Waveguiding Effect in the Gigahertz Frequency Range in Pillar-based Phononic-Crystal Slabs

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Experimental Evidence of Waveguiding Effect in the GHz Frequency Range in Pillar-based Phononic Crystal Slabs

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Waveguiding effect for a phononic crystal (PnC)-based device operating in the GHz frequency regime is experimentally demonstrated. To that end, a metallic pillar-based PnC membrane with a PnC bandgap (PnBG) in the GHz frequency range is designed, and based on that, an acoustic waveguide operating in the GHz regime is designed and fabricated. To characterize the fabricated PnC waveguide, a new set of focusing interdigital transducers (IDTs) is designed and fabricated, enabling efficient excitation and detection of acoustic signals inside the PnC waveguide. The finite element method (FEM) is used to study the acoustic properties of the proposed structures and optimize their design. Experimental evidence supporting the existence of waveguiding effect in the proposed structure in the GHz frequency regime is provided, showing reasonable agreement with the numerical calculations.

I. INTRODUCTION

Pillar-based phononic crystal (PnC) membranes are two-dimensional (2D) periodic structures composed of metallic or non-metallic pillars placed on the surface of a single- or multi-layer membrane (e.g., see Fig. 1). The acoustic properties of these structures, including phononic bandgaps (PnBGs, which enable three-dimensional acoustic confinement in membranes) and their local-resonance properties as well as their potential to exhibit Bragg PnBGs have been the subject of extensive theoretical and experimental studies in the last two decades.[1–5] Such properties make pillar-based PnC structures a potential alternative platform for ultra-high frequency (UHF) signal processing, given the promising results demonstrated with hole-based PnC membrane devices for MHz signal processing applications.[6, 7] Frequency-manipulating devices are the building blocks of such a platform, and utilizing PnBGs designed at the desired frequency can facilitate the development of more sophisticated signal processing modules such as frequency multiplexers/demultiplexers,[8] delay lines, and filters.

Designing PnCs with UHF PnBGs are only the first step in developing a complete PnC-based signal processing platform in this frequency regime. The next logical step is to develop the frequency-selective building blocks such as PnC resonators [7, 9, 10] along with the devices that can guide the acoustic waves inside a phononic line defect (i.e., a PnC waveguide [11–14]). These building blocks can be combined by coupling the acoustic waves between PnC waveguides,[15] PnC resonators,[16] or a combination of the two [8] to form all-phononic signal processing systems.

Scaling PnC devices to operate in the UHF regime requires shrinking geometrical dimensions. This frequency scaling through geometry scaling may seem rather trivial; however, experimental demonstration of PnC waveguides and resonators in such UHF regime is still a challenge. Additionally, efficient coupling of the acoustic energy generated by an acoustic transducer to the PnC waveguides in the system poses a design challenge at high frequencies. Several theoretical studies have shown that using a specialized PnC-based structure known as the gradient index (GRIN) waveguide can improve the coupling efficiency of a plane-wave source to a PnC-based waveguide.[17–19] However, an effective GRIN waveguide relies on having a weakly anisotropic acoustic mode (i.e., acoustic modes with almost circular equal frequency contours).[19] This condition limits the feasibility of GRIN waveguides to certain polarizations within certain frequency ranges.

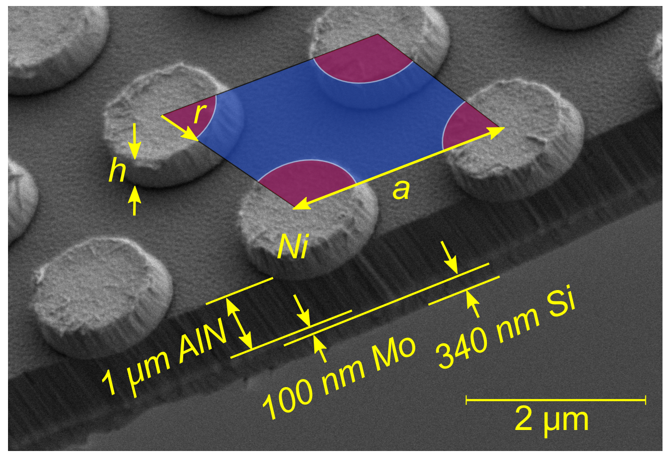

FIG. 1. Scanning electron microscope (SEM) image of a pillar-based PnC with triangular lattice composed of Ni pillars on a three-layer membrane of AlN, Mo, and Si. The area outlined by the parallelogram illustrates a primitive unit cell of this lattice.

In this paper, we present a systematic method to address both challenges, i.e., 1) to design and demonstrate a PnC waveguide operating in the GHz frequency range, and 2) to design and demonstrate a piezoelectric transducer for efficient coupling of acoustic energy into a PnC

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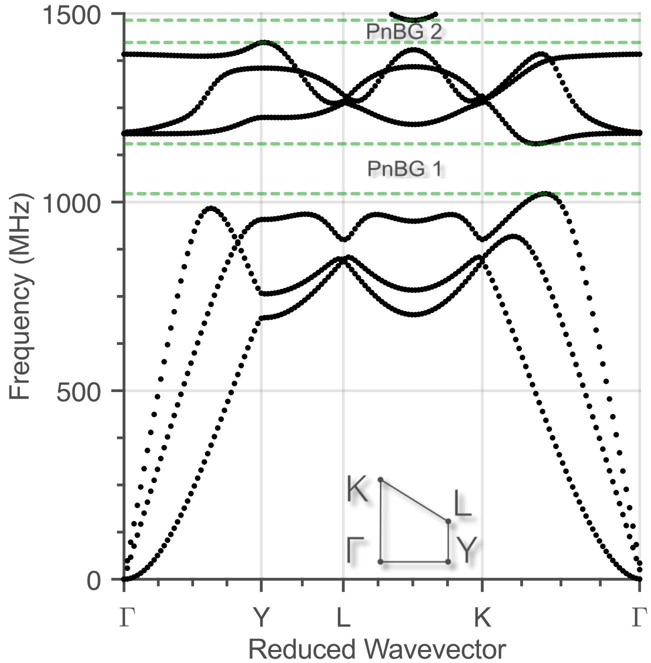

FIG. 2. Phononic band structure of the triangular pillar-based PnC membrane of Fig. 1 along the edges of the irreducible Brillouin zone of the PnC structure, as shown in the inset. The extents of the complete PnBGs are shown by the dashed lines. The radius and height of the Ni pillars are 750 nm and 400 nm, respectively. The thicknesses of AlN, Mo, and Si layers are 1 μm, 100 nm, and 340 nm, respectively. The lattice constant, a, is 2.5 μm.

waveguide at high frequencies. In Sec. II, we discuss our approach to design and fabricate a metallic pillar-based PnC membrane operating in the GHz frequency range. In Sec. III, we outline the design of the acoustic waveguide based on the developed GHz PnC. In Sec. IV, we explain the design of a new focusing IDT to enable the efficient coupling of the acoustic energy into the aperture of a PnC waveguide.[20–23] Our fabrication details and experimental results are presented in Sec. IV. The final conclusions are made in Sec. V.

II. DESIGN OF A PILLAR-BASED PNC WITH GHZ PHONONIC BANDGAP

The starting point for the design of a PnC-based waveguide is choosing an optimal PnC structure that supports a PnBG in the desired frequency range. Given our target frequency range (i.e., beyond 1 GHz), our focus will be in optimizing a PnC structure that supports widest PnBGs formed by the Bragg effect. Our previous study on the physics of the bandgap formation in pillar-based PnC membranes[4, 5] suggests that using shorter pillars or pillars with reduced diameter leads to PnBGs at higher frequencies, but at the same time, it results in a narrower PnBG and eventually closing of the bandgap. Another geometrical parameter that can have substantial effect on the center frequency of the PnBG is the lattice constant (a, specified in Fig. 1). As a single integrated phononic chip might house multiple PnC structures with different center frequencies, all of which have to share a common membrane, it is preferable to push the boundaries of what is possible by only optimizing the pillars—both their dimensions and material properties—along with a conservative change to the lattice constant without altering the membrane structure.

To design a PnC with the aforementioned properties and geometrical constraints, we use nickel (Ni) instead of gold (Au) as the metal of choice for the pillars. Ni is both lighter and stiffer (i.e., it has lower density and higher Young's modulus) and has lower acoustic material loss compared to Au,[24] pushing the center frequency of the PnBGs higher. Using Ni as the material of choice for the pillars, an exhaustive search was conducted over the height and radius of the pillars in the unit cell as well as allowing up to ±30% change in the lattice constant. This search resulted in an optimum PnC design shown in Fig. 1. As seen in this figure, the PnC of choice has a triangular lattice structure with Ni pillars on a three-layer membrane of aluminum nitride (AlN, 1 μm thick), molybdenum (Mo, 100 nm thick), and silicon (Si, 340 nm thick) from top to bottom.[5] The radius and height of all pillars are 750 nm and 400 nm, respectively, and the lattice constant is $a = 2.5$ μm.

The dispersion diagram of the designed PnC, calculated by the finite element method (FEM) implemented in the COMSOL software package, is shown in Fig. 2, depicting the boundaries of a PnBG in the 1030 MHz–1155 MHz frequency range (i.e., gap-to-midgap ratio of 11.4%) along with a second narrower PnBG around 1450 MHz. The irreducible Brillouin zone of the structure (see inset in Fig. 2) is derived by considering both the PnC lattice symmetry and the anisotropy of the Si layer in the membrane. As such, Γ–Y, Γ–L, and Γ–K directions are not equivalent; hence, the irreducible Brillouin zone boundary of Γ–Y–L–K is used. It should be noted that based on our previous work on the physics of PnBG formation in pillar-based membrane PnCs,[4] neither of these PnBGs are dominantly caused by the pillars local resonance effect. Because of the small height of pillars as compared to the PnC lattice constant ($h/a = 0.16$), the pillars local resonance occur at frequencies much higher than the PnBG frequencies caused predominantly by the Bragg scattering in the PnC, and changing the pillars height does not drastically affect the position of the PnBG. For the purpose of this work, we will focus on utilizing the first PnBG due to its wider extent to form waveguides and resonators.

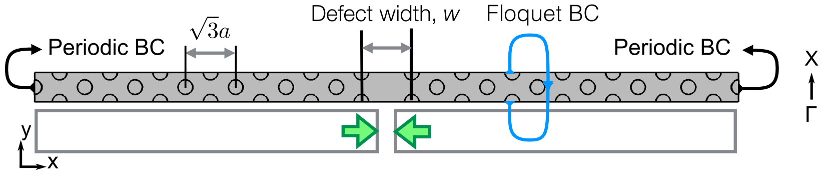

FIG. 3. Unit cell of a PnC waveguide based on pillar-based PnC composed of pillars arranged in a triangular lattice. The boundary conditions (BCs) and the separation distance between the two PnC parts (or the defect width) are overlayed on the schematic of the structure for a PnC waveguide formed by removing one column of pillars from a perfect PnC ($w = \sqrt{3}a$, with a being the lattice constant). The propagation direction of the confined guided wave is along the Γ–X direction (in the k domain) or the y-direction (in the real domain), as both illustrated in the figure.

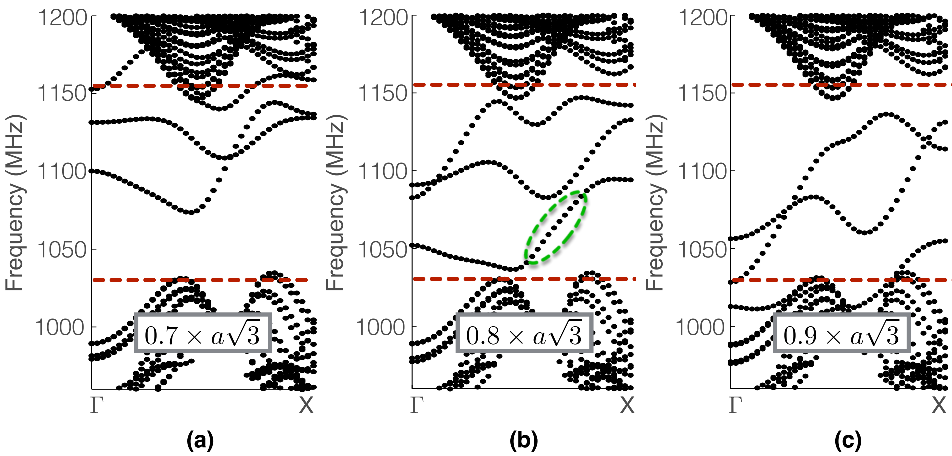

FIG. 4. Dispersion diagram of the PnC waveguide in Fig. 3 for the defect width of (a) 0.7, (b) 0.8, and (c) 0.9 times $\sqrt{3}a$. Dashed horizontal lines show the boundaries of the PnBG in the original PnC. The structure and the geometric dimensions of the underlying PnC are the same as those in Fig. 1.

III. STRUCTURE AND DISPERSION DIAGRAM OF PNC-BASED WAVEGUIDES

To construct a waveguide from the PnC introduced in Sec. II, one may form a line defect by removing one column of pillars in the Γ–K direction from the perfect PnC lattice (see, Fig. 3). This type of defect in the PnC lattice usually leads to guided or stationary modes confined inside the region without pillars, known as the *defect region*. The width of this region (defect width, w, in Fig. 3) is a design parameter that can be changed to engineer the number and dispersion of the guided modes. To effectively simulate a PnC waveguide, we define a waveguide unit cell and apply Floquet boundary conditions (BCs) to two sides and fixed BCs to the other two sides (as shown in Fig. 3) to model the periodicity and propagating nature of the elastic waves inside the defect region. It is important to note that in this arrangement, the propagation direction of the guided modes will be along the y axis, as shown in Fig. 3. As such, we will define the high-symmetry point Γ of this structure as corresponding to Floquet BC phase of zero rad and the high-symmetry point X, to Floquet BC phase of π rad.

To calculate the dispersion diagram of this structure (for waves propagating in the y direction in Fig. 3), we sweep the Floquet BC phase from 0 rad (i.e., high-symmetry point Γ) to π rad (high-symmetry point X) with a step size of $\pi/40$ rad, and the eigenmodes of the structure are computed at each value of Floquet phase using FEM. To accurately tune the frequency of these confined modes, the waveguide defect width (w in Fig. 3) can be changed and the resulting dispersion diagram examined. The simulated dispersion diagrams for three PnC waveguides with different defect widths are shown in Figs. 4(a), 4(b), and 4(c). In each dispersion diagram, the modes inside the PnBG (i.e., 1030 MHz–1155 MHz) correspond to the guided acoustic modes of the PnC waveguide.

The importance of the defect width (i.e., w in Fig. 3) in engineering the number of guided modes and their dispersion is clear from Fig. 4. For a practical PnC waveguide, single-mode operation is highly desired. In addition, the polarization of the selected guided mode must be such that their excitation by an interdigital transducer (IDT) is possible. Comparing the three PnC waveguides analyzed in Fig. 4, it is clear that the structure with $w = 0.8 \times a\sqrt{3}$ [see Fig. 4(b)] provides single-mode operation in the largest bandwidth (i.e., 1060 MHz –1080 MHz). One important fact to consider in designing PnC waveguides is that the polarization as well as the in-plane symmetry of the guided modes gradually change as we sweep the wavenumber (k_y or equivalently the Floquet BC phase) from Γ to X. Specifically, the slanted oval in Fig. 4(b) shows a portion of the dispersion diagram of a guided mode with AS-type polarization while being symmetric in-plane. The displacement profile of this mode associated with a Floquet BC phase of 0.6756π rad in the Γ–X direction (corresponding to frequency $f = 1067$ MHz) in Fig. 4(b), is shown in Fig. 5. The out-of-plane displacement of this mode and its lateral in-plane symmetry make the excitation and detection of the mode by IDTs straightforward. Another unique property of this eigenmode is that, in a reasonable range of frequencies (from 1060 MHz to 1090 MHz), it is the only guided mode of the structure. It should be noted that the other modes (other than those inside the slanted oval region) are either of shear-horizontal (SH) type or they are in-plane antisymmetric.[5] Unable to be excited by the surrounding IDTs, these waveguide modes fall in the deaf band of the device.[25–27] Based on theses properties, we choose the PnC waveguide with $w = 0.8 \times \sqrt{3}a$ [the structure corresponding to Fig. 4(b)] as the optimal structure to experimentally demonstrate the waveguiding effect.

IV. DESIGN OF FOCUSING IDTS FOR COUPLING ELASTIC WAVES TO PNC WAVEGUIDES

Figure 6(a) shows the structure for experimentally studying a PnC waveguide. A key requirement in this structure is the ability to focus the elastic energy into a small opening corresponding to the guiding region of the PnC waveguide. A similar device needs to be designed with PnC waveguide replaced by a defect-free PnC [see Fig. 6(b)] to compare the transmission of the elastic wave with the designed polarization and the desired frequency with that of the PnC waveguide. This focusing requirement makes the design of IDTs more complex. In contrast to flat-aperture IDTs that are conventionally used to excite plane waves, focusing IDTs are usually formed by curved electrodes as seen in Fig. 6(a). Similar focusing

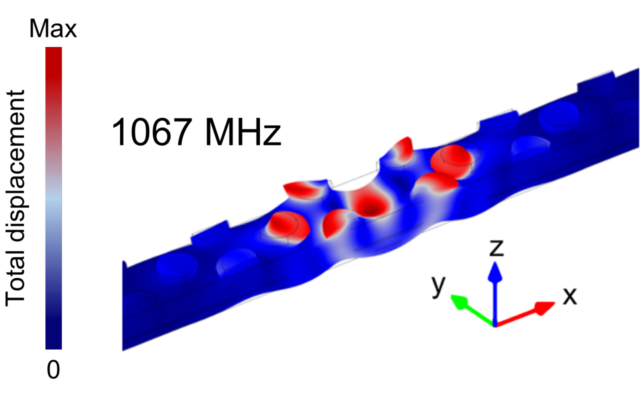

FIG. 5. Displacement profile of the guided mode, with AS polarization, of the membrane PnC waveguide, the dispersion diagram of which is shown in Fig. 4(b). The defect width is $w = 0.8 \times a\sqrt{3}$. The phase difference associated with Floquet boundary condition is 0.6756π rad in the Γ–X direction.

IDTs are also needed at the output of the structure to efficiently collect the elastic waves out of a PnC waveguide [see Fig. 6(a)].

Several methods can be envisioned for designing a focusing IDT, including, but not limited to, calculating the phase velocity of the desired elastic wave (with the desired polarization) at the desired operating frequency and calculating the corresponding phase-front (i.e., equiphase contours) for a point source (emanating elastic waves from the focal point of the focusing IDT). By matching the location of the IDT electrodes (or fingers) to these equi-phase contours, we can design a focusing IDT that meets the design criteria. However, this approach has certain limitations. First, the assumption of a pure polarization emanating from the focal point of the IDT is not correct for most PnC waveguide modes of interest as these guided modes have (in most cases) a hybrid of different polarizations. Second, this design process uses approximation of the ray tracing models from a point source in the far field, but they neglect the near field effects of the point source. Therefore, it limits our ability to design a focusing IDT close to its focal point to make the designed devices more compact.

To address the aforementioned limitations, we have developed a systematic design method for focusing IDTs that relies on calculating the equi-phase contours of the elastic wave generated by the mode of a truncated waveguide with its actual polarization—instead of a single-polarization point source—using the FEM simulations. In addition to enabling near-field displacement profile calculations, this approach account for the hybrid nature of the waveguide mode polarization as it enters the half-space (i.e., the membrane region outside the waveguide boundaries).

The phase-front calculation for the design of focusing IDTs involves two separate FEM simulations. The first step is the eigenmode analysis of the PnC waveguide structure with the desired phase for the Floquet boundary condition followed by exporting the displacement profile of the cross-section of the waveguide. This displacement profile is used in the second simulation as the displacement boundary condition for the half-space, in which a half-circular domain with the perfectly-matched layer (PML) at the outer radius is modeled.

In the rest of this section, we use the waveguide mode shown in Fig. 5 [for the PnC waveguide in Fig. 4(b)] as the basis of our focusing IDT design. As such, we expect the designed IDTs to attain their maximum frequency response around the frequency of the target waveguide mode at 1067 MHz. Figure 7 shows how the displacement profile from eigenmode analysis of the waveguide unit cell is mapped onto the boundary of the half-space. It should be noted that the displacement values extracted from the eigenmode analysis of the waveguide unit cell are treated as phasors; hence, the boundary condition for the displacement phasor is formulated accordingly.

After the boundary condition is applied, the second simulation, which is a frequency domain analysis, is per-

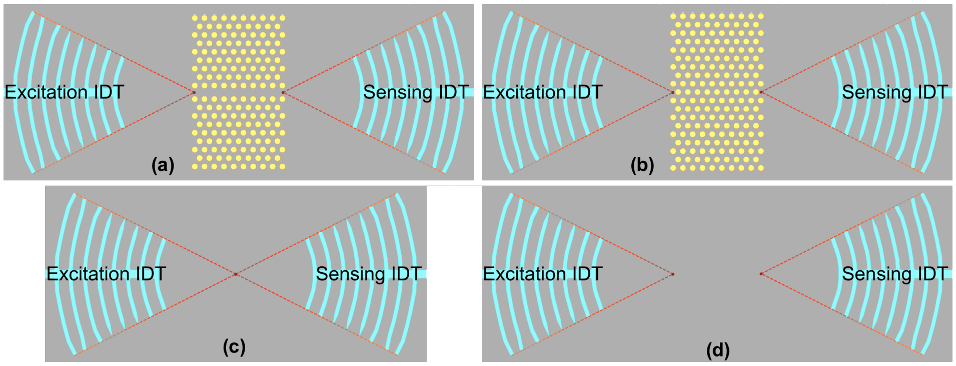

FIG. 6. Arrangement of the excitation and sensing focusing IDTs with (a) the PnC waveguide and (b) the PnC in between. Arrangement of (c) the near and (d) the far focusing IDTs in the fabricated devices. The intersection of the dashed lines in all figures show the focal point of the corresponding focusing IDTs.

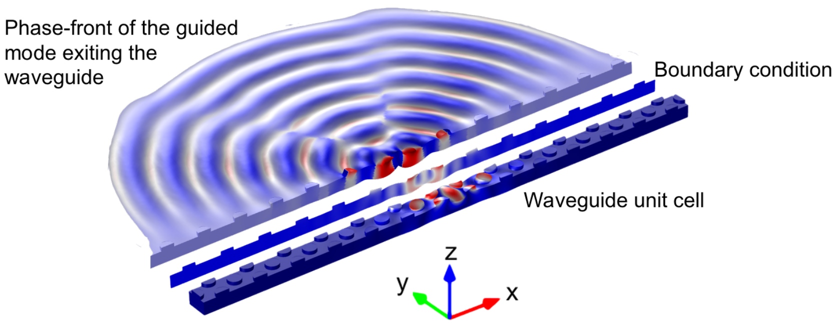

FIG. 7. Displacement profile of the guided mode at the exit of the PnC waveguide. The displacement profile of the eigenmode of the PnC waveguide unit cell is extracted and applied to the boundary of the half-space as its driving boundary condition. The outer shell of the half-space (seen as the half-circular domain) is surrounded by PML (see Fig. 8).

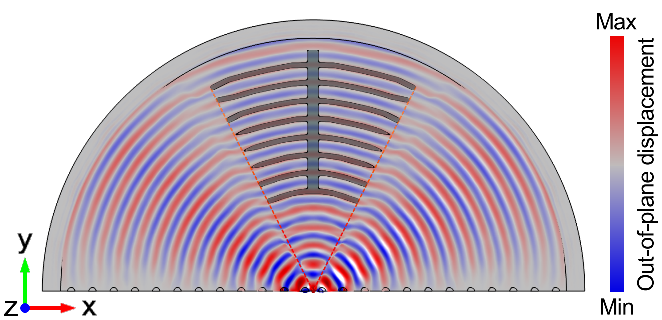

FIG. 8. Equi-phase fronts of the guided mode of the PnC waveguide after exiting the waveguide. The driving boundary condition is applied to the bottom of the structure. The outer shell of the half-circle is surrounded by PML. The layout of the derived focusing IDT is overlaid on the displacement profile and its azimuthal extent is shown by the red dashed line.

formed to calculate the steady state response for the half-space when exposed to the exiting PnC waveguide mode profile at the desired frequency. Note that this simulation is a single-frequency simulation at the same frequency as that of the eigenmode from which the boundary condition is extracted. The peaks and valleys of the diffracted wave in the half-space as calculated by the frequency response simulations are shown in Fig. 8.

Post-simulation processing of the displacement profile in Fig. 8 reveals the exact location of the peak contours and their distance. The peak contours are used to design the positions and the shapes of the IDT electrodes. As we will use a Mo ground layer at the bottom of the AlN layer, the location of the valley contours are not needed. The distance of these contours is used to design the width of the electrodes of the IDTs. As seen in Fig. 8, the phase-front in the half-space has a distinct diffraction pattern resulting in slight aberrations in the peak contours of the displacement profile. To simplify the fabrication process and ensure the connectivity of the IDT electrodes, we decided to use only the middle part of the phase-front for designing focusing IDTs, leading to the overlaid pattern of the IDT shown in Fig. 8.

To investigate the properties of the focusing IDTs, we also design and fabricate two pairs of focusing IDTs. The first pair is the same as those shown in Fig. 6(a) with the PnC waveguide removed from the middle, while the second pair is similar to arrangement of the first pair with their distance changed such that the focal points of the excitation and sensing IDTs coincide [see Figs. 6(c) and 6(d)]. We will refer to the former as the "far IDTs" and the later as the "near IDTs," as shown in Figs. 6(c) and 6(d), respectively. Comparing the measured transmission (S_{21}) of these two sets of IDTs helps us understand the effectiveness of the focusing phenomenon augmented by the design of the IDTs. We expect to observe a much larger S_{21} for near IDTs compared to that of far IDTs. Additionally, we expect that putting a waveguide between the far IDTs (as shown in Fig. 6(a)) will result in

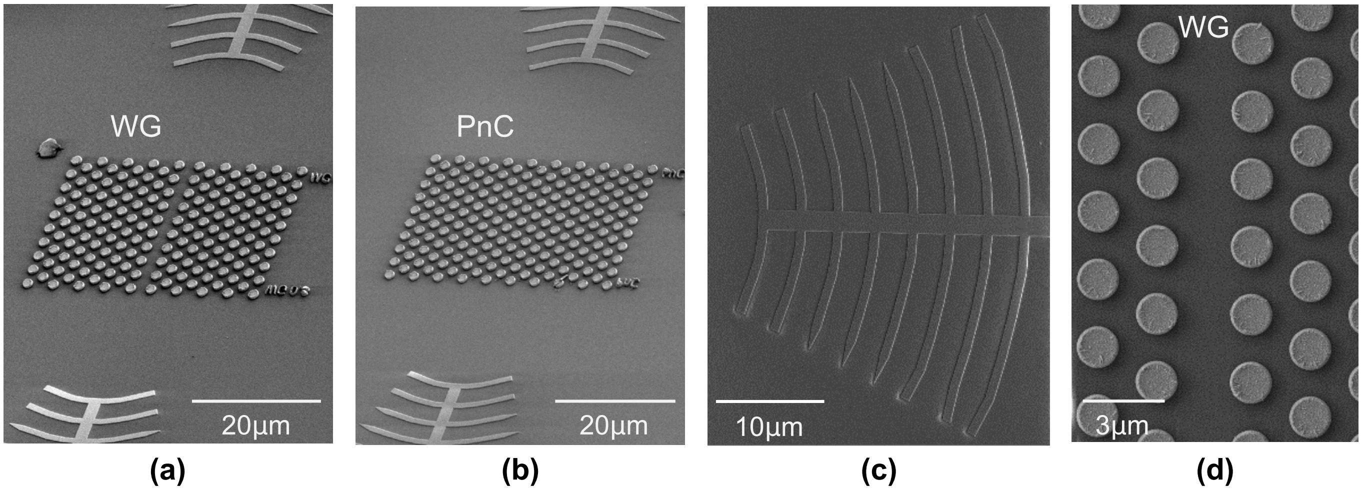

FIG. 9. SEM images of (a) the PnC waveguide structure and (b) PnC with input and output focusing IDTs on the sides. SEM image of the fabricated focusing IDT. (d) SEM image of the guiding region of the fabricated waveguide structure. The geometrical properties of the PnC structure is the same as those in Fig. 1.

improved S_{21} measurement as the waveguide starts from one focal point and ends at the other.

V. FABRICATION AND CHARACTERIZATION OF THE PNC-BASED WAVEGUIDES

A. Fabrication Process

To fabricate the PnC waveguide device and the corresponding reference device [see Figs. 6(a) and 6(b)] along with the input, output, and the PnC structure, we start with a Si-on-insulator (SOI) wafer with layers of Mo (100 nm thick) and AlN (1 μm thick) deposited on top by Tegal Corporation (Fig. 1). Using photolithography with a silicon dioxide (SiO_2) hard mask, wide openings in the AlN is etched to enable the electrical contact, with the bottom Mo layer acting as the ground layer. The top electrodes are patterned by electron-beam lithography (EBL) using PMMA as the electron-beam resist, followed by the electron-beam evaporation of the chromium (Cr, 5 nm thick), as the adhesion layer, and aluminium (Al, 80 nm thick) and the lift-off process. Deposition of Ni pillars was conducted in a similar way to that of Al electrodes (i.e., using EBL, Cr/Ni deposition, and lift-off). It should be noted that the evaporation schedule of Ni was optimized to avoid damaging the underlying PMMA resist. Releasing the PnC membrane using the backside alignment photolithography, Bosch process, and etching the buried oxide layer is performed similar to the steps outlined in our previous work.[5] These fabrication processes were developed and optimized at the cleanroom facilities at the Georgia Tech's Institute for Electronics and Nanotechnology (IEN). Figures 9(a) and 9(b) show the SEM images of the fabricated waveguide structure and PnC with their corresponding input and output focusing IDTs, respectively. Close-up SEM images of the fabricated focusing IDT and the PnC waveguide are shown in Figs. 9(c) and 9(d), respectively.

B. Characterization Results

We measure the S_{21} scattering parameter of the fabricated devices using an HP 8753D network analyzer. In all of our measurements, we use an averaging factor of at least 500 to reduce the noise, enabling the characterization of very low signal levels (down to -120 dB). With regards to electrical port definitions of the IDTs, it is important to note that the electrodes on the structure, as shown in Fig. 6, are connected to the signal port of the network analyzer, while the underlying Mo layer is connected to the ground port.

To benchmark the waveguiding effect, we compare the measured S_{21} parameter of the device in Fig. 9(a) with that of a reference device in Fig. 9(b), both consisting of 9 lattice periods along the direction of wave propagation. The reference device is similar to the waveguide with the waveguide structure replaced with the same number of layers of the corresponding PnC structure. We expect the waveguide to show higher transmission around the frequency of the guided mode and demonstrate similar transmission values to that of the defect-free PnC at frequencies farther from the guiding region. As discussed earlier, the guided modes of interest are the eigenmodes surrounded by the slanted oval in Fig. 4(b).

Figure 10(a) shows the measured S_{21} parameter for the near and far IDTs (as defined in Sec. IV) in the 1000 MHz–1150 MHz frequency range with the operating frequency of the focusing IDTs tuned to a specific eigenmode of the waveguide at 1067 MHz. As expected, the near IDT attains its maximum transmission in the

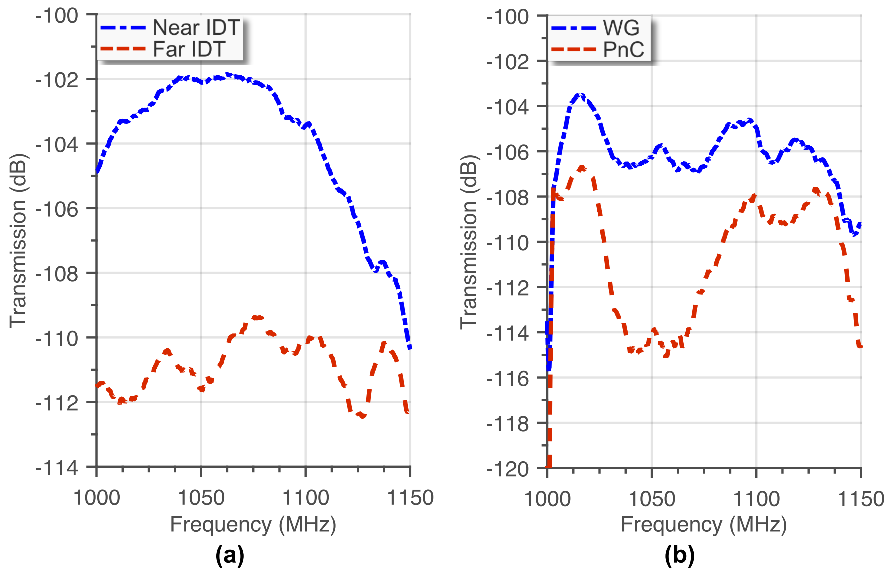

FIG. 10. Measured transmission (S_{21} parameter) of (a) the near and far focusing IDTs, whose design are shown in Fig. 6, and (b) the far IDTs with the PnC waveguide and the PnC in between [Figs. 6(a) and 6(b), respectively].

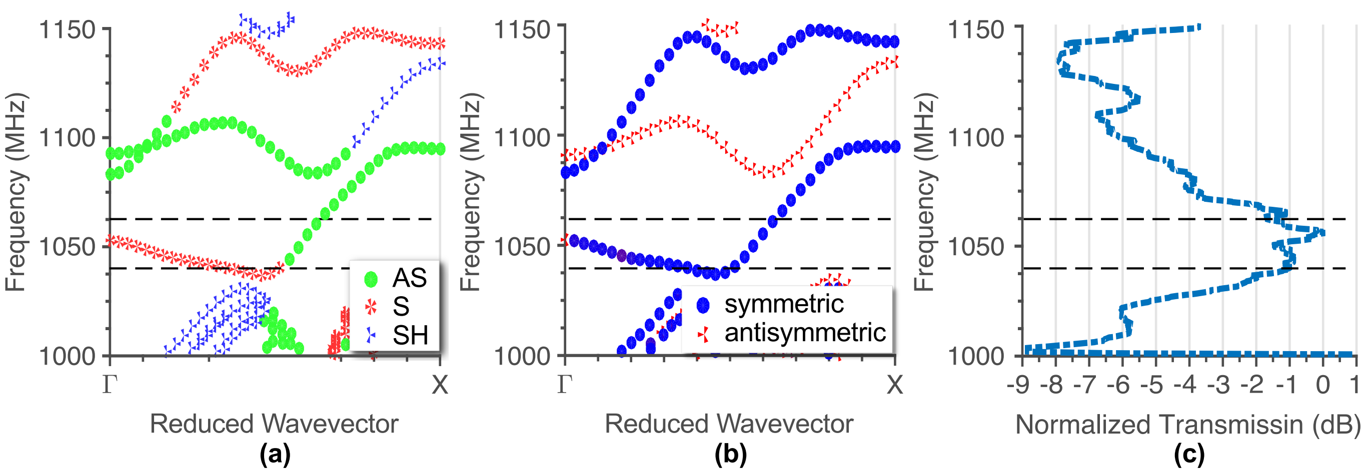

FIG. 11. Comparison of the dispersion diagram of (a) the types of the PnC waveguide modes (i.e., antisymmetric Lamb (AS), symmetric Lamb (S), and shear horizontal (SH) waves) and (b) their symmetry/antisymmetry along the in-plane perpendicular axis. (c) Measured normalized transmission of the fabricated waveguide in Fig. 9(a). The high-transmission window (i.e., 1040 MHz – 1060 MHz) corresponds to the AS symmetric mode as shown by the horizontal dotted lines.

1040 MHz–1060 MHz frequency range, which is within 2.5% of the target frequency for maximum transmission of 1067 MHz. We also observe from Fig. 10(a) that when the focal points of the IDTs are not overlapping (i.e., far IDTs), the transmission drops by at least 7 dB in comparison to that of near IDTs, consistent with the numerical prediction. The results shown in Fig. 10(a) strongly indicate that our fabricated focusing IDTs are functioning as expected.

Figure 10(b) compares the transmission (S_{21}) of the PnC waveguide and the reference PnC structure using focusing IDTs [Figs. 6(a) and 6(b), respectively]. It is evident from Fig. 10(b) that the PnC structure considerably suppresses the acoustic signal transmission at frequencies corresponding to its PnBG where the waveguide structure shows a strong waveguiding effect (i.e., transmission) at frequencies corresponding to its excited guided mode.

To understand the effect of the polarization on the frequency response of the PnC waveguide, Fig. 11 shows the polarization and in-plane (anti-)symmetry of the modes[5] supported by the fabricated waveguide and compares the frequency of these modes with the frequency response of the WG transmission normalized to that of the reference PnC structure. As expected, the high-transmission frequency range of the PnC waveguide corresponds to the single-mode frequency range of its AS mode that has in-plane symmetry (see the region identified by the dashed lines in Fig. 11). The measured maximum transmission at 1055 MHz is within 2% of the target wavgeuide mode (1067 MHz, see Fig. 5) obtained from numerical calculations. There are other in-plane symmetric modes with S polarization that can also contribute to the transmission response of the waveguide. However, we do not expect the SH modes or in-plane antisymmetric modes to have any effect on the waveguide transmission performance as they are not excited by the focusing IDTs in Fig. 6.

VI. CONCLUSION

In this paper, we demonstrated a systematic approach for the design and numerical analysis of the PnC waveguides. A triangular-lattice PnC—composed of Ni pillars on a three-layer membrane of AlN, Mo, and Si—that supports a PnBG around 1100 MHz was designed to provide a platform for the design of a GHz PnC waveguide. Based on this design approach, we developed and optimized a PnC waveguide structure that supports a single guided mode around 1050 MHz. The optimization process included careful selection of the geometrical dimensions of the PnC structure as well as the frequency of operation that could easily be excited by the piezoelectric property of AlN. For the purpose of experimental demonstration of the waveguiding effect, we designed and analyzed new type of focusing IDTs, to facilitate the coupling of the elastic energy to the waveguide and vice versa. Our experimental results corroborate our theoretical understanding of the physics of waveguiding and demonstrate the feasibility of waveguiding of elastic energy at GHz frequencies, a result that is in good agreement with our FEM simulations.

The practical requirement for low-loss PnCs, waveguides, and resonators demands deeper physical understanding and modeling techniques for the loss mechanisms such as viscoelastic damping, thermoelastic loss, electronic processes affecting the material loss (especially in semiconductors), fabrication-imperfection-induced loss, and friction modeling for the contact surfaces between different layers of the device.[28–32] To have a robust signal processing platform based on PnCs, all of these mechanisms should be understood to effectively model the micron- and sub-micron-scale structures to form more complex low-loss frequency-selective building blocks.

ACKNOWLEDGMENTS

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