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Fully-disposable multilayered phononic crystal liquid sensor with symmetry reduction and a resonant cavity

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ABSTRACT

Phononic crystals are artificial structures with unique capabilities to control the transmission of acoustic waves. These novel periodic composite structures bring new possibilities for developing a fundamentally new sensor principle that combines features of both ultrasonic and resonant sensors. This paper reports the design, fabrication and evaluation of a phononic crystal sensor for biomedical applications, especially for its implementation in point of care testing technologies. The key feature of the sensor system is a fully-disposable multi-layered phononic crystal liquid sensor element with symmetry reduction and a resonant cavity. The phononic crystal structure consists of eleven layers with high acoustic impedance mismatch. A defect mode was utilized in order to generate a well-defined transmission peak inside the bandgap that can be used as a measure. The design of the structures has been optimized with simulations using a transmission line model. Experimental realizations were performed to evaluate the frequency response of the designed sensor using different liquid analytes. The frequency of the characteristic transmission peaks showed to be dependent on the properties of the analytes used in the experiments. Multi-layered phononic crystal sensors can be used in applications, like point of care testing, where the on-line measurement of small liquid samples is required.

1. Introduction

Phononic crystals, PnC, are composite materials possessing a periodic and spatial modulation of their acoustic properties, allowing them to have control over a selective transmission of mechanical elastic waves in solids, and pressure waves in liquids. Like their optical counterparts, photonic crystals, these crystals enable the configuration of their working frequency by fine-tuning the geometry and dimensions of the structure. Some authors have even worked in frequency control strategies by means of using materials with very interesting magnetoelastic and electrorheological properties [1–4].

The graphical representation of a phononic crystal shown in Fig. 1(a) is composed of a homogeneous matrix and a number of scattering centers with an acoustic impedance different to the matrix to facilitate the dispersion of waves. The most obvious feature of PnCs are frequency bands in which the crystal behaves like a mirror reflecting waves of all directions of incidence, Fig. 1(b). These frequency bands are called bandgaps or forbidden bands and their design allows controlling the selective transmission of waves in phononic crystals [1,2,5].

Phononic crystals can be classified by their topology in two categories: cermet or network. Crystals with a cermet topology are also called acoustic phononic crystals and are composed of a liquid matrix and embedded solid scatterers with high density. On the other hand, crystals with a network topology, or elastic phononic crystals, have a solid matrix and low-density scattering units [6,7].

The design of PnC can also be conceived in structures with a reduction in their dimensionality using an approximation to 1-D. These structures are not formed by a matrix with embedded scattering units, but by a series of consecutive thin layers with large acoustic impedance mismatch and with lateral dimensions much larger than their thickness. The layers are organized in a periodic way that enables a spatial modulation of the acoustic properties throughout the structure and facilitates the selective reflection of acoustic and elastic waves and therefore the generation of bandgaps. A graphical representation of a 1-D phononic crystal can be observed in Fig. 2 [8].

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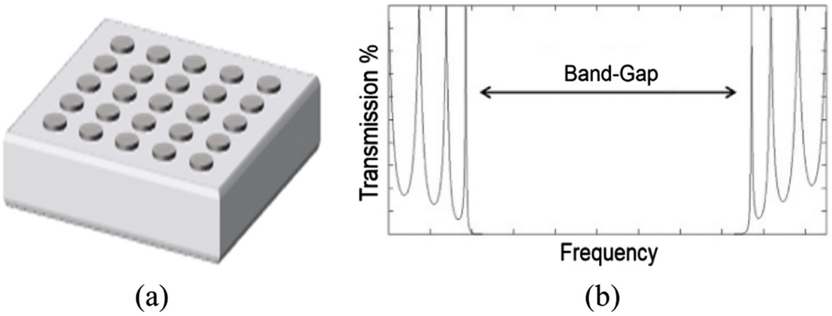

Fig. 1. Graphical representation of a phononic crystal composed of a homogeneous matrix and a series of cylindrical inclusions arranged in a square matrix (a) and its respective frequency response displaying an ideal bandgap (b).

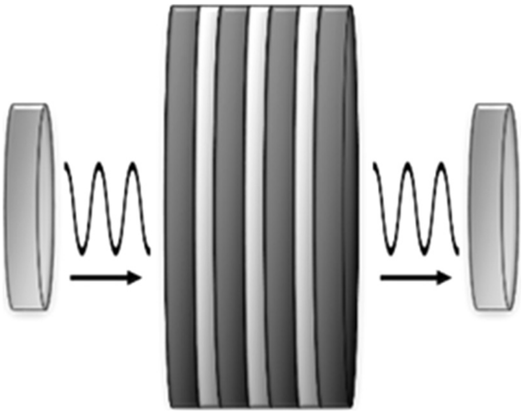

Fig. 2. Graphical representation of a 1-D phononic crystal composed of a series of consecutive thin layers with high acoustic impedance mismatch. On the sides are two ultrasonic transducers, represented by gray discs, generating and receiving the signal used to characterize its frequency response.

The design of bandgaps in 1-D phononic crystals is performed by adapting the thickness of each layer so that the maximum reflection, or minimum transmission, is located in the wanted frequency range. The bandwidth and depth of the generated bandgap will depend on the ratio of acoustic impedances between consecutive layers. The larger it is, the larger the scattering effect of the structure, generating a wider frequency range with large acoustic rejection over which acoustic waves are not transmitted [8].

There are numerous methods for simulating the frequency response of phononic crystals including the one-dimensional transmission line model (TLM), the eigenmodes matching theory (EMMT), the layer multi-scattering theory (LMST), the plane wave expansion method (PWE), the finite element method (FEM) and the finite difference time domain (FDTD) among others. The transmission line model is especially used when calculating multi-layered structures, giving adequate results and reducing the amount of computation power and time to realize the simulations. It has been previously used to calculate the transmission spectrum of phononic crystals with good results [9–14].

The propagation of acoustic waves in phononic crystals is described in the TLM using an analogy to electrical waves, see Table 1. This model considers homogeneous, isotropic, uniform layers with minimum effect of the lateral dimensions on the propagation of acoustic waves. The effective acoustic impedance contains the relevant characteristic acoustic parameters and layer thickness, e, of each layer composing the PnC. The transmission and reflection coefficients are calculated using an overall effective acoustic impedance of the PnC, Z_L. It is important to notice that the effective acoustic impedance is frequency dependent and is different from the characteristic impedance of the material, Z_c, which is equal to the density, ρ, multiplied by the speed of sound of the material, c. The concept considers the reflection and transmission of waves in layer interfaces and also inside each layer [9,13]. The effective acoustic impedance of layer i can be calculated using Eq. (1).

Table 1
Equivalences between the electrical and acoustic parameters.

Mechanical tension	T ⇒ U	Electrical voltage
Particle velocity	v ⇒ I	Electrical current
Acoustic impedance	Z = T/v ⇒ Z = U/I	Electrical impedance

$$Z_{L(i+1)} = Z_{c(i)} \frac{Z_{L(i)} + jZ_{c(i)} tan(2\pi fe/c)}{Z_{c(i)} + jZ_{L(i)} tan(2\pi fe/c)} \tag{1}$$

The selective control of elastic and acoustic waves using phononic crystals more and more attracts the attention of the scientific community around the world to apply the novel resonant structures in diverse applications, among which are: wave guiding, acoustic insulation, acoustic cloaking, heat phonon transmission, multiplexing and demultiplexing of waves, and more recently, sensing [15–24].

Both surface acoustic waves, SAW, and bulk acoustic waves, BAW, have been studied in the development of phononic crystal sensors. SAW resonators have working frequencies up to GHz frequencies and the lattice constant goes down to micrometers and even micrometers [22,25,26]. Some authors have even explored the possibility of designing dual phononic-photonic crystals, these structures are called phoxonic crystals and they are used to study the simultaneous control of the propagation of acoustic and electromagnetic waves [23,27–29]. BAW sensors typically work in the range of MHz and can use both pressure and/or shear waves. The lattice constant of respective PnC sensors is in the order of 100's of micrometers to a few millimeters. Those dimensions agree with common MEMS technology and enable the implementation of microfluidic systems and solid/liquid sub-structures [16–21,24].

The concept of the phononic crystal sensors for liquids is based on the introduction of defect modes that appear as relevant transmission features inside bandgaps and are visible in the transmission spectrum of the phononic crystal. Defect modes can be realized by point, line or plane defects that are introduced in an otherwise regular periodic structure. Liquid samples that are going to be analyzed, shortly analytes, become part of the phononic crystal. Therefore, any variation in the acoustic properties of the analyte causes changes in the frequency of the defect modes. Phononic crystal liquid sensors basically measure the longitudinal speed of sound of small liquid samples. However, the speed of sound of liquids and liquid mixtures is finally defined by molar mass, molar volume and adiabatic compressibility of the components as well as the molar ratio and is directly linked to