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Comment on "Negative refraction in 1D photonic crystals" [Solid State Communications 147 (2008) 157–160]

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ABSTRACT

It can be shown that negative refraction cannot occur in one-dimensional photonic crystals oriented as in Srivastava et al. (2008) [1].

In a recent publication [1], Srivastava et al. explain why they expect negative refraction to occur in the gap of a one-dimensional photonic crystal with a periodicity along the optical axis (see Fig. 1).

Negative refraction occurs when the velocity group in the x direction is negative. Following [1] we have established the analytical expression of that velocity, using the same notations:

$$
\begin{aligned}
V_{g_x} = \frac{c^2\beta}{w} \Bigg[& \left(\frac{\varepsilon_1 a}{k_1} + \frac{1}{2}\left(\frac{k_1}{k_2}+\frac{k_2}{k_1}\right)\frac{\varepsilon_2 b}{k_2}\right) \\
& \times \sin(k_1 a)\cos(k_2 b) + \left(\frac{\varepsilon_2 b}{k_2} + \frac{1}{2}\left(\frac{k_1}{k_2}+\frac{k_2}{k_1}\right)\frac{\varepsilon_1 a}{k_1}\right) \\
& \times \cos(k_1 a)\sin(k_2 b) \\
& + \frac{1}{2}\left(\left(\frac{k_2\varepsilon_1}{k_1} - \frac{k_1\varepsilon_2}{k_2}\right)\left(\frac{1}{k_2^2}-\frac{1}{k_1^2}\right)\right)\sin(k_1 a)\sin(k_2 b)\Bigg]^{-1} \\
& \times \Bigg[\left(\frac{a}{k_1} + \frac{1}{2}\left(\frac{k_1}{k_2}+\frac{k_2}{k_1}\right)\frac{b}{k_2}\right)\sin(k_1 a)\cos(k_2 b) \\
& + \left(\frac{b}{k_2} + \frac{1}{2}\left(\frac{k_1}{k_2}+\frac{k_2}{k_1}\right)\frac{a}{k_1}\right)\cos(k_1 a)\sin(k_2 b) \\
& + \frac{1}{2}\left(\left(\frac{k_2}{k_1}-\frac{k_1}{k_2}\right)\left(\frac{1}{k_2^2}-\frac{1}{k_1^2}\right)\right)\sin(k_1 a)\sin(k_2 b)\Bigg]. \qquad (1)
\end{aligned}
$$

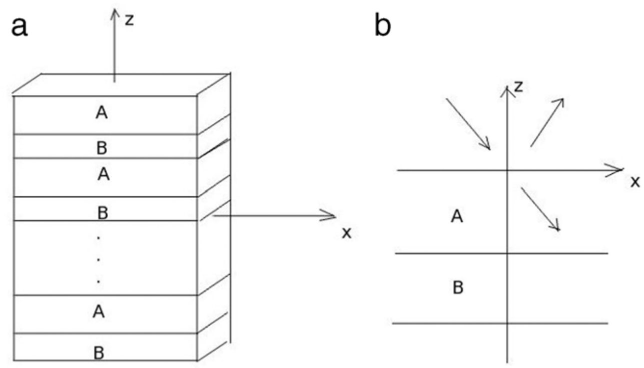

Fig. 1. As in [1], we study a stack of alternating layers. Layer A has an optical index of 1 ($\varepsilon_1 = 1$) and has a thickness of $a = 0.75$ in arbitrary units. Layers of type B present an optical index of 2.3 ($\varepsilon_2 = 5.29$) and are $b = 0.25$ thick. The finite structure contains 10 periods. The wavelength is of 1.0744 to get a negative group velocity.

The latter expression is defined even in the gap of the photonic crystal, where it may present negative values. Since the transmission coefficient [2] is not null in some gaps for a finite structure, the authors of [1] conclude that negative refraction can occur when expression (1) is negative.

Using a numerical tool some of us have developed and which is freely available [3], we have computed the propagation of a Gaussian beam in the structure when negative refraction is expected. The result is presented Fig. 2. It is obvious that the lateral shift of the transmitted beam is positive, so that there is definitely no negative refraction in this situation, although we have checked

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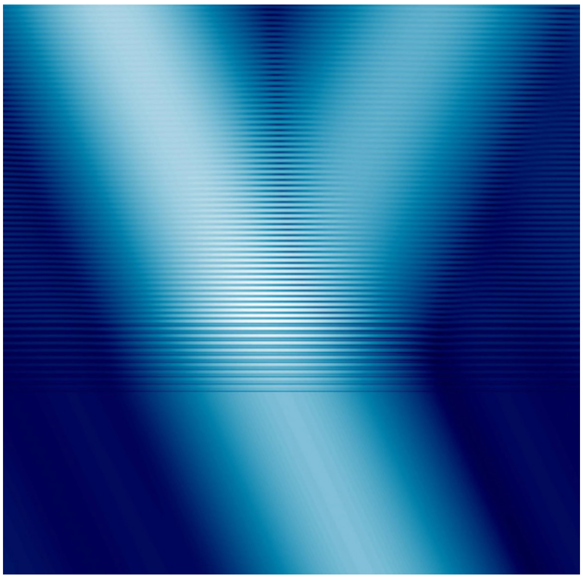

Fig. 2. (Color online) Modulus of the field in a structure alternating a layer of optical index 1 and thickness 0.75 and a layer of optical index 2.3 with a thickness 0.25. The structure contains 10 periods. The wavelength is 1.0744, and the waist is 25λ.

that expression (1) is actually negative. This underlines that in the gap the group velocity is not well-defined and its expression should then be considered meaningless.

We have finally two arguments which strengthen the idea that negative refraction cannot occur for such a structure.

First, when a finite structure with a negative refractive index is illuminated by a beam, this beam undergoes a negative lateral shift [4]. This shift is linked to the opposite of the derivative of the transmission coefficient's phase (Artmann's formula). Since the phase of the transmission coefficient (see Fig. 3) is always decreasing, then the transmitted beam is always positively shifted and not negatively, as would happen in the case of a negative refraction. That result is in agreement with previous works on the lateral shift of beams reflected by one-dimensional photonic crystals [5].

Second, when the group velocity is well-defined (outside a gap), it is related to the Poynting vector along the x axis by

$$V_{g_x} = \frac{\langle P_x \rangle}{\int_{\text{period}} \epsilon_d \, dz} \tag{2}$$

where ϵ_d is the energy density and $\langle P_x \rangle$ is the averaged Poynting vector [6,7]. After a simple calculation, the averaged Poynting vector can be written in TE polarization

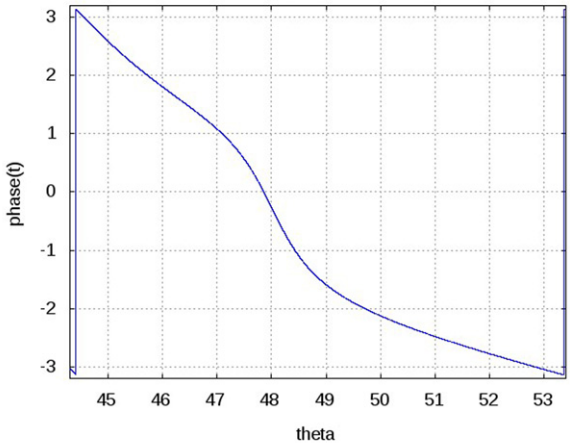

Fig. 3. Phase of the transmission coefficient in the same conditions.

$$\langle P_x \rangle = \frac{1}{2} \frac{k_x}{\omega \mu_0} \int_0^a |E_{y_1}|^2 \mathrm{d}z \tag{3}$$

$$+ \frac{1}{2} \frac{k_x}{\omega \mu_0} \int_a^{a+b} |E_{y_2}|^2 \mathrm{d}z. \tag{4}$$

Since $\left(\frac{1}{2} \frac{k_x}{\omega \mu_0} |E_{y_1}|^2 \right) \geqslant 0$ and $\left(\frac{1}{2} \frac{k_x}{\omega \mu_0} |E_{y_2}|^2 \right) \geqslant 0$, $\langle P_x \rangle$ is always positive and so is the velocity group V_{g_x}, as long as it is well-defined. That is the case in TM polarization as well. Negative refraction can thus not occur outside the gap. Inside a gap, the Poynting vector cannot be averaged, but it is linked to the lateral shift. A positive Poynting vector whatever the layer means a positive lateral shift, as mentioned above.

We finally came to the conclusion that the purely dielectric structure described in [1] cannot produce negative refraction, contrary to metallo-dielectric structures [6] or to Bragg mirrors oriented in another direction [8,9].

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