Applied Acoustics 76 (2014) 402–406

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

A sonic crystal diode implementation with a triangular scatterer matrix

Serkan Alagoz *

Department of Physics, Inonu University, Malatya, Turkey

ARTICLE INFO

Article history:
Received 10 October 2012
Received in revised form 9 April 2013
Accepted 10 September 2013
Available online 10 October 2013

Keywords:
Sonic crystals
Acoustic diodes
Nonreciprocal sound transmission

ABSTRACT

This paper investigates a nonreciprocal sound transmission effect provided by a triangular lattice two-dimensional sonic crystal made of rods in a triangular cross-section. This sonic crystal (SC) device works as a frequency selective acoustic diode operating at a frequency of 8950 Hz. The scatterer matrix of the sonic crystal diode prototype was composed of triangular shaped wood rods that break the symmetry of the spatial inversion and provide nonreciprocal wave transmission with a contrast rate of 89% in experiments. This acoustic diode device can provide a high contrast, narrow band, one-way sound transmission for acoustic wave control applications.

1. Introduction

Sonic crystals (SCs) are composed of periodic arrays of solid scatters embedded in a host material, such as air. Recent research on SCs has demonstrated that they are efficient materials for controlling the propagation of sound. Several extraordinary properties of these artificial crystal structures present many practical outcomes. For example, band gaps inhibiting wave propagation inside certain frequency bands of SCs have been used for acoustic filtering and noise-reduction [1–6]. A negative effective refraction index of SCs within the second band led to subwavelength focusing when SCs were used as flat lenses [7–14]. The self-collimation effect has been shown to facilitate acoustic wave propagation inside SCs without much diffraction [15–17]. The unidirectional transmission effect presented potential applications, including acoustic rectifiers and acoustic diodes [18–24]. These developments promise the realization of complex acoustic circuits designed for wave energy flux steering, advanced acoustic imaging, and sensor technologies.

SCs have shown promise in acoustic devices and applications for guiding and manipulation of acoustic wave propagation and they are currently considered good candidates for implementing nonreciprocal and unidirectional sound propagation [18]. Many mechanisms were proposed for nonreciprocal sound propagation in the literature [18,19,21–30]: Acoustic nonlinear effects combined with SCs were used to implement the broken time reversal symmetry [23,24]. Li et al. [19] suggested a sonic-crystal-based acoustic diode that had broken the spatial inversion symmetry. They proposed an acoustic model for a one-way effect with higher efficiency, broader bandwidth depending on the nonlinear acoustic effect, and broken time-reversal symmetry. Boechler et al. [21] reported bifurcation-based acoustic switching and rectification using granular crystals composed of 19 stainless steel spherical particles and a light mass defect. Tanaka et al. [28] proposed a phononic rectifier of elastic waves in a thin plate made of an elastically isotropic material containing a periodic array of triangular holes as scatterers. This nonreciprocal propagation mechanism benefits from the geometric effects on wave scattering due to the asymmetric nature of a triangular scatterer array. Shirota et al. [29] and Krishnan et al. [30] presented detailed analyses on the transmission rate and rectification efficiency of single and double arrays of phononic structures with triangular holes. We utilized this mechanism to implement a frequency selective one-way sound transmission using an SC structure working in audible frequency ranges. The proposed acoustic device contains eight scatterer arrays in the triangular lattice geometry to enhance the frequency selectivity of the SC diode model.

This nonreciprocal propagation mechanism is well-explained by considering the ray-trace analysis in [29]. This effect appears at wavelengths that are comparable to the dimensions of the scatterers, as described in Fig. 1(a) [29]. At these wavelengths, due to the periodicity of the crystal structure, wave propagation in a crystal structure becomes directional and interference of refracted waves takes effect in the wave propagation inside the SC. Therefore, the geometrical factor of the triangular scatterers in the SC becomes very effective in transmission, due to the reflection surface asymmetries, and results in a one-way sound transmission between the forward (I) and the backward (II) directions, as illustrated in Fig. 1(a) and (b). In this paper, the transmission in the forward direction (I) is referred as to forward transmission and the transmission in the backward (II) direction is referred to as backward transmission.

* Tel.: +90 5443048889; fax: +90 4223711189.
E-mail address: serkan.alagoz@inonu.edu.tr

0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.09.010

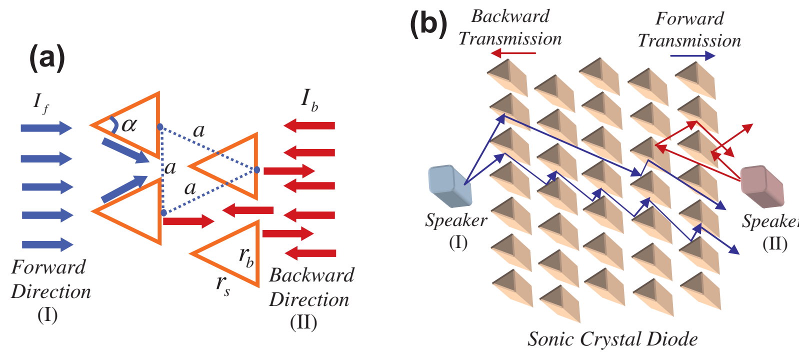

Fig. 1. (a) Schematic diagram of triangular scatters in triangular lattice and wave propagation directions and (b) an SC-based acoustic diode model and some possible wave beam traveling illustrations for the forward and backward sound transmissions inside the SC.

The proposed SC diode prototype is composed of a triangular wood scatterer matrix in air with triangular lattice geometry. Experimental measurements show that a contrast rate of 0.89 is possible between the backward and the forward transmissions in the 8940–8960 Hz frequency range. FDTD simulation of the SC diode confirms the nonreciprocal wave propagation effect observed in experiments.

2. Methodology

2.1. Nonreciprocal sound propagation by triangular lattice sonic crystals with triangular scatterers

A great deal of research has investigated wave propagation in triangular lattice SCs with circular scatters [9–14]. Due to the symmetric nature of circular scatterers, circular scatterers do not support nonreciprocal propagation in SCs. However, the lattice geometry of SCs takes effect in wave propagation anisotropy inside the SCs when the wavelengths of incident waves approximate about half of the lattice constant. This is because the waves effectively scatter and travel around the high reflective solid scatterers inside the SC structures at these wavelengths and Bragg diffraction is effective in wave propagation inside the SC structure [30]. Correspondingly, the wave propagation in the crystal structure becomes directional and the interference of the refracted waves takes effect in the wave propagation inside the SC. When circular scatters are replaced with triangular scatterers, both the lattice geometry and the scatterers geometry have an effect on the wave propagation inside the SCs. Due to the asymmetric nature of the triangular scatterers, which also results in broken spatial inversion symmetry, the SC with the triangular scatterer matrix provides a nonreciprocal wave propagation, as represented in Fig. 2(a) and (b). Specifically, the SC exhibits a greater reflectance in the backward direction than the forward direction due to back reflections from the bases of the triangular scatterers in the triangular lattice. On the other hand, it presents a sufficient transmission in the forward direction so that the diffraction from the side edges of the triangular scatterers allows the wave to travel inside the crystal structure.The nonreciprocal transmission gain can be defined as the ratio of the measured forward intensity (I_f) to the average backward intensity (I_b). The nonreciprocal transmission gain is depended of the monochromatic wave frequency and the measurement location at output of the SC and it can be expressed as (I_f/I_b). As nonreciprocal transmission gain increases, the SC diode device exhibits superior one-way transmission effect.The contrast ratio between the forward and the backward transmissions was another important parameter that is commonly used for the performance assessment of an acoustic diode device [19,27]. This was also referred to as the rectifier efficiency [28–30]. Depending on the angular frequency of the waves ($w = 2\pi f$) and the measurement location ($\vec{r}$), the contrast ratio can be expressed as:

$$R_c(w,\vec{r}) = \frac{I_f(w,\vec{r}) - I_b(w,\vec{r})}{I_f(w,\vec{r}) + I_b(w,\vec{r})}. \quad (1)$$

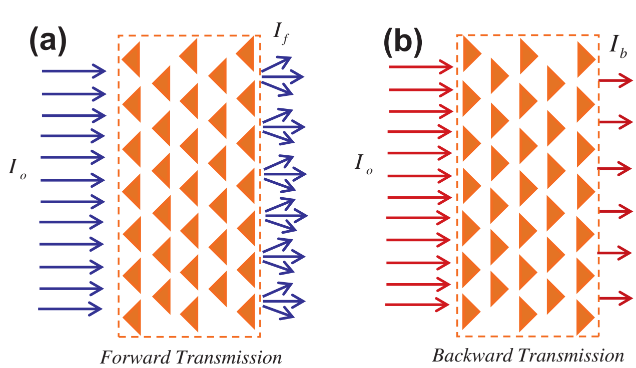

Fig. 2. The forward transmission (a) and the backward transmission and (b) for parallel and constant flux density of wave beams (I_o).

2.2. Numerical and experimental investigations

Sound waves propagation in sonic crystals of an arbitrary finite shape were described by,

$$\frac{\partial \vec{v}}{\partial u} = -\underline{\rho}\nabla p \quad \text{and} \quad \frac{\partial p}{\partial u} = -\overline{B}\nabla \cdot \vec{v} \quad (2)$$

where $\vec{v}$ denotes the normalized particle velocity and the normalized time is expressed as $u = c_h t$, where the sound velocity in host material is written as $c_h = \sqrt{B_h/\rho_h}$. The material parameters of crystal structures are described by the normalized medium density, $\underline{\rho} = \rho_h/\rho_s$, and the normalized bulk modulus, $\overline{B} = B_s/B_h$ [31]. The parameters ρ_h and ρ_s denote densities of host and scatterer materials and the parameters B_h and B_s denote bulk modulus of host and scatterer materials, respectively.

A single second-order inhomogeneous differential equation was derived from Eq. (2) in the normalized form:

$$\nabla \cdot (\underline{\rho}\nabla p) - \frac{1}{\overline{B}} \cdot \frac{\partial^2 p}{\partial u^2} = 0 \quad (3)$$

Eq. (3) was solved to obtain the band-gap structure of sonic crystals by plane wave expansion (PWE) method [31,32].