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Spectral hole filters using tilt-modulated chiral sculptured thin films

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ABSTRACT

A defect-free chiral sculptured thin film (STF) reflects light of one circular polarization state and transmits that of the other in a spectral regime, called the Bragg regime. A tilt-modulated chiral STF reflects light of both circular polarization states in the Bragg regime if the amplitude of modulation is sufficiently large. A twist defect in an unmodulated chiral STF results in either a narrow passband or an ultranarrow stopband filter depending upon the thickness of that STF. An ultranarrow passband filter can also be realized using a twist defect in the tilt-modulated chiral STF, if that STF is sufficiently thick. Furthermore, it was seen that the polarization-insensitive mirrors fabricated using tilt-modulated chiral STFs are very tolerant of twist defects if the amplitude of modulation is sufficiently large.

1. Introduction

Chiral sculptured thin films (STFs) are anisotropic dielectric materials with helical morphology, reflect normally incident light of one circular polarization state and transmit that of the other circular polarization state [1]. The spectral regime in which this discrimination of circularly polarized light takes place is called the Bragg regime and this phenomenon is called the circular Bragg phenomenon [2]. The bandwidth and the center wavelength of the Bragg regime can be engineered, chiefly, by controlling the period of the helixes formed during fabrication commonly achieved by directing a vapor flux obliquely at a rotating substrate. Chiral STFs find applications in optical filtering, laser mirrors, integrated circuits, and biochemistry [3–5].

Circular polarization-independent band-rejection filters can be realized of two chiral STFs [6]. Same filters can also be made with matched pairs of cholesteric liquid crystals (CLCs) that differ only in structural handedness [7] though filters made of chiral STFs are not sensitive to minor temperature variations and spacer layers needed for liquid crystals [8] are unnecessary for STF technology. A tilt-modulated chiral STF is an alternative technology to obtain polarization-insensitive filters [9].

Narrow bandpass filters and ultranarrow bandstop filters can be fabricated using structural defects in a chiral STF [10–12]. If the thickness of the chiral STF with the structural defect is small, a narrowband bandpass filter results. When the thickness is increased beyond the cross-over point [11] the narrow filter is replaced by an ultranarrow filter and the filter becomes a bandstop filter instead of a bandpass filter. The same behavior is observed for structural defects in chiral liquid crystals [13–17]. Such filters are called spectral-hole filters. These filters can appear in fiber Bragg gratings [18] as well and are exploited for narrow-bandpass filtering in optical fiber communication [19]. Spectral-hole filters find applications as notch filters [6] and circularly polarized light sources [20]. All these filters are sensitive to the circular polarization state of incident light. Polarization-insensitive spectral-hole filters can be fabricated using rugate filters with structural defects [21].

Can the bandwidth of the narrowband and ultranarrowband filters be controlled for circularly polarized light? What is the tolerance of these filters to small variations in the direction of vapor flux during deposition of chiral STF? Can the polarization-insensitive narrowband and ultranarrowband filters be made with single section chiral STFs? To answer these questions, we investigated the structural twist defect in a tilt-modulated chiral STF, where the direction of vapor flux arriving at the substrate is modulated with a periodic function [9,22]. The reason for selecting the tilt-modulated chiral STF is its ability to behave as circular-polarization insensitive Bragg filter [9,23,24]. This has been demonstrated experimentally in Ref. [22].

The tilt-modulated chiral STF is briefly discussed in Section 2 and numerical results are presented and discussed in Section 3. Concluding remarks are presented in Section 4. An $\exp(-i\omega t)$ time-dependence is implicit, with ω denoting the angular frequency. The free-space wavenumber, the free-space wavelength, and the intrinsic impedance of free space are denoted by $k_0 = \omega\sqrt{\varepsilon_0\mu_0}$, $\lambda_0 = 2\pi/k_0$, and $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$, respectively, with μ_0 and

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ε_0 being the permeability and the permittivity of free space. Vectors are in boldface and dyadics are underlined twice. The Cartesian unit vectors are identified as $\hat{\mathbf{u}}_x$, $\hat{\mathbf{u}}_y$, and $\hat{\mathbf{u}}_z$.

2. Theory in brief

Let us consider a chiral STF occupying the region $-L < z < L$ with a twist defect at $z=0$, as shown schematically in Fig. 1. The periodically nonhomogeneous permittivity dyadic of the STF is given as

$$\underline{\underline{\varepsilon}}(z) = \varepsilon_0 \underline{\underline{S}}_z(\zeta^\pm)\cdot\underline{\underline{S}}_y(\chi)\cdot\underline{\underline{\varepsilon}}^{\circ}_{ref}(z)\cdot\underline{\underline{S}}_y^{-1}(\chi)\cdot\underline{\underline{S}}_z^{-1}(\zeta^\pm), \quad 0 \lessgtr z \lessgtr \pm L. \tag{1}$$

The locally orthorhombic symmetry is expressed through the diagonal dyadic:

$$\underline{\underline{\varepsilon}}^{\circ}_{ref}(z) = \varepsilon_a(z)\hat{\mathbf{u}}_z\hat{\mathbf{u}}_z + \varepsilon_b(z)\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \varepsilon_c(z)\hat{\mathbf{u}}_y\hat{\mathbf{u}}_y \tag{2}$$

and the local tilt of the nanoscale columns with respect to the xy plane is captured by the dyadic:

$$\underline{\underline{S}}_y(\chi) = (\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \hat{\mathbf{u}}_z\hat{\mathbf{u}}_z)\cos\left[\chi(z)\right] + (\hat{\mathbf{u}}_z\hat{\mathbf{u}}_x - \hat{\mathbf{u}}_x\hat{\mathbf{u}}_z)\sin\left[\chi(z)\right] + \hat{\mathbf{u}}_y\hat{\mathbf{u}}_y. \tag{3}$$

The relative permittivity scalars $\varepsilon_{a,b,c}(z)$ and the tilt angle $\chi(z)$ depend on the vapor incidence angle $\chi_v(z)$. The sinusoidal modulation of vapor incidence angle is expressed as [9]

$$\chi_v = \tilde{\chi}_v + \delta_v \sin\left(2N_{mod}\frac{\pi z}{\Omega}\right), \tag{4}$$

where $\tilde{\chi}_v$ is the average value of χ_v, δ_v is the amplitude of modulation and N_{mod} is the number of oscillations over one-half structural period of tilt-modulated chiral STF, which may be integer or half-integer.

The third dyadic in Eq. (1) is stated as

$$\underline{\underline{S}}_z(\zeta^\pm) = (\hat{\mathbf{u}}_x\hat{\mathbf{u}}_x + \hat{\mathbf{u}}_y\hat{\mathbf{u}}_y)\cos\zeta^\pm + (\hat{\mathbf{u}}_y\hat{\mathbf{u}}_x - \hat{\mathbf{u}}_x\hat{\mathbf{u}}_y)\sin\zeta^\pm + \hat{\mathbf{u}}_z\hat{\mathbf{u}}_z, \quad 0 \lessgtr z \lessgtr \pm L, \tag{5}$$

where

$$\zeta^\pm = h\left(\frac{\pi z}{\Omega} + \zeta_t^\pm\right), \quad 0 \lessgtr z \lessgtr \pm L, \tag{6}$$

which contains 2Ω as the structural period; $h=1$ for structural right-handedness and $h=-1$ for left handedness, and $\zeta_t^+ - \zeta_t^-$ shows the twist at $z=0$. The boundary-value problem of finding the reflectances and transmittances for normally incident plane of waves of circular polarization states has been formulated elsewhere [1,2] where the chiral STF has been modeled using piecewise-uniform approximation [1]. In this technique, the chiral STF is divided into thin slices parallel to the xy plane and the permittivity of the chiral STF is taken to be uniform in the slice and equal to its value at the middle of the slice. We used the same technique with a slice thickness of 0.5 nm after ascertaining that reflectances and transmittances converged to within $\pm$ 0.1% of their value when the slice thickness was 1 nm.

3. Numerical results and discussion

Let us now proceed to illustrative numerical results. For this purpose, the principal relative permittivity $\varepsilon_{a,b,c}$ of the tilt-modulated chiral STFs were taken to be that of a columnar thin film made by evaporating titanium oxide provided by Hodgkinson et al. [25]:

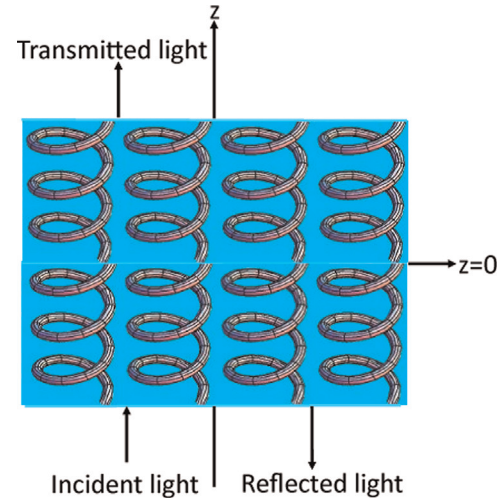

Fig. 1. Schematic of a twist defect in a tilt-modulated chiral STF when $h=1$. The incidence, reflection, and transmission for normally incident plane waves (along z-axis) is also shown.

$$\varepsilon_a = \left[1.0443 + 2.7394\left(\frac{2\chi_v}{\pi}\right) - 1.3697\left(\frac{2\chi_v}{\pi}\right)^2\right]^2, \tag{7}$$

$$\varepsilon_b = \left[1.6765 + 1.5649\left(\frac{2\chi_v}{\pi}\right) - 0.7825\left(\frac{2\chi_v}{\pi}\right)^2\right]^2, \tag{8}$$

$$\varepsilon_c = \left[1.3586 + 2.1109\left(\frac{2\chi_v}{\pi}\right) - 1.0554\left(\frac{2\chi_v}{\pi}\right)^2\right]^2, \tag{9}$$

with

$$\chi_v(z) = \tan^{-1}\left[\tan\chi(z)/2.8818\right]. \tag{10}$$

Furthermore, we chose $\Omega=200$ nm, $\tilde{\chi}_v = 35°$, $h=1$, $N_{\rm mod} = 1$, and δ_v was kept variable.

Spectrums of transmittances T_{RR}, T_{LL}, T_{LR}, and T_{RL} are presented in Fig. 2 for a normally excited tilt-modulated chiral STF when $\delta_v \in \{0°, 2°, 4°, 6°, 8°, 12°\}$ and $L = 30\Omega$. The data for these plots were computed with a wavelength resolution of 0.1 nm. The transmittance for right circularly polarized (RCP) incident light is represented by T_{RR} for RCP transmitted light and T_{LR} for left circularly polarized (LCP) transmitted light. Similarly, T_{LL} and T_{RL} represent, respectively, the transmittance of LCP and RCP transmitted light when LCP light is made incident. When $\delta_v = 0°$, the tilt-modulated chiral STF reduces to unmodulated STF and the STF behaves as narrow bandpass filter for RCP incidence as shown in Fig. 2(a). When δ_v increases to 6°, the modulated STF behaves as a narrow bandpass filter for both circular polarization states, though the bandwidth and the center frequency for both are different from each other. However, when δ_v increases even further, the narrowband begins to vanish as is evident from Fig. 2(f). In fact, when $\delta_v \geq 14°$, the narrowband vanishes completely and the tilt-modulated chiral STF with the twist defect behaves as a polarization insensitive reflector, just like a thick tile-modulated chiral STF would act *without* a twist defect. Therefore, a structural defect in a sufficiently modulated chiral STF does not affect suppression of circular Bragg phenomenon, showing the robustness of the tilt-modulated chiral STF as a polarization insensitive mirror.

When $L = 120\Omega$, the spectrums of tilt-modulated chiral STF are