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Lucklum, Frieder

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Evolution and Future Perspectives of Phononic Crystal Liquid Sensors

Frieder Lucklum

Centre for Acoustic-Mechanical Microsystems (CAMM), DTU Electrical and Photonics Engineering,
Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Ørsteds Plads 352, Denmark
e-mail: fluc@dtu.dk

Phononic crystals (PnCs) and acoustic metamaterials offer unique and novel opportunities to control acoustic and elastic wave propagation in fluids and solids. The main principle are sub-wavelength structures that yield unique material properties and band structures not found in standard materials. Engineering desired properties and wave bands can lead to a level of wave control similar to semiconductor energy bands. With well-designed addition of defects and gradients to a phononic lattice, unique effects appear such as (negative) refraction and reflection, wave conversion, waveguiding, and, most important here, localized resonance modes.

Phononic crystal liquid sensors typically exploit resonance modes in fluid cavities [1]. This puts them in contrast to resonant acoustic sensors, where standing waves are usually confined to a solid resonator. There, the interaction with the fluid is therefore limited to the penetration depth of the evanescent field at the surface in contact with an analyte. Depending on the operating frequency, this means properties and processes in the bulk fluid volume may be invisible to these sensors. In PnC or metamaterial sensors a well-designed liquid volume confines a resonance mode to the bulk liquid. This mode acts as a defect within the band structure and in the ideal case its resonance frequency is only dependent on the volumetric properties of the bulk fluid, primarily the complex speed of sound, and subsequently density, compressibility, and viscosity (Fig. 1). The advantage of sensors exploiting resonance conditions is a significantly longer interaction path and therefore higher sensitivity. A phononic or metamaterial lattice can offer ideal boundary conditions for these resonance modes, specifically when they are designed to be located within a phononic band gap. However, a real-world sensor has a finite size and experiences material losses both in its solid and fluid domains. This can strongly dampen and even destroy any highly sensitive resonance effects and severely limits the usefulness of (semi-)infinite and/or lossless simulation models. This is demonstrated by adding merely a low loss factor to liquid and solid domains in an analytical transmission calculation (Fig. 2).

Since the first demonstration of a phononic crystal sensor more than a decade ago, the concept evolved through a number of theoretical and experimental studies that investigated one-dimensional [2], two-dimensional [3], and three-dimensional [4] implementations using various designs (Fig. 3). Recent investigations focused on theoretical and practical demonstration of narrow-band PnC designs [5], numerical analysis of solid-liquid PnC waveguide and interferometric sensor concepts [6], and unique tubular PnC design concepts using Fabry-Perot cavities [7] and combinations with 2D lattices. The current challenge for the existing and future concepts is to advance modelling and experimental implementation to take all real-world constraints into account during the design and conceptualization phase. One avenue is to find and utilize the resonance modes with the highest quality factors, where the mode shapes yield the least losses due to liquid viscosity [8]. Secondly, the effect of finite three-dimensional size of any sensor element needs to be considered and investigated [9]. Furthermore, computational studies using shape and topology optimization can be extended from two-component phononic lattice optimization [10] to multi-physics multi-component optimization of solid-liquid structures to maximize sensitivity and quality factor of a phononic crystal liquid sensor. Examples from these advanced and future developments are showcased in Fig. 4.

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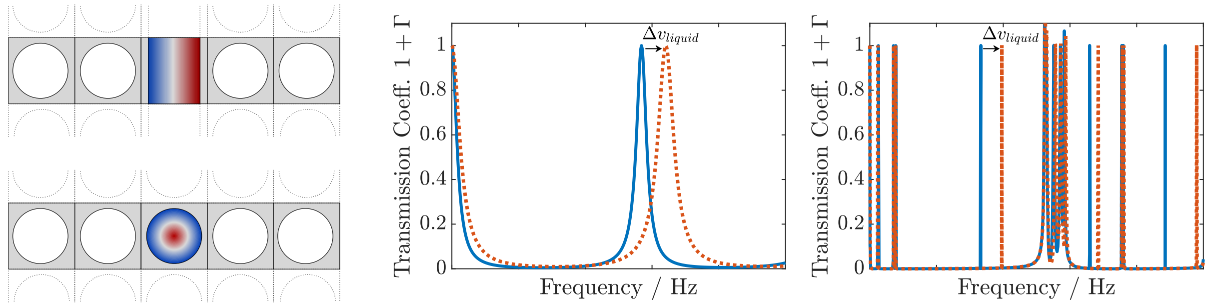
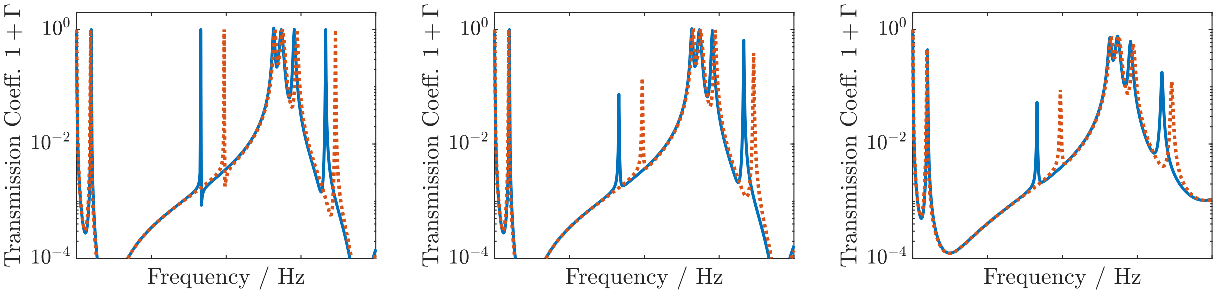


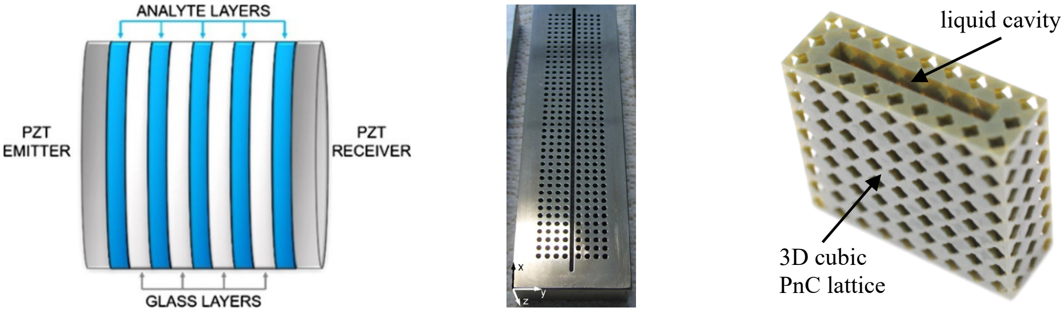
(a) (b) (c)

Figure 1. Sensor concept: (a) Rectangular (top) and single cell (bottom) cavity, (b) response of only cavity for two different liquids (solid blue and dotted red lines), and (c) response of same cavity in a PnC lattice.



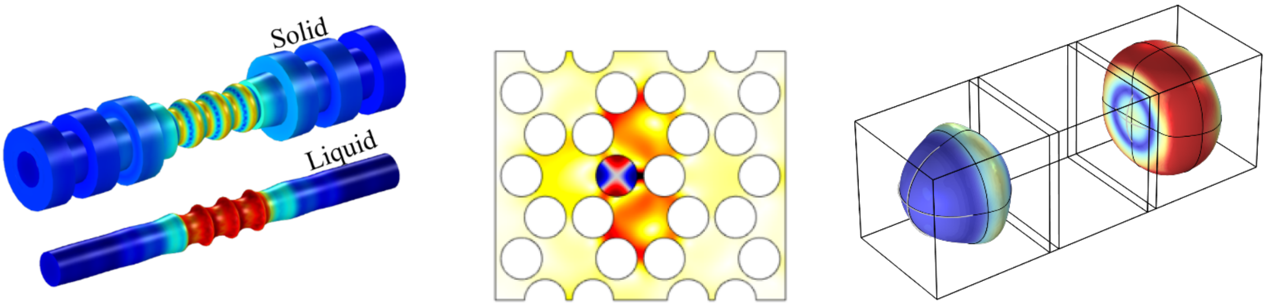
(a) (b) (c)

Figure 2. Calculated transmission through a PnC liquid cavity sensor for two different liquids (solid blue and dotted red lines), with (a) no losses, (b) adding losses in liquid domain due to viscosity affects only liquid resonance modes, and (c) adding only 0.1% loss factor in solid domain affects the whole spectrum.



(a) (b) (c)

Figure 3. Photographs and schematics of (a) disposable multi-layer 1D PnC liquid sensor (with permission from [2]), (b) slit cavity sensor with 2D square PnC lattice (with permission from [3]), and (c) liquid cavity sensor surrounded by 3D cubic PnC lattice.



(a) (b) (c)

Figure 4. Current and future perspectives: (a) Tubular Bell with Fabry-Perot liquid cavity resonator (with permission from [7]), (b) selecting singular liquid defects in a hexagonal lattice (with permission from [5]), and (c) shape optimization of an originally spherical void in PnC unit cells around rectangular cavity.