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Acoustic Mach–Zehnder interferometer utilizing self-collimated beams in a two-dimensional phononic crystal

Olgun Adem Kaya [a,*], Ahmet Cicek [b], Aysevil Salman [a,c], Bulent Ulug [d]

[a] Department of Computer Education and Educational Technology, Faculty of Education, Inonu University, 44280 Malatya, Turkey
[b] Department of Physics, Faculty of Arts and Science, Mehmet Akif Ersoy University, 15030 Burdur, Turkey
[c] TUBITAK BIDEB-2218 Domestic Post-Doctoral Research Fellow Programme, 06100 Ankara, Turkey
[d] Department of Physics, Faculty of Science, Akdeniz University, 07058 Antalya, Turkey

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ABSTRACT

Numerical investigation of a Mach–Zehnder interferometer implemented by steering self-collimated acoustic beams in a two-dimensional phononic crystal is presented. Mirrors of the interferometer are optimized by modifying the radii of the steel cylinders in water so that the working frequencies lie in a band gap. The beam splitters optimized in a similar manner ensure equal splitting of the beams. In the all-water case of host liquid, the interferometer operates unidirectionally such that transmission through only one of the two output terminals is achieved. Corresponding transmittances are 85.9% and 6.0% for the transmitting and blocked terminals, respectively. The device can be utilized in sensing variations in the weight fraction of ethanol in water in a cell on the path of one of the two split beams. Phase difference accumulated in the sample cell varies linearly with ethanol weight fraction up to 15%. Contrast ratio of the calculated transmittances can be used as a measure of ethanol content in water, as it varies as a cosine function of ethanol weight fraction.

1. Introduction

Interferometers are means for accurate determination of relative variations in physical properties, such as the index of refraction or mass density. Mach–Zehnder (MZ) interferometers, which have already been realized in photonic crystals (PCs) in several schemes, are commonly utilized in this sense. A way of splitting and recombining light waves in a MZ interferometer is to use linear defect waveguides (WGs) in two-dimensional (2D) PCs [1–4]. Either Y [1,2,4] or T [3] branches of WGs are appropriate for this purpose. Such interferometers in 2D PCs can be employed as optical biosensors [4]. Another means of designing MZ interferometers in 2D PCs is through the self collimation phenomenon [5–8]. Such interferometers usually possess two output terminals and operate either unidirectionally [5,6], where output from only one terminal is possible, or bidirectionally [5,7,8], such that both terminals function as output. Bidirectional design can be used in polarization splitting for light waves [7,8].

Phononic crystals (PnCs), acoustic analogs of PCs, have been utilized in sensing liquid properties under several schemes. For instance, to facilitate extraordinary acoustic transmission (EAT), a PnC slab can be introduced into wave path, where 2D PnC plane normal is parallel to the acoustic axis [9–11]. This approach can be utilized to measure concentration of propanol in water, or speed of sound in such a mixture of known concentration [9–11]. EAT is not limited to PnCs but can also be obtained through structures, such as a one-dimensional grating of subwavelength apertures in a metallic film [12] or through ultrathin acoustic metamaterials by coiling up space through curled acoustic channels [13].

In another scheme, defect modes are excited in a one-dimensional PnC composed of a periodic array of liquid and solid materials [14,15]. If one of the identical liquid cells is replaced by an analyte of interest, the induced shift of the defect peak in the transmission spectrum can then be analyzed to deduce analyte concentration. In case of 2D PnCs, localized mode of a cavity bisecting a square PnC normal to the acoustic axis can be utilized to determine propanol concentration in water [16] or gasoline properties, such as the octane number [17,18]. A linear defect WG in a 2D PnC slab can also be used in determining liquid properties, such as ethanol concentration in water [19]. However, use of interferometric means, such as MZ interferometers as in PCs could be appropriate for determining liquid properties in a more sensitive manner.

Simultaneous optical and acoustic transmission can also be utilized in liquid concentration sensing through the use of phoXonic

* Corresponding author. Tel.: +90 422 3774498.
E-mail addresses: oakaya@inonu.edu.tr, oademkaya@gmail.com (O.A. Kaya).

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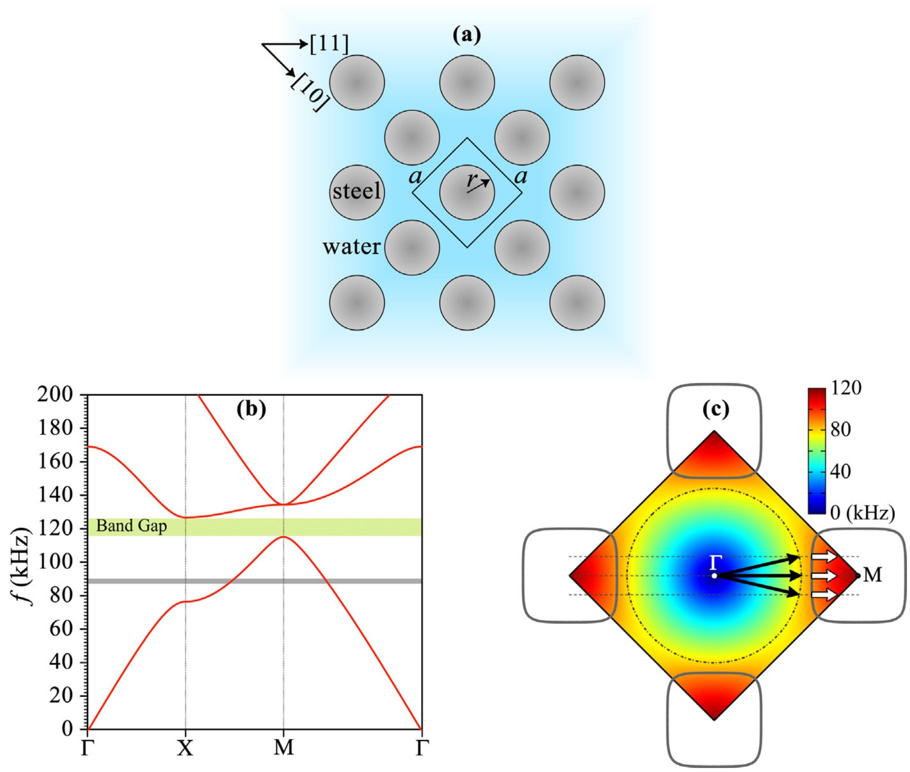

Fig. 1. Unit cell parameters of the PnC (a), its band structure obtained through FEM calculations (b) and EFCs of the first band (c). Solid rectangles in (a) and (c) represent unit cell and the 1st Brillouin zone, respectively. The grey horizontal strip in (b) denotes the frequency range of interest (i.e. 87–90 kHz). Dash-dotted circle and solid rounded squares in (c) represent EFCs at 87.7 kHz of water and PnC, respectively. Solid and hollow arrows in (c) denote wave and group velocity vectors, respectively, whereas dashed horizontal lines represent corresponding construction lines.

crystals, periodic structures tailored for dual-wave operation [20]. Composed of a square array of cylindrical voids in silicon host where one of the columns normal to wave propagation direction is filled with the analyte under study, the phoXonic crystal can be used to sense variations in elastic wave and light speed inside itself. Tracking the wavelength shift in positions of sharp transmission peaks and dips in acoustic and optical spectra of the crystal, one can predict the concentration of analyte, such as propanol, butanol, benzene, etc. [20].

In this work, a MZ interferometer in a 2D PnC is numerically investigated. The interferometer is based on splitting and recombining self-collimated beams in the PnC. The optimal PnC parameters, as well as geometries of the involved beam splitters (BSs) and mirrors are determined from band structure computations employing the finite-element method (FEM). Asymmetric device operation where one of the interfering beams encounters a domain filled with a binary mixture of ethanol and water is also investigated. Dependence of the phase difference between the split beams and transmission spectra through the two output terminals of the interferometer on ethanol weight fraction are investigated in detail.

2. Interferometer design

A square array of steel cylinders in water compose the 2D PnC whose geometry and unit cell is depicted in Fig. 1(a). The densities of steel and water are $\rho_S = 7870.0\,\text{kg/m}^3$ and $\rho_W = 998.2\,\text{kg/m}^3$, respectively. The longitudial and transverse sound speeds in steel are $c_S^L = 6100.0\,\text{m/s}$ and $c_S^T = 3235.0\,\text{m/s}$, respectively, while the speed of sound in water is $c_W = 1482.4\,\text{m/s}$. Lattice constant and scatterer radii, $a = 7.1$ mm and $r = 2.5$ mm, respectively, are chosen so that a sufficiently-large band gap (the hatched area in Fig. 1(b)) appears between the first two acoustic bands obtained through FEM calculations under periodic boundary conditions. Band structure calculations are carried out by means of the Acoustic-Solid Interaction Model of Comsol Multiphysics software, which takes the shear modulus of steel scatterers into account. In contrast, approximating the solid scatterers as rigid fluid cylinders as in the plane-wave expansion method (PWE) is only validated when the acoustic impedance mismatch between the host and scatterers is significantly large, e.g. in the case of solid cylinders in air [21]. In more realistic applications utilization of FEM through incorporating the fluid–structure interactions [22] or other methods, such as the multiple-scattering theory (MST) [23,24] is required.

Variation of the first acoustic band which extends up to 116.0 kHz, Fig. 1(b), is such that the equifrequency contours (EFCs) are centered on the M point at high frequencies, Fig. 1(c). When the PnC is laid along the [11] (ΓM) direction, a normally-incident plane wave with a frequency roughly between 80 kHz and 100 kHz propagates in a self-collimated manner. The mechanism for this is depicted in Fig. 1(c) with a representative EFC at $f = 87.7$ kHz. The EFC is flat and normal to the ΓM direction such that all waves with an angle of incidence smaller than 15° are self collimated along the ΓM direction. All group velocity vectors (hollow arrows) for all coupled spatial modes (solid arrows) in Fig. 1(c) are parallel so that the Fourier components of the propagating beam travel along the same direction. Considering the finite extent of the incident plane wave along the transverse direction, where the diffractive effects deteriorate self-collimation behavior [25,26], our attention is focused on frequencies between 87 kHz and 90 kHz, denoted by the grey horizontal strip in Fig. 1(b). In this frequency range, the EFCs are flat and extend sufficiently along the transverse direction such that self collimation is maintained over long distances. This is confirmed by FEM simulations by considering a $50b$-long (where $b = a\sqrt{2}$) PnC.

The self-collimation behavior discussed above is not unique to solid scatterers in a liquid host, such as water. Thus, an air-solid PnC