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Resonance-dependent extraordinary reflection and transmission in PC-symmetric layered structure

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ABSTRACT

In order to achieve controllable enhanced reflection and transmission in part-time (*PT*) symmetric systems, we combine a cavity resonance effect with the layered *PT*-symmetric structure. At the resonance wavelength, except for the nonreciprocal extraordinary reflection, an enhanced transmission is also obtained. Both the extraordinary reflectance and transmittance are dependent on the modulation depth and period number in a discrete form.

1. Introduction

Natural material generally includes absorption loss. For any designed passive optical structure, the sum of transmittance and reflectance cannot be larger than unit. Recently, optical analogues of parity-time (PT)—symmetric systems were established in optical structures [1–15]. Many exotic phenomena with PT—symmetric systems are predicted and observed, such as loss induced transparency [1], power oscillations and nonreciprocity of light propagation [2], coherent perfect lasing and absorption [3–5], reconfigurable Talbot effect [6], on-chip optical isolation [7–10], and anisotropic transmission resonances [11]. Among the miscellaneous *PT* symmetric systems, the sinusoidal and layered *PT* symmetric complex crystals with balanced gain/loss modulations show rather unusual scattering and transportation properties [12–15]. These optical PT systems also show enhanced one-way reflection, while remains reciprocal total transmission (unidirectional invisibility) [12,13]. These phenomena usually appear when PT-symmetry breaking occurs at PT thresholds. Recently, Longhi [14] has demonstrated that unidirectional invisibility in sinusoidal *PT* symmetric complex crystals is dependent on the number of unit-cells. When the number surpasses a threshold the unidirectional invisibility will break down. It shows the importance of boundary effect in describing the Bragg scattering and coupling of counter-propagating waves in the sinusoidal *PT* symmetric system of a finite length. Zhu et al. also verify that periodic multilayer structures with *PT* symmetries imposed by a balanced arrangement of gain and loss exhibit anisotropic reflection oscillation patterns as the number of unit-cells is increasing [15]. In fact, there are still many interesting phenomena related to *PT* symmetries worth to be explored. In this paper we study resonance-dependent optical properties of periodic multilayer structure with *PT* symmetry. Due to the resonance effect, the simultaneously enhanced reflection and transmission do not only occur at PT threshold, but also at some other special discrete modulation depths. In addition, the period number plays an important role in determining the extraordinary reflection and transmission at the resonance wavelength.

2. Theoretical model and methods

Our discussion is based on the PT-symmetric structure shown in Fig. 1. This model is a periodic structure with N cells. Each cell consists of 3 layers: A, B and C, which is made from gain doped, normal dielectric and loss doped media, respectively. The model is placed in SiO_2 background, same to the host of layer A and C. The thickness of layer A, B and C are denoted as d_A, d_B, and d_C, respectively. The permittivity of layers A and C are taken as $\varepsilon_A = \varepsilon_h - i\rho$, $\varepsilon_C = \varepsilon_h + i\rho$. The ε_h represents the permittivity of the host material of layer A and C, which can be described by Sellmeier dispersion relation [13]:

$$\varepsilon_h - 1 = \sum_i \frac{C_i \lambda}{\lambda^2 - \lambda_i^2} \, (i = 1, 2, 3) \tag{1}$$

where λ is the incident wavelength. C_i is the oscillator strength constant. The values of C_1, C_2, C_3 are 0.7, 0.41, 0.9, respectively. The λ_i is characteristic oscillator wavelength. The values of $\lambda_1, \lambda_2, \lambda_3$ are 68 nm, 116 nm, 9896 nm, respectively. Different from Ref. [13], the permittivity of layer B is taken a larger value of $\varepsilon_B = 6$ to take a cavity resonance effect.

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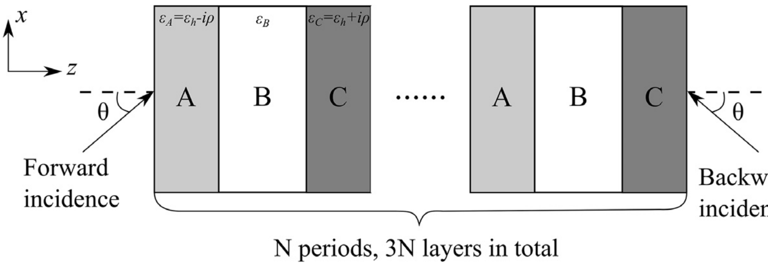

Fig. 1. Schematic view of the PT-symmetric periodic structure. Layers A and C are made from gain and loss media, respectively. Layer B is normal dielectric material.

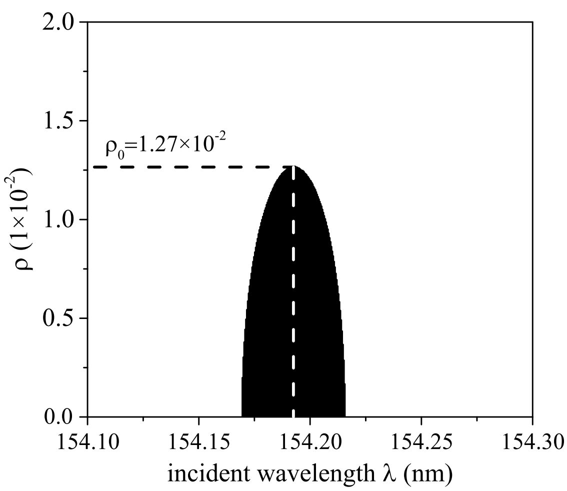

Fig. 2. In normal incidence, the gap disappears with ρ grows under $d_B = 62.83$ nm and $\lambda_0 = 154.19$ nm.

Firstly, we assume that the incident wave is TM wave. The relation of magnetic field in two layers can be written as:

$$\begin{pmatrix} H_i^+ \\ H_i^- \end{pmatrix} = M_{i,j} \begin{pmatrix} H_j^+ \\ H_j^- \end{pmatrix} \quad (2)$$

where H_i^+ and H_i^- are the magnetic field intensities of transmitted and reflected waves in layer i , respectively. H_j^+ and H_j^- are field intensities of in layer j. $M_{i,j}$ is the transfer matrix from layer i to layer j , which can be regarded as the production of several phase shift matrices (P matrices) and boundary transfer matrices (T matrices) [16]:

$$M_{i,j} = T_{i-1,i} P_i T_{i,i+1} P_{i+1} T_{i+1,i+2} \cdots T_{j-1,j} P_j \quad (3)$$

where P matrix represents the phase shift when waves pass through each layer, which is given to be:

$$P_i = \begin{pmatrix} e^{-ik_{z,i}d_i} & 0 \\ 0 & e^{ik_{z,i}d_i} \end{pmatrix} \quad (4)$$

d_i is the thickness of layer i. $k_{z,i} = k_0\sqrt{\varepsilon_i - \varepsilon_h(\sin\theta)^2}$ is the z-component of wave vector in layer i. k_0 is the wave number in free space. ε_i and ε_h are the permittivities of layer i and the background material, respectively. T matrices represent the field change at the boundary of two layers. If $N_j = k_{z,j}/\varepsilon_j$, the T matrix between two adjoin layers can be written as:

$$T_{i,i+1} = \frac{1}{2N_i} \begin{pmatrix} N_i + N_{i+1} & N_i - N_{i+1} \\ N_i - N_{i+1} & N_i + N_{i+1} \end{pmatrix}. \quad (5)$$

Then, for a single period cell in our model, the transfer matrix from one to the next is:

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = T_{C,A} P_A T_{A,B} P_B T_{B,C} P_C. \quad (6)$$

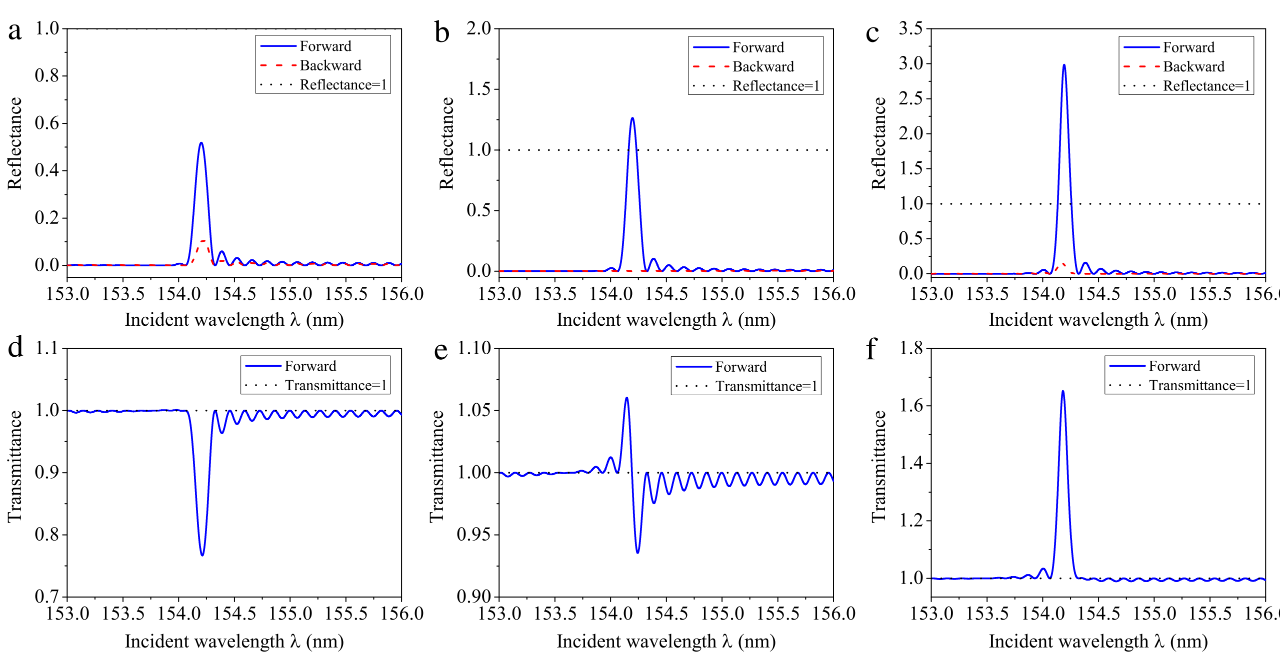

Fig. 3. The reflectance spectra under normal incidence for (a) $\rho < \rho_0$, (b) $\rho = \rho_0$ and (c) $\rho > \rho_0$, respectively. The transmittance spectra under normal incidence for (d) $\rho < \rho_0$, (e) $\rho = \rho_0$ and (f) $\rho > \rho_0$, respectively.