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Obstacle Detector with Metamaterial Luneburg Lens

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***Abstract*—We design and fabricate an obstacle detector based on an acoustic Luneburg Lens. Similar to its optical counterpart, the gradient-index phononic crystal Luneburg Lens can focus sound waves to a point. The sample lens is fabricated by three dimensional printing and the performance of sound focusing is validated through finite element simulation and experiment. In experiment, an acoustic signal processing system is designed to process the collected data for calculating the direction and distance of the obstacle.**

Keywords—phononic crystals, lens, obstacle detector, focus, 3D printing

I. INTRODUCTION

Phononic crystals consisting of ordered array of structures can manipulate the propagation of sound waves. At present, a large number of literature have reported the study of phononic crystals [1,2,3]. It has been theoretically and experimentally proved that phononic crystals behave like homogeneous medium in the linear frequency band lower than the first band gap, and its effective acoustic parameters such as modulus and density are mainly determined by the filling fraction [4,5,6]. Based on the effective medium theory [7], Climente designed a gradient-index (GRIN) acoustic lens with flat surface and can converge incident plane waves to the point on the lens axis [8]. Acoustic Luneburg lens is a kind of GRIN device that is capable of bending plane waves to a focal point producing minimal spherical aberration, which provides unique advantages in imaging. Degertekin once proposed a phononic crystal Luneburg lens with blind holes of different diameters for omnidirectional elastic wave focusing and enhanced energy harvesting [9]. In general, the size of phononic crystals are very small and the structure of them are very complex. It is a time consuming or even an impossible task for conventional manufacturing methods to achieve the required size and structure of phononic crystals. Three-dimensional (3D) printing of metamaterial brings new ideas to the fabrication of phononic crystal devices [10]. However, these works are mainly theoretical proofs, and no actual equipment based on acoustic Luneburg lens is fabricated. In this paper, we will design and fabricate an obstacle detector base on the focus function of phononic crystal Luneburg Lens to identify the orientation of obstacles. The detector operates at 41 kHz, and can detect an area with a radius of 50 cm and an angle of 60°. It may greatly change the obstacle detection system of the intelligent machine.

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II. DESIGN OF OBSTACLE DETECTOR

A. Design of Acoustic Luneburg Lens

Phononic crystals can manipulate the propagation of sound waves in a way which is impossible with conventional materials. However, fabrication of phononic crystals has been a challenge. In recent years, the rapid development of 3D printing technology, such as stereo lithography apparatus, makes it possible to direct print phononic crystal devices. The adopted geometry of the two-dimensional hexagon lattice with the lattice constant of a = 2mm, is shown in Fig. 1(a). The cylinder in the crystal lattice with different diameters is made of photosensitive resin, whose sound velocity is 2700 m/s. According to the effective medium theory [7], a series of refractive index can be obtained by changing the filling rate of the solid. The graph of filling rate and refractive index is obtained through finite element simulation and experiment in this work, which is close to the empirical formula proposed by Torrent [11], is illustrated in Fig. 1(b). Fig. 1(c) shows the refractive index of the unit cell when the incidence angle changed. It can be seen that the lattice adopted in this work is isotropic and its effective refractive index n only relate to the filling fraction f. It is known that Luneburg lens has an refractive index distribution of $n = (2 - (r / R)^2)^{0.5}$, where r is the distance from the center of the lens to the lattice, and R is the outer radius of the lens. The relationship between the filling rate f and the diameter of the cylinder d in lattice used

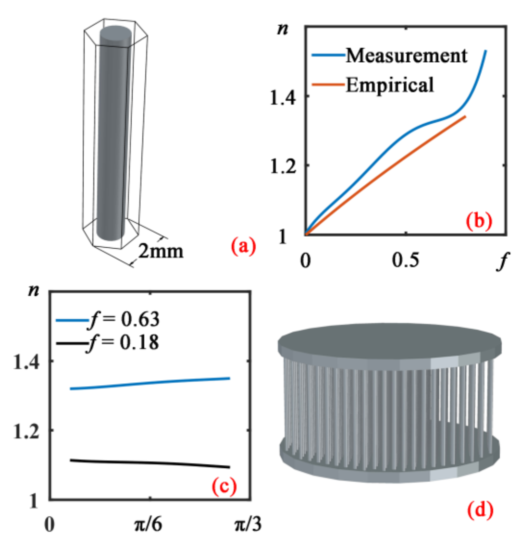

Fig. 1. Geometry of the unit cell comprising photosensitive resin and air (a). Effective refractive index at 41 kHz (b). Refractive index with different incident angles (c) and 3D model for printing (d).

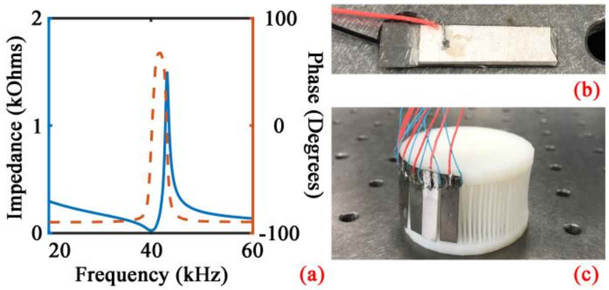

Fig. 2. Impedance and phase graph of the transducer between 20 and 60 kHz (a), piezoelectric ceramic (0.2 mm in thick) bonded to thin steel plate (0.1 mm in thick) (b) and transducer bonded along the side of the lens (c).

in this implementation is $f = 2\pi\,(d\,/\,2a)^2\,/\,1.73$ [7], where d is the diameter of the cylinder. According to the results in Fig. 1(b), phononic crystal with corresponding filling rate is selected at the corresponding position. The gradient-changed refractive index reduces the impedance mismatch between the air and the lens, increases the acoustic energy transmission, and reduces reflection. The maximum cylindrical diameter in lattice is 1.6 mm, with corresponding refractive index is 1.414 ($f = 0.83$), and the minimum radius is 0.3 mm, with corresponding refractive index is 1.071 ($f = 0.08$). The 3D model of the lens is depicted in the Fig. 1(d). The 3D printer used in this work has a printing accuracy of 0.1 mm.

B. *Design of Signal Receiving System*

A piezoelectric ceramic bonded to the steel sheet acts as a receiver collecting the sound waves from the acoustic lens. The received signals are pre-amplified, stored and processed by a computer to calculate the direction and distance of obstacles. The transducer used to receive the signal is shown in Fig. 2(b). It is made of piezoelectric ceramic (pzt4) and stainless steel with a thickness of 0.1 mm. It is long in the length direction and can act to amplify the signal. Impedance characteristic curve shows an operating frequency of 41 kHz, as shown in Fig. 2(a). Figure 2(c) shows the geometric structure of the system, which consists of a white acoustic lens printed from photosensitive resin by stereo lithography apparatus and nine receiving transducers bonded to the backside of the lens.

III. Simulation And Experimental Results

Simulation and experiments were conducted to verify the performance of acoustic Luneburg lens and the detection system.

A. *Performance of The Lens*

To keep the consistency with the experimental setup, in the simulation the plane waves were generated using a point source. An anechoic chamber made of Plexiglas was used to prevent the interference of external sound field. Half of the acoustic lens is exposure to the external sound field, and the other half is set in the anechoic chamber. The receiving transducer is carried by a step motor and can scan the test area in the anechoic chamber point by point. The test area is large enough so that the reflection on walls will not interfere with the measurement. A source of 41 kHz is placed far away to ensure that the sound waves hitting the lens surface can be treated as plane waves. Sound pressure is measured and normalized by averaging ten cycles of the received sine signal. Fig. 3 shows the result of finite element simulation and experimental measurements illustrating that the designed lens can focus plane waves to a point as predicted by the design theory proposed above. As shown in the figure, the measured amplitude have good agreement with those extracted from the simulations. There is a focal point on the right edge of the lens and the sound pressure is about 0.8 with respect to the focal sound pressure without the lens. The velocity of sound waves at the edge of the lens (the area with small filling ratio) is slightly higher than that inside the lens (the area with high filling ratio) and sound waves finally focus at (21, 0). Figure 3(c) shows the sound pressure along the edge of the lens in the anechoic chamber side. The measured (red circle) sound pressures agree very well with the simulated values (blue curve).

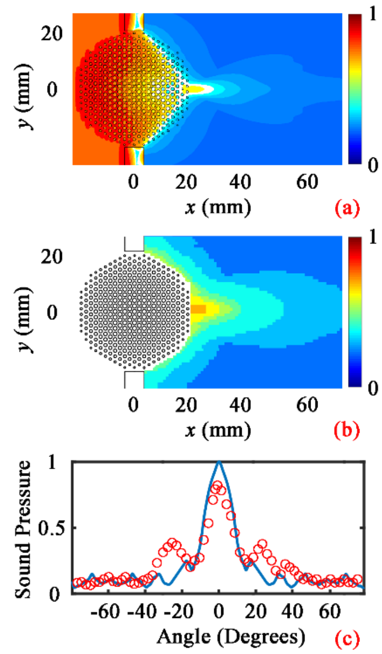

Fig. 3. The simulated (a) and measured (b) results of the 2D acoustic Luneburg lens, and normalized sound pressure along the right side of the lens (c).

B. *Performance of The System*

Schematic diagram of the experimental setup of obstacle position detection is depicted in Fig. 4(b). There are two obstacles in the test area, numbered A (width L = 5 cm) and B (width L = 2cm). Receiving system is placed in the anechoic chamber made of two paralleled Plexiglas plates. The plates ensure that the initial signal does not interfere with the experiment. The transmitting transducer is placed on the top plate. The echo signals were picked up by the receiving system and were imported to the computer for post-processing. The distance is calculated through the phase difference between the transmitted and received signals. The obtained obstacle position is shown in Fig. 4(a). In the work, there are only nine receiving devices installed on the edge of the lens, thus the directional accuracy is not as good as the distance accuracy. In future work, a receiving array will be designed to improve the directional resolution.

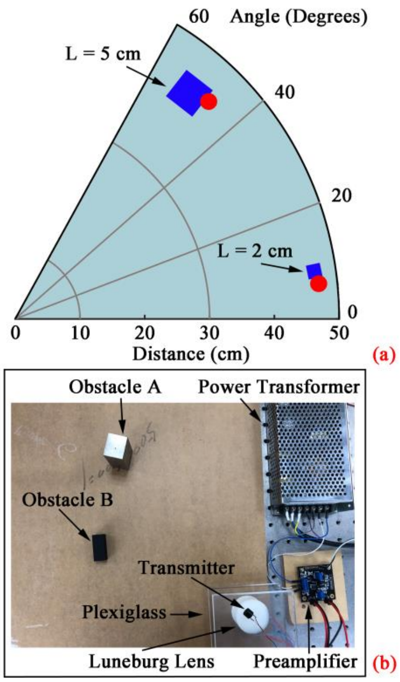

Fig. 4. Detection experiment of obstacle positions. Result of the two obstacles detection (a), blue squares represent the actual location of the obstacles, red circles represent the calculated position of the obstacles and the size of the circle does not indicate signal intensity. The experimental setup of the obstacle detection experiment (b).

IV. Conclusion

A phononic crystals based Luneburg lens has been carefully studied and a detect system based on the focus function of the lens is proposed for obstacle detection. The lens is capable of focusing omnidirectional sound waves, which enables the detector to have a large detection angle. Experimental results of the detect system show that the detection range is 50 cm and the detection angle is 60°. Directional accuracy can be further improve by using a receiving array.

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