Evanescent wave induced polarization-insensitive self-organization of stratified single-negative materials

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Abstract

Optical fields can induce optical forces between macroscopic objects, giving rise to different structures. Through rigorous calculation, we show that a collection of single negative slabs which possesses either negative permittivity or negative permeability (i.e. \(\varepsilon < 0, \mu > 0\) or \(\varepsilon > 0, \mu < 0\)) in water can be self-organized into one-dimensional photonic crystals, due to the coupling of propagating wave and evanescent wave. We further demonstrated that the optical binding is irrespective of the polarization and angle of the incident plane wave. We call such a phenomenon —polarization-insensitive optical binding. We also demonstrate that polarization-insensitive optical binding can be achieved on microscale and millimeter scale. Polarization and angle insensitive band edge is the key to achieve polarization and angle insensitive optical binding. This work provides a new strategy to tailor the photonic crystals containing single negative materials towards the development of fine-tuning optical devices.

1. Introduction

Optical binding refers to the spontaneous self-organization of particles into stable configurations due to the multiple scattering of light \([1, 2]\). The scattered light interferes with the background incident light, redistributing the electromagnetic fields surrounding the particles, which in turn alters the optical force and couple the particles together. Optical binding is thought to have great potential in the self-organization of nano- or micro-particles, it has been studied experimentally \([3–12]\) and theoretically \([13–16]\).

Counter-propagating waves are frequently used in realizing optical binding, as standing-wave interference patterns can be created, in which the particles are automatically driven to the intensity antinodes of the pattern \([2–7]\). Counter-propagating evanescent waves are also an alternative mean to achieve optical binding \([15–18]\). As the standing-wave patterns are strongly dependent on the number of incident waves, incident angles and polarizations, generally, optical binding depends strongly on the incident angle and polarization \([15–19]\). However, here, we show that polarization and angle insensitive optical binding can be achieved due to the coupling of propagating wave and evanescent wave.

In this paper, first, we design a one-dimensional photonic crystal (1D PC) possessing a polarization and angle-insensitive band edge. The PC is composed of water and single negative materials (SNG) \([20]\), with three layers in the unit cell \((ABC)\). The first layer \(A\) is permeability negative (MNG) media \((\varepsilon > 0, \mu < 0)\), the second layer \(B\) is permittivity negative (ENG) media \((\varepsilon < 0, \mu > 0)\) and the third layer \(C\) is water. Since the SNG layers in the PC are separated by water, they can be modulated by the light induced force. In SNG materials, as the refractive index is purely imaginary, thus, the electromagnetic fields are evanescent while the electromagnetic fields in water are propagating, the self-organization of the SNG is due to the coupling
of the propagating wave and evanescent wave. By using the transfer matrix method [21], the electromagnetic fields for the 1D PC are calculated. We compute the time-averaged optical forces acting on the homogenous slab using a surface integral of the Maxwell stress tensor [22]. Then, using molecular static simulation [23], equilibrium configurations of the 1D PC is identified when illuminated by TE and TM polarized incident plane waves, respectively. Finally, the stabilities of the self-organized PCs are verified using linear stability analysis. Dynamical matrix approach [24–26] was also employed to verify the stability of the self-organized PC with infinitely many unit cells. We rigorously show that when the incident frequency of light located at the polarization-insensitive and angle-insensitive band edge, after relaxation, the PC always rearranges itself into one same mechanically stable PC, with the band edge coincides with the incident frequency, irrespective of the incident angles and polarizations of the light.

2. Results

2.1. Photonic crystal with a polarization-insensitive bandgap

In all of our simulations, if the obtained equilibrium configuration is a PC, one of its upper band edges is always aligned with the incident frequency (see appendix A (https://stacks.iop.org/NJP/23/073037/mmedia)). It seems that the band edges play a decisive role in the self-organization of 1D PC. Therefore, we first investigate the possibilities of the PC with polarization and angle insensitive bandgap.

We consider an N periods PC \((ABC)^N\) composed of alternating MNG (A), ENG (B), and water (C), as is shown in figure 1, with lattice constant being \(\Lambda\). The violet layer denotes water, while the golden and green layers denote MNG and ENG materials, respectively. Metamaterials with effective negative permittivity (permittivity) in a particular frequency range have been obtained by utilizing split ring resonators (wire elements) [20, 27].

Since the MNG and ENG will move as an entirety in our simulation, for the sake of mathematical simplicity, they are regarded as an isotropic homogenous slab (layer \(D\)), in the framework of effective medium theory. Accordingly, the 1D structure can be denoted as \((DC)^N\).

Based on the same transmission and reflection coefficients, the effective relative permittivity and permeability of layer \(D\) for TM and TE polarization can be respectively written as [28]

\[
\begin{align*}
\varepsilon_D &= \rho \varepsilon_A + (1 - \rho) \varepsilon_B \\
\mu_D &= \rho \mu_A + (1 - \rho) \mu_B - \sin^2 \theta \left( \frac{\rho}{\mu_A} + \frac{1 - \rho}{\mu_B} - \frac{1}{\varepsilon_D} \right) \\
\mu_D &= \rho \mu_A + (1 - \rho) \mu_B \\
\varepsilon_D &= \rho \varepsilon_A + (1 - \rho) \varepsilon_B - \sin^2 \theta \left( \frac{\rho}{\varepsilon_A} + \frac{1 - \rho}{\varepsilon_B} - \frac{1}{\mu_D} \right),
\end{align*}
\]

where \(\theta\) is incident angle, \(d_D = d_A + d_B, \rho = d_A/d_D\) is the filling fraction of layer \(A\) where \(d_A(d_B), \varepsilon_A(\varepsilon_B)\) and \(\mu_A(\mu_B)\) are the thickness, the relative permittivity and permeability of layer \(A\) (B).
For a bilayer one-dimensional PC, the band structure for TM polarization is given by [21]

\[
\cos(k_B \Lambda) = \cos(k_{Cz} d_C) \cos(k_{Dz} d_D) - \frac{1}{2} \left( \frac{k_{Cz} \varepsilon_D}{k_{Dz} \varepsilon_C} + \frac{k_{Dz} \varepsilon_C}{k_{Cz} \varepsilon_D} \right) \sin(k_{Cz} d_C) \sin(k_{Dz} d_D) \tag{3a}
\]

and for TE polarization

\[
\cos(k_B \Lambda) = \cos(k_{Cz} d_C) \cos(k_{Dz} d_D) - \frac{1}{2} \left( \frac{k_{Cz} \mu_D}{k_{Dz} \mu_C} + \frac{k_{Dz} \mu_C}{k_{Cz} \mu_D} \right) \sin(k_{Cz} d_C) \sin(k_{Dz} d_D). \tag{3b}
\]

Here, \(k_B\) denotes the Bloch wave vector, \(k_{iz} = k_0 \sqrt{\varepsilon_i \mu_i - \sin^2 \theta}\), \(i = C, D\) denotes the \(z\)-component of wave vector in layer \(i\), \(k_0\) is the wave vector in free space. \(\Lambda = d_C + d_D\) is the lattice constant where \(d_i\) denotes the thickness of layer \(i\). When \(|k_{iz}| > 1\), there is no real value for \(k_B\), denoting the band gap in which the light is prohibited to pass through the PC. Since \(k_{iz}\) is angle-dependent, generally, the band structure is angle-dependent.

In order to obtain a band gap which is polarization and angle insensitive, we consider the situation that \(|k_{iz}| d_i \ll 1\), by making Taylor expansion of equations (3a) and (3b) and keeping \(k_{iz} d_i\) to the square terms, we obtain

\[
\begin{align*}
\cos(k_B \Lambda) & = 1 - \frac{(|k_{Dz}| d_C)^2 + (|k_{Cz}| d_D)^2}{2} - \frac{1}{2} \left( \frac{|k_{Cz}| \varepsilon_D}{|k_{Dz}| \varepsilon_C} + \frac{|k_{Dz}| \varepsilon_C}{|k_{Cz}| \varepsilon_D} \right) (|k_{Cz}| d_C) (|k_{Dz}| d_D) \tag{4a}
\end{align*}
\]

\[
\begin{align*}
\cos(k_B \Lambda) & = 1 - \frac{(|k_{Dz}| d_C)^2 + (|k_{Cz}| d_D)^2}{2} - \frac{1}{2} \left( \frac{|k_{Cz}| \mu_D}{|k_{Dz}| \mu_C} + \frac{|k_{Dz}| \mu_C}{|k_{Cz}| \mu_D} \right) (|k_{Cz}| d_C) (|k_{Dz}| d_D). \tag{4b}
\end{align*}
\]

For brevity, we let

\[
\begin{align*}
& m_1 = \frac{(|k_{Dz}| d_C)^2 + (|k_{Cz}| d_D)^2}{k_0^2} + \frac{1}{k_0^2} \left( \frac{|k_{Dz}| \varepsilon_C}{|k_{Cz}| \varepsilon_D} + \frac{|k_{Cz}| \varepsilon_D}{|k_{Dz}| \varepsilon_C} \right) (|k_{Cz}| d_C) (|k_{Dz}| d_D) \\
& = (\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_A d_A + \varepsilon_B d_B + \mu_C d_C) - (\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_B \varepsilon_C d_A + \varepsilon_A \varepsilon_C d_B + \varepsilon_A \varepsilon_B d_C) \sin^2 \theta \\
& m_2 = \frac{(|k_{Dz}| d_C)^2 + (|k_{Cz}| d_D)^2}{k_0^2} + \frac{1}{k_0^2} \left( \frac{|k_{Cz}| \mu_C}{|k_{Dz}| \mu_D} + \frac{|k_{Dz}| \mu_D}{|k_{Cz}| \mu_C} \right) (|k_{Cz}| d_C) (|k_{Dz}| d_D) \\
& = (\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_A d_A + \varepsilon_B d_B + \mu_C d_C) - (\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\mu_B \mu_C d_A + \mu_A \mu_C d_B + \mu_A \mu_B d_C) \mu_A \mu_B \mu_C \sin^2 \theta.
\end{align*}
\]

To achieve polarization and angle insensitive band edge, \(m_1 \equiv m_2 \equiv 0\), we have

\[
\begin{align*}
(\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_A d_A + \varepsilon_B d_B + \mu_C d_C) &= 0 \tag{6a} \\
(\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_B \varepsilon_C d_A + \varepsilon_A \varepsilon_C d_B + \varepsilon_A \varepsilon_B d_C) &= 0 \tag{6b} \\
(\varepsilon_A d_A + \varepsilon_B d_B + \varepsilon_C d_C)(\varepsilon_A d_A + \varepsilon_B d_B + \mu_C d_C) &= 0 \tag{6c} \\
(\varepsilon_A d_A + \varepsilon_B d_B + \mu_C d_C)(\mu_B \mu_C d_A + \mu_A \mu_C d_B + \mu_A \mu_B d_C) &= 0. \tag{6d}
\end{align*}
\]

If we let

\[
\begin{align*}
d_C &= - \frac{\varepsilon_A d_A + \varepsilon_B d_B}{\mu_C} = - \frac{\varepsilon_B \varepsilon_C d_A + \varepsilon_A \varepsilon_C d_B}{\varepsilon_A \varepsilon_B} \tag{7}
\end{align*}
\]

then, equations (6a)–(6d) can be satisfied at the same time, thus achieving a band gap that is polarization and angle insensitive. We also notice that there are other solutions to fulfill equations (6a)–(6d), which will not be discussed in detail here.

Solving equation (7), we can further obtain

\[
\begin{align*}
\frac{d_B}{d_A} &= \frac{\varepsilon_B (\varepsilon_C \mu_C - \varepsilon_A \mu_A)}{\varepsilon_A (\varepsilon_C \mu_C - \varepsilon_B \mu_B)} \tag{8}
\end{align*}
\]

We assume [29]

\[
\begin{align*}
\varepsilon_A &= 3, \quad \mu_A = 1 - \frac{\omega_{m p}^2}{\omega^2}, \\
\varepsilon_B &= 1 - \frac{\omega_{m p}^2}{\omega^2}, \quad \mu_B = 1.2 \tag{9, 10}
\end{align*}
\]
\[
\varepsilon_C = 1.33^2, \quad \mu_C = 1.0, \quad (11)
\]

where \(\omega_{mp} = 10^{15} \text{ rad s}^{-1}\) and \(\omega_{ep} = 11.925 \times 10^{15} \text{ rad s}^{-1}\) are the magnetic and electronic plasma angular frequency, respectively.

Without loss of generality, the band edge is set to be 112 THz, then we have

\[
\varepsilon_A = 3, \quad \mu_A = -1.0193
\]
\[
\varepsilon_B = -1.8715, \quad \mu_B = 1.2. \quad (12)
\]

Substituting equation (12) in equation (8), we arrive at

\[
\frac{d_B}{d_A} = 0.75. \quad (13)
\]

Then we assume \(d_A = 100 \text{ nm}\) so that \(|k_B| d_i \ll 1\) can be achieved, according to equation (13), \(d_B = 75 \text{ nm}\). Substituting equation (12), \(d_A\) and \(d_B\) into equation (7), we obtain \(d_C = 11.9 \text{ nm}\). The results are not limited to nano-scale, it can apply to micro-scale, even millimeter scale as well, as long as equations (6a)–(6d) are satisfied under the prerequisite \(|k_B| d_i \ll 1\).

The band structures of \((ABC)^N\) and \((DC)^N\) for TM and TE polarized incident beams are plotted in figures 2(a) and (b), respectively, where \(d_A = 100 \text{ nm}, d_B = 75 \text{ nm}, d_C = 11.9 \text{ nm}\). The frequency range is from 50 THz to 150 THz. A polarization and angle insensitive band edge is located exactly at 112.0 THz in figure 2(a), which is right the band edge we set above. The polarization and angle insensitive band edge in figure 2(b) is located at 111.80 THz, slightly deviate from 112.0 THz, indicating the effective medium method is applicable. The color bar denotes the absolute value of \(\cos(k_B\Lambda)\) where \(k_B\) denotes the Bloch wave vector. The violet color lines denote the band edge where \(|\cos(k_B\Lambda)| = 1\). The calculation of the band structure for \((ABC)^N\) is shown in appendix B.

### 2.2. Optical force

Under light illumination, the slabs in a PC will experience optical forces. The time averaged optical force exerted on the slabs is given by

\[
F = \sum_{i=1}^{N} \int_{\text{surface}_i} \mathbf{T} \cdot d\mathbf{a} = \int_{\text{surface}_1} \mathbf{T} \cdot d\mathbf{a} + \int_{\text{surface}_2} \mathbf{T} \cdot d\mathbf{a}, \quad (14)
\]
where $a$ is the area of the surface. The red dotted lines in figure 1 denote the surfaces 1–4, the front and back surfaces 5 and 6 are not shown. Due to symmetry, the contributions of surfaces 3, 4, 5, and 6 cancel each other out. The time-averaged Maxwell stress tensor is given by [22]

$$T_{ik} = \frac{1}{2} \varepsilon_0 \left[ \varepsilon_w E_i E^*_k + c^2 B_i B^*_k - \frac{1}{2} (\varepsilon_w E \cdot E^* + c^2 B \cdot B^*) \delta_{ik} \right],$$  \hspace{1cm} (15)

where $\delta_{ik}$ is Kronecker delta function, $E$ and $B$ are the electric and magnetic fields. $\varepsilon_0$ denotes the permittivity of the free space, $\varepsilon_w$ indicates the relative permittivity of water, $c$ is the light speed in vacuum, and $\cdot$ indicates complex conjugation.

### 2.3. Equilibrium configuration

The optical force acting on a PC is generally nonzero. To investigate whether polarization-insensitive optical binding of 1D PC can be achieved or not, dynamical equilibrium configurations are searched. Dynamical equilibrium corresponds to the configuration where the optical force acting on each slab is identical and nonzero. In this situation, the entire structure will move as a single entirety with a fixed shape according to Newton’s second law.

We consider the situation where the PC is illuminated by one single plane wave. The thickness of $A$ and $B$ are the same with those in figure 2(a). We let the incident frequency be the higher band edge (111.8 THz) of the $(DC)^N$ in figure 2(b), where $N = 500$. Initially, the separation between two adjacent layers $D$ (the thickness of layer $C$—water) is set to be 5 nm. At normal incidence, using molecular static simulation, after relaxation, the equilibrium configuration is found with the separation being about 11.80 nm. Then we keep the incident frequency fixed (111.8 THz), but vary the incident angle from $0^\circ$, $30^\circ$, $60^\circ$, and $80^\circ$. We still set the separation between two adjacent layers $D$ being 5 nm before relaxation. Surprisingly, for TM (TE) polarization, after relaxation, equilibrium configurations are found as well with the separations being 11.7 (11.8), 11.4 (11.7) and 11.2 (11.6) nm for $30^\circ$, $60^\circ$, and $80^\circ$, respectively, as plotted in figures 3(a) and (b). All the separation between two adjacent layer $D$ (thicknesses of layer $C$—water) of the newly self-organized PC are generally uniform except near the end of the PC, and only slightly diverge from the thickness of layer $C$ (water, 11.9 nm) in figure 2(b), i.e., the newly formed PCs illuminated by the plane wave at different incident angles and polarizations are always nearly the same with the PC we design in figure 2(b). Consequently, polarization-insensitive optical binding is achieved. As layer $A$ and $B$ are SNG materials, the wave is evanescent in them. Therefore, the binding is achieved due to the interaction of the evanescent wave in layer $A$ and $B$ and the propagation wave in water. Besides, this kind of equilibrium is dynamical equilibrium, because the force acting on each of the slabs is identical and nonzero, as shown in figures 3(c) and (d).
The situation that the incident light frequency located at the lower band edge (82.8 THz) of the PC in figure 2 is also considered. At normal incidence, the equilibrium can still be found, however, the separation between two adjacent layers $D$ (thickness of layer $C$—water) in the newly self-organized PC is about 195 nm (figure 4(a)), 16.3 times the thickness of water (11.9 nm) of the PC in figure 2. The band structure at normal incidence is plotted in figure 4(b). The blue solid denotes the band structure of the PC in figure 2(b) at normal incidence while the red dashed line denotes the band structure of the newly self-organized PC. Clearly, the upper band edge of the newly formed PC aligns with the incident frequency 82.8 THz.

The existence of a stable PC when illuminated at the upper band edge can be understood heuristically [30]. At upper band edge, standing wave is formed when the equilibrium is found. As the slab moves away from the equilibrium position, the gradient force tends to drive it back where the electromagnetic energy is high, thus the self-organized PC is stable. However, at lower band edge, the situation is quite different. Although standing wave are formed as well, as the slab move away from the equilibrium position, the gradient force tends to drive it far away, thus is unstable.

Furthermore, the polarization-insensitive binding of microscale and millimeter scale PCs are showed in appendix C, if the PCs possess band edges that are polarization and angle insensitive.

2.4. Stability analysis and dynamical matrix approach

Using linear stability analysis [12], we investigate the stabilities of the self-organized PCs. The stabilities are dominated by the natural vibration frequencies $\Omega$, through the dependence in $e^{\Omega t}$. An equilibrium configuration can possess several different types of vibration modes, such as stable modes (real natural vibration frequency), unstable modes (imaginary frequency), neutral modes (zero frequency) and quasi-stable modes (complex frequency) or complex unstable modes (complex frequency), depending on the characteristic of the natural vibration frequencies. Figures 5(a) and (b) show the natural vibration frequencies of the stable equilibrium configurations in figures 3(a) and (b). All the equilibrium configurations we found are stable due to the real natural vibration frequencies.

By using the dynamical matrix method [24–26] (see appendix D), the stability of an infinite PC is also considered. The force matrix formed by 100, 200, and 500 slabs are used to calculate the dynamical matrix approximately. The natural vibration frequencies for 100 (solid line), 200 (dash line), and 500 (dotted line) periods agree excellently well with each other, as is plotted in figure 6, indicating a good convergence of our
results. Besides, the real natural vibration frequencies imply that even for an infinite PC, stable polarization-insensitive optical binding can be achieved when it is illuminated by a plane wave with the frequency located at the upper band edge.

3. Conclusion

In summary, we demonstrated that a collection of slabs made of SNG materials can be self-organized into one same mechanical PC due to the coupling of propagating wave and evanescent wave, irrespective of the polarization and angle of the incident light. The stability of the bounded PC is also verified using linear stability analysis. Besides, by using the dynamical matrix approach, we showed that a PC composed of an infinite number of slabs can be stably bounded as well. Our detailed studies on optical force also allowed an additional degree of freedom in fine-tuning devices consisting of slabs, such as photonic crystals, superlattices, planar cavities, etc.

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