OPTICS OF PHOTONIC CRYSTALS AND THEIR POTENTIAL APPLICATIONS

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SUMMARY

Over the past decades, energy storage and high-speed Internet problems are great problems across the globe. Researchers have been working in developing materials for enhancing energy storage and speed-up Internet problems. In the present scenario, 90% of electronic devices are used to resolve these two problems, but researchers are working on the photonic devices, which have no loss and high gain in comparison to the electronic devices. However, the research on optics of photonics at the nano scale is going on theoretically and the fabrication of photonic devices is also going on using different methods and theoretical data. For the development of the photonic devices, we go through the simple concept of optics of the materials for a periodic structure, and the periodic structure of dielectric, metal, semiconductor, plasma, magnetized cold plasma, superconductor, graphene etc. materials called photonic crystals [1-4]. Photonic crystals (PCs) are the periodic arrangement of the binary or ternary dielectric constants with the thicknesses of micro to nanometer scale. If the lattice parameter of the photonic crystal is of the order of the wavelength of light, then light cannot propagate through the photonic crystal for some range of the wavelength is called *Photonic Band Gap* (PBG) [5, 6]. The photonic band gap materials have the great applications in research of the optical engineered materials because photonic band gap can be used to manipulate and control the flow of light or EMW. Therefore, the photonic band gap is a unique property of photonic crystals, which can be used to control the flow of light by adjusting the refractive index contrast, scalability, periodicity, symmetry and unit cell of the binary or ternary periodic materials especially one-dimensional structures, made of the metal, dielectric, semiconductor, plasma, magnetized cold plasma, superconductor material, etc.

The thesis is divided into seven chapters and chapter-wise research works are outline below:

In Chapter 1, we have discussed the history of optics, and how the optics of materials are used to the optics of photonics for the periodic structure of dielectric materials and discussed that what are the main application of the periodic structures in optical

devices. The developments of periodic structure and types of periodic structure have been discussed in detail, and the best applications for the science society have also been elaborated. Our studies have been also shown theoretically that which optics of materials are used for optics of photonics, and the importance of photonics for the best application in the science and technology has been discussed for the fabrication point of view. We reviewed the literature survey and reached on the possible outcome for the development of recent optical sciences for the field of nanoscience and nanotechnology. Nanotechnology is the hot topic for the researchers due to small size, low cost and high durability of material. On the basis of the optical properties of the photonic crystal, we have proposed different applications of the photonic crystals in the direction of science and technology. In this study, we have explained the basic idea of the optics of photonics through the introduction in the thesis in which the chapter included the theories, fabrications, experiments and possible applications of one-dimensional periodic structure.

Chapter 2 is started with Maxwell's equations, which have been used to solve the one-dimensional binary or ternary periodic structure containing dielectric, metallic, semiconductor, plasma, magnetized cold plasma and high temperature superconducting material etc. Using Maxwell's equations, many researchers had developed different methods for all types of photonic crystals where they studied the optical properties of the considered periodic materials including dispersion relations, reflection spectra, transmission, and absorption spectra, which have been discussed in brief [7]. In the entire thesis, we have used the Transfer Matrix Method (TMM) for the study of band structure, transmission, reflection and absorption spectra of one-dimensional periodic structure due to simple formulation for layered periodic materials and this method is equivalent to the Fresnel's law for reflectance and transmittance coefficients [8]. Therefore, we have adopted TMM as the key method for all chapters of the present thesis.

Chapter 3 shows theoretical calculations of the band gap structure and the transmittance of the periodic structure containing dielectric and magnetized cold plasma materials. The band gap structure and the transmittance of the considered periodic structure against frequency (GHz) have been plotted with varying the plasma parameters like external magnetic field (B), electron density (n_e) and effective collision frequency (γ), with lattice period i.e. N=10 and normal incidence angle i.e. $\theta_0=0^0$.

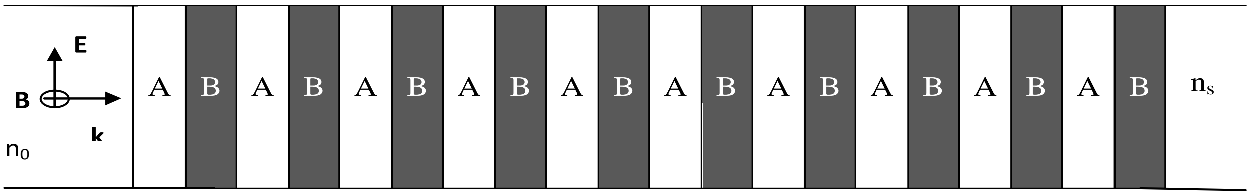


Figure 1: Schematic diagram of dielectric (air) and magnetized cold plasma (MCP) photonic crystal

Plasma is a wide variety of macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules, which exhibits collective behavior due to long-range columbic force, is called *plasma* [9]. The study of wave motion inside plasma in presense of external magnetic field is called magnetized plasma. Here, two cases are occurred first the EM wave inside the internal wave, and second the external wave and electromagnetic (EM) wave incident from outside in the presense of external magnetic field [10].

Each parameter of the magnetized cold plasma has an important role, but the external magnetic field has more important role in the magnetized cold plasma due to positive and negative values of external magnetic field, it acts as right hand and left hand polarizations, respectively. In addition to this, we have calculated all the transmittances corresponds to the band gaps for the dielectric having refractive index $n_A = 1$ (air) and thickness $d_A = 12\text{mm}$, and the refractive index of the magnetized cold plasma has been taken from Ref. [11] and thickness of magnetized cold plasma layer is chosen $d_B = 15\text{mm}$ as shown in Figure 1. The periodic structure of the air/right hand polarization and air/left hand polarization is called right hand polarization and left hand polarization structures, respectively.

A tunable narrow band filter and multichannel filter for right hand polarization structure have been proposed in which the tunable narrow band filter and multichannel filter properties are found in the increased value of the magnetic field of the magnetized cold plasma, and a broadband reflector or high pass filter has been proposed in which the reflector or filter property is found for the left hand polarization structure at low value of the magnetic field of the magnetized cold plasma.

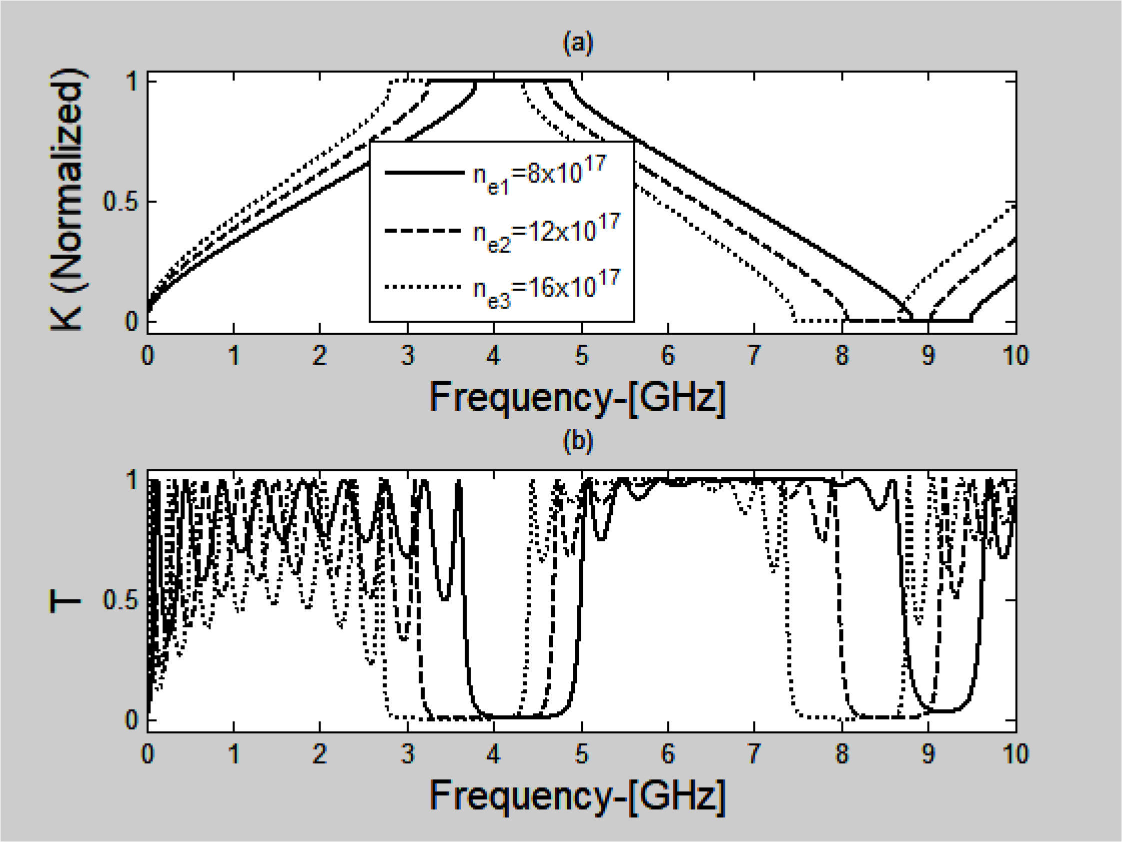


Figure 2: (a) Dispersion relation and (b) Transmittance versus frequency plots with varying plasma density of the magnetized cold plasma for right hand polarization.

Besides this, we have theoretically proposed a design of tunable narrow band filter for right hand polarization structure with different values of electron density of magnetized cold plasma. The width broadband reflector and high pass filter for left hand polarization structure are increased with an increase in the value of electron density of magnetized cold plasma. On the basis of our calculated results of the periodic structure with right hand polarization and left hand polarization structure, we investigated a new idea for formation of the broadband reflector and narrow tunable filter at lower and higher frequency ranges. Thus, this analysis may be useful in the design of tunable photonic devices that are to be controlled by changing the parameters of the magnetized cold plasma, as shown in Figures 2 and 3.

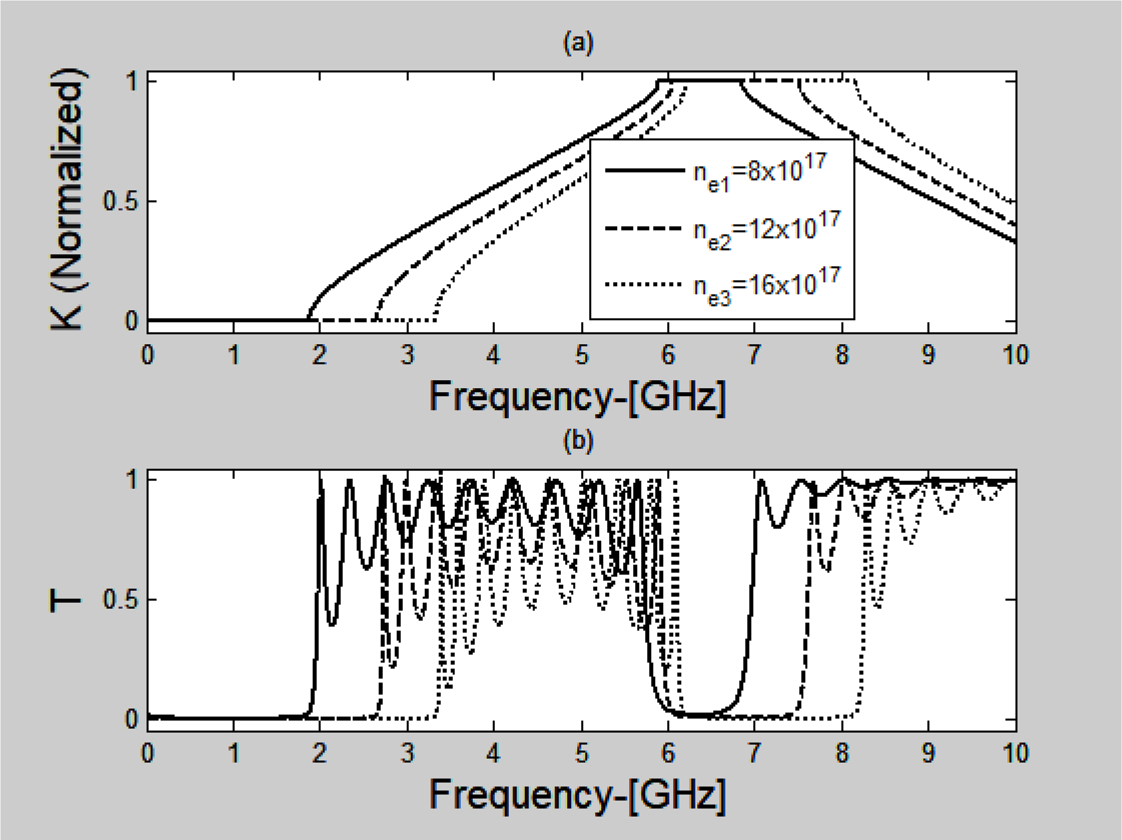


Figure 3: (a) Dispersion relation and (b) Transmittance versus frequency plots with varying plasma density of the magnetized cold plasma for left hand polarization

In the Chapter 4, the optical properties of one-dimensional ternary photonic crystal composed of alternating dielectric, magnetized cold plasma, and superconducting material have been studied theoretically using simple transfer matrix method [8]. As we know that the magnetized cold plasma demonstrates the right-hand polarization and the left-hand polarization in the considered photonic crystals are obtained by changing the direction of the magnetic field only i.e. positive/negative values of the magnetic field [11]. The applied transverse magnetic field also changes the permittivity of the superconducting material and magnetized cold plasma. Due to simple fabrication of the one-dimensional (1-D) photonic crystal, the transmittance of the right-hand polarization and the left-hand polarization 1-D ternary photonic crystal against frequency (GHz) have plotted by varying most valuable parameters: the angle of incidence, the magnetic field, the electron density of magnetized cold plasma, the temperature of superconductor, and the thicknesses of magnetized cold plasma and superconducting materials. The transmittance studies of the right-hand polarization and the left-hand polarization 1-D ternary photonic crystal give an informative idea for optical applications in filters.

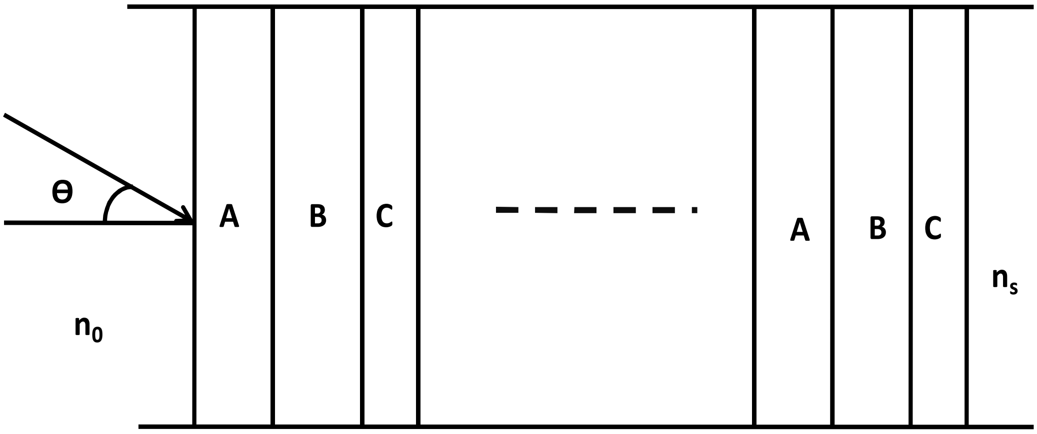


Figure 4: Schematic diagram of a ternary periodic structure with dielectric (A), magnetized cold plasma (B) and superconductor (C)

As shown in the Figure 4, the ternary photonic crystal is $(ABC)^N$ where A, B, and C represent the air, the magnetized cold plasma and superconducting material ($YBa_2Cu_2O_7$) with critical temperature T_c=92K, and the operating temperature T=4.2K respectively. The thickness of the A, B, and C materials are 18mm, 18mm, 80nm, respectively. The refractive indices of layer A, B, and C are $n_A=1$, $n_B=\sqrt{\varepsilon_B\mu_B}$, $n_C=\sqrt{\varepsilon_C\mu_C}$ respectively [11, 12]. The periodicity of the lattice (N) is taken three periods i.e. N=3.

Transmittance of the one-dimensional ternary photonic crystal with varying most valuable parameters: the angle of incidence, the magnetic field, the electron density of the plasma, the temperature of superconductor and the thickness of the magnetized cold plasma and superconducting material have been discussed. Firstly, we have calculated the transmittance of the considered structure with varying the angle of incidence for the right-hand polarization and left-hand polarization structure.

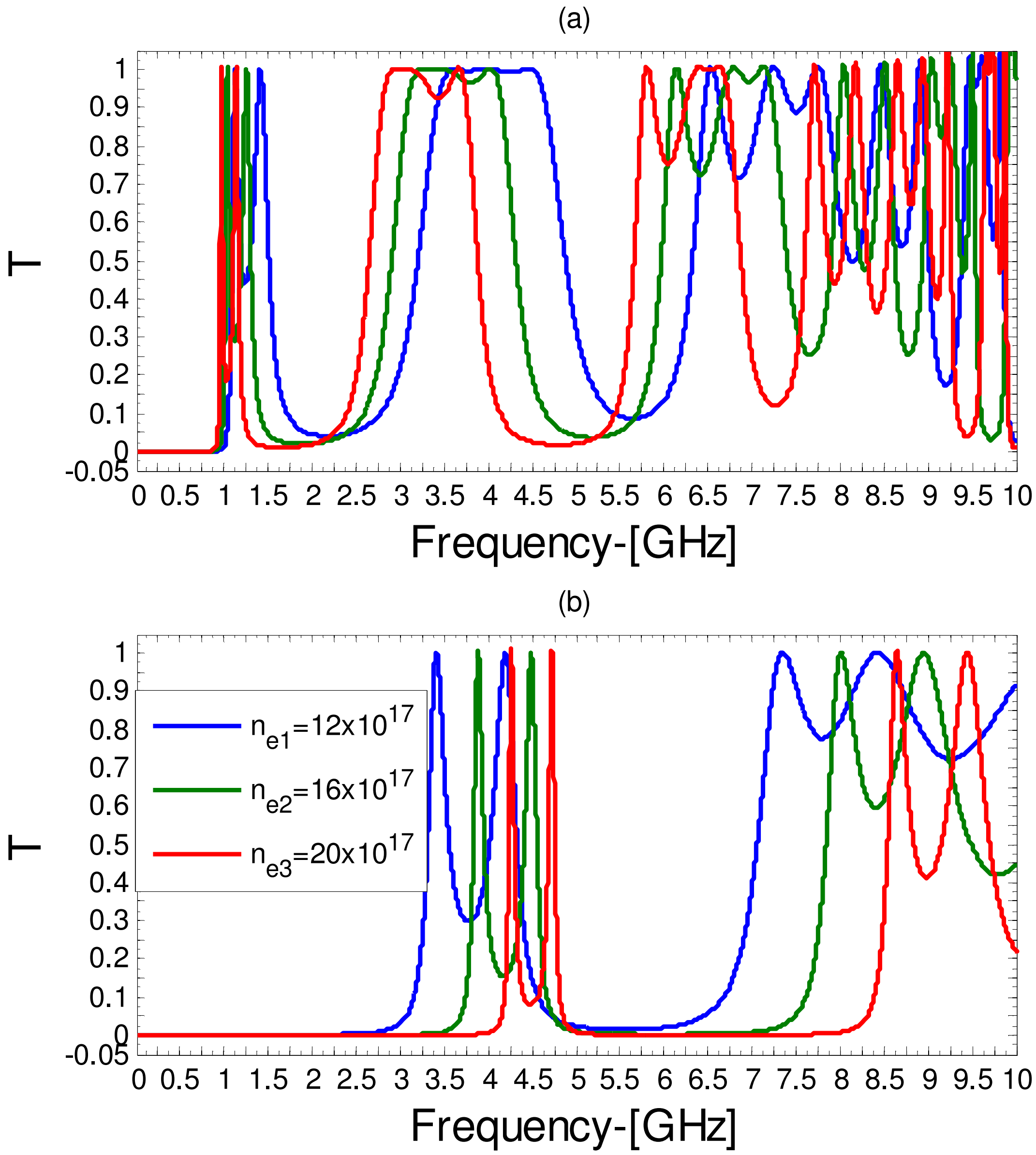


Figure 5: Shows the transmittance versus frequency with varying electron density of magnetized cold plasma for (a) right hand polarization structure and (b) left hand polarization structure

The transmittance of the considered ternary photonic crystal against frequency (GHz) with thickness d_A=18mm, refractive index n_A=1 (air), incident angles $\theta = 0^0$ external magnetic field B=0.4T, effective collision frequency of magnetized cold plasma $\gamma=1x10^7$ GHz, transition temperature of high temperature superconductor ($YBa_2Cu_2O_7$) T_C=92K and operating temperature T=4.2K [13] with varying plasma density $n_e=12x10^{17}/m^3$, $n_e=16x10^{17}/m^3$, $n_e=20x10^{17}/m^3$ have been studied as shown in

Figure 5. The transmittance of the dielectric/magnetized cold plasma/high temperature superconducting material based space ternary photonic crystal against frequency (GHz) with varying the angle of incidence, the magnetic field, the electron density of the magnetized cold plasma, the temperature of superconductor and the thickness of the magnetized cold plasma for the right hand polarization/the left hand polarization structure have been discussed.

The optical properties of the right-hand polarization and the left-hand polarization ternary photonic crystal are affected by the effective parameters of the magnetized cold plasma and the superconducting material. Transmittance against frequency (GHz) with variation of plasma density $n_e=12x10^{17}/m^3$, $n_e=16x10^{17}/m^3$, $n_e=20x10^{17}/m^3$ found better results for left hand polarization as comparable to right hand polarization as shown in Figure 5. The transmittance of the left-hand polarization ternary photonic crystal has been found with better results compared to the transmittance of the right-hand polarization ternary photonic crystal due to the presence of the superconducting layer that is influenced by the temperature and the magnetic field itself. The large band gap of the left-hand polarization ternary photonic crystal may be used as the broadband reflector or high pass filter applications. The superconducting layer has played the important role to form the band gap of the ternary photonic crystal. On the basis of our calculated results, we have proposed an innovative idea to design the broadband reflector or the high pass filter and the narrow tunable filter of the ternary photonic crystal containing the magnetized cold plasma and the superconducting material under certain the transverse magnetic field and the operating temperature.

Chapter 5 shows the analyzed transmittance characteristics of symmetric and asymmetric 1-D periodic structures of zinc sulfide (ZnS) and titanium dioxide (TiO_2). Based on the Transfer Matrix Method (TMM), transmittance of considered periodic structure has been analyzed by inserting the one and two plasma layers in symmetric structure. The parameters for ZnS material are taken as $\varepsilon_A = 6.25$, $\mu_A = 1$, $d_A = 0.0188\,\mathrm{mm}$; and for TiO_2 material are taken as $\varepsilon_B = 5.05$, $\mu_B = 1$, $d_B = 0.0375\,\mathrm{mm}$ [14-17]. The parameters for magnetized cold plasma material are taken from Ref. [11].

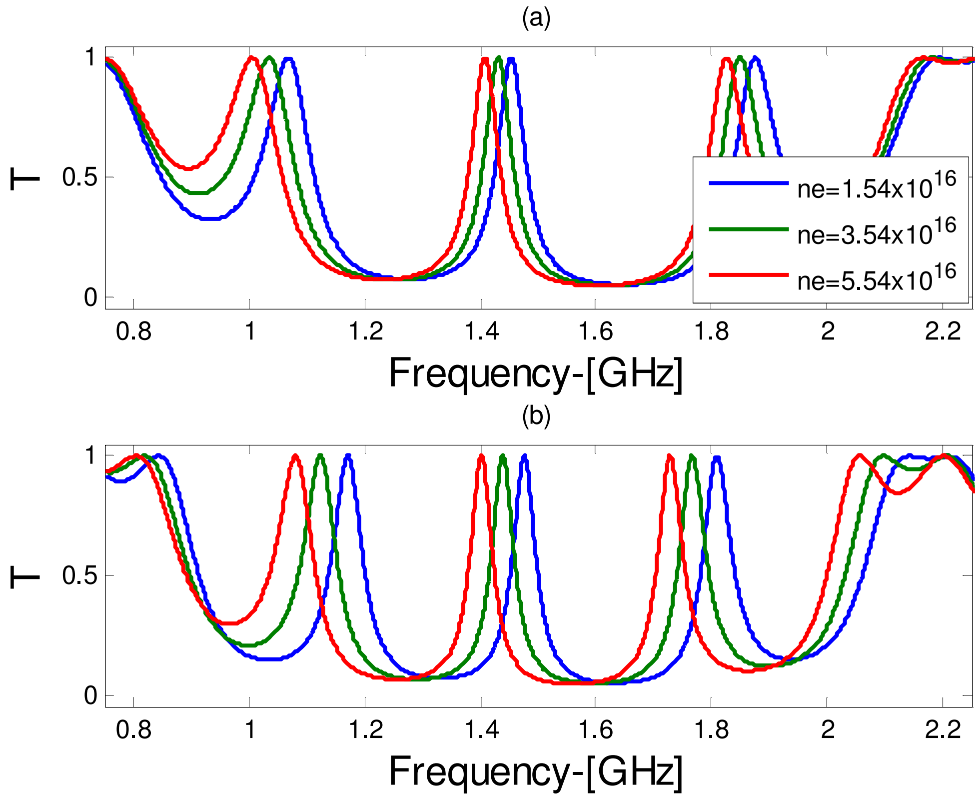
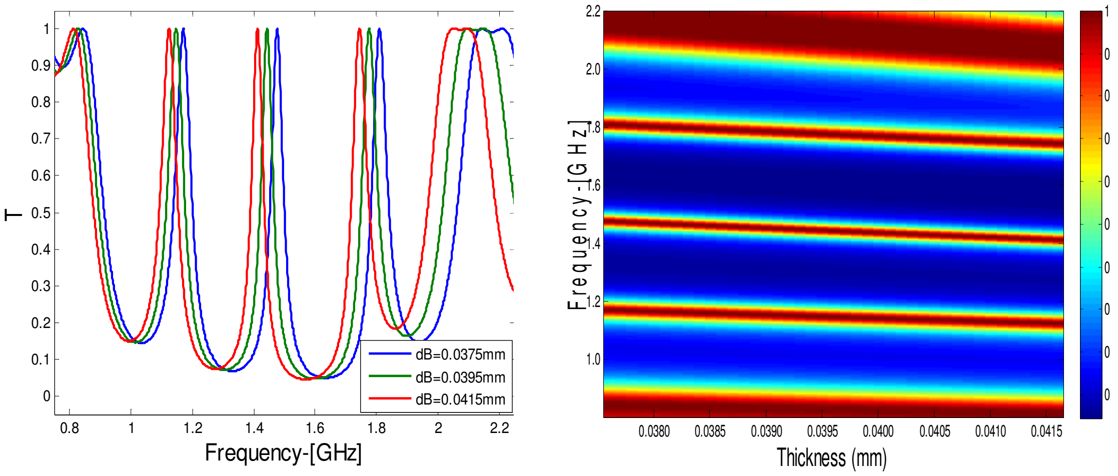


Figure 6: Transmission spectra versus normalized frequency of the one dimensional periodic structure of ZnS and TiO_2 with varying $n_e = 1.54\times10^{16}, n_e = 3.54\times10^{16}, n_e = 5.54\times10^{16}/m^3$ for (a) one defect layer of magnetized cold plasma, (b) two defect layers of magnetized cold plasma



(a) (b)

Figure 7: (a) Transmittance versus frequency with variation of thickness of TiO_2 material (b) 2D image plot of frequency versus variation of thickness of TiO_2 material

A detailed analysis of the transmittance of asymmetric and symmetric one dimensional periodic structure containing zinc sulfide and titanium dioxide with one or two defect of magnetized cold plasma layer versus frequency (GHz) has been done using Transfer Matrix Method (TMM). The transmittance of the symmetric one dimensional periodic structure containing zinc sulfide and titanium dioxide with one or two defect of magnetized cold plasma layer has been analyzed with variation of incident angles, electron densities, and magnetic field of the magnetized cold plasma material. The transmittance of two MCP layer inserted in symmetric periodic structure with variation of electron density of plasma as well as thickness of ZnS and TiO_2 material found better response as comparison to one layer defect of magnetized cold plasma in same periodic structure as shown in Figures 6 and 7. These calculated results suggested that the proposed structure is a simple and innovative idea to fabricate the tunable multichannel filter at microwave region.

In Chapter 6**,** we have discussed the optical constant of the hyperbolic meta-material, and the optical property of the ternary periodic structure. The permittivity, perpendicular and parallel, of hyperbolic meta-material against normalized frequency $\left(\frac{\omega}{\omega_p}\right)$ have been theoretically analyzed by varying filling fraction, electron collision frequency. The filling fraction $\left(f = \frac{d_{plasma}}{d_{HM}}\right)$ is the specific property of Hyperbolic Meta-material (HMM). The hyperbolic material is a composite material and the electric permittivity of the HMM shows an anisotropic property. In our case, we have been considered the hyperbolic material that is the composite material of dielectric and plasma materials.

We have considered the ternary periodic structure containing hyperbolic meta-material, which is composed with of dielectric (air) and plasma material [18, 19]. The HMM has $d_{HM} = d_{plasma} + d_{die(air)} = 2mm$ and $f = \frac{d_{plasma}}{d_{HM}}$ with a thickness of the plasma material $d_{plasma} = 0.2mm$, plasma frequency $\omega_p = 28.4 \times 10^9$ [20]. The dielectric of the air is $\varepsilon_{die(air)} = \mu_{die(air)} = 1$. The permittivity of hyperbolic material varies along perpendicular and parallel directions. As we know that the hyperbolic material property is purely depending upon the dispersion relation of relative permittivity. The dispersion relation shows that the product of perpendicular and parallel permittivity is less than zero then the dispersive curve shows the hyperbolic behavior having the metallic behavior $\left(\varepsilon_{\perp}\varepsilon_{\parallel} < 0\right)$. On the other hand, the dispersion relation shows that the product of perpendicular and parallel permittivity obtains greater than zero; the dispersive curve shows dielectric behavior $\left(\varepsilon_{\perp}\varepsilon_{\parallel} > 0\right)$. We have plotted the relative permittivity against normalized frequency and it shows the hyperbolic behavior for the parallel and perpendicular permittivity in a particular range of the frequency, which can be predicted in Figures 8 and 9.

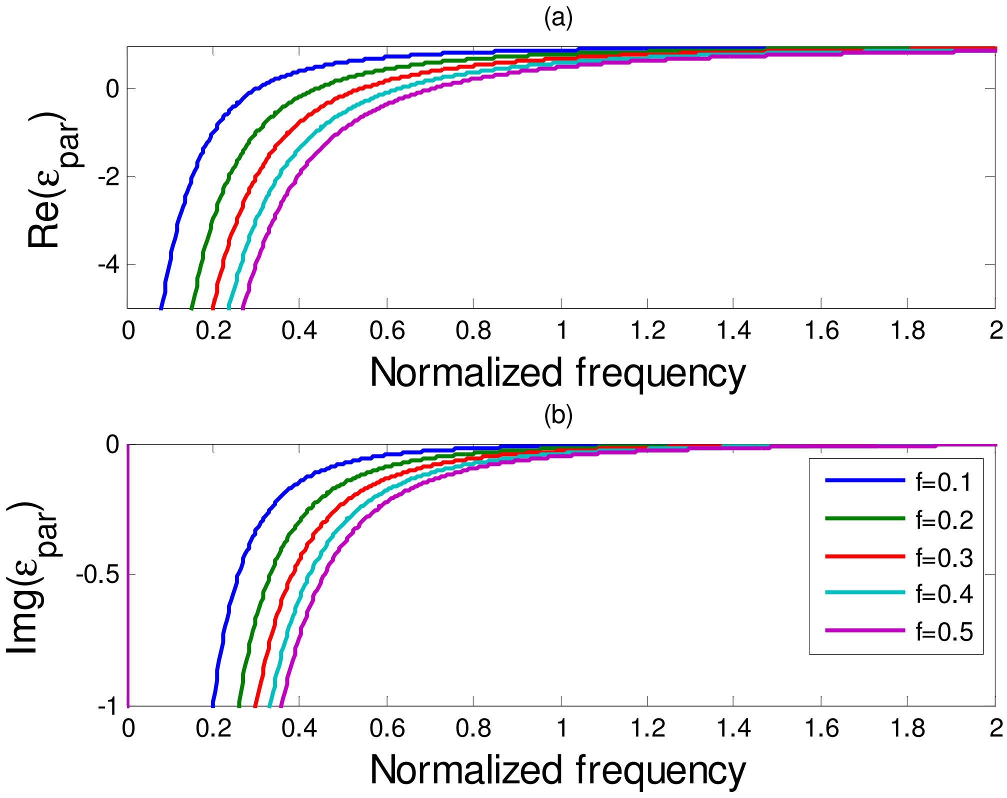


Figure 8: (a) Real part of $\varepsilon_{\parallel}$ for different value of filling fraction against normalized frequency, (b) Imaginary part of $\varepsilon_{\parallel}$ for different value of filling fraction versus normalized frequency

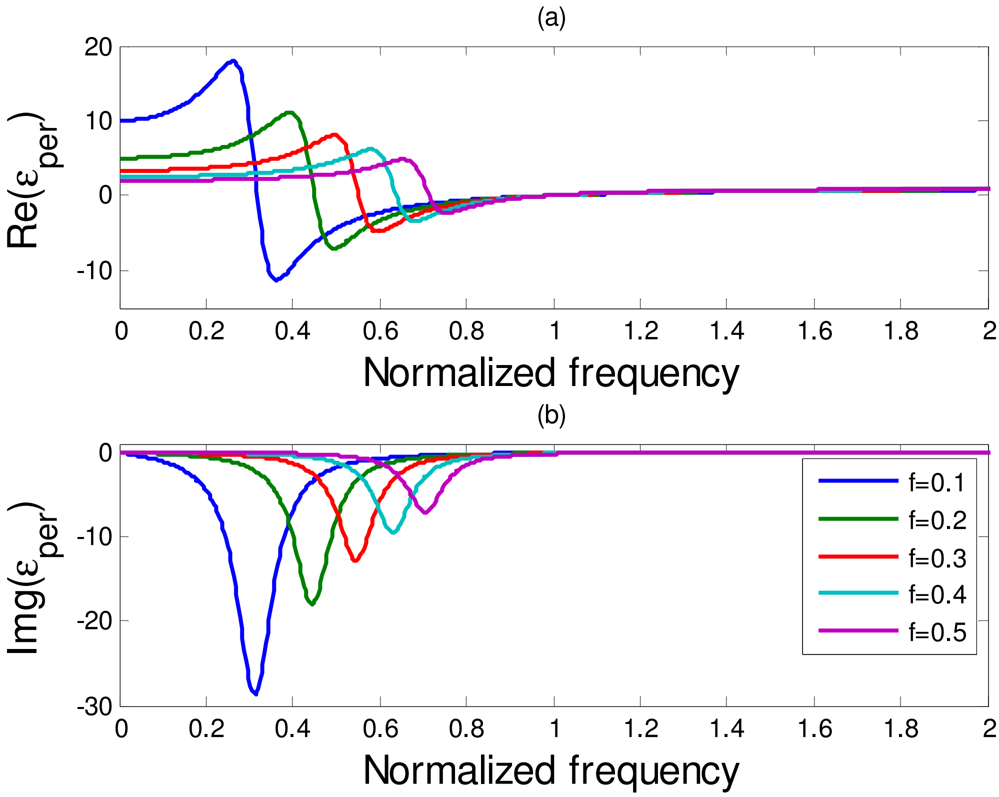


Figure 9: (a) Real part of $\varepsilon_{\perp}$ for different value of filling fraction against normalized frequency, (b) Imaginary part of $\varepsilon_{\perp}$ for different value of filling fraction against normalized frequency

A detailed discussion on the parallel and the perpendicular permittivity of hyperbolic meta-material has been made theoretically with the variation of filling fraction and effective collision frequency. The study shows that the real part of the parallel and the perpendicular permittivity of hyperbolic meta-material have been found with the metallic and the dielectric behaviors at certain frequency range. Using these concepts of the hyperbolic meta-materials, the absorption of one-dimensional ternary periodic structure containing dielectric, silicon dioxide and hyperbolic material have been studied with varying incident angle, filling fraction, electron collision frequency as well as the thicknesses of dielectric (A) material. All absorption properties have been calculated by using the well-known simple transfer matrix method.

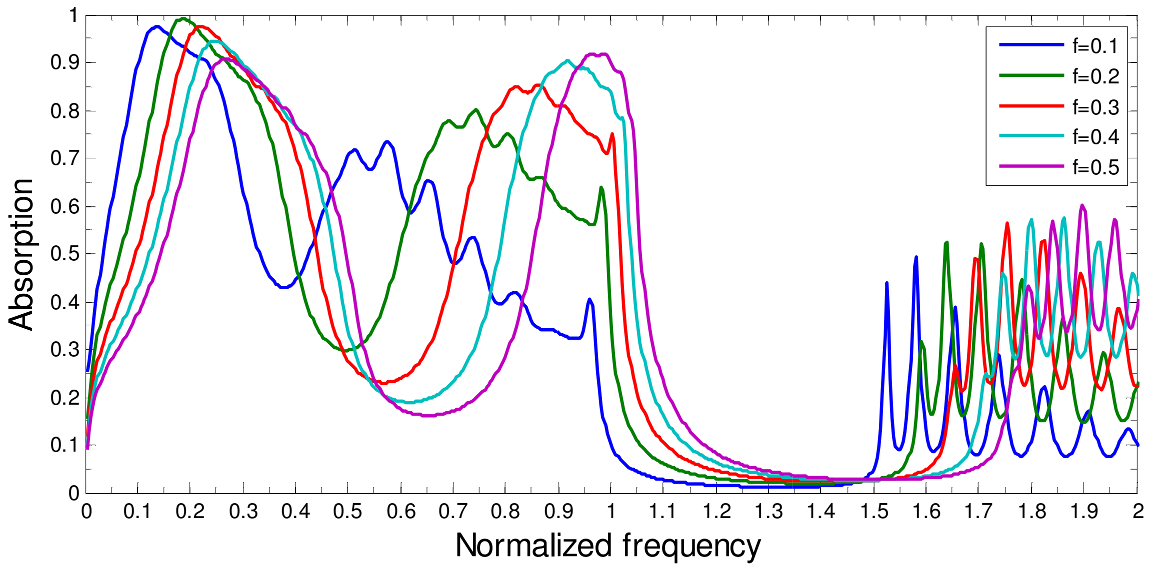


Figure 10: Absorption of multilayer structure at different value of filling fraction against normalized frequency

In these calculations, we have calculated the absorption of the considered structure with varying the angles of incidence (θ) and shown the maximum absorption at $\theta = 80^0$. The study shows that nearly 100% tunable absorption has been found due to the metallic nature of effective permittivity of the hyperbolic material. The absorption of ternary periodic structure against normalized frequency with variation of filling fraction f=0.1, f=0.2, f=0.3, f=0.4, and f=0.5 found nearly 100% at certain frequency as shown in the Figure 10. The study of the absorption property of the ternary periodic structure containing hyperbolic materials are very innovative results to design the optical switch, logic gate, sensor as well as the absorber at microwave region.

Chapter 7 summarizes the work done in the whole thesis and outlines the conclusion and future prospects of the thesis.

Conclusion and the scope of further research work

In this thesis, we have studied the optics of materials and the optical properties of periodic structures, especially one-dimensional, and their potential applications. These calculations of the one-dimensional periodic structure containing dielectric, metal, semiconductor, plasma, magnetized cold plasma and superconductor have been performed theoretically to achieve the research works for productive and efficient optical devices. For the understanding of the role of the magnetic cold plasma (MCP) in the periodic structure, we have considered the periodic structures of the MCP with other materials: dielectric, metal, superconductor and semiconductor. The study includes incorporation of the recovery aspects into the application of optical science and technology:

- Wave optics is one of the oldest divisions of optics but today exponentially growing optical coating technology in the field of thin-film optics is a necessary feature of the practical branch of optics. The feasibility of the thin films of the materials by optical coating technology may enhance the study of photonic materials.
- The electromagnetic wave interacts with single layer of refractive index. The wave reflects and refract due to its optical properties of the material. This optics of the materials is used to formulate the optics of photonics especially one-dimensional photonic crystals.
- The optics of one-dimensional photonic crystal is used as the optical filter, which is based on the interference of a thin film of the two different dielectric materials. The photonic crystal exhibits a unique property is called photonic band gap, which is analogous to the electronic band gap. One-dimensional photonic crystals are already used in wide spread applications in the form of thin-film optics from low and high reflection coating on lenses and mirrors. Besides this, one-dimensional photonic crystal is also used to change the colors of paints and inks.
- The cold plasma materials are used for fabricating very potential optical photonics devices because such material has variable parameters which can change the property of the material when it is interacted with the electromagnetic wave.
- The superconducting material at room temperature is very exciting material for photonic device fabrication. Our studies show that the superconducting photonic crystal may be useful for excellent filter applications.
- The symmetric periodic structure with two defect of cold plasma has the multichannel filter properties and the fabrication of the device may be used in optical computing devices.
- Recently, conversional electric devices are replaced by photonic devices. But the photonic devices are based on optoelectronic devices. So, it is necessary to study the new material which can replace the electron with photon. It is only

possible if we study the hyperbolic meta-material having large absorption may be useful in metatronic devices.

For the advancement of the optical thin film coating and their potential applications in the various devices, the study of the optical property of the one-dimensional photonic crystals with different materials becomes the very popular topic in the thin-film technology because the fabrication/synthesis of the optical devices based on thin films may require these calculated data which are obtained in the study of the optical property of one-dimensional photonic crystals containing dielectric, metal, semiconductor, plasma, magnetized cold plasma and superconductor. Therefore, the studies of the optics of materials and the optics of photonics are to be the best concepts, which may be used to fabricate the optical devices that may fulfill the requirement of the huge data storage and the high-speed Internet.

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LIST OF PUBLICATIONS

Part of the thesis published and communicated in the refereed journals:

1. **Asish Kumar**, N. Kumar and K. B. Thapa, Tunable broadband reflector and tunable narrowband filter of a dielectric and magnetized cold plasma photonic crystal, Eur. Phys. J. Plus 133 (2018) 250-8. https://doi.org/10.1140/epjp/i2018-12073-3
2. **Asish Kumar**, K. B. Thapa and S. P. Ojha, A tunable broadband filter of ternary photonic crystal containing plasma and superconducting material, Ind. J. Phys. 93(6) (2018) 791-798. DOI: 10.1007/s12648-018-1335-9
3. **Asish Kumar**, K. B. Thapa, Multichannel filter application of a magnetized cold plasma defect in periodic structure of ZnS/TiO_2 materials, Opt. Quant. Electron 51(11) (2019) 355-14. https://doi.org/10.1007/s11082-019-2070-y
4. **Asish Kumar**, K. B. Thapa and A. K. Yadav, Enhancement of absorption property of one-dimensional ternary periodic structure containing plasma based hyperbolic material for the application of microwave devices, J. Mag. Mag. Mater 93 (2019)165371-9. https://doi.org/10.1016/j.jmmm.2019.165371
5. **Asish Kumar**, N. Kumar, G. N. Pandey, D. Singh and K. B. Thapa, Metamaterial-plasma based hyperbolic material for sensor, detector and switching application at microwave region, J. Phys.: Cond. Matt. 32 (2020) 325701-13. DOI: 10.1088/1361-648X/ab858f
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region, AIP Conf. Proc. 2220(1) (2020) 020068-4. https://doi.org/10.1063/5.0002138

10. **Asish Kumar**, K. B. Thapa, N. Kumar and Anil K. Yadav,” Tunable Broadband Reflector in a One-Dimensional Meta-Photonic Crystal with Symmetrically Introduced Magnetized Cold Plasma as Defect” book chapter “Advances in Photonic Crystals and Devices”, CRC Press, Taylor & Francis USA (2019). DOI: 10.1201/9781351029421-9
11. N. Kumar, A. K. Poonia, **Asish Kumar**, K. B. Thapa, G. N. Pandey, B. Suthar, Analysis of the impact of graphene coating on reflectivity of a silicon substrate for optoelectronic devices, AIP Conf. Proc. 2220(1) (2020) 020038. https://doi.org/10.1063/5.0001390
12. **Asish Kumar**, P. Singh, K. B. Thapa, Study of super absorption properties of 1-D graphene and dielectric photonic crystal for novel applications, revised in Opt. Quant. Electron 2020. (Communicated)