Phonon propagation dynamics in band-engineered one-dimensional phononic crystal waveguides

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Abstract
The phonon propagation dynamics in a phononic crystal waveguide, realized via a suspended one-dimensional membrane array with periodic air holes, is investigated as function of its geometry. The bandstructure of the phononic crystal waveguide can be engineered by modifying the characteristics of the phonon waves by varying the waveguide width and the pitch of the air holes. This enables the phonon transmission bands, the bandgaps, the velocity and the nonlinear dispersion in the phononic crystal to be controlled. Indeed the engineered bandstructure can even be tuned to sustain multiple phonon modes in a given branch which while being spectrally degenerate can be temporally resolved via their differing group velocities. Furthermore, the ability to tune the bandstructure and thus the nonlinear dispersion can be harnessed to efficiently activate nonlinear phenomena such as mechanical four wave mixing. This systematic study reveals the key geometric parameters that enable the phonon transport in phononic crystal waveguides to be fully controlled.

1. Introduction
Phononic crystals (PnCs) have emerged as novel platform in which the phonon propagation dynamics can be controlled [1–14]. PnCs are usually composed from a periodically modulated elastic media with the period determined by the wavelength of the corresponding phonon waves. The long range periodic modulation in these structures results in phonon standing waves to be established that give rise to phonon bandgaps. This concept was first put into practice in the macroscopic regime within a two-dimensional (2D) periodic arrangement of stainless steel cylinders which could block sound waves at frequencies corresponding to the bandgap [2]. The ultimate evolution of this concept has led to the development of 2D PnCs which consist of a 2D periodic arrangement of air holes typically in a silicon crystal [6–9, 13]. The 2D PnC can not only completely block phonons at the bandgap frequencies but the introduction of point and line defects, by modulating the air holes, even enables phonons to be guided and trapped within these structures. Indeed this platform can control different flavors of phonons i.e. ultra-/hyper-sound [7, 8, 13] and even heat [1, 14] and their high confinement efficiencies have enabled concepts such as phonon multiplexing to be established for signal processing applications [7]. The key to accessing such advanced functions is underpinned by the phonon dispersion relation in these structures which can be engineered by careful design of the 2D periodic air hole matrix.

More recently, a variation of 2D PnCs has been developed in PnC waveguides (WGs) where phonons are confined and guided via a one-dimensional (1D) array of suspended electromechanical membranes [12]. In contrast to 2D PnC WGs, where phonons are confined within the line defect defined WG via the phonon bandgap of the surrounding 2D PnC, the phonon confinement in the 1D PnC WG is achieved by the acoustic impedance mismatch between the suspended membrane and the local bulk environment. However, the periodic air hole array used to suspend the membranes also imparts a periodic elastic potential that is experienced by the phonons confined within the WG and it results in the emergence of phononic bands, bandgaps, slow phonons and even nonlinear dispersion.
The availability of bandstructure in the same spatial region in which phonon propagation occurs offers a novel means to engineering phonon transport by manipulating the underlying periodic structures. To that end a systematic study to evaluate the key physical parameters of the PnC WG architecture, that can enable phonon transport to be manipulated by the bandstructure within the WG, is needed. Here systematic experimental investigations, underpinned by finite element method (FEM) analysis, reveal that adjusting the geometry of the PnC WG not only enables the phonon dispersion to be controlled as in earlier studies but it also allows both degenerate phonon bands and nonlinear dispersion to become available. Fundamentally, this study provides the knowledge to observing the latter two in an experimental setting where temporal measurements permit the degenerate phonon bands to be resolved and spectral measurements enable four wave mixing (FWM) to be activated via the tailored nonlinear dispersion [15, 16] where both of these effects have yet to be observed in other PnCs.

2. Experiment

The availability of bandstructure in the same spatial region in which phonon propagation occurs offers a novel means to engineering phonon transport by manipulating the underlying periodic structures. To that end a systematic study to evaluate the key physical parameters of the PnC WG architecture, that can enable phonon transport to be manipulated by the bandstructure within the WG, is needed. Here systematic experimental investigations, underpinned by finite element method (FEM) analysis, reveal that adjusting the geometry of the PnC WG not only enables the phonon dispersion to be controlled as in earlier studies but it also allows both degenerate phonon bands and nonlinear dispersion to become available. Fundamentally, this study provides the knowledge to observing the latter two in an experimental setting where temporal measurements permit the degenerate phonon bands to be resolved and spectral measurements enable four wave mixing (FWM) to be activated via the tailored nonlinear dispersion [15, 16] where both of these effects have yet to be observed in other PnCs.

The 1D PnCs reported in this study are shown in figure 1(a) and were synthesized from an epitaxially grown single crystal GaAs/AlGaAs heterostructure as detailed in figure 1(b). From this substrate, three PnC WGs with different hole pitches (a) of 8, 10 and 12 μm were fabricated on the same chip as shown in figure 1(c). In total three chips were prepared each sustaining three WGs of fixed widths (w) of 22, 29 and 34 μm, which yielded 9 different PnC WGs that were investigated.

Specifically, the PnC WGs were fabricated by first patterning a mesa structure on the heterostructure via photolithography that was subsequently wet etched using a H3PO4(6%):H2O2(6%):H2O(88%) solution. The mesa structure was exposed to a height of approximately 500 nm in order to eliminate electrical cross-talk between the neighboring PnC WGs through the Si-doped GaAs layer. Next, electrodes were patterned at the edges of the WGs via photolithography and were deposited with gold using the lift-off technique. The 1D air hole array was then defined along the [110] crystal orientation where the number of holes were chosen to fix the length of all PnC WGs to approximately 1.0 mm. The holes with a radius of 2.5 μm were also patterned with photolithography and were then wet etched all the way down to the Al0.65Ga0.35As layer with H3PO4:H2O2:H2O solution. Finally, each chip was immersed in HF(5%):H2O(95%) solution to isotropically etch the Al0.65Ga0.35As sacrificial layer which yielded the suspended membrane array that composed the PnC WG [12, 17, 18]. By varying the HF immersion time between 25, 33 and 40 min, three chips sustaining three PnC WGs with w = 22, 29 and 34 μm were prepared. In order to ensure high quality mechanical performance, all the chips were also...
cleaned post fabrication via an ultraviolet and O₃ dry stripper to remove any residual contamination on the surface of the WGs. The experiments were then performed at room temperature and in high vacuum (∼2 × 10⁻⁴ Pa) where the phonons were piezoelectrically generated in the WGs with the application of alternating voltage between the gold electrode and the Si-doped GaAs layer from a signal generator (NF WF1974 or HP89410A) as shown in figure 1(a). The resultant vibrations, confined to the WG, were optically detected with He–Ne laser Doppler interferometer (Neoark MLD-230V-200). The electrical output from the interferometer’s photodetector was measured either in a vector signal analyzer (HP 89410A) or in an oscilloscope (Agilent DSO6014A) in which case the output from the interferometer was first preamplified (NF SA-220F5).

3. Results and discussions

3.1. Spectral response

First, in order to evaluate the bandstructure as function of the PnC geometry, the transmission of all nine PnC WGs were spectrally measured via the protocol depicted in figure 1(a). The spectral responses of three WGs with \((w, a) = (22, 10), (29, 12)\) and \((34, 8)\) in microns corresponding to devices 1, 2 and 3 henceforth are shown in figures 2(a)–(c) respectively. In addition, the corresponding dispersion relations extracted from FEM simulations (COMSOL Multiphysics) are also shown in these figures. In device 1, phonon propagation in the WG emerges above a cut-off frequency of 3.8 MHz which corresponds to the 1st dispersion branch from mode A detailed in figure 2(d). However, as the WG width increases in devices 2 and 3, the cut-off frequency reduces to 2.2 and 1.6 MHz as shown in figures 2(b) and (c). Physically this trend arises from the larger membranes composing the WGs in these devices sustaining lower frequency resonances [19]. Indeed the inverse dependence of the cut-off frequency to the WG width is observed irrespective of the hole pitch and is reproduced by the FEM simulations as shown in figure 3(a).
The transmission measurements in device 1 (figure 2(a)) also reveal a phonon bandgap at 6 MHz that is created when the half wavelength of the phonon vibrations in the WG corresponds to the hole pitch length. This results in Bragg reflection that leads to standing waves which suppress phonon propagation at the corresponding frequencies. Meanwhile, the FEM analysis reveal that this bandgap corresponds to the 1st and 3rd dispersion branches that sustain mode shapes with an antinode (A in figure 2(d)) or a node (B in figure 2(d)) between the holes in the WG with the same wavelength. In other words, the WG can support 2 vibrations of the same wavelength but different energies corresponding to the different mode profiles. On the other hand, as the hole pitch is increased to 12 μm in device 2 shown in figure 2(b), the bandgap between the 1st and 3rd branches closes due to the greater overlap between their corresponding mode shapes as a consequence of their longer wavelengths. Consequently, this observation naturally suggests that a shorter hole pitch will yield shorter wavelengths for the phonon modes in the 1st and 3rd branches giving rise to less overlap which should result in a more distinct bandgap emerging. However, experimentally decreasing the hole pitch to 8 μm in device 3 shown in figure 2(c) reveals a much less pronounced phonon bandgap. This unexpected observation originates from the 3rd dispersion branch in this device sustaining mode shapes labeled D (see figure 2(d)) that overlaps with the 1st bandgap at the Brillouin zone boundary and thus mask it as revealed by the FEM simulations in figure 2(c).

The dispersion relations extracted from the FEM simulations, shown in figures 2(a)–(c) indicate that the PnC WGs can sustain a range of phonon branches whose corresponding mode shapes are detailed in figure 2(d). However, the phonon modes corresponding to the 2nd and 4th branches (gray lines in figures 2(a)–(c)) arising from mode shapes labeled C and E in figure 2(d) make a negligible contribution in the present study due to the piezoelectric transducer’s inability to activate them as a consequence of the electrodes being located at their nodal position. In contrast, the 5th branch sustains mode shapes that exhibit tension mediated intermodal interactions with the modes in the 3rd branch that results in their anti-crossing which opens up a new bandgap around 7–9 MHz in devices 2 and 3 as shown in figures 2(b) and (c) [20, 21]. Although the spectral transmission measurements are unable to clearly resolve these higher order bandgaps as they are located far from the Brillouin zone boundary, surprisingly the temporal measurements detailed below can do so.

3.2. Phononic bandgap

The spectral transmission measurements in all nine PnC WGs enable both the cut-off frequency (described above) and the phonon bandgap to be systematically evaluated as function of the WG’s geometry and are summarized in figures 3(a) and (b) respectively.

This analysis unsurprisingly reveals that the spectral positions of the 1st bandgap is strongly dependent on the WG width and the hole pitch length as shown in figure 3(b). Specifically, reducing the hole separation gives...
rise to shorter wavelength standing waves in the WG thus yielding a bandgap at higher frequencies, whereas the WG width determines the spectral position of all the phonon branches as referenced to the cut-off frequency detailed in figure 3(a). Indeed the FEM simulations confirm the former trend as shown by the solid line in figure 3(b) for a PnC WG with $w = 29 \mu m$ where $a$ is continuously varied from 7 to 13 $\mu m$. The spectral width of the 1st bandgap also shows an inverse correlation with the hole separation. However this trend is not captured by the widest WG with $a = 8 \mu m$ as a consequence of the emergence of the 3rd branch which overlaps the 1st bandgap as described above.

Somewhat surprisingly, the spectral position of the 2nd bandgap also reveals a stronger than expected correlation on the hole separation even though this bandgap arises from the interaction between the phonon modes in the 3rd and 5th branches. However as the hole pitch is reduced for a given PnC WG width, all the phonon branches migrate to higher frequencies which consequently results in the anti-crossing between the 3rd and 5th branches also occurring at higher frequencies. Again this trend is confirmed by the FEM analysis as shown by the dotted lines in figure 3(b).

Consequently these systematic analyses reveal that the spectral positions of the bandgaps and somewhat generally their spectral widths can be tailored by simply controlling the hole pitch in the PnC WGs.

### 3.3. Temporal response

In order to gain a deeper understanding of the phonon propagation dynamics in the 1D PnC WGs, temporal measurements are also performed. In figure 4, the spatially mapped phonon propagation in device 2 in response to a rectangular shaped input pulse of 2 $\mu s$ duration is shown. This measurement is executed with a pulse frequency of 5.6 MHz at which phonon modes sustained by the 3rd dispersion branch are activated as detailed in figure 2(b). The mechanical vibrations corresponding to these phonons are excited from one edge of the PnC WG and they subsequently propagate through the WG with a constant speed of $134 \text{ m s}^{-1}$ and a loss of $0.4 \text{ dB mm}^{-1}$. Once these phonons reach the opposite edge of the WG, they are reflected, resulting in an enhanced signal that can be identified by the equally spaced peaks in the spectral measurements as highlighted in figure 2(b).

Next to evaluate the temporal characteristics of the phonon propagation in the WG with respect to the underlying bandstructure, similar time of flight measurements are performed as function of frequency in all 3 devices. Phonons in the PnC WGs are excited by rectangular input pulses from the WG’s right edge with durations of 2 $\mu s$ and 8 $\mu s$ which are then only detected at the left edge, in contrast to the spatial mapping measurements detailed above, and are shown in figures 5(a)–(c). As expected, phonons in all 3 devices could only be observed above the cut-off frequency irrespective of the pulse duration. Once the phonons reached the opposite edge of a WG they are reflected resulting in an enhanced signal (highlighted in figure 4). Indeed multiple reflections occur as identified by the enhanced intensity fringes in all 3 devices. Although the phonons propagate with constant velocity in the WGs but when the pulse frequencies approach the edges of the bandgap,
phonon slowing occurs namely the phonon group velocity \(v_g\) is reduced. This can be clearly seen by the change in curvature of the reflection fringes as highlighted by the black arrows in figures 5(a)–(c). The physical origin of this effect arises from a change in the profile of a dispersion branch with respect to wavenumber at frequencies

Figure 5. (a)–(c) The temporal response of the phonon propagation in the PnC WGs when excited with a pulse of 2 \(\mu s\) (left panel) and 8 \(\mu s\) (right panel) duration with an amplitude of 0.5 Vrms in devices 1, 2 and 3 respectively. The black arrows indicate the positions of the bandgaps. The region highlighted in pink in (c) indicates the pulse fringe from the slow phonons corresponding to mode shape D in figure 2(d) that are sustained by the anti-crossed 3rd branch in addition to the fast pulse fringe originating from mode B as seen in the other two devices.
around the bandgap [12, 22, 23]. Indeed this group velocity dispersion (GVD) can also broaden the phonon pulse packet as it travels down the PnC WG as detailed below.

In contrast to devices 1 and 2 where the extremities of the 1st bandgap could be identified from the phonon slowing, such unambiguous identification of the bandgap in device 3 was not possible. In fact the temporal measurements indicate the existence of an interference like response in this spectral region which is also observed in the spectral measurements depicted in the inset to figure 2(c). These observations can be understood from the FEM simulations (also shown in figure 2(c)) which indicate that the 3rd dispersion branch overlaps with the 1st bandgap. Consequently the suppression of modes A and B (see figure 2(d)) in parallel with the availability of mode D (see figure 2(d) and the subsequent overlap of their modal profiles gives rise to the complex temporal response observed in this device for frequencies in and around the bandgap. It should be noted that in contrast to the spectral measurements, the bandgap region in device 3 could be more easily identified in the temporal measurements due to this highly pronounced interference effect.

3.4. Group velocity

The time of flight measurements detailed above also enable the group velocity to be quantitatively extracted. Specifically, the first fringe corresponding to a one way trip in the PnC WG is Gaussian fitted at a given frequency. The group velocity at this frequency can then be readily determined from the ratio of the WG’s length to the time obtained from the center of the Gaussian fit. Extending this analysis to all the frequencies displayed in figures 5(a)–(c) yields the spectral dependence of the group velocity in all three PnC WG as shown in figures 6(a)–(c).

First, the extracted group velocities show no dependence on the pulse width where clearly the narrower pulse corresponds to a spectrally broader frequency packet and vice versa. Second, in the 1st and 3rd dispersion branches (away from the 1st bandgap and only for mode shapes A and B in figure 2(d)) spanning 3 different frequency ranges of 3.8–10 MHz, 2–7 MHz and 2–6 MHz in devices 1, 2 and 3 respectively, almost identical group velocities are obtained. Indeed the group velocities determined directly from the FEM simulated bandstructure shown in figures 2(a)–(c), from the relation \( v_g = \frac{2\pi}{\lambda} \frac{df}{dk} \) where \( f \) and \( k \) are frequency and wavenumber respectively, not only reproduce the experimentally observed group velocities but they also confirm that the phonon velocities are inextricably linked to their dispersion branches. Finally, the extracted group velocities not only exhibit the slowing effect in the proximity of the 1st bandgap, but it can also be seen around the 2nd bandgap (see figures 6(b) and (c)) even though these bandgaps cannot be resolved in the spectral measurements described in figures 2(b)–(c). These results also unsurprisingly indicate that the broader 8 \( \mu s \) pulse, corresponding to a spectrally pure input, can probe the rapidly changing dispersion branches in the spectral regions around the bandgaps with a higher resolution than the 2 \( \mu s \) pulse.

The suppression in the group velocity can also modify the temporal waveforms of the pulse fringes as depicted in figures 6(d)–(f). This effect originates from the GVD whose spectral position can be identified experimentally from the group velocities in the lower panels of figures 6(a)–(c) and is theoretically confirmed via the second derivative of the FEM simulated dispersion branches in figures 2(a)–(c), namely the GVD coefficient \( k_5 = \frac{1}{2\pi^2} (\frac{\partial^2 k}{\partial f^2})^2 \) as shown in the upper panels of figures 6(a)–(c) [24, 25]. As \( k_5 \) becomes non-zero in the proximity of the cut-off and the bandgaps at 4.3 MHz in devices 1 and 2 respectively (see figures 6(a) and (b)), the reflection fringes are both broadened and distorted as shown in the upper panels of figures 6(d) and (e). In the proximity of the band edges where \( k_5 \) is maximized, this results in the velocity of phonons rapidly changing which experimentally manifests itself in the broadened temporal waveforms. In contrast, this frequency corresponds to the middle of the 1st dispersion branch located away from the band edges for device 3 (see figure 6(c)) where \( k_5 \) is negligible and thus the corresponding group velocity is more explicitly defined. As a result the reflection fringes at this frequency exhibit clearly defined waveforms without any broadening as shown in the upper panel of figure 6(f). Similar observations are also made in devices 1 and 3 at 7.5 MHz as detailed in the lower panels of figure 6(d) and (f) where as in device 2 the waveform is distorted as shown in the lower panel of figure 6(e). Consequently, designing the phonon bandstructure by simply tuning the geometry of the PnC WG enables not only the phonon group velocity at given frequency to be selectively adjusted but the corresponding waveforms can also be modified on demand via the nonlinear dispersion.

3.5. Degenerate phonon transport

Most interestingly, the temporal measurements shown in figure 5(c) clearly reveal the existence of two different reflection fringe profiles with different curvatures above 6 MHz (where this new fringe is highlighted in pink). Since this effect is most clearly observed with the 2 \( \mu s \) input pulse (left panel in figure 5(c) and lower panel in figure 6(f)), their temporal waveforms are selectively fitted with two different Gaussians. This analysis reveals the existence of two different group velocity profiles above 6 MHz in device 3 as shown in figure 6(c). As described above, at these frequencies the 3rd dispersion branch interacts with the 5th dispersion branch and the resultant
Figure 6. (a)–(c) The frequency dependence of the group velocity (lower panel) in devices 1, 2 and 3 extracted from the measurements shown in figures 5(a)–(c) where the circles and squares correspond to 2 and 8 μs pulses respectively. The solid lines depict the theoretical group velocities extracted from the FEM derived bandstructure detailed in figures 2(a)–(c) with the same color coding enabling the different branches to be identified. For frequencies above 6 MHz in (c), two different group velocities can be identified via the shorter pulse data corresponding to the two different wavenumber phonon modes (B and D in figure 2(d)) in the 3rd dispersion branch. The upper panels show the experimental GVD coefficient $k_2$ extracted from the group velocities in the lower panel. The solid lines depicts the theoretical GVD calculated from the inverse 2nd derivative of the FEM derived bandstructure detailed in figures 2(a)–(c) where again the same color coding is used enabling the different branches to be identified. This calculation permits the spectral positions at which GVD is maximized or minimized to be located which results in the temporal waveform of the phonon propagation becoming either broadened or unaffected as it travels down the PnC WG. (d)–(f) The output waveforms at 4.3 and 7.5 MHz as indicated by the purple and orange arrows in (a)–(c) respectively at which the GVD is maximized or minimized depending on the GVD coefficient in a given PnC WG.
anti-crossing modifies the 3rd branch so that it can sustain 2 distinct phonon modes (B and D shown in figure 2(d)) with different wavenumbers but at the same frequency. Indeed the above analysis indicates that the additional fringe structure (see lower panel in figure 6(f)) yields slower group velocities which correspond to phonons in the 3rd branch whose mode profile is described by D. On the other hand, the faster group velocities at these frequencies correspond to phonons whose mode shape is described by B from the 3rd branch as in devices 1 and 2.

The combination of temporal measurements in the PnC WGs with the FEM derived bandstructure provides a powerful approach to probing the phonon dynamics in this platform. Indeed these investigations have even opened up the path to identifying different phonon modes within a particular dispersion branch. This new degree of freedom, where different vibration modes are available at the same frequency, is akin to engineering the orbital angular momentum of photons to increase the information throughput at the same frequency in optical fibers [26, 27]. Consequently, these investigations bring forth the exciting prospect of geometrically engineering PnC WGs so that their bandstructure can sustain multiple vibration modes at the same frequency which in turn can be identified from temporal measurements via for example their different group velocities.

3.6. Phonon dispersion tailored for mechanical FWM

The ability to control the phonon dispersion is central to the efficient activation of nonlinear phenomena. For instance, degenerate optical FWM can create a new idler wave which arises from the interaction between co-propagating pump and signal waves in a medium with a third-order nonlinear susceptibility [24]. The phononic analogue of FWM can also be expected in the PnC WG due to the availability of mechanical third order nonlinearity in the restoring force namely the well-known Duffing term [28]. However efficient FWM requires a small phase mismatch $\Delta k = k_s + k_i - 2k_p$ where $k_s$, $k_i$ and $k_p$ are wavenumbers from the signal, idler and pump waves respectively. For phase matching namely $\Delta k \to 0$, the nearly linear dispersion relation with $k_2 \to 0$ is desired. In other words the key to activating FWM is to minimize the GVD which in turn ensures phase matching thus enhancing the efficiency of this process.

Based on the above detailed investigations of the bandstructure in the PnC WG, it is straightforward to identify frequencies where GVD is minimized from figures 6(a)–(c). For example in device 2, zero dispersion ($|k_2| < 5 \times 10^{-11}$) is available at 5.994 MHz as is highlighted in the gray dashed line in the upper panel of figure 6(b). The pump phonons excited at this frequency with the simultaneous excitation of signal phonons generate idler phonons from mechanical FWM as shown in figure 7. When the signal frequency is tuned to 6.066 MHz, idler phonons appear at 5.921 MHz, yielding energy conservation with $2f_p - f_s - f_i = 0$ where $f_p$, $f_s$ and $f_i$ are frequencies from the pump, signal and idler waves respectively. Furthermore, low GVD parameters...
are available in a broad range of frequencies in the 3rd phonon band, as shown in figure 6(b), which enables idler phonons to be even generated at 5.645 MHz which is separated by nearly 700 kHz from the signal frequency at 6.343 MHz (see figure 7). Such tunable broadband frequency conversion of phonons in the 1D PnC WG is unavailable in conventional mechanical resonator devices due to their narrow frequency bandwidths [29, 30]. Consequently these results vividly demonstrate that knowledge of the bandstructure in the PnC WG and the ability to tune it via geometry is fundamental to managing the GVD which plays a critical role in the harnessing of novel nonlinear phonon transport phenomena in this platform.

4. Conclusion

The 1D PnC WG architecture is systematically investigated as function of its geometry via a combination of spectral and temporal measurements in conjunction with its bandstructure extracted from FEM simulations. These investigations reveal that the cut-off frequency, the spectral position and width of a given phonon band and bandgap in the PnC WG can be controlled by simply varying the width of the WG and the pitch of the holes used to suspend the membranes. Consequently, the speed of phonons and even their temporal profile can be controlled via the GVD at given frequency. Indeed the ability to tune the GVD plays a fundamental role in efficient generation of nonlinear phonon transport phenomena such as FWM. Furthermore the FEM simulations also indicate that phonons in only certain dispersion branches can be activated due to the position of the piezoelectric transducers on the PnC WG. Consequently this analysis provides design directions in future devices where multiple piezoelectric transducers will be incorporated to selectively activate phonons in a particular dispersion branch. Most unexpectedly, the tension induced interaction between dispersion branches not only results in the creation of new bandgaps but the highly modified branches also sustain different wavenumber vibration modes which coexist at the same frequency. Although the spectral measurements can not resolve these degenerate states, the temporal measurements uniquely can discriminate between the coexisting phonon modes in a given dispersion branch via their differing group velocities.

Consequently, this study vividly indicates that the combination of the FEM simulated bandstructure and temporal measurements are the key to ascertaining detailed knowledge of the phonon dynamics in the PnC WG architecture. Ultimately these investigations have yielded insights into the relationship of the WG’s geometric parameters to its underlying bandstructure which can now be harnessed to engineer and exploit both the well-known phonon dynamics and the more exotic phononic degrees of freedom arising from the nontrivial bandstructure in PnC WGs.

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