Observation of wavelength-dependent shift in Brewster angle in 3D photonic crystals

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Abstract
The interaction of polarized light with photonic crystals exhibits unique features due to its sub-wavelength nature on the surface and the periodic variation of refractive index in the depth of the crystals. Here, we present a detailed study of polarization anisotropy in light scattering associated with three-dimensional photonic crystals with face centered cubic symmetry over a broad range of wavelength and angle. The polarization anisotropy leads to a shift in the conventional Brewster angle defined for a planar interface with certain refractive index. The observed shift in Brewster angle depends strongly on the index contrast and lattice constant. Polarization-dependent stop gap measurements are performed on photonic crystals with different index contrasts and lattice constants. These measurements indicate unique stop gap branching at high-symmetry points in the Brillouin zone of the photonic crystals. The inherited stop gap branching is observed for TE polarization whereas it is suppressed for TM polarization as a consequence of the Brewster effect. Our results have consequences in the scattering of polarized light from plasmonic structures and dielectric meta-surfaces and are also useful in applications such as nanoscale polarization splitters and lasers.

Keywords: metamaterials, diffraction and scattering, photonic crystals

(Some figures may appear in colour only in the online journal)

1. Introduction
The polarization of light is a peculiar property that is inherited from the vectorial nature of the wave equation that governs the propagation of light in material media [1]. The polarization of light is defined as the orientation of the associated electric (or magnetic) field with respect to the plane of incidence. It is possible to decompose the polarization of incident light into two orthogonal components and discern the optical properties on this basis. When the electric field is oriented perpendicular to the plane of incidence, it is called transverse electric (TE) polarization, and when it is oriented parallel, it is called transverse magnetic (TM) polarization. The reflectivity and transmittance of light at a planar interface are described on the basis of the angle and polarization state of the incident light. A set of equations can be derived for the reflection and transmission coefficients by satisfying the boundary conditions for electric and magnetic fields at the interface. This set of equations, specified according to the angle of incidence (θ), the polarization state of light and the difference in refractive index, are known as Fresnel equations [2]. These equations suggest that the reflectivity increases with increasing θ for TE-polarized light. However, in the case of TM polarization, the reflectivity decreases first, reaches a minimum value at a certain value of θ, and thereafter it increases. It is interesting to note the zero reflectivity for TM polarization at particular value of θ known as the Brewster angle (θB), which depends on the ratio of the refractive indices of the two materials. The predictions of the Fresnel equations have been proved subsequently in many isotropic materials, which has resulted in many applications in the design of thin-film filters, multi-channel filters, polarizers and Brewster mirror windows [2]. These polarization-dependent optical phenomena have been studied and explored for applications considering smooth planar semi-infinite isotropic dielectric materials [3].

Contemporary research interest in the field of nanophotonics has introduced artificially tailored dielectric materials at the optical wavelength scale called photonic metamaterials.
The Brewster effect was originally interpreted for a homogeneous medium but now there is an inhomogeneity at the material interface that entails a modification in the traditional Brewster law for photonic metamaterials [4, 5]. Recent advances in nano-fabrication techniques show a great possibility in the synthesis of photonic metamaterials with exotic optical properties that are otherwise absent from conventional systems [6]. Photonic crystals are a class of metamaterials wherein the dielectric constant is varied periodically in either two or three orthogonal directions [7, 8]. They are generally characterized by direction- and polarization-dependent frequency gaps known as photonic stop gaps, wherein certain frequencies of light are forbidden to propagate inside the crystal [9]. The stop gap arises due to the Bragg diffraction of light from the crystal planes in the direction of propagation. With a careful design of the crystal symmetry and appropriate choice of refractive indices, direction- and polarization-independent frequency gaps are observed called a photonic band gap [10]. A consequence of a photonic band gap is a rigorous modification of the photon density of states in a finite frequency range, which affects the fundamental properties of light–matter interactions and has applications in nano-lasers [11], quantum electrodynamics [12] and waveguides [13].

Other interesting symmetry-dependent optical processes that occur in two- and three-dimensional photonic crystals are sub-Bragg diffraction [14] and stop gap branching [15–17]. These occur when the incident wavevector passes through certain high-symmetry points in the Brillouin zone of the crystal. Photonic crystals with different symmetry can be synthesized using various approaches such as colloidal self-assembly [18], laser-writing [19] and reactive ion etching [20] methods. Among these, the self-assembly approach is more attractive for the synthesis of a 3D photonic crystal because of its ease of fabrication and affordability [21]. Such 3D photonic crystals using colloids with sub-micron diameters are always assembled in the face centered cubic (fcc) symmetry [22].

The synthesis and optical characterization of 3D self-assembled photonic crystals with fcc symmetry are well documented in the literature [21]. It has been remarked that self-assembled photonic crystals do not exhibit a 3D band gap but rather possess only photonic stop gaps [21]. Recent interest in angle- and polarization-resolved stop gaps has indicated interesting optical effects such as stop gap branching, band repulsion and inhibition of spontaneous emission [23–29]. It has been shown that TE-polarized light interacts strongly with the photonic crystal structure and results in stop gap branching, whereas this is absent for TM-polarized light due to the prevailing Brewster effect [29]. A detailed study of polarization-induced stop gap formation has shown a direction- and wavelength-dependent shift in $\theta_B$ at the stop gap wavelength as compared to its conventional definition [17]. Hence, there is polarization anisotropy in the light scattering in photonic crystals. However, the influence of dielectric contrast and the role of refractive index dispersion on polarization anisotropy are yet to be analyzed.

In the present work, we investigate the role of index contrast and the wavelength dispersion of the material’s refractive index on the polarization anisotropy in photonic crystals. We discuss the shift in $\theta_B$ as a function of index contrast. Further, we elucidate the polarization-dependent stop gap branching for photonic crystals in different spectral ranges and for different index contrasts. The present study will amplify our knowledge about the strong interaction of polarized light with photonic crystals, leading to multiple prospects in photonics and plasmonics. Additionally, the eccentric Brewster effect in sub-wavelength nanophotonic structures has an impact in various applications, giving them a new edge with enticing properties, relevant to the polarization of light.

2. Experimental details

2.1. Sample details

The photonic crystals used in the present work are synthesized using the method of convective self-assembly [18]. A clean glass substrate is placed vertically in a cuvette containing colloidal suspension of appropriate volume and concentration, which is kept inside a temperature-controlled oven for 4–5 days. It is well known that self-assembled photonic crystals grown using sub-micron spheres are always organized into fcc geometry because it is the minimum energy configuration [22]. We have chosen photonic crystal samples made of polystyrene (PS) microspheres of diameter 803 ± 20 nm (sample A) and 287 ± 8 nm (sample B) to study the role of refractive index dispersion in the origin of polarization anisotropy. Also samples are grown using poly-methyl methacrylate (PMMA) microspheres of diameter 286 ± 10 nm (sample C) to study the impact of index contrast on the polarization anisotropy in photonic crystals of similar lattice constant.

2.2. Measurement details

A scanning electron microscope (SEM) is used to visualize the structure of photonic crystals. The SEM image of our photonic crystal exhibits high-quality ordering on the surface as well as in the depth [16]. The surface shows the hexagonal array of microspheres that denotes the (111) plane of a crystal with fcc symmetry [16]. Angle- and polarization-dependent reflectivity measurements are made in the specular reflection geometry using a PerkinElmer Lambda 950 spectrophotometer. The sample is mounted in a way that enables us to access high-symmetry points in the Brillouin zone of the crystal with fcc symmetry [30]. The light source used is a tungsten–halogen lamp. The reflected light is collected using a photomultiplier tube and a lead sulfide detector for the visible and near-infrared spectral ranges, respectively. The spot size of the beam on the sample is 5 × 5 mm. The plane of incidence is perpendicular to the top surface of the crystal. The polarizer (Glan-Thomson, wavelength range 300–3000 nm) is mounted in the incident beam path to select either TE or TM polarization of light.
3. Results and analysis

3.1. Calculated stop gap crossing

When the light is incident normally on the samples, a stop gap is formed due to the diffraction of light from the (111) planes of the crystal. This corresponds to (111) stop gap in the ΓL direction for a crystal with fcc symmetry [30]. For higher values of θ (θ > 45°), the incident wavevector approaches other high-symmetry points in the hexagonal facet of the Brillouin zone of a crystal with fcc symmetry. In the vicinity of a high-symmetry point, the diffraction conditions can be satisfied for multiple crystal planes in a complex manner, leading to interesting optical processes such as stop gap branching and band crossing [15–17]. The stop gap wavelengths (λ_hkl) from different crystal planes with Miller indices (hkl) as a function of θ can be calculated using Bragg’s law [26]:

\[ \lambda_{hkl} = 2n_{eff}d_{hkl} \cos \left[ \frac{\alpha - \sin^{-1}\left(\frac{1}{n_{eff}} \sin \theta \right)}{2} \right], \]

where \(d_{hkl}\) is the interplanar spacing, \(n_{eff}\) is the effective refractive index and \(\alpha\) is the internal angle between the \((hkl)\) and \((111)\) planes.

Figure 1 shows the calculated stop gap wavelengths at different θ using equation (1) for samples B and C. Samples B and C are chosen specifically to show the effect of index contrast and thus different values of \(n_{eff}\) for photonic crystals having nearly the same lattice constant. The calculations are done for the case when the tip of the incident wavevector spans across the LK and LU lines in the cross section of the Brillouin zone (figure 1 inset). The stop gap calculations assume certain values of \(n_{eff}\) and \(d_{hkl}\), and their estimation will be discussed later in section 3.3. The (111) stop gaps for sample B (solid line) and sample C (dashed) are shifted towards shorter wavelengths. The (111) stop gaps for sample B (short dashed) and sample C (dash dot-dot) are shifted towards longer wavelengths. The (200) stop gaps for sample B (dash-dot) and sample C (dotted) also shift towards longer wavelengths with increasing θ. The (111) stop gap intercepts the (111) and (200) stop gaps at the high-symmetry points K (solid symbols) and U (dotted symbols), respectively, for the same value of θ for a given photonic crystal. This is due to the fact that the lengths of lines LK and LU are equal on the hexagonal facet of the Brillouin zone of the crystal with fcc symmetry [23]. The stop gap crossing at both K and U points occurs at different θ for sample B (circles) and C (squares) due to the difference in their index contrast. The stop gap crossing for sample C occurs at a much earlier θ value, which signifies the role of \(n_{eff}\) in the crossing θ value.

The crossing of stop gaps at a certain θ clearly suggests the presence of multiple diffraction resonances due to (111) and (111) or to (111) and (200) planes depending on the K or U high-symmetry point. The formation of multiple diffraction resonances can be explained through diffraction conditions at the K (U) point as shown in figure 1 (inset). When the wavevector is incident along the ΓK direction, diffraction conditions are satisfied for the (111) and (111) planes simultaneously with conditions \(k_0 + G_{111} = \vec{k}_1\) and \(k_0 + G_{111} + G_{111} = \vec{k}_2\), where \(\vec{k}_1\) and \(\vec{k}_2\) are the diffracted wavevectors from the (111) and (111) planes with reciprocal vectors \(G_{111}\) and \(G_{111}\), respectively. In a similar way, diffraction conditions can also apply at the U point. This process is known as multiple Bragg diffraction and is accompanied by the branching of stop gaps in the reflectivity or transmission measurements [27]. It is also noticed that the stop gap branching depends on the polarization states of light due to the unique vectorial nature of light as discussed below.

3.2. Optical reflectivity measurements

We have performed an extensive set of angle- and polarization-resolved optical reflectivity measurements on photonic crystals. At near-normal incidence (θ = 10°), which corresponds to the L point, the reflectivity spectra show a (111) stop gap for samples A and B centered at 1770 ± 2 nm and 667 ± 9 nm, respectively, and that for sample C occurs at 593 ± 7 nm. The measured stop gap widths are in complete
agreement with calculated photonic band structure at near-normal incidence [30]. The reflectivity spectra for the samples clearly show the Fabry–Perot (F–P) fringes in the long-wavelength limit. The thickness estimated from these F–P fringes is 13 ± 0.37 μm (~20 layers) for sample A, 8 ± 0.47 μm (~32 layers) for sample B, and 6.4 ± 0.92 μm (~27 layers) for sample C.

To elucidate the formation of stop gaps at higher θ in our measurements, the crystal is oriented in such a way as to scan the stop gap along the line LK or LU in the Brillouin zone. It is seen in section 3.1 that at higher values of θ the incident wavevector passes through the high-symmetry points, which results in the excitation of new diffraction resonances from crystal planes other than the (111) plane. There is a considerable debate in the literature regarding the assignment of crystal planes other than the (111) plane. The internal angle between directions ΓL and ΓK is 35.5°, and by applying Snell’s law to this geometry we can estimate neff = 3/2 sin θK. The value of θK corresponds to the θ value at which the stop gap branching occurs in the measured reflectivity spectra for TE-polarized light. The estimated values of neff are 1.38 for sample A, 1.40 for sample B and 1.33 for sample C. Sample B thus has the highest neff, and therefore it also has the highest index contrast among our samples.

3.3. Estimation of neff and dhkl from measurements

The calculation of stop gap wavelengths using equation (1) at different θ is performed using certain values of neff and D. The precise extraction of neff in a photonic crystal structure is quite complicated and many models have been explored [31]. However, we use a unique way to estimate value of neff from the measured reflectivity spectra [17, 31]. This means of estimating neff is quite useful in explaining many optical effects associated with self-assembled photonic crystals.

Assume that the stop gap branching discussed in section 3.2 for TE polarization occurs for the wavevector incident along the ΓK direction (see figure 1 (inset)) in the Brillouin zone. The internal angle between directions ΓL and ΓK is 35.5°, and by applying Snell’s law to this geometry we can estimate neff = 3/2 sin θK. The value of θK corresponds to the θ value at which the stop gap branching occurs in the measured reflectivity spectra for TE-polarized light. The estimated values of neff are 1.38 for sample A, 1.40 for sample B and 1.33 for sample C. Sample B thus has the highest neff, and therefore it also has the highest index contrast among our samples. The reflectivity spectra at θ = θK show a clear trough between the two peaks. This suggests that the light is transmitted through the sample, and the crystal structure as a whole behaves like a homogeneous material at that particular wavelength (λK). Therefore, we can use the free photon dispersion relation, which can be written as

\[ \omega = \frac{c |\overline{\Gamma K}|}{n_{\text{eff}}}, \]

where ω is the angular frequency, c is the speed of light in vacuum, D is the thickness of the sample, and neff is the effective refractive index of the photonic crystal.
where $|\mathbf{K}| = \frac{3\pi}{\sqrt{2} d_{111}}$ is the length of the incident wavevector at $\theta_k$, $d_{111} = 0.816D$ and $c$ is the speed of light. In equation (2), substituting $\omega$ in terms of $\lambda_k$ as $\omega = \frac{2c}{\lambda_k}$ gives the value of calculated diameter ($D$) as

$$D = \frac{3\lambda_k}{4n_{eff}},$$

(3)

The estimated values of $D$ are 809 nm for sample A, 305 nm for sample B and 288 nm for sample C. In order to check the reliability of our estimation, we have calculated the stop gap wavelength using Bragg’s law at near-normal incidence for sample B. The calculated stop gap wavelength is 696 nm, which is in close agreement with measured value. Hence, using our estimated values of $n_{eff}$ and $D$, the angular dispersion of the stop gap is calculated and compared with the measurements, as discussed below.

3.4. Comparison between the measured and calculated stop gaps

Figure 3 shows the measured (symbols) and calculated (lines) stop gap wavelengths using TE (left panel) and TM (right panel) polarized light as a function of $\theta$. The calculations are done for (111) (solid), (1I1) (dashed) and (200) (dotted) planes, which are the only relevant planes that can intersect at the K or U point. The measured (111) stop gap wavelengths (squares) are in close agreement with the calculations, until the appearance of new stop gaps (circles) for TE polarization. The measured (111) stop gap appears to be shifted away from the calculated curve and avoids crossing the new stop gap at the calculated crossing value of $\theta$. Beyond the crossing, the new stop gap is in good agreement with the (1I1) stop gap. In contrast, the stop gap for TM polarization follows the calculated (111) stop gap wavelengths at all $\theta$ values. However, the new stop gap (circles) that appears well above the crossing value of $\theta$ is in good agreement with calculated (1I1) stop gaps. The (1I1) stop gap for TM polarization emerges at $\theta$ that relates to $\theta_B$ for a given photonic crystal, and it is only because of the Brewster effect that the (1I1) stop gap is absent for any $\theta < \theta_B$ for TM polarization. The polarization-dependent stop gap branching is illustrated here for photonic crystals having different index contrast but with different lattice constant.

Figure 3 confirms the good agreement between the measured new stop gaps and the calculated (1I1) stop gaps irrespective of photonic crystal samples for both TE and TM polarizations. This strong agreement guarantees that the new reflectivity peak is a (1I1) stop gap and the incident wavevector is shifted along a line connecting the L and K points in the Brillouin zone. It is worth mentioning that $n_{eff}$ and $D$ used in the calculations are estimated from measured reflectivity spectra assuming that the light is incident along the $\Gamma K$ direction. This atypical polarization-induced stop gap branching in different spectral ranges and for crystals with different index contrasts is addressed here for the first time.

The stop gap branching is observed for a broad range of angle and wavelength for TE polarization using samples with different index contrast as seen in figure 3. Apparently, the measured (111) stop gap is repelled from the calculated curve near the crossing $\theta$ value. As the (111) stop gap approaches the exact crossing angle ($\theta_k$), the band repulsion occurs due to the presence of the (1I1) stop gap. The (111) and (1I1) stop gaps are diffraction resonance modes that are trying to appear at the same wavelength and therefore exhibit an avoided crossing behaviour. However, for TM polarization, stop gap branching is not observed at all until $\theta = \theta_B$, and the (1I1) stop gap appears for $\theta > \theta_B$ for all the samples. This suggests that the stop gap branching is absent due to the prevailing Brewster effect for TM-polarized light. We have clearly observed the origin of the (111) stop gap for TM polarization at $\theta = \theta_B$ (i.e. far away from the crossing regime) for all the samples. It is interesting to note the appearance of the (1I1) stop gap at different $\theta_B$ values for samples A, B and C, which is due to the difference in the value of $n_{eff}$. The estimated $n_{eff}$ values for samples A and B are nearly equal and this results in nearly the same $\theta_B$ value, whereas the $\theta_B$ value for sample C is much lower because of the reduced value of $n_{eff}$.

4. Measured and calculated polarization anisotropy

It is seen that the polarization-dependent angular dispersion of stop gaps for all the samples is differentiated on the basis of $n_{eff}$ and the difference in their index contrasts. Such unique interaction with polarized light is not only due to 3D periodicity within the bulk of the crystal but is also inherited from the sub-wavelength nature of the top crystal surface. To explain the anomalies with regard to the TE- and TM-polarized stop gaps quantitatively, we estimate a factor called the polarization anisotropy ($P_a$) [29]. It is defined as the ratio of reflectivity of TM- to TE-polarized light at a certain wavelength for a given $\theta$ value. Figures 4(a)–(c) show the measured $P_a$ values at different $\theta$ for off-resonance wavelengths (squares), which corresponds to $D/\lambda = 0.39$, and for on-resonance wavelengths (circles), which corresponds to the (111) stop gap for samples A, B and C, respectively. Figures 4(a)–(c) also show the $P_a$ values (dotted line) calculated using Fresnel equations, assuming the sample to be a thin film with a corresponding $n_{eff}$ value. This is a good approximation in the long-wavelength limit of our photonic crystals. The insets in figures 4(a)–(c) show the $P_a$ values for the on-resonance wavelengths corresponding to the (111) stop gap (diamonds) for samples A, B and C, respectively.

It is to be noted that the measured and calculated $P_a$ values are the same at $\theta \sim 0^\circ$ due to the identical nature of TE and TM polarization. The $P_a$ value first decreases, reaches a minimum at a certain $\theta$, and then increases again with increasing $\theta$ for all the samples. The calculated and measured off-resonance $P_a$ values show a minimum at the same $\theta$ value. This is because the crystal structure responds to the incident light at off-resonance wavelengths (long-wavelength limit) as if it is a homogeneous medium. This minimum $P_a$ value corresponds to $\theta_B$ of the photonic crystal, which is related to the value of $n_{eff}$, and for $\theta > \theta_B$ the $P_a$ value increases with
increasing $\theta$ as expected from the Fresnel equation. The calculated and measured off-resonance $\theta_B$ clearly correspond to the same value of $n_{\text{eff}}$, which further validates our estimation of $n_{\text{eff}}$.

It is astonishing to observe the shift in $\theta_B$ for on-resonance wavelengths as compared to off-resonance wavelengths and the calculated $\theta_B$ value. This clearly suggests that the on-resonance $P_a$ minimum is shifted to the higher side due to the complex nature of $n_{\text{eff}}$ at the on-resonance wavelength and to light scattering at the photonic crystal surface. This also shows that there is competition between the Brewster effect and Bragg diffraction, due to which the Brewster angle is shifted to higher $\theta$ values for on-resonance wavelengths. The shift in the value of $\theta_B$ defines the wavelength-dependent Brewster effect in photonic crystals due to the strong dispersion of $n_{\text{eff}}$. The definition of $n_{\text{eff}}$ at the stop gap wavelength is a subtle issue that further complicates the interpretation of the shift in $\theta_B$ in addition to the role played by the fabrication-induced intrinsic disorder. Hence an advanced theoretical formulation and simulations by taking care of the sub-wavelength nature of the surface is required, which is beyond the scope of the present work.

The on-resonance $P_a$ value for the (111) stop gap also shows a shift in $\theta_B$ for all the samples as compared to the calculated and off-resonance value as seen in the insets to figures 4(a)–(c). However, the observed shift in $\theta_B$ is not
constant; rather it depends on the index contrast and the lattice constants of photonic crystals. The $P_a$ values depicted in figure 4 (insets) clearly show the absence of the (111) peak for $\theta < \theta_B$. This is due to the fact that the process of energy exchange between planes within the crystal is inhibited by the Brewster effect, and therefore the (111) plane is not able to diffract, leading to the absence of the (111) stop gap for $\theta < \theta_B$.

The measured shift in the on-resonance $P_a$ minimum is different for all the samples, which is related to the difference in the values of $n_{eff}$. The measured shift in $\theta_B$ for sample B is 6°, which is in accordance with the theoretical calculations done for similar crystals with an ideal fcc lattice symmetry [29]. The shift in $\theta_B$ observed for samples A and C is 3°. The shift in $\theta_B$ varies with $n_{eff}$ in the diffraction regime due to its wavelength dispersion for samples A and B and the change in index contrast for sample C. Sample B has the largest index contrast because it has the highest $n_{eff}$ value among our samples, which ensures a large shift in $\theta_B$. Sample C shows the smallest shift in $\theta_B$ because it possesses the lowest $n_{eff}$ value among the samples and therefore has the lowest index contrast. This clearly shows that the shift in $\theta_B$ depends strongly on the index contrast. This further supports the role played by the index contrast in photonic crystals; the larger the contrast, the stronger will be the light–matter interaction.

The wavelength-dependent shift in $\theta_B$ gives rise to polarization anisotropy, which can be manipulated through the choice of specific lattice constant and index contrast because both determine the optical response of photonic crystals. Samples A and B show a difference in the value of $n_{eff}$ due to the refractive index dispersion of the PS because the lattice constant of the crystal is quite different. Samples B and C have nearly the same lattice constants, which results in the stop gap branching being in the same wavelength range. But the strong change in the index contrast between samples B and C is shown by a larger shift in the value of $\theta_B$.

The present study clearly signifies that an increase of 0.1 in the value of $n_{eff}$ results in double the increase in the shift of $\theta_B$ at on-resonance wavelengths. Our results emphasize the fact that polarization anisotropy can be tuned by meticulous selection of index contrast and lattice constant, which determines the wavelength range of interest. The results manifest wavelength-dependent polarization anisotropy that can be useful in many applications such as in angle- and polarization-selective nanoscale beam-splitters or polarizers.

5. Conclusions and perspective

We have shown the influence of refractive index contrast and lattice constants in the origin of polarization anisotropy in 3D photonic crystals with fcc symmetry. The wavelength-dependent polarization anisotropy is studied using the angle-and polarization-resolved stop gaps along the $\Gamma$–L–K–L$_1$ path in the Brillouin zone. The TE-polarized light shows stop gap branching in the vicinity of the K point, which is due to multiple Bragg diffraction from the (111) and (111) planes. The stop gap branching can also be explained as an inflow of energy between the (111) and (111) planes in the depth of the crystal. In contrast, we have observed that the stop gap branching is not seen for TM-polarized light in crystals with fcc symmetry. This is due to the prevailing Brewster effect, which inhibits energy exchange within the crystal. A new stop gap is formed beyond $\theta_B$, which further confirms the role of energy exchange in the formation of a secondary stop gap in crystals with fcc symmetry. At any rate, the new stop gap formed is in good agreement with the calculated (111) stop gap for TE and TM polarizations, and the incident wavevector is shifted towards the K point in the Brillouin zone.

It is observed that stop gap repulsion occurs, leading to the avoided crossing in the vicinity of the K point for TE polarization. Conversely, no such stop gap repulsion is observed for TM polarization and hence the avoided crossing of the stop gaps is absent. The (111) stop gap for TM polarization is in complete agreement with calculated stop gaps for all $\theta$. However, the stop gap branching originates at a much higher $\theta$ value due to the presence of the (111) stop gap for TM polarization.

The avoided crossing occurs at different values of $\theta_k$ for all the photonic crystal samples considered in our work. We
have observed a shift of $4^\circ$ in $\theta_B$ for sample C compared to sample B, which can be ascribed to the difference in index contrast even though the samples have nearly equal lattice constants. A minor shift in the crossing angle is observed for sample A as compared to that for sample B even though they are made using the same material. By virtue of the dispersion properties of PS, the stop gap wavelengths occurring in different wavelength regimes experience a different $n_{\text{eff}}$ for the photonic crystal structure. The PS photonic crystal with larger lattice constant shows a stop gap in the near-infrared wavelength range whereas one with a smaller lattice constant shows it in the visible range. Consequently, the crossing is achieved earlier for the medium that possesses a lower $n_{\text{eff}}$ value.

The measured $P_u$ factor validates the shift in $\theta_B$ for the on-resonance wavelengths as compared to the off-resonance wavelengths for all the samples in our work. The largest shift in $\theta_B$ ($\sim 6^\circ$) is observed for sample B, which has the highest index contrast, whereas samples A and C exhibit a small shift ($\sim 3^\circ$) in $\theta_B$. This notion of change in $\theta_B$ depends strongly on the wavelength region of interest, which reflects the value of $n_{\text{eff}}$. For an increase of 0.1 in the value of $n_{\text{eff}}$, there is a twofold increase in the shift of $\theta_B$ for the on-resonance wavelengths. This anomalous shift in $\theta_B$ supports the idea that the shift is primarily influenced by the index contrast and hence the photonic strength of the photonic metamaterials in general.

Our results establish a strong interaction of polarized light with photonic crystals that can be tuned with regard to the refractive index contrast and lattice constant of the crystal. Moreover, the strong wavelength-dependent character of $\theta_B$ in photonic crystals will help in designing them for various applications based on polarization. Furthermore, this study advances the modification of the Brewster effect in photonic metamaterials such as photonic crystals, which is also instructive for other sub-wavelength dielectric photonic structures.

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