All-angle negative refraction with an acoustic fishnet structure

J. Christensen[1] **and F. J. Garcia de Abajo**[1,2]

[1]IQFR-CSIC Serrano 119, 28006 Madrid, Spain
[2]Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom
email: johan.christensen@gmail.com

Abstract

We study a class of acoustic metamaterials formed by layers of perforated plates and producing negative refraction and backward propagation of sound. Our study constitutes a nontrivial extension of similar concepts from optics to acoustics, capable of sustaining negative refraction over extended angular ranges, with potential application to enhanced imaging for medical and detection purposes, acoustofluidics, and sonochemistry.

1. Introduction

Optical negative refraction is a counterintuitive phenomenon that consists in bending light the wrong way at the interface between suitably engineered materials. Homogeneous substances with refraction indices of opposite signs provide an ideal combination on which this effect can take place. Over four decades ago, Veselago [1] realized that a material with simultaneous negative magnetic permeability and electric permittivity must have negative index and, therefore, can produce negative refraction. Subsequently, Pendry [2] showed that a slab of such material can amplify evanescent fields, from which a perfect lens can be constructed, capable of yielding images with deep subwavelength resolution. These concepts have been realized in artificial metamaterials, textured on a small scale compared to the wavelength and displaying homogeneous resonant electric and magnetic response [3,4]. Inspired by these exotic optical phenomena, the quest for acoustic superlensing and negative refraction started with the prediction of negative index of refraction in materials exhibiting negative effective mass density and negative bulk modulus at the operating frequency [5]. In this context, several acoustic metamaterial designs have been proposed containing resonators in the form of coated metallic spheres [6], lumped elements [7], or perforations [8]. However, isotropic acoustic negative-index materials have not been experimentally realized to date, despite a long tradition of sound control using resonant linear devices [9,10], including applications to diffraction-limited imaging [11]. An alternative approach to acoustic negative refraction and lensing is suggested by electromagnetic metamaterials relying on anisotropy [12,13].

2. Analysis

The acoustic fishnet structure is a metamaterial containing multiple stacks of perforated rigid plates [13]. We assume the holes to be small compared to both the sound wavelength λ and the lattice parameters, and we disregard elastic interactions in the hard screens. Under these conditions, it is safe to retain only the monopolar component of the field scattered by each hole in response to an incident pressure field. We need to define scattering coefficients both for the near-side and the far-side of the hole.

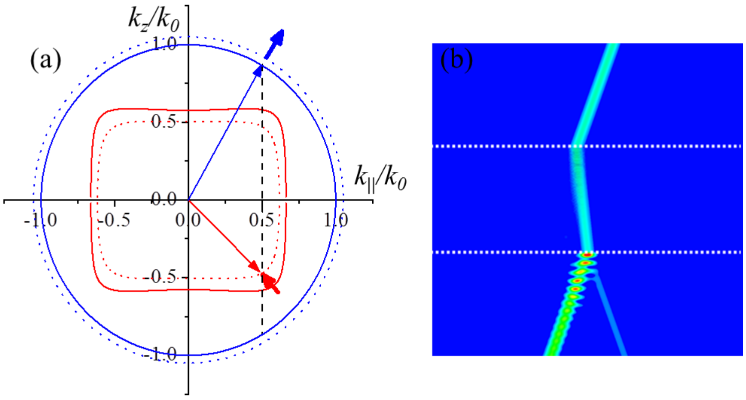

Fig. 1: (a) Equifrequency curves both in the homogeneous background medium air (blue circle of radius $k = 2\pi/\lambda$) and in the fishnet metamaterial (red isotropic dispersion curves) as a function of the wave vector parallel and perpendicular to the layers, $k_{||}$ and k_z, respectively. (b) Pressure-field simulation for a finite metamaterial containing 250 layers. The dotted lines indicate the slab interfaces. Negative refraction for a Gaussian beam incident with angle $\theta = 30°$ at the bottom interface.

Inside the metamaterial, the incident field (from the hole point of view) originates in the scattered fields of the rest of the holes. In this way, one can write a set of self-consistent equations, which take a particularly simple form when the periodicity of the hole arrays is taken into consideration [13]. This method enables us to calculate equifrequency curves such as simulating the pressure field as illustrated in Fig. 1. In Fig. 1(a) we study the equifrequency curves for an acoustic fishnet structure where we have fixed the operation frequency at 190 kHz and filled the holes with a fluid of mass density $\rho_h = 0.6\rho_0$. The blue circle represents the free-space dispersion relation whereas the red circle corresponds to the metamaterial. The dashed curves are dispersion relations of the corresponding media at a slightly higher frequency. It can be seen that the present metamaterial is an isotropic medium and provide a negative index for all angles of incident sound. In order to confirm this behaviour we have simulated an impinging Gaussian beam which irradiates the metamaterial at the bottom side as depicted in Fig. 1(b). Despite the presence of reflection at the metamaterial interface the Gaussian beam refracts with a negative angle inside the slab until it leaves the metamaterial at the far-side.

3. Conclusion

We have demonstrated that holey stacked metamaterials produce negative index behaviour over a broad range of incidence angles. Our illustrative calculations are made for ultrasound frequencies in ranges of operation that are common in ultrasonography and general biomedical applications, for which these metamaterials provide a versatile fabric.

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