

A REVIEW ON ADVANCEMENTS OF MAGNETO-PHOTONIC CRYSTALS**Rajeev, M.T. Beig**

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Abstract: Photonic crystals (PCs) that include magnetic constituent materials or even just a magnetic flaw display highly distinctive optical and magneto-optical capabilities. In present review article, we examined the research on photonic crystals (PCs), also known as photonic band gap materials, which are 1D, 2D and 3D superstructures with periods that are comparable to the wavelengths of electromagnetic radiation of magnetic constituents. The inclusion of magnetically arranged components is the fundamental attribute of this new type of PCs with external magnetic field. Further, we discussed with details about theoretical, simulation, and experimental developments in magneto-photonic crystals research. After that, we reviewed how photonic crystals came to exist with historical development in the field of ferrite photonic crystals.

Keywords: Photonic Crystal, Photonic Band Gap, Magneto optics, Ferrite Photonic Crystal

Introduction

Novel artificial materials photonic crystals (PhCs), Metamaterials, Nonlinear optical Metamaterials, optical Metamaterials incorporating gain media, graphene, chiral optical metamaterials, and plasmonics) allow the development of unique electromagnetic (EM) capabilities previously unattainable in natural materials. In the last 10 years, these materials, referred to as MMs below, have been at the forefront of scientific study. There has been an incredible amount of innovation in recent years, and more is on the way.

Clearly, the field of PhCs and metamaterial has the potential to develop game-changing technologies for a wide range of applications involving light control, including telecommunications, solar energy harvesting, biological and THz imaging and sensing, optical isolators, nanolasers, quantum emitters, wave sensors, switching and polarizers, and diagnostic imaging and sensing for the medical field. solar energy harvesting, biological and THz imaging and sensing, optical isolators, nanolasers, quantum emitters, wave sensors, switching and polarizers, and diagnostic imaging and sensing for the medical field. But before the extraordinary potential of MMs, particularly in the area of optics, can be realised in practical applications, a number of critical difficulties need to be overcome. PhCs are EM media that are periodically structured and feature periodic refractive index variation on a length scale similar to the wavelength of the EM wave concerned (Joanpolous et al. 2008). A characteristic feature of EM wave propagation in such media is the existence of PBGs, i.e., a range

of frequency spectrum for which, in the ideal case, the propagation is strictly inhibited. The geometrical arrangement of the PhCs, the particular geometry of the elements inside the PhCs, and their sizes determine the frequency domain and the breadth of the PBGs (Joanpolous et al. 2008). It also depends on the separation between the components and the contrast in refractive indices of the materials used to make the PhCs. Depending on the periodicity in the dielectric contrasts/refractive index, the PhCs may be categorized as 1D, 2D, or 3D. If the refractive index variation the PhCs is periodic in one direction and homogeneous along other two directions, the crystals are termed as 1D PhCs (Figure. 1.1). The example is Bragg stack or Bragg reflector, where there are alternate layers with various refractive indices.

In such structure, the PBGs are not complete, i.e., it appears for specific angle of incidence. When the PBGs are "full," they exist for all polarizations and incidence angles of the EM waves (Joanpolous et al. 2008).

The 1D PhCs is simple in nature and may be easily fabricated, which is basic advantage. Moreover, 1D PhCs are used as selective filters in thermo-photovoltaic applications (Mostafa et al. 2012). In 2D PhCs (Figure. 1.1), the periodicity in refractive index extends to two directions, and one direction is homogeneous in nature. Any feasible incidence angle of EM waves travelling in the periodicity plane may cause it to display PBGs.

The 2D PhCs structures onto silicon wafers have been used to improve the performance of silicon based photovoltaic cell (Dominguez et al. 2013). Examples of 2D PhCs are Dielectric rods are placed in a periodic arrangement in air or the silicon substrate with etched holes. In 3D PhCs (Figure 1.1), the structure has periodicity of refractive index in all three directions. It may possess PBGs for any propagation direction. In face-centered cubic structures, complete PBGs can be produced. The propagation of specified frequencies and orientations of EM waves is prohibited in the presence of PBGs. This property gives the PhCs a great foundation for engineering the material's properties for optical control and manipulation.

Naturally occurring stone, opal is a good example of 3D PhCs. It shows different colors caused by the number of microspheres positioned at the cubic lattice's face-centered nodes, when viewed at different angle.

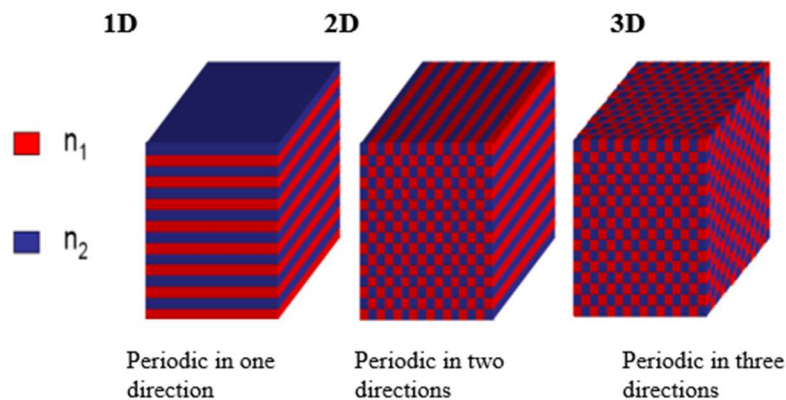


Figure 1.1: Diagram showing 1D, 2D and 3D PhCs structures

The propagation of the wave in the 1D periodic medium consisting of periodic multilayer stack was discussed by Lord Rayleigh in 1887. In his study, he demonstrated the presence of the allowed and spectrum of the wave with band gaps (Rayleigh 1887). In 1987, about 100 years later, Eli Yablonovitch (Yablonovitch 1987; John 1987) and predicted the complete PBGs in 3D PhCs. Now, both physicists are now considered as the founders of this field. In 1990, K. M. Ho et al. demonstrated the presence of PBGs in the PhCs using computational technique (Ho. et al. 1990). The first experimental PBGs in the microwave region demonstrated by E. Yablonovitch and his coworkers in 1991 (Yablonovitch et al. 1991). This material was named as “Yablonovite”, and was able to restrict the propagation of microwaves in all three directions and possess complete PBGs. Thereafter, scientists explore the presence of PBGs in near infrared spectrum of EM waves also (Grüning et al. 1995). Later on, the field of photonics research has exponential growth in the terms of publications. Most of the novel applications of PhCs like preventing spontaneous emission, localization of light, unidirectional mirrors with high reflection and little wave loss, PhCs based cavity, designing of band edge laser, micro-scale light circuits, optical multiplexers or de-multiplexers, wave-guiding, super-prism phenomenon (Guida et al. 2003) etc. are based on the presence of PBGs in the EM wave spectrum. So, it is necessary to understand the basic concepts behind the formation of PBGs. Therefore, the next section is devoted to understand of physical origin of PBGs.

2. Why Photonic Crystals have Photonic Band Gaps

The physical origin of the PBGs may be demystify by the considering the EM wave propagation in 1D PhCs structure as shown in figure 1.2 (1). The physical origin of the PBGs in 1D PhCs is based on the multiple reflection/refraction of EM waves from each boundary/interface. To fully understand the origin of PBGs in 1D PhCs structure, let us assume that the considered 1D PhCs structure has periodic arrangement of dielectric slab (coloured slab) and air (white region). The width of dielectric slab and air satisfy quarter wave stacking condition. It is believed that a typical incident EM wave with wavelength (λ) struck the building. The incident EM wave is partly refracted and partly reflected at each interface. Let us assume that the structure has PBGs for wavelength λ . In this case, all the reflected waves from each interface satisfy Bragg condition (Yablonovitch et al. 2001), hence are in phase. They interfere constructively and reinforce to each other (Figure 1.2 (2)). When they superpose with incident EM wave, a standing wave pattern is formed. This standing wave pattern is not allowed to propagate through the structure (Figure 1.2(3)).

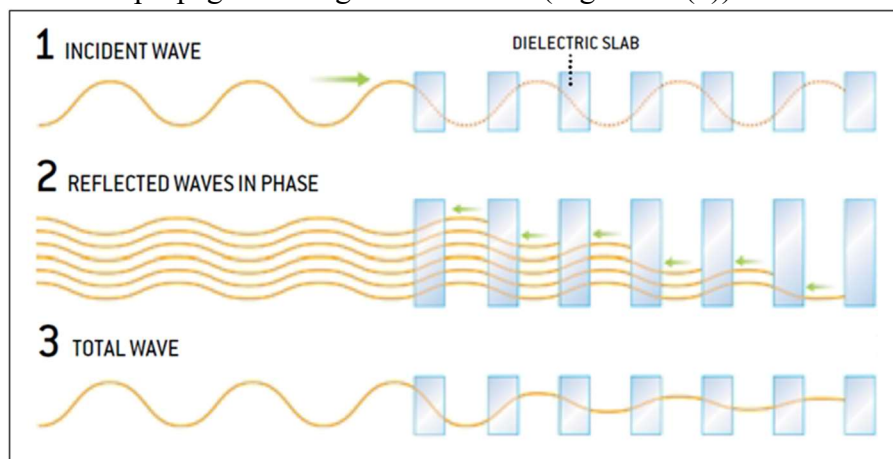


Figure 1.2 EM waves propagation in 1D PhCs whose wavelength lie in the PBGs [Yablonovitch (2001)].

If the wavelength of the incident EM wave does not exist within the PBGs of considered 1D PhCs structure, then again there are reflections/refractions each interface. For this wavelength, the Bragg condition does not satisfy (Figure 1.3(2)). The back reflected waves from each interface are out of phase and hence interfere destructively. When they superpose with incident EM wave, it is transmitted through the structure with slightly attenuated amplitude as shown in (Figure 1.3(3)).

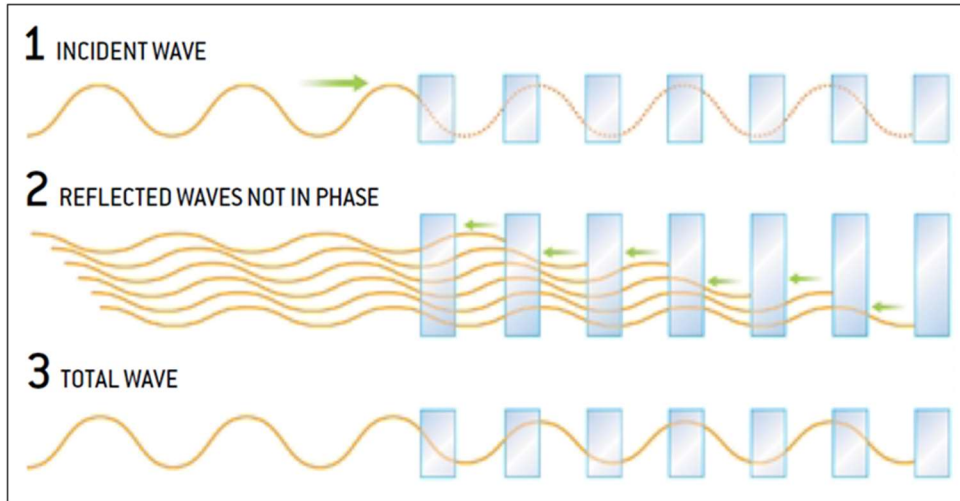


Figure 1.3 EM waves propagation in 1D PhCs whose wavelength does not lie in the PBGs [Yablonovitch (2001)].

The existence of PBGs in 2D PhCs can be explained on the same line as described for 1D PhCs structure whenever a regular EM wave strikes the structure. A portion of this electromagnetic wave produces forward and backward waves, and a distinct portion is diffracted in various directions. When a new set of discontinuities interfere with the forward electromagnetic wave, the process is repeated. Depending on the geometrical and physical characteristics of the structure, viz. the refractive index, radius of holes/cylinders, and lattice periodicity, EM waves may interfere with each other. The reflectance of EM wave increases while the transmittance decreases, and hence PBGs can be created. Similar phenomenon occurs in the case of 3D PhCs structures. It is found that the width of PBGs in PhCs structures depend on the refractive index contrast. For normally incident EM waves, the edges of the PBGs centered at frequency ω_0 occur at $\omega_0 \pm \Delta\omega$ where

$$\frac{\Delta\omega}{\omega_0} = \frac{2}{\pi} \sin^{-1} \left(\frac{n_{high} - n_{low}}{n_{high} + n_{low}} \right) \quad (1.1)$$

where n_{high} and n_{low} are refractive indices of high index and low index materials in the 1D PhCs. Here, width of PBGs is independent of EM wave polarization (Lekner 2000). For obliquely incident EM waves, the edges of the PBGs and the reflectivity of the structure become polarization dependent.

3. Brief Overview of Magneto-Photonic Crystals

3.1 Theoretical Developments in Magneto-Photonic Crystals

M. Inoue et al. made theoretical investigation of Magneto optical (MO) effects in 1D multilayer stack consisted of magnetic materials and air gaps called magneto-photonic crystals (MPhCs) in 1996 for the first time (Inoue et al. 1996). They explored the dispersion properties and polarization states of EM waves and found that apparent Faraday spectra of the multilayer structure vary to a large extent from those of a continuous medium depending strongly on multilayer structure. Using a random matrix technique, the MO characteristics of silicon dioxide (SiO₂) and bismuth-substituted yttrium iron garnet (Bi:YIG) films that are layered in a random order are examined (Inoue et al. 1997). Periodic multilayer films are unable to achieve the increase of Faraday rotation angle, which is approximately seven times more than that of a single Bi: YIG film. In instance, at $\lambda = 1.15 \mu\text{m}$, the film's Faraday rotation angle reaches a high of $1.4^\circ/\text{m}$. These investigations overwhelmingly suggest that films with a sizably significant MO impact may be produced even if the film structure only partially satisfies the so-called 1D PhCs. In 1998, Inoue et al. obtained a enormous Faraday rotation angle to $-280^\circ/\mu\text{m}$ at $\lambda = 1.15 \mu\text{m}$ in 1D PhCs made of dielectric films like SiO₂ and TiO₂ and yttrium iron garnet films replaced with bismuth. In these structures, the MO interaction occurs in the central Bi:YIG film, which is sandwiched between two dielectric multilayers serving as the light reflection layers. A 1D semiconductor-based MPhCs made of hybrid GaAs:MnAs and GaAs/AlAs distributed Bragg reflectors was created by H. Shimizu et al. At a regulated wavelength and at ambient temperature, these structures displayed a considerable MO effect augmentation (Shimizu et al. 2001). Theoretically, Kato et al. demonstrate that the isolator properties (reflectance $R > 99$ percent and Kerr rotation angle $= 45^\circ$) may be readily satisfied when the 1D MPhCs are operated in reflection mode. One single, thin magnetic garnet sheet makes up the whole construction. The usual multiplayer architectures of 1D MPhCs consist of two types of SiO₂ and Ta₂O₅ dielectric films and a Bi substituted YIG (Bi:YIG) film. According to theoretical calculations performed by Kato et al. in 2002, the 1D MPhCs can operate at double- and triple-cavity multi-cavity structures and simultaneously achieve very high transmittance of 100 percent and very large Faraday rotation of 450, both of which can be utilised in optical isolators. H. Kato et al. looked at how absorption affected the ability of a 1D MPhCs film made of SiO₂, Ta₂O₅, and thin layers of rare-earth iron garnet to isolate. By adopting a high refractive index material like Si, the structure of a 1D MPhCs film with adequate optical isolation has an industrially advantageous structure.

Additionally, it was discovered that an optical isolator's features were unaffected by a film's optical absorption (extinction coefficient), which had to be less than 0.000001. (Kato et al. 2003). Two geometries—Faraday and Voigt—were used to study the band structure of the model 2D MPhCs. We demonstrate that, in the case of Faraday geometry, the optical activity eliminates degeneracy from the PBGs structure and lowers the system's symmetry. Additionally, it is discovered that the dispersion at band boundaries is extremely susceptible to outside magnetic effect (Khanikaev et al. 2005).

According to research by I.L. Lyubchanskii et al., a change in the direction of light propagation inside MPhCs has a significant impact on the transmittivity and Faraday rotation angle. We address potential uses of MPhCs as Faraday rotators (Lyubchanskii et al. 2006). A. M. Merzlikin and

colleagues investigated a unique class of Tamm states that exist at the interface between a 1D MPhC built of MO material and a material with naturally occurring anisotropy that is subject to external magnetic field control (Merzlikin et al. 2007). In elliptically birefringent MPhCs, M. Levy et al. developed analytical formulas for the band structure and Bloch modes. Gyrotropy and linear birefringence, which are frequently present in MO thin-film devices, were modelled for their effects. Their formulation allows for alternating birefringence from one layer to the next and is applicable to layers of any thickness and elliptical birefringence level. Investigation is done into the transmission properties of a two-defect MPhC with regard to obliquely incident EM waves for both circularly and linearly polarised EM waves (Levy et al. 2007). The magnetic super prism effect, which occurs when an external magnetic field causes a very significant deviation of a light beam in PhCs, has been proven in 1D MPhCs by A. M. Merzlikina et al (Merzlikina et al. 2008). S. V. Eliseeva and colleagues evaluated the effects of magnetic fields on the reflection spectra of periodic layered defect-free magnetic-dielectric structures and magnetically active defects sandwiched between dielectric PhCs mirrors. A considerable reconstruction of the spectrum in the frequency domain is produced when the magnetic resonance frequency is near to the centre frequency of one of the PBGs or the frequency of the defect mode. In particular, it can result in the suppression of the oscillation spectrum and the defect mode, allowing for effective spectrum control of such a structure by an external magnetic field (Eliseeva et al. 2013). In 1D MPhCs at Bloch surface wave resonance, M. N. Romodina et al. examined numerically and experimentally the spectrum dependency of the Faraday rotation angle. They discovered a Fano-type Faraday rotation spectrum, which is brought about by the connection of the p-polarized waveguiding modes of the MPhCs and the s-polarized BSW (Romodina et al. 2017). W. Guangbin et al. investigated the polarisation characteristics of the defect mode in MPhCs made of gyrotropic material using the 4×4 transfer matrix approach. The polarisation of the incident light, the strength of the applied magnetic field, and the thickness of the magnetised material are found to have a substantial impact on the location of the defect mode (Guangbin et al. 2017). For MPhCs, A. H. Gevorgyan et al. provided a straightforward geometric method to compute Bragg frequencies and the perimeters of banned bands. The suggested approach works almost identically for low values of modulation depths, but at high levels, there is a slight variance (Gevorgyan et al. 2018).

3.2 Experimental Developments in Magneto-Photonic Crystals

M. Inoue et al. fabricated two types of 1D MPhCs dielectric and magnetic materials make up viz. $(\text{SiO}_2/\text{SiN})_K/\text{Co}/(\text{SiN}/\text{SiO}_2)_K$ K number of layers and $(\text{SiO}_2/[\text{Ta}]_{205})_K/\text{Bi:DyIG}/([\text{Ta}]_{205}/\text{SiO}_2)_K$ for the first time in 1999. They showed that these structures have distinctive optical and MO features, such as a significant increase in Kerr and Faraday rotations that appeared to originate from the localization of light near the magnetic layers (Inoue et al. 1999). S. Sakaguchi et al. looked into the layer stacking structure in relation to the transmission characteristics of multilayer films made of MO and dielectric materials. These fundamental structures have improved Faraday rotation in films. Additionally, it is noted that when the rotation of these films increases, the transmittance decreases (Sakaguchi et al. 1999). A 1D MPhCs with a magnetic layer of Co-ferrite sandwiched between two dielectric multilayer reflectors with a $(\text{SiO}_2/\text{TiO}_2)_7$ structure was created

by E. Takeda et al. The Fabry-Perot resonator's structure was studied because the resonance peak is regulated by an external magnetic field (Takeda et al. 2000). A magneto-optic spatial light modulator powered by an electric field in $(\text{Pb}(\text{Zr}_{0.52}\text{Ti}_{0.48})\text{O}_3)$ was created and tested by J-H. Park et al. The stress field created by the PZT film in this modulator lowers the anisotropy energy of the structured garnet film, allowing for simple switching of the pixels with or without the external bias field (Park et al. 2003). In 1D MPhCs made of $(\text{Ta}_2\text{O}_5/\text{SiO}_2)_9/\text{Bi:YIG}/(\text{SiO}_2/\text{Ta}_2\text{O}_5)_9$ and $(\text{Si}/\text{SiO}_2)_3/\text{Bi:YIG}/(\text{SiO}_2/\text{Si})_3$, H. Kato et al. demonstrated that the multilayer structure's Faraday rotation angle was more than 150 times greater than that of a Bi:YIG single-layer film (Kato et al. 2004). The MO characteristics of 3D MPhCs based on synthetic opals were experimentally researched and manufactured by A. V. Baryshev et al. They have shown that magnetic materials created in opal lattice gaps exhibit normal magnetic characteristics in the composites (Baryshev et al. 2004). According to S. Kahl et al., a 1D MPhCs made up of 17 heteroepitaxial layers of yttrium iron garnet and bismuth iron garnet was prepared and characterised. At the design wavelength of 750 nm, the MO Faraday rotation increased by 140% but transmission fell by just 16% as compared to a single-layer bismuth iron garnet film of the same thickness (Kahl et al. 2004).

The perfect three-port circulators with total isolation and transmission were suggested by Z. Wang et al. using an optical circulator made of a MO cavity in a 2D PhCs. It was demonstrated that this cavity could be built to support a pair of counter rotating states at different frequencies (Wang et al. 2005). MOPhCs have been used by V. I. Belotelov et al. to regulate EM radiation in integrated-optics devices (Belotelov et al. 2005). According to M. Levy et al. studies of the intermodal coupling in PBGs optical channels in magnetic garnet films, the nonreciprocal polarisation rotation can be accelerated (Levy et al. 2006). A. G. Zhdanova and colleagues proposed a novel method for enhancing the Faraday effect in 1D magnetic PBGs structures by spatially localising light with a wavelength that corresponds to the PBGs edge (Zhdanova et al. 2006).

According to M. Inoue et al. description of the 1D, 2D, and 3D MPhC preparations, magnetic defects are surrounded by high photon confinement, which causes a significant amplification of the media's linear and nonlinear MO responses. Additionally, they have roused novel functionalities in these structures, including the magnetic super-prism effect, non-reciprocal or magnetically controlled photonic band structure, and band Faraday effects (Inoue et al., 2006a; 2006b).

Focused-ion-beam (FIB) milling was utilised by X. Huang et al. to create multimode Bi-substituted iron garnet film waveguides with single-defect PhCs structures. Multiple stop-bands and a sizable polarisation rotation were seen (Huang et al. 2006). M. Inoue et al. reported using localised surface plasmon resonances in bismuth-substituted yttrium iron garnet (Bi:YIG) films impregnated with Au nanoparticles to create different nano-structured media and nano-composites to improve the MO response (Inoue et al. 2008).

At the junction of magneto-photonic and PhCs, surface states that are spatially confined have been the subject of experimental experiments by T. Goto et al. Strong light coupling to the magnetic components of the MPhCs is responsible for the significant augmentation of the Faraday rotation for

the wavelength of the optical Tamm state that was seen in this structure (Goto et al. 2009). In order to better understand the optical and MO characteristics of 3D MPhCs made of magnetite Fe₃O₄ implanted in an opal film matrix, V. V. Pavlov et al. In the spectral region where the MO effect flips its sign, they discovered remarkable alterations in hysteresis curves and their dependency on photon energy (Pavlov et al. 2009).

By utilising a defect layer, K. H. Chung et al. developed reflection type MPhCs to improve the MO property of MO spatial light phase modulator. The MO property of the structure was demonstrated experimentally to be approximately 25 times greater than that of a single garnet film (Chung et al. 2010). K. Nakamura et al. discussed how MPhCs were used to create a 3D MO spatial light modulator. The MPhCs were used to reconstruct 3D pictures, and the results reveal a notable improvement in brightness with less power usage (Nakamura et al. 2016). The 3D MPhCs were created by S. Mito et al. utilising electro-less plated maghemite. At 440 nm, the faraday rotation was demonstrated with considerably lower absorption than magnetite (Mito et al. 2017).

3.3 Numerical Studies & Simulation in Magneto-Photonic Crystals

In their investigation of the MPhCs and its nonreciprocal characteristics, A. Figotin et al. discovered that the layered spatial structure of the MPhCs produces asymmetry in the dispersion properties as a result of unidirectional wave propagation. The MO crystals exhibit unusual propagation characteristics in the form of frozen mode (Figotin et al. 2003). The various forms of 1D MPhCs structures were improved by M. Vasiliev et al. for usage in MO visualizers, sensors, and on boosting the magnetic and MO sensitivity in sensor-type applications. When compared to the case of single layer MO sensing films, they discovered a considerable improvement in the sensitivity of devices (Vasiliev et al. 2008). Using a finite difference time domain (FDTD) technique, R. Nishino et al. modelled the effects of propagating and reflected EM on the surface-layer MO. They discovered that when the surface layer's dielectric constant was low, the polarisation rotation angle of the reflected electromagnetic wave rose with frequency and peaked right below the second PBGs (Nishino et al. 2009). In order to prevent counterfeiting and for applications such as tagging, tracking, and locating objects, P. Sun et al. created and simulated photonic paint, which is composed of 3D metallic tilted woodpile PhCs implanted into a visible and infrared transparent polymer film. To confirm the location or contents of a package, these crystal formations offer a distinctive reflected infrared optical signature that may be seen and recorded (Sun et al. 2012). Devices, including as isolators, circulators, and crossing waveguides, were created by L. Zhang et al. on the basis of 2D MOPhCs. With the use of the finite element approach, dispersion, mode distributions, and the transmission spectrum were examined (Zhang et al. 2013). Using 3D methodologies, L. Shuangbao et al. simulated the axial propagation of EM waves in 2D YIG-based MPhCs. On the polarisation of the output EM waves, the impacts of the lattice's filling rate, structure, incoming light's wavelength, and the external magnetic field were studied. A particular structure with a 25% filling rate, 1.2m wavelength, and 2m lattice constant was tuned for a satisfactory MO response in defect-free MPhCs (Shuangbao et al. 2017).

3.4 Historical Development in Field of Ferrite Photonic Crystals

Ferrites, which can be made from various metal oxides as well as iron oxides like hematite (Fe_2O_3) or magnetite (Fe_3O_4), are typically non-conductive ferrimagnetic ceramic compounds. Like the majority of other ceramics, ferrites are hard and brittle. Since ferrite compounds are comprised of iron oxide, they are quite inexpensive. It also has very good corrosion resistance. In microwave frequency domain, it has extremely low conductivity (typically from 10^{-6} to 10^{-4} mho per meter for ferrites as compared to 107 mho per meter for iron). Due to this, EM wave can penetrate much deeper in ferrite medium without much reflection or attenuation. Thus, EM wave has an opportunity to interact with electron inside ferrite. These interactions results into various reciprocal and non-reciprocal effects produced (Baden et al. 1989). M. M. Sigalas and colleagues investigated how magnetic permeability affected PBGs. It is observed that when the dielectric constant and the magnetic permeability acquire their maximum values in the same material, PBGs disappear. The PBGs maximize when dielectric constant and the magnetic permeability acquire their maximum values in the different materials (Sigalas et al. 1997). E. Takeda et al. fabricated a 1D MPhCs consisting of couple of dielectric multilayer reflectors with ($\text{SiO}_2/\text{TiO}_2$) structure with magnetic layer of Co-ferrite as defect working as a Fabry- Perot resonator. They found that the Faraday rotation was enhanced by 5.4 times (Takeda et al. 2000). M. J. Steel et al. investigated the enhancement of MO rotation in periodic magnetic garnet thin-film stacks with defects. It is found that high transmission with high rotation per unit length is possible using double defects (Steel et al. 2000). M. Levy et al. analyzed theoretically the flat-top transmission and Faraday rotation characteristics of 1D MPhCs in cerium-substituted YIG with multiple defects in the optical band-gaps. Also, 7nm transmission bands are predicted, which is improvement over previously predicted band width for MPhCs (Levy et al. 2001). N. Dib et al. calculated the propagation parameters of cylindrical transmission lines incorporating magnetised ferrite material using the FDTD approach.

To investigate the relationship between the MO characteristics and the localization effect of light, H. Kato et al. theoretically and experimentally studied the properties of multilayers including bismuth-substituted YIG and dielectric films (SiO_2 & Ta_2O_5). They used the symmetrically periodic structure $(\text{Ta}_2\text{O}_5/\text{SiO}_2)_n/\text{Bi:YIG}/\text{SiO}_2/\text{Ta}_2\text{O}_5)_n$, where n is the number of repetitions, and discovered that the multilayer structure with $n = 6$ had a Faraday rotation 150 times greater than that of a Bi:YIG single-layer film.

The characteristics of MO defect states in 2D PhCs were examined by Z. Wang et al. The splitting of doubly degenerate TE states into two counter-rotating modes at various frequencies is found to occur as a result of MO coupling. Additionally, the degree of spatial overlap between the modal fields' cross product and the cavity domain structures substantially influences the intensity of MO coupling (Wang et al. 2005). Using a periodic lattice of gold-wire pairs, (Linden et al. 2006) created 1D MPhCs for the first time. Each pair in the unit cell may be thought of as a magnetic coil with two slits, which stands in for a magnetic atom. They discovered that a nearby dielectric slab waveguide achieves high coupling between the resultant magnetic-dipole resonance and the Bragg resonance, leading to an avoided crossover at near-infrared wavelengths. In ferrite-piezoelectric bi-layers, G. Srinivasan et al. investigated the microwave magnetoelectric interactions. They discovered that when

an electric field is applied to a bilayer, the piezoelectric deforms mechanically, causing a shift in the frequency or magnetic field of the ferrite's ferromagnetic resonance absorption spectra (Srinivasan et al. 2006).

A 1D MPhCs based on the ferrite magnetic periodic multilayered structure was the subject of experimental and theoretical investigations by S. V. Chernovtsev et al. Experimental tests are conducted to verify the predictions of the phenomenological description of this crystal in the millimetre waveband (Chernovtsev et al. 2007). (Grishin et al. 2008) looked into the characteristics of garnet-based MPhCs and discovered that these structures may be utilised to customise significant Faraday rotations and acceptable transmittance from the visible to the infrared. In a structure made by periodically stacking ferrite and semiconductor layers, O. V. Shramkova et al. investigated the characteristics of TE wave propagation. They studied the transmission spectra and dispersion properties of obliquely encountered EM waves on such structures (Shramkova et al. 2009). The reflectance spectra of PhCs filled with ferrites were examined by V. S. Gorelik and colleagues. They discovered that under magnetization, the reflectance of the manufactured MPhCs rises by up to 80%. (Gorelik et al. 2009). R. Antos et al. used the plane wave expansion approach by complicated Fourier factorization to model the photonic band structure of a 2D MPhCs made up of Bismuth substituted yttrium iron garnet rods organised in square lattice (Antos et al. 2009).

To improve the MO property of the magneto-optic spatial light phase modulator, K. H. Chung et al. developed reflection type MPhCs with defect layer. Theoretical simulations clearly showed that raising the repetition number k , or the number of dielectric layers, can improve Kerr rotation (Chung et al. 2010). S. Y. Liu and colleagues investigated the characteristics of the meta-material-based magnetically controlled unidirectional EM wave-guiding devices. In a geometrically symmetric magnetic meta-material system, they observed a severely asymmetric reflection that results from the coupling of EM waves to magnetic surface plasmon resonance states and the broken time reversal symmetry in meta-materials. They created a unidirectional EM waveguide, a wave bender, and a beam splitter based on their models, and these devices have the advantages of being resistant against significant defects and disorder and controllable by an external magnetic field (Chung et al. 2010). H. J. El-Khozondar looked into the characteristics of TE surface waves in a slab of ferrite that was encased in metamaterials. They quantitatively examined how various meta-material factors, such as the thickness of the ferrite slab and others, affected the dispersion properties of TE surface waves (El-Khozondar et al. 2010).

The transient study of MPhCs with lossy ferrite was modelled by G. Singh et al. utilising a productive complex envelope alternating-direction-implicit FDTD technique. They discovered that the suggested strategy may be achieved in a relatively brief manner using just a few straightforward right-side phrases. The suggested method's effectiveness is verified and contrasted with the explicit FDTD (Singh et al. 2011).

Fan et al. investigated the characteristics of silicon FPhCs with magnetic tunability for terahertz

circulator. They discovered that the direction of external magnetic fields affects the tenability of the PBGs spectrum. They created a magnetically adjustable circulator with a maximum isolation of 65.2 dB and a central working frequency that can be set between 180 and 205 GHz. Additionally, their additional research revealed that the transmission and isolation properties of this device are significantly impacted by the gyrotropy, dispersion, and ferromagnetic loss of ferrite materials under the various external magnetic fields. Additionally, they discovered that this circulator is adaptable enough to accomplish controlled splitting, routing, filtering, and isolation capabilities by altering the external magnetic field for THz applications (Fan et al. 2012).

Experimentally, R. Kekesi et al. created the 3D MPhCs using a silica composite made of cobalt ferrite nanoparticles and organised as an inverse opal, and they discovered that transmittance measurements reveal a combination of PBGs and the absorption of the nanoparticles. They discovered that these band gaps' centres correspond to the starting spheres' diameters via the Bragg law, and they used a Faraday effect hysteresis loop to show that the non-reciprocal MO effect occurs in inverse opals (Kekesi et al. 2013). M. F. Ubeid and colleagues used numerical analysis to determine how well EM waves were reflected and transmitted via FPhCs. The reflection and transmission coefficients are determined using TMM in a closed form after problem creation. These coefficients are used to determine the FPhCs' reflected, transmitted, and lost powers. When the damping coefficient varies, the aforementioned powers are calculated and displayed in the numerical results as a function of frequency, incidence angle, dielectric layer width, and applied magnetic field strength (Ubeid et al. 2014).

According to research by J. W. Kos et al., the system comprises of alternating layers of TiO₂ and SiO₂ that make up finite-size dielectric PhCs and are periodically dispersed dielectric magnetic slabs of YIG. They discovered that at the GHz and PHz frequency ranges, this structure possesses both magnonic and PBGs. According to their findings, the PBGs of the structure under consideration are extremely sensitive to the incident angle and polarisation of EM waves. This information can be used to design devices that can operate simultaneously in the near-infrared and optical regimes for EM waves in photonic applications (Kos et al. 2014). Na. Zhu et al. examined the characteristics of the PhCs waveguide with broad bandwidth, compact size, and varied design of the waveguide structures. With PhCs coupled-cavity waveguides infused with ferrite magnetic fluid, this structure was created to increase delay-bandwidth (Zhu et al. 2015). A tunable left-handed material made up of a variety of plasma and ferrite layers was the subject of an investigation by H. Mehdian et al. on its optical and MO characteristics. They discovered that a homogeneous composite's effective index of refraction is negative at a particular frequency. Additionally, the frequency, the external magnetic field, and the electron density of the plasma layer all affect how large the extremum of the negative effective refraction index is. They discovered that the frequency range where the system exhibits the left-handed behaviour has a significant Faraday rotation angle (Mehdian et al. 2015). K. Bi et al. used simulations and tests to examine the characteristics of the ferrite-dielectric meta-material made up of cuboids of ferrite and dielectric material. They discovered that the metamaterial's effective permittivity may be modified by the applied magnetic field, allowing for the creation of tunable microwave devices. Additionally, when a certain magnetic field is supplied, the ferromagnetic

precession of ferrite cuboids can affect the electric Mie resonance of the dielectric cuboids (Bi et al. 2015). The cerium-substituted YIG was used as a defect layer in the MPhCs that T. Yoshimoto and colleagues created and then examined for characteristics. This structure can function in the near-infrared wavelength range, which might be a significant advancement for future device applications (Yoshimoto et al. 2016). The optical bistable structure based on a single graphene layer sandwiched between two MO layers that are positioned between two PhCs was proposed by A. G. Ardakani et al., and its characteristics were investigated. Their research suggests that this type of structure exhibits optical bistability characteristics in the near infrared range that are effectively regulated by relatively modest external magnetic fields of less than 1.5 mT. (Ardakani et al. 2017).

Using the FDTD approach, J.-X. Liu et al. looked at the characteristics of ferrite photonic crystal filters that are magnetically controlled. They discovered that left- and right-handed circularly polarised waves are two different types of Eigen propagation modes that result from electromagnetic waves propagating in anisotropic ferrite material. They also discovered that the MPhCs with bias magnetic fields to the left and right hand circular waves generate distinct pass bands and band gaps, which may yield various polarised wave patterns. Additionally, by altering the bias magnetic field, which may be utilised to create a magnetic control filter, the PhCs' pass band and prohibited band can be obtained (Liu et al. 2017).

Theoretically, biased ferrite and a magnetically opaque media can interact to form a unidirectional surface mode that occurs in the bulk medium's frequency gap, as shown by S. A. H. Gangaraj et al (Gangaraj et al. 2017). For structural optimization and the computation of tensor elements of the anisotropic medium, C. Umamaheswari et al. employed the finite element method. They discovered that the ferrite post put at the joint's centre may enable non-reciprocal transmission of electromagnetic waves together with high calibre isolation and low insertion loss. Additionally, this optimised device has strong technical compatibility for chip-level integration into photonic integrated circuits and can perform the functions of routing, splitting, and isolation (Umamaheswari et al. 2017). Using the 3D FDTD approach, J. Liu et al. simulated the axial propagation of EM waves in 2D YIG-based MPhCs. They investigated how polarisation of the output EM waves was influenced by structure, lattice filling rate, incoming EM wave wavelength, and the external magnetic field. When a specific degree of polarisation was maintained, it was found that a significant Faraday rotation could be achieved in a short propagation distance and employed in MO modulation devices (Liu et al. 2017).

As a result of the interaction between the s-polarized Bloch surface wave and the MPhCs' p-polarized wave guiding modes, M.N. Romodina et al. discovered that the Fano-type Faraday rotation spectrum they saw in a 1D MPhC at the Bloch surface wave resonance is caused by this. The spectral splitting and relative positions of the modes influence the resonance's form (Romodina et al. 2017). R. Ali et al. used a plasma medium sandwiched between two ferrite sheets to research the characteristics of TE surface waves. They discovered that there are two propagation areas surrounding a gap for each thickness. For larger values of effective wave index, the lower area of propagation becomes

independent of the thicknesses for some fixed value of frequency, in contrast to lesser values of effective wave index where the propagation gap rises as thickness lowers (Ali et al. 2018). The study on the 2D PhCs ferrite and plasma-based polarization-independent circulator was conducted by (Xi et al. 2018). The results of their studies show that for both polarizations, the insertion loss and isolation for the polarization-independent circulator are less than 0.15 dB and more than 20 dB, respectively.

4. Conclusion

In this article, we reviewed the research on PCs, formation of band gap, photonic band gap materials that are comparable to the wavelengths of electromagnetic radiation of magnetic constituents. The last section covered the theoretical, modeling, and experimental advancements in magneto-photonic crystal research as well as the history of photonic crystals and the Field of Ferrite Photonic Crystals.

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