2D and 3D Phononic Crystals - A New Class of (Bio)Chemical Microsensors and Sensor Networks

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***Abstract*—We introduce concepts of a new class of acoustic sensor devices, so-called phononic crystal sensors. Small volumes of a complex liquid act as network of individually addressable acoustic resonators in its most promising realization. Resonance frequency reveals bulk properties of the mixture, for example the concentration of a compound. We furthermore suggest an acoustic analog to Photonic Crystal Enhanced Microscopy, PCEM, a spatially distributed metamaterial microacoustic sensor network for visualization of liquid and recognition layer properties.**

Keywords-phononic crystal; metamaterial; acoustic microsensor; (bio)chemical sensor

I. MOTIVATION

Phononic crystals (PC) have been introduced in the early 1990s [1][2]. There are a lot of different phononic crystal realizations accomplishing translation symmetry in 2D and 3D designs. Bulk phononic crystals have a periodic modulation in their density and sound velocities for longitudinal and transverse polarization, creating band gaps at wavelengths commensurate to their lattice constant, i.e., acoustic (through liquids) or elastic mechanical (through solids) waves with certain frequencies cannot travel though the crystal at least in certain crystallographic directions. Since one can design properties not known in nature they are sometimes described as metamaterials. Major efforts in phononic crystal studies have been devoted to the search of absolute band gaps in perforated solids or solid/solid structures. Only recently reports on technical applications have been published, including sensing. The ability to magnify the interaction of acoustic waves with matter through specific geometries that are capable of confining acoustic waves in a small volume provides the basis for this novel type of sensor.

Linear or point defects are the characteristic feature of phononic crystal sensors. Defect modes can be designed to create a well separated mini-transmission band within the band gap and appear as transmission peak within the transmission spectrum of phononic crystals. The position of the respective mode on the frequency scale, shortly called peak frequency, f_p, is sensitive to defect properties, specifically geometry and material properties of the confined matter. They can be changed by the measurement value of interest. Promising applications are the measurement of concentration of some compound, x_i, in a liquid confined in the cavity, concentration of a component, conversion rate during a chemical reaction, (bio)chemical activity or size of associates or molecule conformation etc. These values should become effective via a distinct change in speed of sound, v [7]-[9], of the liquid mixture:

$$f_p = f(v) = f(v(x_i)) \qquad (1)$$

or in terms of sensitivity, S_f:

$$S_f = \frac{\partial v}{\partial x_i}\frac{\partial f_p}{\partial v} \qquad (2)$$

The key difference to competing microacoustic sensors is that phononic crystal sensors give access to **volumetric** mechanical properties of the mixture whereas most classical sensors measure properties at the **interface** to the sensor element. Since the first term in (2) must be expected to be small at concentrations relevant to (bio)chemical applications, key design objective of phononic crystals sensor development is a large second term in (2). It can be realized by strong confinement of acoustic energy in a high-*Q* cavity resonator. A second important issue is that the respective acoustic cavity mode is the only allowed mode or that it is at least well separated from other modes. Finally, the modes must 'survive' under experimental conditions.

II. REALIZATIONS

The first phononic crystal sensor version has been introduced in [3]. A 2D phononic crystal fabricated in steel and having a slit cavity perpendicular to the propagation direction of longitudinal acoustic waves has been published in [4]. The 4-row phononic sub-crystals provide optimized boundary conditions for the slit cavity resonator. This sample has been applied to a first technical application [5]. On-going research deals with the introduction of a disposable liquid container in response to medical needs [6]. Key design challenge is insensitivity to unavoidable variations in the coupling layer between phononic crystal and glass capillary.

A metamaterial sensor applies the so-called extra-ordinary transmission through a perforated plate [7]. We have shown that dynamic metastructures are created, defined by bi-medium oscillatory states at a certain frequency at normal incidence of plane longitudinal waves. On-going research is motivated by PCEM [8]. We focus on the acoustic analog. It is a spatially distributed sensor array for visualization of liquid and recognition layer properties based on an individually addressable network of metamaterial microacoustic elements. Acoustic waves are generated and detected by phased array US transducers, Figure 1.

A very challenging project is the development of a tubular phononic crystal [9] and its application as network of tubular phononic sensors, the so-called tubular bell. This development is motivated by the fact that pipes and vessels are the most prominent elements in modern technical environment and in nature to transport fluids like water or blood. By keeping the inner surface of the tube cylinder free of any obstacles, one of the major concerns in chemical, biochemical, and petrol or food industry, as well as in medicine, will be overcome. Figure 2 shows the first ever published result of a simulation of one of our ideas. Additional structural elements are periodically arranged at the outer wall of the pipe only. We can demonstrate the appearance of band gap and sharp resonance-like transmission peaks. The latter are governed by properties of the liquid inside the pipe.

Another aspect which must be considered at early stage is the fabrication technology of the sensor element. High-resolution stereolithography-printing technology enables the maskless, single-step fabrication of freeform 3D microstructures. This allows rapid prototyping of novel designs, fast optimization and finally customized products. Figure 3 shows a proof-of-concept 3D design extending the established 2D array of holes in a solid matrix to all three Cartesian directions.

III. CONCLUSIONS

First results prove the excellent perspectives of phononic crystals as new sensor class. They merge unique features of ultrasonic sensors and resonant sensors, specifically usage of ultrasonic wave propagation allowing for separation between electronics and measurement ‘cell’ and resonant cavities giving access to high resolution frequency measurement. However, application as chemical or biosensor introduces new challenges, e.g. volume and shape of the measurement cell, disposable materials, and highly variable fabrication technology.

All these specific aspects again have major influence on the design of the phononic crystal, the theory behind and the models to compute band diagram and transmission spectrum.

On the other hand photonic crystal sensors, the optical counterpart having a longer history have already found their application as chemical and biosensors because of their excellent features like sensitivity, selectivity and reliability. The obvious analogy of the basic sensor principle, despite their also obvious difference, justifies further efforts in this still very young research field.

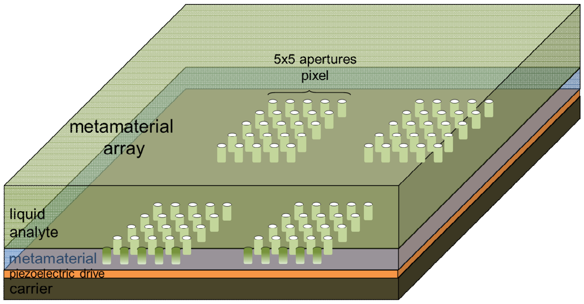

Figure 1: Idea of the metamaterial microacoustic array

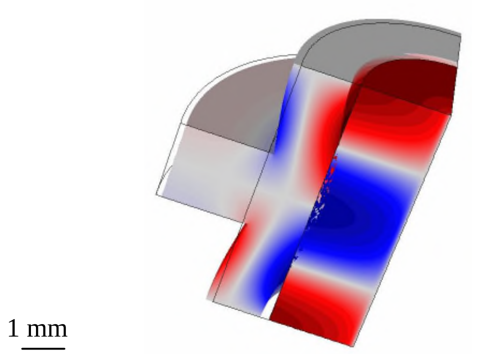

Figure 2: Quarter of a single element of a tubular bell. Colors represent deformation/pressure results of a numerical analysis (Comsol). Geometric dimensions scale with wavelength; here the mid-frequency is 1 MHz.

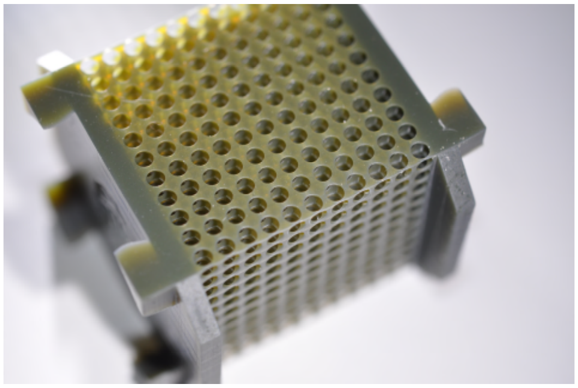

Figure 3: Stereolithography fabrication sample: 11x11x11 3D phononic crystal with 2 mm lattice constant [10]

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