# Simultaneously photonic and phononic metamaterials

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## Abstract

Metamaterials have been primarily studied in electromagnetics and acoustics to date. In the fields of photonic and phononic crystals, structures simultaneously exhibiting both photonic and phononic—so-called phoXonic—properties have been proposed, but this has not been done for metamaterials. Here we propose the concept of a phoxonic metamaterial, and demonstrate a working design in the GHz electromagnetic and kHz acoustic range that can simultaneously exhibit negative electromagnetic refraction at the same time as being a single-negative acoustic metamaterial. Possibilites for *quadruple-negative* phoxonic metamaterials, that exhibit dual double-negative behaviour, and applications to acousto-optic modulation are envisaged.

## 1. Introduction

Phoxonic crystals are periodic structures that are at the same time photonic and phononic crystals. First proposed theoretically,[1, 2] they were later verified experimentally.[3, 4] Simultaneously confining photons and phonons because of photonic or phononic band gaps, they show applications in sensing and cavity optomechanics.[4, 5]

Metamaterials are artificial media composed of unit cells much smaller than the wavelength. First developed for electromagnetic waves, they exhibit counterintuitive properties such as negative refractive index[6] and cloaking[7]. Such behavior is determined by the electrical or magnetic character of the constitutent meta-atoms. Over a similar period of time, acoustic metamaterials showing negative effective density and modulus were introduced.[8, 9] In the acoustic case, many studies have focused on various phenomena analogous to those in electromagnetism.

In spite of this progress, the obvious step of combining electromagnetic with acoustic metamaterials in one structure, i.e., the creation of a phoxonic metamaterial, does not appear to have been carried out. Such a system would have similar advantages to phoxonic *crystals*, but with the added convenience of easier miniaturization. Phoxonic metamaterials with simultaneously negative dielectric constant, magnetic permeability, density and modulus—which could be termed quadruple-negative phoxonic metamaterials—may make interesting candidates for acoustic-optic modulators in the form of flat superlenses.

Here we propose a realisable design for a phoxonic metamaterial, that exhibits negative electromagnetic refraction for GHz electromagnetic waves at the same time as a complete metamaterial band gap for kHz acoustic waves, and demonstrate its properties by numerical simulation.

## 2. Phoxonic metamaterial design

Our design is based on a modification of the double-negative microwave electromagnetic metamaterial proposed in Ref. [11], by incorporating a low elastic-modulus silicone rubber layer, as shown for a unit cell in Fig. 1. A central high-dielectric constant ($\epsilon$=38, loss tangent $\gamma$=$10^{-4}$) ceramic disc (Murata Manufacturing, radius 2.33 mm, height 2.03 mm) of Young's modulus $E$=174 GPa, Poisson's ratio $\nu$=0.31 (from resonant ultrasonic spectroscopy) and density $\rho$=5136 kg $\mathrm{m}^{-3}$ is embedded in an epoxy block (Rogers Corp. RT Duroid 5880, $\epsilon$=2.2, $\gamma$=$9\times10^{-4}$, $E$=965 MPa, $\nu$=0.34, $\rho$=2200 kg $\mathrm{m}^{-3}$), itself surrounded by a thin layer of silicone rubber (Ecoflex 00-30, $\epsilon$=2.5, $\gamma$=0.01, $E$=71500 Pa, $\nu$=0.44, $\rho$=1030 kg $\mathrm{m}^{-3}$). Two copper layers of thickness 9 $\mu$m (conductivity $5.7\times10^{-7}$ S $\mathrm{m}^{-1}$, $E$=128 MPa, $\nu$=0.36, $\rho$=8960 kg $\mathrm{m}^{-3}$) containing hole arrays complete the unit cell, of dimensions 6×6×3.5 $\mathrm{mm}^3$. The electromagnetic properties refer to the $\sim$10 GHz regime. We carried out numerical simulations in both electromagnetism (ANSYS) and acoustics (COMSOL) to determine dispersion relations and propagation characteristics at selected points thereon. The unit cells and their internal elements are assumed to be in good acoustic contact (facilitated in practice, for example, by strong clamping or very thin adhesive), including disc-shaped gaps in the thin copper layers which we assume are filled with silicone rubber.

## 3. Dispersion relations

Figure 2 shows the electromagnetic and acoustic $\Gamma-X$ dispersion relations, both calculated in the absence of losses. We have marked with a red dot points on the dispersion relation to focus on. In the electromagnetic case, for a frequency of 11.7 GHz, this corresponds to a point in which the material exhibits negative permittivity and permeability

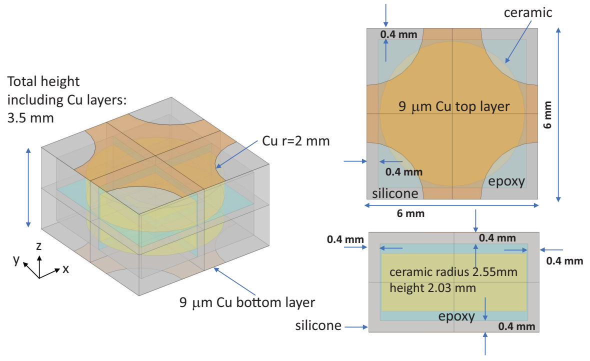

Figure 1: Schematic diagram of the phoxonic metamaterial. The thin Cu layers are not shown on the bottom-right.

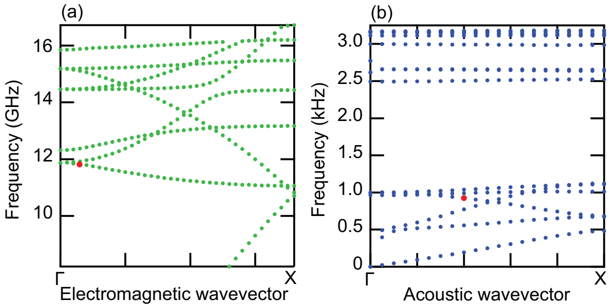

Figure 2: Numerically calculated (a) electromagnetic and (b) acoustic dispersion relations in the $\Gamma - X$ direction for the phoxonic metamaterial in the absence of losses. The red dots indicate particular points on the dispersion relation of interest.

with a $y$-polarized electric field. For the acoustic case, at a similar point on the dispersion relation, we can identify an $xz$-polarized wave at a frequency of 0.924 kHz, below a complete (i.e., for all propagation directions) metamaterial band gap that opens because of the introduction of the silicone rubber layer which supports vibrations of the central epoxy/ceramic mass. We suspect that the structure corresponds to a metamaterial with a negative effective density, i.e., a single-negative acoustic metamaterial, exhibited in the frequency range of the acoustic band gap.

Although we have not yet introduced elements in the design to produce a double-negative acoustic metamaterial, the existence of an acoustic metamaterial gap arising from a local mechanical resonance implies that our structure is an example of a phoxonic metamaterial with triple-negative character (i.e., single-negative acoustic and double-negative electromagnetic).

## 4. Conclusions

We have demonstated by numerical simulation a triple-negative phoxonic metamaterial. In the electromagnetic case a backward wave is identified for a chosen point on the dispersion relations below the band gap. For the acoustic case we have identified a band gap that arises because of a local resonance.

In future one would hope to demonstrate by calculation a metamaterial with the four negative effective parameters $\epsilon$ (permittivity), $\mu$ (permeability), $B$ (bulk modulus) and $\rho$ (density), i.e. a quadruple-negative phoxonic metamaterial.

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