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Effective modulation of the photonic band gap based on Ge/ZnS one-dimensional photonic crystal at the infrared band

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ABSTRACT

This study investigated both numerically and experimentally one-dimensional photonic crystals with periodic structures composed of Ge and ZnS. Numerical simulations indicated that the refractive index, physical thickness, reference wavelength, and periodicity have a great effect on the position and width of the photonic band gap. We fabricated three different thicknesses of structures within the range of 3–5 μm, with average reflectance values of 89.1%, 94.9%, and 87.9%; the corresponding emissivity values were 0.096, 0.079, and 0.143, respectively. The results indicated that the high reflectance or transmittance at any required wave band could be achieved by selecting suitable materials and structures.

1. Introduction

In recent years, photonic crystals (PCs) have attracted a great deal of attention as artificial periodic structure optical composite materials due to their potential applications in designing novel and high-performance optoelectronic devices. Their photonic band gap (PBG) structure and localized photonic states allow PCs to be used to manipulate the emission and the propagation properties of electromagnetic waves or lights [1–3]. PCs usually consist of two or more kinds of dielectric materials stacked vertically together, inducing the propagation of electromagnetic (EM) waves modulated by the coherent scattering of different medium layers [4,5]. The propagation of electromagnetic waves or lights is halted when the frequency falls within the PBG range. In this way, PCs can be applied to suppress the spontaneous emission of a target object [6,7].

Reasonable PCs structure design can achieve complete omnidirectional PBG [8,9]. Many researchers have reported that high reflectivity and low emissivity in the infrared (IR) range can be achieved by selecting appropriate materials and projecting different structures [10,11]. The PBG can be regulated and controlled as needed for the desired application. Identifying the factors that determine the position and width of the forbidden gap requires further research in order to guide applications.

In this study, we researched one-dimensional (1D) PCs, which consist simply of layers of different materials stacked alternately. Compared with previous 2D and 3D PCs [12–15], our proposed PCs with reasonable material and structure design could achieve omnidirectional high reflectivity. When an infrared wave propagates in a medium, the propagation characteristics can be expressed by Maxwell's equations [16,17]. The propagation characteristics between different mediums can be also connected by a transfer matrix [18–20] similar to optical thin-films. According to the electromagnetic field boundary conditions [21–23], the tangential components of the electromagnetic field on both sides of one interface are continuous. Following propagation, a phase difference emerges for the vertical components at the inside of one layer. The position and width of the PBG can be calculated by solving the wave equation, as can the reflectance and the transmittance in the PBG range [24,25].

We used germanium (Ge) and zinc sulfide (ZnS) as coating materials to deposit finite 1D PCs. First, thin film simulation software was used to set the experimental conditions as follows. The incident wavelength was set from 3 to 5 μm, with a normal incident electromagnetic wave. The refractive indices of Ge and ZnS were 4.0 and 2.3 as the average high refractive index material (H) and the low refractive index material (L), respectively. We designed three 1D PCs with different thicknesses, each of which was composed of

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multilayer dielectric films. The optical thicknesses of these three samples were a quarter of the center wavelengths which were 3.4, 4.0, and 4.3 μm, respectively. Then, according to the optimal design, these 1D PCs with three different film thicknesses were fabricated by ion assisted electron-beam vacuum deposition technology. The results agree with the simulation and demonstrate that these 1D PCs films can achieve near-perfect reflection around their center resonance wavelengths. We also explored the refractive index, physical thickness, reference wavelength, and periodicity in order to determine the different position and width of the PBG within the range of 3–5 μm.

2. Theory, design, and calculations

In an infinitely extended 1D periodic structure PCs, two kinds of dielectric materials are arranged alternately in the z direction, and each layer is isotropic on the x-y plane. The dielectric function of the structure is periodic ($\varepsilon(z) = \varepsilon(z + d)$), where d is a constant determined by the total cell thickness (d=$d_a + d_b$) for the alternate deposition in the z direction. Here we assume that each layer of material is nonmagnetic and transparent; then, the relationship between the refractive index and the dielectric constant is $n = \sqrt{\varepsilon}(\mu = 1)$, and the absorption of materials is minimal. When the electromagnetic wave is vertical incident on the multi-layer films, the propagation properties can be described by Maxwell's equations.

For a 1D periodic structure, as depicted in Fig. 1, incidence, reflectance, and transmittance occur when light propagates in the medium. The transfer matrix method can be used to connect the electromagnetic field of each layer:

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = M_a \begin{bmatrix} E_2 \\ H_2 \end{bmatrix} = M_a M_b \begin{bmatrix} E_3 \\ H_3 \end{bmatrix} \tag{1}$$

where M_a and M_b are transfer matrices for the two kinds of dielectric materials, both of which are second order matrices, depending on the incident wavelength (λ), incident angles (θ_{i0}), refractive index (n_a, n_b), and physical thickness (d_a, d_b) of each homologous layer. The transfer matrix is as follows:

$$M_a = \begin{bmatrix} cos\delta_a & \dfrac{i}{\eta_a} sin\delta_a \\ i\eta_a sin\delta_a & cos\delta_a \end{bmatrix} \tag{2}$$

$$M_b = \begin{bmatrix} cos\delta_b & \dfrac{i}{\eta_b} sin\delta_b \\ i\eta_b sin\delta_b & cos\delta_b \end{bmatrix} \tag{3}$$

where $\delta_a \left(\delta_a = \frac{2\pi}{\lambda} n_a d_a \cos\theta_{i1}\right)$ and $\delta_b \left(\delta_b = \frac{2\pi}{\lambda} n_b d_b \cos\theta_{i2}\right)$ are the phase displacement values. The relationship of the angles of each interface, such as θ_{i1} and θ_{i2}, can be determined by the refraction law ($n_0 \sin\theta_{i0} = n_a \sin\theta_{i1} = n_b \sin\theta_{i2}$) layer by layer. Here, η_a ($\eta_a = n_a \cos\theta_{i1}$) and η_b ($\eta_b = n_b \cos\theta_{i2}$) are the equivalent admittance. We only studied s polarization due to the structures' symmetry.

Above-mentioned structure represents a single cell, when extending it to multiple periodic structures, the periodicity is N, such that the multi-layers have $2N$ layers and $2N + 1$ interfaces. The total transmission equation can be expressed as follows:

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = (M_a M_b)^N \begin{bmatrix} E_{2N+1} \\ H_{2N+1} \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}^N \begin{bmatrix} E_{2N+1} \\ H_{2N+1} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} E_{2N+1} \\ H_{2N+1} \end{bmatrix} \tag{4}$$

where the matrix elements (A, B, C, and D) are complex functions of the layers' properties, connecting the field of the incident end and the exit end. The reflection coefficient of the multilayer structures is calculated as follows:

$$r = \left|\frac{E_{r,0}}{E_{i,0}}\right| = \frac{\eta_0(A + B\eta_{2N+1}) - (C + D\eta_{2N+1})}{\eta_0(A + B\eta_{2N+1}) + (C + D\eta_{2N+1})} \tag{5}$$

where $\eta_0 = n_0 \cos\theta_{i0}$ (the incident medium is air, which has a refractive index of n_0=1) and $\eta_{2N+1} = n_s \cos\theta_{t2N+1}$ (the exit medium is glass, n_s=1.49). The reflectance is related by the following equation:

$$R = |r|^2 \tag{6}$$

The reflectance at the corresponding wavelength can be calculated according to Eq. (6), where the high-reflectance corresponds to the forbidden band, and the high-transmittance corresponds to the pass band on the contrary.

Based on the Bloch theorem, the wave equation of an electromagnetic wave propagating along the z direction with frequency ω and wave vector $\vec{K}$ can be expressed as follows:

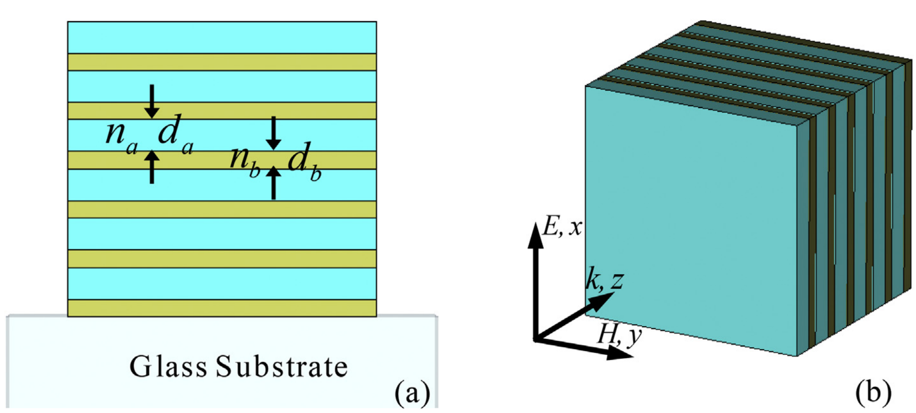

Fig. 1. The schematic of the 1D PCs structure: (a) lattice view (b) multi-layers structure 3D stereogram.