Optica Applicata, Vol. XLIX, No. 1, 2019
DOI: 10.5277/oa190104

Narrow transmission mode in one-dimensional symmetric defective photonic crystal containing metamaterial and high T_c superconductor

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We theoretically investigate the properties of narrow transmission mode (defect mode) within the reflection band in one-dimensional symmetric defective photonic crystal containing double negative metamaterial and high temperature superconductors. The transmittance spectrum of the proposed structure is obtained by using the characteristic or transfer matrix method. The results show that by increasing the thickness of air defect, transmission mode shifts towards the lower frequency side. But when the thickness of a superconductor layer is increased, transmission mode shifts towards the high frequency side. Further, the effect of temperature variation of superconducting defect on the defect mode has been investigated and found that when the temperature of superconducting layer increases the frequency of defect mode is red shifted. The shift in frequency has smaller value in the lower temperature region than in the higher temperature region, even if the change in temperature is same. Finally we have discussed the effect of variation of thickness on the defect mode by using the double negative metamaterial as defect layer in place of superconductor layer. The result shows that we get two modes for smaller thickness of double negative layer but only a single mode for larger thickness.

Keywords: photonic crystal, photonic band gap, transmission spectra, transmission mode, defect mode, metamaterial, negative index material, superconductor photonic crystal.

1. Introduction

Photonic crystals (PCs) are a new kind of optical materials with periodic modulation in dielectric constant and the period equivalent to optical wavelength. In the past three decades much attention has been focused on theoretical and experimental investigations on photonic crystals. Due to their ability to control and manipulate the propagation of light waves, PCs possess many potential applications in modern photonics [1–8]. The most fundamental property of PC is the existence of photonic band gaps (PBGs) or forbidden bands also called stop bands. The frequencies or wavelength of electromagnetic waves which fall within PBG are not allowed to propagate through the PCs. Photonic crystals composed of metamaterials have also generated much interest to the scientists and engineers in recent years. Metamaterials are defined as artificial composites having simultaneously negative permittivity and permeability also called as negative index materials (NIMs) or double negative (DNG) index materials. In these materials direction of Poynting vector **S** becomes opposite to that of the wave vector **k** so that **k**, **E** and **H** form a left handed set of vectors so they also called as left-handed materials (LHMs) and firstly proposed by Veselago in 1968 [9]. Further, Pendry's theoretical investigation and demonstration on negative index materials and its application in the realization of perfect lens has generated the tremendous interest in the field of metamaterials [10–19]. In the beginning Smith *et al.* have carried out the experiment in this field to confirm the existence of negative refractive index materials [12–14]. There also exists another kind of metamaterial which includes ε negative but μ positive called ENG and μ negative but ε positive called MNG [20–23]. ENG and MNG metamaterials usually called as single negative (SNG) metamaterials possess zero effective phase gaps and can be used to realize the potential optical devices [21–25]. In the past few years PCs based on superconducting material have drawn much attention due to their tunable characteristics. This is due to the fact that the response of electromagnetic wave in superconducting material depends on the London penetration depth that is a function of temperature and applied magnetic field [26–28]. Thus the photonic crystals composed of superconducting layers have emerged as a growing area of research and possess many potential applications [29–32]. By introducing the defect into conventional 1D PC, a tunneling mode (or transmission mode) can be generated in the photonic band gap. This can be done by changing the geometrical parameters or dielectric constants of the stacked materials in the normal PC. In recent years much attention has been focused to obtain the tunability in the PBG as well as transmission mode. Tunable characteristics of PBG or transmission modes can be realized by changing the refractive indices of the materials which can be done by applying the external fields such as electric/magnetic fields or optical fields and by changing the temperature [33–39].

In this work, we will investigate the properties of narrow transmission mode or defect mode within the photonic band gap (reflection band) in one-dimensional (1D) symmetric defective photonic crystal containing DNG metamaterial and high temperature superconductors. The defect has been introduced in the normal PC structure in the unit of three layers in the form of air–superconductor–air and air–DNG material–air respectively. In the numerical computation we will see the effect of thickness variation of different defect layers on the transmission peak of defect modes. Further, the influence of temperature variation of superconducting defect on the narrow transmission mode will be discussed. In order to obtain the transmittance spectra, we employ characteristic or transfer matrix method (TMM).

2. Theoretical model and formulations

Schematic diagram of 1D symmetric defective PC structure composed of DNG material and high T_c superconductor $Bi_2Sr_2CaCu_3O_8$ (BSCCO) is shown in Fig. 1. The first layer in the proposed structure possesses a negative refractive index n_A in the microwave region with complex relative permittivity ε_A and permeability μ_A and thickness d_A is given by the following equations [13]

$$\varepsilon_A(v) = 1 + \frac{5^2}{0.9^2 - v^2 - iv\gamma_e} + \frac{10^2}{11.5^2 - v^2 - iv\gamma_e} \tag{1}$$

$$\mu_A(v) = 1 + \frac{3^2}{0.902^2 - v^2 - iv\gamma_m} \tag{2}$$

where v is the frequency measured in the GHz, γ_e and γ_m are the electric and magnetic damping frequencies, respectively, also measured in GHz.

The refractive index and thickness of the second layer which is a high T_c superconductor is denoted by n_B and d_B, respectively. The refractive index of superconductor layer is described by Gorter–Casimir two-fluid model, in the absence of external magnetic field [40]. Basically, a two fluid model describes the electrodynamics of superconductor at non-zero temperature; according to this, the electrons in the superconductor occupy one of the two states, namely superconducting and normal state. The electromagnetic response of a superconductor is described in terms of complex conductivity and can be expressed as $\sigma = \sigma_1 - j\sigma_2$, where σ_1 (real) and σ_2 (imaginary) and represents the conductivity of normal and super electrons.

The real part of complex conductivity can be neglected for the lossless superconductor, so the conductivity can be expressed as [40, 41]

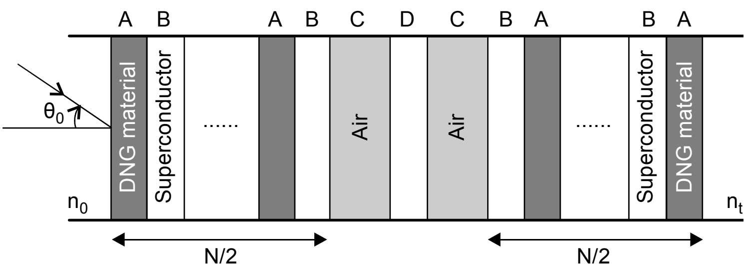

Fig. 1. Schematic diagram of 1D symmetric defective PC structure composed of DNG metamaterial and high T_c superconductor.

$$\sigma = \frac{-j}{\omega \mu_0 \lambda_L^2} \tag{3}$$

where μ_0 is the permeability in vacuum, λ_L is the temperature-dependent London penetration depth given as

$$\lambda_L = \frac{\lambda_L(0)}{\sqrt{1 - (T/T_c)^2}} \tag{4}$$

Here, $\lambda_L(0)$ is the penetration depth at $T = 0$ K, and T_c is the critical temperature of the superconductor. The refractive index of the superconductor can be derived from the Eq. (3) and expressed as follows:

$$n_B = \sqrt{1 - \frac{c^2}{\omega^2 \lambda_L^2}} \tag{5}$$

where ω, is the angular frequency of incident electromagnetic wave and c is the speed of light.

The proposed 1D symmetric defective PC structure is constructed from two 1D photonic crystals and expressed as air/(AB)$^{N/2}$CDC(BA)$^{N/2}$/air. Here, A and B represent metamaterial and high temperature superconductors, respectively, C is taken as air and D is a high T_c superconductor in one case and in other case as a DNG metamaterial.

For the calculation of transmission spectra we use the transfer matrix method which is a very effective technique to study the transmission properties of the finite PCs. The total characteristics matrix for the proposed defective PC can be represented as

$$M(d) = (M_A M_B)^{N/2} M_C M_D M_C (M_B M_A)^{N/2} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \tag{6}$$

where M_A, M_B, M_C and M_D are characteristic matrices of layers A, B, C and D, respectively, N is the number of periodic layers.

The characteristic matrix M_j for the j-th layer in the PC for transverse electric (TE), *i.e.* s-polarized and transverse matrix (TM), *i.e.*, for p-polarized waves can be given as [42, 43]

$$M_j = \begin{bmatrix} \cos\delta_j & \frac{1}{iq_j}\sin\delta_j \\ -iq_j \sin\delta_j & \cos\delta_j \end{bmatrix} \tag{7}$$

and

$$\delta_j = \frac{2\pi v}{c} n_j d_j \cos\theta_j$$

$$q_j = \sqrt{\frac{\varepsilon_j}{\mu_j}} \cos\theta_j \quad \text{for TE wave}$$

$$q_j = \sqrt{\frac{\mu_j}{\varepsilon_j}} \cos\theta_j \quad \text{for TM wave}$$

$$\cos\theta_j = \sqrt{1 - \frac{n_0^2 \sin^2\theta_0}{n_j^2}}$$

and θ_j is the ray angle inside the layer j of refractive index n_j (j = A, B, C, D); v is the frequency of light in the incidence medium, n_0 is the refractive index of incident medium and θ_0 is the incident angle.

The transmission coefficients for TE (s-polarized) and TM (p-polarized) waves are given by [43]

$$t(s) = \frac{2q_0(s)}{\left[M_{11} + q_t(s)M_{12}\right]q_0(s) + \left[M_{21} + q_t(s)M_{22}\right]} \tag{8}$$

$$t(p) = \frac{2q_0(p)}{\left[M_{11} + q_t(p)M_{12}\right]q_0(p) + \left[M_{21} + q_t(p)M_{22}\right]} \tag{9}$$

where M_{11}, M_{12}, M_{21}, M_{22} are the elements of the total characteristic matrix of the N period multilayer structures. The values of q_0 and q_t for TE (s) and TM (p) polarized waves are given as

$$q_0(s) = n_0 \cos\theta_0 \tag{10a}$$

$$q_t(s) = n_t \cos\theta_t \tag{10b}$$

$$q_0(p) = \frac{\cos\theta_0}{n_0} \tag{10c}$$

$$q_t(p) = \frac{\cos\theta_t}{n_t} \tag{10d}$$

Here, n_t is the refractive index of the substrate and θ_t is ray angle inside it.

Finally, the transmittance of the proposed PC structure can be obtained by using the expression

$$T(s, p) = \frac{q_t}{q_0} |t(s, p)|^2 \tag{11}$$

3. Numerical results and discussion

In this section we numerically compute the transmission spectrum of the proposed symmetric defective PC structure composed of high T_c superconductor $Bi_2Sr_2CaCu_3O_8$ (BSCCO) and DNG metamaterials placed in air. The symmetric defective PC structure has been taken in the form of air/$(AB)^{N/2}CDC(BA)^{N/2}$/air; in this structure there are two defect layers C and D in the unit of CDC where C is taken as air and D is a high T_c superconductor in one case and in other case it is taken as a DNG metamaterial. The critical temperature T_c of BSCCO is 95 K and its penetrations depth at 0 K is 150 nm. Electric and magnetic damping frequencies of the metamaterial layers are chosen as $\gamma_e = \gamma_m = 2 \times 10^{-3}$ GHz and the thickness of alternate metamaterial layers d_A and superconductor d_B are 10 mm and 40 nm, respectively with the total number of periods $N = 10$. The London penetration depth and refractive index of BSCCO at operating temperature $T = 4.2$ K can be determined by using Eqs. (4) and (5), respectively. Figure 2 shows the transmittance curves for thickness of superconductor defect $d_D = 10$ nm and thickness of air defect $d_C = 7$, 9, 11, and 13 mm. From this curve we observe that a single defect mode is obtained for the proposed structure even if the defect is taken in the unit of three layers. The defect mode shifts towards the lower frequency side by increasing the thickness of air defect which lies at frequency 1.990, 1.892, 1.755 and

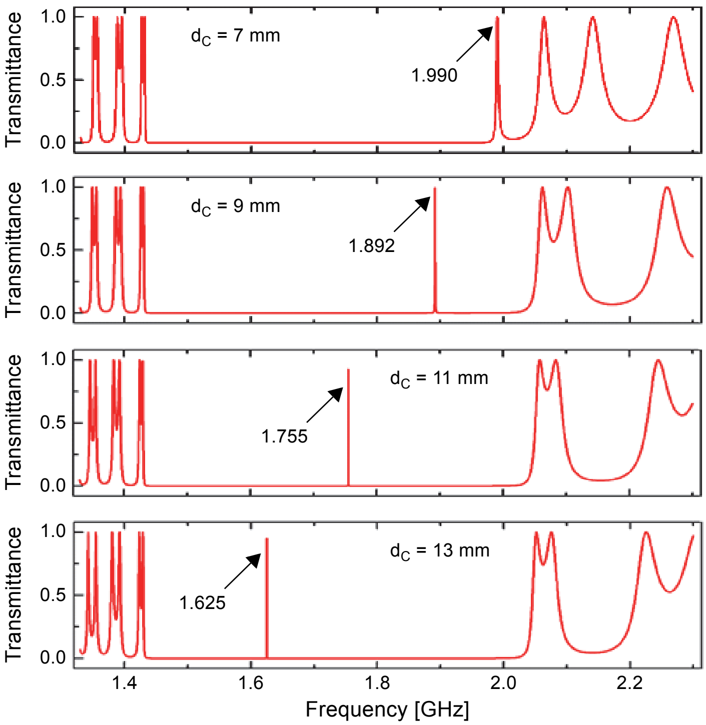

Fig. 2. Transmittance curves for thickness of superconductor defect $d_D = 10$ nm and thickness of air defect $d_C = 7$, 9, 11, and 13 mm; $d_A = 10$ mm, $d_B = 40$ nm.

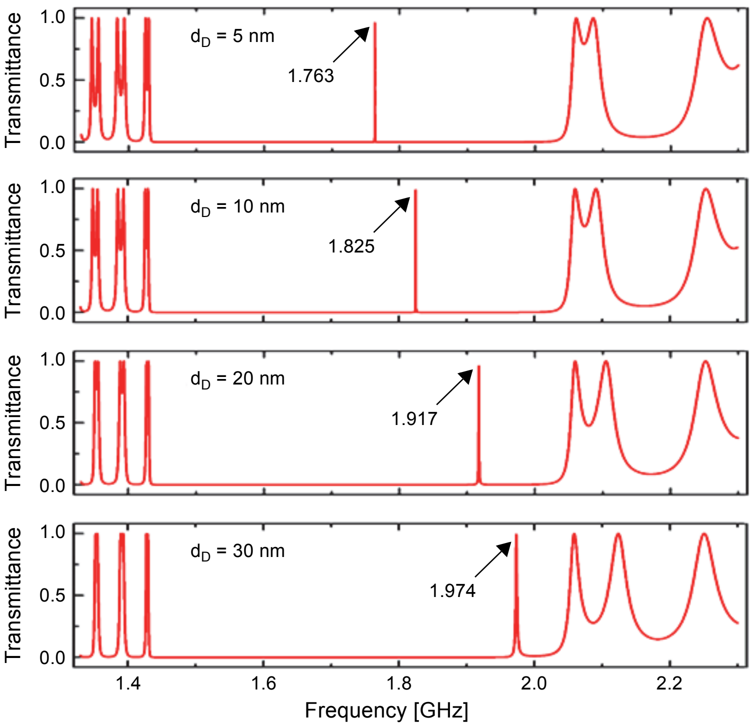

Fig. 3. Transmittance curves for thickness of air defect $d_C = 10$ mm and thickness of superconductor defect $d_D = 5$, 10, 20 and 30 nm; $d_A = 10$ mm, $d_B = 40$ nm.

1.625 GHz, respectively. In Fig. 3 transmission curves for thickness of air defect $d_C = 10$ mm and thickness of superconductor defect $d_D = 5$, 10, 20 and 30 nm has been plotted. In this case also a single defect mode is observed but the transmission peak shifts towards the higher frequency side that lies at 1.763, 1.825, 1.917 and 1.974 GHz,

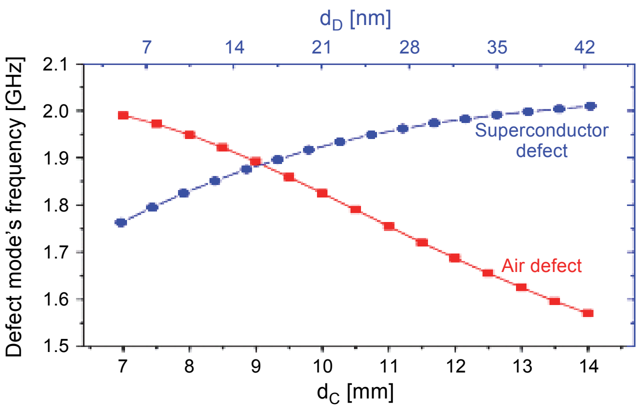

Fig. 4. Effect of thickness of air defect and superconductor defect on the frequency of transmission peaks at $d_A = 10$ mm and $d_B = 40$ nm.

respectively. In Fig. 4, we demonstrate the effect of thickness of air defect and superconductor defect on the frequency of transmission peaks in more details, here squares are used for air defect and circles – for superconductor defect. It can be observed that the peak frequency of defect mode shows the decreasing nature when the thickness of air defect is varied whereas the increasing nature for the variation in thickness of superconductor defect. Both curves cross each other at a common frequency of defect mode which lies at 1.825 GHz for d_D = 10 nm and d_C = 10 mm. Figure 5 shows the effect of variation in operating temperature on the defect modes. Operating temperature is taken as T = 20, 40, 60 and 80 K, respectively, while the other parameters are d_A= 10 mm, d_B = 40 nm, d_C =10 mm and d_D = 20 nm. It is found that when the temperature of superconducting layer increases, the frequency of defect mode (or transmission peak) decreases, *i.e.* the defect mode is red shifted. The transmission peak has frequency 1.894, 1.817, 1.681 and 1.508 GHz, respectively, at temperature T = 20, 40, 60 and 80 K. The change in frequency $\Delta \nu$ corresponding to temperature change ΔT of 20 K is found to 0.074, 0.136 and 0.173 GHz, respectively. Thus it is clear that the frequency shift has a lesser value in the lower temperature region than in the higher temperature even for the same change in temperature.

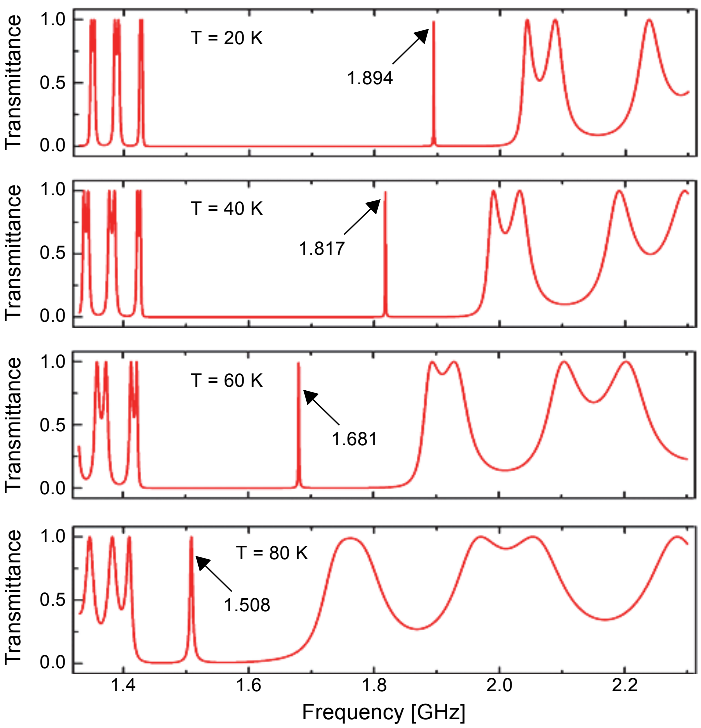

Fig. 5. Transmittance curves at T = 20, 40, 60 and 80 K for d_A = 10 mm, d_B = 40 nm, d_C = 10 mm, and d_D = 20 nm.

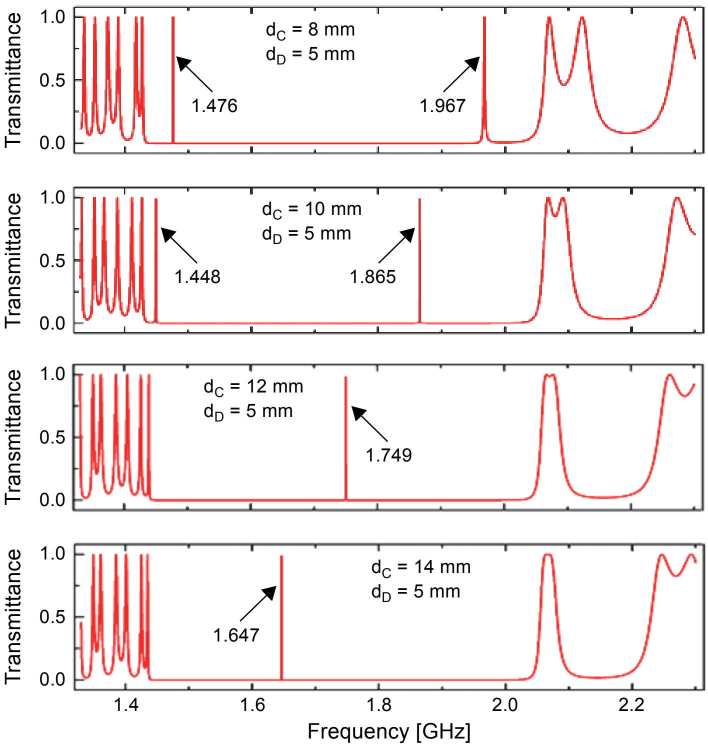

Fig. 6. Transmittance curves for thickness of DNG metamaterial defect d_D = 5 mm and thickness of air defect d_C = 8, 10, 12, and 14 mm; d_A = 10 mm, d_B = 40 nm.

In the next part, we investigate the defect mode by taking DNG metamaterial as a defect layer in place of superconductor defect in the same defective PC structure as considered above. The transmission curves for thickness of DNG metamaterial defect d_D = 5 mm and thickness of air defect d_C = 8, 10, 12 and 14 mm, respectively, are depicted in Fig. 6. In this case we find two defect modes for the thickness 8 and 10 mm, one of which lies on the lower side of central frequency and the other lies at a higher side of it. But when the thickness of defect layer is further increased, the transmission peak which lies on the lower frequency side disappears and only a single defect mode remains there. Moreover, the defect mode shifts toward the lower frequency side with the increase in the thickness of the air defect. The transmission spectra depicted in Fig. 7 show the defect modes for thickness of air defect d_C =10 mm and thickness of DNG metamaterial defect d_D = 2, 4, 6 and 8 mm, respectively, keeping other parameters same as taken previously. On examining the curves, we find that there is a single defect mode for d_D = 2 and 4 mm but at higher values, *i.e.* at d_D = 6 and 8 mm there are two defect modes. The entire modes (single as well as double) shift towards the high frequency side when the thickness of the defect layer is increased, which is opposite to

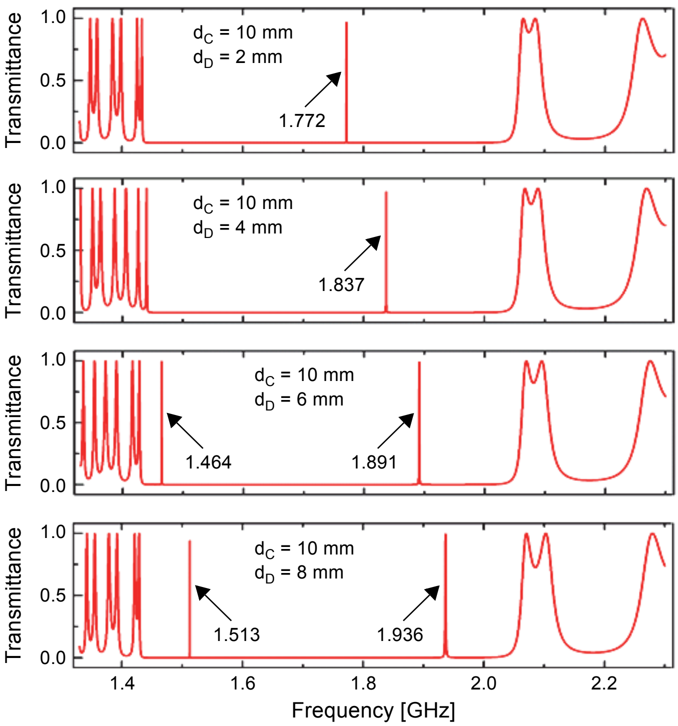

Fig. 7. Transmittance curves for thickness of air defect d_C = 10 mm and thickness of DNG metamaterial defect d_D = 2, 4, 6 and 8 mm; d_A = 10 mm, d_B = 40 nm.

the previous result. Finally, the effect of air defect and DNG material on the frequency of peak has been demonstrated together in Fig. 8, where squares are used for air defect and circles – for DNG material defect. In this case also the peak frequency of the defect

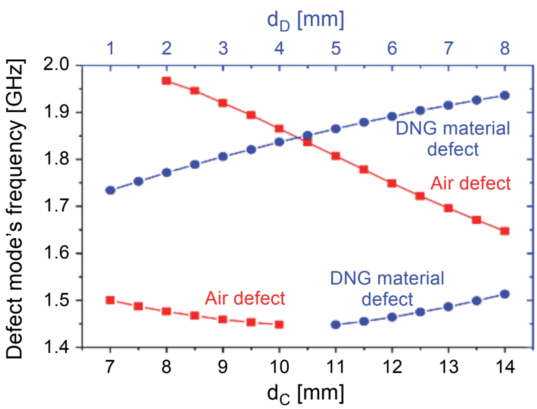

Fig. 8. Effect of thickness of air defect and DNG material defect on the frequency of transmission peaks at d_A = 10 mm and d_B = 40 nm.

mode shows decreasing nature with the thickness variation of air defect but here we get two modes for the thickness less than or equal to 10 mm (d_C). Similarly, variation in thickness of DNG material defect shows increasing behavior of frequency of transmission peak and in this case again we find two modes for the thickness greater than 4.4 mm (d_D). Moreover, both curves intersect each other at a frequency 1.865 GHz for d_D = 4.5 mm and d_C = 10.5 mm.

4. Conclusions

In summary, theoretical investigation and study of the narrow transmission mode in 1D symmetric defective photonic crystal containing metamaterial and high temperature superconductor have been presented and discussed. We have used the transfer matrix method (TMM) to calculate the transmittance spectra of the proposed structure taken in the form: air/$(AB)^{N/2}CDC(BA)^{N/2}$/air. From the analysis of the transmission curves we found that by increasing the thickness of air defect, transmission mode shifts towards the lower frequency side, but when the thickness of superconductor layer is increased transmission mode shifted towards the high frequency side. The effect of temperature variation of superconducting defect on the defect mode has also been investigated and noted that when the temperature of superconducting layer increases, the frequency of defect mode (or transmission peak) shifted to lower frequency side. The shift in frequency has a smaller value in the lower temperature region than in the higher temperature region, even if the change in temperature is same. Finally we have discussed the influence of variation of thickness on the defect mode by using the DNG metamaterial as defect layer in place of superconductor layer. The result shows that we get two modes for smaller thickness of DNG layer but only a single mode for larger thickness. From the above discussion it can be inferred that the narrow transmission mode can be tuned to different frequency by varying the thickness of the defect layers. Thus the proposed structure can be used as a single or double channel filter for the selected value of thickness of the defect layers. Moreover, since the frequency of transmission mode also changes with temperature (without changing the other parameters), hence the proposed structure can also be used as a thermal tunable filter.

Acknowledgements – One of the authors Dr. Sanjeev K. Srivastava is also thankful to Amity Institute of Applied Sciences, Amity University Uttar Pradesh, Noida, India, for providing the necessary facilities for this work.

References

[1] YABLONOVITCH E., *Inhibited spontaneous emission in solid-state physics and electronics*, Physical Review Letters **58**(20), 1987, pp. 2059–2062, DOI: 10.1103/PhysRevLett.58.2059.

[2] JOHN S., *Strong localization of photons in certain disordered dielectric superlattices*, Physical Review Letters **58**(23), 1987, pp. 2486–2489, DOI: 10.1103/PhysRevLett.58.2486.

[3] Weiss S.M., Haurylau M., Fauchet P.M., *Tunable photonic bandgap structures for optical interconnects*, Optical Materials **27**(5), 2005, pp. 740–744, DOI: 10.1016/j.optmat.2004.08.007.

[4] Fink Y., Winn J.N., Shanhui Fan, Chiping Chen, Michel J., Joannopoulos J.D., Thomas E.L., *A dielectric omnidirectional reflector*, Science **282**(5394), 1998, pp. 1679–1682, DOI: 10.1126/science.282.5394.1679.

[5] Mekis A., Chen J.C., Kurland I., Shanhui Fan, Villeneuve P.R., Joannopoulos J.D., *High transmission through sharp bends in photonic crystal waveguides*, Physical Review Letters **77**(18), 1996, pp. 3787–1390, DOI: 10.1103/PhysRevLett.77.3787.

[6] Chigrin D.N., Lavrinenko A.V., Yarotsky D.A., Gaponenko S.V., *Observation of total omnidirectional reflection from a one-dimensional dielectric lattice*, Applied Physics A **68**(1), 1999, pp. 25–28, DOI: 10.1007/s003390050849.

[7] Srivastava S.K., Ojha S.P., *Broadband optical reflector based on Si/SiO_2 one-dimensional graded photonic crystal structure*, Journal of Modern Optics **56**(1), 2009, pp. 33–40, DOI: 10.1080/09500340802428330.

[8] Noda S., Yokoyama M., Imada M., Chutinan A., Mochizuki M., *Polarization mode control of two-dimensional photonic crystal laser by unit cell structure design*, Science **293**(5532), 2001, pp. 1123–1125, DOI: 10.1126/science.1061738.

[9] Veselago V.G., *The electrodynamics of substances with simultaneously negative values of ε and μ*, Soviet Physics Uspekhi **10**(4), 1968, pp. 509–514, DOI: 10.1070/PU1968v010n04ABEH003699.

[10] Pendry J.B., *Negative refraction makes a perfect lens*, Physical Review Letters **85**(18), 2000, pp. 3966–3369, DOI: 10.1103/PhysRevLett.85.3966.

[11] Pendry J.B., *Light run backward in time*, Physics World **13**, 2000, pp. 27–29.

[12] Smith D.R., Padilla W.J., Vier D.C., Nemat-Nasser S.C., Schultz S., *Composite medium with simultaneously negative permeability and permittivity*, Physical Review Letters **84**(18), 2000, pp. 4184–4187, DOI: 10.1103/PhysRevLett.84.4184.

[13] Shelby R.A., Smith D.R., Schultz S., *Experimental verification of a negative index of refraction*, Science **292**(5514), 2001, pp. 77–79, DOI: 10.1126/science.1058847.

[14] Jensen Li, Lei Zhou, Chan C.T., Sheng P., *Photonic band gap from a stack of positive and negative index materials*, Physical Review Letters **90**(8), 2003, article ID 083901, DOI: 10.1103/PhysRevLett.90.083901.

[15] Srivastava S.K., Aghajamali A., *Study of optical reflectance properties in 1D annular photonic crystal containing double negative (DNG) metamaterials*, Physica B: Condensed Matter **489**, 2016, pp. 67–72, DOI: 10.1016/j.physb.2016.01.036.

[16] Srivastava S.K., Aghajamali A., *Analysis of reflectance properties in 1D photonic crystal containing metamaterial and high-temperature superconductor*, Journal of Superconductivity and Novel Magnetism **30**(2), 2017, pp. 343–351, DOI: 10.1007/s10948-016-3788-4.

[17] Shadrivov I.V., Sukhorukov A.A., Kivshar Y.S., *Beam shaping by a periodic structure with negative refraction*, Applied Physics Letters **82**(22), 2003, pp. 3820–3822, DOI: 10.1063/1.1579849.

[18] Ramakrishna S.A., *Physics of negative refractive index materials*, Reports on Progress in Physics **68**(2), 2005, pp. 449–521, DOI: 10.1088/0034-4885/68/2/R06.

[19] Parimi P.V., Lu W.T., Vodo P., Sridhar S., *Photonic crystals: Imaging by flat lens using negative refraction*, Nature **426**, 2003, p. 404, DOI: 10.1038/426404a.

[20] Haitao Jiang, Hong Chen, Hongqiang Li, Yewen Zhang, Jian Zi, Shiyao Zhu, *Properties of one-dimensional photonic crystals containing single-negative materials*, Physical Review E **69**(6), 2004, article ID 066607, DOI: 10.1103/PhysRevE.69.066607.

[21] Li-Gang Wang, Hong Chen, Shi-Yao Zhu, *Omnidirectional gap and defect mode of one-dimensional photonic crystals with single-negative materials*, Physical Review B **70**(24), 2004, article ID 245102, DOI: 10.1103/PhysRevB.70.245102.

[22] Heng-Tung Hsu, Kuan-Chung Ting, Tzong-Jer Yang, Chien-Jang Wu, *Investigation of photonic band gap in a one-dimensional lossy DNG/DPS photonic crystal*, Solid State Communications **150**(14), 2010, pp. 644–647, DOI: 10.1016/j.ssc.2009.12.027.
[23] Mishra A., Awasthi S.K., Srivastava S.K., Malaviya U., Ojha S.P., *Tunable and omnidirectional filters based on one-dimensional photonic crystals composed of single-negative materials*, Journal of the Optical Society of America B **28**(6), 2011, pp. 1416–1422, DOI: 10.1364/JOSAB.28.001416.
[24] Aghajamali A., Alamfard T., Barati M., *Effects of loss factors on zero permeability and zero permittivity gaps in 1D photonic crystal containing DNG materials*, Physica B: Condensed Matter **454**, 2014, pp. 170–174, DOI: 10.1016/j.physb.2014.07.067.
[25] Xin-Hua Deng, Nian-Hua Liu, *Polarization dependent angle fitters based on one-dimensional photonic crystals using mu-negative materials*, Journal of Modern Optics **56**(4), 2009, pp. 482–486, DOI: 10.1080/09500340802471843.
[26] Takeda H., Yoshino K., *Tunable photonic band schemes in two-dimensional photonic crystals composed of copper oxide high-temperature superconductors*, Physical Review B **67**(24), 2003, article ID 245109, DOI: 10.1103/PhysRevB.67.245109.
[27] Ooi C.H.R., Yeung T.C.A., Kam C.H., Lim T.K., *Photonic band gap in a superconductor-dielectric superlattice*, Physical Review B **61**(9), 2000, pp. 5920–5923, DOI: 10.1103/PhysRevB.61.5920.
[28] El-Naggar S.A., Elsayed H.A., Aly A.H., *Maximization of photonic bandgaps in two-dimensional superconductor photonic crystals*, Journal of Superconductivity and Novel Magnetism **27**(7), 2014, pp. 1615–1621, DOI: 10.1007/s10948-014-2500-9.
[29] Berman O.L., Lozovik Y.E., Eiderman S.L., Coalson R.D., *Superconducting photonic crystals: numerical calculations of the band structure*, Physical Review B **74**(9), 2006, article ID 092505, DOI: 10.1103/PhysRevB.74.092505.
[30] Srivastava S.K., *Study of defect modes in 1D photonic crystal structure containing high and low T_c superconductor as defect layer*, Journal of Superconductivity and Novel Magnetism **27**(1), 2014, pp. 101–114, DOI: 10.1007/s10948-013-2274-5.
[31] Yan-bin Chen, Chao Zhang, Yong-yuan Zhu, Shi-ning Zhu, Nai-ben Ming, *Tunable photonic crystals with superconductor constituents*, Materials Letters **55**(1–2), 2002, pp. 12–16, DOI: 10.1016/S0167-577X(01)00610-3.
[32] Aly A.H., Sang-Wan Ryu, Heng-Tung Hsu, Chien-Jang Wu, *THz transmittance in one-dimensional superconducting nanomaterial-dielectric superlattice*, Materials Chemistry and Physics **113**(1), 2009, pp. 382–384, DOI: 10.1016/j.matchemphys.2008.07.123.
[33] Srivastava S.K., Upadhyay M., Awasthi S.K., Ojha S.P., *Tunable reflection bands and defect modes in one-dimensional tilted photonic crystal structure*, Optics and Photonics Journal **2**(3A), 2012, pp. 230–236, DOI: 10.4236/opj.2012.223035.
[34] Suthar B., Bhargava A., *Temperature-dependent tunable photonic channel filter*, IEEE Photonics Technology Letters **24**(5), 2012, pp. 338–340, DOI: 10.1109/LPT.2011.2178401.
[35] Hui-Chuan Hung, Chien-Jang Wu, Shoou-Jinn Chang, *Terahertz temperature-dependent defect mode in a semiconductor-dielectric photonic crystal*, Journal of Applied Physics **110**(9), 2011, article ID 093110, DOI: 10.1063/1.3660230.
[36] Skoromets V., Němec H., Kadlec C., Fattakhova-Rohlfing D., Kužel P., *Electric-filed-tunable defect mode in one-dimensional photonic crystal operating in the terahertz ragne*, Applied Physics Letters **102**(24), 2013, article ID 241106, DOI: 10.1063/1.4809821.
[37] Srivastava S.K., *Electrically controlled reflection band and tunable defect modes in one-dimensional photonic crystal by using potassium titanyl phosphate (KTP) crystal*, Journal of Nanoelectronics and Optoelectronics **11**(3), 2016, pp. 284–289, DOI: 10.1166/jno.2016.1895.
[38] Huiping Tian, Jian Zi, *One-dimensional tunable photonic crystals by means of external magnetic fields*, Optics Communications **252**(4–6), 2005, pp. 321–328, DOI: 10.1016/j.optcom.2005.04.022.

[39] MCPHAIL D., STRAUB M., MIN GU, *Optical tuning of three-dimensional photonic crystals fabricated by femtosecond direct writing*, Applied Physics Letters **87**(9), 2005, article ID 091117, DOI: 10.1063/1.2037862.
[40] CHIEN-JANG WU, MEI-SOONG CHEN, TZONG-JER YANG, *Photonic band structure for a superconductor -dielectric superlattice*, Physica C: Superconductivity **432**(3–4), 2005, pp. 113–139, DOI: 10.1016/j.physc.2005.07.019.
[41] TINKHAM M., *Introduction to Superconductivity*, 2nd Ed., McGraw-Hill, New York 1996.
[42] YEH P., *Optical Waves in Layered Media*, Wiley, New York 1988.
[43] BORN M., WOLF E., *Principles of Optics*, Cambridge University Press, Cambridge 1998.

Received December 21, 2017