Refraction of surface acoustic waves through 2D phononic crystals

J. Pierre, B. Bonello, O. Boyko, L. Belliard

INSP, UPMC, 140 rue de Lourmel, Campus Boucicaut, 75015 PARIS, France.
bernard.bonello@insp.jussieu.fr

Abstract. We report on the first experimental evidence of negative refraction of surface acoustic waves, through a prism-shaped 2D phononic crystal having a solid matrix. The sample is constituted by a periodic array of air holes drilled in a Si substrate. The experiments are performed using a laser-ultrasonic technique.

1. Introduction
The negative refraction of electromagnetic waves is a well known phenomenon in optics. It was first predicted by V. G. Veselago who investigated in the late 60’s [1], the behavior of virtual media with both permittivity \( \varepsilon \) and permeability \( \mu \), simultaneously negative. These “double-negative” optical materials (also called “right-handed” media) are potentially interesting to create perfect optical lenses suitable to overcome the diffraction limit and to focus into a perfect image, all the Fourier components issued from a 2D object. More recently, M. Notomi has shown [2] that the effective index of a photonic crystal can also be controlled through its band structure and that negative refraction can also be observed in these artificial materials. In that case the negative refraction is the direct consequence of the bands folding and of the negative slope of some optical branches.

Similar approaches can be adopted with acoustic waves. Indeed, it is expected that the negative refraction of ultrasounds can be observed either in elastic metamaterials or in phononic crystal (PC’s). The former are constituted by a set of local resonators embedded into a matrix; the dimensions of these resonators must be much less than the acoustic wavelength in the host media, so that both negative specific mass and negative bulk modulus can be defined through homogenization theories. However, for this condition to be fulfilled, the local resonators must be coupled to the matrix through a medium exhibiting very specific physical property, making these artificial structures hard to elaborate. As well as for the photonic crystals, which are their optical counterparts, negative refraction can also occur in PC’s and actually, experimental evidences of this phenomenon were recently given by Sukhovitch et al.[3] who studied the refraction of bulk longitudinal waves, caused by a 2D PC immersed in water. However, in spite of their interest for potential applications, the negative refraction of acoustic waves propagating at the surface of 2D PC embedded into a solid matrix has not yet been investigated. Actually, these systems are good candidates to manipulate high frequency acoustic waves and better spatial resolution could therefore be achieved in acoustic lenses applications. In this work, we were interested in the refraction of Rayleigh waves at the interface of a silicon/air 2D PC. We first examine the refraction at the interface between two media and what are the necessary conditions for the phenomenon to occur. We then describe our laser-based experimental setup and we present results.
obtained with a prism-shaped 2D PC. The last part of this paper is devoted to discussion and conclusion.

2. Refraction in phononic crystals

One knows that an elastic wave impinging at the interface between two media with different elastic properties is refracted according to the Snell-Descartes law. The most usual situation is when the incident and the refracted beams are each on one side of the normal to the interface, giving rise to “positive refraction” and to the relation $v_g k > 0$, where $k$ is the wave vector and $v_g$ the group velocity.

There is another situation allowing the Snell-Descartes law to be fulfilled as well: it corresponds to the “negative refraction”, i.e. the case where the incident and the refracted beams are both on the same side of the normal. However, in that case, the continuity of $k//$, along the interface imposes that the group velocity and the wave vector obey the relation $v_g k < 0$. This situation is never encountered with natural media but can be achieved in artificial periodic structures like PC’s. Indeed, the periodic modulation of their elastic properties confers the PC’s remarkable properties such as the opening of band gaps, the folding of some branches and in turn, dispersion curves with negative slopes (Fig. 1). It is also important for a good understanding of the experimental results below, to notice that in these systems, the propagation of waves with $k$ vectors outside the first Brillouin zone is allowed as well. This can be seen from Fig. 2 where we have plotted two refraction schemes, that both are compatible with Snell-Descartes law. This shows that negative and positive refractions can simultaneously be observed in these systems.

3. Experiments

3.1 Experimental details

Refraction experiments were carried out on a silicon based 2D prism-shaped phononic crystal. The choice of silicon matrix was obviously related to further implementation in micro-system devices. The silicon substrate was patterned by photolithography and anisotropic chemical etching, with an air holes array drilled over a depth of a few hundred micrometers. The air inclusions were arranged at (100) surface with the triangular symmetry, the rows being parallel to the crystallographic directions [100] and [010] of silicon. The air holes array was arranged as a 2D prism-shaped phononic crystal.

We used a conventional laser ultrasonic setup to measure the vibrationnal properties of this sample. Our experimental technique is based on the laser generation and detection of surface acoustic waves.
(SAW’s) with a broad spectrum. Broadband acoustic pulses were generated at the surface of the sample by focusing light pulses issued from a frequency-doubled (532 nm) Q-switched Nd:YAG through a cylindrical lens (f:40 mm). The optical pulse duration was about 30 ps, the repetition rate was 20 Hz and the line shaped spot was about 5 mm long and 70 μm across. In all the experiments, the excitation zone was located a few millimeters ahead of the PC itself, in a region of the sample free from any air inclusion. The time dependence of the surface displacements was recorded using a Michelson interferometer in which the light source was a He-Ne laser. One beam of the interferometer was focused on the sample acting as one of the mirrors of the interferometer, to a spot size of ~25 μm, whereas the reference beam was reflected by an actively stabilized mirror. The interference pattern was collected with a high-speed photodiode. Both the cylindrical lens and the sample were mounted on translation stages in such a way that the probe beam could be scanned across the sample with a precision of about 1 μm. This noncontact technique allowed us to record the displacements field at any point at the surface of the sample and to resolve hence fine details of the interaction of the acoustic waves with the PC. Note that this interferometric method is only sensitive to the normal component of the displacements but not to the in-plane components and allows to record SAW’s having a spectral content extending up to a few MHz.

In the present case, the incident elastic waves generated in front of the structured area entered the PC at normal incidence; the refraction occurs at the interface PC/Si, where the waves are incident at 30°, after they have interacted with a large number of unit cells. The normal displacements were recorded in a large area of the sample, free from air inclusions, i.e. after the waves have travelled through the holes lattice (red dots in Fig. 3). The sample being semi infinite, the only surface modes to consider are Rayleigh waves.

3.2 Results and discussion

Two processes are at the origin of the signal measured within the “positive refraction zone”. One is obviously related to the refraction of Rayleigh modes along a non-folded branch, i.e. in the low frequencies part of the Brillouin zone. These modes having large wavelength as compared to the lattice parameter, they propagate in a homogenised medium and undergo therefore standard refraction. Another mechanism contributes to this positive refraction as well. It corresponds to modes along a folded branch but with k vectors outside the reduced Brillouin zone (k^2 in Fig. 2). In that case a translation by a Bloch vector (g in Fig. 2) leads to a “positive refraction”.

We show in Fig. 4, four typical experimental signals, recorded in the negative refraction zone, where according to the “standard” refraction scheme, no waves are expected. These data were recorded along a line parallel to the incident beam (green arrow in Fig. 3), far above the stripe in which the elastic energy would remain confined if the waves had not been refracted. An elastic
signature is clearly visible on these records that we ascribe to the negative refraction of the Rayleigh waves. We have checked that this signal cannot be the consequence of the natural anisotropy of silicon. Indeed, the slowness surface of Rayleigh waves, from which one can calculate the group velocity $v_g$ (i.e. the direction of propagation of the elastic energy), is almost circular in the plane (001) of silicon. As a consequence, both the phase velocity (parallel to the $k$ vector) and the group velocity (normal to the slowness surface) are almost parallel, whatever the direction of propagation in the plane of the sample.

![Figure 4](image.png)

**Figure 4.** Four taces showing the Rayleigh waves propagating in the negative refractive area

4. Conclusion

We attribute the observed signals to negatively refracted Rayleigh waves. The phenomenon is closely related to the folding of the dispersion curves and it appears therefore for some frequencies only. The next step of this study will be to investigate the frequency dependence. Fourier analysis is generally implemented to do this, but a good accuracy requires a good S/N, which is difficult to obtain after the waves have undergone diffusions on the inclusions. Another way is to excite monochromatic elastic waves through a transient grating scheme.

References

[1] V. G. Veselago, Sov. Phys. Usp. 10, 509 (1968).
[2] N. Notomi, Phys. Rev. B 62, 10696 (2000).
[3] A. Sukhovich, L. Jing, J. H. Page, Phys. Rev. B 77, 014301 (2008).
[4] T. Brunet, J. Vasseur, B. Bonello, B. Djafari-Rouhani, A.-C. Hladky-Hennion, J. Appl. Phys. 104, 043506 (2008).