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Dual-band windows (DBW) transparent for fundamental and second harmonic generation frequencies

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Abstract

Using the known "looking glass" transformation property ($z\rightarrow 2\pi - z$, $y\rightarrow 2\pi - y$) of the optical phase thickness z and y of matching layers of two-layer anti-reflection coating, together with the fact that optical characteristics of any film do not change after addition of a half-wavelength layer, we designed dual-band anti-reflection coatings transparent at any preset wavelengths λ_1 and λ_2. On the basis of this result common fractional anti-reflection coatings for second and higher harmonics generation using dispersionless coating materials are developed. Explicit analytical relationships between refractive indices of the layers and substrate are deduced. Since for second harmonic generation the dispersion of materials may be a factor we show how to compensate the known dispersion of the coating materials by special choice of dispersion of a suitable substrate.

Keywords: Anti-reflection coatings; Harmonics generation

1. Introduction

A good anti-reflective coating is vital for solar cell performance, nonlinear optics and many other applications[1–3]. For a substrate with low refractive index, s, often it is very difficult or even impossible to find for manufacture of a single-layer anti-reflection coating an optical material with still lower refractive index, $\sqrt{s}$. The conventional adoption of the double-layered coatings effectively reduces limitations on values of the refractive indices of a suitable pair of the coating materials. Two remaining free parameters of a double-layer coating, i.e., thicknesses of the layers, after selection of suitable materials, are always enough to attain null reflectivity of the double-layered interface. Moreover, we will show that under this generally accepted approach *not all* potentialities of such coatings are utilized and will demonstrate how to extend these potentialities. Limiting ourselves to the case of the normal light incidence one finds that any two-layer anti-reflection coating with phase thickness $z=\frac{4\pi n d_n}{\lambda}$ and $y=\frac{4\pi t d_t}{\lambda}$ (d_n and d_t physical thickness of the first and second layers, correspondingly, λ is the wavelength), always allows the following "looking-glass" transformation: $z_+\rightarrow 2\pi - z_-$, $y_+\rightarrow 2\pi - y_-$. In each of such pairs of the solution (z_-,y_+) or (z_+,y_-) one of the layers is always thicker and another thinner than quarter-wavelength thickness π [4–6]. An example of phase thickness dependences is shown in Fig. 1. Equations for lower (z_-,$y_-\le\pi$) and upper (z_+,$y_+\ge\pi$) branches have the form

$$
\begin{aligned}
z_- &= 2\arctan n\sqrt{\frac{(s-1)(t^2-s)}{(n^2-s)(t^2-n^2 s)}}\\
y_- &= 2\arctan t\sqrt{\frac{(s-1)(n^2-s)}{(t^2-s)(t^2-n^2 s)}}\\
y_+ &= 2\pi - y_-,\ z_+ = 2\pi - z_-,
\end{aligned}
\qquad (1)
$$

where n, t and s are indices of the first, second layers and substrate, correspondingly.

2. Double-band anti-reflection coatings

Duality of the solutions prompts a hypothesis that one may to yield zero reflectance at two different wavelengths λ_1 and λ_2 (assume $\lambda_1>\lambda_2$). It means that passing from solution ($z_-(\lambda_1)$, $y_+(\lambda_1)$) to ($z_+(\lambda_2)$, $y_-(\lambda_2)$), under change of wavelength from λ_1

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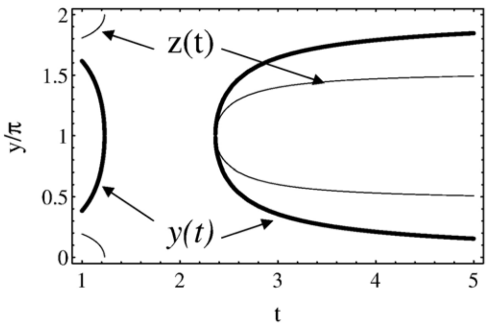

Fig. 1. Upper (z_+, $y_+ \geq \pi$) and lower (z_-, $y_- \leq \pi$) branches of the phase thicknesses z (thin lines) and y (thick lines) of the first and second layers as function of the refractive index t of a second layer under fixed value of the first layer index n=1.92 and substrate's index s=1.515. The "branch-converging" point $y=z=\pi$ corresponds to $t = n\sqrt{s}$. This graphic relates to the values n ant t into domain I (see Fig. 3).

to λ_2 while maintaining null reflectivity, one should guarantee implementation of the equality

$$\frac{y_+(\lambda_1)}{y_-(\lambda_2)} = \frac{z_-(\lambda_1)}{z_+(\lambda_2)} = \frac{\lambda_2}{\lambda_1}. \tag{2}$$

Since y_+, $z_+ \geq \pi$ and y_-, $z_- \leq \pi$ the first fraction always should be ≥ 1, while the second fraction should be ≤ 1. Therefore, at first sight it seems that unique solution is the trivial one: $y=z=\pi$, i.e. $\lambda_1=\lambda_2$ (see the lower-upper "branch-converging" point in Fig. 1). It is possible, however, to overcome this obstacle if take into consideration such evident fact that optical properties of any layer do not change after of the quarter-wavelength increase of its phase thickness. Therefore, the optical characteristics of any film with phase thickness z are identical to characteristics of a film with $z+2\pi p$, where p is an integer. Let us choose wavelengths with scaling ratio parameter $\gamma = \frac{\lambda_1}{\lambda_2}$. If one starts from sufficiently long wavelength λ_1 then the solution $z_+(\lambda_1)$, $y_-(\lambda_1)$, with lesser total double-layer thickness always may be realized under $p=0$ condition. With decreasing λ on the road to the "looking-glass" solution $z_-(\lambda_2)$, $y_+(\lambda_2)$ the value $z_-(\lambda_2)$ may surpass 2π, i.e. reach some zone with $p \geq 1$, whereas the phase thickness y occurs to be larger π. Then the solution $z_-(\lambda_2)+2\pi p$, $y_+(\lambda_2)$ may be realized. The condition for such realization is

$$\frac{y_+(\lambda_2)}{y_-(\lambda_1)} = \frac{z_-(\lambda_2)+2\pi p}{z_+(\lambda_1)} = \frac{\lambda_1}{\lambda_2} = \gamma > 1 \tag{3}$$

where $y_-(\lambda_1)+y_+(\lambda_2)=2\pi$, $z_+(\lambda_1)+z_-(\lambda_2)=2\pi(p+1)$.

In terms of two auxiliary parameters α and β Eqs. (1),(3) acquire the form

$$\frac{n}{t}\frac{t^2-s}{n^2-s} = \alpha \qquad nt\frac{s-1}{t^2-n^2 s} = \beta. \tag{4}$$

These parameters depend on selected for realization scaling parameter γ and branch p.

$$\alpha = \tan\pi\frac{\gamma-p}{\gamma+1}/\tan\frac{\pi}{\gamma+1}, \qquad \beta = \tan\pi\frac{\gamma-p}{\gamma+1}\tan\frac{\pi}{\gamma+1}. \tag{5}$$

When $p=1$ (the first branch) between these parameters springs up the relationship $\beta=\alpha+2$ [7]. Then parametric equations for n and t take the form

$$t^2 = \frac{s(x+\alpha)}{x(1+\alpha x)}, n = xt, \text{ where } x = \frac{s-1+\sqrt{(s-1)^2+4\beta^2 s}}{2\beta s}. \tag{6}$$

In Fig. 2 are shown the dependences of the refractive indices n and t on the scaling parameter γ for substrate with a given refractive index s. The value of the variable parameter x (as function γ) strongly depends on the permissible domain in (n,t) plane (see Fig. 3). In the domain I the value $x<1/\sqrt{s}$, in the domain II $1/\sqrt{s}<x<1$ and in the domain III $x>1$. In domains I and III exist only solutions $z=2y$ (branch $p=1$) and $z=3y$ ($p=2$), correspondingly. In the domain II there are both of these

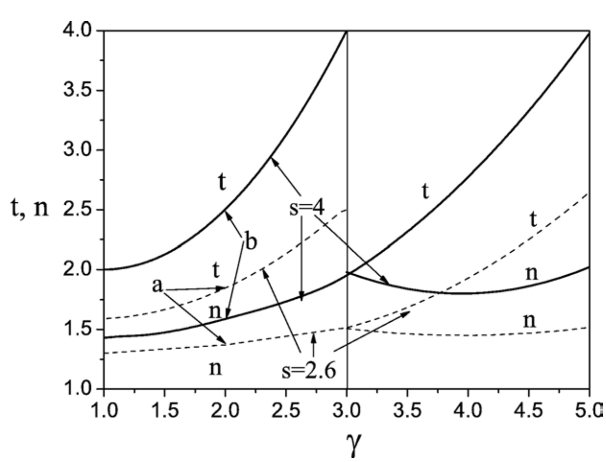

Fig. 2. The dependences of the refractive indices n and t on the scaling parameter γ. The solution $z=2y$ corresponds to the branch $p=1$ and located in the interval $1<\gamma<3$, whereas solution $z=3y$ lies in the interval $3<\gamma<5$ and corresponds to branch $p=2$. These values are acceptable for practical realizations. The points a and b under $\gamma=2$ correspond to the values n and t given in Table 1 (lines 3 and 4).

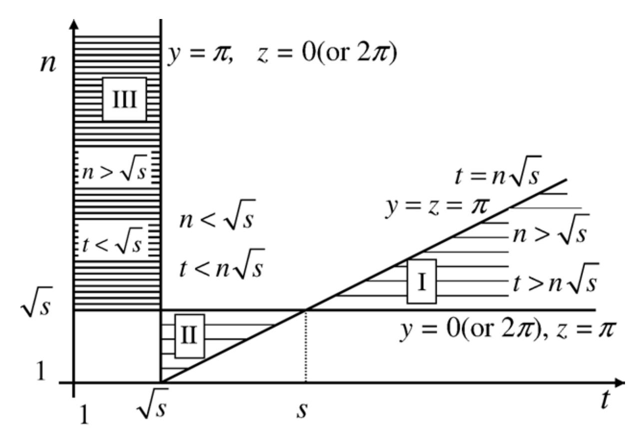

Fig. 3. The allowable domains (I–III) of the refractive indices n, t of a pair of optical materials for a fixed substrate s. The most practically interesting for DBWs is the domain II, where $\sqrt{s}<t<n\sqrt{s}$ and $t/\sqrt{s}<n<\sqrt{s}$.