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Phononic Crystals: Physical Principles and Novel Structures

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ABSTRACT: Phononic crystals (PnCs) are periodic materials that can control and manipulate the propagation of acoustic (or elastic) waves. The importance of paying attention to this area can be seen in applications such as wireless telecommunications, communication systems in shallow water, sensors, acoustic signal processing, and ultrasonic imaging. During the last two decades, various devices have been proposed, fabricated, and measured and a great amount of research has implemented topology optimization for designing these structural materials as well as the associated functional devices. In this study, a comprehensive overview of the state-of-the-art advances in governing principles of PnC operations are discussed, including the study of the background of PnCs, their types, and topologies, their applications in different fields, as well as their filtering and guiding properties. In this paper, we've reviewed two of our own work. First, a 1x2 multiplexer which is designed from two ring resonators and estimated Quality(Q) factor and frequency channel crosstalk at different temperatures($10<T<40$ ℃) and pressures($0.1<P<5$MPa). Second, an acoustic channel drop filter and evaluation of Q-factor with changes in parameters such as pressure, temperature, and molality ($0.9<M<0.1$ mol/Kg). In addition to our works, some of the other proposed simulated or fabricated structures are also presented. The relations and computational methods for solving the equations used in these structures are investigated which is the Finite Difference Time Domain (FDTD) method.

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1- Introduction

Investigation of acoustic waves in phononic crystals (PnC) which are periodic structures has always been considered due to their unique features. They are composed of a periodic arrangement of two different types of materials in which the propagation of acoustic/elastic waves is completely forbidden[1-9]. The destructive interference of the scattered waves by the rods (inclusions) of the PnC is the general mechanism for the opening of a phononic band gap. On the other hand, the main property of PnCs is that at a certain range of frequencies, they do not allow mechanical waves (acoustic or elastic) to propagate inside the structure. According to the size of inclusions, the filling factor, the topology, and the lattice constant of the PnC, mechanical waves are to be reflected in a certain range of frequencies and not to be propagated in the lattice. As a result, it can be used to control and manipulate mechanical waves with the desired frequency. Stated otherwise, Bloch waves become evanescent inside band gaps[10-17].

It should be noted that the position and width of the various types of bandgaps depend on the direction of motion of the acoustic wave inside the crystal[18]. Such gaps may take place for specific directions of the wave vector. In other words, the formation of a wide acoustic bandgap depends on two factors. (1) The existence of a high contrast between the elastic properties of the materials should be required. (2) The filling factor of the inclusions should be sufficient. The PnCs are used to tune the acoustic/elastic waves[19-29], which have many important properties, such as band gaps[30-41], band-edge states[42-49], and having the ability to slow-wave effect[50-55].

In terms of dimensions, the PnCs are divided into three categories. The first is one-dimensional systems (superlattices, comb-like structures, or Bragg lattices)[56-63] that allow longitudinal, transverse, and mixed modes. The second is two-dimensional systems which are the arrays of infinitely long rods embedded in the background matrix[64-69]. The third is three-dimensional systems[40, 70-75] (spherical inclusions that are suspended in a host matrix) in which the longitudinal and transverse modes are strongly coupled, complicating the nature of the eigenmodes and the corresponding computations. The transverse and longitudinal waves are decoupled in a homogeneous bulk medium which are propagated independently. In a longitudinal wave, the

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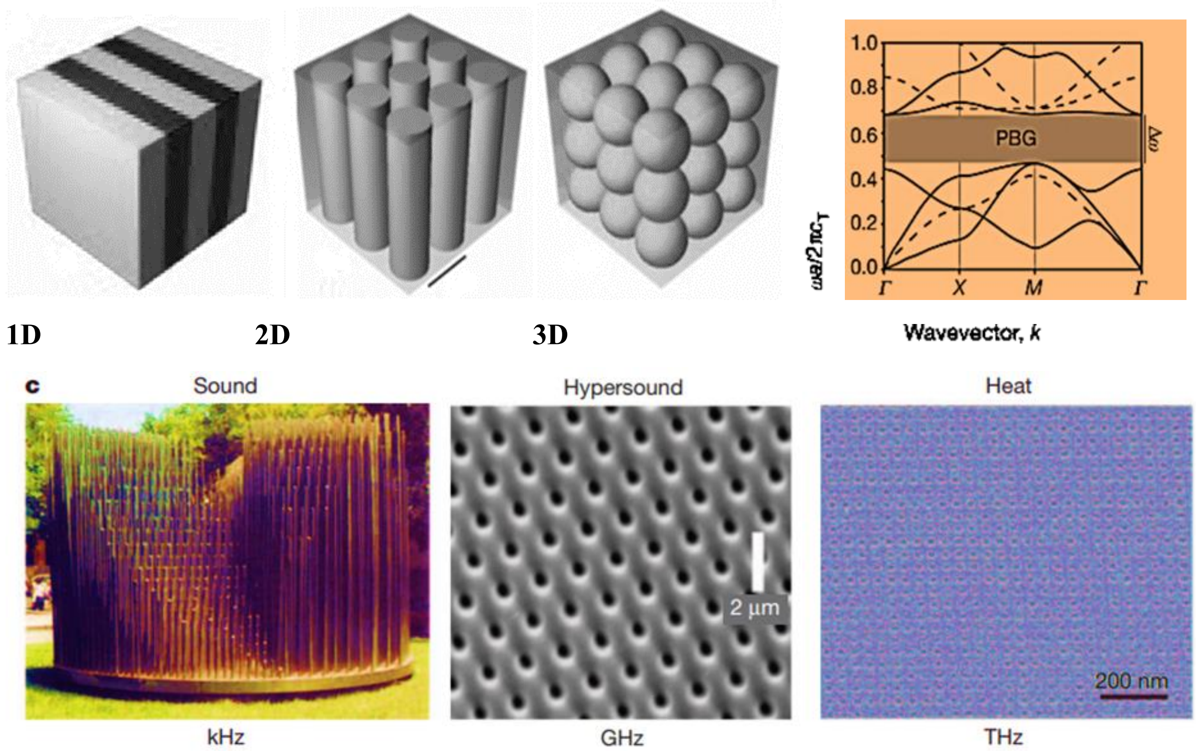

Fig. 1. Phononic crystals. (a) 1D, 2D, and 3D PnC; (b) An example of a phononic band structure; (c) 2D PnCs with periodicities in the range of kHz (sound), GHz (Hypersound), THz (Heat), which are indicated from left to right, respectively, Ref[79].

displacement vector field $\boldsymbol{u}$ is potential ($\nabla \times \boldsymbol{u}=0$), while, it is solenoidal ($\nabla .\boldsymbol{u}=0$) in a transverse wave. The continuity of the displacements and stresses causes to mixing of these two modes in the presence of a boundary[76-78]. The different types of the PnC based on dimensions are shown in Fig. 1(a), similar to[79]. The different colors in this Figure represent materials with different properties. An example of a band structure is shown in Fig. 1(b). Since the band structure is also small compared to the dimension of the structure (the band gap can be tuned to any mechanical wavelength), many macroscopic structures from the frequency range of sonic (kHz)[80-82], to ultrasonic (MHz)[83-85] would be studied. Nowadays, there is a great interest in band structure in new structures and materials, fabrication technology of sub-micron structures, and working in hypersonic regimes (GHz)[86-88], as well as heat control (THz)[89-91], which are shown in Fig. 1(c). It should be noted that phonons can be excited electrically in the frequency range of GHz. They are used in sensing and imaging applications as well as Micro or Nanoelectromechanical systems, known as MEMS/NEMS. The sources of phonons in the very-high-frequency range are the thermal vibrations of atoms or molecules which are called thermal phonons.

In this reviewal study, in section 2, we'll categorize different types of PnC. Section 3 describes the fabrication of PnC. Bulk elastic wave equations in solids and fluids and also dispersion relation, will be discussed in section 4. Effects of defects and guiding in PnC will be explained in sections 5 and 6. Filtering and de-multiplexing will be reviewed in sections 7 and 8. At last, we'll have a conclusion section 9.

2- CATEGORIZING DIFFERENT TYPES OF PHONONIC CRYSTALS

In terms of the types or the forms of material, the PnCs are divided into three other categories which are solid-solid[92-96], solid-liquid[97-99], and liquid-liquid[100].

There have also been some PnCs designs that show self-collimation of elastic waves[101, 102], PnCs with different properties in different directions[103], PnCs in which they are robust to imperfections[104-106], topology optimization of PnCs[107], piezoelectric PnCs[108], the wave attenuation in viscoelastic materials[109] and maximizing absolute and relative band gaps[110].

The progress in the field of PnCs (or PC) goes in parallel with their photonic crystal (PtC) counterparts. However, the variety of materials in PnCs is much greater than those of PtCs. In this regard, there is the possibility of high contrast among the elastic properties, large acoustic absorption, and the solid or fluid nature of the constituents[78, 111]. The electromagnetic equations are as follows [112]:

Table 1. Comparison between the electromagnetic and acoustic variables and material properties[112]

Acoustic	Electromagnetic	Comparison
Acoustic Pressure (P)	Electric Field (E_z)	$-E_z \leftrightarrow P$
Particle Velocity ($u_x u_y$)	Magnetic Field ($H_x H_y$)	$H_y \leftrightarrow -u_x \quad H_x \leftrightarrow u_y$
Dynamic Density ($\rho_x \rho_y$)	Permeability ($\mu_x \mu_y$)	$\rho_x \leftrightarrow \mu_y \quad \rho_y \leftrightarrow \mu_x$
Dynamic Compressibility (β)	Permittivity (ε_z)	$\varepsilon_z \leftrightarrow \beta$

$$\frac{\partial E_z}{\partial x} = -i\omega\mu_y H_y \tag{1}$$

$$\frac{\partial E_z}{\partial y} = -i\omega\mu_x H_x \tag{2}$$

Where E and H are electric and magnetic fields, respectively. The acoustic equations are as follows [112]:

$$\frac{\partial P}{\partial x} = -i\omega\rho_x u_x \tag{3}$$

$$\frac{\partial P}{\partial y} = -i\omega\rho_y u_y \tag{4}$$

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = -i\omega\beta P \tag{5}$$

Where P and U are acoustic pressure and displacement, respectively. The comparison between electromagnetic and acoustic variables is shown in Table 1[112].

It should be noted that all the ordinary (electronic) crystals, PtCs, and PnCs with identical lattices give rise to the same Bragg diffractions. However, the characteristics of these mentioned periodic crystals have significant differences which are explained in Table 2[113].

3- FABRICATION OF PnC

In this section, we will explain the procedure of fabricating a functional device based on PnC slab, which is made by an array of holes in a Si membrane[114]. The conformity of the frequency range of operation of such devices to the frequencies appropriate for sensing applications and wireless communication plays a vital role in the designing and fabricating process. Choosing the suitable thickness of the slab and the appropriate radius of the holes in the square lattice of PnC are effective parameters in opening the complete phononic band gag (PnBG). In this case, the hole radius is r=6.4µm, the lattic constant is a=15µm, and the thickness of the Si layer is d=15µm with the frequency range of 119MHz< f <150MHz.

First of all, the silicon on insulator (SOI) is used as substrate and the thickness of the Si layer is 15µm which is shown in Fig. 2(a). To form the lower electrode of the transducer, a thin layer of gold (with a thickness of ~100nm) in the lift-off process is evaporated and patterned on the Si layer, shown in Fig. 2(b). To add the effect of piezoelectric for exiting the elastic wave, a 1µm layer of Zinc oxide (ZnO) is deposited and patterned using sputtering and wet etching, which are shown in Fig. 2(c). To form the second set of electrodes, a layer of aluminum is patterned which is shown in Fig. 2(d). The PnC holes are patterned in Si layer using optical lithography which is followed by deep plasma etching (Fig. 2(e)). In order to form the PnC membrane, the Si substrate and oxide layer are removed by backside lithography which is shown in Fig. 2(f). The top view and the cross-sectional view of scanning electron microscope (SEM) images for a typical fabricated device are shown in Fig. 3.

The lowest anti-symmetric Lamb wave in micro-fabricated piezoelectric phononic plates is investigated. The structure is based on an AT-cut quartz plate which consists of a gradient-index phononic crystal (GRIN PC) lens and a linear phononic plate waveguide[115]. Fig. 4 shows the micro-fabrication

Table 2. Comparison between the properties of three periodic systems of electronic crystal, PnC and, PtC[113]

Property	**Electronic Crystal**	**Photonic Crystal (PtC)**	**Phononic Crystal (PnC)**
Materials	Crystalline (Natural or grown)	Constructed of two dielectric materials	Constructed of two elastic materials
Parameters	Universal constants, atomic numbers	Dielectric constants of constituents	Mass densities, sound speeds C_T, C_L of constituents
Lattice constant	1-5Å (microscopic)	0.1μm to 1cm (mesoscopic or macroscopic)	Mesoscopic or macroscopic
Waves	de Broglie (electrons) ψ	Electromagnetic or light (photons) $\bar{E}$, $\bar{B}$	Vibrational or sound (phonons) $\bar{u}$
Polarization	Spin (up, down)	Transverse: $\nabla.\bar{D}=0$ $\nabla\bar{E}\neq 0$	Coupled Transverse - Longitudinal. $\left(\nabla.\bar{u}\neq 0,\nabla\times\bar{u}\neq 0\right)$
Free particle limit	$W=\frac{\hbar^2k^2}{2m}$ (electrons)	$\omega=\frac{c}{\sqrt{\epsilon}}k$ (photons)	$\omega=c_{t,l}k$ (phonons)
Band-gap	Increases with crystal potential; no electron states	Increases with $\lvert\epsilon_a-\epsilon_b\rvert$ no photons, no light	Increases with $\lvert\rho_a-\rho_b\rvert$, etc. no vibration, no sound
Spectral region	Radio wave, microwave, optical, X-ray	Microwave, optical	$\omega \lesssim 1GHz$

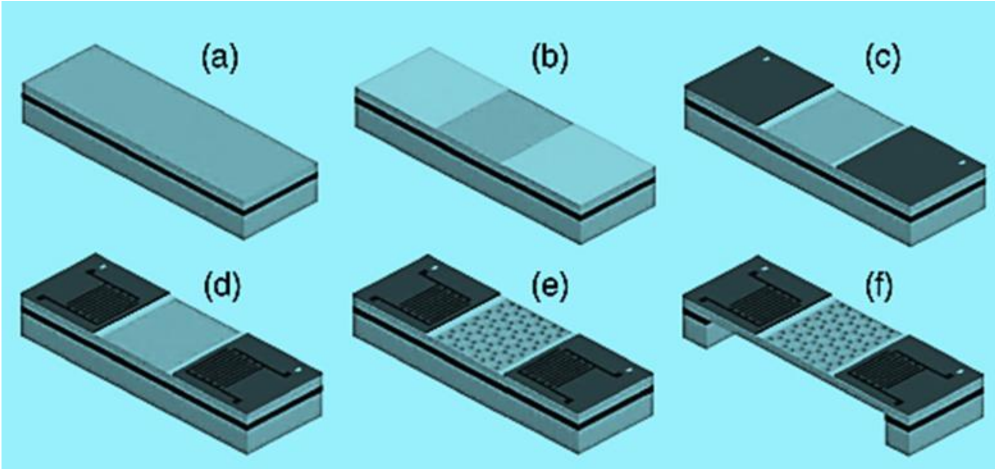

Fig. 2. Fabrication steps for Si PC plate structures. (a) SOI substrate; (b) deposition of the lower electrode and patterning; (c) sputtering and patterning of ZnO layer; (d) deposition of the top metal electrode and patterning; (e) etching process and creating PnC holes; (f) final structure is achieved by plasma etching of the lower Si substrate, Ref.[114].

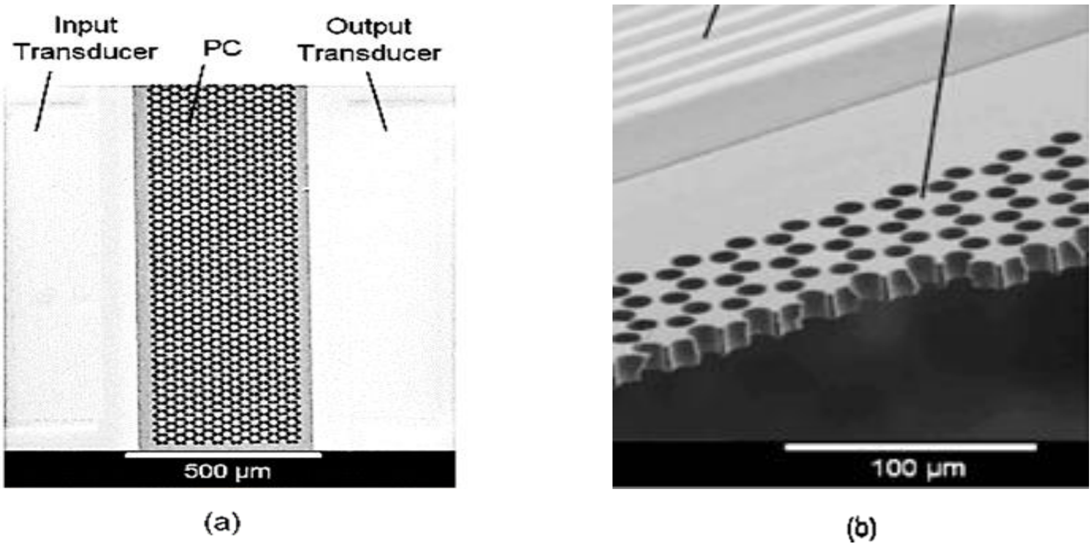

Fig. 3. Top view (a) and cross-sectional view (b) of the fabricated devices, Ref.[114].

process of this device. In order to make the sidewall of the holes close to vertical, the upper and lower sides of the quartz plate were etched. On both sides of the quartz plate, the Gold-Chromium (Au/Cr) films were sputtered. The Cr film which is located between the Au film and the quartz plate acts as the adhesion layer (Fig. 4(a)). To form the periodic cylinders, the photoresist with a thickness of 8µm was patterned on the front side of the quartz plate (Fig. 4(b)). To prevent the 80µm thick quartz plate from bending and breaking the double-side Au/Cr seed layers and the double-side Nickel (Ni) electrodeposition was used (Fig. 4(c)). Then the photoresist was removed (Fig. 4(d)). The Au/Cr layer was not covered by the Ni mask. So, the Xenon (Xe) gas is used to remove it. The Sulfur hexafluoride (SF6) gas was used to etch (with the etching rate of 450nm/min) the front side of the quartz plate. To fabricate the vertical sidewall of the cylindrical air hole, the etching process should be divided into two steps. In the first step, the depth of etching of the front side should be 40µm and the Ni mask was removed by using the nitric acid (Fig. 4(e)). In the next step, the back side of the quartz

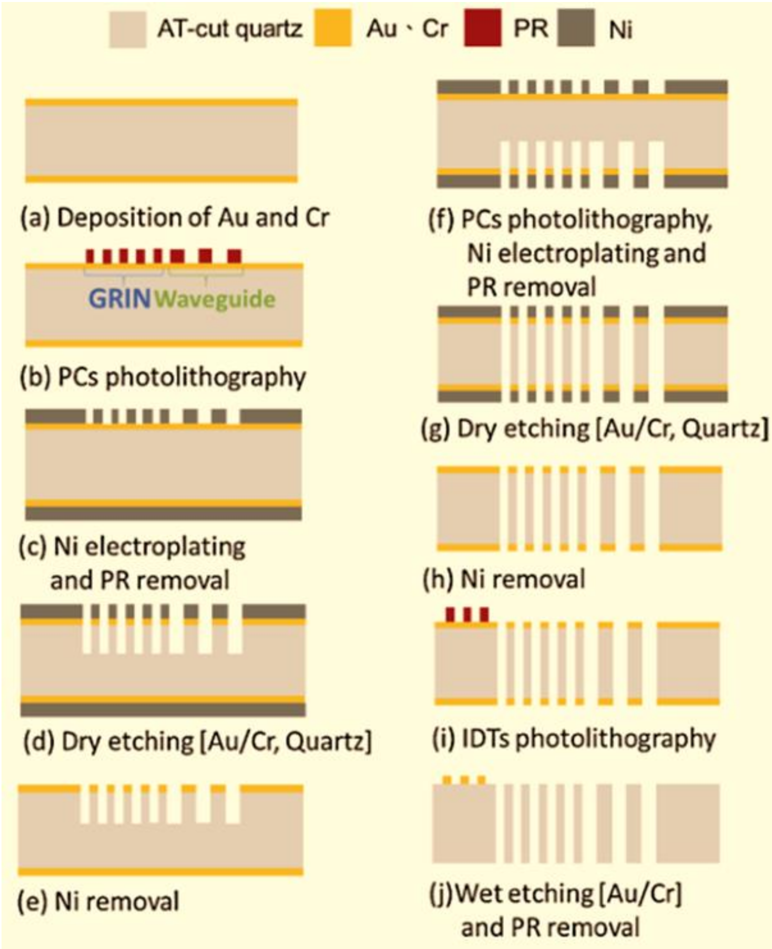

Fig. 4. The micro-fabrication process of the GRIN PC lens and waveguide, Ref[115].

plate was patterned again, followed by Ni electroplating and photoresist removal. By using the same process for the front side, the back side of the quartz plate was etched and the selectivity of the Ni mask to the quartz plate was 20. Then, the Ni mask was removed by using nitric acid, and the PC gratings were accomplished (Fig. 4(f)-(h)). At the end, the interdigital transducers (IDT) were fabricated onto the left side of the GRIN PC plate lens to generate 10MHz Lamb waves using the photolithography process (Fig. 4(i) and (j)).

4- EQUATIONS

4- 1- The Bulk Elastic Wave in Solid Inhomogeneous Material

In this section, we want to investigate the propagation of elastic waves in solids. Solid materials are made of periodic and precise order of atoms in space. When the plane wave of the elastic wave with the wave vector of k propagates inside the crystal, the collective and coherent movements of atoms take place[116-118]. The displacement of the atom from its equilibrium position is due to a forward perturbation caused by the elastic plane wave and is indicated by the displacement vector of $U(r, t)$[119-121].

When atoms move perpendicular to the direction of propagation, the displacement vector $U(r, t)$ is perpendicular to the direction of propagation, and the elastic plane wave is called the transverse plane wave (Fig. 5(a)). When atoms move along the direction of propagation, the elastic plane wave is called the longitudinal plane wave (Fig. 5(b)). An important feature of the elastic wave propagation inside the homogeneous solid is that the transverse or longitudinal elastic waves propagate at different speeds and they are independent of each other. In solids, the transverse velocity of the elastic plane wave is denoted by Ct, while the longitudinal velocity of the elastic plane wave is denoted by Cl. The propagation of transverse/longitudinal elastic plane wave with the frequency of ω in the solid material is denoted by[119, 120].

$$U_T\left(r.t\right) = \mathrm{Re}\left(u_{T0}\ e^{i(k.r-\omega t)}\right) \tag{6}$$

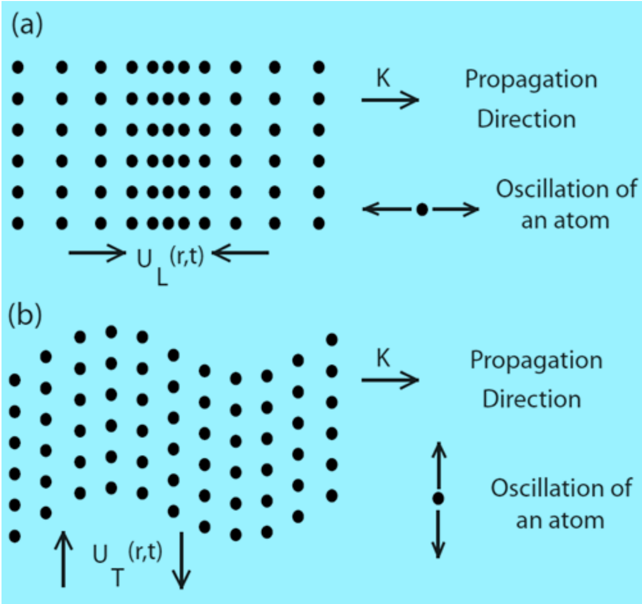

Fig. 5. The displacement of a square lattice during the propagation of bulk waves: (a) Longitudinal UL(r, t), and (b) Transverse UT(r, t), Ref. [121].

$$U_L(r.t) = \mathrm{Re}\left(u_{L0}\, e^{i(k.r-\omega t)}\right) \tag{7}$$

where $UT(r;\ t)$ and $UL(r;\ t)$ are the transverse and longitudinal displacement, respectively. They are also perpendicular and parallel to the wave vector of k, respectively. u_{T0} And u_{L0} are the amplitude of the displacement vector. In solid homogeneous material[119, 120]

$$\nabla_T^2 u = \frac{1}{C_T^2}\frac{\partial_T^2 u}{\partial t^2} \tag{8}$$

and

$$\nabla_L^2 u = \frac{1}{C_L^2}\frac{\partial_L^2 u}{\partial t^2} \tag{9}$$

Substitution of Eq.s (6 and (7 into Eq.s (8 and (9 leads to calculating the equations for transverse/ longitudinal wave number

$$\boldsymbol{k_T} = \frac{\boldsymbol{\omega}}{\boldsymbol{c_T}} \tag{10}$$

and

$$\boldsymbol{k_L} = \frac{\boldsymbol{\omega}}{\boldsymbol{c_L}} \tag{11}$$

c_T and c_L are determined by the mechanical properties of the material and calculated by

$$c_T = \sqrt{\frac{\mu}{\rho}} \tag{12}$$

and

$$c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{13}$$

Where ρ is mass density, λ and μ are the Lame coefficients. The Lame coefficients describe the mechanical properties of solids which are calculated by the following equations

$$\lambda = \frac{E\vartheta}{(1+\vartheta)(1-2\vartheta)} \tag{14}$$

and

$$\mu = \frac{E}{2(1+\vartheta)} \tag{15}$$

Where E and ϑ are the Young modulus and Poisson coefficient. ω

4- 2- Acoustic Waves in Fluid Materials

The important point is that only longitudinal waves propagate in fluid materials. No transverse mods are allowed in any fluid-fluid materials[116, 117]. In homogenous fluid-fluid systems, the propagation of acoustic waves is expressed in the form of instantaneous pressure $p(r.t)$ which is defined by [78]

$$p(r.t) = -\lambda \nabla . u(r.t) \tag{16}$$

The acoustic wave of instantaneous pressure with the frequency of ω is calculated by

$$p(r.t) = Re\left(p_0 e^{i(k.r-\omega t)}\right) \tag{17}$$

Using the above equations, the propagation of acoustic waves in the homogenous fluid materials is calculated by

$$\nabla^2 p = \frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} \tag{18}$$

Where c_0 is the velocity of the acoustic wave. The equation for acoustic wave number is

$$\boldsymbol{k}_0 = \frac{\boldsymbol{\omega}}{\boldsymbol{c}_0} \tag{19}$$

Where the c_0 is calculated by

$$c_0 = \sqrt{\frac{\lambda}{\rho}} \tag{20}$$

4- 3- Dispersion Relationship

One of the most common methods for investigating the phononic gaps is the structure of the PnC is assumed to be infinite, filling the entire space with a one-dimensional structure.

Generally, the dispersion relationship of $\omega=\omega(k)$ for the propagation of the elastic wave in the infinite solid-solid PnC structure is calculated by solving the wave equation for heterogeneous solid materials[78]:

$$\nabla \cdot \left(\rho c_T^2 \nabla u_i + \rho c_T^2 \frac{\partial u}{\partial x_i}\right) + \frac{\partial}{\partial x_i}\left(\left(\rho c_L^2 - 2\rho c_T^2\right) \nabla u\right) = -\rho\left(\omega(k)\right)^2 \; u_i \tag{21}$$

Where $u = u_r(r)$ is displacement vector of the elastic wave inside the PnC structure with the wave vector of k.

4- 4- One-Dimensional PnC

In one-dimensional PnCs, the change in material properties is only in one direction. We want to consider the periodic solid layers. The elastic waves propagate perpendicular to the layers with the wave vector of $\boldsymbol{k} = k_x \hat{x}$.

In order to obtain the band structure of the 1D PnC, the Eq. (21 is divided into the following three equations in x, y and z directions[78]:

$$\frac{\partial}{\partial x}\left(\rho c_L^2 \frac{\partial u_x}{\partial x}\right) = -\rho\left(\omega(k)\right)^2 u_x \tag{22}$$

$$\frac{\partial}{\partial x}\left(\rho c_T^2 \frac{\partial u_y}{\partial x}\right) = -\rho\left(\omega(k)\right)^2 u_y \tag{23}$$

$$\frac{\partial}{\partial x}\left(\rho c_T^2 \frac{\partial u_z}{\partial x}\right) = -\rho\left(\omega(k)\right)^2 u_z \tag{24}$$

Where $u_x = u_x(x)$, $u_y = u_y(y)$ and $u_z = u_z(z)$. It should be noted that these three equations are independent of the displacement vector of u_x, u_y and u_z. It means that the elastic wave can propagate inside the PnC structure independently as either a longitudinal elastic wave with *ux* or a transverse elastic wave with *uy* and *uz*. It should be pointed out that the mentioned PnC structure has periodic layers in the *X* direction. As a result, it could not prevent the propagation of waves that are parallel to the layers (*X* and *Y* directions).

4- 5- Two-dimensional PnC

In two-dimensional PnCs, the change in material properties is in two directions (x, y), and there are no changes in z direction. In other words, the parameters of the structure change in the form of $\rho(x.y)$, $c_T(x.y)$ and $c_L(x.y)$. Using Eq. (21, the dispersion curve in two-dimensional structures is obtained as follows[78]:

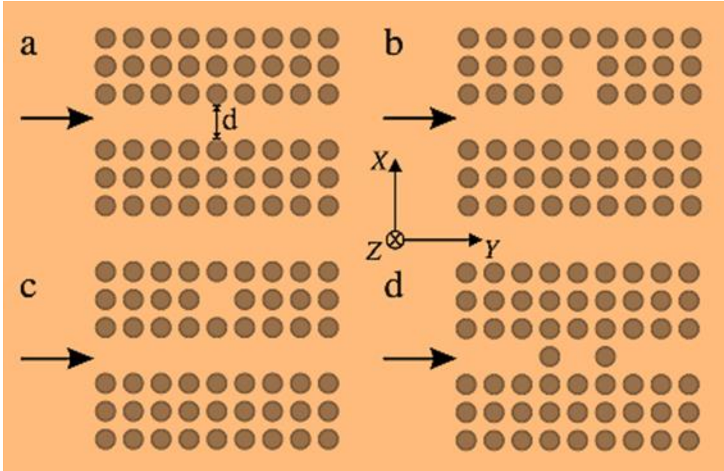

Fig. 6. The 2D cross-sections of (a) a linear waveguide with the width of d, (b) A stub located vertically to the waveguide, (c) A side-coupled waveguide cavity, and (d) A cavity inside the linear waveguide, Ref. [123].

$$\frac{\partial}{\partial x}\left(\rho c_L^2 \frac{\partial u_x}{\partial x}+\left(\rho c_L^2-2\rho c_T^2\right)\frac{\partial u_y}{\partial y}\right)+\frac{\partial}{\partial y}\left(\rho c_T^2 \frac{\partial u_x}{\partial y}+\rho c_T^2 \frac{\partial u_y}{\partial x}\right)=-\rho\left(\omega(k)\right)^2 u_x \tag{25}$$

$$\frac{\partial}{\partial y}\left(\rho c_L^2 \frac{\partial u_y}{\partial y}+\left(\rho c_L^2-2\rho c_T^2\right)\frac{\partial u_x}{\partial x}\right)+\frac{\partial}{\partial x}\left(\rho c_T^2 \frac{\partial u_y}{\partial x}+\rho c_T^2 \frac{\partial u_x}{\partial y}\right)=-\rho\left(\omega(k)\right)^2 u_y \tag{26}$$

$$\frac{\partial}{\partial x}\left(\rho c_T^2 \frac{\partial u_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho c_T^2 \frac{\partial u_z}{\partial y}\right)=-\rho\left(\omega(k)\right)^2 u_z \tag{27}$$

These equations show that elastic waves inside the PnC can be propagated in two ways. The Eq.s (25 and (26 show the propagation of coupled elastic waves whose displacement vectors have coupled the components of u_x and u_y. These elastic waves are called In-Plane waves. Eq. (21 shows the propagation of independent waves that are specified by the component of the displacement vector and are perpendicular to the plane. This elastic wave, which propagates independently and perpendicular to the k wave vector, is called the Out-of-Plane wave.

5- THE POINT DEFECT AND LINE DEFECT ON PnCs

Applying point defects and line defects in the structure of PnC makes it possible to use them in devices such as acoustic waveguides and cavities. In other words, the defect modes can be created within the acoustic (elastic) wave band gaps due to the local breaking of the periodicity of the structures[122]. Point defects create straight bands in the phononic gap that cause wave confinement and form cavities. An example of these defects is shown in

Fig. 6[123].

The transmission and attenuation spectra due to the presence of cavities inside the waveguide path as well as outside the waveguide path are shown in Fig. 7. As can be seen from Fig. 7(a), the presence of cavities in the waveguide path causes a narrow passband in the transmission spectrum. On the other hand, the presence of these cavities outside the waveguide path and on one side of it will cause a narrow attenuation band in the transmission spectrum at some frequencies. As a result, by changing the structure of the cavity, specific frequencies can be selected and passed or deleted.

In order to measure the transmission spectrum, the experimental setup is fabricated. The transmission spectrum of the perfect structure with a single point defect is measured in Fig. 8. According to Fig. 8(a), the defect mode occurs at a resonant frequency of $f0$=287.7kHz. Then, two rods are removed in the propagation direction (y direction) and the transmission spectrum is examined in Fig. 8(b). It is observed that the localized mode for two-point defects is divided

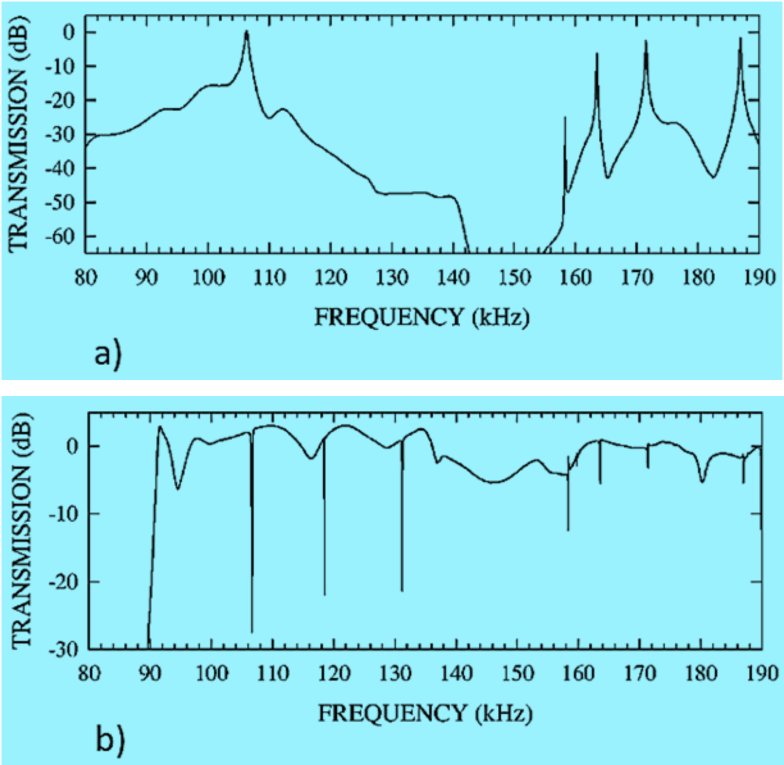

Fig. 7. (a) Transmittance for Fig. 6(d) with d=11mm, (b) Transmittance for Fig. 6(c) with d=6.5mm, Ref. [123].

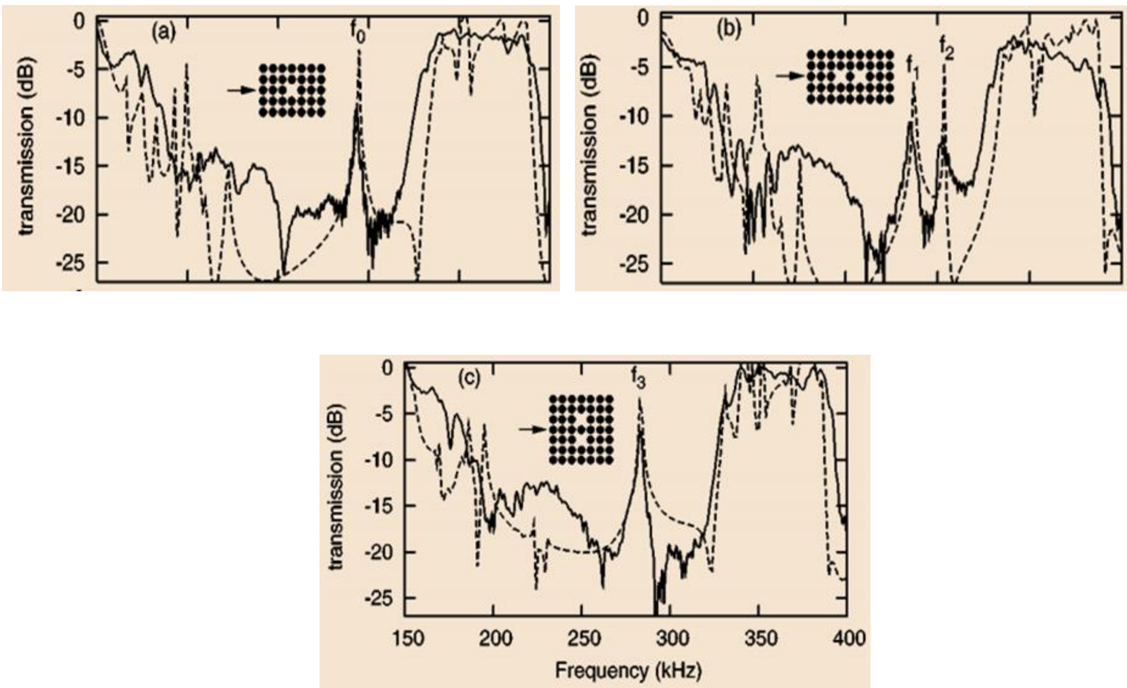

Fig. 8. The transmission of Experimental (solid lines) and calculated (dashed lines). (a) a single defect induces a resonance mode with f0. (b) Two defects in the propagation direction make it have two split resonance modes at frequencies f1 and f2. (c) Two defects in perpendicular to the propagation direction, Ref[124].

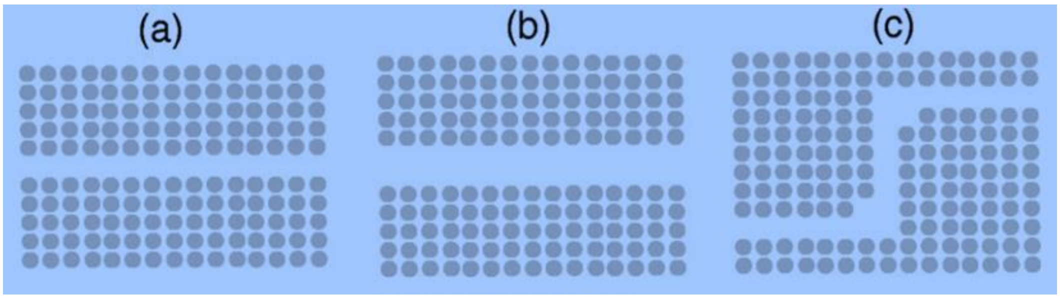

Fig. 9. 2D cross-sections of (a) one-period wide straight waveguide (W1), (b) A two-period-wide straight waveguide (W2), and (c) A one-period-wide bent waveguide, Ref[128].

into two resonance modes with frequencies of $f1$=280 and $f2$=296.5kHz. The transmission spectrum for the two coupled cavities perpendicular to the y axis is shown in the Fig. 8(c). In this structure, the cavity modes are coupled and symmetrical, as in Fig. 8(b), except that the location of the x and y axes has changed. Although there are two separate modes, only one of them appears at a resonant frequency of $f3$=279.3kHz. In fact, due to the longitudinal polarization in water, the mode which is anti-symmetrical relative to the y-axis, cannot be excited[124].

The line defects contain hollow cylinders of smaller outer radius and a high ratio for inner to outer radii making it possible to create narrow-band transmission spectra which can be suitable for designing the output waveguides of the demultiplexer. It should be noted that a defect containing a hollow cylinder of high outer radius can have a wide transmission. This property makes it possible to tune the frequency behavior by changing the inner-to-outer radii ratio[125, 126].

It should be noted that the defects are divided into three kinds of geometry which are square defect, circular defect, and rectangular defect, respectively. For both square and circular defects, the modes of defects are only related to the defect filling fraction, however, in the rectangular defect, the defect modes could be tuned by changing the ratio of edge width of the defect[122]. For the bending waves, when a point defect is introduced, the bending waves are highly localized at or near the defect, leading to defect modes[127].

6- GUIDING

By removing one row of rods along the x-axis (propagation direction), the straight waveguide ($W1$) is formed, which is shown in Fig. 9(a). The width $W1$ is the distance between neighboring rods on both sides of the waveguide. The transmission spectrum is shown in Fig. 10(a). According to this Fig., full transmission for acoustic waves at specific frequencies is seen within the stopband of PnC. It is observed that the confinement of the wave inside the waveguide is good enough and the propagation of the wave has low losses. It can be seen that the Finite Difference Time Domain (FDTD) calculations are in good agreement with the measurements[128].

The effect of changing the width of the waveguide has also been investigated and shown in Fig. 9(b). In this case, the two-row of rods are removed to form $W2$. The FDTD calculations, as well as the measured transmission, are shown in Fig. 10(b). It can be seen that two distinct waveguiding bands are located inside the stopband. There is also a strong attenuation at 285kHz. This is due to destructive interference at this frequency, which causes a stopband. The bending waveguide of 90° is also investigated in the $W1$ structure which is shown in Fig. 9(c). The two transmission drops to be seen around 281 and 299 kHz which is shown in Fig. 10(b). It can be concluded that the whole waveguiding band for bending waveguide covers about 70% of the full bandgap. The properties of the waveguides containing a row of hollow cylinders in a 2D PnC made of filled steel cylinders is investigated[129].

The wave propagation of acoustoelastic in 2D phononic epoxy metaplate is investigated. The coupled-resonator acoustoelastic waveguides (CRAEWs) formed in the perfect PnC metaplate by locally emptying certain cups[9]. Fig. 11(a) shows a straight line of defects with adjacent cavities which is separated by the two lattice constants. the phononic band structure of CRAEWs with the frequency response functions (FRF) are shown in Fig. 11(b-d) (numerical and experimental). It can be seen in the FRF that there are 10 dB differences between the experiments and the numerical simulations. This is due to the excitation sources of the simulations and experiments are not exactly the same. Fig. 11(e) shows the CRAEW supercell and the modal shape for the guided wave at point NL.

The additional guiding bands in the frequency range of 8.09kHz to 8.27kHz are depicted in Fig. 11(b) which are

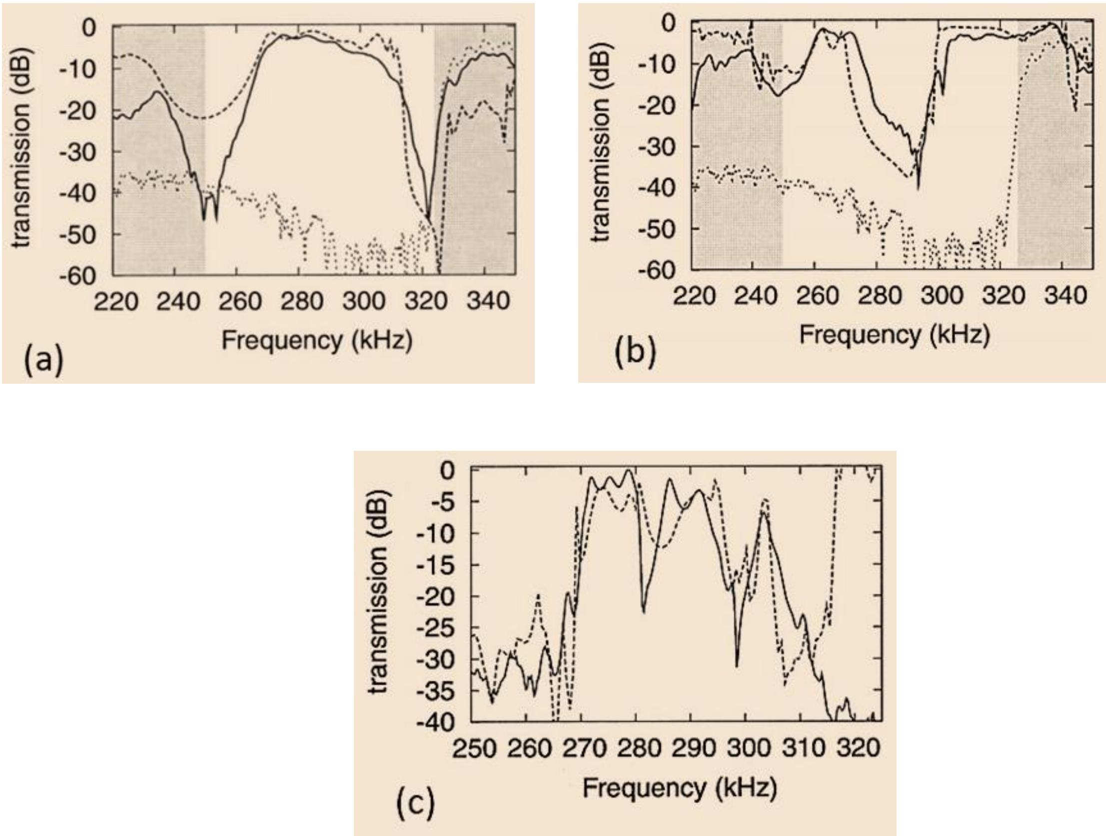

Fig. 10. The transmission of Experimental (solid lines) and calculated (dashed lines). (a) the perfect crystal in the direction for W1, (The gray areas delimit the full bandgap for the perfect crystal), (b) the perfect crystal in the direction for W2, (c) the perfect crystal in the direction for the one-period-wide bent waveguide, Ref[128].

very sensitive to local changes in the resonators. In this case, the coupling strength between the resonators defined the dispersion relationship. The out-of-plane displacement field for the finite sample for numerical (at 8.27kHz) and experiment (at 8.16 kHz) are shown in Fig. 11(f) and Fig. 11(g).

7- FILTERING

7- 1- Acoustic Channel Drop Tunneling Using Point Defect Cavity

The acoustic channel drop tunneling in PnC based on point defect is shown in Fig. 12(a)[130]. The 2D square array of steel rods is embedded in water to form the PnC structure. An appropriate coupling element is coupled between the two waveguides to transfer a specific wavelength. By removing the two rods (point defects) the stubs are formed as well as the two waveguides are composed of line defects.

The transmission of the structure is investigated on different ports which are shown in Fig. 12(b). By applying the input signal to port 1, a significant transmission peak is observed at port 3 at the frequency of 290 kHz. On the other hand, all the input signals in port 2 drops to zero and transfer to port 3, with a weak loss on port 4.

The effect of line defect and subs on the transmission spectrum are also investigated, separately. The waveguide has a wide passband in the range of 270<f<300kHz on which, the full transmission is observed in Fig. 13(a). By creating a point defect at the side of the waveguide, the stub is formed and causes to reject a narrow frequency in Fig. 13(b). It was also found that the single cavity inside the crystal cases to filtering of a narrow frequency band which is shown in Fig. 13(c). It should be noted that the resonances of both defects occur almost at the same frequency _f =290 kHz_, which again is in favor of the coupling geometry shown in Fig. 12.

7- 2- Acoustic Add-drop Filter Using Ring Resonator

It is well known that ring resonators are very useful choices for filtering, reducing energy loss, and exhibiting high-quality factors[131]. The multi-mode nature of the ring resonator offers some advantages like flexibility in

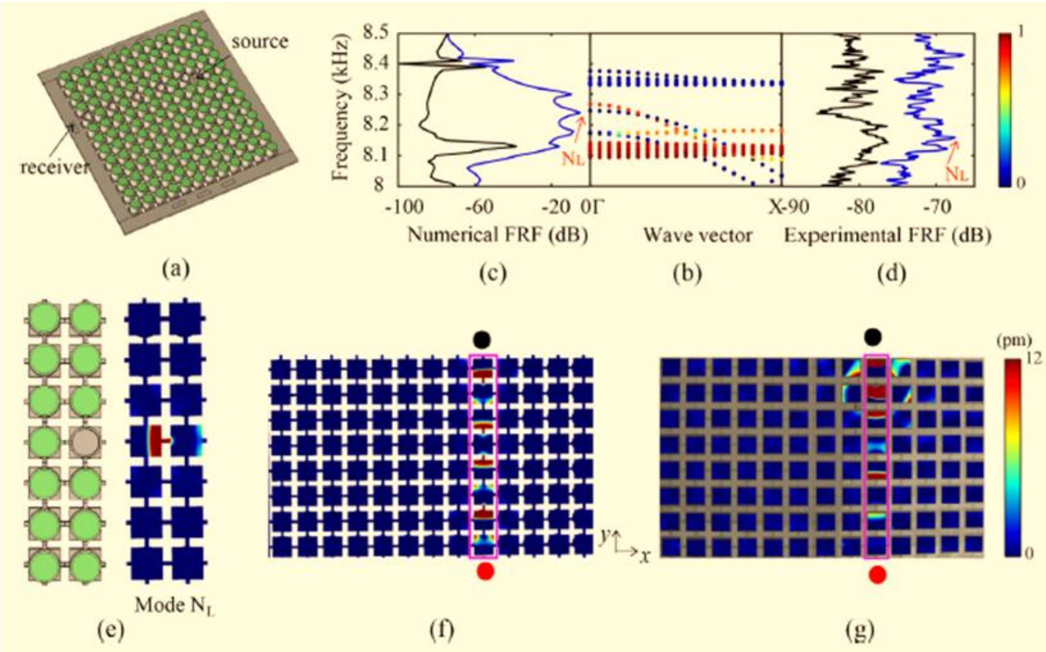

Fig. 11. The wave propagation of acoustoelastic in 2D phononic epoxy metaplate is investigated. (a) schematic of the epoxy metaplate with straight CRAEW formed by locally emptying a line of cups. The green is water and gray parts is epoxy materials. (b) band structure of perfect phononic metaplate with all cups filled with water (solid lines) and the straight CRAEW (dash lines) for a selected frequency range. (c) simulation and (d) experiment for the FRFs of the perfect phononic metaplate with all cups filled with water (black line) and for the straight CRAEW (blue line) (c) The CRAEW supercell and eigenmode NL. (e) the numerical and (f) experimental and (g) out-of-plane displacement distributions are shown at 8.27 kHz and 8.16 kHz, respectively. The pink lines show the propagating circuits[9], Ref. [9].

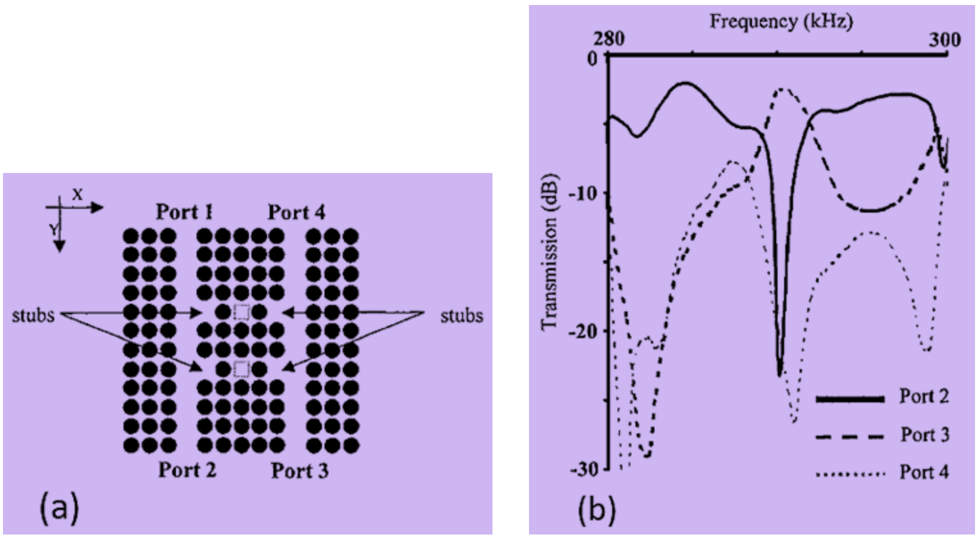

Fig. 12. (a) Schematic of the Filter with the two stubs along the guides, and (b) Transmission for output ports of 2, 3, and 4, Ref. [130].

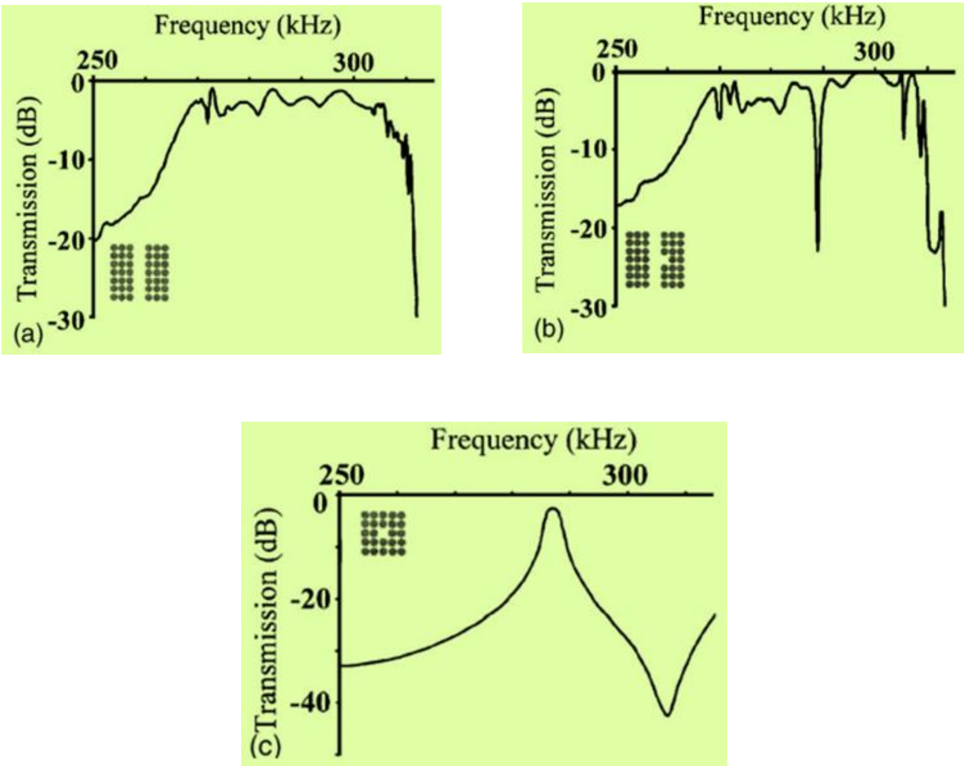

Fig. 13. Transmission for (a) straight waveguide, (b) straight waveguide with the stub located at the side of the guide, and (c) single cavity inside the crystal, Ref. [130].

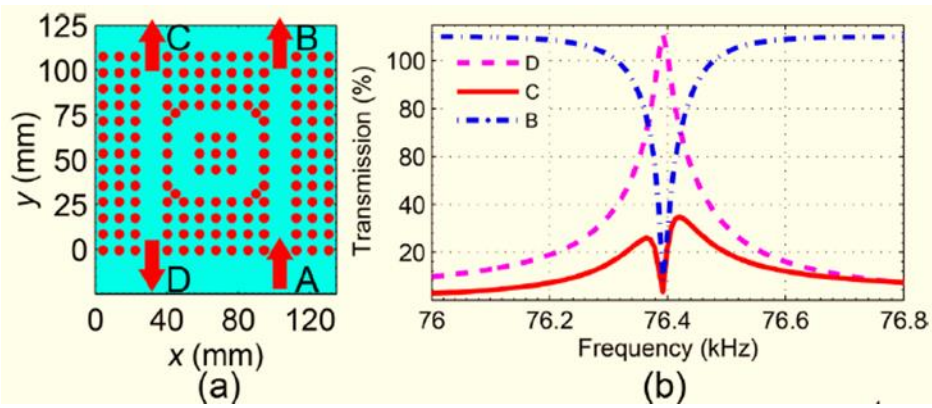

Fig. 14. (a) Schematic and (b) the transmission of the add-drop filter, Ref. [116].

mode design and scalability in size[117, 132]. It also has adaptability in structure design due to the multiple design parameters as compared to the point-defect resonator[130, 133]. These reasons made the ring resonator to be used as a cavity and coupling element. An acoustic ring resonator containing surface modes of a 2D PnC was numerically investigated[134]. Employing spoof surface acoustic waves (SSAWs) as- compact RRs on the surface phononic crystals makes them suitable for designing the 1D[135-137] and 2D[138, 139] corrugations on solid slabs in which around the corrugations, energy is confined in air regions.

The general mechanism is that when the acoustic wave is circulating in a ring resonator, the wave amplitude is amplified due to the resonance phenomenon. Fig. 14(a) shows the structure of the add-drop filter using a ring resonator. In this structure, the water rods are embedded in the mercury matrix to form the PnC platform. Fig. 14(b) shows the transmission spectrum with the quality factor of $Q \approx 1700$. It can be seen

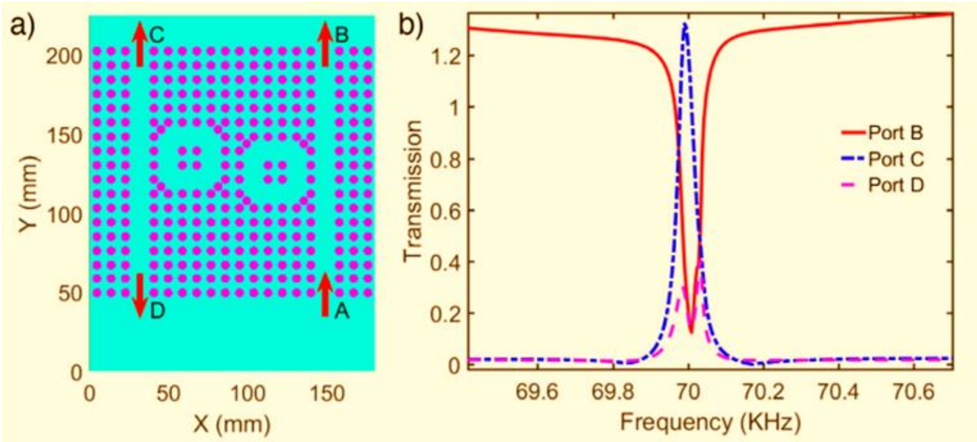

Fig. 15. Schematic (a) and the transmission (b) of double-ring resonators channel drop filter (DRR-CDF), Ref. [140].

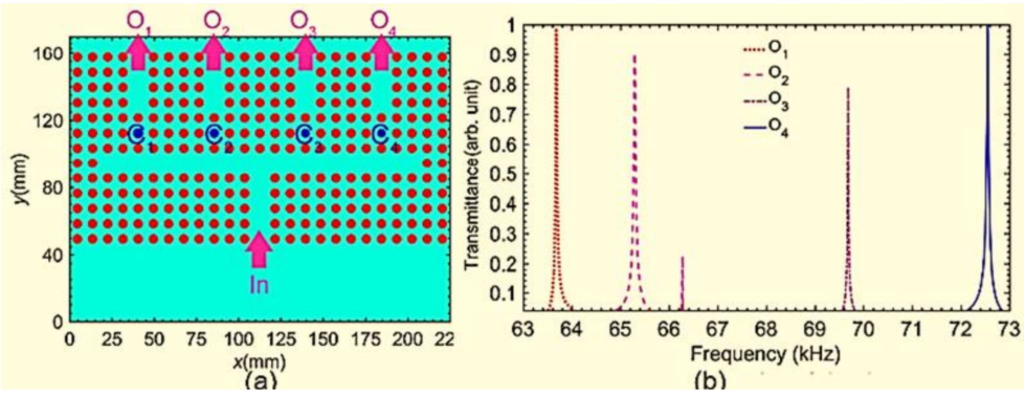

Fig. 16. Schematic (a) and the transmission (b) of the four-channel acoustic demultiplexer, Ref. [141].

that the four scatterer rods are added to the four corners of the structure. The presence of these four scatterer rods results in the so-called blue shift in the frequency. This is due to it can suppress the nonresonant modes, and the wave rotation path inside the ring becomes smoother. It can also be observed that adding the mentioned rods causes to appear a dip in port C, which is centered around $f0$=76.39kHZ. It means that the leakage in port C has been minimized[116].

In order to improve the performance in the design of the filter, some methods can be applied. The structure of the double-ring resonator channel drop filter (DRR-CDF) based on the phononic crystal is shown in Fig. 15(a). In this structure, the location of the left ring resonator is shifted upwards as much as a row of rods. Fig. 15(b) shows the transmission spectrum with the quality factor of Q≈2000. It can be observed that the capability of ultrafine tuning of the output resonant frequency, as well as fine-tuning the output port, was done by changing the location of each ring. All details about the mentioned method are given in Ref[140].

8- DEMULTIPLEXING

8- 1- Tunable Four-channel Acoustic Demultiplexer Using Point Defect Cavity

It is well known that the addition of point defects to the perfect PnCs gives them unique abilities for the design of many PnC-based acoustic devices like waveguides and cavities to enable novel functionalities in a compact structure. In the point defect cavity, the eigenmodes can be used to induce either narrow passing bands in the stopband or narrow stopping bands within the passband[116, 129, 132]. The structure of the demultiplexer with point defect cavity and its transmission spectrum is shown in Fig. 16(a) and (b). This structure contains four cylindrical cavities filled with methyl nonafluorobutyl ether (MNE) that each cylinder has a different radius. The difference in dimension of the four arms makes it possible to have demultiplexing functionality[141]. The demultiplexer structure includes four different cavities are also investigated[142].

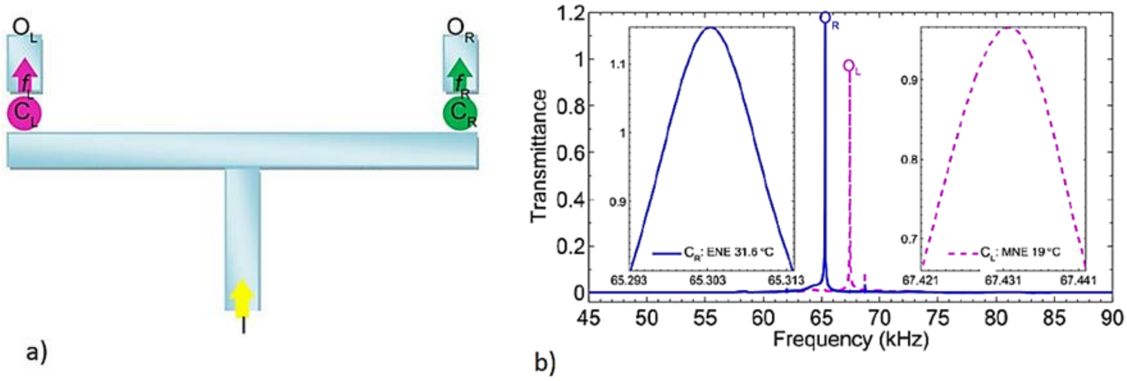

Fig. 17. Schematic (a) and (b) the transmission of the acoustic demultiplexer. The temperature for MNE and ENE are set at 19℃ and 31.6℃, respectively. CL and CR are the point defect cavities and fL and fR are resonant frequencies for left and right, respectively, Ref. [132].

8- 2- Acoustic Switchable Demultiplexer

Fig. 17(a) shows the structure in which the two arms are coupled to two output ports by two dissimilar point defect cavities (*CL, CR*) and two different resonant frequencies (*fL, fR*), filled with methyl nonafluorobutyl ether (MNE) and ethyl nonafluorobutyl ether (ENE). The difference in acoustic properties of these two materials causes the cavities' resonant modes to be different, required for the demultiplexing functionality. It should be pointed out that choosing two different temperatures for the two cavities makes the structure act as an acoustic switch too. Fig. 17(b) shows the effect of the temperature dependence of point defects on the resonant frequencies of the cavity, in which the transmission peaks are switched. When the temperature changes, the speed of sound and mass density will change. As a result, the output frequency will change. Switch-ability is expressed as the temperatures at which the center frequency of MNE (*CL*) switches with that of ENE (*CR*), and vice versa. It means that by setting the specific temperature for MNE and ENE (*CL*=19℃, *CR*=31.6℃), the frequencies of output channels can switch to the new conditions[132] The switchable demultiplexer which have improved dual separating and switching performances are investigated[142].

8- 3- Acoustic 1×2 Demultiplexer Using Ring Resonator

Taking advantage of the basic idea of using the ring resonator which is mentioned earlier, an acoustic demultiplexer is designed. The scheme and the transmission spectrum of 2×1 demultiplexer, having two output channels, are shown in Fig. 18(a) and (b). In this structure, the acoustic wave rotates inside the ring resonator, and the amplitude of the wave can be amplified by the resonance phenomenon. By changing the physical and geometrical properties of inclusions, the effective path length of the acoustic wave is varied. The quality factors (Q) of the structure are $Q1$=3997 and $Q2$=8145 which are centered around 63.960kHz and 73.312kHz[117]. The heterostructure demultiplexer based on solid-solid PnC ring resonators in the range of GHz is investigated. In this structure, they achieved a very high average quality factor of 4570 among the output channels[118].

9- CONCLUSIONS

To conclude, PnCs are one of the most critical platforms of future acoustic integrated circuits containing waveguides and cavities. Recent devices are more promising for controlling and manipulating acoustic waves. In this regard, different types of PnCs, e.g., solid-solid, solid-liquid, and liquid-liquid in comparison to the PC were investigated. It is proved that by changing the structure of the cavity through point defects and line defects, specific frequencies can be selected and passed or rejected. The effect of changing the width of the waveguide causes two distinct waveguiding bands which are located inside the stopband. The multi-mode nature of the ring resonator makes it has scalability in size, adaptability in structure design and flexibility in mode design in comparison to the point-defect resonator which are the reasons for using them as a cavity and coupling element. In these studies, the lattice constant of the structures is a = 9mm and the filling fraction of ff = 0.3 and the interested range of frequency falls within 43 KHz to 119 kHz which is suitable for practical guiding applications. The Interchannel crosstalks for the demultiplexer are less than 32 dB and also the quality factors for each port of this system are Q1 = 3997 and Q2 = 8145. On the other hand, the quality factor for the filter is Q = 2000. The main object of this study was to present the basic results of the fabrication process, defects, and band gaps in phononic crystals, as well as the related equations in FDTD method. Besides the guiding, filtering, and demultiplexing properties and their functionalities in acoustic devices have been widely studied. With such a platform, it is possible to have tunable

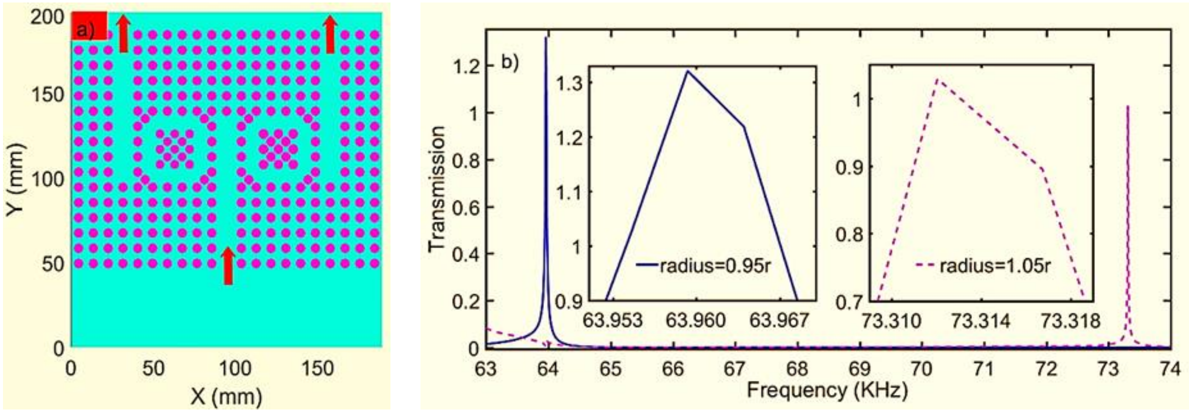

Fig. 18. Schematic (a) and (b) the transmission of acoustic demultiplexer using two different ring resonators. The left radius is 0.95r and the right radius is 1.05r, Ref. [117].

acoustic devices based on PnCs.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Author Contribution

Amir Rostami (AR)
Babak Rostami-dogolsara (BR)
Hassan Kaatuzian (HK)

AR and BR conceived of the presented idea. They are also involved in planning the work.

AR wrote the manuscript with support from HK and BR. HK encouraged the team to investigate and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

Abbreviation List

CRAEW	Coupled-Resonator Acoustoelastic Waveguides
DRR-CDF	Double-Ring Resonators Channel Drop Filter
ENE	Ethyl Nonafluorobutyl Ether
FRF	Frequency Response Functions
FDTD	Finite Difference Time Domain
GRIN PC	Gradient-index Phononic Crystal
MNE	Methyl Nonafluorobutyl Ether
MEMS	Micro-Electromechanical System
NEMS	Nano-Electromechanical System
PnC/PC	Phononic crystal
PtC	Photonic crystal
PnBG	Phononic Band Gag
SOI	Silicon on Insulator
SSAW	Spoof Surface Acoustic Wave
ZnO	Zinc oxide

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