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Optics Communications 259 (2006) 479–483

OPTICS COMMUNICATIONS

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Towards the design of elliptical-polarization rejection filters

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Received 15 August 2005; accepted 21 September 2005

Abstract

Ambichiral layered structures can be designed to function reasonably well as rejection filters for elliptical polarization states, although the proposed design strategy is inadequate for linear and quasilinear polarization states.

PACS: 42.25.Fx; 42.40.Eq; 42.79.Dj; 77.55.+f; 78.20.Fm

Keywords: Ambichirality; Elliptical polarization; Polarization filters; Rejection filters; Sculptured thin films

1. Introduction

That chiral (i.e., either left- or right-handed) arrangements of otherwise identical layers of uniaxial dielectric layers distinguish between normally incident left- and right-circularly polarized (LCP and RCP) plane waves in certain wavelength regimes was known more than 14 decades ago [1]. Off and on since then, such structures have drawn the attention of researchers. Most recently, these structures were classified into (i) ambichiral, (ii) equichiral, and (iii) finely chiral types [2]. A finely chiral layered structure exhibits the phenomenon of Bragg resonance for normally incident plane waves of only one circular polarization state, just like cholesteric liquid crystals [3] and chiral sculptured thin films [4]. In contrast, an ambichiral layered structure evinces Bragg resonances of different handenesses for different circular polarization states, while an equichiral layered structure evinces the same Bragg resonance for both circular polarization states. All three types of structures can be fabricated using thin sections of crystals just like for Šolc filters [5] as well as using sculptured-thin-film (STF) technology [4,6].

Although the filtration of circular polarization states has been the chief focus of STF researchers in optics for many years, attention is now shifting towards other kinds of filters and mirrors. A linear polarization state can be rejected by a periodically modulated finely layered chiral structure [7,8], whilst a specific elliptical polarization state can be rejected by interleaving the layers of an ambichiral layered structure with effectively homogeneous, biaxial layers [9]. These studies confirm that the rejection of a specific polarization state is intimately tied to the morphology of the chiral structure.

This observation suggests that the morphology can be chosen so as to reject a specific polarization state, which thought motivated this communication. We present here a simple strategy to design a periodically modulated ambichiral layered structure for that purpose. The underlying theoretical principles are presented in Section 2, and theoretical results obtained from implementing the design strategy using an extremization algorithm are shown in Section 3.

2. Theory of the design strategy

Let the halfspaces $z < 0$ and $z > L$ be vacuous, whereas the region $0 < z < L$ is occupied by the polarization filter. An arbitrarily polarized plane wave is normally incident

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2005.09.051

on the chosen layered structure from the halfspace $z < 0$. As a result, a plane wave is reflected into the halfspace $z < 0$ and another is transmitted into the upper halfspace $z > L$. The objective of our design strategy is to ensure that an incident plane with a specified elliptical polarization state is maximally reflected (and therefore rejected), whereas the incident plane wave with the orthogonal polarization state is minimally reflected, in a certain wavelength band with the design wavelength $\lambda_0^{\rm des}$ as its nominal center-wavelength. The minimally reflected state will be maximally transmitted if the absorption losses are sufficiently low.

2.1. Reflection and transmission

The electric field phasors associated with the two plane waves in the halfspace $z < 0$ are stated as

$$\underline{E}_{\rm inc}(\underline{r}) = (-a_{\rm p}\underline{u}_x + a_{\rm s}\underline{u}_y)\exp({\rm i}k_0 z), \qquad z < 0, \tag{1}$$

$$\underline{E}_{\rm ref}(\underline{r}) = (r_{\rm p}\underline{u}_x + r_{\rm s}\underline{u}_y)\exp(-{\rm i}k_0 z), \qquad z < 0, \tag{2}$$

where $k_0 = \omega\sqrt{\epsilon_0\mu_0}$ is the free-space wavenumber, ϵ_0 is the permittivity of free space, μ_0 is the permeability of free space, and ω is the angular frequency. Likewise, the electric field phasor in the halfspace $z > L$ is represented as

$$\underline{E}_{\rm trs}(\underline{r}) = (-t_{\rm p}\underline{u}_x + t_{\rm s}\underline{u}_y)\exp[{\rm i}k_0(z-L)], \qquad z > L. \tag{3}$$

Here, $a_{\rm p}$ and $a_{\rm s}$ are the known amplitudes of the p- and s-polarized components of the incident plane wave; $r_{\rm p}$ and $r_{\rm s}$ are the unknown amplitudes of the components of the reflected plane wave; while $t_{\rm p}$ and $t_{\rm s}$ are the unknown amplitudes of the components of the transmitted plane wave.

A standard procedure to obtain the unknown amplitudes leads to the 4×4 matrix relation

$$[\underline{f}_{\rm exit}] = [\underline{\underline{M}}_{\rm dev}]\cdot[\underline{f}_{\rm entry}], \tag{4}$$

where the 4-component column vectors

$$[\underline{f}_{\rm entry}] = \begin{bmatrix} r_{\rm p} - a_{\rm p} \\ r_{\rm s} + a_{\rm s} \\ (r_{\rm s} - a_{\rm s})/\eta_0 \\ -(r_{\rm p} + a_{\rm p})/\eta_0 \end{bmatrix} \tag{5}$$

and

$$[\underline{f}_{\rm exit}] = \begin{bmatrix} -t_{\rm p} \\ t_{\rm s} \\ -t_{\rm s}/\eta_0 \\ -t_{\rm p}/\eta_0 \end{bmatrix} \tag{6}$$

denote the electromagnetic fields at the entry and the exit pupils, respectively, and $\eta_0 = \sqrt{\mu_0/\epsilon_0}$ is the intrinsic impedance of free space. The transition matrix $[\underline{\underline{M}}_{\rm dev}]$ of the device is determined by the method described next.

2.2. Transition matrix of the device

The device is the structurally chiral layered structure confined within the planes $z = 0$ and $z = L$. This structure is periodically nonhomogeneous. Each period comprises N layers labeled by the integer $n \in [1, N]$ of thicknesses

$$d_n = d_1[1 + a\sin(2\phi_n)], \quad n \in [1, N], \tag{7}$$

where

$$\phi_n = 2\frac{(n-1)\pi}{N}, \tag{8}$$

whereas the average layer thickness d_1 and the modulation amplitude a are specified in Section 2.3. The total number of periods is set as $N_{\rm t}$. Thus, the total thickness of each period is Nd_1, and that of the entire structure is $L = N_{\rm t}Nd_1$.

The permittivity of the nth layer in a period is specified as

$$\underline{\underline{\epsilon}}_n = \epsilon_0\underline{\underline{S}}_z(h\phi_n)\cdot\underline{\underline{S}}_y(\chi)\cdot\left[\epsilon_a\underline{u}_z\underline{u}_z + \epsilon_b\underline{u}_x\underline{u}_x + \epsilon_c\underline{u}_y\underline{u}_y\right] \cdot\underline{\underline{S}}_y^{-1}(\chi)\cdot\underline{\underline{S}}_z^{-1}(h\phi_n), \quad n \in [1, 2N], \tag{9}$$

where the tilt dyadic

$$\underline{\underline{S}}_y(\chi) = \underline{u}_y\underline{u}_y + (\underline{u}_x\underline{u}_x + \underline{u}_z\underline{u}_z)\cos\chi + (\underline{u}_z\underline{u}_x - \underline{u}_x\underline{u}_z)\sin\chi, \tag{10}$$

and the rotation dyadic

$$\underline{\underline{S}}_z(\phi) = \underline{u}_z\underline{u}_z + (\underline{u}_x\underline{u}_x + \underline{u}_y\underline{u}_y)\cos\phi + (\underline{u}_y\underline{u}_x - \underline{u}_x\underline{u}_y)\sin\phi. \tag{11}$$

Finally, the parameter $h = 1$ for structural right-handedness and $h = -1$ for structural left-handedness. The relative permittivity scalars $\epsilon_{a,b,c}$ are implicit functions of ω.

For the nth layer in a period, we also define the transition matrix as

$$[\underline{\underline{M}}_n] = \exp({\rm i}[\underline{\underline{P}}_n]d_n), \tag{12}$$

where

$$[\underline{\underline{P}}_n] = \omega\begin{bmatrix} 0 & 0 & 0 & \mu_0 \\ 0 & 0 & -\mu_0 & 0 \\ h\epsilon_0(\epsilon_c - \epsilon_d)\cos\phi_n\sin\phi_n & -\epsilon_0(\epsilon_c\cos^2\phi_n + \epsilon_d\sin^2\phi_n) & 0 & 0 \\ \epsilon_0(\epsilon_c\sin^2\phi_n + \epsilon_d\cos^2\phi_n) & -h\epsilon_0(\epsilon_c - \epsilon_d)\cos\phi_n\sin\phi_n & 0 & 0 \end{bmatrix} \tag{13}$$

and

$$\epsilon_d = \frac{\epsilon_a\epsilon_b}{\epsilon_a\cos^2\chi + \epsilon_b\sin^2\chi}. \tag{14}$$

Using the transition matrixes for individual layers, we set up the transition matrix of the device as follows:

$$[\underline{\underline{M}}_{\rm dev}] = \left([\underline{\underline{M}}_N]\cdot[\underline{\underline{M}}_{N-1}]\cdot\ldots\cdot[\underline{\underline{M}}_2]\cdot[\underline{\underline{M}}_1]\right)^{N_{\rm t}}. \tag{15}$$

Eq. (4) can now be solved for $r_{\rm p,s}$ and $t_{\rm p,s}$ for specified $a_{\rm p}$ and $a_{\rm s}$.

2.3. Design strategy

Recall that $\lambda_0^{\rm des}$ is the design wavelength, and let the frequency variations of $\epsilon_{a,b,c}$ in the neighborhood of this wavelength be small enough to be ignored. Let us also assume that absorption in the device is small enough to be ignored.