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Investigation of defect modes in a defective photonic crystal with a semiconductor metamaterial defect

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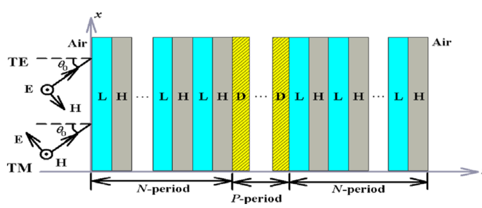
HIGHLIGHTS

- Tunable defect modes with a semiconductor metamaterial are analyzed.
- Number of defect modes decrease as the defect thickness increases
- Defect mode frequency is blue-shifted for both TE and TM waves.

GRAPHICAL ABSTRACT

We theoretically investigate the properties of defect modes in a defective photonic crystal containing a semiconductor metamaterial defect. It is found that, within the photonic band gap, the number of defect modes (transmission peaks) will decrease as the defect thickness increases, in sharp contrast to the case of using usual dielectric defect.



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ABSTRACT

In this work, we theoretically investigate the properties of defect modes in a defective photonic crystal containing a semiconductor metamaterial defect. We consider the structure, $(LH)^N/D^P/(LH)^N$, where N and P are respectively the stack numbers, L is SiO_2, H is InP, and defect layer D is a semiconductor metamaterial composed of Al-doped ZnO (AZO) and ZnO. It is found that, within the photonic band gap, the number of defect modes (transmission peaks) will decrease as the defect thickness increases, in sharp contrast to the case of using usual dielectric defect. The peak height and position can be changed by the variation in the thickness of defect layer. In the angle-dependent defect mode, its position is shown to be blue-shifted as the angle of incidence increases for both TE and TM waves. The analysis of defect mode provides useful information for the design of tunable transmission filter in semiconductor optoelectronics.

1. Introduction

Over the past two and half decades, a new class of material called photonic crystals (PCs) has emerged. PCs are periodic layered structures and can possess frequency regions in which the propagation of electromagnetic waves is forbidden. These regions are called photonic band gaps (PBGs) [1,2]. In all-dielectric PCs, PBGs are also called Bragg gaps because they originate from Bragg scattering in the periodic structure. Engineering PBGs in one-dimensional (1D) PCs has been proven to be of technical use in some potential applications such as photonic devices, optical filters, resonance cavities, laser applications, high reflecting omnidirectional mirrors, and the optoelectronic circuits [3–5].

By breaking the periodicity of the PC structure, we will have a defective PC. This can be performed by changing physical parameters, such as changing the thickness of one of the layers, adding

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another medium to the structure, or removing a layer from PCs [6–8]. By introducing a layer with different optical properties, localized defect modes, which are represented by resonant transmission peaks, can be generated within the PBG due to the change of the interference behavior of light [8,9]. The presence of defect modes is very similar to the defect states generated in the band gap of in a doped semiconductor. PCs with tunable defect modes can be used to design the tunable transmission filters which are of particular use in photonic applications. To make defect modes tunable, it is necessary to adopt a relevant defect material such as semiconductor, ferroelectric, or superconductor [10–12].

In the past decade, the realization of metamaterials (MTMs) with simultaneously negative permittivity (ε) and negative permeability (μ) has triggered a flood of researches in the community. Electromangetic MTMs now called double-negative (DNG) materials were first theoretically studied by Veselago early in 1968 [13]. An important consequence for a DNG material is that the corresponding refractive index is negative. As a result, it is referred to as a negative index material (NIM). In addition to DNG materials, MTMs can also be single-negative (SNG). There are two kinds of SNG materials. One is called the epsilon-negative (ENG) materials with $\varepsilon < 0$ and $\mu > 0$. The other called mu-negative (MNG) has $\mu < 0$ and $\varepsilon > 0$. All of the DNG and SNG are artificially periodic and metal-based structures. Researches on MTMs, including fundamental and applicational issues, continue to be hot today.

Recently, an MTM based on the semiconductor has been reported by Naik et al. [14]. This semiconductor metamaterial is formed by depositing 16 alternating layers of Al-doped ZnO (AZO) and ZnO, each about 60 nm thick in one period, on a silicon substrate [14]. This semiconductor metamaterial (ZAO/ZnO) operated in near infrared has two features, i.e., it belongs to an ENG material and its permittivity is anisotropic [15]. With these novel features, ZAO/ZnO could be of potential use in semiconductor optoelectronics.

In this work, based on the use of semiconductor metamaterial, ZAO/ZnO, as a defect layer, we would like to investigate the filtering properties in a defective photonic crystal structure of $(LH)^N/D^P/(LH)^N$, as depicted in Fig. 1. Here, the PC $(LH)^N$ is taken to be $(SiO_2/InP)^N$ and D is ZAO/ZnO. P represents the repetition number of the defect layer and N is number of periods of the PC. The analysis of filtering properties will be made on the basis of the transmittance spectrum calculated by making use of the transfer matrix method (TMM) [16]. The results reveal that a tunable filter can be achieved in this proposed structure.

2. Basic equations

In the analysis that follows, we shall use the calculated transmittance for a one-dimensional defective photonic crystal shown in Fig. 1 to study filtering properties. As mentioned above, the defect layer is taken to be AZO/ZnO. Thus, it is necessary to know its permittivity and permeability. The permittivity is anisotropic written by [15]

$$\varepsilon_D = \begin{pmatrix} \varepsilon_p & 0 & 0 \\ 0 & \varepsilon_p & 0 \\ 0 & 0 & \varepsilon_v \end{pmatrix}, \quad (1)$$

where ε_p and ε_v are, respectively, the parallel and perpendicular components and they are related to the permittivity functions of both constituents of AZO and ZnO. The permittivity function of AZO can be described by the combination of Drude and Lorentz model. As for that of ZnO, it can be expressed as a Lorentz- type. We denote the permittivities of AZO and ZnO as ε_a and ε_b, respectively. In addition, the corresponding thicknesses are d_a and d_b, respectively. Then the permittivity function of AZO is expressible as [15]

$$\varepsilon_a(f) = \varepsilon_{a1}(f) + \varepsilon_{a2}(f) \quad (2)$$

where the Lorentz part is given by

$$\varepsilon_{a1}(f) = 1 - \frac{f_{ap1}^2 - f_{ao1}^2}{f^2 - f_{ao1}^2}, \quad (3)$$

and the Drude part is

$$\varepsilon_{a2}(f) = 1 - \frac{f_{ap2}^2}{f^2}. \quad (4)$$

The total permittivity functions of the composite AZO/ZnO in Eq. (1) are given by

$$\varepsilon_p = h\varepsilon_a + (1-h)\varepsilon_b, \quad (5)$$

and

$$\varepsilon_v = \frac{1}{h\varepsilon_a^{-1} + (1-h)\varepsilon_b^{-1}}, \quad (6)$$

where the parameter h is the filling factor of AZO, namely

$$h = \frac{d_a}{d_a + d_b}, \quad (7)$$

where $d_D = d_a + d_b$ is the thickness of layer D. As for the permeabilities of AZO and ZnO, they are taken be unity because both materials are nonmagnetic.

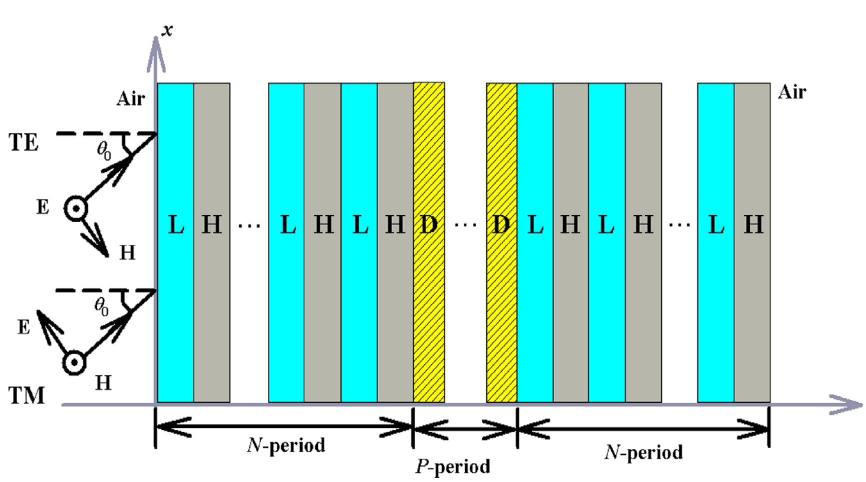

Fig. 1. A one-dimensional filter structure, $(LH)^N/D^P/(LH)^N$, where $L=SiO_2$, $H=InP$ are the low-, high-index layers, respectively, and the defect is D=AZO/ZnO. Two polarizations of the incident wave, TE and TM, are shown, and the incident angle is θ_0.