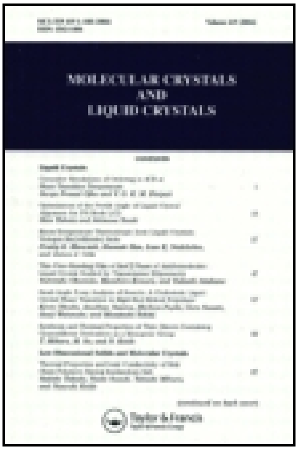

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Propagation of Light in Polymer Dispersed Liquid Crystal Films: The Adding Model for Coherent Field

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The adding method is used to investigate the light propagation in the film with high concentration of spherical isotropic scatterers. The equations to determine the reflection and transmission coefficients of a layer added are derived on the basis of similar characteristics of particulate monolayers calculated according to single-scattering and quasi-crystalline approximations.

Keywords: composite films; isotropic phase; multiple scattering

1. INTRODUCTION

This paper is devoted to the problem of light propagation through a disperse layer of concentrated particles, i.e., when we deal with the so-called dependent-scattering regime [1–5]. In this regime the system of scatterers requires the knowledge of the location of each particle in the layer, and the absorption and scattering of light by each particle is affected by the presence of the other particles. There are two fundamental mechanisms which result in the dependent-scattering regime. The first one is the near-field interparticle effect (the internal field of the particle is affected by the presence of the other particles). The second one is the interference of waves in the far field. We use the quasi-crystalline approximation (QCA) [6] to consider coherent transmittance, reflectance, and phase of the light leaving the layer. Results according to the QCA are compared with the calculations based on the

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single-scattering approximation (SSA) [2] relevant to the independent-scattering regime. In this regime each particle absorbs and scatters light independently of the presence of other particles.

Our results refer to films composed of monodisperse homogeneous isotropic spherical particles. These results are applicable to liquid crystal (LC) films with the LC in an isotropic state. The analysis of scattering in such films makes it possible to predict the concentration effects in the films with anisotropic droplets of LC. These results allow one to find the ranges of variation of particle concentration, refractive indices, and sizes within which the phase of a transmitted wave can be efficiently modulated. The results of this work can be used for development of polymer dispersed liquid crystal (PDLC) thin films and composite films of other types. We consider a PDLC layer as a collection of sublayers. The equations to describe amplitude coefficients of coherent transmission and reflection are derived and investigated.

2. BASIC EQUATIONS FOR ADDING METHOD

Let a plane parallel layer of discrete scatterers with thickness y is illuminated by the plane wave normally incident on its upper surface. Scheme of light propagation through this layer is shown in Figure 1. The plane wave has a wave number $k = 2\pi/\lambda$, λ is the wavelength. We calculate the coherent reflection $R(y)$ and coherent transmission $T(y)$ of the combined layer of thickness $y + \Delta y$, starting from the beforehand known transmission and reflection coefficients of the separate layers with thickness y and Δy, respectively. Taking into account multiple scattering between the layer of thickness y and a layer added (sublayer) with thickness Δy, we can write the system of equations for increments of transmittance $\Delta T\ (y)$ and reflectance $\Delta R\ (y)$ as a function of Δy [7]:

$$\left.\begin{aligned} \Delta R(y) &= \frac{R(\Delta y)T^2(y)\exp(2iky)}{1 - R(y)R(\Delta y)} \\ \frac{\Delta T(y)}{T(y)} &= \frac{T(\Delta y)}{1 - R(y)R(\Delta y)} - 1 \end{aligned}\right\}. \tag{1}$$

The system (1) can be rewritten as a system of two differential equations:

$$\left.\begin{aligned} R'(y) &= k_1 T^2(y)\exp(2iky) \\ \frac{T'(y)}{T(y)} &= k_1 R(y) - k_2 \end{aligned}\right\}. \tag{2}$$

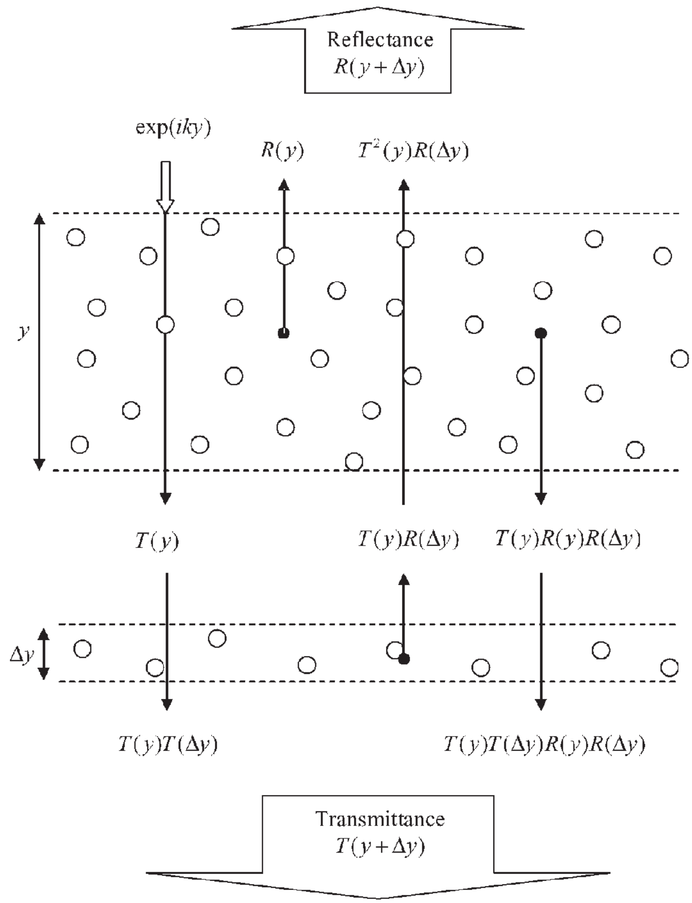

FIGURE 1 Scheme of light propagation through a layer of thickness $y + \Delta y$ normally illuminated by a plane wave. Quantities $R(y), T(y), R(\Delta y), T(\Delta y)$ are the amplitude coherent transmittance and reflectance for layers with thickness y and Δy, correspondingly. Each arrow in the figure represents the sum of all possible scattering events, which result in the coherent reflectance and transmittance of the whole layer. The arrows are shown shifted from one another to get space for better presentation of the written equations. The formulas near the arrows indicate the amplitude reflection and transmission coefficients due to the first, second, third, etc. scattering events between layers. The dashed lines indicate the imaginary (because we consider scatterers in the free space) interfaces of layers. The gap between layers is only to indicate more clearly the multiple scattering events between layers and to get more space for the equations. Quantities $R(y + \Delta y)$ and $T(y + \Delta y)$ are reflectance and transmittance of the layer of thickness $y + \Delta y$.

Here coefficients k_1, k_2 are determined by characteristics of the sublayer:

$$k_1 = R'(0)(y), \tag{3}$$

$$k_2 = -T'(0)(y), \tag{4}$$

where $R'(a)(b)$ and $T'(a)(b)$ are the derivatives of the reflection and transmission coefficients of sublayer of thickness a located at a depth b in the layer considered with respect to thickness.

We assume that (i) parameters of the layer do not depend on the variable y and (ii) Δy is sufficiently small to proceed from Eqs. (1) to the differential Eq. (2). If $\partial k_1/\partial y \equiv 0$ and $\partial k_2/\partial y \equiv 0$, we can write:

$$k_1 = R'(0)(0), \tag{5}$$

$$k_2 = -T'(0)(0). \tag{6}$$

We consider the sublayer of monodisperse spherical scatterers of diameter d as a monolayer. The distances between droplets in the monolayer are chosen the same as in the film. The formulas for the amplitude coefficients of transmission and reflection of a monolayer of scatterers can be written [5,7] as follows:

$$T = 1 - \frac{2\eta}{x^2} s(0), \tag{7}$$

$$R = \frac{2\eta}{x^2} s(\pi), \tag{8}$$

where $\eta = 0.907(\eta_3/0.74)^{2/3}$ is the filling coefficient of the monolayer; η_3 is the volume filling coefficient of the layer; $x = kd/2$ is the size parameter of a scatterer, $s(\alpha)$ is the amplitude function of scattering; α is a scattering angle.

From Eqs. (7), (8) we obtain the equations for k_1 and k_2:

$$\left.\begin{aligned} k_1 &= \frac{3\eta_3 k}{2x^3} s(\pi) \\ k_2 &= \frac{3\eta_3 k}{2x^3} s(0) \end{aligned}\right\}. \tag{9}$$

The solution of the system of Eq. (2) has to satisfy to conditions:

$$\left.\begin{aligned} T(y, k_1, k_2, k) &= \exp(-iky) T(y, k_1, k_2 - ik, 0) \\ R(y, k_1, k_2, k) &= R(y, k_1, k_2, 0) \end{aligned}\right\}. \tag{10}$$

The solution of system (2) is:

$$R(z, K_1, K_2) = R_\infty \frac{1 - \exp(-2Lz)}{1 - R_\infty^2 \exp(-2Lz)}, \quad (11)$$

$$T(z, K_1, K_2) = (1 - R_\infty^2) \frac{\exp(-(L + 2i)z)}{1 - R_\infty^2 \exp(-2Lz)}. \quad (12)$$

Here

$$L^2 \equiv (K_2 - 2i)^2 - K_1^2, \quad (13)$$

$$R_\infty \equiv (K_2 - L - 2i)/K_1, \quad (14)$$

$$K_1 = \frac{3\eta_3}{x^3} s(\pi), \quad (15)$$

$$K_2 = \frac{3\eta_3}{x^3} s(0), \quad (16)$$

$z = \pi y/\lambda$ is the dimensionless thickness.

3. BASIC EQUATIONS FOR AMPLITUDE SCATTERING FUNCTIONS

Under the SSA the amplitude function $s^{ss}(\alpha)$ at scattering angles $\alpha = 0$ and $\alpha = \pi$ is [8]:

$$s^{ss}(0) = \frac{1}{2} \sum_{j=1}^{N} (2j + 1)(a_j + b_j), \quad (17)$$

$$s^{ss}(\pi) = -\frac{1}{2} \sum_{j=1}^{N} (-1)^j (2j + 1)(a_j - b_j). \quad (18)$$

Here $N = x + 4\sqrt[3]{x} + 2$; a_j, b_j are the coefficients of the Mie scattering series for a sphere.

Under the QCA the amplitude functions $s^{ms}(\alpha)$ at $\alpha = 0$ and $\alpha = \pi$ are determined by using the equations published in [6].

4. RESULTS

The calculations of $|R|^2$ and $|T|^2$ are presented in Figures 2 and 3. The oscillating dependence of $|T|^2$ and $|R|^2$ on the layer thickness takes

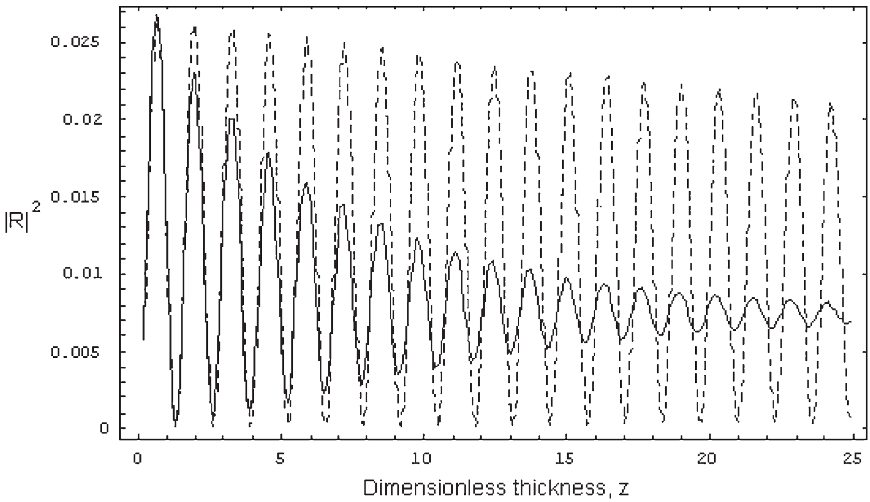

FIGURE 2 Reflection coefficient $|R|^2$ as a function of layer thickness z. Solid and dashed lines show the results of calculation under the QCA and the SSA, respectively. $\eta_3 = 0.4$, $x = 0.4$, $m = 1.6$.

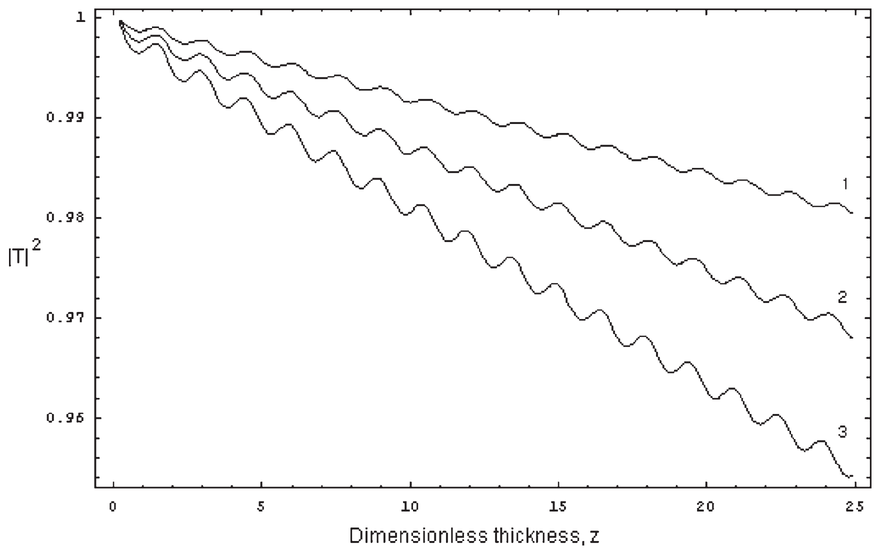

FIGURE 3 Transmission coefficient $|T|^2$ as a function of layer thickness z under the QCA. $x = 0.1, m = 1.1$. $\eta_3 = 0.3$ (curve 1); $\eta_3 = 0.4$ (curve 2); $\eta_3 = 0.5$ (curve 3).

place at small particle sizes. The largest amplitude of the oscillations increases with the filling coefficients increasing. The oscillations in transmittance and reflectance decay with a higher rate, when we take multiple scattering into account. With increasing particle sizes, the oscillations disappear and the dependence of transmittance on layer thickness turns exponential [7].

The phase of transmitted light calculated under the SSA and QCA is a linear function of the layer thickness. The results are practically the same for small particles with the refractive index close to unity. With the size and refractive index increasing there is more pronounced discrepancy in the results. Multiple scattering results in increasing phase values. The phase is in direct proportion to the layer thickness:

$$\varphi_t = k_\varphi z, \tag{19}$$

where $k_\varphi \equiv k_\varphi(\eta_3, x, m)$. The values k_φ according to both the SSA and QCA are linear functions of η_3 at small refractive index to be practically the same. At high refractive index the k_φ values under the SSA and QCA are different. It means that the influence of multiple scattering is essential at large refractive indices. In this case, coefficient k_φ according to the SSA is a linear function of η_3 at any volume concentrations, but it remains linear by the QCA only at the relatively small volume concentrations to become clearly nonlinear with η_3 increasing.

5. CONCLUSIONS

The model of coherent light transmission and reflection by a disperse layer with discrete scatterers is proposed. The equations which allow one to consider reflection and transmission coefficients and phases of the transmitted and reflected waves at small and high concentrations of scatterers are set and their solution is derived. It is shown that there are oscillations of the dependence of the reflection and transmission versus the film thickness for layers with small particles.

Phase of transmitted wave is a linear function of the thickness. The calculations in the single scattering and quasi-crystalline approximations give practically the same results for small particles with the refractive index close to unity. Phase of the reflected light is the oscillating function of the thickness. The decay of the oscillations is more pronounced, when the dependent-scattering regime is implemented.

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