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RESEARCH ARTICLE

PROPERTIES OF DEFECT MODES COMPOSED OF METAMATERIALS

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ABSTRACT

The two important material parameters, electrical permittivity and magnetic permeability determine the optical properties of the materials. Together, the permittivity ε and permeability μ determine the response of the material to the electromagnetic radiation. Photonic crystals are artificial materials having periodic modulation in dielectric constant whose Bragg gap is highly sensitive to the lattice constant, incident angle and polarization of the incident light. The properties of photonic crystals are also affected by disorder, randomness and fabrication tolerances. Here, the defect modes composed of metamaterials are discussed which would be immune from the random thickness error in the fabrication procedure and be insensitive to the scale length change, angle of incidence and polarization.

INTRODUCTION

Meta-materials can be strictly distinguished from other structured photonic materials, i.e. photonic crystals or photonic band-gap materials. In the photonic crystals the band-gaps arise as a result of multiple Bragg scattering in a periodic array of dielectric scatterers. The periodicity of the structure here is of the order of the wavelength, and hence homogenization in this sense cannot be carried out. In meta-materials the periodicity is by comparison far less important and all the properties mainly depend on the single scattered resonances. The material that Veselago (Veselago, 1968), hypothesized more than thirty-five years ago can now be realized using artificially constructed metamaterials. It made the discussion of negative refractive index more than a theoretical curiosity as shown by various experiments and applications. The question of whether such a material can exist has been answered, turning the development of negative index structures into a topic of materials - or metamaterials - physics. As the metamaterials are now being designed, we are free to consider the ramifications associated with a negative index-of-refraction. This material property has enabled the rapid design of new electromagnetic structures perhaps because some of them having very unusual and exotic properties. The random thickness error caused in the fabrication procedure for the conventional photonic crystal may destroy the properties of the photonic band gap (PBG).

To overcome this problem, two new kinds of PBGs have been proposed recently: the “zero averaged refractive index” gap and the “zero effective phase” gap (Li, 2003 and Jiang, 2004). The first one exists in the periodic multilayer of alternating layers of positive refractive index materials and negative refractive index materials, whereas the second one appears in multilayer containing two different single-negative materials (permittivity or permeability-negative). In contrast to usual PBGs formed by the Bragg scattering, both the ”zero averaged refractive index” and the ”zero effective phase” gaps are almost invariant to scale- length changes and insensitive to disorder. The stacking alternating layers of ordinary (positive-n) and negative-n materials can lead to a new type of photonic gap with properties very different from that of a Bragg gap which arises when the volume averaged effective refractive index (n_{av}) equals zero (Li, 2003). They demonstrated that the zero- n_{av} gap is invariant with respect to a (length) scale change and insensitive to randomness as long as the $n_{av} = 0$ conditions are satisfied. The μ-negative (MNG) - Ɛ-negative (ENG) multilayered periodic structures can possess another new type of photonic band gaps that is distinct from the Bragg gaps (Jiang, 2004). The PBGs of this new type are surrounded by “propagation modes,” which originate from the interaction of forward and backward evanescent waves in the SNG frequency regime. It has been pointed out that such a gap is also invariant with the change of scale length and is insensitive to thickness symmetric fluctuation of pair layers (Jiang, 2004). Therefore, the properties of this gap versus the incident angles and the polarizations will be different from that of the Bragg gaps. The edge of zero-n_{av} gap is insensitive to the incident

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angle for different polarizations leading to an omnidirectional gap as investigated by Jiang *et al.* (Jiang, 2003). They found that defect mode inside the zero- n_{av} gap is independent of the scaling and has weak dependence on the incident angle. The angular dependence of the band gap for the 1-D photonic crystal consisting of alternating slabs made of ordinary and negative refractive index materials was investigated by Daninthe *et al.* (Daninthe, 2006). For a certain type of constituent left-handed medium, around the frequency where n_{av} is zero, they found an omni gap, independent of both angle and polarization. The metamaterials include double-negative (DNG) materials and single-negative (SNG) materials. DNG materials are artificial composites with both permittivity ($£$) and permeability ($«$) simultaneously negative. In addition to the DNG materials, there are also we can also have single negative (SNG) materials in which only one of the two material parameters $£$ and $«$ is negative. The SNG materials consist of the mu-negative (MNG) materials with negative $«$ but positive $£$ and the epsilon-negative (ENG) materials with negative $£$ but positive $«$. New effects are produced by the dispersive character of metamaterials. When ordinary materials and dispersive metamaterials are combined (Monsoriu, 2006; Depine, 2007; Singh, 2007; Scher, 2011; Tunable, 2011; Muhan Choi, 2013; Laxmi Shiveshwari, 2013; Liwei Zhang, 2014; Pandey, 2017; Born, 1980 and Yeh, 1988), this effect is produced by the interaction between two kinds of non-Bragg gaps. In this communication, the properties of defect modes are theoretically investigated which is formed at oblique incidence in a photonic band gap structure composed of alternate DPS-ENG, DPS-MNG and DPS-DNG multilayer structures.

Mathematical Formulation

Here, DPS-ENG, DPS-MNG and DPS-DNG multilayer structures are investigated. These 1-D metamaterial PCs are constituted by the multilayers of DPS, ENG, MNG and DNG materials. These materials have different expressions of permittivity and permeability accordingly. For the DNG material, the permittivity and permeability can be expressed as

$$£(μ)=1+\frac{5^2}{0.9^2-μ^2}+\frac{10^2}{11.5^2-μ^2}$$

$$«(ω)=1+\frac{3^2}{0.902^2-μ^2}$$

where $μ$ is frequency in GHz.

Similarly, the permittivity and permeability for the MNG material,

$£=1$, and $«(ω)=1+\frac{3^2}{0.902^2-μ^2}$ and for ENG material, the permittivity and permeability can be written as,

$$£(μ)=1+\frac{5^2}{0.9^2-μ^2}+\frac{10^2}{11.5^2-μ^2}\text{, and } «=1.$$

For the DPS material, both $£$ and $«$ are positive constants and taken as 1.

The optical constants (permittivity, permeability, refractive index and extinction coefficient) of MNG, ENG and DNG materials are shown in figure 1. Consider the 1-D PC with the periodic structure of $(AB)^N$, where A and B denote two kinds of different materials and N is the number of periods. The relative permittivity and permeability of these two materials are denoted by $£$ and $«$. Let a plane wave be incident from the vacuum into the 1-D PC at an incident angle $¯$ with +Z direction. The amplitudes of the electric and magnetic fields at any two positions z and $z+\Delta z$ on the two surfaces of a layer can be related via a transfer matrix (Born, 1980 and Yeh, 1988).

$$T_j(\Delta z, μ)=\begin{pmatrix} \cos[k_z^j \Delta z] & i\frac{1}{q_j}\sin[k_z^j \Delta z] \\ iq_j \sin[k_z^j \Delta z] & \cos[k_z^j \Delta z] \end{pmatrix}$$

where $k_z^j = μ/c\sqrt{£_j}\sqrt{«_j}\sqrt{1-\left(\sin^2 ¯/£_j «_j\right)}$ is the z component of the wave vector k^j in the jth layer, c is speed of light in the vacuum and $a\,z$ is the thickness of the layer. For TE wave, $q_j=\sqrt{£_j}\big/\sqrt{«_j}\sqrt{1-\left(\sin^2 ¯/£_j «_j\right)}$; for TM wave, $q_j=\sqrt{«_j}\big/\sqrt{£_j}\sqrt{1-\left(\sin^2 ¯/£_j «_j\right)}$.

If $x_{ij}(μ)\ (i,j=1,2)$ are the elements of the matrix $X_N(μ)=\prod_{j=i}^{N} T_j(d_j, μ)$, which represents the total transfer matrix connecting the amplitudes of the transmitted and the reflected waves at the incident end and those at the exit end, then the transmission coefficient $t(μ)$ for both TE and TM waves passing through this 1-D PC into a vacuum can be obtained as

$$t(μ)=\frac{2q_0}{[q_0 x_{22}(μ)+q_s x_{11}(μ)]-[q_0 q_s x_{12}(μ)+x_{12}(μ)]}$$

where, $q_0=q_s=\sqrt{£_0}\big/«_0\sqrt{1-\sin^2 ¯/£_0 «_0}=\cos ¯$ for the vacuum ($£_0=1$ and $«_0=1$) of the space z < 0 before the incident end and the space z > d after the exit end, where d is the total length of the 1D PC.

RESULTS AND DISCUSSION

Here, the localized defect modes created by introducing a defect layer are studied. Consider a defect 1-D MPC structure $(AB)^M C\,(AB)^M$, where M is an integer taken 8 here. A and B are the DPS and MNG or ENG or DNG materials respectively. The defect layer C is a DPS material with $£_C>0$, $«_C>0$ and having thickness d_C. In this study, the defect layer has $£_C=5$, $«_C=1$. The dependency of the defect modes on the angle of incidence and scale change are shown by plotting the graphs. Figure 2 shows the dependency of defect mode in the case of DPS-MNG structure when we insert a 24 mm thick defect layer. It is seen that the defect mode inside the first new gap is invariant with scaling and affected slightly with angle change for both TE and TM modes. The defect mode inside second new gap, which is only in TE mode, changes its position with angle but is insensitive to the scale length change.

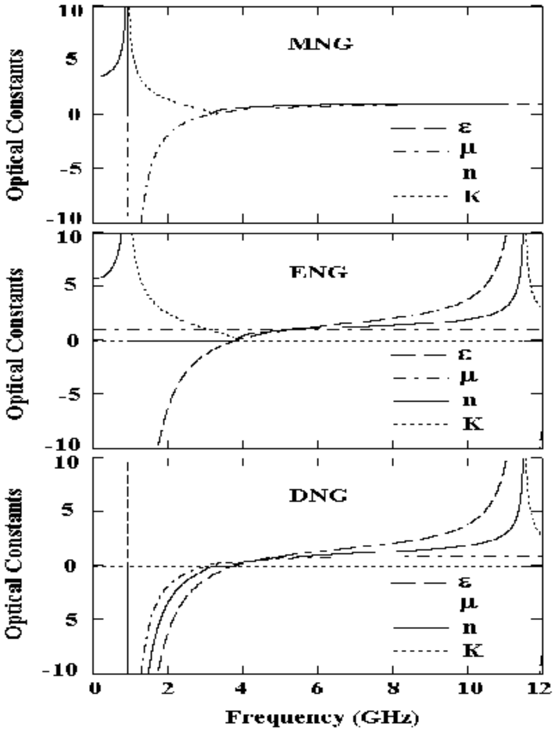

Figure 1 Optical properties of MNG, ENG and DNG materials

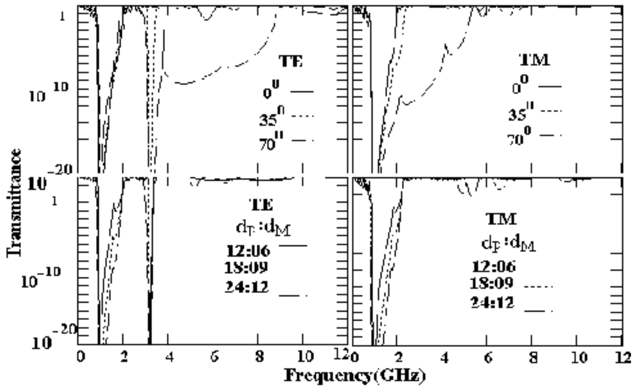

Figure 2 The dependence of defect mode of (DPS-MNG)^8 C (DPS-MNG)^8 1D PC on the scaling of unit cells and incident angle

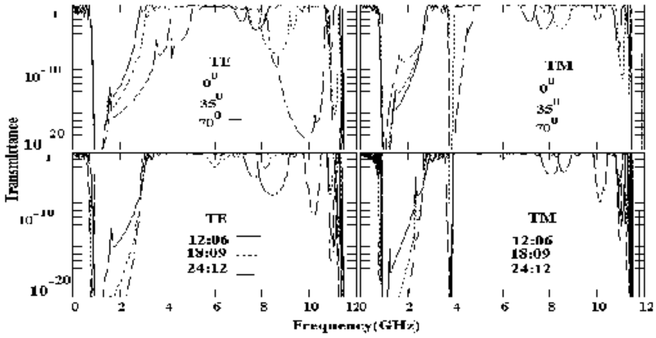

Figure 3. The dependence of defect mode of (DPS-ENG)^8 C (DPS-ENG)^8 1D PC on the scaling of unit cells and incident angle

The DPS-ENG structure is doped with defect layer of thickness 24 mm. The dependence of defect mode frequency on the angle of incidence and scaling can be seen in figure 3. The defect mode varies very slightly with the change in angle of incidence in both the new gaps for both TE and TM polarizations and remains invariant with scale length change.

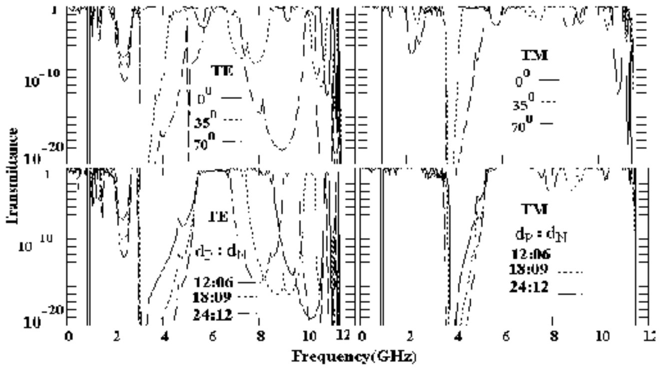

Figure 4. The dependence of defect mode of (DPS-DNG)^8 C (DPS-DNG)^8 1-D PC on the scaling of unit cells and incident angle

In the case of DPS-DNG multilayer structure, the defect layer have the thickness of 36 mm. Figure 4 shows that the spectral position of the defect mode inside the new gap varies slightly with angle and is nearly invariant with scaling change.

Conclusion

When we introduce a defect layer of positive index material is introduced in three types of 1-D metamaterial PCs formed by the alternating layers of dispersive materials (DPS-MNG, DPS-ENG and DPS-DNG), defect modes appear inside the new gaps and the spectral position of the defect mode is invariant with the scaling of the lattice constant and changes a little with the incident angles. This band gap appears at the position where either permittivity or permeability becomes zero and it appears only for the angles other than normal incidence (i.e. it exists only for oblique incidences).

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