Acoustic Metamaterials through Coiling up Space

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Abstract

We show that by curving fluid perforations within a solid with proper control of phase delay, a two dimensional acoustic metamaterial with extreme indices can be constructed. It can be used to achieve a large refractive index, negative refraction and tunneling with a density-near-zero material in the effective medium regime.

Acoustic metamaterials are analog to their electromagnetic counterpart. They often employ local resonances given by subwavelength resonators. For example, to achieve a negative refractive index in acoustics, we need to have two different types of resonances [1-5]. One of them is a monopolar resonance which contributes to a negative response in bulk modulus while another is a dipolar resonance which contributes to a negative response in density. For example, in a one dimensional system for acoustic wave propagating along a waveguide, the analog of the monopolar resonance is a resonance creating symmetric radiating pressure field (in both the forward and backward directions). It can be achieved by a Helmholtz resonator connected as a side branch to the waveguide. [2] The analog of the dipolar resonance is an antisymmeric resonance. It can be achieved by membrane-type resonance. [3] On the other hand, it has been shown that phononic crystal can also be used to achieve negative refraction [6-7] with the working regime shifted to the diffraction regime instead of the effective medium regime. Here, we propose an acosutic metamaterial by simply coiling up space. It can achieve a negative refractive index in the effective medium regime and tunelling at a density-near-zero can be demonstrated.

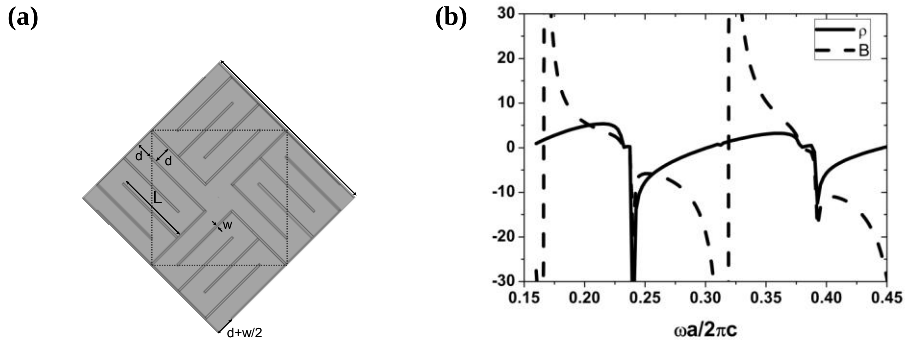

Fig. 1 (a) Structural unit cell in coiling-up space. Dashed-line encloses square unit cell of width *a*. (b) Effective density ρ and bulk modulus *B* of the metamaterial.

Figure 1 (a) shows the repeating units in constructing the acoustic metamaterial. Solid hard-plates are inserted into a background fluid (air) to route the acoustic waves in a curved manner so that the path lengths between the four corners are much elongated comparing to the original distances between the four corners. Alternatively, each channel can be viewed as a straight channel but with a refractive index many times larger than the background fluid. The size of the a single unit cell is subwavelength

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and when these units are repeated. These unit cells form a two-dimensional acoustic metamaterial with a valid effective medium description. Figure 1(b) shows the effective density and bulk modulus of the metamaterial. When the normalized frequency ($\omega a/(2\pi c)$ where c is the sound velocity in background fluid) is from around 0.25 to 0.31, both the effective density and the bulk modulus become negative. A negative refractive index results from this approach of coiling up space. If the elements are assembled into a prism, negative refraction results and is shown in Figure 2(a) when the incident wave is coming from the left hand side of the prism. In this case, the effective refractive index is around -1 and the beam is refracted at the inclined interface of the prism with a negative angle approximated the same as the incident angle to the interface.

As another example usage of the metamaterial, at the normalized frequency around 0.31, the effective density is around zero and tunneling through a narrow waveguide becomes possible. This is the analog of epsilon-near-zero material in electromagnetic waves [8]. Figure 2(b) shows the tunneling of a plane wave through a narrow waveguide (with hard solid boundaries) filled with the metamaterial with density near zero while figure 2(c) shows the same situation but with the metamaterial removed. Before adding the metamaterial, the scatterer attaching to the top side of the waveguide blocks more than half of the cross-section of the waveguide. Severe scattering is observed. Now, if the scatterer is enclosed by the metamaterial working at a frequency in which density is nearly zero, the plane wave from the left squeezes through the narrow channel and exit as a plane wave at another end of the waveguide.

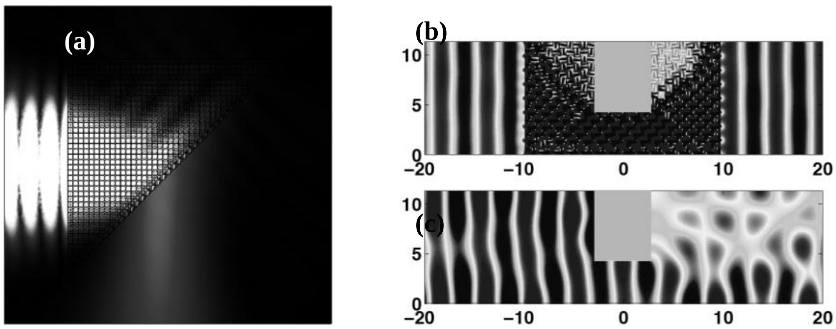

Figure 2 (a) Negative Refraction by a prism constructing from the elements (coiled-up channels). (b) Tunneling of incident wave from the left through a narrow channel filled with the metaterial of density-near-zero while the same wave is scattered severely by the blockage at the middle when the metamaterial is removed in (c).

In conclusion, we have designed an acoustic metamaterial by coiling up space using curved perforations. It can generate a large range of refractive indices to bend acoustic waves in extreme manners including negative refraction and tunneling at a density near to zero. Such a metamaterial would be useful for designing acoustic devices and transformation media utilizing extreme constitutive parameters.

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REFERENCES

[1] J. Li and C. T. Chan, Double-negative acoustic metamaterial, *Phys. Rev. E* vol. 70, 055602(R), 2004.
[2] N. Fang, D. Xi, J. Xu, M. Ambati, W. Srituravanich, C. Sun and X. Zhang, Ultrasonic metamaterials with negative modulus, *Nature Materials* vol. 5, pp. 452, 2006.
[3] Z. Yang, J. Mei, M. Yang, N. H. Chan and P. Sheng, Membrane-type acoustic metamaterial with negative dynamic mass, *Phys. Rev. Lett.* vol. 101, pp. 204301, 2008.
[4] S. H. Lee, C. M. Park, Y. M. Seo, Z. G. Wang, and C. K. Kim, Composite acoustic medium with simultaneously negative density and modulus, *Phys. Rev. Lett.* vol. 104, pp. 054301, 2010.
[5] L. Fok and X. Zhang, Negative acoustic index metamaterial, *Phys. Rev. B* vol. 83, pp. 214304, 2011.

[6] M. H. Lu, C. Zhang, L. Feng, J. Zhao, Y. F. Chen, Y. W. Mao, J. Zi, Y. Y. Zhu, S. N. Zhu, and N. B. Ming, Negative birefraction of acoustic waves in a sonic crystal, *Nat. Materials* vol. 6, pp. 744, 2007.
[7] A. Sukhovich, B. Merheb, K. Muralidharan, J. O. Vasseur, Y. Pennec, P. A. Deymier, and J. H. Page, Experimental and theoretical evidence for subwavelength imaging in phononic crystals, *Phys. Rev. Lett.* vol. 102, pp. 154301, 2009.
[8] M. Silveirinha and N. Engheta, Tunneling of electromagnetic energy through subwavelength channels and bends using ε-near-zero materials, *Phys. Rev. Lett.* vol. 97, pp. 157403, 2006.