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Influence of Extinction Coefficient on Electromagnetic Wave Transmission in Thin Superlattices

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In this paper, the impact of the extinction coefficient on electromagnetic wave transmission in a quasi-one-dimensional thin superlattice structure is investigated. The system consists of several layers of optical materials with different densities, and the focus is put on the transmission of light through this arrangement. Using theoretical modeling via the transfer matrix method, it is found that the extinction coefficient significantly influences transmission properties. Furthermore, the impact of altering the extinction coefficient of specific layers on the overall transmission behavior is investigated through systematic variations of the extinction coefficient and exploration of how changes in the optical properties of individual layers influence the transmission spectrum and the emergence of transmission peaks and valleys. These results provide valuable insights into the design and optimization of superlattice structures for various applications, including optical devices and photonic systems enabling precise light control.

topics: transfer matrix method, UV filters, tunable, electromagnetic (EM) propagation

1. Introduction

In the realm of optical materials and their intricate interactions with light, the optical extinction coefficient stands as a fundamental parameter that significantly influences light transmission behavior [1]. This coefficient characterizes the attenuation of light intensity as it traverses a material due to absorption and scattering processes. Its accurate determination is pivotal in understanding and engineering the optical response of various systems, ranging from thin films to multilayered structures [2–5]. By quantifying the rate at which electromagnetic energy is dissipated within a material, the extinction coefficient serves as a cornerstone in predicting the material's behavior across a wide spectral range. In this pursuit, computer simulations grounded in the transfer matrix method have emerged as a powerful analytical tool [6, 7]. Leveraging its prowess in modeling the propagation of light through layered media, this method offers an effective means to unravel the intricate interplay between material properties, layer thicknesses, and incident wavelengths.

In the context of thin superlattices, the impact of the extinction coefficient on light transmittance cannot be simply omitted. These systems, composed of alternating layers of different materials, exhibit unique optical characteristics driven by the layer material type and its spatial configuration, including thickness, refractive index, and optical extinction coefficient [8]. Fundamental studies elucidating the relationship between the extinction coefficient and light transmission in such intricate arrangements hold paramount significance. These investigations provide invaluable insights into the underlying mechanisms governing light–matter interactions, enabling the tailoring of optical responses for a myriad of applications ranging from advanced coatings and optical filters to photovoltaics and sensors. By comprehensively exploring the impact of the extinction coefficient on the propagation and behavior of light within thin superlattices, this study not only advances our understanding of fundamental optical principles but also lays the groundwork for the design and optimization of next-generation optical devices with enhanced performance and versatility.

In the present study, the capabilities of the transfer matrix method are used to explore the influence of the optical extinction coefficient on light transmission, shedding light on the nuanced interrelationships that underpin the optical performance of complex multilayer systems.

2. Computational methods

2.1. Transfer matrix and extinction coefficient

The transfer matrix method (TMM) [1, 9] provides a robust framework for analyzing the optical properties of multilayer systems, such as thin

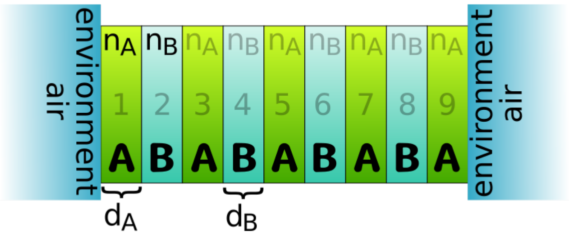

Fig. 1. Schematic diagram of studied superlattice; d_A and d_B represent layer thickness. The superlattice is submerged in $n = 1.0$ and $\kappa = 0$ environment.

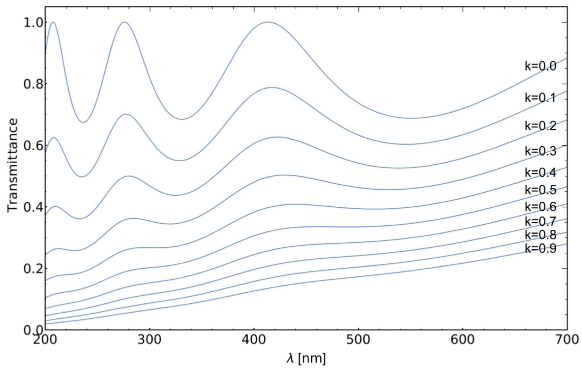

Fig. 2. The influence of layer B extinction coefficient κ increase on system transmittance.

superlattices. This method allows for the efficient calculation of the transmission and reflection coefficients by treating each layer within the system as a linear optical element [10]. The main equation of this method is as follows

$$\begin{bmatrix} E_{in}^{(+)} \\ E_{in}^{(-)} \end{bmatrix} = \Gamma \begin{bmatrix} E_{out}^{(+)} \\ E_{out}^{(-)} \end{bmatrix} \tag{1}$$

and describes incident wave $E_{in}^{(+)}$ incident on the boundary of the mediums, and $E_{in}^{(-)}$ is reflected wave propagating in an anti-parallel direction, $E_{out}^{(+)}$ is a wave coming out of the system, and the last term $E_{out}^{(-)}$ is zero. The characteristic matrix Γ defined as

$$\Gamma = D_{in,j}\Big(\prod_{j=1}^{J} P_j D_{j,j+1}\Big) \tag{2}$$

is a central component in the calculations. The characteristic matrix, also known as the transfer matrix, relates the incoming and outgoing electromagnetic fields at the interfaces between different layers. This matrix describes how the incident electric and magnetic fields are transformed as they propagate through the layer. By multiplying the characteristic matrices of all the layers in the multilayer structure, the overall transformation of the fields and the transmission and reflection coefficients for the entire structure can be calculated. In (2),

$$P_j = \begin{bmatrix} e^{\,i\varphi_j} & 0 \\ 0 & e^{-i\varphi_j} \end{bmatrix} \quad \text{and} \quad \varphi_j = d_j n_j \frac{2\pi}{\lambda}\cos(\phi_j) \tag{3}$$

describe all the parameters of the system, such as refractive indices n_j, quantities describing the physical dimensions (d_j) of incident wavelength λ and at layer incidence angle ϕ_j. In fact, $D_{j,j+1}$ is called the transmittance matrix. The optical extinction coefficient, represented by the imaginary component κ in the complex refractive index $n = n + i\kappa$, plays a crucial role in elucidating the interaction between light and materials. As light traverses a medium, it undergoes absorption, leading to a reduction in intensity. This phenomenon is inherently captured by κ, which is responsible for the exponential decay observed in the propagation of light through a material, aligning with the principles outlined in the Beer–Lambert law. The relationship between κ and the absorption coefficient α is manifested in the expression $\alpha = 4\pi\kappa/\lambda_0$, where λ_0 is the vacuum wavelength, offering a direct quantification of the material's absorptive characteristics. Further insight into the penetration depth δp, the distance after which intensity diminishes by a factor of $1/e$, reveals $\delta p = \lambda_0/(4\pi\kappa)$. Both the real part n and the imaginary part κ are frequency-dependent, with $\kappa > 0$ indicating absorption and $\kappa = 0$ implying lossless propagation.

2.2. System parameters

In the present calculations, the following materials were used for the multilayer system: material A, which is BK7 glass ($n = 1.5168$, $\kappa = 9.7525\times10^{-9}$), and material B, which is fused silica ($n = 1.45704$, $\kappa = 0$). The layer structure consists of 9 alternating layers in the form of $\{A,B,A,B,A,B,A,B,A\}$. The system is quasi-one-dimensional due to an infinite layer size in the X–Y directions, while the layer thicknesses d_A and d_B were kept fixed at 50 nm and 15 nm, respectively. Then, the extinction coefficient κ of layer B was systematically changed, and the transmission characteristics were calculated.

The schematic illustration of the studied system is presented in Fig. 1.

3. Results and discussion

Figure 2 presents the transmission for a set of structures, where the κ extinction coefficient was increased from $\kappa = 0.0$ to $\kappa = 0.9$ in 0.1 step size. Note that the extinction coefficients of all layers denoted as B were changed together uniformly. Also, the angle of incidence of the incoming electromagnetic wave is set to 45° to the plane of the first layer. In this case, there are two kinds of effects visible, namely a lowering in total transmission as κ increased and a simultaneous flattening of the peak

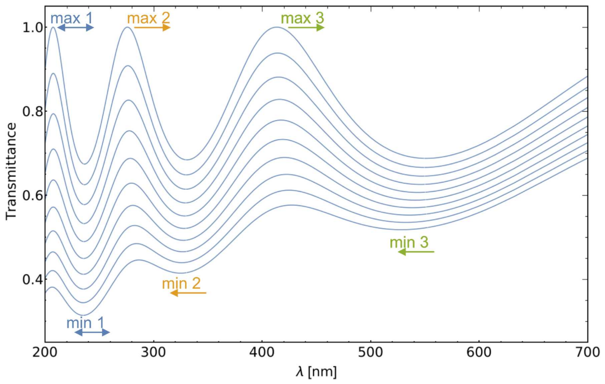

Fig. 3. Single *layer 2* extinction coefficient change from $\kappa = 0.0$ (top line) to $\kappa = 0.9$ (bottom line).

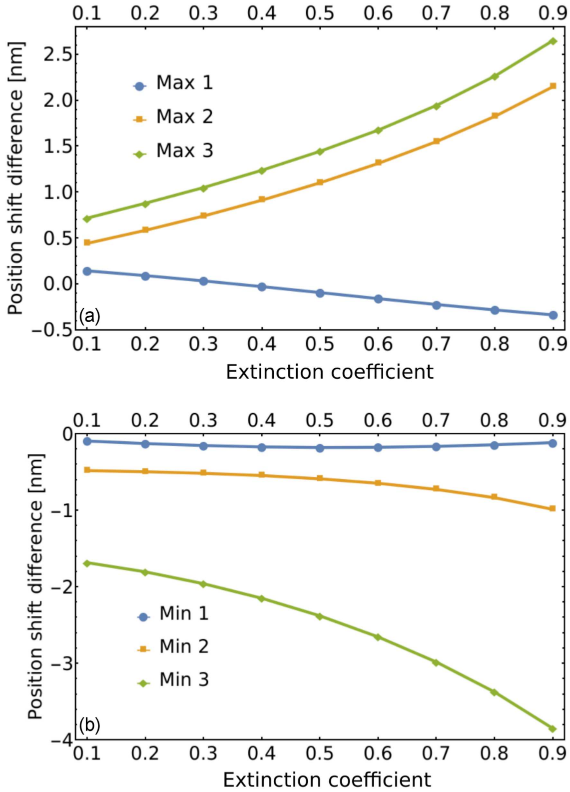

Fig. 4. The impact of increasing the coefficient κ on the change in the location of local transmission extremes.

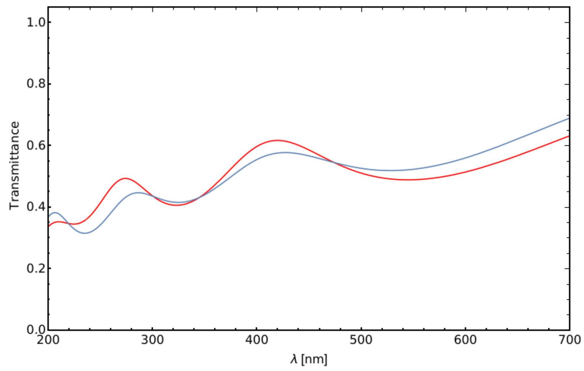

Fig. 5. Red line presents transmission spectra of the system with modified κ of layers 2 or 7; blue line is the transmission where κ of layers 4 or 6 is modified.

intensity. Obviously, because the extinction coefficient increases, the absorption of the electromagnetic wave of each B layer also increases, therefore, the last mentioned effect is the most expected behavior.

The aforementioned flattening of the transmittance peaks is less intuitive, as, in general, the formation of peaks and valleys is usually related to the geometrical parameters of the layers and their topological ordering. However, since the appearance of these local extremes is also associated with the phenomenon of reduced impact of constructive interference at the boundary of layers A and B, a strong influence of this phenomenon is observed when increasing the κ coefficient.

In order to investigate the effect of changing the extinction coefficient in a single layer from a multilayer system, in this step, only layer number 2 (for reference, please see Fig. 1) was modified, and the results of this modification are shown in Fig. 3.

Please note that, as in Fig. 2, the extinction coefficient also changes from $\kappa = 0.0$ to $\kappa = 0.9$; this time, however, the results differ. First, as in the case of changing the extinction coefficient in each layer B, a decrease in transmittance intensity is also observed this time. It is worth noting, however, that although the number of affected layers has decreased from 4 to just one layer, the total transmittance drops roughly by half, which is unexpected. Secondly, the positions of minima and maxima on the wavelength axis are shifting. It is also worth noting that although there is a flattening effect of the transmittance maxima, this effect is much less visible compared to the original change in the extinction coefficient for 4 layers simultaneously.

From the further analysis of Fig. 3, data on displacements of local extremes were collected and are presented in Fig. 4. As can be seen, not all local transmission maxima shift towards increasing wavelengths (the first maxima after $\kappa > 0.4$ changes its shift direction). The same applies to the minima positions, where the first minimum also changes its shift direction. This shows how complicated the nature of the simple increase in wave absorption in one layer is introduced, while giving the possibility of quite precise tuning of the position of these extremes. In this study, the symmetry breaking of the modified layer was also investigated. In the next step, the number of layers in which the extinction coefficient increased was modified so that it now applied to layers $1, 2, 3$, or 4 (the fifth layer lies in the middle, therefore it was not considered this time). The results of this simulation are shown in Fig. 5.

Through the analysis of Fig. 5, it can be seen that modification of κ extinction coefficient results in the same transmission when layers 2 or 7 are set to the same value of κ. The same situation is when considering the change in layers 4 or 6. Therefore, the system maintains symmetry about the center (layer no. 5), while the difference in transmittance between the two curves is visible.

4. Conclusions

In this paper, a comprehensive investigation of the influence of the extinction coefficient on electromagnetic wave transmission in thin superlattices sheds light on the intricate relationship between the optical extinction coefficient and the transmission properties of these multilayer systems. Through meticulous computational analyses, we have unveiled several trends. Specifically, an increase in the extinction coefficient yields a noticeable flattening of the electromagnetic wave transmission profile across the superlattice structure. This phenomenon is accompanied by a proportional reduction in the overall transmittance of the system. Intriguingly, elevating the extinction coefficient, whether universally across all layers or within a single layer, introduces intricate shifts in the positions of local extreme transmission peaks. The nature of these shifts, while complex, underscores the intricate interplay between material properties and wave propagation dynamics. Notably, even a singular augmentation of the extinction coefficient of a solitary layer results in a substantial reduction in total transmission, underscoring the sensitivity of the system to such perturbations. Remarkably, the alteration of the extinction coefficient in a single layer induces modest shifts in the extreme peak positions, a characteristic that offers fine-tuning capabilities. Additionally, it was established that symmetrical adjustments to a single layer maintain the system's symmetry about its center. These findings collectively contribute to a deeper understanding of the interdependence between extinction coefficients and wave transmission within thin superlattices, paving the way for informed design strategies in the realm of advanced optical systems.

Acknowledgments

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