Anomalous transmission properties of ultranarrow, zero-density acoustic metachannels

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Abstract

We present the acoustic equivalent of supercoupling through subwavelength channels. Extraordinary matched transmission, energy squeezing and anomalous quasistatic tunnelling through narrow channels are obtained for acoustic waves by designing a 2D, density-near-zero metachannel. Transmission-line theory is used to describe this peculiar phenomenon, and full-wave simulations are presented to confirm the exotic transmission properties of the metamaterial. It is shown that acoustic waves may provide a unique possibility of squeezing energy in arbitrarily small channels in 3D, overcoming limitations usually arising in the electromagnetic case.

1. Introduction

Metamaterials with extreme values of constitutive parameters have been the subject of extensive research over the past few years. They are often associated with extraordinary physical phenomena, like anomalous refraction or wave tunnelling. In the field of electromagnetic (EM) metamaterials, a counterintuitive phenomenon, called supercoupling [1], based on matched transmission through epsilon-near-zero (ENZ) subwavelength channels, has been shown to have very promising and peculiar characteristics. Supercoupling is observed when a narrow ENZ channel is used to connect two waveguides with much larger cross-sectional areas. Interestingly, the phenomenon can be obtained very simply by operating a hollow rectangular waveguide at its cut-off frequency, since the propagation of the dominant mode is equivalent to the one of a TEM wave in a material with zero permittivity [1]-[2]. Unlike tunnelling based on Fabry-Perot (FP) resonances, ENZ transmission is totally independent of the channel's length and is associated with a completely uniform field enhancement along the channel. In addition, the tunnelling is robust to the possible presence of conductor losses. The possibility to bend the channel at will and the drastic energy squeezing capability of supercoupling make it very attractive for a variety of applications, including distant coupling, filtering, light concentration, harvesting, impedance matching, boosting emission, and sensing. Here we translate this phenomenon into the acoustic domain. Inspired by the EM case, we look for a transmission phenomenon based on acoustic impedance matching, for which a geometrical impedance mismatch can be totally compensated by the extreme value of one of the constitutive parameters. The lack of polarization and longitudinal nature of acoustic waves allows squeezing the energy in the whole channel cross-section, making this phenomenon even more appealing than in the EM scenario, as we detail in the following.

2. Theoretical formulation

Consider two identical infinite acoustic waveguides connected together via another waveguide with smaller radius. The cross-sectional areas are noted as S_{wg} and S_{ch}, $S_{wg} \gg S_{ch}$. An acoustic plane wave is assumed to be incident on the channel from one of the outer waveguides. There exist two scenarios in which total transmission happens. One of them is the FP resonance condition $\tan(\beta_{ch} l) = 0$. The other possibility is the equality of the normalized acoustic line impedances:

$$\frac{\sqrt{\rho_{ch}\kappa_{ch}}}{S_{ch}} = \frac{\sqrt{\rho_{wg}\kappa_{wg}}}{S_{wg}} \tag{1}$$

where ρ and κ denotes the densities and bulk moduli of the acoustic media within the waveguides. With conventional materials, Eq. (1) is extremely difficult to satisfy since the mismatch between the cross-sections requires a precise compensation of geometrical and material mismatch. However, if it were possible to construct a metamaterial channel such that $\rho_{ch}\kappa_{ch}$ is small, one can achieve anomalous matched transmission even for $S_{wg} \gg S_{ch}$. In the limit where $\rho_{ch}\kappa_{ch} \to 0$, total transmission is paradoxically achieved for a channel of infinitely small cross-section. Since the guided wavevector in the channel is $\beta_{ch}^2 = \rho_{ch}\kappa_{ch}^{-1}$, if we would like to simultaneously achieve matched transmission and constant phase along the channel, we would require a metamaterial with *near-zero* density, while ensuring $\kappa_{ch} = \kappa_{wg}$. From (1), the required effective density value is very close to zero, which ensures that the wavelength becomes extremely large within the channel.

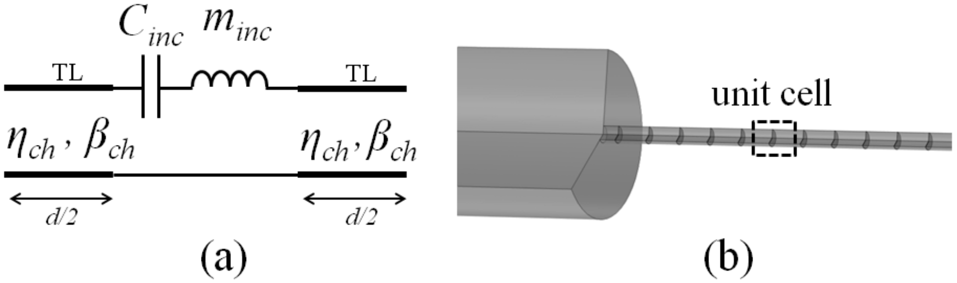

Fig. 1: (a) TL model of a unit cell. (b) Larger view of the geometry.

3. Implementation

Following [4] we propose to use a host acoustic cylindrical waveguide and load it with subwavelength inclusions to cancel the density of the fluid within each of the metamaterial cells, whose length is denoted by d. Using transmission-line analysis, it is possible to cancel the series impedance of the line by adding an extra capacitance C_{inc} in the series branch. In practice, this punctual capacitance is simply realized by a membrane clamped at its circumference to the host channel, which also adds a mass m_{inc}, as represented in Fig.1. The effective density in the channel becomes:

$$\rho_{eff} = \rho_0 + \frac{m_{inc} S_{ch}}{d}\left(1 - \frac{1}{m_{inc} C_{inc} \omega^2}\right) \tag{2}$$

The density is negative at low frequencies and takes the targeted near-zero value given by (1) at some frequency below the resonance frequency of the membrane. The values of m_{inc} and C_{inc} are well-known functions of the material properties, of the membrane and its geometry [5]. Using TL theory it is possible to solve for the acoustic fields and calculate the predicted transmission as a function of frequency.

4. Preliminary results toward an experimental verification

3D full-wave simulations were performed using the acoustic-structure interaction module of COMSOL Multiphysics® to validate our theoretical findings. Fig.2a compares the transmission calculated by the TL model and full-wave simulations for channels consisting of 5 and 10 unit cells. The first peak is due to the DNZ condition, which is independent of the channel length and has constant phase, indicated by the membrane displacements in Fig.2b. Conversely, the second peak for the 5 cell channel is the 1st FP resonance, for which the membrane displacements are antisymmetric about the centre of the channel (Fig.2c).

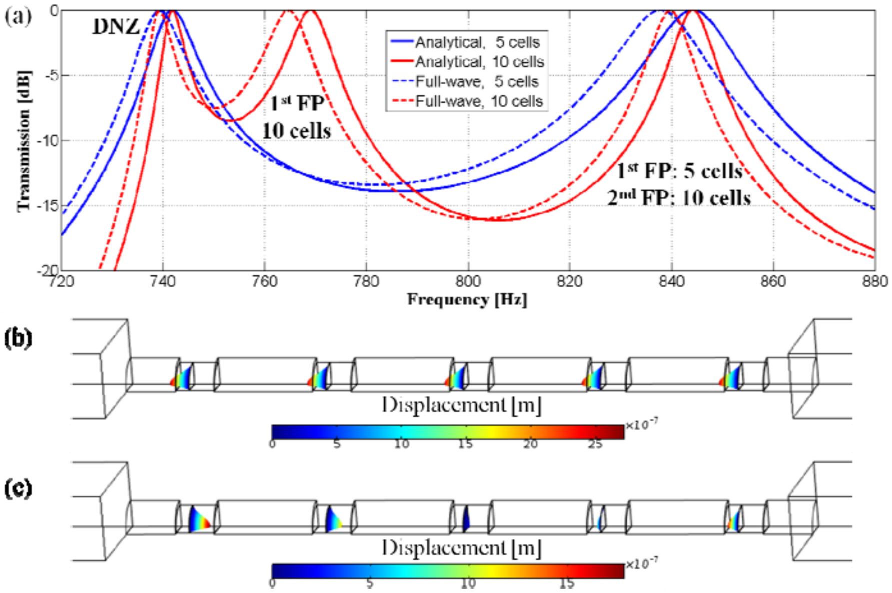

Fig 2. (a) Transmission through a DNZ channel. Membrane displacement in a channel consisting of 5 unit cells for (b) DNZ resonance and (c) 1st FP resonance.

Conclusion

We have shown how ENZ supercoupling can be successfully transposed to acoustic waves. We are currently setting up an experiment to verify the energy squeezing and rerouting capabilities of these DNZ channels. One evident advantage of the acoustic supercoupling phenomenon, compared to EM, is provided by the possibility of squeezing the wave in the whole cross-section of the channel, with exciting advantages in terms of energy squeezing, concentration, absorption and harvesting.

References

[1] M. Silveirinha and N. Engheta, Tunneling of electromagnetic energy through subwavelength channels and bends using ε-near-zero materials**,** *Physical Review Letters,* vol. 97, p. 157403, 2006.

[2] A. Alù, M. G. Silveirinha and N. Engheta, Transmission-line analysis of ε-near-zero–filled narrow channels, Physical *Review E,* vol. 78, p. 016604, 2008.

[3] B. Edwards, A. Alù, M.E. Young, M. Silveirinha and N. Engheta, Experimental verification of epsilon-near-zero metamaterial coupling and energy squeezing using a microwave waveguide**,** *Physical Review Letters,* vol. 100, p. 033903, 2008.

[4] S. H. Lee, C. M. Park, Y. M. Seo, Z. G. Wang and C. K. Kim, Acoustic metamaterial with negative density, *Physical Letters A,* vol. 373, p. 4464, 2009.

[5] F. Bongard, H. Lissek, and J. R. Mosig, Acoustic transmission line metamaterial with negative/zero/positive refractive index, *Phys. Rev. B*, vol. 82, no. 9, p. 094306, 2010.