EXPERIMENTAL FULL BAND-GAP OF A SONIC-CRYSTAL SLAB MADE OF A 2D LATTICE OF ALUMINUM RODS IN AIR

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Abstract

We present here experimentally obtained band-gap characteristics of a sonic-crystal slab composed of a two-dimensional square-array of aluminum rods in air, which is constructed between a pair of parallel metallic sheets with a spacing smaller than the wavelength. We observed a full band-gap, that is a band-gap common to the [100] and [110] directions of plane-wave propagation, between 14.1 kHz and 18.7 kHz, in the normalized frequency between 0.49 and 0.65, with a transmission ratio smaller than -30 dB using a tone-burst technique. These results agree well with the numerical ones. The realization of a full band-gap in the sonic-crystal slabs indicates a further development to various shapes of sonic wave-guides and sonic circuit including directional couplers, ring resonators, filters and splitters.

Introduction

Wave propagation in the periodic structures has been reviewed for photonic crystals by Yablonovitch[1] in 1993, and the concept of full band-gap was introduced, where a plane wave can not propagate in the photonic crystal in any direction. The theoretical possibility of sharp bend of the waveguide on a wavelength scale, discussed by Mekis *et al.*[2] in 1996, stimulated the practical research on photonic crystals.

Following the theoretical discussions for elastic waves by Economou and Sigalas[3] and Kushwaha *et al.*[4], Montero de Espinosa *et al.*[5] presented the first observation of an ultrasonic full band-gap in a two-dimensional composite of a mercury alloy cylinder array embedded in aluminum. For sound waves, Sánchez-Pérez *et al.*[6] showed an insufficient band-gap of a two-dimensional array of rigid cylinders in air.

We reported the correspondence relationships between two-dimensional sonic crystals and photonic crystals, and obtained full band-gaps of two-dimensional sonic crystals made of rigid rods in air[7], developing the FDTD method for the numerical simulation of sound waves in the sonic crystals. In order to realize a two-dimensional wave propagation in the three-dimensional real world, we constructed a sonic crystal made of an array of long acrylic-resin rods in air, and observed experimentally a full band-gap[10].

An alternative promising realization of a two-dimensional sonic crystal is reported in this presentation. Namely an array of short aluminum rods was constructed between a pair of parallel metallic sheets in air. The longitudinal modes of the sound waves in the wave-guide slab, whose wave fronts are perpendicular to the slab surfaces, were injected by a tweeter, a high-frequency acoustic transducer of a long plane membrane. We observed a relatively wide "full band-gap" of a transmission ratio smaller than -30 dB using a tone-burst technique. The results agree well with the numerical ones obtained by FDTD method.

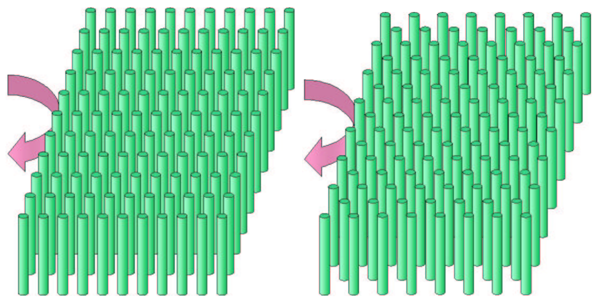
The realization of a full band-gap in sonic-crystal slabs indicates a further development to various shapes of sonic wave-guides and sonic circuits including directional or filtered couplers, ring resonators and splitters.

Two-dimensional sonic-crystal bulk

First we describe the fundamentals of sonic-crystal bulk, and show the measured band-gap structures of a two-dimensional sonic-crystal bulk.

Characteristics of sonic crystal

A type of two-dimensional sonic crystals in the three-dimensional space has a uniform structure along an axis long compared with a wave-length, as shown in Fig. 1. If a plane wave cannot propagate in the crystal along any symmetrical axes, [100] and [110] for the square lattice, any two-dimensional wave cannot enter into the crystal. Such a frequency range is called "full (or complete) band-gap." These characteristics are determined first by geometrical parameters, namely the ratio of the sonic wavelength λ to the lattice constant a, and the ratio of the radius r of a scattering rod to the lattice constant, in other measure, the filling fraction $\pi r^2/a^2$;



(a) Direction [100] (b) Direction [110]

Figure 1: Sonic-crystal. Red arrows show the incident and reflected plane waves.

second by the material parameters, namely $\overline{K}$ the bulk modulus of the scatterers normalized with that of the host, and $\underline{\rho}$ the density of the host normalized with that of the scatterers[7].

Construction of a two-dimensional sonic-crystal bulk and full band-gap measurement

Based on the numerical simulations of the sound wave propagations in a periodic structure of acrylic-resin rods in air[10], we constructed a sonic-crystal bulk shown in Fig. 2. The lattice constant is 24.0 mm, and

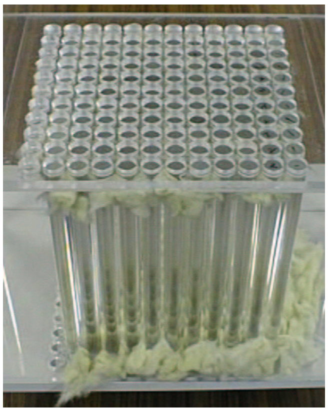


Figure 2: Sonic-crystal bulk of acrylic-resin rods in air.

the radius of the scattering rods is 10.2 mm. The number of the scatterers is only 10×11.

Using burst sound waves of a temporal duration of 8 ms, and gating the steady-state part of the transmitted sound waves, and further using a curve-fitting technique, a wide-range dynamic measurement of the transmission ratio of the sonic crystal was achieved. As

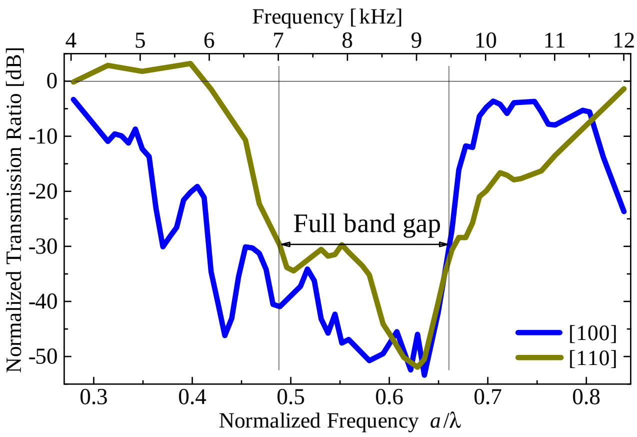


Figure 3: Measured transmission ratio of the sonic-crystal bulk of acrylic resin rods in air.

shown in Fig. 3, a full band-gap was obtained clearly between 7.0 kHz ~ 9.5 kHz, and in the normalized frequency a/λ, between 0.48 and 0.66 with the transmission ratio smaller than -30 dB.

Constraint of two-dimensional wave propagation

This type of sonic crystals are only for two-dimensional sound waves whose wave-fronts are uniform in the direction parallel with scattering rods. The sound waves from a speaker of a finite radius have diffracted and curved components of the wave-front. In order to eliminate the diffracted waves from the detection, we have placed a sufficient mount of glass wool at both ends of the scattering rods as shown in Fig. 4.

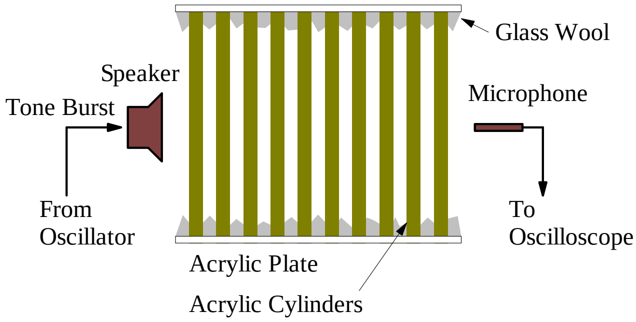


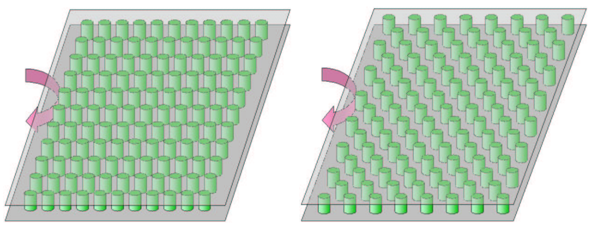
Figure 4: Measurement of the transmission ratio of sonic crystal.

sonic-crystal slab

Alternatively a two-dimensional wave propagation is expected to be achieved by the mode selection properties of a thin wave-guide slab. We describe a construction of a two-dimensional sonic-crystal slab and the measured band-gap characteristics.

Structure of a sonic-crystal slab

First we prepare a sonic wave-guide slab in air made of a pair of parallel rigid plates, whose spacing should be smaller than a wavelength. A periodic array of scatterers are constructed in the wave-guide slab, as illustrated in Fig. 5. The guided modes of the wave-guide slab whose wave-fronts are parallel to the scatterers will behave as two-dimensional sound waves, and will have a theoretically expected band-gap characteristics.

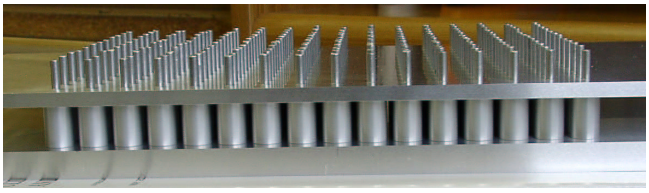


(a) Direction [100] (b) Direction [110]

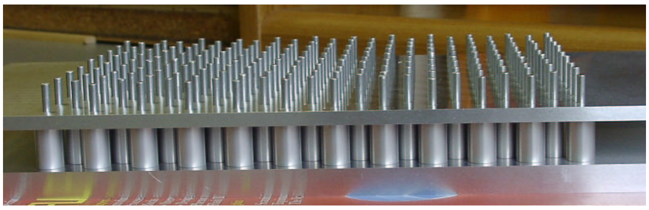
Figure 5: Sonic-crystal slab. Red arrows illustrate the reflected plane waves.

Construction of a sonic-crystal slab

We have constructed two sonic-crystal slabs to measure the fundamental transmission characteristics, one for a [100]-direction plane wave as shown in Fig. 6(a), and the other for a [110]-direction plane wave as shown in Fig. 6(b). The materials are all aluminum metal. Both wave-guide slabs have a spacing of 15 mm. The



(a) For direction [100]



(b) For direction [110]

Figure 6: Sonic-crystal slabs of aluminum rods.

lattice constant is 12.0 mm, and the radius of the scattering rods is 5.0 mm. The number of the scatterers is 16×12 for [100]-direction, and the equivalent number of scatterers are aligned for [110]-direction.

Band-gap measurement

Applying a burst wave like in the case of the two-dimensional sonic-crystal bulk, and gating the steady-state response of the transmitted sound waves, and finally using a curve-fitting technique, a wide-range dynamic measurement was achieved. The magnitude of the sound-wave transmitted through the sonic-crystal slab was normalized by that transmitted through the sonic wave-guide slab without any scatterer. Figure

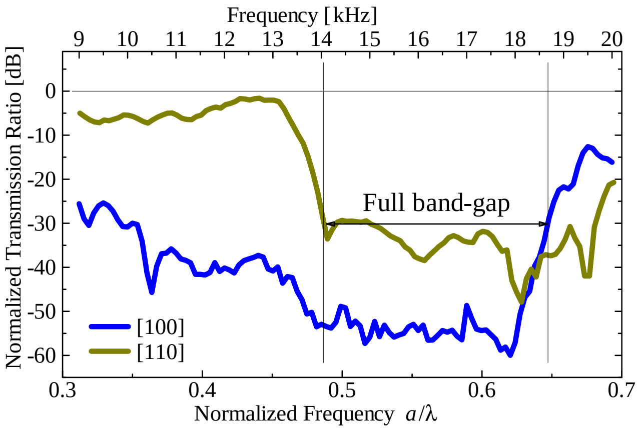


Figure 7: Measured transmission ratio of the sonic-crystal slab.

7 is a preliminary result of the transmission characteristics, and shows a full band-gap between 14.1 kHz $\sim$ 18.7 kHz, and in the normalized frequency between 0.49 and 0.65 with the transmission ratio smaller than -30 dB. The scaling property of the photonic crystal[8] is fulfilled also in the full band-gap between this sonic-crystal slab and the sonic-crystal bulk shown in Fig. 3.

Flexible sonic wave-guides in the sonic-crystal slab

Sonic wave-guides are most interesting application of the full band-gap properties of sonic crystal[7][11][12]. To remove any scatterer or replace it with a scatterer of different size, we have invented a flexible structure of sonic-crystal slab as shown in Fig. 8. The structure is already adopted for the sonic-

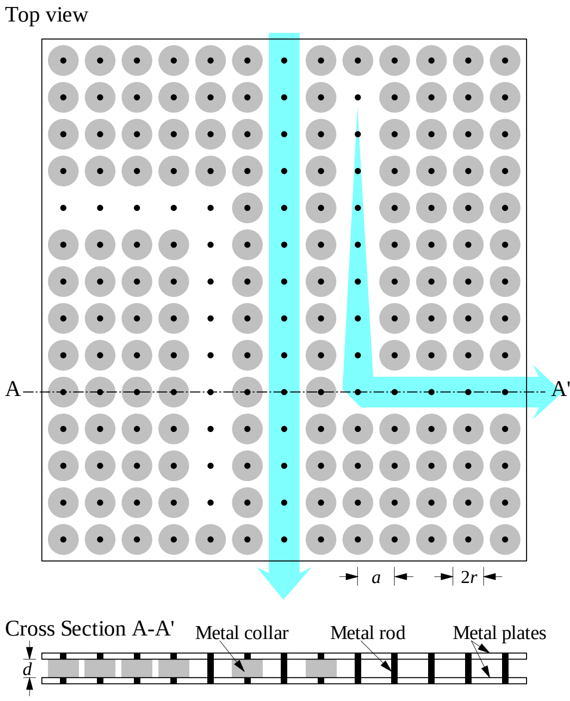


Figure 8: A structure of sonic-crystal slab flexible for sonic circuits.

crystal slabs shown in Fig. 6. A thin aluminum rod of a radius of 3.0 mm is placed at every lattice point. An actual scatterer is made by an aluminum collar through the rod. The thin rod alone does not practically effect the sound wave propagation in the wave-guide, and it may be removed there. An example of coupled wave-guides is shown in Fig. 8. Coupling ratio is controlled by the radius of the collars between the wave-guides. Sharp bends of the wave-guides in half-wavelength scale are allowed for the sound waves in the full band-gap of the sonic-crystal slab.

Concluding Remarks

We have reported a new idea of sonic-crystal slab which is an experimental realization of the theoretical two-dimensional sonic crystal, and obtained a full band-gap in the theoretically expected frequency range. Based on the theoretical and experimental results, we have invented a structure of flexible functional integrated acoustic circuit composed of coupled wave-guides, wave splitters, filters and ring resonators, including sharp bends of the wave-guides.

Acknowledgments

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