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Phononic crystal surface mode coupling and its use in acoustic Doppler velocimetry

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ABSTRACT

It is numerically shown that surface modes of two-dimensional phononic crystals, which are Bloch modes bound to the interface between the phononic crystal and the surrounding host, can couple back and forth between the surfaces in a length scale determined by the separation of two surfaces and frequency. Supercell band structure computations through the finite-element method reveal that the surface band of an isolated surface splits into two bands which support either symmetric or antisymmetric hybrid modes. When the surface separation is 3.5 times the lattice constant, a coupling length varying between 30 and 48 periods can be obtained which first increases linearly with frequency and, then, decreases rapidly. In the linear regime, variation of coupling length can be used as a means of measuring speeds of objects on the order of 0.1 m/s by incorporating the Doppler shift. Speed sensitivity can be improved by increasing surface separation at the cost of larger device sizes.

1. Introduction

In recent years, phononic crystals (PnCs) have found increasingly broader range of applicability in bio/chemical sensing. Utilization of PnCs in this respect is generally based on tracking the shift of isolated localized modes in the dispersion relation of the PnCs. Thus, slight variations in the concentration of an analyte can be determined by analyzing the modifications in a transmission peak [1–3]. PnCs including a longitudinal cavity were also studied for liquid concentration sensing [4,5]. Besides, linear defect waveguides (WGs) formed in two-dimensional (2D) fluid/fluid PnCs were studied such that determination of concentration of ethanol in a binary mixture with water is presented [6]. Liquid-filled linear defect WGs in a steel host are used to form a Mach–Zehnder interferometer where ethanol concentration can be determined with higher sensitivity [7]. Another Mach–Zehnder interferometer design involves steering-self collimated waves in a PnC of solid scatterers in water [8]. Biomolecular sensors utilizing PnCs were proposed where a piezoelectric surface acoustic wave (SAW) device incorporating two interdigital transducers and a PnC in between is considered [9]. PnCs are not only used for bio/-chemical sensors but also for physical sensors, such as a SAW mass sensor in the 100 GHz range [10].

The above-mentioned localized modes can easily be obtained through zero-dimensional (0D) or one-dimensional (1D) defect states within a band gap of the PnC [11–16]. WGs can also be realized by utilizing graded-index profiles with continuous alterations in the filling ratio or physical properties of the unit cell content [17]. Moreover, PnCs with azimuthal symmetry can be used to obtain pliable radial WGs, corresponding to defect states in the radial band gap, to guide acoustic waves through long distances [18]. Another way of obtaining WG modes is through strip or slab PnCs, which have finite heights comparable to lattice periodicity by exciting either Lamb or Rayleigh wave modes within the band gap of the PnC [19–24].

Still another means of obtaining isolated transmission modes is through the surface modes, i.e. Bloch states within the band gap arising due to the finite nature of a PnC in a plane of periodicity. Existence of surface modes, in a 2D PnC of steel cylinders in air matrix is numerically investigated by Zhao et al. [25]. Supercell band structure (BS) calculations reveal that surface modes appear at very high filling ratios within a narrow frequency range. Surface

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modes are localized at the interface of the 2D PnC with the air host in a length scale of lattice periodicity and decay rapidly on either side away from the interface [25]. Zhao et al. also reported that surface modes can be excited either by an external point-like source incident at a large angle on the PnC surface or through a perpendicular WG [25]. Surface waves propagate in a beating manner along the surface. An experimental study of surface modes in a 2D PnC focuses on steel cylinders in water, where a WG is created by removing the central column of scatterers and a point source are located at the center of the PnC to excite surface modes [26]. The coupling between WG and corrugated surface modes are demonstrated [26]. Cicek et al. studied dispersion properties of surface modes in a square PnC for both (10) and (11) surfaces where surface mode excitation by airborne sound and guidance of the modes were demonstrated both numerically and experimentally [27].

It is known from photonic crystal studies that when two WGs are brought in close proximity, their localized modes interact due to their evanescent nature in the transverse direction [28,29]. The wave energy switches back and forth between two hybridized states due to mode overlap, where the scale of transition known as the coupling length depends inversely on the separation of the two split modes in the reciprocal space [28,29]. Coupling between localized modes in the PnCs has also been studied [30–33]. Resonant tunneling is demonstrated experimentally and theoretically for symmetrical stubs created at the sidewalls of the two parallel WGs [31] and with additional two vacancies [34]. Modification of the dispersion relation of PnCs through cavities is investigated to determine the coupling strength between resonators [33]. Cavities in PnCs effect the propagation of waves and coupling of modes so that they can be used to design filters and multiplexers [30–34].

Mode coupling can be utilized in high-sensitivity applications as the separation in the reciprocal space (k-space) between the modes can exhibit significant variations depending on small variations in a parameter, such as the density of the surrounding medium. Since this, in turn, manifests itself as measurable variations in the coupling length, devices based on the coupling of localized modes in PnCs for both physical and bio/chemical sensors can be designed. It can also be used in physical sensing, such as in acoustic Doppler velocimeters (ADVs).

In this work, it is numerically demonstrated through finite-element method (FEM) computations that surface modes of two 2D PnCs can couple when the PnCs are brought to close proximity. Surface mode coupling mechanism is utilized in proposing physical sensor devices for determining speeds of objects based on Doppler effect. Coupling properties of surface modes are investigated through band analyses and FEM simulations. The paper is organized as follows: Section 2 introduces the investigated PnC surfaces and the computational methods, as well as the dispersion properties of isolated and interacting surfaces. This section also deals with dependence of the coupling length on surface separation and frequency. Then, FEM simulation results of surface mode coupling are presented in Section 3. Proposed utilization of surface mode coupling in Doppler-shift based velocity sensing is introduced in Section 4. The text is finalized with brief conclusions in Section 5.

2. Dispersion analysis of surface mode coupling

We consider a square PnC of steel cylinders in air laid along the (10) orientation. Densities of steel and air are $\rho_s = 7850\ \mathrm{kg/m^3}$ and $\rho_a = 1.21\ \mathrm{kg/m^3}$, respectively, whereas the corresponding longitudinal speed of sound values are $c_s = 6100$ m/s and $c_a = 343$ m/s. Thus, a 2D FEM approach which treats steel as a rigid fluid-like medium to solve the scalar wave equation

$$\nabla \cdot \left(\frac{1}{\rho}\nabla p(\boldsymbol{r})\right) - \frac{\omega^2}{\rho c^2}p(\boldsymbol{r}) = 0 \quad (1)$$

is implemented through the pressure acoustics model of the Comsol Multiphysics software. Here, ρ, ω and c stand for density, angular frequency and longitudinal speed of sound, respectively, whereas $p(\boldsymbol{r})$ is the pressure field which has a harmonic temporal behavior. The motivation behind neglecting shear wave components in steel depends on three factors: (i) air medium can only support longitudinal waves while steel cylinders can support both longitudinal and transverse wave components, (ii) acoustic impedance of steel is orders of magnitude higher than that of air and (iii) the problem is completely 2D as PnC cylinders are assumed to extend indefinitely in orthogonal direction [27]. The first two imply that even though transverse modes can be excited in steel to a negligible level, they cannot couple back into air. Thus, they can be safely ignored and Eq. (1) can be used to describe the 2D problem. Such a simplification in solid–fluid PnCs with large acoustic impedance mismatch has been utilized in simulation and BS calculations of PnC structures through discretized methods such as finite-difference time-domain (FDTD) [12,14,15,31,34] and FEM [17,27]. In both unit cell and supercell BS computations through FEM, Bloch–Floquet periodic-boundary conditions are utilized. In frequency domain FEM simulations, on the other hand, non-reflecting boundary condition based on Givoli and Neta's implementation of Higdon conditions for plane waves to the second order is employed [35]. Such a boundary condition ensures that spurious reflections of a plane wave impinging on the computational domain boundary, which can be estimated by $R_S = |(\cos(\theta) - 1)/(\cos(\theta) + 1)|^2$ where θ is the incidence angle to boundary, at near-normal incidence are minimal. This is the case in the present study where at most $\theta = 5°$ incidence angle, and thus $R_S = 3.6 \times 10^{-4}\%$, is involved.

Lattice constant of the PnC is $a = 100\ \mu$m, whereas the radii of the cylinders are $r = 0.49a$, as surface modes can be observed for large values of the r/a ratio [25,27]. The dashed curve in Fig. 1(a) denoted as the surface band (SB) is the dispersion curve for an isolated PnC surface. The projected BS in Fig. 1(a) is obtained by a supercell calculation where a 1×35 symmetric supercell with 17 rows of PnC at the center and 9 periods of air layer on each side is considered [27]. The SB emerges from the bulk bands of the PnC and extends into the full band gap while following the air line, i.e. the dispersion curve of homogeneous air medium ($\omega = c_a k_x$), where k_x is the parallel wave vector component along the surface. The SB deviates more and more from the air line as k_x approaches π/a. Analysis of the eigen-modes on the SB reveals that the acoustic field in a surface mode is confined to small area extending approximately a period into both air and PnC, where it decays smoothly into air [25,27]. The SB of the isolated PnC surface for $r = 0.49a$ extends into the band gap in a broad frequency range, whereas it always lies below the air line throughout the available k_x range, Fig. 1(a).

If two identical PnC surfaces are in close proximity on the order of a, the decaying surface modes start interacting and the SB in Fig. 1(a) is split into two SBs (solid lines). The degree of overlap can be tuned by the surface separation, W, depicted in Fig. 1(b). The smaller W, the larger mode overlap and splitting of the SBs. In fact, as W approaches infinity, the two split SBs converge to the SB of the isolated PnC. The SBs in Fig. 1(a) correspond to $W = 3.5a$ the choice of which will be clarified below.

One of the SBs in Fig. 1(a) is initially above the air line and falls below the line at a specific k_x value. The modes in this SB where it is above the air line are air-guided, rather than surface-guided. In contrast, the other SB is always below the air line. Thus, the effective surface mode coupling frequency range extends from the point where the upper SB, denoted as SB_A, intersects the air line to the top of the lower SB, denoted as SB_S. For $W = 3.5a$, this corresponds