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Invited paper

Negative refraction of photonic and polaritonic waves in periodic structures[§]

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Abstract. Negative refraction can be achieved in photonic crystals. We briefly summarize recent studies in this field, and show that such effects are also possible in polaritonic and plasmonic structures, such as the dipole crystal. We propose a practical realization of this crystal, a periodic lattice of dielectric spheres. We study its mode structure, and preliminary results demonstrate the negative refraction on a polaritonic band.

Key words: negative refraction, photonic, polaritonic waves, periodic structures.

1. Introduction

While the negative refraction was initially proposed by Veselago already in 60's [1], it has recently attracted strong research interests [2–14], since the negatively refractive materials can now be realized with the nanotechnology. For electromagnetic waves incident from air on a slab of such a material, the angle of refraction is negative, which implies via Snell's Law a negative refractive index. The most exciting consequence of this is the possibility of the subwavelength lensing [13]. A slab made of a material with an isotropic refractive index $n = -1$ restores not only phases of the transmitted propagating waves, but also amplitudes of the evanescent waves that are responsible for the subwavelength details of the source geometry [13]. Such a material (metamaterial) can be used to make a lens capable of the subwavelength imaging. Limitations of this imaging, resulting from the inherent losses in the media, have also been investigated [15, 16]. Various approaches were proposed to fabricate systems, which simulate the metamaterials. In one approach, a model metamaterial was made of the splitring resonators, and a network of wires [3–5]. Recently, structures have been examined, which could lead to subwavelength lensing at infrared and visible frequencies [17–19].

In another approach, it has been shown that a dielectric, two-dimensional (2D) photonic crystal (PC) can act as a metamaterial, with an effective negative refractive index [20]. It was also demonstrated [21, 22], that a negative refraction can be achieved in a PC in which an isotropic refractive index cannot be defined. In this case, an equi-frequency contour in the band structure is chosen so that the group velocities of photon modes excited by an incident wave on this contour, point always in a negative refraction direction. This all-angle negative refraction can lead to subwavelength lensing, but the imaging is severely restricted [23].

2. Negative refraction in photonic crystals

In Ref. 24, it was shown that an unrestricted subwavelength lensing is possible in PCs of various geometries. The PCs studied consisted of a periodic array of infinitely long, cylindrical air-holes, embedded in a thick slab of dielectric matrix. The photonic band structures were obtained by numerically solving the Maxwell equations. The standard plane wave expansion [25], and the finite-difference time-domain (FDTD) simulations with perfectly matched layer boundary conditions have been employed [26–28]. It was shown, that in the square PC, the all angle negative refraction [29] can occur, but the subwavelength lensing in this crystal is restricted, and the image formation possible only in the highly non-geometric near-lens mode. Figure 1 shows wave propagation maps for this case. Clearly, the image of the point source, placed at

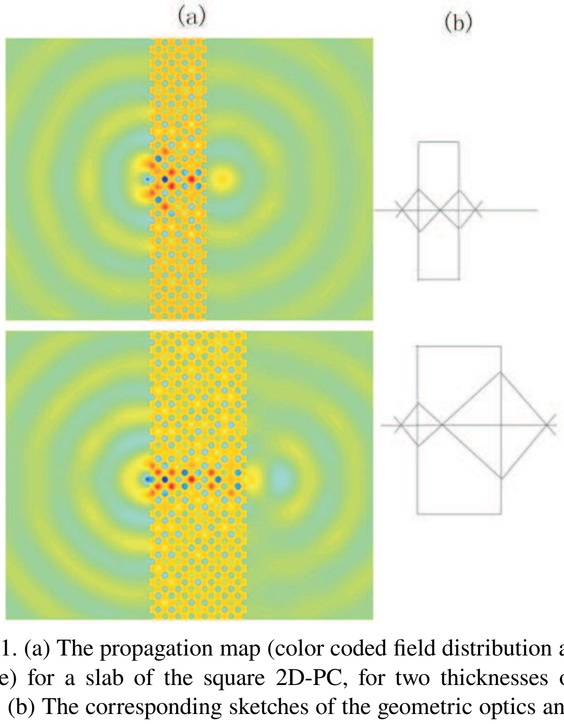

Fig. 1. (a) The propagation map (color coded field distribution across space) for a slab of the square 2D-PC, for two thicknesses of the slab; (b) The corresponding sketches of the geometric optics analysis (Snell's Law), showing that for a thicker slab (lower panel) the image must be further away from the crystal edge (taken from Ref. 24)

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the left surface of the crystal does not follow the rules of the geometric optics. Instead it remains “attached” to the right surface of the crystal. In contrast, in the triangular 2D-PC the propagation maps (Fig. 2) demonstrate that the PC acts as a metamedium with $n = -1$, and therefore the subwavelength lensing is unrestricted.

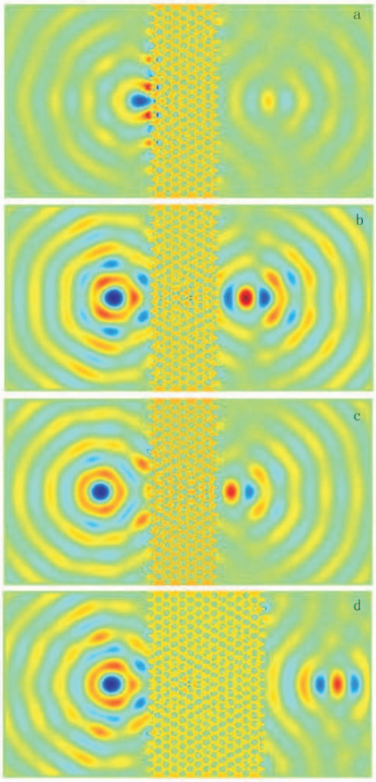

Fig. 2. The propagation maps for a slab of the triangular 2D-PC for varying source positions and thickness of the slab. Positions of the images follow the geometric optics analysis, in which the PC is considered an effective medium with $n = -1$, and a Snell’s Law refraction occurs at each interface (taken from Ref. 24)

A systematic scheme for increasing the subwavelength resolution of lensing of PCs was proposed in Ref. 32. It was shown that the resolution of a subwavelength lens based on PC can be increased by reducing the normalized frequency at which the subwavelength lensing occurs. The idea was demonstrated in PCs of various lattice structures, made of dielectric cylindrical rods.

3. Polaritonic crystals

The PC could consist of metallic units. It can be shown that for such PCs band gap opening is possible even at optical frequencies (very difficult with dielectric PCs). To avoid the metallic losses, it is advantageous to work in the polaritonic domain of the frequency spectrum. This assures that the frequency of operation of such a polaritonic crystal is sufficiently lower than the plasma frequency of the metallic units. This avoids generation of plasma waves in the metallic units, and thus reduces the absorption associated with the electromagnetic waves penetrating metal.

A two dimensional polaritonic crystal was studied in Ref. 33. The crystal consisted of infinitely long metallic rods, immersed in a background dielectric matrix. The electromagnetic response of each rod was described by a Drude dielectric function. It was found that a band gap opens in the photonic spectrum, as the photons acquire a mass while transforming (via interactions with electrons in the metallic rods) into the coupled plasmon-polariton mode. The detailed analysis showed that the plasmon-polariton bands are parabolically soft at *all* the band edges, and thus one obtains also highly symmetric convex equal-frequency surfaces, ideal for subwavelength lensing. Figure 3 shows the simulated subwavelength lensing with this crystal.

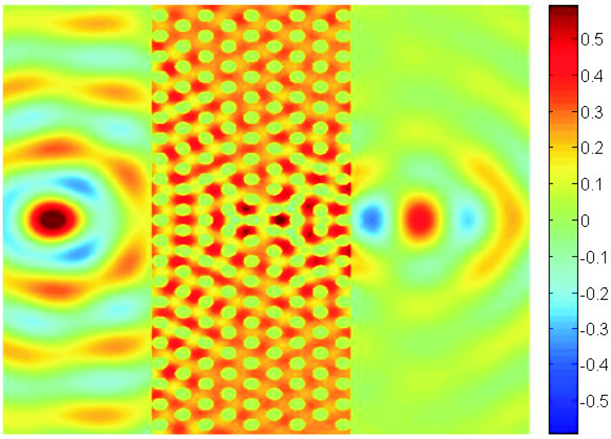

Fig. 3. The propagation map produced by a point source placed to the left of the slab of a 2D polaritonic crystal. In this system, a nonrestricted subwavelength lensing occurs even for relatively large metallic losses (taken from Ref. 33)

It is important to note that the resolution of this subwavelength lensing depends on the losses in the metal. It was shown [33], that a resolution of $\sim 0.5\lambda$ (λ is the wavelength of the radiation in vacuum) is still observed for a large $\Gamma = 0.04\omega_p$ (Γ is the damping parameter entering the Drude formula, and $\omega_p$is the bulk plasma frequency of the metal).

4. Dipole-like crystal

A detailed study of electromagnetic properties of a 3D cubic crystal of point-dipoles, has been presented in Ref. 34. It was shown, that the system is a non-local polaritonic crystal that allows for bulk and surface plasmon wave propagation in addition to the usual photonic crystal effects (bands, gaps, etc.). Also, negative refraction and subwavelength lensing can occur for properly chosen parameters of the system. In one scenario, a very thin film (with thickness $<< \lambda$) of a crystal made of Ag nanoparticles (as the point dipoles) was shown to exhibit negative refraction, in similar fashion to a thin Ag film, but with less efficiency [13, 35, 36]. Subsequently [34], a thick film of the crystal was considered with each dipole assumed to have the following polarizability

$$\alpha(\omega) = \frac{\omega_p^2}{4\pi(\omega_0^2 - \omega^2)} = \frac{\Omega_p^2}{4\pi(\Omega_0^2 - \Omega^2)}, \tag{1}$$

where $\Omega = \omega a/c$, $\Omega_0 = \omega_0 a/c$, $\Omega_p = \omega_p a/c$ (a is the lattice constant and c speed of light), ω_0 is the resonance frequency of the charges, and ω_p is a constant with dimensions of frequency. Next, the parameters were adjusted so that the mode structure acquired the form as shown in Fig. 4.

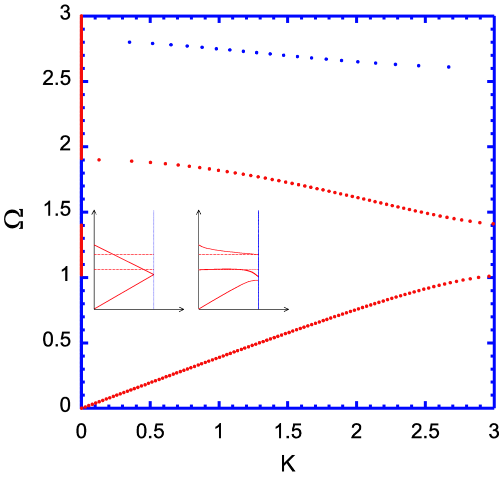

Fig. 4. Band structure for a point dipole crystal with $\Omega_0 = \Omega_p = 3$, and $\varepsilon_b = 5$. The inset shows a schematic of the light line anti-crossing with the dipolar modes (the horizontal TP and LP, dashed lines). The normalized wave vector is $K = ka$ (taken form Ref. 34)

There are three TEM mode branches, with the middle, and the top one exhibiting strong negative slopes. The sketch in the inset in Fig. 4 clarifies the topology of the bands. It is the minimum-bending avoided-crossing of the photon line with the longitudinal polarization (LP) and transverse polarization (TP) asymptotics. The photon line is "Umklapped" at the Brilluoin zone before crossing the asymptotics. Left panel in the inset shows the case before, and right panel after the mode interaction has been "switched on". Both upper branches have a negative slope, controlled by a choice of two parameters, Ω_0 and Ω_p, and therefore the negative refraction is expected at the frequency given by intersection of the vacuum light line with these branches. This negative refraction is mediated by polaritonic waves rather than by the pure TEM modes, which is usually the case in PCs.

To verify the occurrence of the negative refraction and lensing in the polaritonic band of this crystal, we have performed the FDTD simulations for a slab of a realistic crystal, which has the dipolar response of individual entities similar to that described by Eq. (1). The cubic crystal consists of a lattice of dielectric spheres with large dielectric constant ($\varepsilon = 53$), embedded in a material with dielectric constant $\varepsilon_b = 3$. The large dielectric constant assures the essentially dipolar charge displacements. The radius of each sphere is $r = 0.23$ cm, the lattice constant is $a = 1$ cm. The photonic band structure of the crystal is shown in Fig. 5. As expected, the band structure is similar to that for a lattice of perfect dipoles (Fig. 4). The negative refraction is expected at the intersection of the light line (crosses) with the upper two bands with negative curvature.

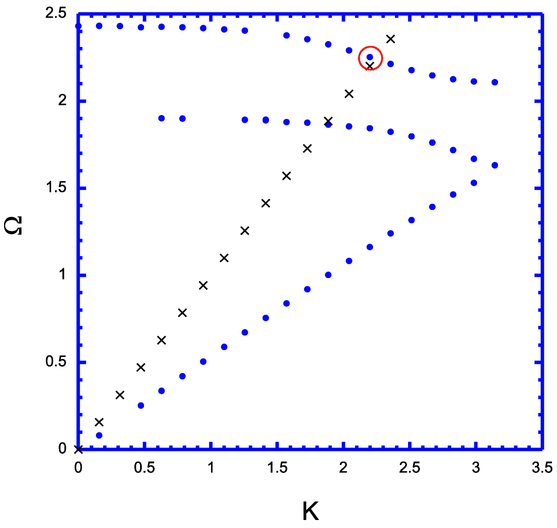

Fig. 5. Band structure for a cubic crystal of dielectric spheres (dipole-like crystal). Crosses represent the vacuum light line (photon dispersion). The circle indicates the conditions for the negative refraction shown in Fig. 6

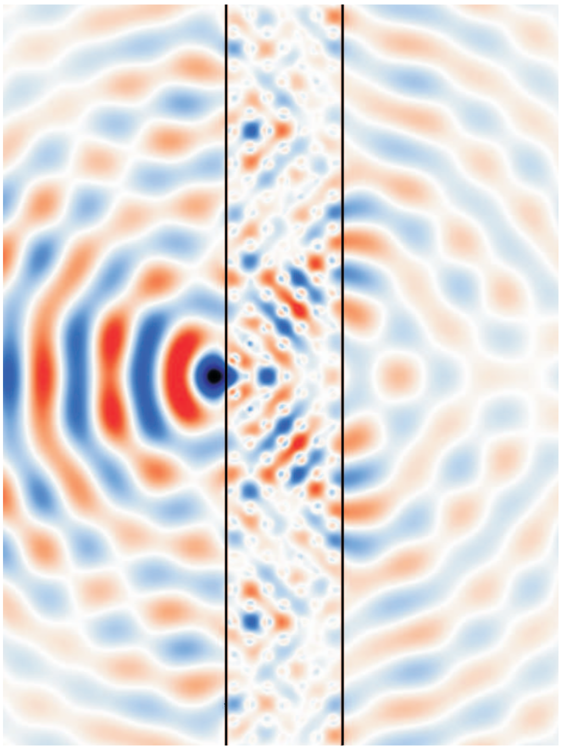

Fig. 6. Negative refraction and lensing in a cubic 3D polaritonic, dipole-like crystal

To observe the negative refraction in this crystal, we chose the second polaritonic band (circle in Fig. 5). We chose a final slab of the crystal with thickness D = 4.7 cm. The simulated map of the electric fields is shown in Fig. 6. Shown are field components perpendicular to the plane of Fig. 6. While the color intensity scales with the field amplitude, color change indicates the change of the vector direction. The point source of the electromagnetic waves is placed .65 cm from the surface of the crystal (left). Clearly visible is the dipolar response of each sphere (change of the color from red to blue in each sphere), indicating that the spheres indeed well simulate the point dipoles. The corresponding point image forms outside of the crystal (close to the surface on the right). These are preliminary results, and more work is needed to improve the image quality, and to clarify if the lensing is unrestricted and subwavelength.

The parameters of the crystal assure that the frequencies of interest are in the gigahertz range ($\lambda \sim 2$ cm). The crystal is easily manufacturable, and easy to measure its response. We would like to encourage such an experimental effort.

5. Conclusions

We have reviewed recent studies involving negative refraction and subwavelength lensing in photonic, and polaritonic crystals. The 3D polaritonic crystal of point dipoles has been proposed earlier, and shown to exhibit interesting optical effects, including photonic and polaritonic band gap formation, plasma waves, and negative polaritonic refraction. In this work we propose a practical realization of such a system: the dipole-like crystal of dielectric spheres with very large dielectric constant. Such spheres respond to electromagnetic radiation in a very similar way to point-dipoles. The proposed system is easy to fabricate, and the negative refraction was designed to occur in the easily accessible microwave range.

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