Beam Steering at Higher Photonic Bands and Design of a Directional Cloak Formed by Photonic Crystals

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Abstract

Beam steering due to anomalous dispersion at higher photonic bands in dielectric photonic crystal is reported in this work. Based on this concept, directional cloak is designed that conceals a larger dimensional scattering object against the normal incident, linearly polarized electromagnetic waves.

1. Introduction

Photonic crystals (PCs) are the periodic arrangement of dielectric/magnetic constituents in one, two, three dimensions offer varieties of electromagnetic phenomena such as the band gap, negative refraction, self-collimation, ultra-divergence, sub-wave focusing and so on [1]. Their utilities in microwave photonics, communications systems and optical sciences are on high demand. Particularly, these periodic structures serve as an avenue to realize some of the transformational electromagnetic applications such as the cloaking/invisibility [2, 3 -5] and source transformation devices [6].

Comparing to the metamaterials (sub-wavelength structures that possess the negative dispersion characteristics), PCs neither possess the negative permittivity nor the negative permeability. However, the anomalous dispersion in periodic structures entails the realization of transformational applications. For instance, conformal mapping approach is used for the design of a cloaking device using metamaterials [7-11] but in PCs, negative refraction [3], gradient index approach [4], and waveguiding mechanisms [5] are envisaged for the realization of a cloaking structure. Similarly, the reciprocal transformation is used for the design of a source transformer using metamaterials [12] but PC simply realizes its functionality entirely from a dielectric structure based on the near-band gap phenomena [6].

In addition to the above approaches, this paper reports the beam steering mechanism at higher bands in PCs at the vicinity of the strong dielectric anisotropy. Based on this concept, a directional cloaking structure is designed for a normal incident, linearly polarized e-m wave. The proposed design is scalable at all length-scales ranging from radio frequencies to visible light and it could be useful for the development of concealment and stealth technology in communication systems.

2. Beam Steering at Higher Photonic Bands

It is possible to steer the e-m wave as shown in Fig. 1(a) that shows the E_z (Transverse Magnetic (TM) mode polarization) field map at 26.77 GHz for a photonic prism made of a square lattice arrangement of glass rods of relative dielectric permittivity of 5.5 with the radius of 0.3 cm in air background. Lattice constant of the PC is 0.8 cm. This field computation is performed with the finite-element methodology based e-m solver COMSOL RF Module [13]. It is observed that the normal incident e-m beam undergoes positive beam steering at the output interface of a PC wedge.

It is important to note that this kind of beam steering is not realizable in an optically denser medium as the e-m beam is internally reflected when it passes from the denser to the rarer medium. This suggests that the prism wedge's effective index is less than the air background and the steering direction indicates the positive index. While it is intricate to find a naturally available material with the positive index less than the air, PCs are the simplest artificial composites to show this kind of dispersion behavior.

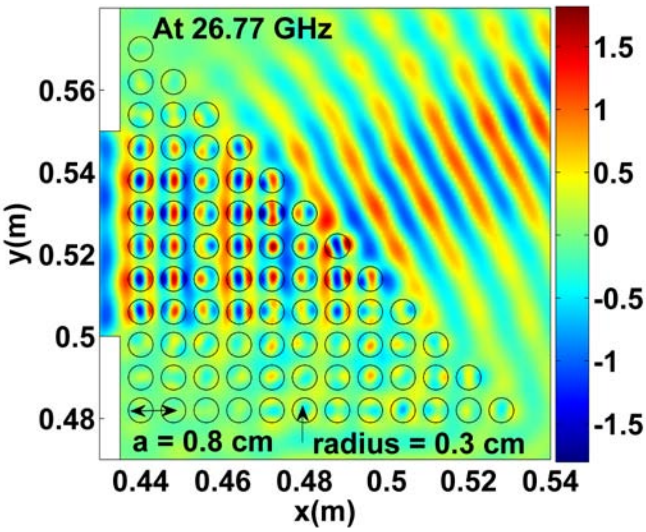

Figure 1: E_z field map at 26.77 GHz for a normal incident e-m wave on a photonic glass prism.

To gain further understanding about its mechanism, band structure and ray tracing results are obtained using the plane wave methodology based free e-m solver MPB [14]. Figure 2(a) shows the TM mode band structure of the square lattice glass PC with the normalized radius of 0.375a, where a is the lattice constant. It is found that the steering frequency 26.77 GHz (normalized angular frequency is 0.714(2πc/a)) overlaps with the fifth and sixth bands of the TM mode band structure in Figure 2(a). It is observed that this steering behaviour is a characteristic feature of the higher photonic bands.

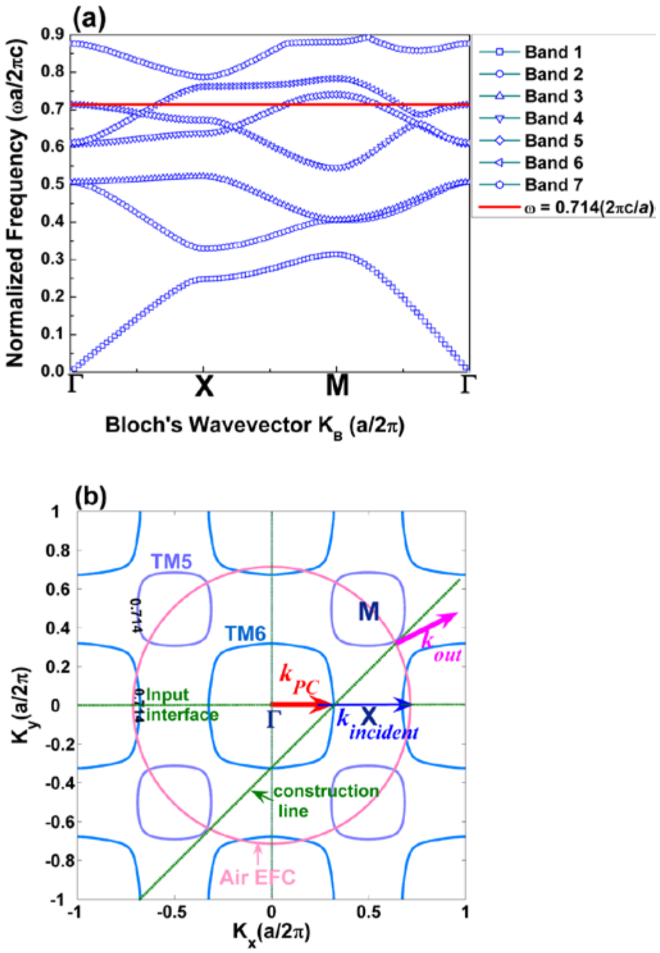

Figure 2: (a) TM mode band structure of a square lattice glass PC. Operating frequency 0.714(2πc/a) is indicated with the solid horizontal line in the plot. (a) Wavevector diagram in the repeated Brillouin zone at 0.714(2πc/a). $k_{incident}$, k_{PC} and k_{out} indicate the directions of incident, propagated and refracted components respectively. Γ, X and M are the highest symmetry points of the Brillouin zone of the square lattice.

To expedite this, one may look around the nature of dispersion at various bands. In general, effective homogenization is possible at first and second band of the PC. However, the prism wedge does not show the beam steering at first band due to the higher refractive index than the air background. Second band frequencies are well known for negative dispersion and one can steer the beam negatively. It may be noticed that Vanbésien *et al* [3] had designed a directional cloak based on the negative dispersion at second band frequencies. Third and forth band of PC reveal an extreme anisotropy towards the Γ symmetry point of the square lattice so that the e-m beam will largely disperse upon the normal incidence. Fifth and sixth bands are the regimes of special interest but it is noticed that the fifth band has a partial band gap towards the ΓX symmetry direction. For instance, the red solid line (at 0.714(2πc/a)) drawn in the band structure (Figure 2 (a)) indicates the opening of band gap along ΓX symmetry direction for the fifth band so that the fifth band forbids the normal incident light to enter into the prism. On the other hand, sixth band dispersion at the same frequency allows the beam to travel along the ΓX symmetry direction of the square lattice PC. Hence the beam steering mechanism is focused on the dispersion nature around the sixth band frequencies.

The wavevector diagram given in Figure 2(b) at the steering frequency 0.714(2πc/a) clarifies the observed beam steering. Since this frequency is shared by fifth and sixth bands, two different dispersion contours are witnessed around Γ and M symmetry directions in Figure 2(b). The corresponding air dispersion contour at 0.714(2πc/a) includes the PC contours and thus indicates the lower effective index of the PC.

When a normal incident e-m beam (represented by $k_{incident}$ in Figure 2(b)) is excited towards the ΓX symmetry direction, e-m ray is maintaining its direction inside the PC with a minimal divergence owing to the curvature of the TM6 contour (refer k_{PC} in Figure 2(b)). The refraction at the second interface (slanted surface of the PC wedge) is determined by the continuity equation, which reveals the positive beam steering of the e-m beam in the air medium (refer k_{out} in Figure 2(b)).

This steering property could be employed for the design of beam expanders and compressors based on the prism combinations. In this work, the steering property is used for the design of a directional cloak.

3. Realization of a Directional Cloak

Directional cloak conceals the scattering objects in one direction at least for a normal incident, linearly polarized e-m waves. It has applications in the development of light protection circuits in microwave photonics and stealth mechanism in communication systems. This paper reports the design of a one such geometry based on the aforementioned beam steering concept. Figure 3 shows the layout of a directional cloak.

It consists of four PC prisms, where the left and right wedges are separated by a distance of 2d$_1$, where d$_1$ is fixed to 6.1 cm. Similarly, top and bottom wedges are separated by a distance of 2d$_2$, where d$_2$ is fixed to 2.1 cm. It is expected that the combination of right angled wedges would split the beam into two components. Top and bottom wedges are used to guide the e-m beam around the scattering object (perfect electric conductor-PEC) placed at the centre of the configuration. The prism at the output port reconstructs the separated beams into a single beam. At the centre of the configuration, a PEC object of diameter of 2 cm is placed for the concealment purpose.

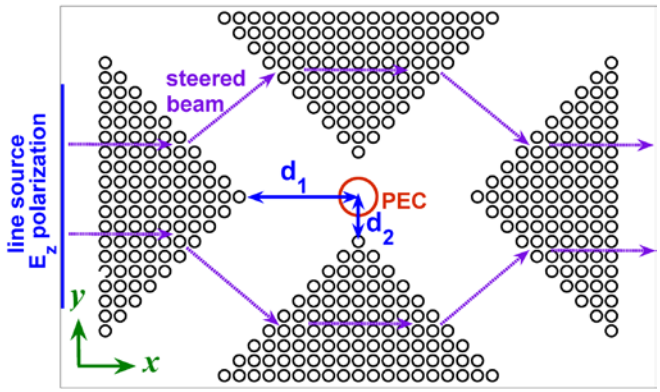

Figure 3: Directional cloak based on the beam steering effect at higher photonic bands. d_1 and d_2 are the horizontal and vertical separation of the prism wedges respectively.

3.1. Wavefront Reconstruction

Field computations are performed for the proposed geometry shown in Figure 3 using the e-m solver COMSOL RF Module [13]. A line source of 12 cm with the TM mode polarization is used for the normal incident excitation. The geometry is surrounded by the computational domain with a size of 32 cm $\times$ 20.5 cm and the open space is terminated by the absorbing boundary conditions. Simulations are done for the in-plane system, where the height of the PC rods is assumed to be infinite.

Figure 4 shows the E_z field map at 26.77 GHz for a normal incident e-m wave impinged on the PC geometry for three different cases namely; (a) without PEC, (b) with PEC and (c) air background respectively. It is found that the beam steering reconstructs the e-m beam at the output port and their wavefront shape is similar to that of the air background. This is further revealed in the field scanning plot in Figure 4(d), which shows the scanned field profiles for all three cases at 26.77 GHz. Though the recorded profiles are influenced by the scattering losses, the observed feature is a desired aspect for the concealment utility in microwave communication systems.

It is learnt that the prism element with the effective index less than the air medium entails the realization of a directional cloak at least for a normal incident, linearly polarized e-m waves. It is interesting to note that such approach can also be attempted with the other mesoscopic systems such as the quasi-periodic, non-periodic and indefinite media. Hence, it is anticipated that optimization of the proposed directional cloak with respect to the scattering losses, polarization state, incident angle will lead to the practical utilities in radar and communication applications.

4. Conclusions

Beam steering arising from the higher photonic bands in dielectric photonic crystal is reported in this work. It is found the investigated dispersion regimes possess the effective index less than the air background. This steers the normal incident beam in a positive direction in PC wedge. This property allows one to design the beam expanders and compressors based on the prism combinations.

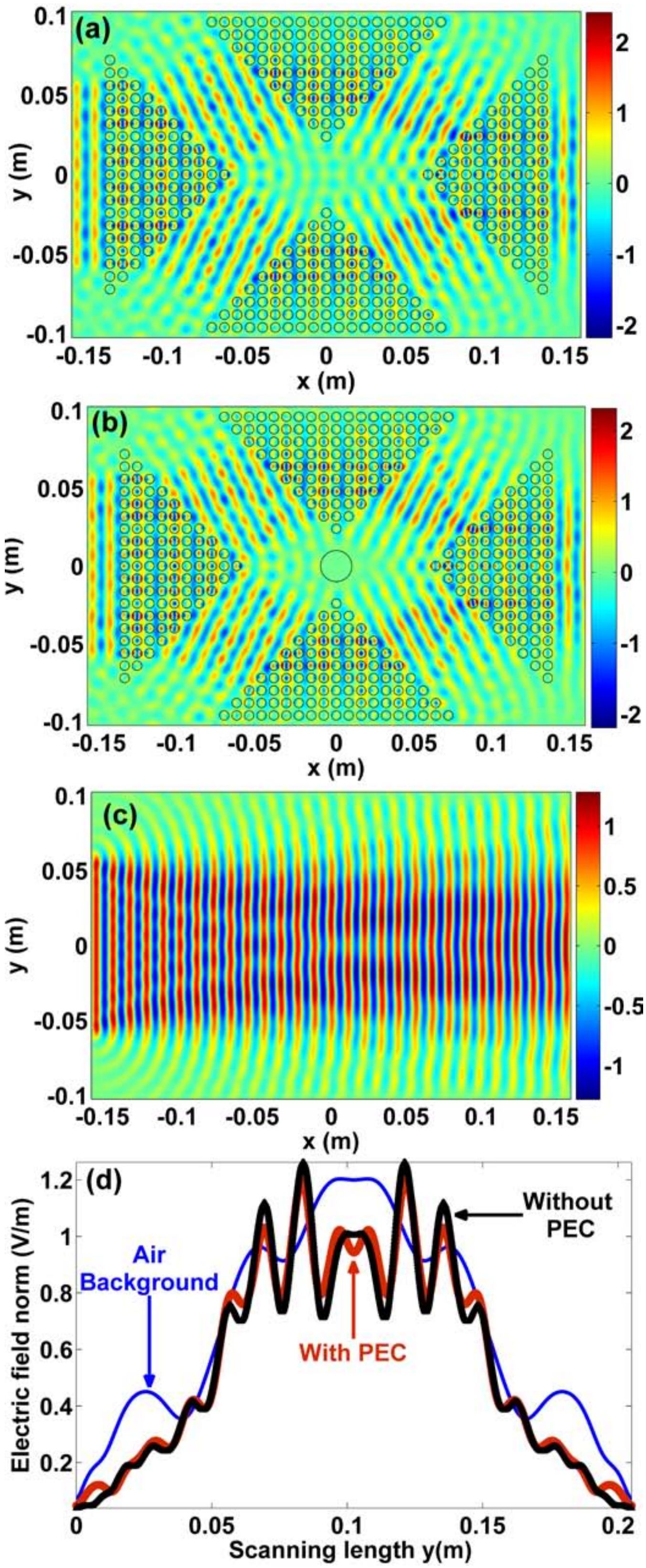

Figure 4 E_z field maps at 26.77 GHz for (a) empty (b) PEC loaded PC geometry and (c) air background respectively. (d) Scanned electric field profiles along the y direction at the detecting plane at $x = 0.157\text{m}$.

As an application point of view, steering concept is employed for the design of a directional cloak. It is numerically demonstrated that the proposed design effectively reconstructs the e-m beam and it maintains the wave shape similar to the air background. This aspect is useful for the development of concealment utilities and stealth technology in microwave systems. Optimizing the design with respect to the scattering losses, oblique incidence and polarization state will entail the real time utilities of a directional cloak.

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