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Large negative lateral shifts due to negative refraction

Jessica Benedicto,[1,2] **Rémi Pollès,**[1,2] **Antoine Moreau,**[1,2,*] **Emmanuel Centeno,**[1,2]

[1] *Clermont Université, Université Blaise Pascal, LASMEA, BP 10448, F-63000 Clermont-Ferrand*
[2] *CNRS, UMR 6602, LASMEA, F-63177 Aubière, France*
[*] *Corresponding author: antoine.moreau@univ-bpclermont.fr*

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When a thin structure in which negative refraction occurs (a metallo-dielectric or a photonic crystal) is illuminated by a beam, the reflected and transmitted beam can undergo a large negative lateral shift. This phenomenon can be seen as an interferential enhancement of the geometrical shift and can be considered as a signature of negative refraction. © 2011 Optical Society of America

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It has been recently shown that when a beam is illuminating a slab presenting negative permittivity and permeability the reflected and transmitted beam could undergo a large negative lateral shift [1]. It has then been suggested that some of these lateral shifts are linked to the negative refraction which occurs when light enters the structure [2,3]. In the present letter, we show for the first time that a large lateral shift explicitely due to negative refraction can be obtained using a very thin slab of photonic crystal, thus confirming the previous assumption. Here we have not used metamaterials designed to present negative permittivity and permeability as in [1], which definitely shows that negative refraction alone is responsible for the negative shift.

In previous works, large lateral shifts have already been obtained using a photonic crystal, but they were either positive [4,5] or negative but due to a guided mode excited by a grating [6].

The lateral shift associated to negative refraction has already been proposed as a signature of that phenomenon [7] in a case where the thickness of the structure is larger than the waist of the incident beam. The lateral shift is in that case purely geometrical. We show in this paper that the large negative lateral shift is finally an interferential enhancement of the geometrical lateral shift. It occurs in very thin structures compared to the waist, and it can be used to characterize negative refraction.

In order to get a physical picture of the phenomenon, let us begin by considering a *lossless* metallo-dielectric multilayer. Such a structure can be considered as a 1D photonic crystal. It is now well-known that negative refraction may occur when TM polarized light enters such a structure [8]. The transparency of that type of structure is due to the excitation of coupled resonances : either coupled guided modes supported by the metallic slabs, or Fabry-Perot resonances of the cavity constituted by the dielectric layers. Here we consider the second case, when the field is propagative in the dielectric layer.

Negative refraction occurs when the dielectric layers are thin and when their relative permittivity is high enough, so that the field is more localized in the metal. We have thus chosen $\epsilon_m = -4.43$, corresponding to the real part of the permittivity of silver at 400 nm and $\epsilon_d = 5.3$ so that $\epsilon_d > |\epsilon_m|$. The thickness of the dielectric (resp. metallic) layers is $h_d = 0.0979\lambda$ (resp. $h_m = 0.0975\lambda$).

The component of the Poynting vector parallel to the interfaces of the metallo-dielectric structure, P_x, controls the direction in which light will propagate in the crystal. When that quantity, averaged on a period of the structure, is negative, then negative refraction occurs [9]. Inside a layer, it can be written

$$P_x = \frac{n \sin(\theta)}{2c\epsilon_0\epsilon_r} |H|^2 \tag{1}$$

where n is the refractive index of the above medium in which the incident beam propagates with an incidence angle θ and ϵ_r is the relative permittivity of the medium in which the vector is calculated.

Using a code based on the scattering matrix method which is freely available [10] we have considered a beam illuminating a thick structure containing 500 periods of the photonic crystal. In that case the waist of the beam (10λ) is small compared to the thickness of the structure (around 100λ) : this is the geometrical regime. Figure 1 (a) shows a situation which is very similar to [7], except that there are many reflected beams inside the structure. This is explained by the high reflectivity of the interfaces between the photonic crystal and the outer media : above the structure we have chosen a dielectric with $\epsilon_r = 6.7$ and under the photonic crystal there is air. Given the incidence angle of the incoming beam, total reflexion occurs at the lowest interface.

When the thickness of the overall structure is reduced, all the beams reflected inside the structure interfere. If they interfere constructively, a Fabry-Perot resonance occurs in the photonic crystal slab. Since we are not at normal incidence, that resonance is actually a leaky mode [3] and it is backward because the beams inside the slab propagate towards the left because of negative refraction. The excitation of this leaky mode leads to enhance the lateral shift by an interferential effect. Figure 1 (b) shows such a situation for an incidence angle of 61.7°.

Despite the very small thickness of the photonic crystal (10 periods for a overall thickness of 2λ), the lateral shift (14.8λ) is much larger than the waist of the beam and it cannot be explained by a geometrical lateral shift.

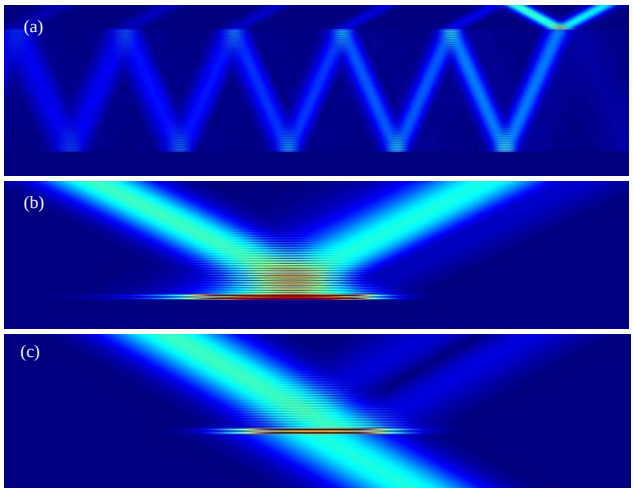


Fig. 1. Metallo-dielectric structure illuminated by a TM polarized gaussian beam with a 61.7° angle of incidence, 10λ waist in two cases (a) when the structure contains 500 periods, in the geometrical regime (b) when the structure is only 10 periods thick, in the interferential regime for which a large negative lateral shift occurs. (c) When it is present, the transmitted beam too undergoes a negative lateral shift (structure with 5 periods, 0.997 nm thick, 60.65°). This shift is accurately given, for large beams, by Artmann's formula (2) considering the phase of the *transmission* coefficient.

Such an interferential effect does not occur for any incidence angle. The angles for which the reflected beam is shifted can be found by considering the phase of the reflection coefficient of the photonic crystal slab. The lateral shift of a reflected beam is actually given by Artmann's formula [4, 11]

$$\Delta = -\frac{1}{nk_0 \cos\theta}\frac{\partial\phi}{\partial\theta}, \qquad (2)$$

where θ is the angle of incidence, n the index of the upper medium, $k_0 = \frac{2\pi}{\lambda}$ the wavenumber in vacuum, and ϕ the phase of the reflection coefficient. That shift is the asymptotic shift, reached when the waist of the incident beam is large enough [10]. Artmann's formula indicates here that a backward leaky mode can be excited for angles for which the phase presents a quick *positive* variation (due to the presence of a pole [3]). Figure 2 (a) shows the phase of the reflection coefficient of the thin photonic crystal slab and how we have chosen the angle of incidence.

But it should be stressed that even though the lateral shift shown figure 1(b) would allow an easy measurement, the waist of the incoming beam is not large enough to reach the asymptotic regime - so that the shift is smaller than what is given by (2). That is however not

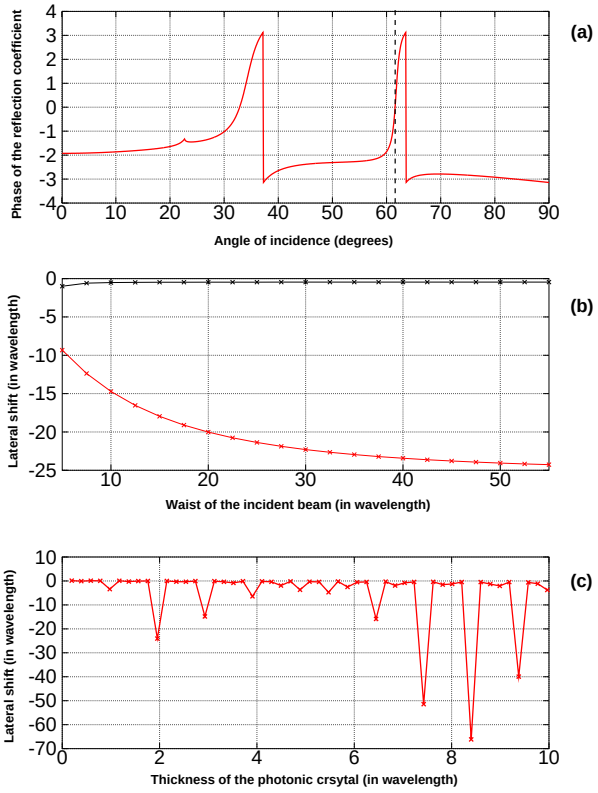


Fig. 2. (a) Phase of the reflection coefficient for the 10 periods structure considered fig. 1 showing that the phase presents a positive derivative, characteristics of the negative lateral shift (b) Lateral shift as a function of the waist for an incidence angle of 61.7° corresponding to a swift variation of the phase (red curve) and for 58° (black curve) leading to a smaller shift.(c) Lateral shift as a function of the thickness.

a problem, because when Artmann's formula is valid the waist is in general so large than the lateral shift is harder to detect [12]. We are confident that such a lateral shift can easily be measured because positive lateral shifts have already been measured either for large lateral shifts [13] or even Goos-Hänchen shifts [14] which are much smaller.

However, for a negative lateral shift to be considered as a sign of negative refraction, one has to be sure that it is not due to the excitation of a leaky surface mode [2, 15]. The only way to make sure a leaky cavity mode has been excited is to study the dependence of the negative lateral shift on the thickness of the structure (see figure 2 (c)). Our structure being a photonic crystal, it is not possible to make the thickness vary continuously. It is then not possible to see a periodical variation of the shift (as could be expected) but a beat between the periodical shift and the sampling rate as shown in the figure. Such a behaviour is characteristic of a cavity resonance.

Since losses shorten the propagation length of light in the structure, they always reduce the number of interfering beams and finally the negative lateral shift. But

the interferential enhancement can be expected to occur as long as the propagation length is several times larger than the actual thickness of the structure. This can be easily verified by considering a slightly lossy metal in the above structures, but not when the losses are realistic. In that case, the propagation length is about a few periods of the structure [8].

We have then chosen in the literature [16] a bidimensional photonic crystal which produces negative refraction and which, since it is purely dielectric, does not suffer from losses. The crystal is made of rectangular rods (width of 0.75λ, height of 0.96λ, permittivity $\epsilon_r = 9$) periodically arranged in air - with an horizontal period of 1.27λ and a vertical period of 2.22λ. In order to obtain an enhancement of the lateral shift, light must be, as much as possible, reflected inside the structure. It is not possible to hinder light from leaking in the above medium here, so that a good solution is always to have light completely reflected at the lower interface. In general, that can be obtained using total reflection like in the previous case, but it is not possible here because the above medium is air. Using a back reflector (a Bragg mirror or a metallic mirror) is a possibility. Here for simplicity we have chosen to place the photonic crystal on a perfect conducting reflector. Figure 3 shows the simulation we have made using a Fourier modal method. Despite the fact that the reflection coefficient between the crystal and air has not been particularly optimized, a Fabry-Perot resonance of the slab can be clearly seen, leading to a -36.6λ lateral shift of the reflected beam (with a waist of 89λ).

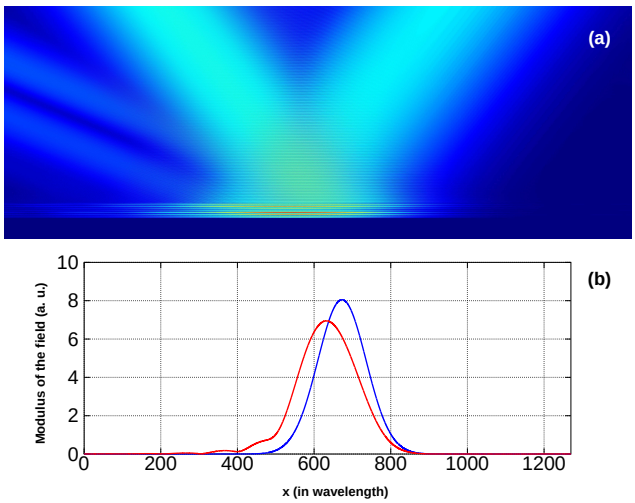


Fig. 3. (a) Gaussian beam illumating a thin slab (7 periods) of a photonic crystal with an incidence angle of 40° and a waist of 89λ (b) profile of the reflected H field showing how it is slightly distorted and shifted towards the left. The field plotted here is the zero-order only. The -1 diffraction order can be seen on the left of the picture - its profile is due partly to the incoming beam and partly to the resonance inside the structure.

To summarize, for a structure producing negative refraction it is possible to obtain a large negative lateral shift provided (i) there is a high reflectivity for light inside the structure, which can be achieve by using either a back reflector or an impedance mismatch between the photonic crystal and the outside media (ii) the thickness of the structure is small compared to the waist of the incident beam, so that the different beams inside the structure can interfere (iii) a correct angle is chosen, so that the interferences inside the structure are constructive and a resonance is excited. This phenomenon takes place even if the waist of the incident beam is not large enough so that Artmann's formula, which is widely used by the community to characterize lateral shifts, is not valid. And in general, it is easier to measure it when the asymptotic regime is not reached.

In conclusion, we have shown in the present paper that photonic crystal slabs could support backward leaky modes which are responsible for a large negative lateral shift of the reflected beam. These large negative lateral shifts can be used to characterize negative refraction because they can be seen as an interferential enhancement of the geometrical negative lateral shift [7]. It must be underlined that by nature these shifts occur when the thickness of the structure is small compared to the waist of the incoming beam.

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