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Light Propagation in Variable-Refractive-Index Materials With Liquid-Crystal-Infiltrated Microcavities

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A liquid-crystal-infiltrated microcavity structure is proposed as a variable-refractive-index material. It has the advantages over previously considered nanostructured materials of having a larger phase-angle change and lower driving voltage. Two-dimensional liquid-crystal director and finite-difference time-domain optical simulations are used to select liquid crystal material parameters and optimize the dimension of the microcavity structured material. © 2003 Optical Society of America


1. INTRODUCTION

One of the most important electro-optical characteristics of a liquid crystal material is that its refractive index can be varied by an external electric or magnetic field. Such material is often used to impose a phase shift on plane-polarized light, rotate the plane of light polarization, and change the light ellipticity.

It is well known that liquid crystal technology has been developed mainly for displays. But because of the electro-optical characteristic of the liquid crystal material, liquid crystal devices are also widely used in many other areas, such as fiber optic telecommunication, beam steering, and optical wave-front correction. There are many advantages of using conventional liquid crystal devices because of their low cost, large change in refractive index at low voltage, large polarization rotary power, and easy fabrication. However, most conventional liquid crystal devices are polarization dependent as well as slow in switching speed, which makes them less attractive for some applications such as fiber optic telecommunication, since the state of polarization may be unknown. Therefore many studies have been devoted to overcoming these disadvantages. The work of Matsumoto et al. showed that nanosized (<100 nm) liquid crystal droplets in polymer matrix can yield polarization diversity and can be used as a polarization-independent Fabry–Perot interferometer wavelength-tunable filter. The randomly oriented liquid crystal molecules in the liquid crystal droplets potentially prevent polarization dependence. Since the droplet sizes are much smaller than the wavelength of light (1550 nm), the medium becomes optically isotropic and the light-scattering effect can be neglected, which is in contrast to what happens in the polymer-dispersed liquid crystal conventional used for display devices, where the droplet size is several micrometers and the droplet has a strong light-scattering effect if the refractive indices of the liquid crystal droplet and the polymer matrix are not matched. Another advantage of these nanosized liquid crystal droplets is that they provide a fast switching speed (~370 μs), which is much faster than that of a conventional liquid crystal device. But the disadvantages of this polymer-confined liquid-crystal-droplet Fabry–Perot interferometer are that the wavelength tuning range is very small (~10 nm) and the driving voltage is very high (~300 V). These disadvantages result from the small droplet size, the low liquid crystal volume fraction (~20%) in the polymer matrix, and the random orientation of the liquid crystal directors when no voltage is applied. From a manufacturing point of view, to control and obtain a uniform droplet size in this type of device is not easy.

In this paper we propose a polarization-independent microcavity material that will overcome the disadvantages of nanosize-droplet polymer-dispersed liquid crystal material. By analyzing a simple two-dimensional rectangular grating with the two-dimensional finite-difference time-domain (FDTD) method and liquid-crystal-director computer simulations, we obtained the optimized cavity size that will yield larger liquid crystal volume fraction, lower driving voltage, and small light diffraction and scattering effect.

2. CONSIDERATIONS ON IMPROVING THE MATERIAL’S PERFORMANCE

The small effective optical anisotropy of the microdroplet device is partially due to the randomness of the alignment of the liquid crystal molecules in the droplets, which demonstrates the material’s isotropic optical property. When no voltage is applied, the effective refractive index of the liquid crystal droplets is $n_{iso} = (n_e + 2n_o)/3$. 
When high voltage is applied, the liquid crystal directors in the droplets are aligned along the electric field direction and the effective refractive index is \( n_0 \). Therefore the change in the effective refractive index between ON voltage and OFF voltage is \( \Delta n_{\text{eff}} = \Delta n/3 \), where \( \Delta n \) is the optical anisotropy of the liquid crystal droplet. However, because of the low volume fraction of the liquid crystal in this material, the total effective optical anisotropy is even smaller, equaling \( \Delta n/3 \) multiplied by the liquid crystal volume fraction. To achieve a larger \( \Delta n_{\text{eff}} \), ordered alignment of liquid crystal molecules and higher liquid crystal volume fraction are required. A nematic liquid crystal confined to cylindrical microcavities under the homeotropic anchoring condition may have such properties. Figure 1(a) shows a scanning electron microscope image of a cylindrical microcavity made of silicon.\(^5\) Figures 1(b) and 1(c) show two possible liquid-crystal-director fields that could exist in these cavities under the homeotropic anchoring condition. Figure 1(b) is known as the planar-radial (PR) director configuration and Fig. 1(c) as the escaped-radial (ER) director configuration. When the cavity diameter is below \(~100 \text{ nm}\), the PR director configuration is favored.\(^3\) It is obvious that both the PR and the ER director configurations could yield polarization diversity, and their effective optical anisotropies are greater than the liquid crystal molecules randomly aligned in the nanosized-droplet case, because the liquid crystal directors tend to align in the plane perpendicular to the light-propagation direction. Since controlling the size and uniformity of the cylindrical microcavities is relatively easier, a larger liquid crystal volume fraction can be obtained. Comparing the ER and PR director configurations lets us see that the PR structure will yield larger effective birefringence, \( \Delta n_{\text{eff}} = \Delta n/2 \), but that the small cavity diameter required for this kind of director field will lower the liquid crystal volume fraction and also needs a larger driving voltage to reach a low retardation state. For a compromise to be reached between the driving voltage and the cavity size, the electric coherence length and the diffraction effect need to be considered. Figure 2 shows the relationship between the driving voltage \( V \) and the electric coherence length \( L \) for a liquid crystal cell spacing \( d \) of 20.0 \( \mu \text{m} \). Here, one elastic constant approximation \( K_i \) of \( 1.5 \times 10^{-11} \text{N} \) is used for the calculation, and the dielectric anisotropies \( \Delta \varepsilon \) are 5, 10, 25, and 35, respectively. The calculations are based on Eqs. (1) and (2) of Ref. 4,

\[
L = \frac{1}{E} \sqrt{\frac{4 \pi K_i}{\Delta \varepsilon}} \quad (1)
\]

and

\[
E = V/d, \quad (2)
\]

respectively. Figure 2 indicates that for reasonable values of \( \Delta \varepsilon \), if the cavity size is of the order of 100 nm, approximately 300 V is needed to reorient the liquid crystal molecules. A lower driving voltage and higher liquid crystal volume fraction can be achieved by choosing a larger cavity size that would not require a short coherence length. If a larger cavity size is considered, then the ER liquid-crystal-director configuration is expected. However, there is an upper limit on the increase in cavity size, since the diffraction effect may appear when the cavity size becomes close to the wavelength of light. Once we know exactly what the maximum size of the cavities

![Fig. 2. Calculated electrical coherence length with different values of \( \Delta \varepsilon \) as a function of voltage. One liquid crystal elastic constant approximation of \( K_i = 1.5 \times 10^{-11} \text{N} \) is used. Cell gap is 20.0 \( \mu \text{m} \).](image)
equation, we have

\[
L \text{ channels, respectively. From the well-known diffraction}
\]

where

\[
\text{L1 and L2 are the widths of the single wall and of}
\]

can be, then a low-voltage-driving, polarization-insensitive, variable-refractive-index material can be obtained.

To obtain the optimized cavity size, we need to find the maximum periodicity \( \Lambda \) of the microcavity structure that will not cause diffraction or scattering. To simplify the analysis, we consider a rectangular riblike structured thin film material shown in Fig. 3. Analyzing this kind of structured thin film material will give information about cavity size and diffraction effect. The periodicity of the structured film shown in Fig. 3 is \( \Lambda = L_1 + L_2 \), where \( L_1 \) and \( L_2 \) are the widths of the walls and the channels, respectively. From the well-known diffraction equation, we have

\[
\sin \theta_m = \frac{m \lambda}{\Lambda}, \quad m = 1, 2, 3, \ldots
\]

where \( \lambda \) is the wavelength in the free space, \( m \) is the order of the diffraction peak, and \( \theta_m \) is the \( m \)th order of the diffraction angle with respect to the grating normal. From Eq. (3) we know that if \( m = 1 \) and \( \lambda = \Lambda \), then \( \sin \theta = 1.0 \) and \( \theta = 90^\circ \), which means that the first-order diffraction peak will not appear. Therefore from this simple calculation we conclude that the maximum material periodicity \( \Lambda \) that will not cause a diffraction effect is equal to the wavelength of the light. However this calculation does not tell us anything about the scattering and diffraction intensity variations created by selecting different dimensions of \( L_1 \) and \( L_2 \). The more accurate calculations will be done by computer simulation in the following sections.

3. TWO-DIMENSIONAL FDTD OPTICAL SIMULATION OF LIGHT PROPAGATION IN A RECTANGULAR RIBLIKE STRUCTURED THIN FILM

To accurately simulate the light propagating through the liquid crystal in a confined rectangular riblike structured-thin-film material and to obtain an optimized material structured periodicity, we must implement a two-dimensional FDTD optical calculation. This method is a numerical approach for directly solving Maxwell’s time-dependent curl equations in the two-dimensional or three-dimensional domain with no other assumptions involved. For sourceless inhomogeneous anisotropic media, Maxwell’s equations can be written as

\[
\frac{\partial \mathbf{E}(r)}{\partial t} = \varepsilon^{-1}(r) \cdot [\nabla \times \mathbf{H}(r)],
\]

\[
\frac{\partial \mathbf{H}(r)}{\partial t} = \mu_0^{-1}(r) \cdot [\nabla \times \mathbf{E}(r)],
\]

where \( \varepsilon^{-1}(r) \) is the inverse of the spatially varying dielectric tensor.

In our computer simulations the explicit central-difference scheme was employed. The discretization technique that we used provides fourth-order accuracy to approximate the first-order derivative in space and second-order accuracy to approximate the first-order derivative in time. The FDTD calculation domain is shown in Fig. 4. The perfectly-matched-layer technique is used for terminating the calculation grid.

Owing to the limitation of computer speed and memory, calculating the far field with the FDTD method is difficult. However, the far-field result can be obtained by near-field-to-far-field transformation. The near-field-to-far-field transformation can be done by means of the Helmholtz–Kirchhoff integral theorem.

\[
\Psi_{\text{far}}(r) = \frac{1}{4\pi} \int \int_{S'} \mathbf{n} \cdot [\Psi_{\text{near}}(r') \times \nabla' G - G \cdot \nabla' \Psi_{\text{near}}(r')] \, ds',
\]

where \( G = \exp(ikR/R) \) is known as Green’s function and \( \Psi_{\text{near}} \) and \( \Psi_{\text{far}} \) represent the near and far electric and magnetic fields, respectively.

For the two-dimensional case (in the xy plane), the near-field-to-far-field transformation scheme is shown in Fig. 5, and Eq. (6) can be approximated as

\[
\Psi_{\text{far}}(r) = \frac{1}{4\pi} \int_{S'} \mathbf{n} \cdot [\Psi_{\text{near}}(r') \times \nabla' G - G \cdot \nabla' \Psi_{\text{near}}(r')] \, ds',
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\]
We elaborate the two conditions as follows:

1. \( \lambda = 2 \mu m \) \((L_1 = 1.0 \mu m, \ L_2 = 1.0 \mu m)\), \( n_{wall} = 1.50, \ n_{fill} = 1.70, \ d = 15.0 \mu m, \ \lambda = 1.55 \mu m. \) In this case \( \Lambda > \lambda; \) the FDTD near-field calculation result is shown in Fig. 6, which is a snapshot of the propagating fields. The two white lines indicate the position of the structured film. The unit of the \( x \) and \( y \) axes of Fig. 6 is the number of grid points. The grid sizes of the \( x \) and \( y \) axes are the same, \( \lambda/20, \) and \( \lambda \) is taken as the value of free space. It can be seen that before the light enters the film, it is a plane wave. However when light propagates inside the structured film, diffraction starts taking place. After light exits the film, it is clearly noticeable that the wave front propagates in three directions. One is parallel to the incident wave front, which forms the zeroth-order diffraction peak. The other two propagate at angles \( \pm \theta, \) which correspond to \( \pm 1st\)-order diffraction peaks. Collecting the near electric field and performing the near-field-to-far-field transform, we obtain the far-field diffraction pattern as shown in Fig. 7. Besides the main zeroth-order peak, \( \pm 1st\)-order peaks can also be observed at the diffraction angle \( \theta = 50.59^\circ, \) which is in good agreement with the theoretical estimated value of \( 50.80^\circ \) from Eq. (3).

2. \( \Lambda = 1.5 \mu m \) \((L_1 = 0.5 \mu m, \ L_2 = 1 \mu m)\), \( n_{wall} = 1.50, \ n_{fill} = 1.70, \ d = 15.0 \mu m, \ \lambda = 1.55 \mu m. \) In this

\[
\Psi_{\text{far}}(x_{\text{far}}, y_{\text{far}}) = \frac{\exp(-i\pi/4)}{\sqrt{8\pi k}} \int_{-a}^{a} \exp(-ikR) \sqrt{R} \left( \frac{\partial}{\partial y} \Psi_{\text{near}}(x', y_0) + ik(y_{\text{far}} - y_0)\Psi_{\text{near}}(x', y_0) \right) \mathrm{d}x',
\]

where

\[
R = [(x' - x_{\text{far}})^2 + (y_0 - y_{\text{far}})^2]^{1/2}, \quad k = 2\pi/\lambda.
\]

Therefore after near-field two-dimensional FDTD calculation is completed, the far-field diffraction pattern can be calculated by Eq. (7).

We will first consider cases in which the isotropic material is the filling in the channel and then consider cases in which the liquid crystal is the filling material. Figure 4 shows that the light source of a plane-wave Gaussian beam is incident from the bottom of the structured film, the beam wavelength is 1550 nm in free space, and the beam width is equal to the width of the calculation domain (in the \( x \) direction). The light source in our FDTD simulations is given in Eq. (8),

\[
E_z(x, t) = E_0 \exp(-x^2/w_0^2) \exp[-i(k \cdot r - \omega t)],
\]

where \( w_0 \) is the Gaussian beam waist and \( k \) is wave vector, here specifically indicating the \( y \)-axis direction.

In Fig. 4, \( L_1 \) and \( L_2 \) are the width of walls and channels, respectively, and their corresponding refractive indices are \( n_1 \) and \( n_2. \) The free-space refractive index is \( n_0 = 1.0. \) The FDTD calculation will be applied for this structured film so that the near-field and far-field results can be obtained.

For the case of isotropic material filling in the channel, two specific conditions are calculated: (1) The periodicity \( \Lambda \) of the structured film is greater than the incident wavelength of the light and (2) the periodicity \( \Lambda \) of the structured film is close to the incident wavelength of light.

We elaborate the two conditions as follows:

1. \( \Lambda = 2 \mu m \) \((L_1 = 1.0 \mu m, \ L_2 = 1.0 \mu m)\), \( n_{wall} = 1.50, \ n_{fill} = 1.70, \ d = 15.0 \mu m, \ \lambda = 1.55 \mu m. \) In this

![Fig. 5. Geometry of the two-dimensional diffraction problem.](image)

![Fig. 6. Near-field propagation snapshot of a rectangular riblike structured film of \( L_1 = 1.0 \mu m, \ L_2 = 1.0 \mu m, \) and \( \lambda = 1.55 \mu m \) in free space, with \( n_{wall} = 1.50, \ n_{fill} = 1.70, \ d = 15.0 \mu m. \) The unit of the \( x \) and \( y \) axes is the grid point, which equals \( \lambda/20. \) The field amplitude is represented by the grayscale bar.](image)

![Fig. 7. Light diffraction pattern at the far field for a rectangular riblike structured film of \( L_1 = 1.0 \mu m, \ L_2 = 1.0 \mu m, \) and \( \lambda = 1.55 \mu m \) in free space, with \( n_{wall} = 1.5, \ n_{fill} = 1.7, \) and \( d = 15.0 \mu m. \)](image)
case, the structured film periodicity \( \Lambda \) is very close to the wavelength of light \( \lambda \). Except for the choice of \( L_1 = 0.5 \, \mu m \) for this case, the parameters remain the same as the above case. A snapshot of the near-field propagating results is shown in Fig. 8. It indicates that although the wave front of the light inside the film is distorted, the exiting wave front at the top of the calculation domain is nearly a plane wave parallel to the incident one and yields a strong zeroth-order diffraction peak. There are also two wave fronts propagating to ±1st-order diffraction with two very large diffraction angles. The corresponding near-field-to-far-field transformation is shown in Fig. 9. The result shows ±1st-order diffraction angles of approximately ±80°, but the intensity of these two peaks is smaller than the 0.1% of the zeroth order. Therefore they are not seen in Fig. 9. This calculation is approximately in agreement with the analytically estimated result, which predicts that when the structured film periodicity \( \Lambda \) is equal to or smaller than the wavelength of light, the film diffraction effect can be ignored.

The FDTD calculation gives not only the field amplitude distribution at every grid point in the calculation domain but also the corresponding electric field phase-angle distribution. So the film-produced phase angle can be obtained by subtracting the phase angle at entering grid points from the corresponding phase angles at exiting grid points. Figure 10 shows the calculated phase angle produced by the structured film. In Fig. 10 the gray solid line (a) is the phase angle produced by the structured film. It has a maximum fluctuation \( \sim 2.4 \) rad, which may come from the limited calculating aperture size and the interference between the liquid crystal and polymer wall boundaries, since those phase values are collected just at the exit of the structured film. The dashed line (b) is the phase angle calculated at the top of the calculation domain, whose position corresponds to the \( y \)-axis grid point of 500 in Fig. 8. The phase angle shows a very small fluctuation, which indicates that the exiting beam forms a good plane wave again after passing through the structured film. In order to define the structured-film-produced phase angle and rule out the fluctuation effect shown in curve (a), we introduce the effective phase angle. Here we define that the effective phase angle equals the phase angle of curve (b) minus the phase angle produced in free space, which is from the top of the film to the top of the calculation domain (at the \( y \)-axis grid point of 500 in Fig. 8). The dark solid line of Fig. 10 indicates the effective phase angle of this structured film.

4. TWO-DIMENSIONAL LIQUID-CRYSTAL-DIRECTOR FIELD AND FDTD CALCULATIONS
In this section we consider using liquid crystalline material as a filling medium. Two different types of liquid-crystal-director configurations, the uniform type and the hybrid type, are discussed. The calculations are still based on the rectangular riblike geometry shown in Fig. 3.
A. Two-Dimensional Liquid-Crystal-Director Calculation

The two-dimensional liquid-crystal simulation program is based on the software LC3D,16 and the initial directors at the channel boundaries—which include top and bottom substrates and surrounding walls—are fixed. Therefore when the relaxation method is used to calculate director configurations, these boundary director orientations do not change.

The LC3D program is based on the Frank–Oseen free-energy density given in Eq. (9)17:

\[
f_g = \frac{1}{2}K_{11}(\nabla \cdot \mathbf{n})^2 + \frac{1}{2}K_{22}(\mathbf{n} \cdot \nabla \times \mathbf{n} + q_0)^2 \\
+ \frac{1}{2}K_{33}(\mathbf{n} \times \nabla \times \mathbf{n})^2 - \frac{1}{2}\mathbf{D} \cdot \mathbf{E}.
\]

Here \( \mathbf{n} \) is the unit vector director, \( K_{11}, K_{22}, \) and \( K_{33} \) are the liquid crystal splay, twist, and bend elastic constants, respectively, \( q_0 \) is the chiral wave number (= 2\( \pi/p \)), \( p \) is the intrinsic chiral pitch of the liquid crystal, \( \mathbf{D} \) is the electric displacement, and \( \mathbf{E} \) is the electric field. The relaxation method is used in our calculation with the update formula given in Eq. (10), which can be derived by setting the viscous torque equal to the elastic torque18:

\[
n_i^{\text{new}} = n_i^{\text{old}} - \frac{\Delta t}{\gamma_1}\left[ f_g \right]_{n_i}, \quad i = x, y, z.
\]

Here \( \Delta t \) is the numerical time step used in the simulation, \( \gamma_1 \) is the rotational viscosity of the liquid crystal material, \( n_i^{\text{new}} \) denotes the new value of the component of the director, \( n_i^{\text{old}} \) denotes the value at the previous time step, and \( \left[ f_g \right]_{n_i} \) is the functional derivative:

\[
\left[ f_g \right]_{n_i} = \frac{\partial f_g}{\partial n_i} - \frac{d}{dx} \left[ \frac{\partial f_g}{\partial (n_i/x)} \right] - \frac{d}{dy} \left[ \frac{\partial f_g}{\partial (n_i/y)} \right].
\]

To determine the new voltage profile, we used a direct method based on the fact that when Gauss’s law \( (\nabla \cdot \mathbf{D} = 0) \) is discretized, an equation linear in the values of the discretized voltage results.19 This equation can then be solved for the new value of the voltage at the current grid point in terms of the values at the surrounding grid points.

B. Uniform Liquid-Crystal-Director Configuration

We will first consider that the liquid crystal directors in the structured film shown in Fig. 3 are aligned along the \( z \) direction at the top and bottom substrates and also at the left and right walls. On the basis of the results that we obtained from Section 3, we chose the width of the channel and wall to be 1.0 and 0.5 \( \mu m \), respectively, and the film thickness is 15.0 \( \mu m \). The incident light is polarized along the \( z \) direction with wavelength 1.55 \( \mu m \) in free space, so the light will “see” only the liquid crystal index of refraction \( n_e \). The considered liquid crystal material is BL006 (Merck), which has \( n_o = 1.530, n_e = 1.816, \Delta \epsilon = 13.5 \). The refractive index of the wall is 1.656.

Two-dimensional liquid-crystal-director field calculations are performed to obtain the uniform liquid-crystal-director configurations at different applied voltages. Figures 11(a) and 11(b) show two examples of the liquid-crystal-director field in one channel of the structured film at the applied voltages of 0.0 and 10.5 \( V \), respectively.

Figures 11(a) and 11(b) show two examples of the liquid-crystal-director field in one channel of the structured film at the applied voltages of 0.0 and 10.5 \( V \), respectively.

Two-dimensional FDTD optical calculations are also performed. The calculated effective phase angle as a function of applied voltage is shown in Fig. 12. The phase-angle tuning range for this specific example is \( \sim 9.20 \) rad.

If a conventional liquid crystal cell is used to generate the same phase-angle tuning range with the same liquid crystal material, the corresponding cell thickness is \( \sim 7.85 \) \( \mu m \) and the simulated relaxation speed \( \sim 138 \) ms. So
when the response time of the conventional liquid crystal cell and the proposed rectangular riblike material with a boundary spacing of 1.0 μm are compared, the latter will be much faster, since the liquid crystal response time is proportional to the square of the boundary space. We expect the switching speed to be close to that of a holographic polymer-dispersed liquid crystal grating with similar periodicity, which gives a switching speed under submillisecond.20

C. Hybrid Liquid-Crystal-Director Configuration

For the hybrid liquid-crystal-director configuration, liquid crystal directors are aligned parallel to the surface of one substrate and perpendicular to surface of another. We assume that the liquid crystal directors at the bulk wall boundaries also have hybrid alignment and strong anchoring. In this case we set the bulk-wall refractive index $n_{\text{wall}}$ to be 1.576. Other than that, the filling liquid crystal material, geometric dimension, wavelength of light, and polarization are to be the same as for uniform device. With the LC3D liquid-crystal-director calculation program, hybrid liquid crystal configurations at different applied voltages are obtained. Figures 13(a) and 13(b) show two examples of the calculated director field, which corresponds to applied voltages of 0.0 and 10.0 V, respectively. The two-dimensional FDTD calculations are then used to obtain a plot of the film effective phase angle as a function of applied voltage. Figure 14 shows the calculation results. The calculated phase-angle tuning range of this film is $\approx 4.86$ rad.

Comparing the two types of liquid-crystal-director configurations, we can see that the phase-angle tuning range for a uniform aligned liquid-crystal-director field is approximately twice as large as for the hybrid one with the same thickness, which is expected from their director configurations. If the structured-film dimensions of 0.5 μm for the wall width and 1.0 μm for the channel width are applied to the cylindrical microcavity shown in Fig. 1, the ER liquid-crystal-director configuration is expected. There are some similarities between the hybrid director field and the ER director field. Therefore if the dimensions of 0.5 μm for the cavity wall and 1.0 μm for the cavity diameter are applied to the microcavity cylindrical structured material, the characteristic of the effective phase angle as a function of applied voltage is expected to be similar to that shown in Fig. 14.

5. SUMMARY

We have proposed a fast-switching, variable-refractive-index material with liquid-crystal-infiltrated microcavity. Accurate calculations of the rectangular riblike structured film are presented for the first time by means of two-dimensional FDTD optical calculations of two-dimensional liquid-crystal-director-configuration calculations. Obviously, this calculated device is polarization dependent. However, if the optimized nondiffraction periodicity $\Lambda$ obtained from this calculation is applied to the cylindrical microcavity shown in Fig. 1, a polarization-insensitive variable-refractive-index material with liquid-crystal-infiltrated microcavity will be expected. It is very important to find out the optimized periodicity $\Lambda$, since it will increase the liquid crystal volume fraction as well as the material phase-angle tuning range and reduce the device’s driving voltage. By comparing Figs. 7 and 9, we find that when the cavity periodicity is equal to or smaller than the wavelength of the light, the calculated diffraction peaks’ intensity is smaller than 0.1% of the zeroth order. Therefore for the proposed ideal structured material, the diffraction effect can be ignored if the periodicity of the structured material is equal to or smaller than the wavelength of incident light.
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