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Study on the propagation mechanism of evanescent waves in one-dimensional periodic photonic crystal ☆

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ABSTRACT

Based on the evanescent waves theory, the formation condition and propagation mechanism of evanescent waves in one-dimensional periodic photonic crystal are studied. When the incident light travels through the periodic photonic crystal at a certain angle, the optical resonance will occur in the optically denser medium, and a unique photonic local feature will occur in photonic bandgap. Furthermore, the influences on transmission performance by the photonic crystal parameters are discussed respectively. The simulation results show that the structure mentioned above can achieve the performance of high transmission and high Q value, which can provide theoretical references for photonic crystal multi-channel filters.

1. Introduction

Photonic crystals [1] (PCs) are the artificial crystal structures which are composed of different refractive index medium materials, whose basic optical characteristics are the photonic band gap [2] and photonic localization [3,4]. Different band gap distributions can be obtained by adopting different structures or materials, therefore, the light transmission performances of PCs can be regulated and controlled effectively by adjusting PC structural parameters. In addition, the PCs have the advantages of simple structures, easy integration, etc., therefore, the design and application of PCs in the optical devices have broad application prospects.

At present, PCs have been widely used in PC filters [5,6], PC lasers [7,8], PC optical switches [9,10], PC sensors [11,12] and many other aspects. A composite PC structure with two symmetrical defect layers at the port is proposed by Hai-bo Chen [13], by controlling the incident light intensity to fine-tune the dielectric constant of PC materials, hence the spectrum utilization efficiency and the channel density can be enhanced greatly. Based on the photonic localization and the surface wave principle, Namda et al. [14] produced an optical fiber nanosensor by introducing negative dielectric constant materials. It can be seen that the design of the PC device is usually achieved based on the photonic localization of the PCs with defects, however, the photonic localization in regular periodic PCs is seldom studied.

When the evanescent wave [15–17] travels through the one-dimensional (1D) periodical PCs, the photonic localization can be obtained by designing PC structure and adjusting PC parameters reasonably. Based on the theory of the total reflection and evanescent waves, the formation and propagation conditions of evanescent waves in 1D periodical PCs are analyzed theoretically, and the periodical PC structure based on the prism coupling is proposed. On this basis, considering the optical resonance [18] of the evanescent waves and the electric field distribution within the PC, the propagation mechanism of the evanescent waves in 1D periodical PCs is studied, at the same time, the influence on the transmission performance of the evanescent waves by the factor of the thickness or the period number is discussed respectively.

2. Structure model and theoretical analysis

2.1. PC structure model

The PC is expressed $(AB)_m A$, as shown in Fig. 1, in which A and B are the dielectric layers with low refractive index and high refractive index, and the PC parameters are taken as $n_A = 1.45$, $n_B = 2.6$, $d_B = 600$ nm. The prisms on the top and bottom of the PC are used to couple light into and out of the PC, the refractive indexes of both prisms are all assumed to $n_D = 2.6$.

☆ Fully documented templates are available in the elsarticle package on CTAN.

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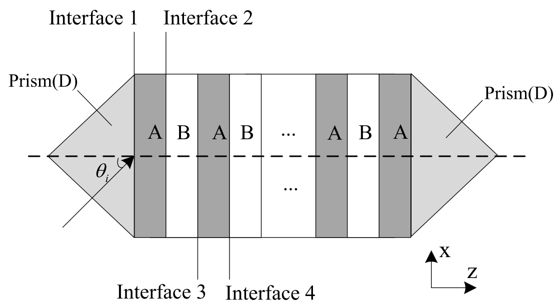

Fig. 1. PC structure model.

When TE wave travels through the periodical PC with the angle greater than the total reflection critical angle by the prism coupling, the total reflection will occur on the surface of the optically thinner medium layer A, in which the evanescent wave is formed. Generally, the evanescent wave can't spread and after penetrating into the optically thinner medium layer with a certain depth, it will return to the incident medium. However, the evanescent wave can be coupled output if we adjust the thickness of optically thinner medium layer reasonably. Due to the existence of evanescent wave, the electromagnetic field distributions within the periodical PC will be changed. Several times reflection will occur on the two interfaces between the optically denser medium layer and the optically thinner medium, in which an optical resonance cavity will be formed, therefore the photonic localization will be observed in the transmission spectrum of the periodical PC.

2.2. *Existence form and transmission mechanism of the evanescent waves*

When incident light is incident on the interface of the optically denser medium and the optically thinner medium with the angle greater than the total reflection critical angle, the total reflection will occur. Due to the continuity conditions of the electromagnetic field, the boundary relationship of the electromagnetic field on the interface may not be broken off, thus the evanescent wave will penetrate into the optically thinner medium layer with a certain depth. The evanescent wave is an inhomogeneous wave, which can propagate along x direction and vibrate along the z direction. Taking x–z plane as the reference plane, the wave function can be expressed as

$$\begin{aligned}\vec{E}_t &= \vec{E}_i \exp[i(\vec{k}\cdot\vec{r}-\omega t)] \\ &= \vec{E}_i \exp[i(k_x x + k_z z - \omega t)] \\ &= \vec{E}_i \exp(-kz)\exp[i(k_x x - \omega t)] \end{aligned} \tag{1}$$

where $\vec{E}_i$ and $\vec{E}_t$ are the field intensity in the optically denser medium and the optically thinner medium respectively, $\vec{k}$ is the incident light wave vector, $k_x = k \cdot n_{\mathrm{D}} \cdot \frac{\sin\theta}{n_{\mathrm{A}}}$ is the component in x-axis of the incident light wave vector, $k_z = \pm ik\sqrt{n_{\mathrm{D}}^2 \frac{\sin^2\theta}{n_{\mathrm{A}}^2}}$ is the component in z-axis of the incident light wave vector.

The amplitude of the evanescent wave will decay with the increment of the penetration depth, and when the amplitude decay to the 1/e of amplitude maximum value, the penetration depth z_d can be expressed as

$$z_d = (k_{\mathrm{D}}\sqrt{\sin^2\theta - (n_{\mathrm{A}}/n_{\mathrm{D}})^2})^{-1} \tag{2}$$

Generally, the evanescent wave will penetrate into the optically thinner medium layer with a certain depth and then return to the incident medium. While if $d_{\mathrm{A}} < z_d$, the evanescent wave will penetrate into the interface 2 and enter into the layer B, and due to the attenuation of evanescent wave, a single evanescent wave cannot propagate through the dielectric layer. The light in the layer B will penetrate the interface 3 with a certain distance, and then return to the dielectric layer B. The total reflection will occur constantly on the interfaces of the both sides for the layer B, in which the Goos–Hänchen shift [19,20] will occur, as shown in Fig. 2.

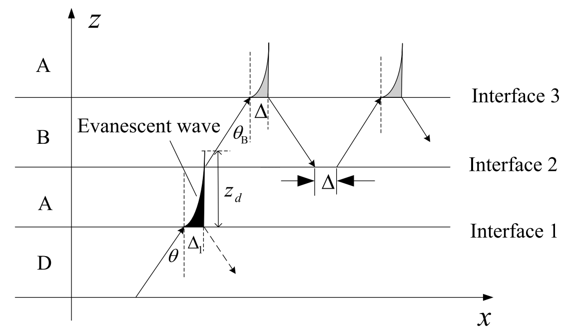

Fig. 2. Total reflection at the interface and the transmission of evanescent wave.

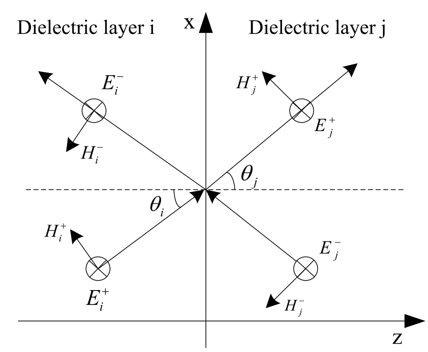

Fig. 3. Electromagnetic waves at the interface.

The dielectric layer B can be regarded as a F–P resonant cavity, thus the relationship between the resonant wavelength and the incident angle can be expressed as

$$2\cdot\frac{2\pi}{\lambda_d}n_{\mathrm{B}}d_{\mathrm{B}}\cos\theta_{\mathrm{B}} + \frac{2\pi}{\lambda}\cdot(2\Delta) = 2k\pi \quad (k = 0, 1, 2, \ldots) \tag{3}$$

where the Goos–Hänchen shift Δ can be expressed as

$$\Delta = \frac{\lambda\tan\theta_{\mathrm{B}}}{\pi(\sin^2\theta_{\mathrm{B}} - \sin^2\theta_{\mathrm{C}})^{\frac{1}{2}}} \tag{4}$$

where λ is the wavelength of the incident light, λ_d is the resonant wavelength, $\theta_{\mathrm{C}} = \arcsin(n_{\mathrm{A}}/n_{\mathrm{B}})$ is the total reflection critical angle at the interface 3.

Similarly, each periodical layer B in the PC all can be regarded as a resonant cavity. The electromagnetic wave among different defects are coupled, which results the eigenmode of defect mode splitting, thus the PC $(\mathrm{AB})_m\mathrm{A}$ may have m number of resonance cavities. Based on the tight-binding theory [21], m defect modes can be obtained in the photonic band gap.

2.3. *Computing method–layered transmission matrix theory*

The electromagnetic waves at the interface is shown in Fig. 3, on the continuity conditions of electromagnetic wave on the boundary, the electromagnetic field can be expressed as

$$\begin{cases} E_i^+ + E_i^- = E_j^+ + E_j^- \\ H_i^+\cos\theta_i - H_i^-\cos\theta_i = H_j^+\cos\theta_j - H_j^-\cos\theta_j \end{cases} \tag{5}$$

where $H = \sqrt{\varepsilon_0/\mu_0}nE$, then Eq. (5) can be given by