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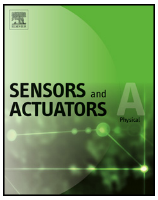

Theoretical research on a two-dimensional phoxonic crystal liquid sensor by utilizing surface optical and acoustic waves

Tian-Xue Ma[a], Yue-Sheng Wang[a,*], Chuanzeng Zhang[b], Xiao-Xing Su[a]

[a] Institute of Engineering Mechanics, Beijing Jiaotong University, Beijing 100044, PR China
[b] Department of Civil Engineering, University of Siegen, Siegen D-57068, Germany

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ABSTRACT

The phoxonic crystal sensor is theoretically investigated in this paper. Based on the phoxonic crystal with dual surface mode bandgaps, both optical and acoustic waves can be confined near the surface. Thus dual cavities, one optical cavity and one acoustic cavity, are designed and integrated in the same phoxonic device. The sensor aims at determining the refractive index and sound velocity of different liquids by utilizing surface optical and acoustic waves. The sensitivities can be estimated by the variations of the cavity resonant frequencies in the response spectra. The relation between the frequency and the measuring physical parameters, i.e., the refractive index or the sound velocity, can be approximated by a linear function. By optimizing each cavity the photonic and phononic sensitivities can reach 199 nm/RIU and 2.79 MHz/ms^{-1}, respectively. This work can serve as a reference for the design of novel phoxonic sensors.

1. Introduction

Photonic crystal (PTC) sensors can be utilized for measuring force, humidity, refractive index (RI), etc. They are promising for lab-on-a-chip applications due to their advantages such as ultra-compact size, high sensitivity and label-free feature. Therefore during the last decades different PTC sensor architectures based on cavities [1,2], waveguides [3,4], PTC lasers [5,6] and slotted structures [7,8] have been studied. Phononic crystal (PNC) sensors, which are the acoustic analogs of the PTC sensors, also draw an increasing attention in recent years [9–17]. However, compared with PTC sensors researches on PNC sensors are still very limited. To the best of our knowledge most of the PNC sensors aim at probing the concentration of a component in the liquid mixture, i.e., sound velocities of different liquid analytes. Sensing efficiencies have been investigated in PNC cavity and waveguide structures as they can confine acoustic energy in a small volume and thus enhance the sound-matter interaction [10–12]. Several sensor platforms by using the extraordinary resonant transmission (EAT) phenomenon through a PNC slab immersed in liquid at a normal incidence of sound have been reported [13–15]. Very recently, sensing the liquid concentration by Mach–Zehnder interferometers in two-dimensional (2D) PNCs has been demonstrated [16,17]. The results of Chen et al. [18] showed that PNCs are capable of suppressing the acoustic interference between the adjacent quartz crystal microbalances (QCMs) in a sensor array. Based on PNC cavity a temperature insensitive resonant mass sensor is studied experimentally [19].

A phoxonic crystal (PXC), which is a periodic structure with simultaneous photonic bandgaps (PTBGs) and phononic bandgaps (PNBGs), originates from the concepts of PTC and PNC [20,21]. This kind of structure can control, guide and confine optical and acoustic energies simultaneously. Furthermore, a PXC can enhance the acousto-optical (AO) or optomechanical interactions. The opening of simultaneous photonic and phononic bandgaps in different materials and geometrical configurations has been investigated [21–27]. Some efforts have been devoted to design PXC cavities [28], waveguides [29] and mode converters [30]. The interaction between phonons and photons in PXC cavities and waveguides has also been studied [31–38]. In the realm of sensors, Lucklum et al. [39] reported on theoretical and experimental works of dual phoxonic sensors performed with macroscopic samples, and thus indicated that PXC sensors can measure optical and acoustic properties of analytes with high sensitivity. Amoudache et al. [40] theoretically investigated a 2D PXC cavity for liquid sensing applications.

The electromagnetic field of surface optical waves (SOWs) penetrates more into the environment, which is very beneficial for optical index sensing in chemical and biological analysis owing to

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[*] Corresponding author.
E-mail addresses: yswang@bjtu.edu.cn, yueshengwang@hotmail.com (Y.-S. Wang).

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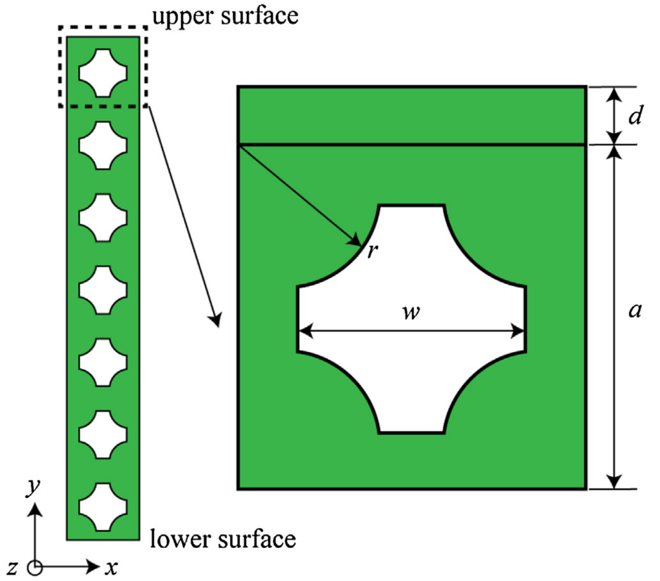

Fig. 1. Schematic sketch of the 2D PXC and enlarged diagram of the upper surface region. The structural geometry is described by the lattice constant *a*, circle radius *r*, hole width *w* and shift parameter *d*.

the strong interaction between the surface waves and the environmental analytes [2,41]. Compared with bulk acoustic waves, surface acoustic waves (SAWs) can be conveniently excited and detected at structural surfaces by making use of piezoelectric materials or an optical excitation [42,43]. However, utilizing SOWs and/or SAWs in PXC structures to detect analyte properties has not been reported yet in literature. Recently we demonstrated the existence of simultaneous surface optical and acoustic waves in 2D PXCs, and then proposed a hetero-structure cavity which can confine dual surface waves [44].

In this work we theoretically investigate the PXC liquid sensor, which is composed of one optical cavity and one acoustic cavity. Different from the previous studies, surface acoustic and optical waves rather than bulk waves are utilized to detect the physical parameters of different liquids. This paper is organized as follows: Section 2 discusses the calculation method and surface waves in PXCs; in Section 3 presents the sensor design; Section 4 is devoted to the discussion of the calculated results of the PXC sensor property, while conclusions are drawn in Section 5.

2. Surface optical and acoustic waves

The crystal design is similar to our previous work in Ref. [44] and the schematic diagram of the PXC is shown in Fig. 1. The PXC is formed by drilling complex holes in a square lattice in silicon matrix. Similar shapes of holes, such as the “cross” [45] and “snowflake” [32] holes in square and triangle lattices, respectively, have been studied experimentally. Here, we note that the liquid solvent is infiltrated in all the holes, which is different from Ref. [44]. The introduction of liquid into the vacuum holes changes the acoustic band structures of the PXC dramatically. For a liquid/solid PNC, it is difficult to obtain a PNBG if the hole shape is a conventional circle [46]. However, the design of the unitcell in this work can generate photonic and phononic bandgaps simultaneously. The PXC is truncated at both upper and lower surfaces to generate surface waves. In the present work the surface modes located at the upper surface is utilized to probe liquid properties, and thus only the upper surface bands are plotted in the band structures. For the purpose of modifying the surface bands, the holes in column are shifted away from the upper surface by a distance of *d*, i.e., a silicon layer is added at the upper surface. In this paper the optical frequency corresponds to the telecommunication regime, i.e., about 1550 nm, and thus the lattice constant *a* is taken as 590 nm.

Throughout this paper, the analysis is performed by the finite element method (FEM) using COMSOL Multiphysics. The in-plane mode is considered for the PNC and the transverse magnetic (TM) mode for the PTC. As the liquid analyte is infiltrated in the holes of the structure, we also consider the solid-liquid interaction at the interface. The solid-liquid interface conditions are given by

$$\begin{aligned} \boldsymbol{\sigma} \cdot \boldsymbol{n} &= p\boldsymbol{n}, \\ \boldsymbol{n} \cdot \left(\frac{1}{\rho_a}\nabla p\right) &= a_n, \end{aligned} \tag{1}$$

where $\mathbf{n}$ and a_n are the normal unit vector and normal acceleration at the interface; p, $\boldsymbol{\sigma}$ and ρ_a are the acoustic pressure in liquid, elastic stress tensor in silicon and mass density of liquid, respectively.

The geometrical parameters of the unitcell are $w = 0.9a$, $r = 0.35a$. When the holes are infiltrated with water, we can find relatively large photonic and phononic bandgaps in the above geometrical configuration. These bulk mode bandgaps are essential for the existence of dual surface modes or dual surface mode bandgaps. Then the dispersion curves of the surface modes with $d = 0.1a$ are plotted in Fig. 2. One photonic surface band (photonic surface mode 1) and one phononic surface band (phononic surface mode I) can be found in the bandgaps. From the modal distributions in Fig. 2(c) and (d) one can observe that both acoustic and optical waves can be highly confined near the surface and attenuate exponentially away from the surface. In the case of the PTC, part of light appears in the liquid region, which may interact with the liquid sample. For acoustics the maximum displacement is located at the structural surface while the maximum pressure is in the first row of holes. It should be indicated that the structure is also periodic in the direction perpendicular to the surface we considered, which differs from the one of a homogeneous half-space with periodic structures deposited on the surface. The latter structure can be usually studied by illustrating sound line [47]. The formation mechanisms of surface waves in the above two structures are different. In the former case, the surface waves generally appear in the bandgap for bulk waves. Owing to the existence of bandgap the acoustic waves cannot propagate into the bulk of the structure, and thus form the waves which propagate along the surface [48].

3. PXC sensor degisn

The case of the holes infiltrated with water is considered. In order to form surface mode cavities, we change the shift parameter *d* to modulate the upper surface bands. Fig. 3 depicts the dispersion curves and the corresponding modal distributions of the photonic and phononic surface modes with different *d*. For $d = 0.2a$ the optical surface band (mode 2) appears near to the lower bandgap edge. The modal distributions of this band is the same as that of photonic surface mode 1. As *d* increases, this band keeps shifting downwards and ultimately moves out of the bandgap. At the same time, a new surface band (mode 3) drops into the bandgap from the upper bandgap edge. Compared with mode 2, in mode 3 more light penetrates into the liquid region, which can enhance the light-liquid interaction and can be used for liquid sensor applications. For the PNC, acoustic surface band II rises up as *d* increases. When $d = 0.2a$, this band shifts out of the bandgap; and then the bulk bandgap changes into the one for both bulk and surface acoustic wave.

The design of the surface mode cavities are based on the mode gap effect [49]. In this work, the PXC sensor is composed of dual cavities, one optical and one acoustic cavity, as illustrated in Fig. 4(a), where the liquid analyte is distributed homogenously in all of the holes. It should be pointed that by appropriate design, light and