



*Research Article*

# Backward Defect States in One with Dispersive Left-Handed Material Defect

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## **ABSTRACT**

*We present a theoretical study of electromagnetic defect states localized at a defect layer with left-handed (LH) material between two symmetric semi-infinite one-dimensional photonic crystals (1DPCs) composed of right-handed (RH) materials. We consider magnetic permeability and electric permittivity of LH layer being dispersive. An analytical direct matching procedure within the Kronig-Penney model was applied to analyze the dispersion properties of the localized defect states. It is shown that the dispersive LH layer act as an effective tool to tune the type of defect modes from backward to forward and vice versa and it plays an important role on the localization of them, when the frequency and the parameters of the defect layer vary. Also, we show that when the LH layers are chosen dispersive, three types of dispersion: positive, zero, and negative dispersion of defect waves are obtained in a wide range of radiation angle and frequency, which is depending on the physical and optical parameters of the defect layer.*

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## **1. INRODUCTION**

Great efforts have been made to study and understand photonic crystals (PCs) and metamaterials, in which two different types

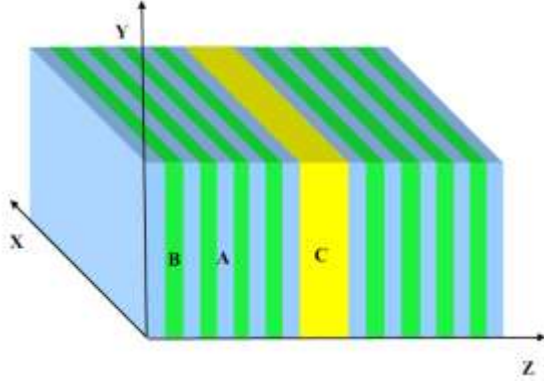
of materials are being evolved in the area of photonics [1, 2]. PCs are periodic optical nanostructures that affect the motion of photons in the same way that ionic lattices

affect the electrons in solids [3, 4]. Photons (behaving as waves or light) propagate through the nanostructures depending or not depending on their frequencies. The frequencies of light that are allowed to travel are known as the modes, and the groups of allowed modes form bands. Disallowed bands of frequency are called photonic band gap (PBG), which is the range of frequency that incident light cannot propagate through the structure due to the inference of the Bragg scattering in this periodic structure [5]. A conventional PC is made of usual dielectric materials, in which both permittivity ( $\epsilon$ ) and permeability ( $\mu$ ) have positive real values called right-handed metamaterials (RHMs), and, consequently, they are referred to as the RH materials. However, Veselago [6] has introduced a new type of material called left-handed metamaterials (LHMs), in which both  $\epsilon$  and  $\mu$  are negative in their real parts. During the past two decades, PCs composed of metamaterials, which are called metamaterial photonic crystals (Meta PCs), have been of interest to the community because of the novel phenomena in optical physics and microwave engineering [7–9]. LHMs are predicted to exhibit many unusual properties such as refraction at a negative angle, an inverse Doppler shift, and a backwards oriented Cherenkov radiation cone [6]. All these phenomena are rooted in the fact that the phase velocity of light in LH material is opposite to the velocity of energy flow, that is, the Poynting vector and wave vector are antiparallel so that the wave vector, the electric field, and the magnetic field form a LH system. Effective dielectric permittivity and effective magnetic permeability of LHMs are, in general,

frequency dependent. Band structure of one dimensional photonic crystals (1DPCs) containing alternative layers of dispersive (and non-dispersive) LH and RH materials have been reported by Li et al. [10]. They focused on zero- $n^-$  gap 1DPCs mentioned above and neglected the influence of absorption on them. Recently it was shown that, absorption has a great influence on zero- $n^-$  gap [11]. It is well known that a defect layer is introduced in to the PC, destroys the periodicity and leads to the appearance of localized modes in the PBG, the so-called defect modes [6]. These defect modes mainly result from the change of the interference approach of light, and such defective photonic structures are often useful in the number of applications like narrow pass band filters, beam shaper and all optical

## 2. MODEL

The schematic diagrams showing the two-layer arrangements under consideration in this paper are shown in Fig. 1. As shown in this figure, the periodicity of the structure is in the ‘Z’ direction. In order to investigate the defect modes dispersion relation, we have supposed that one-dimensional PC is contained two different semi-infinite PC superlattice with a defect layer. Each unit cell is composed of two layers, where  $d_i$ ,  $\epsilon_i$  and  $\mu_i$  are the thickness, the dielectric permittivity and the magnetic permeability of the  $i$ th layer, respectively. also,  $d_c$ ,  $\epsilon_c$  and  $\mu_c$  are the physical parameters of the defect layer. Due to translational invariance in the  $X-Y$  plane, the parallel wave vector,  $k_{||}$  is a conservative quantity in all domains of the crystal.



**Figure 1.** Schematic representation of the defect layer sandwiched between two symmetric semi-infinite IDPCs.

In this paper, we have considered the TE polarization, where the electric field is parallel to the interface referred to as  $Y$ -direction. Only TE modes have been considered in this paper and the TM modes can be considered in a similar way. In a one-dimensional periodic structure, the propagating waves have the form of Bloch modes, for which the electric field amplitudes satisfy the periodicity condition,

$$E(z + d, x) = E(z, 0)\exp(iK_B z + ik_x x) \quad (1)$$

where,  $d = d_1 + d_2$  is the period of the unit cell. Here,  $K_B$  is the Bloch wave number which defines the wave transmission across the layers, and its dependence on the wave vector component perpendicular to the layers  $k_z$  can be found explicitly for two-layered periodic structures via the dispersion relation of the PC [19],

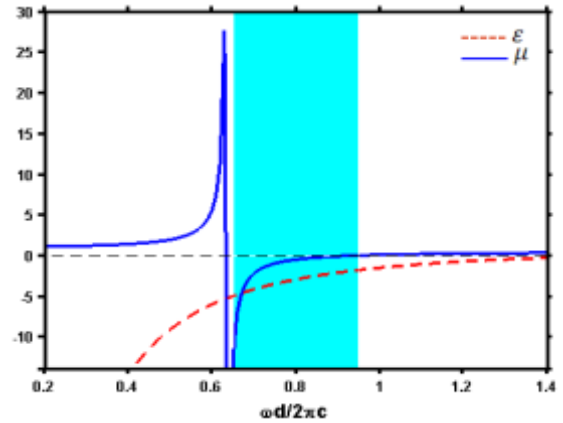
$$\begin{aligned} \cos(K_B d) &= \cos(k_{1z} d_1) \cos(k_{2z} d_2) - \\ &1/2 \left( \frac{F_1}{F_2} + \frac{F_2}{F_1} \right) \sin(k_{1z} d_1) \sin(k_{2z} d_2) = \\ &B(\omega) \end{aligned} \quad (2)$$

where the perpendicular wave vector component in each medium is given by  $k_i = [\mu_i \varepsilon_i (\omega/c)^2 - k_{||}^2]^{1/2}$ ,  $F_i = \frac{k_i}{\mu_i}$ ,  $k_{||}^2 = k_x^2 + k_y^2$ ,  $\omega$  is the angular frequency, and  $c$  is the light speed in vacuum. On the other hand, it is well-known that when any periodic system is limited,  $K_B$  should be complex [18],

$$K_B = i\eta + m \frac{\pi}{d}, \eta > 0, m = 0, \pm 1, \pm 2, \quad (3)$$

### 3. RESULTS AND DISCUSSIONS

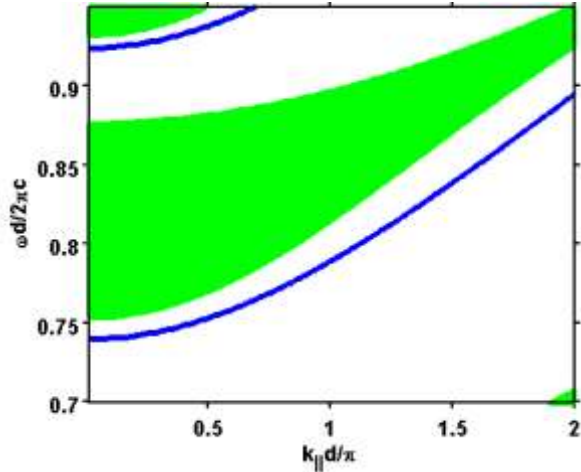
First, we studied the behavior of the defect states of a photonic crystal with RH material a defect layer. In our calculations, the thicknesses and the refractive indices are according to Ref. [21].



**Figure 2.** variation of  $\varepsilon_c$  and  $\mu_c$  elements versus frequency.

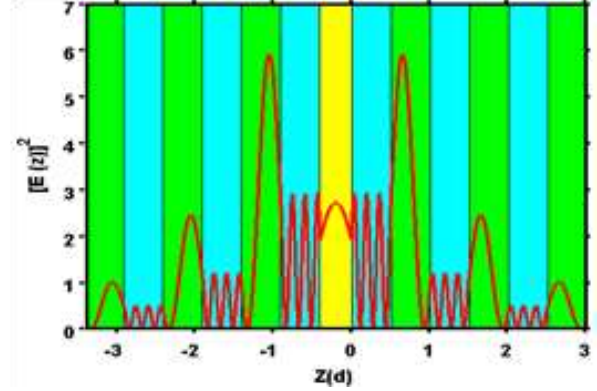
Figure 3 shows TE projected band structure and defect modes for superlattice structure with RH material as a defect layer, which was displayed in Fig.1. The dark areas represent the extending Bloch states, while the light areas are the PBG regions, where localized states such as defect modes can be appeared. We summarize the dispersion properties of the defect states in the first and

second spectral gaps on the plane of the free-space wave number  $\omega$  versus the  $k_{||}$ . The scales for frequency  $\omega$  and parallel wave vector  $k_{||}$  are all normalized to be dimensionless quantities, from  $\frac{\omega d}{2\pi c}$  and  $k_{||}d/\pi$ , respectively.



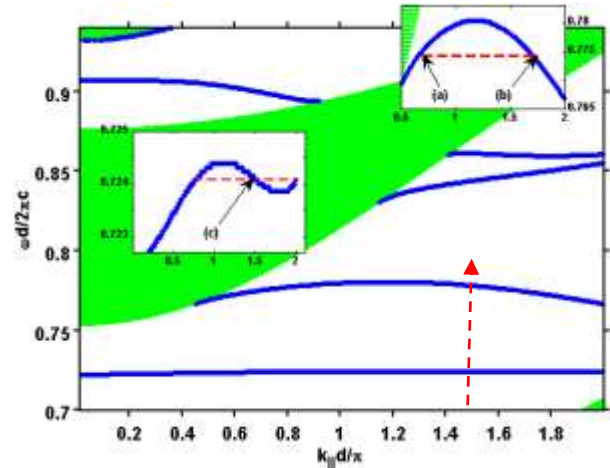
**Figure 3.** Calculated band diagrams and defect modes for TE polarization in a semi-infinite IDPC with RH material, which physical parameters used in are  $d_c = 0.4$ ,  $n_c = 1.4$  and  $\mu_c = 1$ .

For comparison with the RH material in this step, we plot the dispersion of the corresponding defect states in the structure, where the dispersive LH layer is replaced as a defect layer. Fig. 4 shows the band structure and the dispersion properties of created defect states with dispersive LH layer for an arbitrary width of defect layer ( $d_c = 0.4$ ), and the other parameters of PC same as Fig.3 between the two cases is that for the LHM defect modes the slope of the dispersion curve becomes negative for some  $k_{||}$ , and it remains positive for larger longitudinal wave numbers.

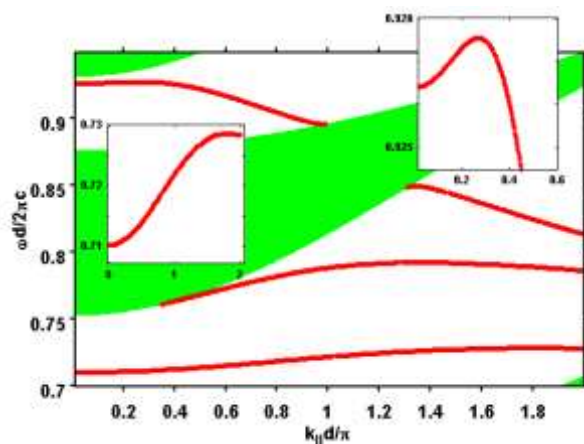


**Figure 4.** Dispersion properties of the defect states in the first and second spectral gaps.

It can be evidently understood from Fig.4 that, variations of permittivity and permeability of defect layer by the variation of frequency, change the type of defect states from backward to forward and vice versa.



**Figure 6.** Dispersion relation of defect states with dispersive LH material. The width for defect layer  $d_c = 0.6d$ . In this figure, three types of defect state dispersion can be seen in the second and first band gap.



**Figure 7.** Dispersion relation of defect modes with dispersive LHM. Same as Fig.4 but in this case the arrangement of layers corresponds to...ABCBA...

The emergence of multiple defect modes may be useful in the design of multiple channeled filters, which is difficult to realize by conventional ones. Therefore, the reason for the strong dependence of localized defect states on the stack sequence of the background PCs and optical parameters defect layer is also closely connected with the field profile of the background band gap mode at the interface between the defect layer and the background PCs.

### 3. CONCLUSION

In conclusion, we have studied electromagnetic defect waves guided by a

dispersive LH defect layer between two homogeneous semi-infinite 1DPC. We have shown that the variation of the electric permittivity and permeability of defect layer as a result of changing the frequency leads to control of the defect waves localization and tuned between forward and backward modes, and shown that in the presence of a left-handed material defect the defect waves can be either forward or backward while for RH structure the defect states are always forward. Also, the dependence of the defect states on the physical parameters of the defect layer has been studied. In addition, the results show that the most of the localized waves appear in the first frequency band gap.

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### DECLARATIONS

**Ethical Approval.** The authors declare that there are no animal studies in this work.

**Conflict of Interest.** The authors declare that they have no conflict of interest.

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