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PROPAGACIÓN DE HACES ULTRASONICOS A LA SALIDA DE UN CRISTAL DE SONIDO

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ABSTRACT

Sonic crystals are media with a periodic modulation of the acoustic parameters, as the density and the bulk modulus. They have recently attracted a great interest, because of their potential applications in the control of sound propagation, used as reflectors, focusers or waveguides. All these properties are related with the dispersion introduced by the crystal anisotropy. We report on a phenomenon related with the spatial dispersion properties of the crystal: we analytically evaluate, numerically (FDTD) calculate, and experimentally measure the focusing properties of the propagated sound beam behind two-dimensional sonic crystal. Support from Spanish MEC, project FIS2008-06024-C03 and C02, from Universitat Politècnica de València through Project 20080025, and from Generalitat Valenciana by project GV/2009/036 are acknowledged.

INTRODUCTION

The spatially modulated materials, also known as sonic crystals (SC) in acoustics, or photonic crystals (PC) in optics, are famous mostly due to their celebrate temporal dispersion properties, in particular due to the appearance of band gaps in the dispersion curves (see [1] for photonic bandgaps in optics and [2] for phononic bandgaps in acoustics). We remind that the temporal dispersion is the frequency dependence on the propagation wavenumber $\omega = \omega(|\mathbf{k}|)$ where, in a 2D geometry, the wavevector defined by its parallel and perpendicular components with respect to propagation direction, $\mathbf{k} = (k_{\parallel}, k_{\perp})$. In addition to the peculiarities of temporal dispersion, the spatially modulated materials are known also to modify the spatial dispersion, allowing to manage the diffraction of the waves. The modification of the spatial dispersion can lead to effects such as the super-refraction, and the lensing and super-lensing (subwavelength focusing), of light [3] and sound [4].

The effects of lensing and super-lensing are, however, often treated inconsistently, in optics, as well as in acoustics. Usually the band structure and spatial dispersion curves (isolines of frequency) are first calculated, basing on the Bloch-wave theory. Then, depending on the slopes of the spatial dispersion curves the effective refraction index is calculated. Based on the calculated effective refraction index the geometric ray approach is applied, and the images of point sources are obtained. Some clarity must be brought into the problem of the lensing effects in PC or SC materials. This work aims to clarify the questions related with the focusing of sound beams behind the sonic crystal. Considering the spectral width of the beam and the dispersion curves of the crystal we distinguish three different propagative regimes (Fig.3). In particular we calculate the focal distances, the beam width and the quality of the beam at the waist (in the focal spot). These evaluations are checked by the FDTD calculations, as well as by experimental measurements.

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Figure 1 illustrates several things. On one hand it shows the frequencies of interest, where focusing is expected to occur. These regimes are close to the upper boundaries of the bands, where the dispersion curves are convex (corresponding to the negative diffraction regime). The curvatures of the dispersion curves at the areas of interest are positive, in contrast to the curves with negative curvature at lower frequencies indicating the normal diffraction. Only in this case of positive curvatures (negative diffraction) of the SC, the focusing of the beams behind the crystal is possible.

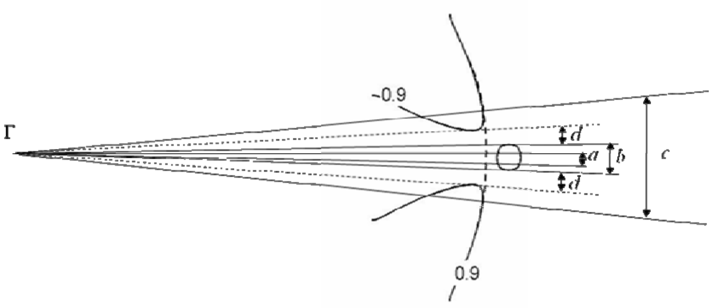

Fig.1. a) *The spatial dispersion curves as calculated by the harmonic expansion (see* [4] *for details of the method). The thick curves represent the areas considered, i.e. are calculated for wave frequencies close to the upper boundaries of the first and second bands. Red and blue curves denote the spatial angular spectrum incident of the incident beams.* b) *Different regimes considered: (a) broad beams with spatial spectra inside the "parabolic" area of the spatial dispersion curve, (b) beams of intermediate width, with spatial spectra filling the full width of the isoline of the given band; (c) narrow beams with the spatial spectra extending over isolines from the neighboring bands, and thus overlapping the bandgaps (in angular domain). The region denoted by (d) corresponds to the forbidden angles (band gaps in space spectra domain).*

Most relevant, Fig. 1 also shows the possibility of three different focusing regimes by a SC, depending on the beam size:

Region a). Broad Gaussian beam. No distortion. The width of the beam at the focal point is always the same as the width of the initial beam.

Region b). Beams of intermediate width. The off axis components acquire a nonparabolic phase shift, so the beam is focused at the same distance as follows from model a, however the width at the waist is not the same as at the incident in the SC.

Region c). Not only the phase of the beam (in the spatial spectrum domain) is distorted, but also its amplitude. The spatial spectrum components are removed (filtered out) at some values, corresponding to the angular band-gap (region *d* in Fig. 1(b)). This results to the complicated waist around the focal point.

NUMERICS

In order to illustrate the existence of the three different focusing regimes, numerical calculations have been performed, by solving Eq. (1) using the FDTD technique (see details e.g. in [4]) with input beams with increasing width. Figure 2 shows the resulting pressure distribution for a beam with constant frequency of 240 KHz, and a decreasing width, relative to the lattice period, of L/a = 8, 4 and 2 respectively. The observed behaviors correspond to the cases (i), (ii) and (iii) discussed above, and illustrated in Fig.1.

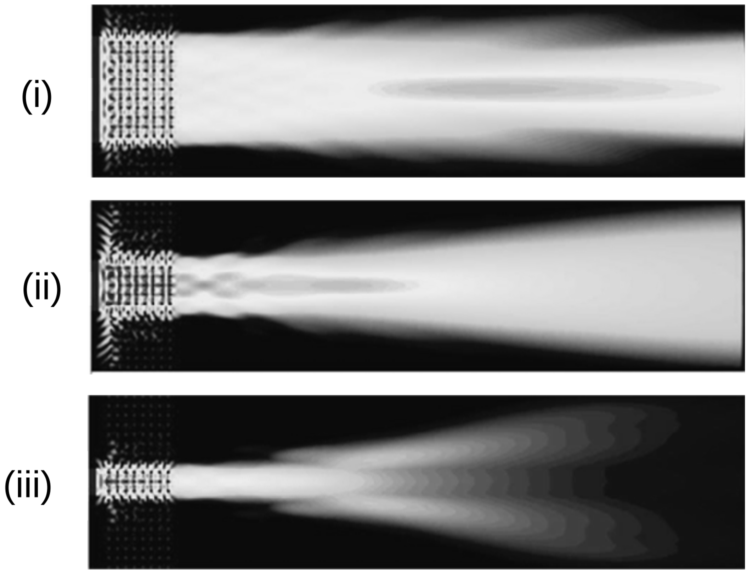

Fig.2. *Numerically calculated beam profiles. Three cases (a), (b) and (c) correspond to three relatively different width of the beams. The parameters are:* (a) *D* = 8*a*, (*b*) *D* = 4*a*, (*c*) *D* = 2*a*, *where D is the source diameter and the lattice period. The frequency is 240 KHz in all three cases.*

EXPERIMENT

The results have been checked experimentally in the case of a narrow beam, excited by a piezoelectric transducer. The emitted beam had a frequency-dependent half-width covering three to four lattice periods. The experimental setup is basically the same used in [5] to demonstrate self-collimation phenomenon of ultrasonic beams: The sonic crystal used was designed according the parameters described above, total length of the crystal being *l* = 10 cm.

The crystal was immersed in a plexiglass tank, filled with water as a host medium. A narrow ultrasonic source with radius R=1.25 cm was placed close to one of the flat boundaries of the crystal (entrance plane) oriented in the <100> direction, and the pressure distribution was measured with a needle hydrophone. The source radiates an ultrasonic beam with measurable amplitude in the frequency interval ranging from 150 to 260 KHz, which covers most of the frequencies of interest in the second propagation band. All the signal generation and acquisition process is based on a National Instruments PXI-technology controller NI8176, which also controls an OWIS GmbH two-axis motorized system that allows the hydrophone to scan the pressure distribution along the whole space beyond the exit plane of the crystal, for a given frequency component.

In order to visualize the beam propagation after the crystal and the focusing effect, in Fig. 3 we show the experimental measurements along the XZ plane, for three different frequencies.

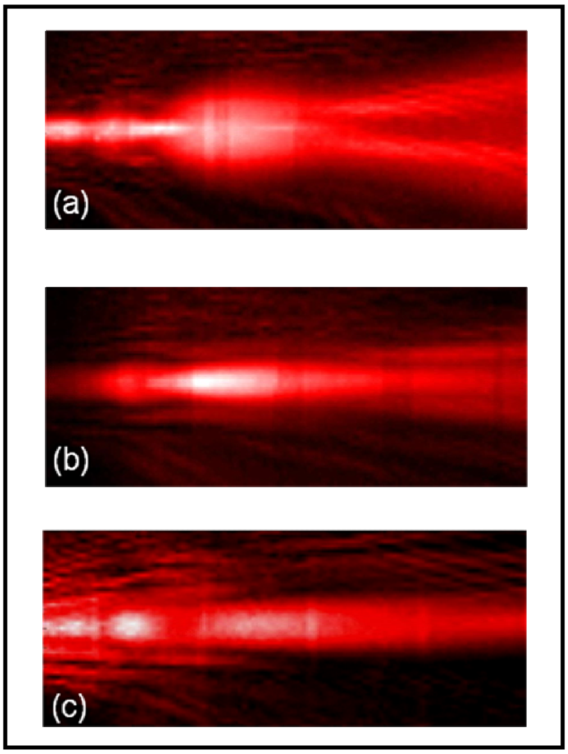

Figure 4. Experimental results for 225 KHz (a), 240 KHz (b) and 255 KHz (c). The spatial dimensions are 20X50 cm.

CONCLUSIONS

The experimental results show some unique features in the spatial distribution of the beams after crossing the crystal. Al low frequencies, close to the self-collimation point [Fig. 3(a)] is apparent a strong distortion of the beam in the neighborhood of the focal region, and a spatial separation of the field beyond the focus. The results are in accordance with the results of the numerical simulation shown in Fig. 2.

Three different propagation regimes behind a sonic crystal have been predicted and experimentally proved, depending on the spatial spectral component of the incident beam.