Experimental Demonstration of a Soft 3D Acoustic Metamaterial with Negative Index

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Abstract-We report a new class of locally resonant ultrasonic metafluids consisting of a concentrated suspension of macroporous microbeads engineered using soft matter techniques.

Many applications call for the full control of acoustic wave propagation and require the synthesis of new smart and responsive materials. Potential uses are numerous and include wave guides, cloaks, filters, attenuators, hyper-lenses with sub-wavelength resolutions etc... It was recently proven that many new propagation properties could be attained by using the "locally resonant" approach to build up metamaterials[1,2]. This consists in the design and fabrication of materials containing large collections of resonators. These are small entities with typical sizes (~ 100 µm in our case) much smaller than the incident wavelength (~ 1-10 mm). Their main characteristic is to resonate with the incoming acoustic wave at a specific frequency value ω_0 that depends on both the size and physical properties of the inclusions. At sufficiently large proportion in the host material, the presence of acoustic resonators can provide unusual properties such as negative acoustic parameters[3]. Recently, it has been shown that Mie resonances (monopolar and dipolar) of "ultra-slow" soft inclusions lead to negative-acoustic-index metamaterials[4]. Such an unusual property originates from the high sound-speed contrast between the inclusions and the surrounding matrix[5]. In that case, the resonance occurs when the wavelength of the sound wave propagating within the inclusions is comparable to their size. The Mie resonance frequency scales as the inverse of the inclusion sizes with an intensity that depends on the magnitude of the sound-speed contrast. Thus, inclusions with very low sound-speed values around 100 m/s would lead to a very intense scattering power when suspended in surrounding dense (either solid or liquid) matrices, which present sound speed around typically 1000 m/s. The longitudinal sound speed c_L in any material reads:

$$C_L = \sqrt{\frac{K + (4/3)G}{\rho}} \qquad (1)$$

where K and G are the bulk and shear elastic moduli, respectively, and ρ is the mass density. Low values of c_L thus imply low values of the elastic moduli K and G and a non-zero mass density ρ. Porous media are known to possess very low sound speeds[6] because they contain a large proportion of gas (providing low values of elastic moduli or high compressibility) and are constituted of a dense skeleton with a non-zero mass density. For example, porous media such as aerogels are well known to have very low sound speeds[7]. Liquid foams also present sound speed as low as 40 m/s depending on the mean bubble radius as recently reported[8]. In the light of their highly porous structure, polymer foams are other possible candidates. Soft polymers as silicone rubbers can be made porous by using the polyHipes (for polymerizable High Internal Phase Emulsions) approach that consists in templating holes in the material using inverted water-in-oil emulsions[9-10]. In this talk, we will show that such silicone polymers can indeed be made porous using this approach and that their insertion as porous beads in a water-based fluid matrix leads to the appearance of a large frequency range over which the materials phase velocity, and consequently also the refractive index become negative (Figure 1).

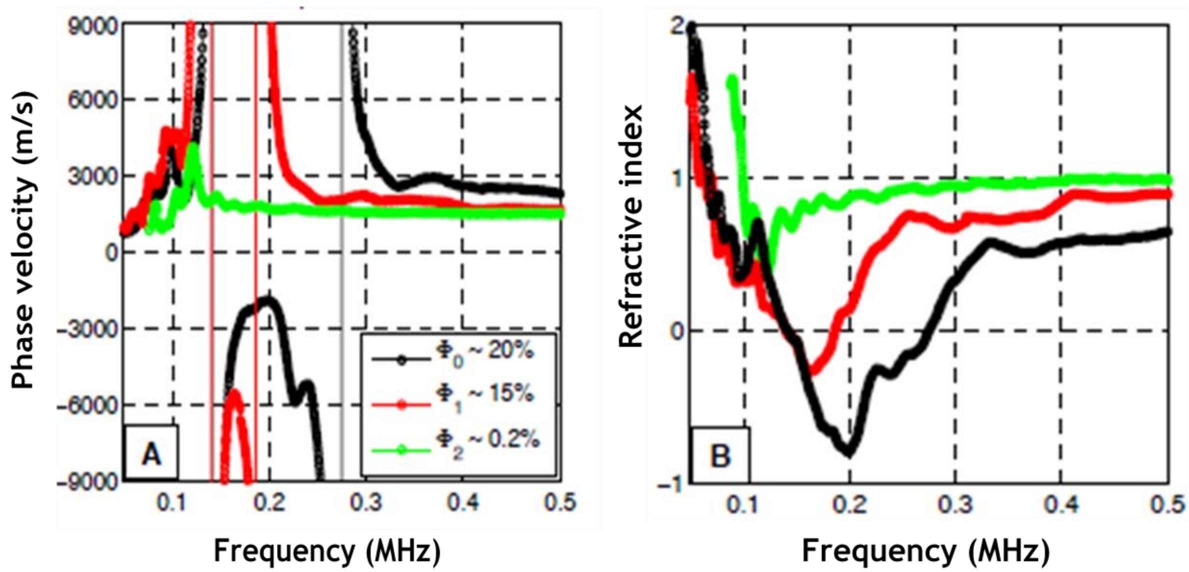

Figure 1 :

Evolution of the phase velocity (**A**) and the refractive index (**B**) as a function of frequency and for three different volume fraction ϕ of acoustic resonators: green: $\phi = 0.2$ %; red: $\phi = 15$ %; black: $\phi = 20$ %

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