Holey structured periodic arrays for subwavelength resolution

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Abstract

The resolution of a conventional imaging system is limited to half the wavelength by natural diffraction limit. To overcome the resolution limit it is important to get the information from the decaying evanescent waves, which is not possible with the conventional imaging system. This paper discusses holey structure metamaterial for achieving resolution beyond the diffraction limit. We experimentally demonstrate a subwavelength resolution of $\lambda/5$ in the ultrasonic regime. Then a practical and cost-effective way of achieving this by plastic tubes is also demonstrated.

Keywords: Holey structured periodic array, Metamaterial, Subwavelength ultrasonic imaging

1. Introduction

Periodically perforated plates or membranes are one of the most common structures for optical/acoustic imaging applications. Photonic [1] and phononic [2] crystals with exotic properties such as band-gaps, localized states, and negative refractive index are already used in many optical and acoustic applications.

The study of interaction of sound waves with periodic structures originated at the end of the 19th century with Rayleigh’s work [3]. This periodic structure problem received more attention after experimental demonstration of extraordinary transmission through a periodically perforated membrane [4,5]. Thereafter enormous amount of research in this area have shown the analogy between photonic and phononic metamaterials [5] and effective transmission of sound was achieved with subwavelength periodic holes on a brass plate, immersed in water [6,7].

Zhu et al. demonstrated the possibility of subwavelength imaging down to a feature size of $\lambda/50$, achieved by enhancing the information from evanescent waves with the help of a periodic holey-structured metamaterial as a meta-lens for imaging [8] in the acoustic regime, thereafter these periodic holey structured metamaterials are also used for subwavelength resolution of the defects in the metallic materials to the ultrasonic regime [9].

In this paper we report the experimental demonstration of subwavelength resolution with periodic holey-structured array as a lens for imaging in the ultrasonic regime.
2. Background

At the Fabry-Perot resonance the transmission coefficient becomes 1 and hence the periodic array (lens) transmits all the waves from input surface to output surface without any loss [9, 10]. With this concept the holey-structured meta-lens transfers both the propagating and evanescent waves from input to output surfaces without any decay and hence subwavelength information is carried by the evanescent waves and constructs the image with better resolution.

2.1 Problem studied

Two thin copper rods of diameter 1.25mm separated by a distance of 3mm (outer to outer) are considered as object/targets for imaging with periodic holey-structured array as a lens. The distance between the two rods (3mm) is about λ/5 for 100 kHz frequency wave in water. We obtain a B-scan (line scan) at the mid span of the targets as shown in Fig. 1(a).

![Fig.1](image)

Fig.1 (a) Illustration showing the problem studied for analysis with copper rods as targets for imaging. (b) Photograph showing the periodic array of plastic tubes which is used as a meta-lens in the experiments.

3. Methods

3.1 Experimental procedure

The experimental setup is based on ultrasonic immersion C-scan technique using through transmission mode as shown in Fig.2. This technique uses 2 transducers one is for transmission while the other is for reception. A transducer of central frequency 100 kHz (Valpey Fisher with 1 inch diameter) is used for excitation. The excitation is done using a 3cycle Hanning windowed tone burst signal provided by a RITEC RPR4000 Pulser-Receiver (Ritec inc., USA). Two copper
rods of diameter 1.25mm are placed right in front of the transmitter with the gap between them as 3mm. Periodic holey-structured array lens which was created with a bunch of plastic tubes of length 60mm (as shown in Fig. 1(b)) was placed immediately in front of the copper rods such that the scattered waves from the rods/targets are coupled into the lens. These scattered waves are detected by using a Polytec fiberoptic vibrometer (Polytec GmbH, Germany) which measures the out-of-plane displacements at the target point using the principle of the Doppler frequency shift effect of the light and consists of an independent OFV 505 optical scanning sensor head and an OFV-5000 controller. The output from the controller is fed to an Agilent DSO 7012B digital storage oscilloscope with a sampling rate of 2 GHz. The entire set up (Immersion probe, scatterers and meta-lens) is immersed in the water for immersion scan. A thin retro-reflective tape is attached to the surface of the immersion tank at the spot illuminated by the laser point so as to enhance the optical backscattering from the laser beam.

4. Results and Discussion

A line scan is obtained at the middle of the periodic array metamaterial by experimentation. After taking the A-scans (on time trace) at all positions, the maximum amplitude variation at the measurement positions along the scan direction is plotted for imaging the targets. The corresponding plot is shown in Fig.3. At the target location, the amplitude drops are observed, which are indicated by vertical lines in the graph. At the scatter regions, the wave energy is reflected by back scattering and diffractions. Maximum energy is reflected, due to
which very low wave transmission is collected by the receiver (Polytech laser vibrometer). This clearly shows that at the target regions there is lower amplitude as compared to the healthy region.

![Graph showing amplitude variation across distance](image)

**Fig. 3** Experimental results for normalized amplitude variation across the measurement positions with the distance moved by laser across periodic array.

### 5. Conclusions

Sub wavelength resolution for ultrasonic regime has been experimentally demonstrated with holey-structured periodic array. This holey structured periodic array lens resolves the features to a subwavelength resolution of $\lambda/5$ in the ultrasonic regime. The lens works on the principle of the Fabry-Perot resonant condition. If we could control the period and the length of the array according to the resonance condition we can further improve the resolution capacity of the holey-structured periodic array lens.

### References


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