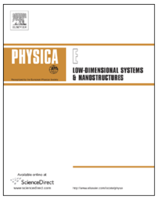
Physica E 79 (2016) 20–25

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe



Near-infrared tunable narrow filter properties in a 1D photonic crystal containing semiconductor metamaterial photonic quantum-well defect

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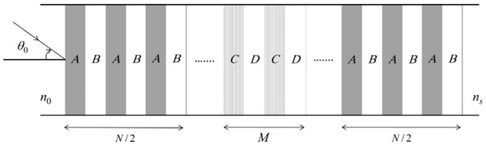
HIGHLIGHTS

- Study the tunable NIR narrow filters with semiconductor metamaterial PQW.
- The number of the defect mode is independent of the periods of the PQW.
- Defect mode's frequency gets red-shifted as the filling factor increases.
- Defect mode's frequency gets blue-shifted for both TE and TM waves.

GRAPHICAL ABSTRACT

We perform a theoretical investigation of the near-infrared narrow filter properties in the transmission spectrum of a one-dimensional photonic crystal doped with semiconductor metamaterial photonic quantum-well defect (PQW). It is found that the defect mode's frequency can be tuned by the variations of the defect structure's period, polarization, incidence angle, and also the filling factor corresponding to the semiconductor metamaterial layer. In addition, the number of the defect mode is independent of the periods of the PQW defect structure, which is in sharp contrast to the case of using usual dielectric or metamaterial defect.



ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
5 December 2015
Accepted 12 December 2015
Available online 15 December 2015

Keywords:
1D photonic crystal
Defect mode
Semiconductor metamaterial
Photonic quantum-well defect

ABSTRACT

The near-infrared (NIR) narrow filter properties in the transmission spectra of a one-dimensional photonic crystal doped with semiconductor metamaterial photonic quantum-well defect (PQW) were theoretically studied. The behavior of the defect mode as a function of the stack number of the PQW defect structure, the filling factor of semiconductor metamaterial layer, the polarization and the angle of incidence were investigated for Al-doped ZnO (AZO) and ZnO as the semiconductor metamaterial layer. It is found that the frequency of the defect mode can be tuned by variation of the period of the defect structure, polarization, incidence angle, and the filling factor of the semiconductor metamaterial layer. It is also shown that the number of the defect mode is independent of the period of the PQW defect structure and is in sharp contrast with the case where a common dielectric or metamaterial defect are used. The results also show that for both polarizations the defect mode is red-shifted as the number of the defect period and filling factor increase. An opposite trend is observed as the angle of incidence increases. The proposed structure could provide useful information for designing new types of tuneable narrowband filters at NIR region.

1. Introduction

Photonic crystals (PCs), possessing some significant optical properties, are artificial materials having periodic multilayer structure in dielectric constant. One of the most interesting optical properties of PCs is existence of forbidden frequency regions in their transmission spectra. The regions known as photonic band gaps (PBGs) or Bragg gaps [1–4]. The possibility of producing metamaterials with negative permittivity and permeability in the past decade [5], the optical properties of PCs with metamaterials known as metamaterial photonic crystals (MetaPCs) have been attracted by many authors [6–8]. In recent years MetaPCs have attracted extensive attention of many researchers for their unique electromagnetic properties and their scientific and microwave engineering applications [9–27]. PCs composed of semiconductors

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http://dx.doi.org/10.1016/j.physe.2015.12.012
1386-9477/© 2015 Published by Elsevier B.V.

have received considerable attention for their several superior features such as tunable PBG which is achieved by thermal tuning of the dielectric function of the semiconductor material which is applicable in optoelectronic investigations. Another feature of semiconductor PCs, is appearance of their PBG in the near-infrared (NIR) to mid-IR frequency regions [28]. In 2012, Naik et al. [29] reported a new semiconductor-based metamaterial. This so called semiconductor metamaterial is an artificially periodic structure made by alternating layers of Al-doped ZnO (AZO) and ZnO on a silicon substrate with 16 pair layers and 60 nm periodicity. This AZO–ZnO metamaterial has an anisotropic and negative permittivity in NIR region [30]. The presence of negative permittivity is reminiscent of metallic permittivity, which is negative for frequencies less than the plasma frequency. Thus, AZO–ZnO metamaterial can be classified as an epsilon-negative (ENG) material in the NIR region. A defected photonic crystal would be generated by breaking the periodicity of the conventional PC structure. In the defected structure, localized defect modes within the PBG would be generated as a result of a change in the interference behavior of waves at interfaces. A PC of $(CD)^M$ can be inserted in the middle of a host PC of $(AB)^N$ rather than a defect layer being added to the PC. Therefore, the structure will be $(AB)^{N/2}\ (CD)^M\ (AB)^{N/2}$, where N and M are the stack numbers of the (AB) and (CD) bilayers, respectively. In such case, the defected structure of $(CD)^M$ will be called the photonic-quantum-well (PQW) [30–33]. The structure $(AB)^{N/2}$ $(CD)^M$ $(AB)^{N/2}$ (with $M < N$) can present multiple filtering feature due to the photonic confinement, contributing to a perception of a multichannel filter [31]. Moreover, the number of channels that can be considered as the basis of the number of peaks in the transmission spectra is equal to the stack number of PQW. Despite the fact that there have been many reports on PQW-based filters [31–38], few studies have been examined in the tuneable multichannel transmission filters. In addition to the above mentioned theoretical studies, some experimental works have been reported [39,40].

The main purpose of this work is the theoretical investigation of the properties of the defect mode in a 1D PC doped by semiconductor metamaterial PQW defect. To this aim, we study the defect mode as a function of the stack number of the PQW defect structure, the filling factor of semiconductor metamaterial layer, the polarization, and the angle of incidence. Our numerical results show that the frequency of the defect modes can be tuned by the above-mentioned parameters as well, which are in sharp contrast with the case where a common dielectric or a metamaterial defect is used. The results also reveal that a new NIR tunable narrow filter can be achieved in this proposed structure. The outline of our paper is as follows: Section 2 presents a 1D PC containing a PQW defect structure, the characteristic matrix method and its formulation, and also the permittivity of semiconductor metamaterial, Section 3 reveals the numerical results and discussions associated with our purpose, and Section 4 describes the conclusions of the investigation.

2. Theoretical framework

A 1D PC with asymmetric structure immersed in free space with a defect structure (PQW defect) at the center of the host PC is shown in Fig. 1. Layers A and B are respectively considered to be SiO_2 (Silica) and InP (Indium Phosphide), layer C is AZO–ZnO (as semiconductor metamaterial), and layer D is air. The number of lattice periods and the number of unit cells (corresponding to the defect structure) are denoted by N and M respectively. In addition, the thickness, the permittivity, and the permeability of the layers are respectively assumed to be d_i, ε_i, and μ_i $(i = A, B, C, D)$. First of all, let us describe the permittivity and the permeability functions of AZO–ZnO layer. The permittivity is anisotropic and is given by [30,41–45]:

$$\varepsilon_C = \begin{pmatrix} \varepsilon_\rho & 0 & 0 \\ 0 & \varepsilon_\rho & 0 \\ 0 & 0 & \varepsilon_\upsilon \end{pmatrix} \tag{1}$$

Here, ε_ρ and ε_υ are the parallel and perpendicular components, respectively, and they are related to the permittivity functions of AZO and ZnO. The total permittivity functions of AZO–ZnO composite are expressed as

$$\varepsilon_\rho = h\ \varepsilon_a + (1-h)\ \varepsilon_b \tag{2}$$

and

$$\varepsilon_\upsilon = \frac{1}{h\ \varepsilon_a^{-1} + (1-h)\ \varepsilon_b^{-1}} \tag{3}$$

where h is the filling factor of AZO, $h = d_a/(d_a + d_b)$ and $d_C = d_a + d_b$ is the thickness of layer C, where d_a and d_b indicate the thickness of the AZO and ZnO layers, respectively. Moreover, the permittivity functions of AZO and ZnO are ε_a and ε_b, respectively. Here, ε_b is a constant and ε_a can be expressed as a combination of Lorentz and Drude models, that is [41–45]

$$\varepsilon_a(f) = \varepsilon_{a_1}(f) + \varepsilon_{a_2}(f), \tag{4}$$

where the Lorentz part is given by

$$\varepsilon_{a_1}(f) = 1 - \frac{f_{ap1}^2 - f_{ao1}^2}{f^2 - f_{ao1}^2}, \tag{5}$$

and the Drude part is

$$\varepsilon_{a_2}(f) = 1 - \frac{f_{ap2}^2}{f^2} \tag{6}$$

here, f_{ap1}, f_{ao1}, and f_{ap2} are constants corresponding with three characteristic frequencies. As for the permeabilities of AZO and ZnO, they are taken to be unity because both materials are nonmagnetic.

In performed calculations, we have applied the characteristic matrix

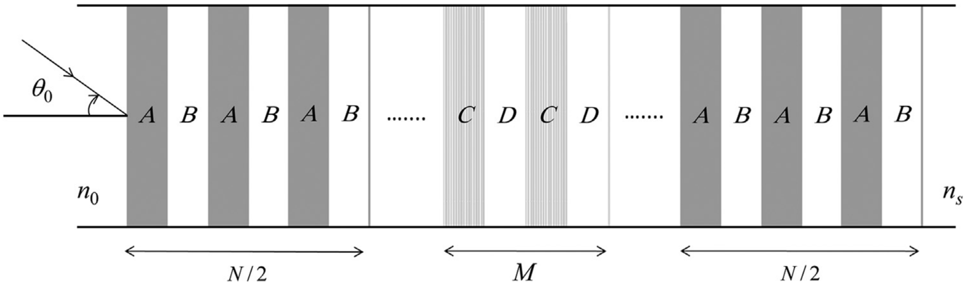

Fig. 1. Schematic diagram of one-dimensional defective photonic crystal immersed in free space with photonic quantum-well defect structure at the center. Where layers A and B corresponding to the main structure are respectively SiO_2, InP, and also layers C and D corresponding to the defect structure are respectively are AZO–ZnO and air. θ_0 is the incident angle and also N and M are respectively the number of the lattice periods of bilayers (AB) and (CD).