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Extended Abstracts

Track 2: Phononic Metamaterials

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Narrow Fluid Channel as a Metamaterial Sound Absorber

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Abstract: Abnormally high level of absorption has been observed for sound waves propagating through a narrow water channel clad between two metal plates. Absorption is due to resonant excitation of Rayleigh waves on the both metal surfaces. These waves may either produce strong turbulent motion in a viscous fluid or radiate its energy into the metal, giving rise to deep minima in the transmission spectrum.

Sound waves can propagate over a long distance in water. In bulk medium attenuation caused by viscosity of water grows quadratically with the wave frequency f. For many practical applications of noise control it is necessary to design materials with high level of absorption. "Perfectly" absorbing metamaterials are of great interest in optics since they may modify thermal emission and increase the efficiency of photovoltaic devices[1,2]. A standard method to increase sound absorption is to perforate a sample with micropores. High porosity strongly increases the area of acoustic impedance mismatch and also increases the effects of internal friction. Here we propose tailored, highly absorptive acoustic metamaterial based on a narrow, but still macroscopic, water channel formed by two massive brass plates. Our motivation is based on the ability of surface plasmons to strongly absorb light incidenting on metal grating (so-called Wood anomaly), as well as to support extraordinary transmission of light through subwavelength holes in thin metallic films. Acoustic counterpart of extraordinary transmission due to excitation of a surface mode has been recently observed[3], while anomalous absorption of sound caused by Rayleigh waves is still missing.

The experimental setup is shown in Fig. 1. We used a couple of 1.5´´ immersion transducers that were placed face to face at a distance of 16 cm. A slit of width d is obtained between two adjacent $12\times\ 12\text{cm}^2$ brass plates of equal thickness h immersed in water. The slit forms a narrow water channel with high aspect ratio $h/d \gg 1$. Transmission through the water channel has been measured within frequencies from 0.2 to 1.5MHz that corresponds to the wavelengths in water from 0.7 to 0.1cm. Due to mismatch of acoustic impedances between water and brass only ~10% of acoustic energy passes through the metal plates. However, at the Fabry-Perot (FP) resonances, when $2h = n\lambda_l$ the plates become practically transparent, giving rise to sharp peaks in the transmission spectra. Here $\lambda_l = c_l/f$ is the wavelength of a longitudinal wave propagating in metal with speed c_l. Away from the FP resonances sound propagates mostly through the water channel. Typical transmission spectra obtained for different plate thicknesses h and apertures d are shown in Fig. 2. The frequency interval between two FP peaks scales as $1/h$, therefore only one peak is displaced for $h = 2\text{mm}$, two for $h = 3\text{mm}$ and three for $h = 5\text{mm}$. Each measured spectrum exhibits a deep minimum (marked by an arrow above it) at frequency lower than the first FP peak. The amplitude of this peak strongly depends on the aperture, unlike its position, which is almost independent on d. The latter means that this minimum is irrelevant to resonant reflection of the wave from a finite aperture. The only reason for such low transmission is dissipation of acoustic energy in the water channel. We argue that resonant increase of dissipation is due to excitation of Rayleigh waves.

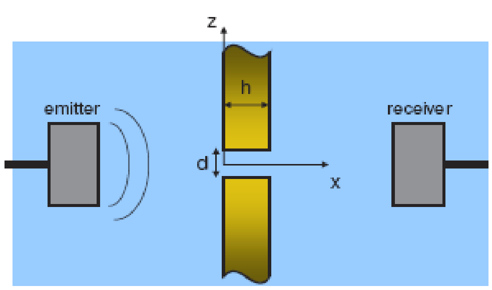

Figure 1 Experimental set up. The plates, the emitter and receiver are immersed in water.

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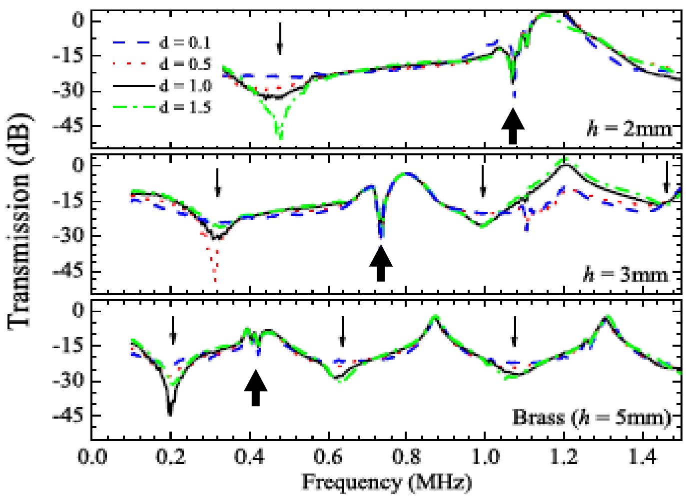

Figure 2 The measured transmission spectra of the water channel with different aspect ratios. The position of each resonance corresponding to a real (complex) solution of Eq. (1) is marked by thin (bold) arrow.t. Note the missing first resonance ($n = 1$) for $\boldsymbol{d} = \mathbf{0.1}$ mm.

In a fluid channel with hard walls the dissipation of acoustic energy is weak since propagating sound wave induces laminar Poiseuille flow where dissipation is due to perpendicular to the walls gradient of fluid velocity, $\frac{\partial V_x}{\partial z}$. If the walls are elastic, the Rayleigh wave can be excited at discrete frequencies in a finite-length channel. Vibrating walls induce turbulent flow where all the derivatives $\frac{\partial V_i}{\partial x_k}$ with $i, k = x, z$ are different from zero. Since the energy dissipated due to viscosity is proportional to $\left(\frac{\partial V_i}{\partial x_k}\right)^2$, it is clear that excitation of Rayleigh wave leads to strong reduction of acoustic transmission.

In a narrow channel the Rayleigh waves propagating along the both surfaces are coupled. Our analysis shows that resonant excitation of coupled Rayleigh waves occurs at the frequencies $f_n = \left(\frac{\pi n}{h}\right) c_t x_n$. Here c_t is the speed of shear wave in metal, $n = 1,3,5$ ..., and x_n is a solution of the following dispersion equation

$$(2 - x^2)^2 - 4\sqrt{1 - x^2}\sqrt{1 - \left(\frac{c_t x}{c_l}\right)^2} = \frac{\rho_f}{\rho_m} x^4 \sqrt{\frac{1-(c_t x/c_l)^2}{\left(c_t x/c_f\right)^2 - 1}} \cot\left(\frac{\pi n d}{2h}\sqrt{\left(\frac{c_t x}{c_f}\right)^2 - 1}\right). \quad (1)$$

Here $\rho_f(\rho_m)$ is the density of the fluid (metal) and c_f is the speed of sound in fluid. Eq. (1) describes the eigenmode with symmetric vibrations of the plates. The real solutions of this equation for $n = 1,3,$ and 5 fit well the resonant minima marked by solid arrows in Fig. 2. For small aperture $d = 0.1$ mm the first minima is missing. Accordingly, there is no real solution for $n = 1$ for such narrow aperture. However, for $n = 3$ and 5 there are real solutions and the corresponding resonances are well observed. Apart from real solutions, Eq. (1) has a complex root for each n. This root gives rise to leaky Rayleigh wave which has been predicted[4] but has never been observed in acoustic experiment. The leaky wave radiates energy into metal plates that leads to the deep minima marked by bold arrows. For the plates with $h = 2$ and 5mm these minima overlap with the FP peaks, therefore for these cases the minima are not very deep. However, for $h = 3$mm this minimum is well resolved. Absorption of sound at each of the minima in Fig. 2 exceeds by orders of magnitude absorption in bulk water, thus demonstrating metamaterial behavior of water in narrow channels with elastic boundaries.

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References

[1] S. Han, A. Stein, D. Norris, *Phys. Rev. Lett.* **99,** 053906 (2007); N.I. Landy, *et al*., *Phys. Rev. Lett.* **100,** 207402 (2008).
[2] E. E. Narimanov and A. V. Kildishev, *Appl. Phys. Lett.* **95,** 041106 (2009).
[3] H. Estrada*, et al*., Phys. Rev. Lett. **102**, 144301 (2009).
[4] N.E. Glass and A.A. Maradudin, J. Appl. Phys. **54,** 796 (1983).

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Fabrication and Experimental Characterization of Anisotropic Fluid-Like Materials

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Abstract: We report a method to obtain acoustic metamaterials or metafluids with cylindrically anisotropic mass density. The method uses a periodically corrugated structure embedded in a two dimensional waveguide. This structure represents a periodic multilayered fluid-fluid composite that, in the low frequency limit, behaves as a fluid-like metamaterial with mass anisotropy. Also, an experimental method to characterize these structures is presented, showing that the resonances in these closed structures can be used to derive the acoustic parameters of these metafluids. An excellent agreement between theory and experiment is obtained.

Radial Wave Crystals [1,2] are a new type of periodic media that present band-gaps and wave localization but in the radial direction, that is, they are crystals in polar or spherical coordinate systems. Fluid-like materials with anisotropic mass density are the basis of radial wave crystals, as well as of cloaking shells [3] and a wide variety of devices based on the field of transformation acoustics. This anisotropy is not a natural property of common materials; therefore it is worth to include these systems in the field of metafluids, despite being parameters with positive values.

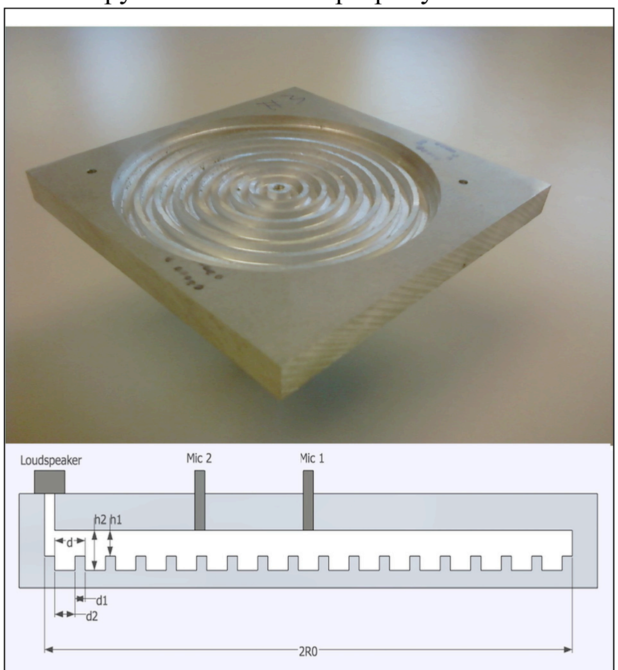

Figure 1: Upper Panel: Picture of one of the samples analyzed in the present work. Lower Panel: Schematic view of the experimental set up.

It has been shown that sonic crystals (periodic arrangement of sound scatterers) in the low frequency limit behave as effective fluid-like materials with anisotropic properties [4], where the anisotropy appears in the dynamical mass density. Even when the scatterers have elastic properties the effective medium behaves as a fluid-like material. These results suggest that mass anisotropy must be based on the periodicity of sub wavelength units placed in non-symmetric lattices.

However the mentioned anisotropy appears in rectangular coordinates, thus anisotropic devices having cylindrical or spherical symmetry cannot be designed with this approach. Such is the case of acoustic cloaking shells and radial wave crystals, in which the mass density tensor has constant components when expressed in a polar or spherical coordinate system, depending on the dimensionality of the problem.

It has been found that one way to obtain cylindrical or spherical anisotropy is by multilayered cylinders or spheres [5], which are special cases of one-dimensional periodic systems. It has been shown that the anisotropic properties obtained from the one-dimensional wave equation can be transformed to polar or spherical coordinates.

However this method need that all the layers are made of fluid-like materials, what implies that the multilayered structure has to be done by a set of alternating fluid materials with different physical properties. It is obvious that such a structure will not be, in principle, stable.

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One solution was reported in [5], where all the layers were made of sonic crystals. However the large amount of cylinder required for realizing such a structure makes that approach difficult to achieve. Another approach could be make every layer of porous materials, but still some elastic effects should be taken into account that could decrease the functionality of the device, apart of having to add strong viscoelastic effects.
In this work the approach reported in [6] is explained, where a corrugated structure embedded into a waveguide was used to produce the multilayered system (see Figure 1). It was shown that the mentioned structure behaves as a fluid-fluid periodic medium, where each groove can be described as a fluid-like material in which the speed of sound is that of air and the density is given by the ratio of the height of the groove and the "background" height [7].
Once assumed that each groove acts as a fluid material, it can be shown that, in the low frequency limit, the structure shown in Figure 1 behaves as an anisotropic fluid-like cylinder where the mass anisotropy ratio is given by

$$\gamma^2 = \frac{1}{2}\left(d_1 + d_2\frac{h_1}{h_2}\right)\left(d_1 + d_2\frac{h_2}{h_1}\right)$$

Therefore the resonances of the structure can be used to characterize the effective medium. These resonances where measured by the set up shown in the lower part of Figure 1. In brief, an external sound field is excited and the response of the structure is measured by the two microphones. The peaks of the taken spectra are analyzed and the experimental values of the anisotropy rations for three different samples are obtained, showing an excellent agreement between theory and experiment.
It will be shown also how to realize metamaterials with the same acoustic parameters but with the tensor rotated 90 degrees, that is, replacing the radial component by the angular one and vice versa. In this case, the corrugated structure is made of angular sections off different height in place of concentric grooves, but the behavior can be shown to be equivalent.
This method allows designing anisotropic fluid-like metafluids with any orientation of the tensorial mass density, being a promising method to fabricate more complex structures requiring such anisotropy, specially radial wave crystals, which are not only anisotropic but also inhomogeneous metafluids.

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References

1. D. Torrent and J. Sánchez-Dehesa, Phys. Rev. Lett. 103, 064301 (2009).
2. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 12, 073034 (2010).
3. S.A. Cummer and D. Schurig, New J. Phys. 9, 45 (2007).
4. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 10, 023004 (2008).
5. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 10, 063015 (2008).
6. D. Torrent and J. Sánchez-Dehesa, Phys. Rev. Lett. 105, 174301 (2010).
7. P.M. Morse and K.U. Ingard, Theoretical Acoustics (Princeton University Press, New Jersey, 1986).

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Metal Water: A Metamaterial for Acoustic Cloaking

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Abstract: A generic metamaterial is described that is suitable for making acoustic cloaking devices. The fundamental property is that it mimics the acoustic properties of water, yet can be modified to display anisotropic elastic properties suitable for cloaking. It has the important property that the amount of void space is conserved: a "conservation of cloaked space".

Acoustic cloaking can, in theory, be achieved using widely different material properties. The reason is that for a given mapping function the transformed version of the original scalar wave equation can be interpreted in terms of different material constitutive theories[1]. In this sense acoustic cloaking is distinct from its counterpart for electromagnetic waves, for which the material corresponding to the transformed Maxwell equations is uniquely defined by the transformation function. The first mechanism proposed for acoustic cloaking[2,3] was based on the concept of *anisotropic density*, and a single bulk modulus. Compressible fluids with anisotropic density are physically permissible[4], by layering homogeneous fluids, for instance. The range of inertial properties required for achieving cloaking is great, however, and could be very difficult to achieve by layering. Significant cloaking of a cylinder was shown to be possible[5] using hundreds of homogeneous fluids to reproduce the smoothly varying properties of the transformed fluids. The number of independent fluids can be reduced to three[6] but only if the three fluids have vastly different properties, e.g. one fluid must have extremely large density, another must have very large compressibility, etc..

An alternative route to acoustic cloaking is possible using *pentamode materials*[7] (PM). These can be considered as generalizations of compressible fluids that have anisotropic compressibility but isotropic density. As such, they are limiting cases of anisotropic elastic materials in which five of the six Kelvin moduli vanish. The Kelvin moduli are the eigenvalues of the 6x6 matrix of elastic moduli in Voigt notation (suitably represented in tensor form). Anisotropic inertia and pentamode materials are in fact limiting cases of a spectrum of material properties that yield the acoustic equation in the original untransformed coordinates. This material non-uniqueness may be ascribed to a "gauge" freedom in how the transformed particle displacement vector is defined; the full range of acoustically transformed material is described in[8]. The transformed elasticity equations display a similar nonuniqueness[9,10] which can also be associated with the choice of the displacement gauge relation[11]. Pentamode materials with anisotropic elastic behavior, like fluids with anisotropic density, are not found in nature. Zero elastic moduli implies structural instability, exemplified by the ability of water to flow. But in the case of water, the PM flows from one isotropic state to an identical one. PMs for cloaking cannot flow without change of state, and must have non-zero but small shear rigidity for stability.

Metal Water: Pentamode Material with Small Shear Rigidity

Water is the quintessential PM, however it is isotropic and therefore of no use in cloaking. Yet, any structural material for an acoustic cloak should be able to replicate homogeneous water in an acoustic sense. It must have the same *effective* compressibility and density as water, and display very small shear rigidity. We describe here a class of metamaterial with these properties, and more importantly, which can be modified to reproduce the PM properties of a cloak. The effective properties hold for wavelengths longer than the microstructure, so that the model is broadband. A metal microstructure in the form of a regular foam is chosen because it has relatively small shear rigidity, while exhibiting the bulk modulus and density of water simultaneously, see Figure 1. The large relative density of metal means that the structure is mostly void space.

An important property of PM cloaking is that the total mass of the cloak must equal the mass of the water in the space occupied by the cloak and the cloaked region[1,8]. Hence the amount of void space present in MW is preserved under the transformation from homogeneous "water" to the inhomogeneous PM. This "Archimedes principle" amounts to a Principle of Conservation of Cloaking Space, as

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shown in Figure 1c. One can think of the original void space in the isotropic MW as micro-cloaked regions. The coordinate transformation has the effect of blowing up one of these while simultaneously shrinking the others.

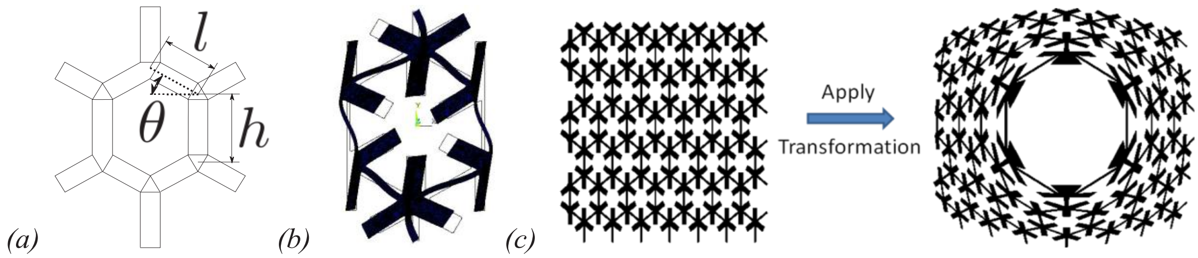

Figure 1 (a) A schematic of a unit cell. (b) Static deformation under a load used to calculate the effective elastic moduli of the periodic system. (c) The isotropic MW is transformed via the coordinate mapping into a functionally graded cylindrically anisotropic MW structure. The total amount of void in both pictures is preserved: Conservation of Cloaking Space.

The MW design begins with a hexagonal unit cell, depicted in Figure 1a. For the 2D structures considered here, the unit cell comprises thin load bearing struts, with islands of mass at the vertices, Figure 1b. The periodic structure is shown in Figure 1c, both in the original isotropic state on the left, and after transformation to the locally orthotropic structure on the right. The effective elasticity of the macroscopic foam can be calculated asymptotically to leading order in the thickness/length small parameter ε as

$$C = \begin{pmatrix} c_{11} & c_{12} & c_{16} \\ c_{12} & c_{22} & c_{26} \\ c_{16} & c_{26} & c_{66} \end{pmatrix} = C_0 \begin{pmatrix} \alpha & 1 & 0 \\ 1 & \dfrac{1}{\alpha} & 0 \\ 0 & 0 & O(\varepsilon) \end{pmatrix}, \quad \alpha = \frac{l \cos^2 \theta}{(h + l \sin\theta)\sin\theta}, \quad \begin{pmatrix} 2.20 & 2.10 & 0 \\ 2.10 & 2.20 & 0 \\ 0 & 0 & 0.016 \end{pmatrix}. \quad (1)$$

By way of comparison, water (or any compressible liquid) is described by stiffness matrix with $\alpha = 1$, $c_{66} = 0$. The matrix of numbers in equation (1) shows the FEM derived effective moduli (in GPa) for the isotropic MW. Note the small value of c_{66}. Numeric results above were obtained using the ANSYS FEM package with MATLAB for data manipulation, utilizing the homogenization theory outlined in[12]. Numerical experiments show that this value of shear modulus produces very small mode coupling and hence scattering of acoustic waves. The parameter α introduces the necessary anisotropy, which is determined by the unit cell parameters θ and l / h via equation (1). The connection with the cloaking transformation is that it defines C_0 and α (and the density) as functions of r. The microstructure is thus directly related to the coordinate mapping.

The presentation will develop these ideas through specific examples of cloak designs. Simulations of acoustic wave scattering will be shown that demonstrate the effectiveness of MW as a candidate metamaterial for not only 2D but 3 dimensional cloaking structures. Results from experiments that are anticipated will be reported if available.

References

[1] A. N. Norris, *Proc. R. Soc.A*, **464**, 2411-2434 (2008).
[2] S. A. Cummer and D. Schurig, *New J. Phys*. **9**, 1367-2630 (2007).
[3] H. Chen and C. T. Chan, *Appl. Phys. Lett*. **91**, 131518 (2007).
[4] M. Schoenberg and P. N. Sen, *J. Acoust. Soc.Am*. **73**, 61-67 (1983).
[5] D. Torrent and J. Sanchez-Dehesa *New J. Phys*. **10**, 023004 (2008).
[6] A. N. Norris and A. J. Nagy, *J. Acoust. Soc. Am*. **128**, 1606-1616 (2010).
[7] G. W. Milton and A. V. Cherkaev, *J. Eng. Mater. Technol*. **117**, 483-493 (1995).
[8] A. N. Norris, *J. Acoust. Soc. Am*. **125**, 839-49 (2009).
[9] G. W. Milton, M. Briane and J. R. Willis, *New J. Phys*. **8**, 248-267 (2006).
[10] M. Brun, S. Guenneau and B. Movchan, *Appl. Phys. Lett*. **94**, 061903 (2009).
[11] A. N. Norris, *Wave Motion* **(**accepted**)** (2011).
[12] B. Hassani, E. Hinton, *Computers & Structures*. **69**, 719-738 (1998).

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Elastic Waves Propagation in a Locally Resonant Phononic Stubbed Plates

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Abstract: We report in this study on the phonon transport in a locally resonant (LR) phononic stubbed plate. First, we will discuss the opening of LR band gap (BG) as function as the nature of the stubs and geometrical parameters to figure out the evolution of the BG. Second, we will discuss the waveguiding in such structures based on the calculation of the band structures and the transmission coefficient.

The propagation of an elastic wave in periodic composite material, called phononic crystal (PC), has received much attention over the past decade. The main mechanisms responsible for the opening of acoustic band gap (BG) are based on the Bragg scattering and local resonance (LR) which can be occurs almost two orders lower than the usual Bragg gap in the frequency region. Since the pioneer work of Liu *et al*[1], most works dealt with the bulk waves. In this communication, we will present the acoustic property of a novel PC structure constructed by periodically depositing a single-layer or two-layer stubs on the surface of thin homogenous plate.

A locally resonant stubbed plate was studied using the finite element (FE) method. We have developed a numerical model capable to cope with a structure having a large elastic constant mismatch. Two structures were investigated: i. simple periodic silicone rubber stubs on epoxy homogenous plate; ii. composite stubs (Pb/silicone rubber) on epoxy plate. The BG and dispersion relation of LR structure were analysed as function of the filling fraction and the thickness of the stubs. The waveguiding of Lamb waves in such structure was also studied using FE method combined to supercell technique.

Numerical results showed that extremely low frequency BG of Lamb waves can be opened by the local resonance mechanism (an example is given in fig. 1.a). We found that the width of such a BG depends strongly on the thickness and the area of the cross section of the stubs. The physics behind the opening of the LRBG in our phononic structures can be understood by a simple "spring-mass" model.

The concept of the proposed structure is simple and easy to perform. The displacement field of the oscillating modes was analyzed to explain how the coupling of the modes induced the opening of the BG. The basis explanation is related to the coupling between the Lamb waves and the localized modes in the stubs (fig. 1.b) when both kinds of modes have the same symmetry and polarization.

Concerning the waveguiding of Lamb modes in the LRPC, we have obtained a very original property compared to the waveguiding in the traditional PC. Indeed, the possibility of guiding only one mode in the waveguide, which is very useful and suitable for filtering and demultiplixing applications, was pointed out.

[1]Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan, and P. Sheng, *Science* **289**, 1734 (2000)

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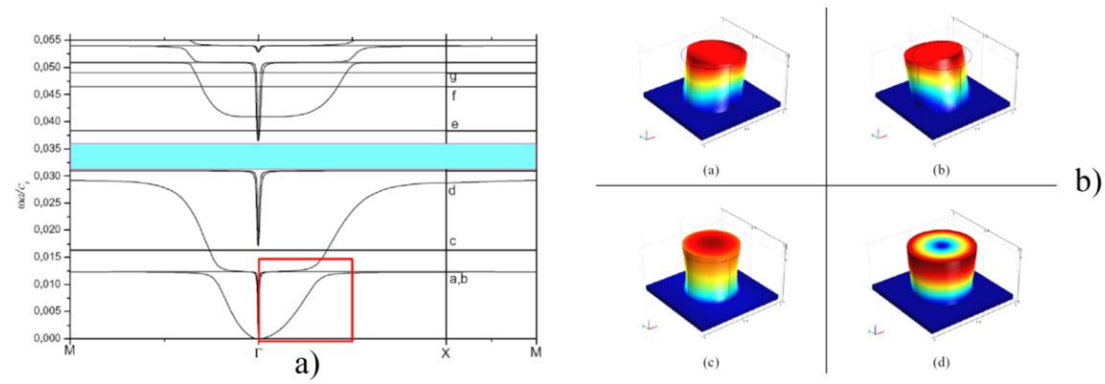

Figure 1. a. Band structures of the plate with the simple stub (only one rubber layer). b. The displacement distribution of the modes labeled as (a), (b), (c) and (d) in Fig. 1.a

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Phononic Metamaterials for Transformation Acoustics Applications

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Abstract: We review the detailed development and derivation of the concept of transformation acoustics and demonstrate several approaches for engineering materials with the acoustic properties needed to realize transformation acoustics devices.

Transformation acoustics[1–4] is a paradigm for the creation of sound-manipulating materials and devices that are either difficult or impossible to derive through other theoretical approaches. It is based on the idea of a coordinate transformation of an arbitrary initial sound field. If the device you imagine can be defined in terms of a coordinate transformation, by squeezing, stretching, and/or displacing the sound field in a finite region, then transformation acoustics provides the mathematics for taking this coordinate transformation and deriving the properties of a material in that same finite region that will have exactly the same effect on the sound field as the coordinate transformation. The technique is very general and can be used to create many different kinds of devices, the most remarkable of which is perhaps the so called "cloak of silence", in which a coating surrounds an objects in order to reduce or eliminate the acoustic scattering from the composite object.[1–3]

Figure 1 shows simulated acoustic wave interaction with and scattering from a rigid cylinder and from a composite object made of the same rigid cylinder surrounded by an anisotropic and inhomogeneous cloaking shell with properties derived through transformation acoustics[1]. With the shell surrounding the cylinder, the net scattering is essentially zero.

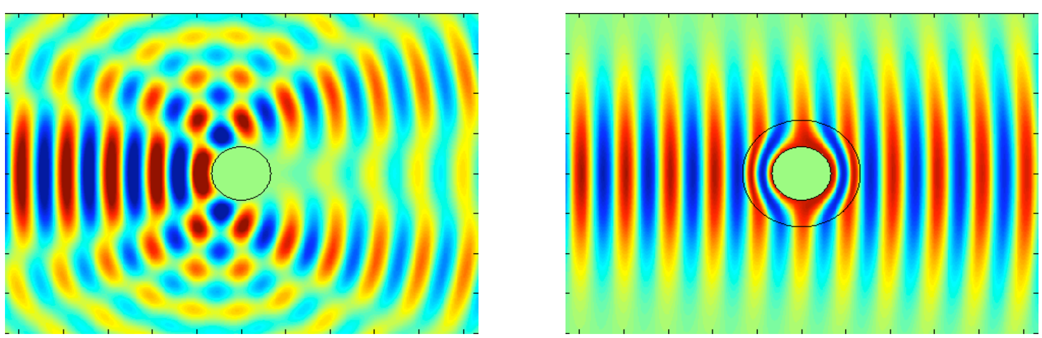

Figure 1 Left: A snapshot of simulated pressure field from an acoustic beam interacting with a rigid scatterer. Right: The same pressure field but one in which the rigid scatterer is surrounded by a shell with material properties defined by transformation acoustics theory. COMSOL Multiphysics was used for the simulations.

Transformation acoustics theory has lead to renewed interest in obtaining a new class of acoustic composites, also known as metamaterials, capable to achieve the large range of material parameters needed by these applications. Metamaterials are typically obtained from periodic arrangements of highly subwavelength unit cells composed of different types of basic materials. For example, alternating layers of very thin materials[5,6], arrays of perforated thin plates[7], and also arrays of inclusions embedded in a background fluid[8,9] have been shown to approximate the inhomogeneous and anisotropic profiles required in cloaking or hyperlens designs. Experimental work has just shown that arrays of rotationally asymmetric inclusions create effective mass anisotropy in close agreement with simulations[10].

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Most metamaterials reported so far are designed through analytical methods and thus are applicable to a relatively small pool of unit cell geometries that can be handled by these analytical techniques. Numerical techniques[11,9], on the other hand, expand the range of available unit cell geometries and, consequently, the range of obtainable material parameters. In this presentation we illustrate this point in two applications.

The first application involves the design of a compact and broadband acoustic ground cloak in air, i.e. a cloak capable of hiding objects positioned on rigid flat surfaces. The good performance of the cloak is assessed experimentally by measuring the acoustic field around the cloak and comparing this field with the target field measured in the absence of the cloak. Furthermore, comparisons of these measurements with simulations of the theoretical device having the target ideal material parameters show the effectiveness of the employed numerical method to design metamaterials with prescribed material properties.

The second application illustrates the extended range of material parameters available in metamaterials obtained through numerical methods. We design and measure a flat graded-index lens similar to that described by Torrent and Sanchez-Dehesa[12]. We show how our design technique allows us to better match the lens impedance to that of the surrounding environment, and in the same time achieve higher contrast between the refractive index of different parts of the device, thus resulting in a thinner lens for a given focal length. As before, measurements of the acoustic fields around the lens agree very well with theoretical predictions, further validating our design method.

References

[1] Cummer, S. A. and D. Schurig, "One path to acoustic cloaking", *New Journal of Physics* **9**, 45 (2007).

[2] Chen, H. and C. T. Chan, "Acoustic cloaking in three dimensions using acoustic metamaterials", *Applied Physics Letters* **91**, 183518 (2007).

[3] Cummer, S. A., B.-I. Popa, D. Schurig, D. R. Smith, J. Pendry, M. Rahm, and A. Starr, "Scattering theory derivation of a 3D acoustic cloaking shell", *Phys. Rev. Lett.*. **100**, 024301 (2008).

[4] Cummer, S. A., M. Rahm, and D. Schurig, "Material parameters and vector scaling in transformation acoustics", *New Journal of Physics* **10**, 115025 (2008).

[5] Torrent, D., and J. Sanchez-Dehesa, "Acoustic cloaking in two dimensions: a feasible approach", *New Journal of Physics* **10**, 063015 (2008).

[6] Cheng, Y., F. Yang, J. Y. Xu, and X. J. Liu, "A multilayer structured acoustic cloak with homogeneous isotropic materials", *Appl. Phys. Lett*. **92**, 151913 (2008).

[7] Pendry, J. B., and J. Li, "An acoustic metafluid: realizing a broadband acoustic cloak", *New. J. Phys*., **10**, 115032 (2008).

[8] Torrent, D. and J. Sanchez-Dehesa, "Anisotropic mass density by two-dimensional acoustic metamaterials", *New Journal of Physics* **10**, 023004 (2008).

[9] Popa, B. I., and S. A. Cummer, "Design and characterization of broadband acoustic composite metamaterials", *Phys. Rev. B* **80**, 174303 (2009).

[10] Zigoneanu, L., B.-I. Popa, A. F. Starr, and S. A. Cummer, "Design and measurement of a broadband 2D acoustic metamaterial with anisotropic effective mass density", J. Appl. Phys., in press (2011).

[11] Fokin, V., M. Ambati, C. Sun, and X. Zhang, "Method for retrieving effective properties of locally resonant acoustic metamaterials", *Phys. Rev. B*, **76**, 144302 (2007)

[12] Climente, A., D. Torrent, and J. Sanchez-Dehesa, "Sound focusing by gradient index sonic lenses", *Appl. Phys. Lett*., **97**, 104103 (2010)

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Phononic Transport in Structural Networks with Internal Resonances and Dissipation

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Abstract: The transport of mechanical energy can be controlled with phononic crystals and acoustic meta-materials. The latter can designed to control wave fields with wavelengths much larger than the meta-material's inner structure. This presentation proposes the employment of structural lattices and dissipation to improve the performance of meta-materials.

Phononic crystals (PCs) and acoustic meta-materials (AMs) are composed of periodic, multiple-phase domains, one of which is usually a solid. These systems are designed to control the propagation of elastic or acoustic waves[1,2]. The periodic modulation of material phases results in acoustic impedance mismatch, which in turn produces an effective medium with stop[1] and pass bands. These are frequency regions where wave propagation is allowed and forbidden respectively. Each of these regimes induces a response that can be exploited to control acoustic fields.

Band gaps encourage the employment of PCs and AMs for sound attenuation[3]; disorder and nonlinearity produce wave modes that allow energy propagation even within band gaps[4,5]. Nonlinearity can also be exploited to shift wave frequencies into a band gap to obtain acoustic rectifiers or acoustic diodes[6]. Pass bands also provide significant acoustic-field control and can be engineered to yield negative refraction[7], which has been used in the past to focus sound[8]. Such disparate response characteristics all arise as a result of nonlinear dispersion.

The geometric and material properties of each phase determine the frequency response of PCs. Phenomena like band gaps and negative refraction occur subsequently at fixed frequencies, which depend upon the design of the crystal. The fixed operational range of PCs restricts their deployment in practical applications. Accordingly, tunable PCs that can be controlled by external fields have been proposed. Some noteworthy examples include: temperature-sensitive[9], magneto-sensitive[10], and electric-sensitive electrorheological materials[10]. Strain-induced geometric transformations of voids in elastomeric domains permit the suppression of certain band gaps and the promotion of new ones[11].

AMs are capable of all these unusual characteristics, but are not restricted to having a lattice constant of the order of the acoustic wavelength[2]. In essence, this allows one to dramatically shrink meta-materials and structures designed to control acoustic fields. In the case of AMs, nonlinear dispersion is attributed to internal resonances[2]. AMs based on split-ring[12] and Helmholtz[13] resonators have been devised to obtain negative refraction and negative phase velocity[12] as well as negative group velocity[13]. While these simple AMs are designed with a lattice constant much larger than the acoustic wavelength, they have a fixed operational regime as they only have a single characteristic internal degree of freedom. Structural lattices (SLs) can be made to be periodic and their internal members can be designed to respond at desired frequencies[14]. Given the continuous nature of internal beam or plate-like members, the operational frequency range of SLs is virtually infinite. The same rich dynamic behavior may even preclude the need for external tuning to match any specific frequency regime.

SLs have been shown to induce band gaps[14,15] and a highly anisotropic response, dependent on frequency, even if the underlying structural network is statically isotropic[14]. The strong dynamic anisotropy, in turn, produces caustics in the wave field. This phenomenon allows the channeling of mechanical energy in preferential directions which depends on the SLs underlying symmetries.

Simple arrangements of SLs have been shown to induce limited band gaps[15] but little effort has been invested to study the repercussions of complexity in SLs. A structural network known as the chiral honeycomb[16] has been shown[14] to have a very complex dynamic behavior, apparent in the band struc-

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ture illustrated in Fig. 1. Significant band gaps are present even at low frequencies. Their appearance at different frequency regimes derives from the complexity of the medium, which is composed of rings connected by slender ligaments. Within the first 10 wavemodes, the first band gap results from dispersion induced by ligament resonance (indicated by dashed red lines in Figure 1) while a second, larger gap coincides with the resonance of rings (indicated by dashed blue lines in Figure 1), which can also yield negative group velocity.

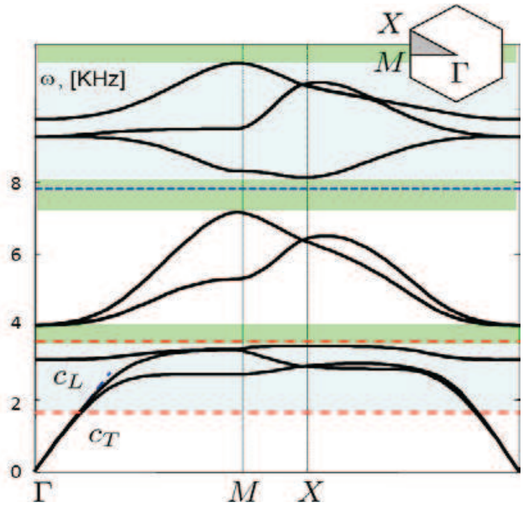

Figure 1 Band structure for a plane chiral lattice with coinciding longitudinal and shear-wave velocities. Red lines indicate resonance of beam-like members while blue lines indicate resonance of rings.

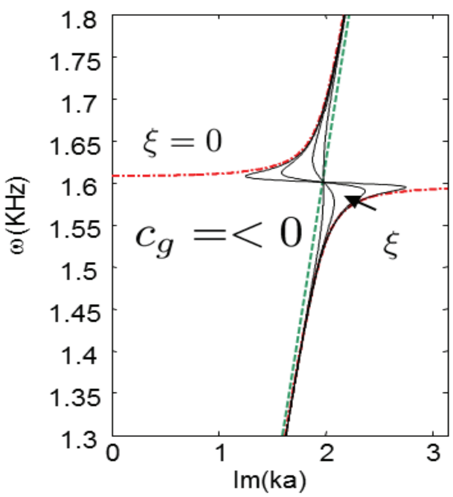

Figure 2 Dispersion relation for a 1D acoustic meta-material with a single characteristic internal resonance with damping. Absence of dissipation leads to localized wavemodes while its presence induces negative and supersonic group velocity.

The presence of dissipation (indicated by ξ in Figure 2) in AMs can induce negative as well as supersonic group velocities. As a result, the unexplored effect of dissipation is a promising research avenue. A lack of dissipation, or its neglect in mathematical models, leads to a system's response with a marked, albeit very narrow, band gap at a frequency corresponding to resonance conditions of the characteristic internal degrees of freedom (indicated by dashed red lines in Figure 2). At this frequency, the group velocity c_g is undefined and strong localization occurs. The phase of internal resonators is responsible for negative group velocity[13]. A simple analogy with a linear oscillator leads to the conclusion that dissipation alters the oscillator's phase and by extension the group velocity in AMs. A simple model shows that weak dissipation up to a critical value induces $c_g < 0$. As this critical value is breached, supersonic velocity can be obtained as the local slope of the dispersion relation becomes positive (Figure 2).

References

[1] M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, *Phys. Rev. Lett* **71**, 2022 (1993).
[2] Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang, C. T. Chan, P. Sheng, *Science* **289**(5485), 1734-1736, (2000).
[3] R. Martinez-Sala, J. Sancho, J. V. Sanchez, V. Gomez, J. Llinares, F. Meseguer, *Nature* **378**, 241 (1995).
[4] K. Aydin, K. Guven, N. Katsarakis, C. M. Soukoulis, and E. Ozbay, *Optics Express* **12**, 5896 (2004).
[5] F. Geniet, and J. Leon, *Phys. Rev. Lett.* **89**, 134102 (2002).
[6] B. Liang, X. S. Guo, J. Tu, D. Zhang, and J. C. Cheng, *Nature Materials* **9**(12), 989 (2010).
[7] X. Zhang, and Z. Liu, *Appl. Phys. Lett.* **85**, 341 (2004).
[8] S. Yang, J. H. Page, Z. Y. Liu, M. L. Cowan, C. T. Chan, and P. Sheng, *Phys. Rev. Lett.* **93**, 024301 (2004).
[9] K. L. Jim, C. W. Leung, S. T. Lau, S. H. Choy, and H. L. W. Chan, *Appl. Phys. Lett.* **94**, 193501 (2009).
[10] J. F. Robillard, O. Bou Matar, J. O. Vasseur, P. A. Deymier, M. Stippinger, A. C. Hladky Hennion, Y. Pennec, and B. Djafari-Rouhani, *Appl. Phys. Lett.* **95**, 124104 (2009).
[11] K. Bertoldi, and M. Boyce, *Phys. Rev. B* **77**, 052105 (2008).
[12] S. Guenneau, A. Movchan, G. Pétursson, and S. A. Ramakrishna, *New Journal of Physics* **9**(399), 1367 (2007).
[13] N. Fang, D. Xi, J. Xu, M. Ambati, W. Srituravanich, C. Sun, and X. Zhang, *Nature Materials* **5**, 452 (2006).
[14] A. Spadoni, M. Ruzzene, S. Gonella, and F. Scarpa, *Wave Motion* **46**(7), 435 (2009).
[15] A. S. Phani, J. Woodhouse, and N. A. Flecka, *J. Acoust. Soc. Am.* **119**(4) (2006).
[16] D. Prall, and R. S. Lakes, *Int. J. Mech. Sci.* **39**(3), 305 (1997).

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Influence of Filling Fraction and Constituent Materials on Acoustic Waves in Phononic Lattice

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Abstract: The purpose of the present numerical study is to elucidate the change of characteristics, of bulk and surface acoustic waves propagating, on the free surface of the half-infinite system when we introduce two-dimensional (2D) periodic elastic implantation.

Introduction

The propagation of elastic/acoustic waves phononic crystal (PC) has received much attentions in the last twenty years. The existence of full band gaps, which have been demonstrated by a lot of theoretical[2] and experimental[3] works, should have many potential applications. In the previous studies, most of works are concentrated on the bulk waves propagation, only few papers are devote to the surface wave propagating on the surface of the half-infinite system[4] or Lamb waves[5] propagating in finite-thickness plate. In fact, surface acoustic wave and Lamb wave device are widely used as detectors and sensors in practice. So it is worthwhile to give more studies on this subject. Several numerical analytical methods, such as plane-wave-expansion method (PWE), the multi-scattering theory(MST), and the finite different time-domain method (FDTD), have been developed to investigate the physical properties of the phononic crystal material.

In the present study PWE procedure is used to obtain the general wave solution in the infinite system firstly, and then the stress-free boundary condition on the surface is used, which lead to a stress-free-boundary-condition determinant. For such determinant, a root searching procedure is usually required to find its zeroes. The shortcoming of the numerical root searching procedure is that the desirable roots usually cannot be selected out easily when the order of the determinant is relatively large

Plane-wave expansion method

In the composite material, in absence of external force, the equations of motions are:

$$\rho(r)\frac{\partial^2 u_i(r,t)}{\partial t^2} = \frac{\partial}{\partial x_j}\left[c_{ijkl}(r)\frac{\partial u_k(r,t)}{\partial x_l}\right] \tag{1}$$

where u(r,t)=u(r)$e^{i\omega t}$ is the position and harmonic time dependent displacement vector of components u_i *(i=1,2,3)* in the Cartesian coordinate system ($Ox_1x_2x_3$). If we limit the wave propagation to the *(x_1Ox_2)* transverse plane, a 2D Bloch wave vector $\boldsymbol{k_0}$ *($\boldsymbol{k}_1$;k_2,0)* is considered. The Bloch theorem is used for the displacement vector $u(r) = \sum_G U_{k_0}^G e^{i(G+k_o)r}$. Where G=($G_1$,$G_2$) is a reciprocal-lattice vector. The physical characteristics (c_{ijkl}, ρ) in the composite system denoted α in a general way are developed in 2D Fourier series in the reciprocal space $\alpha(r) = \alpha_A$ in the cylinder A and $\alpha(r) = \alpha_B$ in the matrix B then $\alpha(r) = \sum_G \alpha_G e^{iGr}$. Then equation (1) can be separated into the following three equations:

$$\omega^2 \sum_{G'} R^{G-G'} U_i^{(k_0+G')} = \sum_{G'} \sum_{j,k,l} C_{ijkl}^{G-G'} (k_0+G)_j (k_0+G')_\ell U_k^{(k_0+G')} \quad (i=1,2,3) \tag{2}$$

In order to obtain the surface wave solution a wave vector $\boldsymbol{k}$ *($\boldsymbol{k}_1$, k_2, λ)* is considered then the problem is reduced to a generalized eigenvalue equation with respect to λ^2, which determines the spatial

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variation of the wave with the distance z from the surface. If we truncate the expansions of equation(2) by choosing n reciprocal lattice vectors, and we put $u(r) = \sum_G A_G e^{i\lambda z} e^{i(G+k_o)r}$ we have

$$(\lambda^2 \delta_{G,G'} - Q_{G,G'})A_{G'} = 0 \qquad (3)$$

where $Q_{G,G'}$ is a 3nx3n matrix. Equation (3) gives 3n eigenvalue λ_l^2, then we put $A_G^l = X_l \varepsilon_G^l$; ε is a unit polarization vector.

We search the surface wave solutions for which the lattice displacement may decay exponentially into the medium (z >0). Hence, all λ_l s must have positive imaginary part. The surface wave should satisfy the stress-free boundary conditions at the surface z=0:

$$c_{i3mn} \partial_n u_m |_{z=0} = 0 \quad \text{(i=1,2,3)} \qquad (4)$$

They lead to 3n homogeneous linear equations for the relative weights X_l of 3n wave amplitudes.

Numerical examples

An example of the numerical calculation, for the propagation of bulk acoustic waves, we consider epoxy (elastically isotropic) is assumed for the background material(B) and two kinds of 2D lattices with the cylinders(A) filled with (i) Si, (ii) Cu. A big difference between mass density quotients $(\frac{\rho(A)}{\rho(B)})$ drags a change in acoustic stop bands extension (Figure 1).

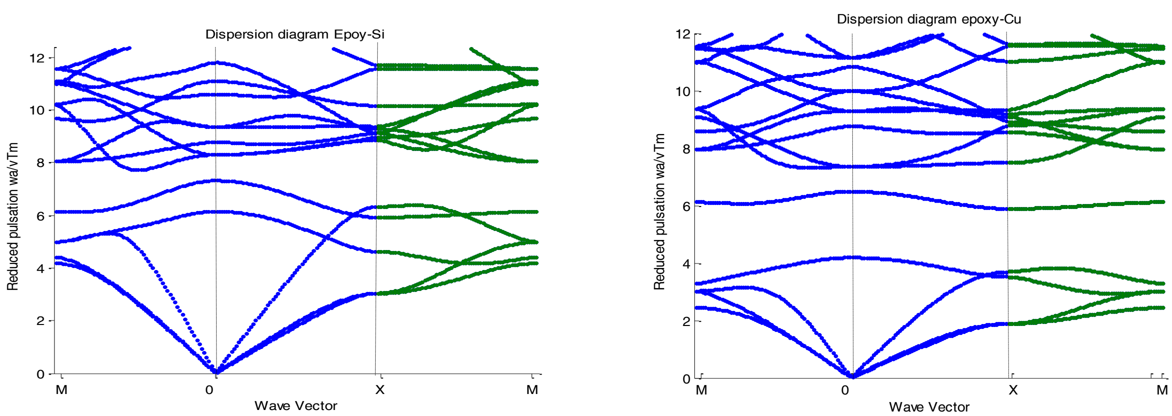

Figure 1 Dispersion relations of bulk acoustic waves in tow-dimensional square lattice consisting of (i) Si, (ii) Cu in a epoxy substrate(vTm= is the transverse sound velocity in epoxy, and a is the lattice spacing)

n=9, f=0.567, $\frac{\rho(Si)}{\rho(epo)} = 1.97, \frac{\rho(Cu)}{\rho(epo)} = 7.568.$

Other examples are treated and significant plots relative to stress and displacement distributions are achieved to recognised diverse bulk and surface wave mode.

References

[1].Y.Tanaka, S.I.Tamura, Physical Review B. 58.7958(1998).

[2]J.O.Vasseur, B. Djafari-Rouhani, L. Dobrzynski, M.S. Kushwaha, and P. Halevi, J. Phys . Condens. Matter 6? 8759 (1994)

[3] R. E. Vines, J. P. Wolfe, and A. G. Every, Phys. Rev. B 60, 11871 (1999).

[4]X. Zhang. T. Jackson, E. Lafond, P. Deymier, J. Vasseur, Appl. Phys. Lett. 88 - 041911 (2006)

[5]A. Khelif, B.Aoubiza, S. Mohammadi, A. Adibi, V. Laude, Phys ; Rev. E 74 – 046610 (2006).

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A wide band underwater strong acoustic absorbing material

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Abstract: To meet the demand of underwater acoustic absorbing material for wide band strong acoustic absorption, we introduced network structure into locally resonant phononic crystal and fabricated a new kind of metal-polymer composites. Experimental and theoretical results showed that excellent underwater acoustic absorption capability and strong mechanical strength could be obtained simultaneously.

Excellent underwater acoustic absorbing materials are urgently needed for their important applications in both military and commercial uses, such as sonar evasion by stealthy coating, underwater acoustic communication system[1-3]. In the past decade, locally resonant phononic crystal (LRPC) has inspired great interest because it can exhibit an obvious phononic band-gap in the acoustic spectrum with crystal lattice constants two orders of magnitude smaller than the relevant sonic wavelength[4-7]. Recent theoretical calculation has indicated that the maximum viscoelastic energy dissipation is generated at locally resonant frequency when considering viscoelastic deformation in LRPC[8-10]. It means that the LRPC can also be employed to expand the content of acoustic absorbing materials study. However, contrary to the aim of producing a strong absorption just at ertain narrow frequency in LRPC, acoustic absorbing material is usually need to be designed to have a strong absorbance in a wide range of frequencies. To solve this conflict, some anomalous structures need to be introduced into LRPC. It should be noticed that composite materials with interpenetrating network structures are usually found to exhibit unexpected merit due to the cooperative interaction among their component materials, such as bones and muscle in mammals and the trunks and limbs in plants[11]. We introduced interpenetrating network structure into LRPC unit, developed a modern underwater acoustic absorbing material[12,13].

The most striking difference between the LRPC and the new material is different resonant unit structures. Resonant units in the LRPC have the same size and distribute discretely in the polymer matrix. Those resonant units in the new material have different sizes and physically connected by the porous metal and the filled polymers. It is reasonable to deduce that a broad size distribution and multiple morphologies of resonant units are helpful for the realization of the wide band acoustic absorption. In this paper, we report the strong underwater acoustic absorption of a new composite material[12,13]. The study is focused on the sound attenuation mechanism in this new material. It should be noticed that these resonant units and interpenetrating network structure are different from the traditional structure of anechoic materials.

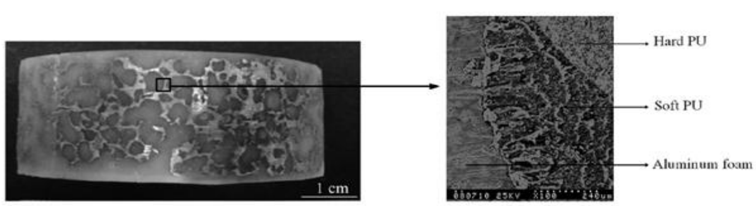

Figure 1 Optical and SEM images of a typical sample.

Figure 1 shows the interpenetrating network structure and hard-soft-hard multilayer morphology in the new material. The interpenetrating network structure is constructed in relatively large scale of millimeter-sized building blocks in the new material to work effectively for sound wave absorption.

Figure 2 illustrates the changes of underwater sound absorption coefficients for the new material and other materials as a function of frequency. Fig. 3 exhibits the engineering stress-engineering strain curves of the new material and its component materials. The comparison of underwater acoustic

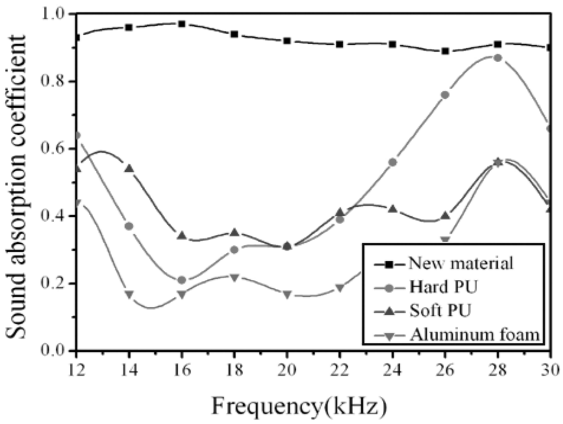

Figure 2 Underwater absorption coefficients for different materials.

absorption and compression resistance tal result between the new material and its separate components shows that the new material possesses both better sound absorption property and higher mechanical strength than its components. Figure 2 is that strong underwater acoustic absorbance with the absorbing coefficient over 0.9 can be achieved in a wide frequency range for the new material, while sound absorbing coefficients for any component materials have the values not higher than 0.9. The underwater acoustic absorption capability of the new material is much better than that of traditional acoustic absorbing materials from the measured spectrum. The strong acoustic absorption characteristic of the new material is not originated from its component or simple linear superposition of the component materials. It is reasonable to deduce that the combination of LRPC structure units and cooperative effect from the interpenetrating network plays an important role in achieving strong wide band acoustic absorbing material.

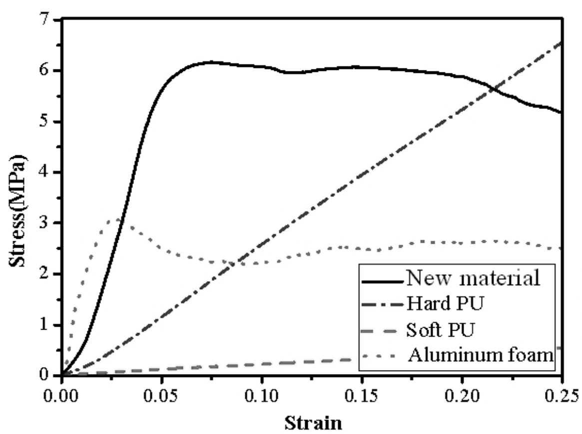

Figure 3 Compressive stress-strain curves of the new material and its component materials.

Figure 3 exhibits the comparison of compression resistance experimental result between the new material and its separate components. The new material shows compressive strength over 6MPa, while that could not be achieved by PU and aluminum foam. It means that the new material can keep a good mechanical behavior even in 500 meters water depth. Compression resistance capacity of this composite material is originated from whole effects achieved by structural design. The interpenetrating network structure unified strong wide band sound absorption capability and high mechanical strength in the new material, while it appears to be conflicting in normal circumstances.

References

[1] M. K. Hinders, B. A. Rhodes, and T. M. Fang, *J. Sound Vib.* **185**, 219-246 (1995).
[2] D. Odell, K. Hertel, and C. Nelson, Oceans'02 MTS/IEEE **1**, 266-271 (2002).
[3] M. Heinemann, A. Larraza, and K. B. Smith, *J. Acoust. Soc. Am.* **113**, 3111-3116 (2003).
[4] Z. Liu, X. Zhang, Y. Mao, Y.Y. Zhu, Z. Yang, C.T. Chan, and P. Sheng, *Science* **289**, 1734-1736 (2000).
[5] G. Wang, X. Wen, J. Wen, L. Shao, and Y. Liu, *Phys. Rev. Lett.* **93**, 154302 (2004).
[6] M. Hirsekorn, *Appl. Phys. Lett.* **84**, 3364-3366 (2004).
[7] C. Goffaux, J. Sánchez-Dehesa, A. Levy Yeyati, Ph. Lambin, A. Khelif, J. O. Vasseur, *Phys. Rev. Lett.* **88**, 225502 (2002).
[8] H. Zhao, Y. Liu, J. Wen, D. Yu, and X. Wen, *Phys. Rev. A* **367**, 224-232 (2007).
[9] H. G. Zhao, Y. Z. Liu, J. H. Wen, D. L. Yu, G. Wang, and X. S. Wen, *Chin. Phys. Lett.* **23**, 2132-2134 (2006).
[10] H. Zhao, Y. Liu, D. Yu, G. Wang, J. Wen, and X. Wen, *J. Sound Vib.* **303**, 185-194 (2007).
[11] X. Jia, *Natural Biomaterials and Bionic Engineering Materials*, Chemical Industry Press, China (2007).
[12] H. Jiang, Y. Wang, M. Zhang, Y. Hu, D. Lan, Q. Wu, and H. Lu, *Chin. Phys. B* **19**, 026202 (2010).
[13] H. Jiang, M. Zhang, Y. Wang, Y. Hu, D. Lan, and B. Wei, *Chin. Phys. Lett.* **26**, 106202 (2009).

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Transformation Acoustics Media with Periodically Layered Structures

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Abstract: Periodically layered structures have been used to construct acoustic superlenses and hyperlenses as precursors for transformation acoustics. With the transformation approach, we can now investigate the bandwidth and relationship between an acoustic hyperlens and superlens and construct transformation media through bending periodically layered structures.

By drawing analogies between electromagnetic and acoustic waves, many recent developments in acoustic metamaterials and transformation acoustics have their roots in the corresponding electromagnetic waves theory. For example, an acoustic cylindrical cloak and an electromagnetic cylindrical cloak share the same coordinate transform in arriving their designs [1,2]. However, similar to the situation in making metamaterials with negative refractive indices, quite different strategies for making the acoustic metamaterials are actually needed due to the different materials properties in the two contexts.

Here, we discuss the usage of periodically layered materials with the transformation approach. Such a scheme has the advantage that acoustic anisotropy can be generated easily and the anisotropy guides sound energy in a well controlled manner. For an acoustic hyperlens, solid plates are stacked in the angular direction to form a cylindrical shell, Figure 1(a), while for an acoustic superlens, planar solid plates are stacked along the horizontal direction [3-5]. By using the transformation approach, we are then able to investigate the acoustic hyperlens using the transfer matrix method. Figure 1 shows the coordinate mapping which transforms the hyperlens with angularly stacked brass plates into its rectangular (Cartesian) equivalence. The transformed rectangular hyperlens still has periodic stacking along the horizontal direction but the material parameters now change along the y-coordinate as well. In fact, the transformed rectangular hyperlens becomes a 2D superlens if we drop the y-dependence of the materials parameter by just employing the material parameters at the bottom boundary. Now, we can calculate the transfer function across the transformed hyperlens and it is shown in Figure 2. The two "light" lines (white dashed lines) now represent the one for air ($k_x = \omega / c_{air}$, with higher slope) and the one at the exit of the lens $k_x = R_2 / R_1 \left(\omega / c_{air}\right)$. The large transfer amplitudes between the two light lines indicate the hyperlens transports the near field information efficiently and also converts them into far field at the exit of the hyperlens. At the same time, there are several bands beyond the second light line, indicating the guiding modes circulating around the hyperlens. While the superlens relies on these guiding modes at Fabry-Perot resoannces to transport the near-field information for deep subwavelength resolution, the hyperlens have these guiding modes at the

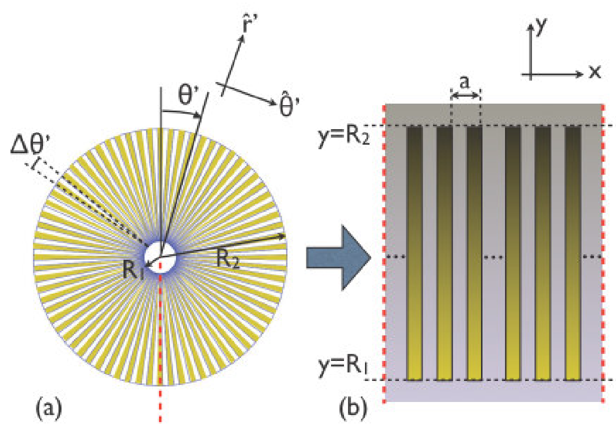

Figure 1 Transforming (a) the cylindrical hyperlens into (b) the transformed rectangular hyperlens through mapping $x = R_1\ \theta'$ and $y = r'$. R_1 = 2.7cm, and R_2 = 21.8cm are set for calculations.

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few particular frequencies indeed stay in near fields after exit of lens and they will quickly decay instead of propagating. The transfer function calculation thus shows the working principle of both hyperlens and superlens and explains how the hyperlens can work in broad frequency bandwidth with sub-wavelength resolution.

Apart from guiding the sound waves along a fixed direction of fluid perforation using the periodically layered material, the same periodic material, after a simple geometrical transformation, can be used to construct transformation acoustical devices. In particular, we bend the metamaterial using a certain mathematical function. The resultant curved metamaterial can be used to construct transformation acoustical devices by cutting the metamaterial into particular shapes. As an example, we demonstrate a design of acoustic carpet cloak using the mentioned strategy. We bend planar solid brass plates which are periodically stacked vertically within water using a squared cosine function. Now, all the brass plates are having the same shape of squared cosine function and the material is still periodic in the vertical direction. The material is then cut into a shape of the carpet cloak which is shown as thin black lines for the curved brass plates in Figure 3. The carpet cloak is working in a background fluid of water and the background fluid can percolate freely between the curved brass plates. Now, instead of guiding the sound waves only along the fluid perforations, the periodically layered structure can guide the sound energy in a two dimensional manner so that the carpet cloak cancels the scattering of the curved bump below the cloak if it is situated on a hard surface. We have simulated a particular situation where a Gausian beam is impinging on the cloak at approximately 60 degrees. Although there is a small impedance mismatch between the cloak and the background water to have a little spurious reflection at the microstructured cloak boundary, the scattering of the bump is largely reduced and there is a reflected beam at the same angle as if it is just a flat hard surface.

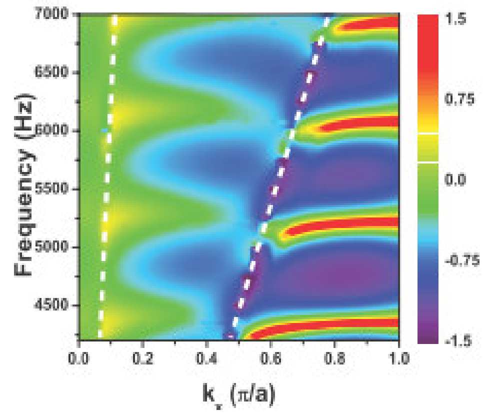

Figure 2 Transfer amplitude (in log10 scale) of the hyperlens against different tangential wave number. The wave number is normalized to π/a where a is the periodicity of the hyperlens at inner boundary.

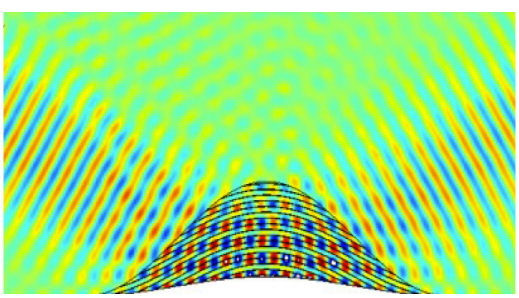

Figure 3 Curved periodically layered metamaterials employing brass plates and background water to guide sound waves in water as a carpet cloak

Therefore, we have investigated how to use periodically layered structure to generate anisotropy and such anisotropy can be well designed and explained with the transformation approach to guide sound waves, either at a single direction for subwavelength imaging or in a two dimensional manner for transformation acoustical devices.

References

[1] S. A. Cummer, and D. Schurig, *New J. Phys.* **9**, 45 (2007).
[2] H. Chen, and C. T. Chan, *Appl. Phys. Lett.* **91**, 183518 (2007).
[3] J. Li, L. Fok, X. Yin, G. Bartal, and X. Zhang, *Nature Mater.* **8**, 931 (2009).
[4] J. Zhu, J. Christensen, J. Jung, L. Martin-Moreno, X. Yin, L. Fok, X. Zhang, and F. J. Garcia-Vidal, *Nature Phys.* **7**, 52 (2011).
[5] H. Jia, M. Ke, R. Hao, Y. Ye, F. Liu, and Z. Liu, *Appl. Phys. Lett.* **97**, 173507 (2010).

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Impedance Matching for Aqueous Inertial Metafluid Devices

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Abstract: Several interesting metafluid devices have been investigated for use at frequencies in the low tens of kilohertz, including gradient index lenses, directional antennas and tuneable scattering elements. For 3D or orthotropic devices whose operating frequencies are less than a few 10's of kHz additional and significant practical issues can arise for inertial metafluids: dynamic impedance matching, mass and volume.

The application of transformational optics to acoustic metamaterials offers promising new acoustic devices, ranging from tunable sound blocking with superior efficiency, to acoustical diodes. Metamaterial designs typically require high anisotropy in either mass density or elastic moduli (or both), which can be achieved through inertial variation of material properties or by using resonant scatterers, though the latter is usually only functional within a narrow bandwidth. Many inertial approaches obtain this anisotropy through the use of rigid scatterers and boundaries, which are easily achievable in air. However, high relative mass densities are restricted to about an order of magnitude in aqueous environments, resulting in poorly approximated rigidity. Similarly, few options exist for scattering constituents with high bulk modulus/low mass density (both relative to water), as in Figure 1. Nevertheless, we have investigated several interesting devices that are functional in water at frequencies of around a few tens of kilohertz, including gradient index lenses, directional antennas and resonance-based vector sensors.[1-3]

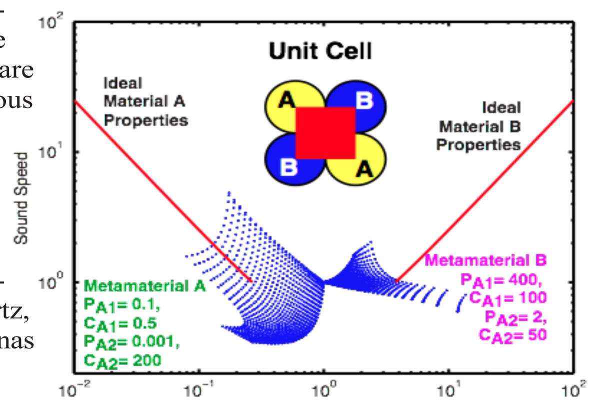

Figure 1 Sample design seeking optimal Pendry parameters using a "diatomic" lattice of cylindrical scattering elements. The filled regions represent effective parameters achievable using already extreme material parameters 2 orders of magnitude larger than the background – they fail to cover the necessary phase space.

One can design and implement a gradient index lens, for example, without impedance matching at the front interface by relying on internal subwavelength scattering from high impedance contrast elements.[1,4] This has the unfortunate effect of seriously degrading the ultimate performance of the device by reflecting much of the incident signal back away from the device. To address this shortcoming, we have investigated a new class of phononic crystal consisting of an interleaved set of two distinct types of scattering centers: One with a mass and bulk modulus much higher than the surrounding medium, the other lower. Through a judicious choice of media and size, a perfect impedance matching can be made at the front interface that has the net effect of substantially increasing the device efficiency.

Figure 2 Design of sample apparatus and placement in NRLs Salt Water Tank Facility at the midway point in the tank. The 10cm acoustic transducer used to ensonify the phononic crystal is seen as the white sphere to the right of the apparatus.

We explore metamaterial applications where device functionality can be obtained without

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extreme material parameters, such as with directional antennas.[2] We also investigate devices with tunable impedance matching; our initial design consists of cylindrical scatterers each consisting of a stainless steel tube wrapped with a single layer of copper wire (i.e., a solenoid) with a standard magneto-rheological fluid consisting of Fe micro-particles suspended in a mineral oil base. Using the "magic number" results of Torrent, *et al.*[4] to achieve effective parameters of an equivalently larger cylinder of equal circumference, seven of these tubes were then arranged in a hexagonal unit cell, as seen in Figure 2.

References

[1] T. P. Martin, M. Nicholas, G. J. Orris, L.-W. Cai, D. Torrent, and J. Sanchez-Dehesa. Sonic gradient index lens for aqueous applications. *Applied Physics Letters*, **97**(11):113503, 2010.
[2] C. N. Layman, T. P. Martin, G.J. Orris, "An Acoustic Directional Antenna with Isotropic Materials", MRS 2011, 1015988, W14.2.
[3] D. Torrent and J. Sanchez-Dehesa. Anisotropic mass density by radially periodic fluid structures. *Phys. Rev. Lett.*, **105**(17):174301, Oct 2010.
[4] D. Torrent, A. Hakansson, F. Cervera, and J. Śanchez-Dehesa. Homogenization of two-dimensional clusters of rigid rods in air. *Phys. Rev. Lett.*, **96**(20):204302, May 2006.

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Locally resonant structures for low frequency surface acoustic band gaps

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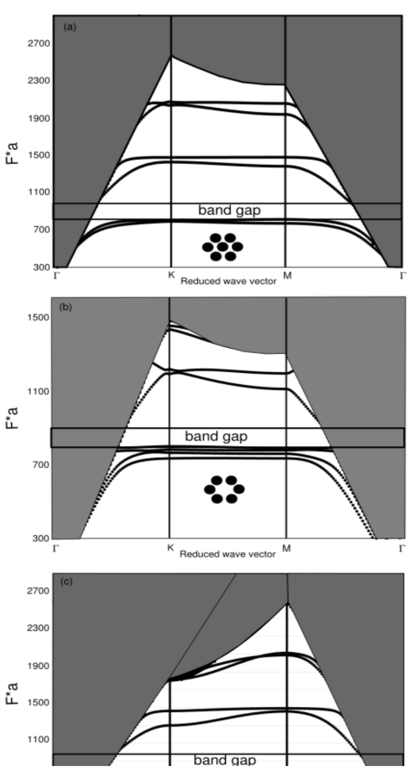
Abstract: We present in this paper a theoretically and experimentally study of the propagation of surface acoustic waves in a two-dimensional array of cylindrical pillars on the surface of a semi-infinite substrate. Low-frequency, markedly lower than those expected from the Bragg mechanism, band gaps were demonstrated.

We investigate theoretically and experimentally the propagation of acoustic waves in a two-dimensional array of cylindrical pillars on the surface of a semi-infinite substrate.

Through the computation of the band structure of the periodic array and of the transmission of waves through a finite length array, we show that the phononic structure can support a number of surface propagating modes in the non-radiative region of the substrate, or sound cone, as limited by the slowest bulk acoustic wave. The modal shape and the polarization of these guided modes are more complex than those of classical surface waves propagating on a homogeneous surface. Significantly, an in-plane polarized wave and a transverse wave with sagittal polarization appear that are not supported by the free surface (ref:1).



In the band structure, guided modes define band gaps that appear at frequencies markedly lower than those expected from the Bragg mechanism. We identify them as originating from local resonances of the individual cylindrical pillars and show their dependence with the geometrical parameters, in particular with the height of the pillars. The frequency positions of these band gaps are invariant with the symmetry and thereby the period of the lattices, which is unexpected in band gap based on Bragg mechanism.

The role of the period remains important for defining the non-radiative region limited by the slowest bulk modes and influencing the existence of new surface mode of the structures. The transmission of surface acoustic waves across a finite array of pillars shows the signature of the locally resonant band gaps for surface modes and their dependence with the symmetry of the source and its polarization. Numerical simulations are based on the efficient finite element method and considering pillars on a Lithium Niobate substrate.

Figure 1: Band structure of a phononic crystal composed of cylindrical silicon pillars on a silicon substrate, calculated along high symmetry directions of the first irreducible Brillouin zone for: **(a)** square; **(b)** triangular; **(c)** honeycomb. The lattice parameter is a for triangular and square lattice and $\sqrt{3}\, a$

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for the honeycomb lattice. The radius is $r/a=0.32$ and the relative height of the cylinders h/a equals 0.6. The gray region represents the sound cone of the substrate. The sound line limiting the sound cone is given by the smallest phase velocity in the substrate for every propagation direction.

References

[1] Locally resonant surface acoustic wave band gaps in a two-dimensional phononic crystal of pillars on a surface», Khelif, A. and Achaoui, Y. and Benchabane, S. and Laude, V. and Aoubiza, B. , *Physical Review B*, Vol.81, 214303, 2010.

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Applications of Metafluids based on Phononic Crystals

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Abstract: Acoustic metamaterials or metafluids based on the homogenization of periodic distributions of sound scatterers (phononic crystals) are reviewed. It will be shown that periodically microstructured solids effectively behave like fluidlike materials with dynamical mass anisotropy. Also, it will be shown that the acoustic refractive index can be locally tailored in order to get molding of the sound waves. Applications of these types of metafluids as acoustic cloaks, gradient index refractive lenses, perfect absorbers and radial sonic crystal will be reported.

It was demonstrated that a periodic distribution of solids rods in air behaves in the homogenization limit like effective fluids in which the dynamical mass density follows a simple analytical expression mainly dependent of the lattice filling ratio [1, 2]. It was shown later that mixing solids of different material in the lattice increases the tailoring possibilities of the mass density and that the acoustic refractive index can be locally adjusted to design, for example, gradient index sonic lenses [3]. Moreover, for the case of non-isotropic distribution of scatterers (i.e., for lattices other than the square or hexagonal) the sound propagation inside the homogeneous structure depends on the direction and the effective mass density becomes a tensor [4], a non-exiting property in fluids or gases found in nature. So, these micro structured solids define a class of acoustic metamaterials or metafluids whose acoustic parameters, mass density and bulk modulus, are both positive and can be easily obtained by using effective medium theories (homogenization). Metafluids with anisotropic mass density are the ingredients that might be possible acoustic cloaks [5, 6] or radial wave crystals [7, 8].

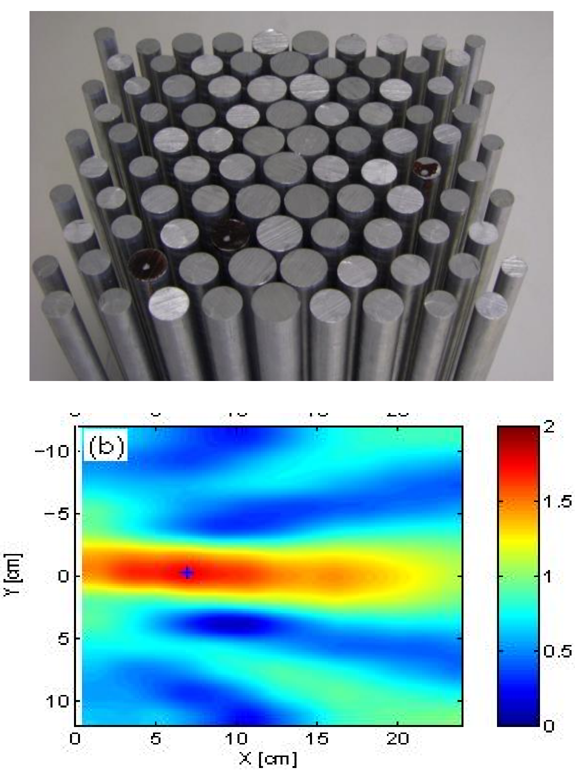

Figure 1: Upper Panel: Picture of a GRIN lens. Lower Panel: Sound amplification obtained.

Gradient index (GRIN) sonic lenses have been fabricated by using the tailoring possibilities of metafluids described above and their focusing performance has been demonstrated for airborne sound [9] and underwater [10]. Figure 1 shows a photograph of GRIN lens together with the sound amplification obtained. A sound amplification of two was obtained by this lens in which the building units are aluminum rods. It has been demonstrated that the position of the focal spot, x_f, follows the analytical formula obtained from ray theory:

$$x_f = d - \frac{y(d)}{y'(d)}\sqrt{\frac{1-(y'(d))^2\left[n^2(y(d))-1\right]}{n^2(y(d))}}$$

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GRIN lenses with larger sound amplification can be achieved by using scattering units having a mismatch of impedance with the background substantially reduced. An approach to achieve this goal will be here introduced.

The feasibility of tailoring the index gradient can be also employed to design perfect absorbers in which the sound energy impinging to some area is guided to a region where its energy is totally dissipated.

Finally, it will be reported how the homogenization theory is applied to obtain the effective parameters of metafluids embedded in viscous media. The viscosity produces two main contributions to the resulting metafluids. Firstly, the homogenization condition is achieved for larger wavelengths. An secondly, the waves propagating inside the metafluid have longitudinal and transversal components that basically depends on the lattice filling ratio. As an example, figure 2 represents a case studied by our effective medium theory.

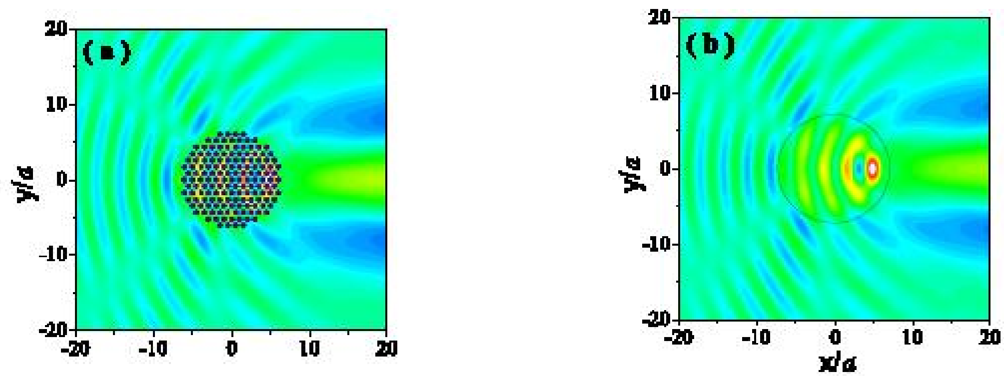

Figure 2. (a) Pressure map (amplitude) representing the scattering of a sound wave impinging a cluster of rigid cylinder embedded in glycerin. (b) The corresponding map obtained for a cylinder made of a metafluid whose parameters are obtained by a homogenization theory that takes into account the viscosity of glycerin.

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References

1. D. Torrent, A. Hakansson, F. Cervera and J. Sánchez-Dehesa, Phys. Rev. Lett. 96, 204302 (2006).
2. D. Torrent and J. Sánchez-Dehesa, Phys. Rev. B 74, 224305 (2006).
3. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 9, 323 (2007).
4. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 10, 023004 (2008).
5. S.A. Cummer and D. Schurig, New J. Phys. 9, 45 (2007).
6. L.W. Cai and J. Sánchez-Dehesa, New J. Phys. 9, 450 (2007).
7. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 10, 063015 (2008).
8. D. Torrent and J. Sánchez-Dehesa, Phys. Rev. Lett. 103, 064301 (2009).
9. D. Torrent and J. Sánchez-Dehesa, New J. Phys. 12, 073034 (2010).
10. A. Climente, D. Torrent and J. Sánchez-Dehesa, Appl. Phys. Lett. 97, 104103 (2010).
11. T. Martin, G. Orris, L.W. Cai, D. Torrent and J. Sánchez-Dehesa, Appl. Phys. Lett. (2010).

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Perforated acoustic metamaterials

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The discovery of the phenomenon of extraordinary optical transmission (EOT) through subwavelength holes by Ebbesen and co-workers has become a milestone theme within the field of nanophotonics and has sparked considerable fundamental but also technological interests [1]. Alongside the discovery of EOT, metamaterials for EM radiation have also become a topic of intense research that has lead to negative refraction, perfect lenses and perfect absorbers [2].
Acoustic metamaterials on the other hand have been introduced in 2000 by locally resonating spheres [3] and has since then given rise to a vast amount of innovative metamaterial structures, e.g., see [4]. In this presentation we focus on perforated plates, which is governing the study of enhanced acoustic transmission through subwavelength apertures [5] and in addition supports metamaterial typical phenomena like perfect imaging [6], negative refraction [7] such as full attenuation of sound [8]. We will discuss both theoretical and experimental results related to these items, e.g., such as the possibility of sub-diffraction-limited imaging by means of a slow fluid slab as shown in Fig. 1, [6].

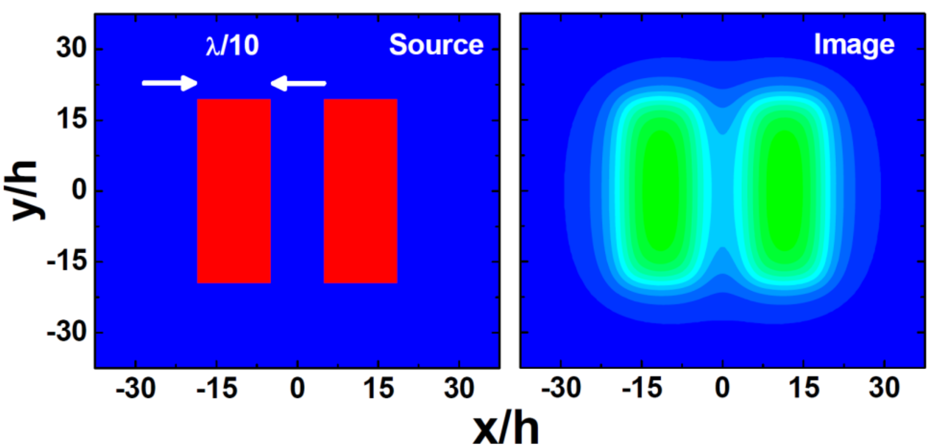

Fig. 1

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References

[1] T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, and P. A. Wolf, Nature 391 , 667 (1998).
[2] J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000), R. A. Schelby, D. R. Smith and S. Schulz, Science 292, 77 (2001), N. I. Landy et al., Phys. Rev. Lett. 100, 207402 (2008).
[3] Z. Liu, X. Zhang, Y. Mao, Y. Y. Zhu, Z. Yang. C. T. Chang and P. Sheng, Science 289, 1734 (2000).
[4] N. Fang, D. Xi, J. Xu, M. Ambai, W. Srituravanish, C. Sun and X. Zhang, Nature Material 5, 452 (2006).
[5] B. Hou et al. Phys. Rev. B 76, 054303 (2007), J. Christensen et al. Nature Physics 3, 851 (2007), J. Christensen, L. Martin-Moreno and F. J. Garcia-Vidal, Phys. Rev. Lett. 101, 014301 (2008)
[6] J. Zhu et al. Nature Physics 7, 52 (2011), J. Christensen et al. Appl. Phys. Lett. 97, 164103 (2010)
[7] J. Christensen and F. J. Garcia de Abajo, under preparation (2011).
[8] J. Christensen, L. Martin-Moreno and F. J. Garcia-Vidal, Appl. Phys. Lett. 97, 134106 (2010)

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Phononic Band Structure of a Silicon Plate with Periodic Array of Cylindrical Metallic Pillars

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Abstract: We investigate theoretically the phononic band structure in a 2D array of cylindrical pillars on the surface of a slab. Simulations are based on the finite element method (FEM) using tungsten pillars on silicon as the structure of interest. We show that the phononic structure supports band gaps and study the behavior of band structure with respect to lattice symmetry and geometrical parameters.

During the past decade, synthetic periodic acoustic structures (i.e., phononic crystals) have attracted significant attention as they enable designers to control the elastic properties of the material. Specific focus of researchers in this field has been on the search for phononic crystal structures that support phononic band gaps (PnBGs). In particular, it has been shown that a honeycomb array of circular holes in a silicon (Si) slab can support sizable PnBGs[1]. However, this requires relatively large aspect ratios that make their fabrication challenging for high frequencies. Recently, 2D structures consisting of an array of cylindrical pillars on a plate have been introduced that display large PnBGs with more relaxed fabrication requirements[2,3].

In this paper we investigate different phononic crystal structures composed of 2D array of tungsten (W) pillars on a silicon plate with different lattice structures, namely, triangular and honeycomb lattices. We show that triangular lattice structures support multiple wider PnBGs for a wide range of geometrical parameters compared to square lattice structures. On the other hand, honeycomb array of pillars do not support any wide PnBGs with similar dimensions.

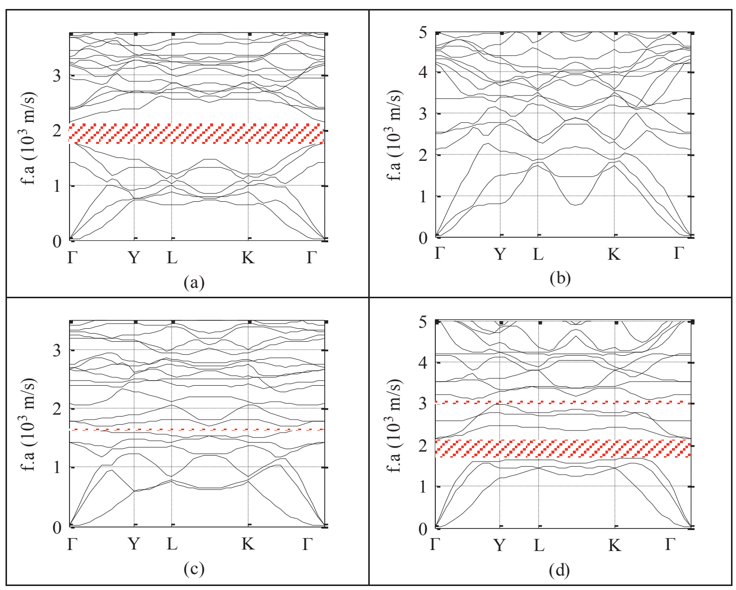

Figure 1 Band diagrams of (a,b) a honeycomb and a triangular array of holes in Si, respectively, with *r/a* = 0.4, *d/a* = 0.87; band diagrams of (c,d) a honeycomb and triangular array of W pillars on Si with *r/a* = 0.25, *h/a* = 0.15, d/*a* = 0.5. Here r, a, and d represent the hole (or pillar) radius, the lattice constant, and the slab thickness, respectively. In the case of pillars, *h* represents the height of the pillar.

Figure 1a shows the band diagram for a sample design of a honeycomb array of holes in Si. The existence of a wide band gap is evident from Fig. 1a. On the other hand, as shown in Fig. 1b, a triangular array of holes with similar dimensions does not support PnBG. On the contrary, Figs. 1c and 1d show that a honeycomb array of W pillars on Si does not support any significant PnBG while its triangular counterpart provides a wide PnBG. In order to investigate this phenomenon, we have studied the effects of the normalized slab thickness (*d/a*), and the normalized radius (*r/a*) and height (*h/a*) of the pillars on the PnBG.

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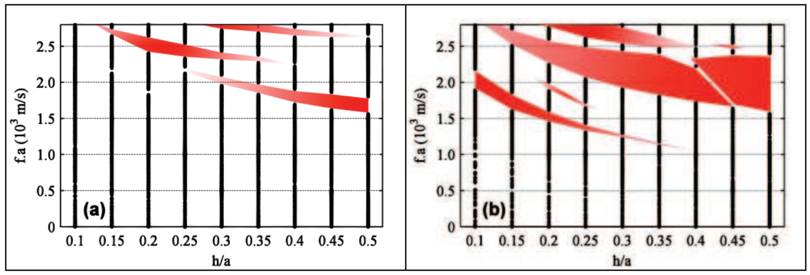

Figure 2 Existence of PnBG openings in (a) honeycomb and (b) triangular array of W pillars (r/a = 0.40) on a Si slab (d/a = 0.5) for different values of h/a.

Figures 2a and 2b show the gap maps (the extent of the PnBG as a function of design parameters) for a honeycomb and a triangular phononic crystal of W pillars on a Si slab, respectively, for a fixed pillar radius and slab thickness. Fig. 2 suggests that a triangular phononic crystal has a wider PnBG with band openings (PnBG frequency extent divided by the PnBG center frequency) of up to 25%. It is also seen that the triangular lattice structure displays band opening at h/a of as low as 0.1. Further assessment of dispersion diagram of this PnBG proves that this band opening is due to the lattice periodicity, which results in the folding of the first order mode of the structure in the dispersion diagram. Also, in this example, we can see the honeycomb lattice starts to open a PnBG at h/a ~ 0.15 around $f.a$ ~ 2700m/s. This behavior is also seen in the triangular lattice only resulting in wider gaps. In addition, other gaps at similar frequencies (with different widths) can be observed for both lattices. Considering the fact that the same band gaps are supported in two structures with similar pillars and completely different lattice constants (the lattice period of the honeycomb lattice is 70% larger than that of the triangular lattice with the same a) we believe that the formation of these band gaps are mainly caused by the strong coupling between locally resonant pillar structures through the silicon slab rather than the periodic perturbation of the slab modes by the pillars.

Lattice type	α (lower edge)	α (upper edge)
Honeycomb (h/a = 0.45)	1.1	0.85
Triangular (h/a = 0.45)	0.82	11.1
Triangular (h/a = 0.1)	0.23	0.34

Table 1 Ratio of average elastic energy density in W pillars and Si slab (α) (r/a = 0.40 and d/a = 0.5)

In order to verify this claim, we calculate the ratio of average total elastic energy density in W pillars and Si slab (denoted as α). α's much lower than one indicate weak effect of the pillar resonances on the PnBG. As shown in Table 1, α for similar behaving band edges in the two lattices are close to one or higher; whereas, this parameter is much lower for band edges formed exclusively in the triangular lattice at lower frequency.

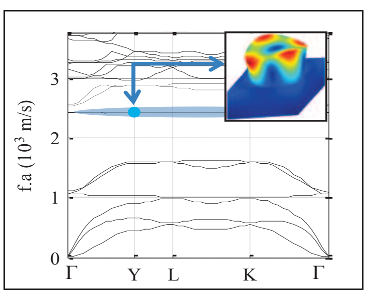

Figure 3 Band diagram of triangular array of W pillars (r/a = 0.40, h/a = 0.45) on Si slab (d/a = 0.50). Shown in the box: mode shape of the lattice unit cell at high symmetry point Y for upper edge of first band gap.

Another way to confirm that wide gaps appearing in the triangular lattice structure at higher pillar heights are due to the strong coupling of the local resonance modes of the W pillars is by visually investigating the mode shape at the band edges for such gaps. Figure 3 shows the band diagram of a triangular lattice with r/a = 0.40, d/a = 0.5, and h/a = 0.45. We can see that first band gap is bound to almost a flat upper branch. Based on our discussion, we expect this branch to correspond to the resonance mode of a W pillar. As shown in this figure, a significant amount of the mode energy for this branch at the high symmetry point Y is concentrated in the pillar.

To summarize, theoretical evidence was provided that a triangular lattice of pillars on a Si slab is more likely to provide wide PnBGs in comparison to honeycomb lattice. Further details on the properties of the PnBGs, the modes of the structure, and the potential applications will also be presented.

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References

[1] S. Mohammdi, A. A. Eftekhar, A. Khelif, W. D. Hunt, and A. Adibi, *Appl. Phys. Lett.* **92**, 221905 (2008),
[2] Y. Pennec, B. Djafari-Rouhani, H. Larabi, A. Akjouj, J. N. Gillet, J. O. Vasseur, and G. Thabet, *Phys. Rev. B* **80**, 144302 (2009),
[3] T. C. Wu, T. T. Wu, and J. C. Hsu, *Phys. Rev. B* **79**, 104306 (2009)

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Dissipative Effects in Acoustic Metamaterials

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Abstract: We demonstrate the consequences of energy dissipation in acoustic metamaterials. A nested mass-spring-dashpot system serves as our model. In the context of Bloch theory, we utilize the familiar structural dynamics techniques of modal analysis and state-space transformation to investigate the damped frequency band structure and its impact on effective properties.

In the context of acoustic wave propagation, a class of acoustic metamaterials (AMs) has the feature of spatial periodicity whereby the repeating unit cell can be orders of magnitude smaller than the travelling wavelength. This "acoustical atom" construction gives rise to effective, frequency-dependent properties including negative mass and negative elastic modulus. Ingenuity may exploit these unnatural properties in such novel applications as superlensing[1] and acoustic cloaking.[2] To date, however, theoretical studies of AMs have not adequately incorporated the effects of energy dissipation (i.e., damping) on the band structure and subsequently on the negative properties. The study of the effects of dissipation in AMs and its potential impact on the expression of negative effective properties is therefore the main objective of our present study.

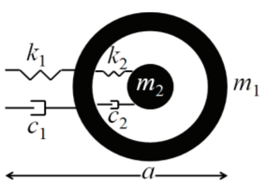

Figure 1. Acoustic meta-material unit cell

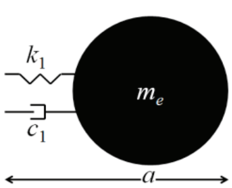

Figure 2. Equivalent model unit cell

To demonstrate the consequences of dissipative wave propagation in AMs, we consider a nested 1D lumped parameter mass-spring-dashpot model similar to that found in the literature.[3,4] Infinite in extent, our metamaterial model is constructed by appending copies of the unit cell of Fig. 1 ad infinitum along the line of motion. Likewise, this construction applies to the equivalent lattice architecture of Fig. 2, which we require to exhibit the same dynamic behaviour as our original model. In both models, the constant a defines the lattice spatial periodicity. For the equivalent model, m_e is the effective mass.

At present, we focus on the acoustic metamaterial model. To establish the damped frequency band structure we reformulate a quadratic eigenvalue problem representation[5] and incorporate the Bloch modal analysis technique.[6,7] Consequently, for this extended abstract, we consider only Rayleigh-type damping, in particular, stiffness-proportional damping. In addition, we consider constant damping parameters; however, the viscous dissipation force is frequency-dependent.

For the AM model, we derive the governing equations of motion, and assume a time-harmonic solution of the following form for the time-dependent displacement u_l of mass l:[6,7]

$$u_l(t) = \widetilde{U}_l e^{\lambda t}. \quad (1)$$

In Eq. 1, $\widetilde{U}_l$ denotes the complex wave amplitude. Naturally, for the undamped scenario, $\lambda = i\omega$. For our study, per the results of Ref. 7, $\lambda = -\omega\left(q\omega - \sqrt{q^2\omega^2 - 4}\right)/2$ where q is the damping intensity.

For the specific set of material properties provided in Table 1, the dispersion curves following our formulation is shown in Fig. 3. The wavenumber $\kappa = \kappa_R + i\kappa_I$ consists of a real component, κ_R (right side of figure), and an imaginary component, κ_I (left side of figure). The damped natural frequency is $\omega_d = \mathrm{Im}[\lambda(\omega; q)]$. In contrast to the

$r_m = m_2/m_1 = 1/100$
$r_k = k_2/k_1 = 3/100$
$\overline{\omega} = \sqrt{m_2/k_2} = 149.07$ rad/s

Table 1. Material properties

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dramatic change seen in the optical branch in response to the changing damping intensity, the change in the acoustical branch is relatively modest.

We now turn our attention to the dynamics of the equivalent model in Fig. 2. In order to exhibit the same dynamic behaviour as the lattice in Fig. 1, the value m_e must become frequency-dependent. The equations of motion are derived anew following the approach in Ref. 7 where the Bloch wave solution is assumed. For the nested-mass lattice model, this avenue yields a homogeneous system of equations with mass matrix $\mathbf{M}$, stiffness matrix $\mathbf{K}(\kappa)$, and damping matrix $\mathbf{C}(\kappa)$ (recall, $\mathbf{C}(\kappa) = q\mathbf{K}(\kappa)$ is our present interest). Specifically,

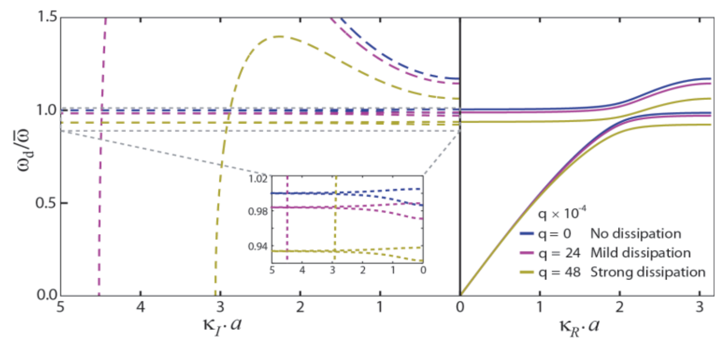

Figure 3. Dissipative frequency band structure

$$\mathbf{M} = m_2 \begin{bmatrix} 1/r_m & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{K}(\kappa) = k_2 \begin{bmatrix} 2(1-\cos\kappa a)/r_k + 1 & -1 \\ -1 & 1 \end{bmatrix}. \tag{2}$$

For the equivalent lattice, the characteristic equation is algebraically manipulated to the following form:

$$-\lambda^2 \frac{m_r(1+r_m)}{\bar{\omega}^2 r_m (1+\lambda q)} = \frac{2}{r_k}(1-\cos\kappa a), \tag{3}$$

where, for convenience, we have defined the effective mass ratio $m_r = m_e/(m_1+m_2)$.

By substituting Eq. 3 into $\mathbf{K}(\kappa)$ in Eq. 2, we tie the dynamic behaviour of the equivalent model to that of the nested-mass model. Using the redefined $\mathbf{K}(\kappa)$and Bloch modal analysis yields two characteristic equations in $\lambda(m_r; q)$. We proceed to solve one of these equations (the choice is inconsequential) for m_r and make the substitution $-\omega\left(q\omega - \sqrt{q^2\omega^2-4}\right)/2$ so that we have $m_r(\omega; q)$. Thus, we are able to produce Fig. 4. Upon closer inspection of Fig. 4, for each value of q, it is evident that the effective mass of the dissipative system is negative over the a region approximating the band gap of Fig. 3.

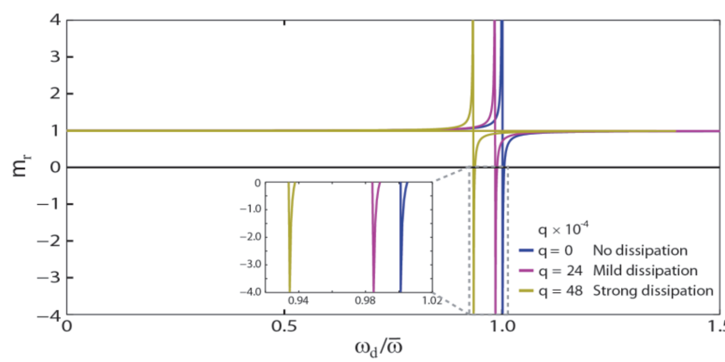

Figure 4. Effective mass ratio for dissipative acoustic metamaterial

References

1. Zhu, J., Christensen, J., Jung, J., Martin-Moreno, L., Yin, X., Fok, L., et al. (2010). A holey-structured metamaterial for acoustic deep-subwavelength imaging. *Nature Physics*, *18* (4), 1-4.
2. Cummer, S.A., Popa, B., Schurig, D., Smith, D., Pendry, J., Rahm, M., et al. (2008). Scattering Theory Derivation of a 3D Acoustic Cloaking Shell. *Phys. Rev. Lett.*, *100* (2).
3. Huang, H., Sun, C., & Huang, G. (2009). On the negative effective mass density in acoustic metamaterials. *International Journal of Engineering Science*, *47* (4), 610-617.
4. Liu, Z., Chan, C. T., & Sheng, P. (2005). Analytic model of phononic crystals with local resonances. *Phys. Rev. B*, *71* (1).
5. Farzbod, F., & Leamy, M.J. (2010). Analysis of Bloch's method in structures with energy dissipation. *ASME International Mechanical Engineering Conference & Exposition.* Vancouver, British Columbia, Canada.
6. Hussein, M.I. (2009). Theory of damped Bloch waves in elastic media," *Phys. Rev. B*, 80, 212301.
7. Hussein, M.I. & Frazier, M.J. (2010). Band structures of phononic crystals with general damping. *J. Appl. Physics, 108* (9).

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Multi-field Internally Resonating Metamaterials

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Abstract: Two examples of internally resonating metamaterials with multi-field coupling are presented. A one-dimensional waveguide with a periodic array of shunted piezoelectric patches features resonant characteristics associated with the shunting electrical impedance. The second part presents the study of piezoelectric superlattices as an additional example of an internally resonant metamaterial.

In this work wave propagation in periodic systems which comprise multi-field elements is analyzed. The study is based on the general observation that the presence of elements capable of energy conversion between two fields offers extensive opportunities for the achievement of unusual and novel wave propagation characteristics. In this regard, multi-field coupling in periodic materials is an excellent candidate for the design of novel metamaterials. One of the concepts illustrated involves the use of piezoelectric materials for the conversion of elastic into electrical energy, and the use of shunting circuits to generate an equivalent resonant system in parallel to the mechanical waveguide. The resonant characteristics of the shunts can be tuned by modifying the circuit electrical impedance, which suggests the possibility for the system to achieve unusual mechanical properties at selected frequencies. The second concept investigates acousto-electromagnetic coupling resulting from the periodic polarization of a piezoelectric waveguide. In this case, the resonant behavior is associated with the generation and excitation of polaritons, which resonate at frequencies defined by the periodicity and physical properties of the lattice. At these frequencies, wave motion is characterized by strong attenuation, and maximum energy transfer between the acoustic and electromagnetic fields.

The analysis of the dispersion properties of the two waveguides underlines the common characteristics associated with internally resonating properties, and suggests potential applications such as vibration attenuation and isolation, and the development of novel acousto-optical devices. Homogenized theories for both types of waveguides are developed to derive expressions for their equivalent properties, which effectively illustrate their resonant characteristics, and show how they affect the propagation of waves.

The two types of multi-field waveguides presented in this work provide examples of systems where wave attenuation occurs through an internal resonance mechanism. The resonant condition is characterized by maximum coupling between the waveguide, acting as a primary system, and a resonating secondary system. The condition of maximum coupling is identified by the matching of the dispersion properties of the primary and secondary system. The dispersion relation for a secondary system comprising a set of periodically placed resonators generally appears as a flat curve, which corresponds to spatially localized modes in the resonators themselves, as defined by a null group velocity. The intersection of this flat mode with the dispersion branch of the primary structure defines the condition of maximum coupling between the two systems. When the primary and secondary systems belong to a multi-field domain, their coupling requires a mechanism through which energy transfer occurs. The presence of such mechanism leads to a new dispersion branch for the coupled system, which essentially coincides with the branches for the primary system away from the intersection condition, and undergoes a resonance at the coupling frequency. This behavior is illustrated in Figure 1 where the dispersion branches of the uncoupled primary and secondary system are respectively represented as dashed black and red dashed lines. The frequency of intersection of the two branches is the frequency of internal resonance for the uncoupled resonating primary system. Coupling leads to the new dispersion branch (solid blue line) which mostly follows the dispersion branch of the primary system, and is distorted by the resonant behavior at the frequency of internal resonance.

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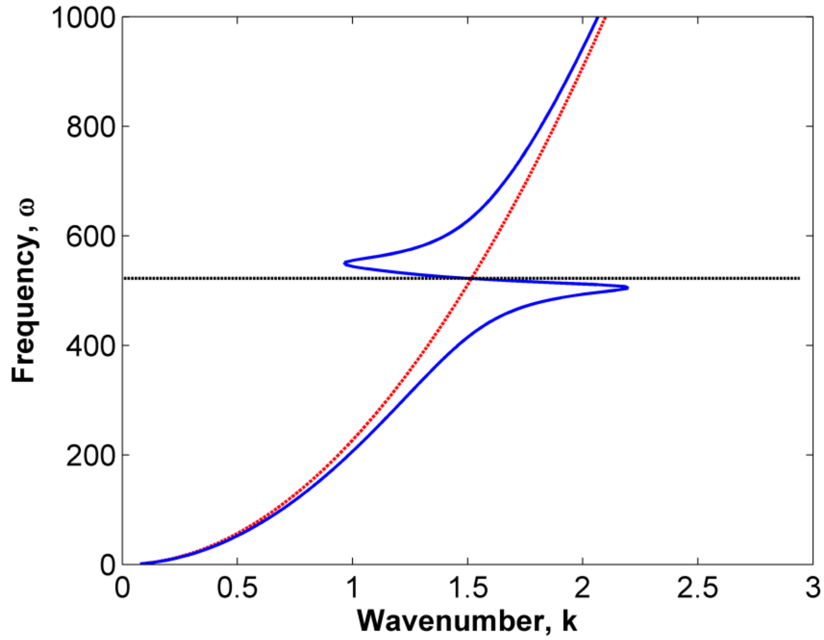

Figure 1. Typical dispersion relations for a waveguide with internal resonators: uncoupled systems (dashed lines), coupled system (solid blue line).

In the considered waveguides, the coupling mechanisms is provided by the piezoelectric effect. In the case of the periodic piezoelectric shunted network, the secondary system is effectively characterized by a flat dispersion mode corresponding to the resonant behavior of the shunting circuits, while for the case of piezoelectric superlattices, the flat dispersion modes corresponds to an elastic mode at very low wavelength. In this case, coupling is made possible by the folding of the branch caused by the periodicity of the waveguide.

The work is organized in two parts covering the two concepts. Part 1 presents the study of one-dimensional waveguides with periodic shunted piezo arrays. Numerical and experimental results illustrate their attenuation characteristics, and their tunable properties. Numerical investigations are performed through the application of the Transfer Matrix method, which is briefly reviewed. Experimental investigations performed on a beam structure, confirm the numerical predictions and show the attenuation characteristics of the waveguide. Part 2 is devoted to the study of piezoelectric superlattices. Numerical studies of one-dimensional and two-dimensional configurations are performed through the application of the Plane Wave Expansion method, which is presented in some detail. Multifield coupling and internal resonant behavior of piezoelectric superlattices are illustrated through a series of numerical examples, and the evaluation of equivalent dielectric properties using a long wavelength approximation approach.