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EXPERIMENTAL STUDIES ON TWO-DIMENSIONAL ACOUSTIC DEFECT-MODE WAVEGUIDES IN A SONIC/PHONONIC CRYSTAL

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Abstract

Two-dimensional acoustic defect-mode waveguides (DMWGs) were constructed by removing every second scatterer from a sonic/phononic crystal along the intended paths for waveguides. The host sonic/phononic crystal was composed of a square array of acrylic resin cylinders in air with a diameter of 5.0 mm. The lattice constant was 6.25 mm with a Bragg reflection at around 27.6 kHz at room temperature. Various shapes of DMWGs were fabricated, namely most simple straight waveguides, a perpendicularly bending one, and a waveguide with a branch or with a crossroads. Their transmission spectra were measured using a network analyzer with a high-frequency speaker, i.e. a tweeter, and a wide-band microphone. The theoretically expected band-pass spectra of DMWGs were confirmed experimentally as follows. (1) A clear 10 dB passband of the straight DMWG was observed between 30.1 and 33.1 kHz with a transmission of -0.52 dB per lattice constant. (2) The transmission was about 0 dB at the center of the passband and about -30 dB at the outside of the passband. (3) The passband was influenced practically neither by the existence of a bend, a branch nor a crossroads in the DMWG. The DMWG was verified to work not only as a novel acoustic waveguide but also as a good band-pass filter.

1. INTRODUCTION

Since the early experimental realization of full, or complete, band gaps of sonic/phononic crystals[1, 2], acoustical waveguides have been the main interest for the application of these crystals. Although theoretical expectations have been reported, few experimental studies have been reported on acoustic waveguides in sonic/phononic crystals. Acoustic waveguide bulks fabricated in a sonic crystal consisting of acrylic resin cylinders in air were first reported by Miyashita and Inoue[2, 3]. The acoustic waveguide was constructed by removing a line of cylinders. The measured guided-to-leakage ratio (GLR) was about 30 dB in the lower-half region of the full band gap of the host sonic crystal bulk. A tunable waveguide fabricated in a phononic crystal composed of steel cylinders in water was theoretically investigated by Khelif *et al*[4]. In this case, the waveguide was fabricated by replacing a line of cylinders with a line of tubular steel cylinders. It was shown numerically that the transmission frequency was tunable and varied with the inner radius of the tubes.

In contrast to these crystal bulks, Miyashita reported experimental studies on acoustic waveguides with a bend and also on coupled waveguides, both of which were fabricated in a universal slab platform used for various types of acoustic waveguides[5]. At the center of the full band gap around 16.9 kHz, the intensity of the guided wave was highest over a bandwidth of 0.5 kHz with a GLR of more than 20 dB. These results were included in a review paper of sonic crystals and sonic waveguides[6].

In contrast to the above mentioned conventional waveguides, the acoustic waves of novel waveguides named defect-mode waveguides (DMWGs) have been studied by Khelif *et al.*[7] and Miyashita *et al.*[8] The former includes a theoretical and experimental study on a short straight DMWG fabricated by removing every second scatterer along a line in a phononic crystal of steel cylinders in water. Nearly 100 % transmission was measured throughout the passband. The latter theoretically investigated waveguides in a sonic crystal of acrylic resin cylinders in air. Although an elastic FDTD method, which includes shear waves in solid, was used, practically no acoustical waves were excited in the acrylic resin cylinders. Namely the longitudinal waves in air played the main role in the acoustic characteristics; thus such artificial crystals are frequently called sonic crystals. Straight and bending DMWGs were discussed in comparison with the conventional waveguides. The clearly distinguished passband of a flat transmission of the DMWG of nearly 0 dB is in a big contrast to the passband of the conventional waveguide with a -6 dB transmission. Another attractive and useful property of the DMWGs was made clear, namely, acoustic waves turn at a bend similarly to successively excited defect modes which travel from a defect to the neighboring defect in a straight DMWG. Both straight and bending DMWGs have a 0 dB flat passband at a normalized frequency between 0.54 and 0.59, where normalized frequency is equal to the lattice constant divided by the wavelength in the host material.

In this paper, we report an experimental study on the above mentioned novel and attractive characteristics of DMWGs in air.

2. EXPERIMENTAL PROCEDURE

We are treating two-dimensional (2-D) waves in our theoretical investigations. Note that 2-D waves in the real three-dimensional world mean that they have a uniform distribution along an axis, usually along the z-axis, such as plane or cylindrical waves propagating in the $x - y$ plane. It is considered that this condition is satisfied practically when the wavefronts are uniform along the z-axis sufficiently wider or longer than the wavelength, e.g. over several or ten times the wavelength of the relevant waves. Based on this point of view, the following experimental investigations were performed.

2.1. Fabrication of a two-dimensional array of acrylic resin cylinders in air

We fabricated a universal platform for two-dimensional sonic/phononic crystals. The platform consists of two parallel aluminum plates which have a precise two-dimensional square array of 31×15 holes with a diameter of 5.0 mm and a lattice constant a of 6.25 mm. A view of the platform partially filled with cylinders is shown in Fig. 1. Here, the distance between the two aluminum plates, namely, the height of the artificial crystal, is 12.0 cm. The spacing of the top

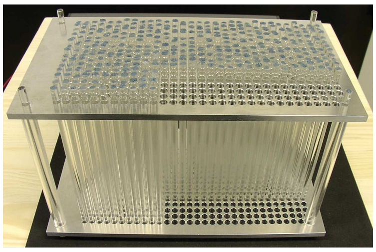


Figure 1. Universal platform for a two-dimensional artificial crystal partially filled with acrylic resin cylinders. The lattice constant a is 6.25 mm and the diameter of the holes for the cylindrical scatterers is 5.0 mm. The maximum size of the array is 15 $\times$ 31.

and bottom plates can be adjusted under the condition of two-dimensional approximation of the wave propagation in the real three-dimensional space, which is fulfilled if the structure is uniform over more than several relevant wavelengths in this direction. The first Bragg frequency, which is most interesting for our sonic/phononic crystals, is around 28 kHz for sound waves in air at room temperature. The scatterers are made of resin, metal, wood, or any other substance from which uniform cylinders or tubes can be made.

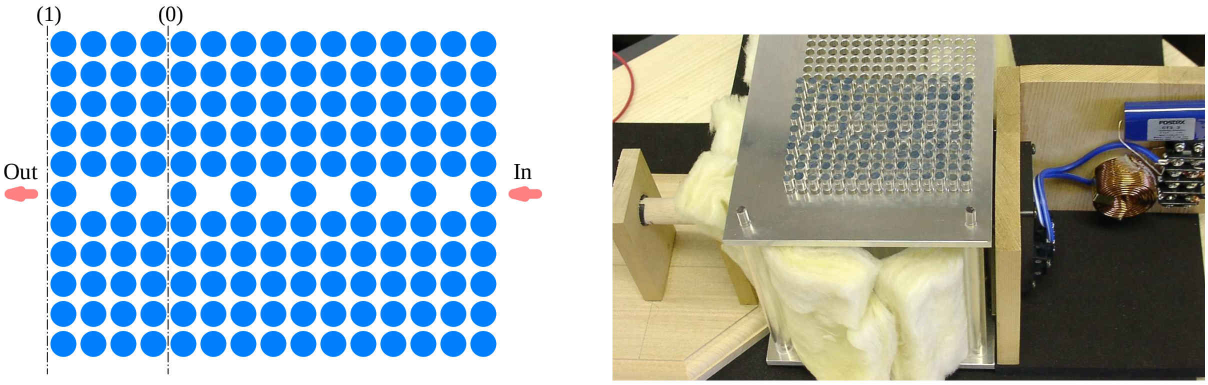
2.2. Experimental method of measurement

In order to achieve two-dimensional sonic irradiation into a narrow slit of the waveguide, we used a tweeter (Fostex FT7RP) with a rectangular aperture of 7 $\times$ 50 mm^2 for a cylindrical sound source. The available frequency range is 3 $\sim$ 45 kHz. Sound detection was performed using a wide-band small-head 1/4 inch microphone (Ono-Sokki MI-1531) with an amplifier (Ono-Sokki MI-3140) and a DC power supply (Ono-Sokki SR-2200). The frequency response is 10 Hz $\sim$ 100 kHz. The source electric signals were generated and the received signals were measured using a network analyzer (Agilent Technologies 4395A) with a reflection/transmission test unit (Agilent Technologies 87512A). The available frequency range is 10 Hz $\sim$ 500 MHz. The sweep frequency range was from 20 to 40 kHz, and the intermediate frequency (IF) bandwidth was adjusted to 100 Hz to prevent the inclusion of the sound signals reflected from the surrounding objects in the usual laboratory. The sweep time was then adjusted to 11.82 s. Normalized transmission spectra were calculated by dividing the raw measured data of the transmitted sounds by the raw data measured just in front of the tweeter in the same alignment without the scatterers of the sonic/phononic crystal.

3. EXPERIMENTAL RESULTS

3.1. Transmission spectrum of straight DMWGs

The most fundamental DMWG, namely, a short straight one was fabricated in a sonic crystal with an array of 11 $\times$ 11 acrylic resin cylinders, and a longer straight DMWG in a 15 $\times$ 11 crystal. Their cross sections are shown in Fig. 2(a), and their ends are indicated by lines (0) and (1), respectively. The experimental setup of the latter DMWG is shown in Fig. 2(b). The tweeter was placed just in front of the inlet of the waveguide. The acoustic waves guided along



(a) (b)

Figure 2. Two-dimensional straight DMWG of acrylic resin cylinders in air. The lattice constant a is 6.25 mm and the diameter of the scatterers is 5.0 mm. The width of the crystal is 11 a and the length of the waveguide is 15 a. (a) Cross section of the straight DMWGs. (b) Photograph of the DMWG with a tweeter (right) and a microphone (left).

the DMWG was detected by the microphone just outside the outlet of the waveguide. Sound reflections from the supporting acrylic resin pipes, from the wooden baffle plates used for the tweeter and the microphone, and from the surrounding objects in the room were reduced by glass wool, as shown in Fig. 2(b), and by an adequately narrow IF bandwidth of 100 Hz for the network analyzer. The frequency range of the observation was from 20 to 40 kHz, i.e., a normalized frequency (a/λ) from 0.362 to 0.724.

The obtained frequency characteristics of the normalized transmission are shown by solid lines in Fig. 3. A clearly distinguishable and relatively flat passband was experimentally ob-

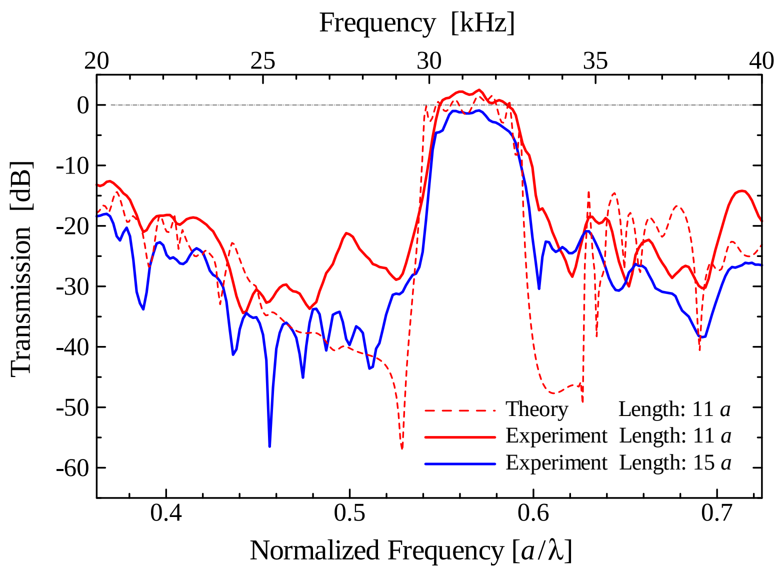


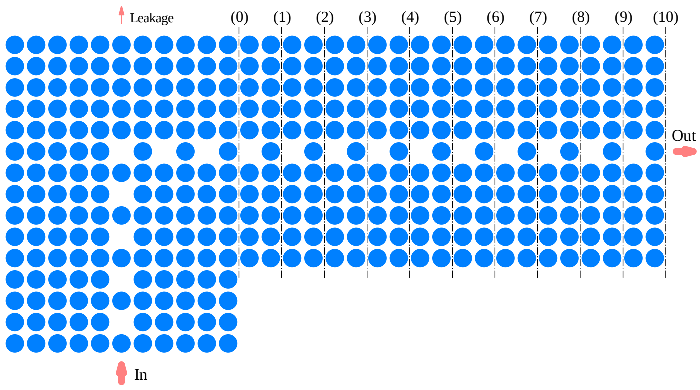
Figure 3. Experimental and theoretical transmission spectra of straight DMWGs.

tained at the normalized frequency from 0.545 to 0.594 for both straight waveguides of lengths of 11 a and 15a. The transmission of the passband of a DMWG with length 11 a was more than

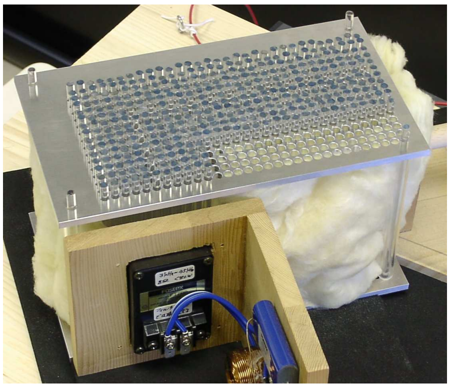
0 dB, as expected from the theoretical prediction[11], which is shown by a broken line in Fig. 3. The transmission decreased from 1.7 dB for a length of 11 a to -1.4 dB for a length of 15 a. The theoretical passband begins at a slightly lower frequency of 0.539 than the experimental frequency of 0.545. The transmission is fragile outside the passband, namely, sensitive to the environmental conditions of reverberation, and difficult to be fairly coincide with the theoretical results in the dB scale.

3.2. Transmission of long DMWGs with a bend

A long DMWG with a bend is very interesting for filtered waveguide applications. Namely the frequency components of the input acoustic waves inside the passband, are selected clearly and guided toward the devices in the next stage. A long DMWG with a bend was constructed as shown in Fig. 4. The first straight section of the DMWG from the inlet to the bend is composed of 10 lattices, and the long straight section from the bend to the outlet is composed of 26 lattices. In order to estimate the transmission of the DMWG, the straight part of the DMWG after the bend was cut back from length (10) to length (0) as indicated in Fig. 4(a).



(a)



(b)

Figure 4. Two-dimensional DMWG with a bend composed of acrylic resin cylinders in air. The lattice constant a is 6.25 mm and the diameter of the scatterers is 5.0 mm. The maximum width is 15 a and the length is 31 a. (a) Cross section of the long bending DMWG. (b) Photograph of the DMWG.

Experimental setup of the full long DMWG is shown in Fig. 4(b). The sound source and its detection and the sonic crystal fabrication were carried out in fundamentally the same manner as the above-mentioned straight DMWGs. Leakage waves were also detected in this layout, which propagated straight without turning around the bend.

In Fig. 5, the obtained frequency characteristics of the normalized transmission are shown by thick black and red solid lines for waveguide lengths (0) and (10), respectively, by dotted and broken lines for lengths (1)-(9), and by a thin gray solid-line for the leakage wave. A passband is clearly recognized for each waveguide length in approximately the same normalized frequency range. The lowest normalized frequency of the passband is 0.545 for all lengths. The highest frequency of the passbands decreases slightly from 0.596 to 0.590 as the waveguide length increases from (0) to (10). For length (0), the maximum transmission is 2.8 dB and the average transmission in the passband is 1.5 dB. For a long DMWG of length (10), the maximum transmission is -7.6 dB and the average is -9.8 dB. From these results, the average transmission along the DMWG is estimated as -0.52 to -0.565 dB per lattice constant a. Finally, the

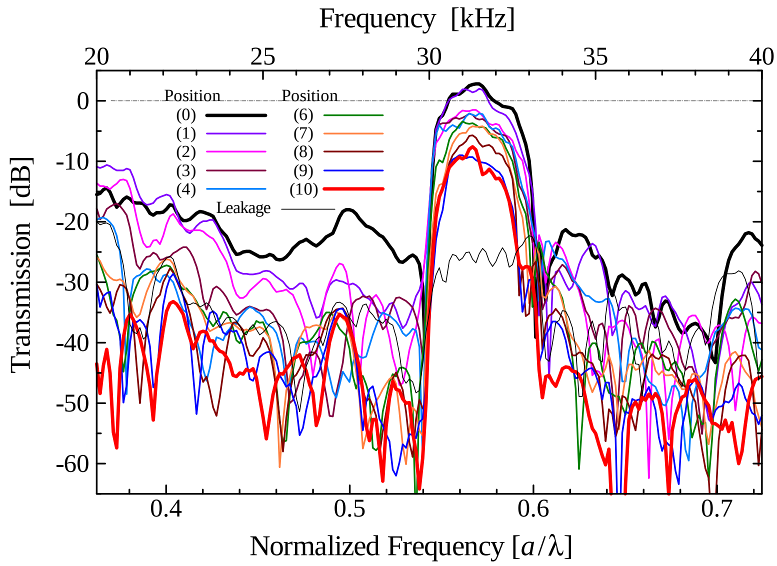


Figure 5. Experimental transmission spectra of bending DMWGs for various lengths of waveguide.

average level of the leakage sound is -26 dB over the passband of the DMWG. It is noted that this level is approximately the same as the transmission outside the passband as shown in Fig. 5.

3.3. Branch or crossroads in DMWG

At the final part of the long DMWG, a branch or a crossroads was constructed as shown in Fig. 6. A defect at the crossroads works as a junction of four waveguides. The acoustic waves which

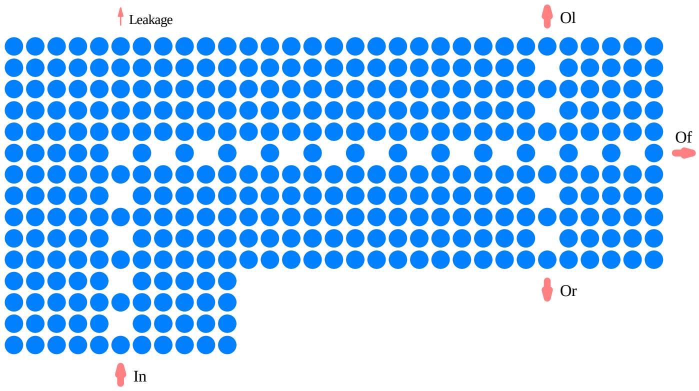


Figure 6. Two-dimensional DMWG with a crossroads.

arrived at the junction defect after propagating along a waveguide are expected to couple with the defects surrounding the junction defect from theoretical and numerical investigations[8, 11, 10]. The sound waves were detected at the straight front outlet Of and at the left outlet Ol, as indicated in Fig. 6. The measured acoustic transmissions are approximately -12 dB for both outlets as shown in Fig. 7. The passband is from 0.545 to 0.594 and practically the same as that of the above long DMWG with no crossroads which is shown also in Fig. 7 by a gray line. The transmissions do not behave in a simple manner in the passband; however, the output acoustic

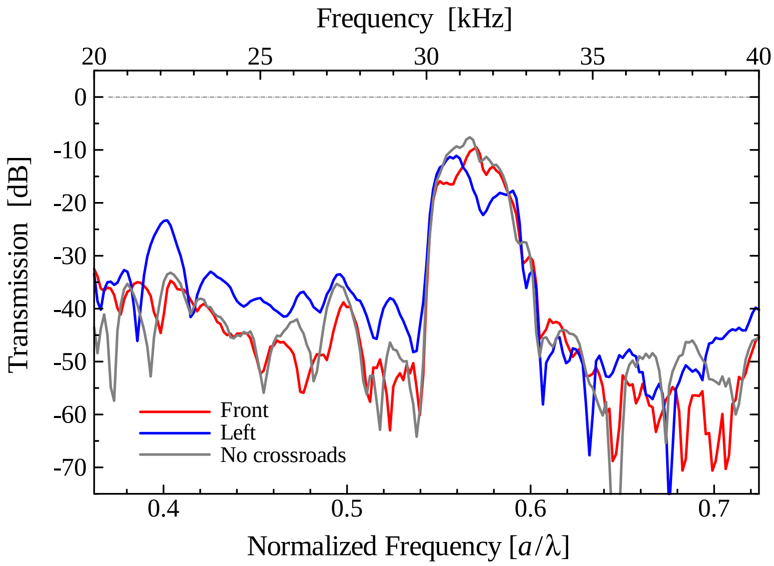


Figure 7. Experimental transmission spectra of a DMWG with a crossroads.

waves are divided almost equally among the three outlets.

4. CONCLUDING REMARKS

Defect-mode waveguides (DMWGs) were fabricated by removing every second scatterer from a sonic crystal, which was composed of an array of acrylic resin cylinders in air, along the intended waveguide path. The transmission spectra of a variety of DMWGs were measured using a network analyzer with a high-frequency speaker, or tweeter, and a wide-band microphone. The following theoretically expected properties of the DMWG were confirmed experimentally. (1) A clearly distinguished passband of the DMWG was observed at a normalized frequency of between 0.545 and 0.590 in a good agreement with the theoretical passband, and with a transmission of -0.52 dB per lattice constant. (2) The passband was influenced significantly neither by the existence of a bend, a branch nor a crossroads in the DMWG.

The DMWG was verified to work not only as a novel and efficient acoustic waveguide but also as a good band-pass filter.

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