Acoustic channel drop tunneling in a phononic crystal

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We study both theoretically and experimentally the possibility of resonant tunneling of acoustic waves between two parallel guides created in a phononic crystal composed of steel cylinders in water. In the absolute band gap of the phononic crystal, ranging from 250 to 325 kHz, a full transmission band exists for propagation inside a straight waveguide. We show that the transfer of a particular wavelength can occur between two parallel waveguides coupled together through an appropriate coupling structure. The latter is composed of isolated cavities interacting with stubs located at the sides of the waveguides. © *2005 American Institute of Physics*.
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The study of phononic crystals, which are the acoustic analogues of photonic crystals,[1] has received increasing attention during the last decade. These composite materials, which are constituted by a periodic repetition of two different solid or fluid constituents, can exhibit absolute band gaps in their transmission spectra.[2,3] Due to their ability to confine and mold acoustic waves in structures whose basic units are at the size of the wavelength, these materials can find new useful applications such as elastic filters, wave guides, mirrors, or transducers. Similarly to their photonic counterparts, several phenomena such as guiding,[4–8] bending,[8,9] filtering,[6,7] and demultiplexing[10] of acoustic waves, have been predicted theoretically and/or observed experimentally in these structures. In particular, during the last few years, we have devoted a great deal of theoretical and experimental effort to the study of the propagation of acoustic waves in a guide (created by removing a row of cylinders) in a two-dimensional phononic crystal composed of steel cylinders in water, as well as the interaction of such a guide with a cavity or a stub. For instance,[6] a cavity inside the guide permits to select a particular frequency to be transmitted, while the presence of a stub at the side of a waveguide leads to zeros of transmission, removing a few frequencies from the transmission spectrum.

Based on the earlier knowledge, the aim of this letter is to investigate for the first time, both theoretically and experimentally, acoustic channel drop tunneling in a phononic crystal, i.e., the possibility of transferring one particular acoustic wavelength between two parallel waveguides coupled through an appropriate coupling element. The basic theoretical ideas for such a selective transfer to occur, leaving all other neighboring states unaffected, have been discussed thoroughly a few years ago by Fan *et al.* [11] The phenomenon was also demonstrated by numerical simulations in a photonic crystal. Subsequent works have adapted the same idea to other systems or models.[12,13] In the case of the phononic crystal discussed later, the coupling element is composed of two coupled cavities interacting with stubs located at the sides of the two parallel guides (see Fig. 1).

Our ultrasonic crystal is composed of a two-dimensional square array of steel cylinders in water. The elastic parameters of the materials are given in Ref. 10. The lattice parameter, a, is 3 mm and the diameter of cylinders is 2.5 mm, resulting in a filling fraction of 55%. Such a phononic crystal displays an absolute band gap ranging from 250 to 325 kHz.[5] Waveguides are formed (Fig. 1) by removing two parallel rods of steel cylinders along the direction of propagation (ΓX). The coupling element is constituted by two single-mode cavities, namely two vacancies obtained by removing two cylinders (see the dotted squares in Fig. 1). However, to ensure an efficient coupling between each cavity and the neighboring guides, we grafted a stub to the side of the guide. Let us notice that due to the simplicity of the geometrical model we were able to perform an experiment which is described in the second part of the letter.

Before going to the experiments, we first discuss the theoretical results. Numerical simulations are based on a finite-difference time-domain (FDTD) program we developed to calculate transmission coefficients through perfect or defect-containing phononic crystals. The FDTD method, first applied to photonic crystals[14] has been proven to be an efficient tool for the numerical simulation of acoustic wave propagation in composite materials and, in particular, in phononic crystals.[15] All details about the method are given in Ref. 15.

The incoming wave is a longitudinal pulse with a Gaussian profile along the X and Y directions. In the X direction, the incoming signal covers the entrance of port 1, leaving port 4 essentially unaffected. The transmitted signals are re-

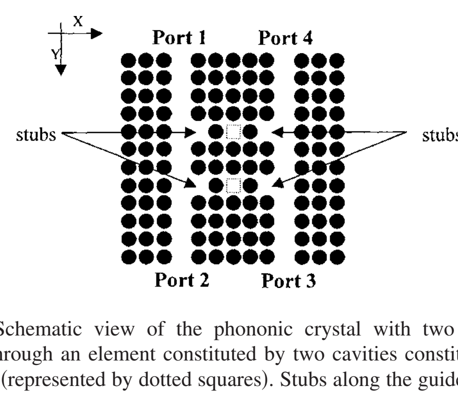

FIG. 1. Schematic view of the phononic crystal with two waveguides coupled through an element constituted by two cavities constituted by two vacancies (represented by dotted squares). Stubs along the guides ensure the efficiency of the coupling. The extremities of the two waveguides are labeled as ports 1–4.

corded as a function of time at ports 2, 3, and 4, integrated over the cross section of each waveguide, and finally Fourier transformed to obtain the transmission coefficients versus frequency. Spectra are normalized with respect to the signal obtained without the phononic crystal sample present.

Figure 2 displays the theoretical transmission along a single straight waveguide in the cases when the guide is perfect, when a stub is inserted at the side of the guide, or when a single cavity is inserted inside the crystal. The guide exhibits a full transmission band in the frequency range (270–300 kHz) that covers a large part of the phononic crystal stop band. The insertion of the cavity (respectively, a stub) gives rise to a filtering (respectively, a rejecting) of a narrow frequency domain around 290 kHz in the transmission spectrum. It is interesting to notice that the resonances of both defects occur almost at the same frequency (f=290 kHz), which again is in the favor of the coupling geometry shown in Fig. 1.

Figure 3 shows the theoretical transmission through different ports of the structure when the incident signal is launched from port 1. It can be observed that the direct transmission at port 2 drops almost to zero at the frequency of 290 kHz. At the same time, a significant peak of transmission occurs at port 3, with a magnitude comparable to the loss at port 2, while the signal at port 4 remains weak. This means that, at this frequency, the incoming signal is essentially transferred to the second wave guide towards port 3, leaving all other exits of the structure unaffected. In other words, the input signal tunneled through the coupling element and dropped inside the second wave guide.

To obtain a direct confirmation of the demultiplexing phenomenon, the FDTD computation was used to simulate a monochromatic source at the frequency of 290 kHz. The computed displacement field along the direction of propagation is displayed in Fig. 4. The transfer of the input signal from port 1 to port 3 is clearly apparent together with an absence of signal at port 2. Let us recall that, due to the periodicity of the structure along the X direction, the displacement field in the exit domain results from a superposition of the signals coming out of ports 3 in two neighboring cells. At port 4, a weak signal is still observed, probably due to the incident waves launched from the sources in two neighboring cells.

As already mentioned, the simplicity of the structure has been chosen with the aim of realizing the corresponding experiment. The experimental setup is based on the ultrasonic immersion transmission technique.[7] A couple of wide-bandwidth transmitter-receiver generator (Panasonic model 5800) produces a short duration pulse which is applied to the source transducer launching the probing longitudinal waves. The signal detected by the receiving transducer is detected by the pulser/receiver, amplified, and then digitized by a digital sampling oscilloscope. To reduce random errors, 1000 measurements are averaged before a fast Fourier transform is performed to obtain the transmission spectrum. The system is first calibrated with no sample present; a reference signal is digitized and its spectrum is used to normalize the subsequent transmission spectra.

The measured transmissions are displayed in Fig. 5. The input transducer was positioned at port 1 and the output transducer at either port 2 or port 3. The continuous and dashed lines represent the transmission spectra at ports 2 and 3, respectively. A sharp drop in the amplitude at port 2 is seen to occur together with a coincident increase in the amplitude at port 3, occurring both at a frequency of 290 kHz as predicted by theory. At resonance, the transmission at port 2 is estimated to be 10–15 dB lower than the plateau far from resonance. At the same time, the amplitude observed at port 3 is much higher at resonance than out of resonance, indicating transfer of energy from port 1 to port 3. These observations are in rather good agreement with theory. However, a

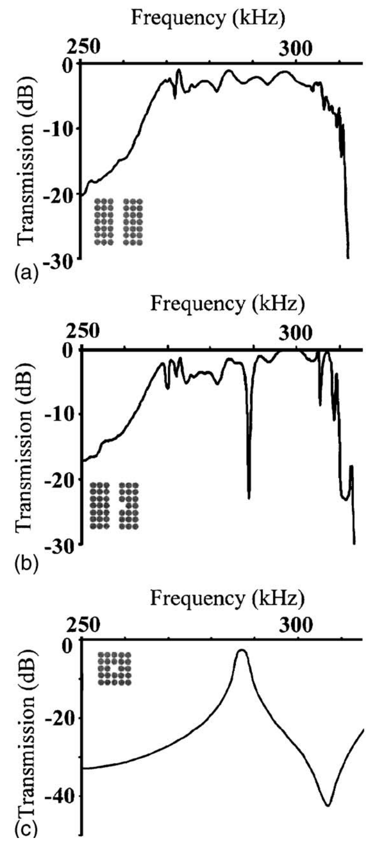

FIG. 2. Calculated transmission spectra: (a) through a straight wave guide in the phononic crystal, in the frequency range of the absolute band gap (from 250 kHz and 320 kHz); (b) through a straight waveguide when a stub is inserted at the side of the guide; (c) for a single cavity inside the crystal.

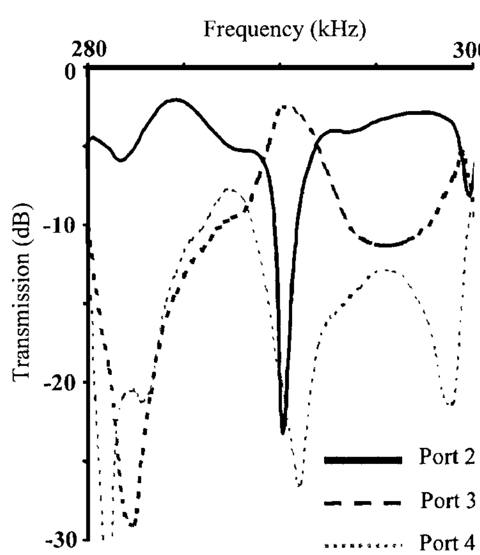

FIG. 3. Numerical transmission spectra at the output ports 2, 3, and 4 for an input Gaussian excitation coming from port 1. At a frequency of 290 kHz, the incident wave drops from the first to the second waveguide.

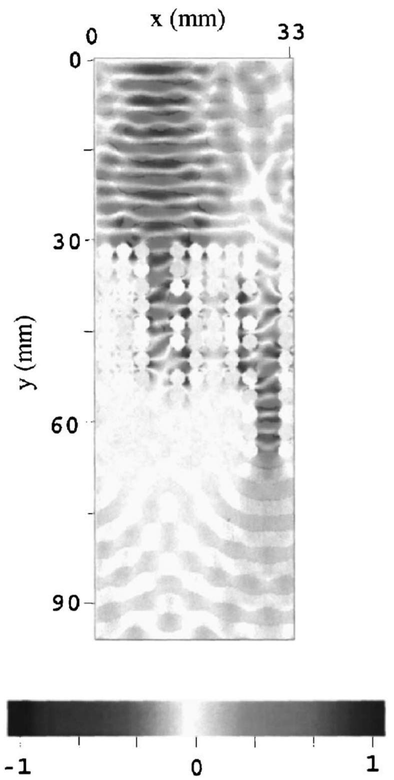

FIG. 4. Calculated displacement field along the direction of propagation at a frequency of 290 kHz, averaged over one period of oscillation. The red color (respectively, blue) corresponds to the highest (respectively, lowest) value of the displacement field given in arbitrary units.

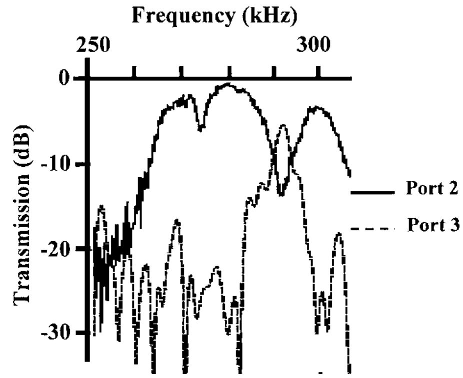

FIG. 5. Experimental transmission spectra for the phononic crystal at the output ports 2 and 3. The channel drop process from port 1 to 3 is observed at 290 kHz as predicted numerically.

slight discrepancy appears between theory and experiment when one compares the magnitude of the maximum transmitted signal at port 3 (at resonance) with the plateau of transmission at port 2 (out of resonance). While these magnitudes are quite comparable in theory, the maximum at port 3 remains 3 to5 dB lower than the plateau at port 2 in experiment. There are at least two reasons to explain this difference. First, our FDTD calculation does not take into account dissipation. For instance, we observed a few years ago[12] a similar behavior in demultiplexing experiments of electromagnetic waves in the microwave frequency range using coaxial cables. Second, the theoretical evaluation of the transmitted signal is performed exactly at the exit of each port, while in experiments the receiver transducer is placed at some distance of the exits. In view of the earlier points, we estimate that the agreement between theory and experiment is convincing as regards the phenomenon of signal drop from one wave guide to the other.

In conclusion, we have investigated experimentally and numerically an acoustic model of channel drop processes, well-known in the community of photonic crystals since the pioneering work of Fan *et al.*[8] The general device is composed of two continuum waveguides and a coupling element constituted by two cavities inserted in a phononic crystal composed of steel cylinders in water. The two cavities are coupled to the waveguides through stubs grafted at the sides of the guides. This basic model has been chosen to achieve experimental measurements to compare with theoretical predictions. We have demonstrated that at a certain frequency an energy transfer between the two continuum waveguides occurs through localized states of the coupling element. We have shown that this frequency corresponds to the resonant mode of the coupling element. Clearly, the demultiplexing could be improved or tuned by adjusting other parameters in the model such as the diameters and the nature of the cylinders surrounding the cavities in order to modify their interaction. Calculations in this direction are underway. Such devices could find applications in frequency division multiplexing in acoustical systems.

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