Negative Uniaxial Optical Behaviour of Laminated Polarization Beam-splitters.

A. Massaro*, A. Di Donato**, T. Rozzi

Department of Electronics and Automatics, University of Ancona,
Via Brecce Bianche, 60131 Ancona,
e-mail: MassaroAle@libero.it*, a.didonato@ee.unian.it**

In the construction of polarization beam-splitters (PBS) and switches a structure can be employed, that is based on the birefringence of periodically laminated dielectric thin films [2,7]. In this work we derive an estimate of the split angle in laminated polarization splitters behaving as negative uniaxial crystals, in the case of oblique incidence. This analysis has been applied to an artificial anisotropic dielectric medium realized by means of layers of a-Si:H and SiO_2 [7].

INTRODUCTION

In several applications, such as polarization-independent optical isolators and optical switches, polarization splitters perform the important function of separating an incident beam in two orthogonally polarized out going parallel beams. Some authors have already proposed laminated polarization splitters (LPS) [7,4,5] and analysed these structures [3]. In this work we provide an analytical characterization of this type of LPS considering oblique incidence of the optical beam. The structure is illustrated in Fig. 1.(a), in which two types of thin dielectric films, having high (n_1) and low (n_2) refractive indices alternate periodically, with thickness sufficiently small as compared to the wavelength λ. The optical axis of the artificial anisotropic dielectric is perpendicular to the laminated layers and slanted to an angle χ from the z direction. The layers (d_1 and d_2) are assumed to be equal thick in order to attain a large splitting angle of the two polarized rays (ordinary Eo and extraordinary Ee) formed in the birefringent structure. The laminated structure behaves as a negative uniaxial crystal.

THEORY

The index ellipsoid of negative uniaxial crystal, referred to its own axis, (Fig.1.b) is given by:

$$\frac{x'^2}{n_e^2}+\frac{y'^2}{n_o^2}+\frac{z'^2}{n_o^2}=1 \quad n_o > n_e \tag{1}$$

denoting by χ the slant angle, the same expression in the (x,y,z) reference system (Fig.1.c) becomes :

$$\frac{x^2 \cdot \sin^2 c}{n_e^2}+\frac{y^2}{n_o^2}+\frac{z^2 \cdot \sin^2 c}{n_o^2}=1 \tag{2}$$

The values of refractive indices of ordinary and extraordinary waves, considering normal incidence on the structure, as shown in Fig.1.c, can be found by intersecting the index ellipsoid with the plane (z = 0) perpendicular to the wave vector **K**. The indices can be written as :

$$n'^2_e=\frac{n_e^2}{\sin^2 c} \quad and \quad n'^2_o=n_o^2 \tag{3}$$

The expressions of the refractive indexes n_o and n_e can be found [6]. The LPS represents an idealized case of a regular assembly of particles that have the form of thin parallel plates. Under the hypothesis of equal layer thickness, having dimensions much smaller than the wavelength and considering plane wave incidence (fig.2), the dielectric constant $\varepsilon_{||}$ and $\varepsilon_{\perp}$, associated with the components of electric field parallel and orthogonal to the layers, can be written, respectively [6]:

$$e_{//}=n_o^2=\frac{1}{2}n_1^2+\frac{1}{2}n_2^2 \quad , \quad e_{\perp}=n_e^2=\frac{n_1^2 \cdot n_2^2}{\frac{n_1^2}{2}+\frac{n_2^2}{2}} \tag{4}$$

where n_1 and n_2 are the refractive indices of the laminated layers. The relationship between the split angle and the incidence angle will be estimated by means of Huygens principle starting from the ordinary and extraordinary wave fronts [1]: in the case of positive and negative uniaxial crystals, the ordinary and the extraordinary wave fronts can be superimposed to the index ellipsoid for particular τ values (τ is the propagation time of the wave front in the crystal). For normal plane wave incidence, if Σ' is the envelope, at the time $t+\tau$, of wavelets emitted from the various points of the wave front Σ at the time t, taking into consideration the reference system in figure 3 and considering a wavelet centered in O, we see that **ON**/τ is the velocity of the wave and **OQ**/τ is the propagation velocity of the ray; moreover $\chi'=\pi/2-\chi$ and $d\chi=-d\chi'$ and $x=-n\cdot\sin\chi$, $y=-n\cdot\cos\chi$ where $n=$**OA** is the refractive index of the Σ wave. The ellipsoid equation:

$$\frac{x^2}{n_e^2}+\frac{y^2}{n_o^2}=1 \tag{5}$$

becomes:

$$\frac{\sin^2\chi}{n_e^2}+\frac{\cos^2\chi}{n_o^2}=\frac{1}{n^2} \tag{6}$$

By differentiation, we get:

$$\frac{dn}{d\chi}=n^3\cdot\left(\frac{1}{n_2^2}-\frac{1}{n_1^2}\right)\cdot\sin\chi\cdot\cos\chi \tag{7}$$

the relation between the split angle ϕ and the variation of the refractive index n with respect to the angle χ' is as follows:

$$\tan\phi=\frac{1}{n}\cdot\frac{dn}{d\chi'}=-\frac{1}{n}\cdot\frac{dn}{d\chi} \tag{8}$$

Substituting equation (7) in (8), we have[1]:

$$\tan\phi=\frac{1}{n}\cdot\frac{dn}{d\chi'}=-n^3\cdot\left(\frac{1}{n_2^2}-\frac{1}{n_1^2}\right)\cdot\sin\chi\cdot\cos\chi \tag{9}$$

Where:

$$n^2=\frac{n_1^2\cdot n_2^2}{n_2^2\cdot\sin^2\chi+n_1^2\cdot\cos^2\chi} \tag{10}$$

From equations (9) and (10) we evaluate the relationship for a negative uniaxial crystal:

$$\tan\phi=\frac{\left(n_o^2-n_e^2\right)\cdot\tan\chi}{n_e^2+n_o^2\cdot\tan^2\chi} \tag{11}$$

This relation can be generalized for non normal incidence ($\alpha_i\neq0$) (Fig.4).

$$\tan\phi'=\frac{\left(n_o^2-n_e^2\right)\cdot\tan\theta'}{n_e^2+n_o^2\cdot\tan^2\theta'} \tag{12}$$

The latter formula can be proved by considering the same analysis as in the previous case of normal incidence, but considering now an ellipsoid having a fictitious optical axis at an angle $\theta'=\chi-\alpha_i$. The refraction index n will change and so will change the new split angle (ϕ'); furthermore we observe that n_o and n_e are the same as in the normal incidence case. Relation (12) can be applied to a laminated structure realized by layers of a-Si:H and SiO_2, as shown in figure 1.a. The operating wavelength is 1.55μm, the thicknesses are $d_1=d_2=67$nm and $n_1=3.24$ (a-si:H), $n_2=1.46$ (SiO_2) [3]. Figures 5 and 6 show the split angle as function of θ' and of $\alpha_i=\chi-\theta'$.

CONCLUSIONS

In summary, conventional polarizers, made of rutile and calcite, have relative small split angles [4]. We have derived the split angle relation in laminated polarization splitters (LPS), behaving as negative uniaxial crystals, in the case of non normal incidence of the optical beam. PBS devices, realized with this kind of laminated anisotropic dielectric medium, are used in practical applications, in which large split angles are desiderable, furthermore they hold promise for the miniaturization of PBS and polarization-indipendent isolators.

FIGURES

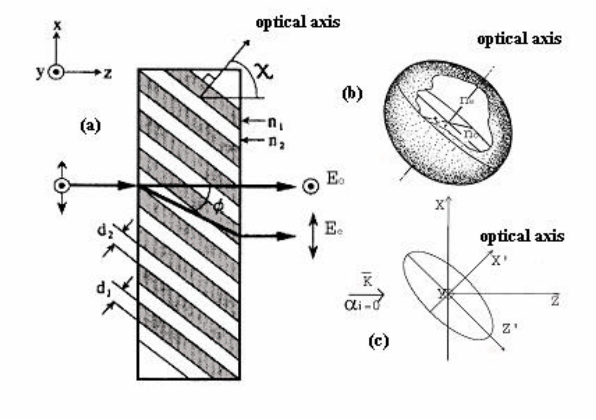

*Figure 1: (a) Laminated polarization splitter, (b) Index ellipsoid (negative case), (c) Intersection between the index ellipsoid and the plane orthogonal to **K**.*

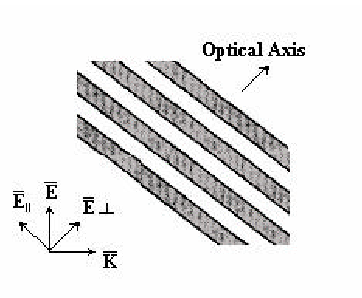

Figure 2: Superposition of effects for normal incidence of a plane wave

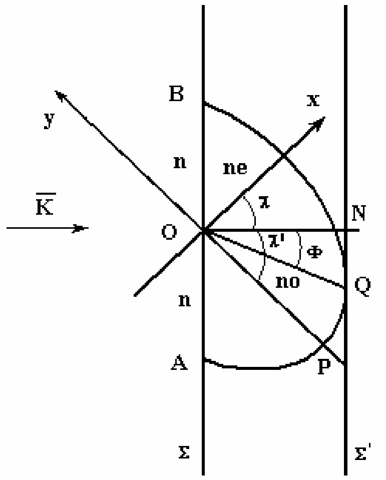

Figure 3: Wave front propagation and geometrical construction of the ellipse

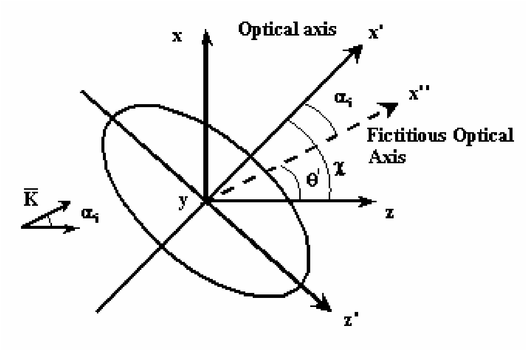

Figure 4: Construction of fictitious ellipsoid

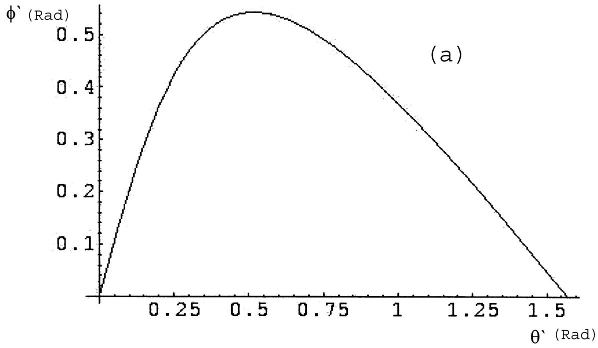

Figure 5:Variation of split angle with angle q'

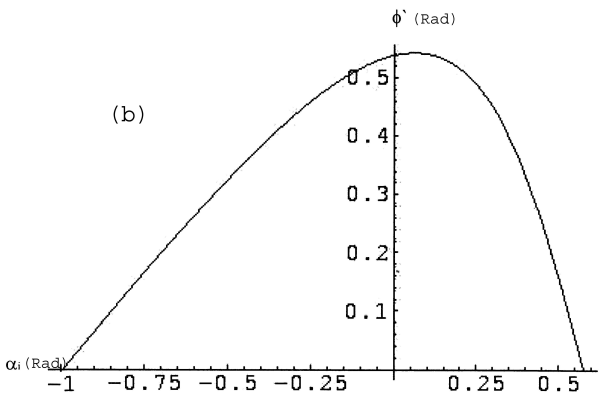

Figure 6: Variation of split angle with incidence angle a_i

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