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Novel theory analysis and new perspective on angular selectivity

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ABSTRACT

Wave propagation of symmetry incidence on the biaxial birefringent film is discussed in this paper based on the characteristic matrix method. Furthermore, based on the refractive index surface, the refractive indices and effective optical admittances of the forward and backward propagating extraordinary waves (p-polarized wave) are analyzed in detail. With regard to the symmetry incidence, optical properties, such as the input optical admittance, transmittance and reflectance, are not identical for an extraordinary wave under common condition, i.e., angular selectivity. Based on an analysis of refractive index surface, the effective optical admittances of the forward and backward propagating extraordinary waves are equal in this particular case; transmittance and reflectance under the symmetry incidence are completely overlapped, similar to findings in the isotropic thin film. We validate our analysis using the developed software package. Based on the novel theory analysis, we can gain a new perspective of symmetry incidence about angular selectivity for the biaxial birefringent film.

1. Introduction

The anisotropy [1,2] of sculptured thin film [3] (STF) is induced by packing columns and inclination of the columnar structures [4]. The sculptured thin film has the advantages of low cost, efficiency, and almost no material restriction [5–8]. An increasing number of studies have focused on the optical properties of STF [9–12]. STF applications are greatly anticipated [13]. One of its applications is in angular selective film. The angular selectivity of STF has been researched by focusing on material microstructure [14–16]. Mbise and Granqvist [17–20] have reported on the fabrication and angular selectivity of Cr film with columnar structure through a sputtering technique. Effective medium methods are often used to discuss STF angular selectivity [21].

In our previous work [22], we built a set of theory analysis for STF based on the characteristic matrix method. We also developed the precise software to analyze the STF optical properties. Based on Huygen's construction, the refractive indices and effective optical admittances of the forward and backward propagating extraordinary rays are discussed [23]. Rays are based on energy flux. However, wave vector propagation affects the phase change. In the current study, we investigate STF angular selectivity through the characteristic matrix method. In general, optical properties, such as the input optical admittance, transmittance and reflectance, are not identical for an extraordinary wave in the case of symmetry incidence. On the contrary, we can obtain the special condition under which the optical properties at the symmetry incidence are completely overlapped by analyzing the refractive index surface for extraordinary wave. Therefore, under the special case, STF angular selectivity can be eliminated. Moreover, we validate our analysis using the developed software package.

2. Theory analysis of symmetry incidence

In terms of optical properties, the biaxial birefringence of STF, due to the inclined columns microstructure, can be characterized by an index n_1 along the columns, an index n_2 normal to the columns in the vapor incidence plane, and an index n_3 normal to the vapor incidence plane [4]. For the biaxial thin film, the coupling of extraordinary wave and ordinary wave may result in a difficult treatment process. According to our previous work [22,23], when the principal section is consistent with the principal plane, s- and p-polarized waves will decouple, and propagate in an ordinary and extraordinary manner. In this case, the incident plane coincides with the vapor incidence plane. The s-polarized wave propagates across STF in an ordinary manner, and the optical properties of the birefringent thin film are equivalent to those of

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the isotropic thin film. This result is the reason why we need not consider the angular selectivity for s-polarized wave. The propagating parameters of extraordinary waves, such as the forward and backward propagating directions of wave vectors and their corresponding refractive indices, are determined in a biaxial birefringent thin film. For the extraordinary wave, the 2×2 characteristic matrix is derived and represented by the following equation:

$$M=\frac{1}{\eta_{+}+\eta_{-}}\begin{bmatrix}\eta_{-}e^{i\delta_{+}}+\eta_{+}e^{-i\delta_{-}} & e^{i\delta_{+}}-e^{-i\delta_{-}}\\ \eta_{-}\eta_{+}(e^{i\delta_{+}}-e^{-i\delta_{-}}) & \eta_{+}e^{i\delta_{+}}+\eta_{-}e^{-i\delta_{-}}\end{bmatrix} \quad (1)$$

where $\delta_{+}=2\pi n(\alpha_1)d\cos\theta_1/\lambda$ and $\delta_{-}=2\pi n(\alpha_2)d\cos\theta_2/\lambda$ denote the phase thicknesses of the forward- and backward-traveling extraordinary waves, respectively. The parameters $\eta_{+}=n(\alpha_1)/\cos(\theta_1)$ and $\eta_{-}=n(\alpha_2)/\cos(\theta_2)$ are the corresponding effective optical admittances, which are determined by the propagating directions of wave vector and corresponding indices of refraction. The refractive indices $n(\alpha_1)$ and $n(\alpha_2)$ can be calculated from the following formula:

$$\begin{cases} n(\alpha_1)=\frac{1}{((\sin^2\alpha_1/n_1^2)+(\cos^2\alpha_1/n_2^2))^{1/2}} \\ n(\alpha_2)=\frac{1}{((\sin^2\alpha_2/n_1^2)+(\cos^2\alpha_2/n_2^2))^{1/2}} \end{cases} \quad (2)$$

For simplicity, the symbols in this letter are in accordance with the convention in Refs. [22,23].

Similar to the isotropic thin film, the STF yields the input optical admittance [24], with the characteristic matrix M expressed as

$$\begin{cases} \begin{pmatrix} B \\ C \end{pmatrix} = M\begin{pmatrix} 1 \\ \eta_g \end{pmatrix} \\ Y=\frac{C}{B} \end{cases} \quad (3)$$

According to Eqs. (1) and (3), we can derive the input optical admittance Y with the incident angle of $+\theta_0$:

$$Y=\frac{C}{B}=\frac{\eta_{+}(\eta_g+\eta_{-})e^{i\delta_{+}}+\eta_{-}(\eta_g-\eta_{+})e^{-i\delta_{-}}}{(\eta_g+\eta_{-})e^{i\delta_{+}}+(\eta_{+}-\eta_g)e^{-i\delta_{-}}} \quad (4)$$

When the incident angle of the p-polarized wave turns into $-\theta_0$, the phase thicknesses and effective optical admittances of the forward- and backward-traveling wave vectors can be denoted by δ'_{+}, δ'_{-}, η'_{+}, and η'_{-}. These optical parameters may connect to the parameters of the incident angles $+\theta_0$ based on the reciprocity principle of wave vectors and rays transfer. Moreover, $\delta'_{+}=\delta_{-}$, $\delta'_{-}=\delta_{+}$ and $\eta'_{+}=\eta_{-}$, $\eta'_{-}=\eta_{+}$ can be obtained. Similarly, we derive the input optical admittance Y' with the incident angles of $-\theta_0$:

$$Y'=\frac{C'}{B'}=\frac{\eta_{+}(\eta_g-\eta_{-})e^{-i\delta_{+}}+\eta_{-}(\eta_g+\eta_{+})e^{i\delta_{-}}}{(\eta_{-}-\eta_g)e^{-i\delta_{+}}+(\eta_{+}+\eta_g)e^{i\delta_{-}}} \quad (5)$$

The reflectance and transmittance of the birefringent thin film at an arbitrary incidence angle are as follows [9]:

$$R=\left(\frac{\eta_0 B-C}{\eta_0 B+C}\right)\left(\frac{\eta_0 B-C}{\eta_0 B+C}\right)^{*} \quad (6)$$

$$T=\frac{4\eta_0\eta_g}{(\eta_0 B+C)(\eta_0 B+C)^{*}} \quad (7)$$

From Eqs. (4) and (5), the difference between Y and Y' can be noticed clearly. Therefore, based on the symmetry incidence, optical properties, such as the input optical admittance, transmittance and reflectance, are generally not identical for an extraordinary wave. We validate our analysis with the developed software package, as shown in Fig. 1. A biaxial anisotropic Ta_2O_5 thin film, with principal refractive indices of $n_1=1.81$, $n_2=1.74$, and $n_3=1.78$ [25], as well as column angle $\beta=70^\circ$ and the physical thickness $d=200$ nm, is used as the computation model. The incident and emergent media are homogeneous isotropic air and glass substrate, respectively. The incident angles of the p-polarized wave are $+\theta_0=+60^\circ$ and $-\theta_0=-60^\circ$.

As shown in Fig. 1, the difference of p-polarized wave transmittance spectra at $\pm\theta_0$ incident angle is very apparent. The coincident points of peaks at 325 and 650 nm are due to that the thin film is the absentee layer at 325 and 650 nm wavelengths.

However, we are unsure whether Y and Y' can be equal under some special conditions. Therefore, we analyze the refractive index surface for the extraordinary wave. The refractive index of extraordinary waves propagating in a biaxial birefringent thin film can be easily and directly described with the refractive index surface, described by the following formula [26]:

$$\frac{\kappa_1^2}{(1/n^2)-(1/n_1^2)}+\frac{\kappa_2^2}{(1/n^2)-(1/n_2^2)}+\frac{\kappa_3^2}{(1/n^2)-(1/n_3^2)}=0 \quad (8)$$

If we incorporate $n^2=x_1^2+x_2^2+x_3^2=n^2k_1^2+n^2k_2^2+n^2k_3^2$ into Eq. (8), we obtain the final form of the refractive index surface for describing the biaxial birefringent thin film, as shown in the following equation:

$$\begin{cases} A=n_1^2(n_2^2+n_3^2)x_1^2+n_2^2(n_1^2+n_3^2)x_2^2 \\ \quad +n_3^2(n_1^2+n_2^2)x_3^2 \\ (n_1^2x_1^2+n_2^2x_2^2+n_3^2x_3^2)(x_1^2+x_2^2+x_3^2)A \\ +n_1^2n_2^2n_3^2=0 \end{cases} \quad (9)$$

where x_1, x_2, and x_3 correspond to coordinates of n_1, n_2, and n_3, respectively. In the refractive index surface, the length of the radius vector is the refractive index of wave vector propagating along the radius vector direction. The refractive index surface for extraordinary wave is ellipsoid, and that for ordinary wave is sphere. Therefore, the refractive index surface should be double-shell surface. In the case of the incident plane that coincides with the vapor incidence plane, we only consider the x_1Ox_2 cross-section equation:

$$(x_1^2+x_2^2-n_3^2)\left(\frac{x_1^2}{n_2^2}+\frac{x_2^2}{n_1^2}-1\right)=0 \quad (10)$$

The s-polarized wave can be described by $x_1^2+x_2^2=n_3^2$ in the incident plane, and the p-polarized wave can be described by $x_1^2/n_2^2+x_2^2/n_1^2=1$. We only consider the refractive index surface for

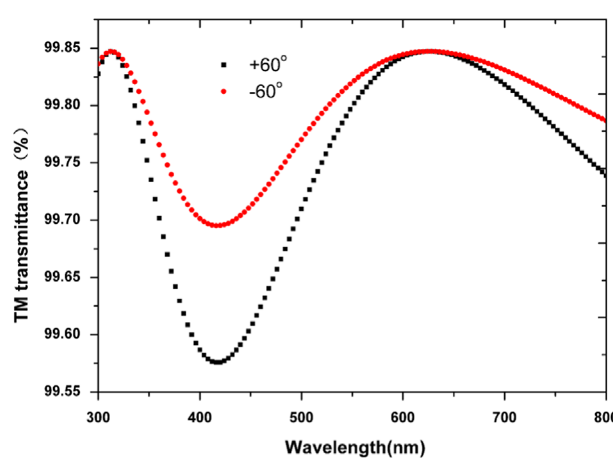

Fig. 1. Transmittance spectra of p-polarized wave at the symmetry incidence.