Polaroid Corporation’s DMP-128 photopolymer filled with the nematic liquid crystal E7. We have shown that the birefringence of the liquid crystal must be included in the theoretical model of the composite system to permit one to predict accurately the observed diffractive properties. In particular, the anisotropy of the relative permittivity tensor plays a key role in determining the diffractive properties of these gratings. We have also obtained information about the alignment of the liquid crystal within the pores of the polymer composite. The values obtained for the refractive indices of the liquid crystal indicate that the alignment may vary between the high- and low porosity regions of the grating.

We gratefully acknowledge useful discussions with T. W. Stone and J. C. Kralik. This work was supported under contract F30602-98-C-0079 issued by Rome Laboratory. M. S. Malcuit’s e-mail address is Malcuit@lehigh.edu.

References