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Tunable waveguiding in origami phononic structures

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ABSTRACT

A novel design of origami phononic structures with tunable waveguiding features are studied in this research. The structure is formed by attaching cylindrical inclusions on top of origami sheet; in this kind of architecture, folding of the underlying origami sheet can change the periodicity of inclusions. Being periodic in nature, the origami structure exhibits bandgaps features and have the potential to steer wave energy through a path of defects (also known as waveguide) created in the lattice of inclusions. Since the spectral content transmitted through the waveguide depends on the periodicity surrounding it, the folding induced lattice transformation in such origami structures can lead to adaptation in waveguide frequency. In fact, in origami structures that can transform between different Bravais-lattice types, for example between a square and hexagon lattice, the waveguide frequency can be drastically tuned. Such phenomenal adaptation is studied in this research by extracting dispersion diagrams of defective origami structures using the plane wave expansion method. Further, numerical and experimental investigations are performed on finite origami structures with waveguides and the transmission results of different folding configurations demonstrate that waveguide frequency can be significantly altered. Overall, the low effort one-degree-of-freedom (1DOF) folding mechanism combined with the scalable nature of the origami architecture makes the origami phononic structure a novel and effective device for waveguiding applications across a range of frequencies.

1. Introduction

Waveguiding is a mechanism of restricting wave energy to a desired path with minimum losses. It is found useful in many applications such as, in filters, multiplexers, de-multiplexers, energy harvesting, structural health monitoring, fluid sensors and also in fundamental research to enhance the interaction between sound and light [1–4]. Such effective wave control mechanism can be achieved in engineered periodic structures called phononic structures with repetitive material properties. The large impedance mismatch between inclusion and host of the phononic structures leads to multiple reflections of waves, propagating inside this composite media. Such complex interference pattern leads to the formation of bandgaps – which are regions in transmission spectra where wave propagation is forbidden. These bandgap features resulting due to periodicity can create an efficient background for steering wave energy.

It is well known that the impurities in a phononic structure can lead to spatially localized modes with frequencies inside the bandgaps. Such defects can be arranged in a desired path to steer the wave energy and eventually creating a waveguide. Because of the wide spread applications of waveguides, studies were performed in the past to tune the waveguide frequency,

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so as to use the same waveguide for steering different spectral content. Some of the works include, either changing the geometric properties or changing the material properties of the defects [1,2,5–11]. However, in such works, the adaptation in waveguide frequency is incremental and is strictly restricted within the bandgap defined by the periodicity of phononic structure.

To advance the state of the art and achieve broadband adaptation in waveguide frequency, we propose a novel concept based on the origami architecture. Origami is an ancient paper folding art, in which a single piece of paper can be folded from a crease pattern to take different shapes be it an animal, or tessellation or an abstract form [12–19]. In this origami phononic structure, cylindrical inclusions are attached onto the vertices of origami sheet, where folding the underlying origami sheet will change the spatial distribution of attached inclusions and result in change of lattice periodicity of inclusions. In some of our previous investigations [20,21], we have shown that such lattice reconfiguration can be tailored to shift between different Bravais-lattice types by designing the origami sheet parameters. As it is known that the differences in lattice symmetry-properties lead to their distinct wave propagation features, in this research, we explore an innovation that can effectively and drastically tune the frequency of waveguide by reconfiguring the lattice topology of origami phononic structures between different Bravais-lattice types.

To achieve such a task, first we explore the effect of folding on waveguide modes in origami structures using analytical tools such as the plane wave expansion method. Numerical and experimental investigations are then performed on finite origami structures and evaluate the broadband adaption in waveguide frequency. Finally, we conclude this article with some final remarks.

2. Model

The proposed origami phononic structures are created by attaching cylindrical inclusions on top of miura-origami sheet, as shown in Fig. 1. Folding of the origami sheet in this architecture leads to spatial redistribution of inclusions; an example of such reconfiguration between different Bravais-lattice types is shown through illustration in Fig. 1. It can clearly be seen that the lattice of inclusions can be transformed between a hexagon and a square via changing the folding angle.

To tailor the lattice transformation, first we identify different design parameters of origami sheet and derive kinematic relations between folding properties and spatial distribution of inclusions. Since the miura-origami sheet is periodic, it can be studied via a unit-vertex given in Fig. 1j and as can be seen in the figure there are three design parameters viz. two crease lengths (a,b) and one sector angle (γ) between them. We also define a dihedral angle (θ), i.e. defined as the angle made by the quadrilateral facet with reference xy plane, to study the folding configurations of origami sheet. When the folding angle is 0°, the origami sheet is flat and parallel to xy plane, while on the other hand when θ is 90° the origami sheet is again flat but perpendicular to xy plane. Since the inclusions in the proposed design are attached onto the vertices of the origami sheet (red ellipses in Fig. 1j), their spatial distribution also change with folding angle and the kinematic relation between folding angle and the relative distance between origami vertices are given through Eq. (1); *H*, *L*, *W* in Fig. 1j and Eq. (1) represent the height, length and width of unit-vertex where *s* is the staggered distance (along y-direction) between adjacent column of vertices.

$$
\begin{aligned}
H &= a \sin\theta \sin\gamma \\
L &= \frac{2b\cos\theta\sin\gamma}{\sqrt{1-\sin^2\theta\sin^2\gamma}} \\
W &= 2\,a\,\sqrt{1-\sin^2\theta\sin^2\gamma} \\
s &= \frac{b\cos\gamma}{\sqrt{1-\sin^2\theta\sin^2\gamma}}
\end{aligned}
\tag{1}
$$

In our previous paper [12], we have shown that, it is possible to design an origami phononic structure whose inclusions can transform between any four Bravais-lattice types (viz. square, rectangle, center-rectangle and hexagon lattices). Here for the purposes of demonstrating waveguide tuning, we select the parameters of origami sheet (viz. crease lengths (a,b) of 0.08 [m], sector angle of 60° and inclusions with radius of 0.0211[m]) that can transform the lattice between a square and a hexagon. For these set of parameters, the lattice transforms from a hexagon (Fig. 1d) to a square (Fig. 1e) and then to a hexagon (Fig. 1f) as the folding angle is shifted from 0° to 55° to 70°. Such kind of lattice transformation, as will be shown, will lead to phenomenal waveguide tuning.

A waveguide in this study is created by removing inclusions along a desired path; for example in Fig. 2(a and b) the top views of a straight-geometry waveguide in origami phononic structure at two different folding configurations are given, where the location of inclusions removed to form waveguide are identified with grey solid circles. It can be clearly seen that by folding the origami structure (from 55° to 70°) the periodicity around the waveguide is changed. Now to study the effect of this change in periodicity on the waveguide frequency, we perform band-structure analysis via super-cell plane wave expansion method and frequency domain analysis using the COMSOL software.

3. Analytical and numerical investigations

3.1. Analytical investigation via super-cell plane wave expansion method

Often times it is desirable to study phononic structures that break periodicity such as structures with defects. One method of extracting dispersion characteristics is to assume such structures to be quasi-periodic and model them as periodic repetitions of super-cell; where the boundary of a super-cell includes large collection of inclusions along with the defects.

In our case, the origami phononic structure with waveguide can be modelled as a periodic repetition of black rectangular super-cells, as shown in Fig. 2(a and b), which includes several inclusions and the defects that form the waveguide. Greater the number of inclusions around the defects in the super-cell, greater is the convergence of the band-structure results; for the simulations in this study, 16 complete inclusions around the waveguide are chosen to achieve desired convergence at reasonable computation cost.

With the definitions of unit cell and lattice vectors (a_1, a_2) given in Fig. 2(a and b) and Eq. (3), the acoustic wave propagation behavior through the 2D plane, transverse to inclusion axis, is evaluated by solving the governing pressure wave equation Eq. (2) – for band structure via plane wave expansion method (PWE) – with the assumption that the material properties of origami structure are invariant along the z direction. In Eq. (2), p represents the pressure field while ρ, c_l represent the density and longitudinal speed of sound. For analytical and numerical investigation, the host media and inclusion material are chosen to be air and rigid PVC and their corresponding material properties are provided in Table 1.

$$\left(\frac{1}{\rho c_l^2}\right)\frac{\partial^2 p}{\partial t^2} = \nabla\cdot\left(\frac{1}{\rho}\nabla p\right) \tag{2}$$

$$\begin{aligned} \overrightarrow{\mathbf{a}_1} &= L\,\widehat{\mathbf{x}} \\ \overrightarrow{\mathbf{a}_2} &= \frac{9W}{2}\,\widehat{\mathbf{y}} \end{aligned} \tag{3}$$

The general idea behind the PWE method is to expand the material properties and pressure field in Eq. (2), in terms of Fourier series expansion. Upon substitution of series expansion into the first principle partial differential equation (Eq. (2)), it can be converted into an eigenvalue problem (EVP) with two variables; viz. wave vector and eigen frequency. The wave vector is swept along the boundaries of first Brillouin zone (given in the inset of Fig. 2a,b) and the eigen frequencies are evaluated to extract the dispersion diagrams as shown in Fig. 2(c and d) (represented by dotted-line curves); more details about the PWE method could be found in reference article [12].

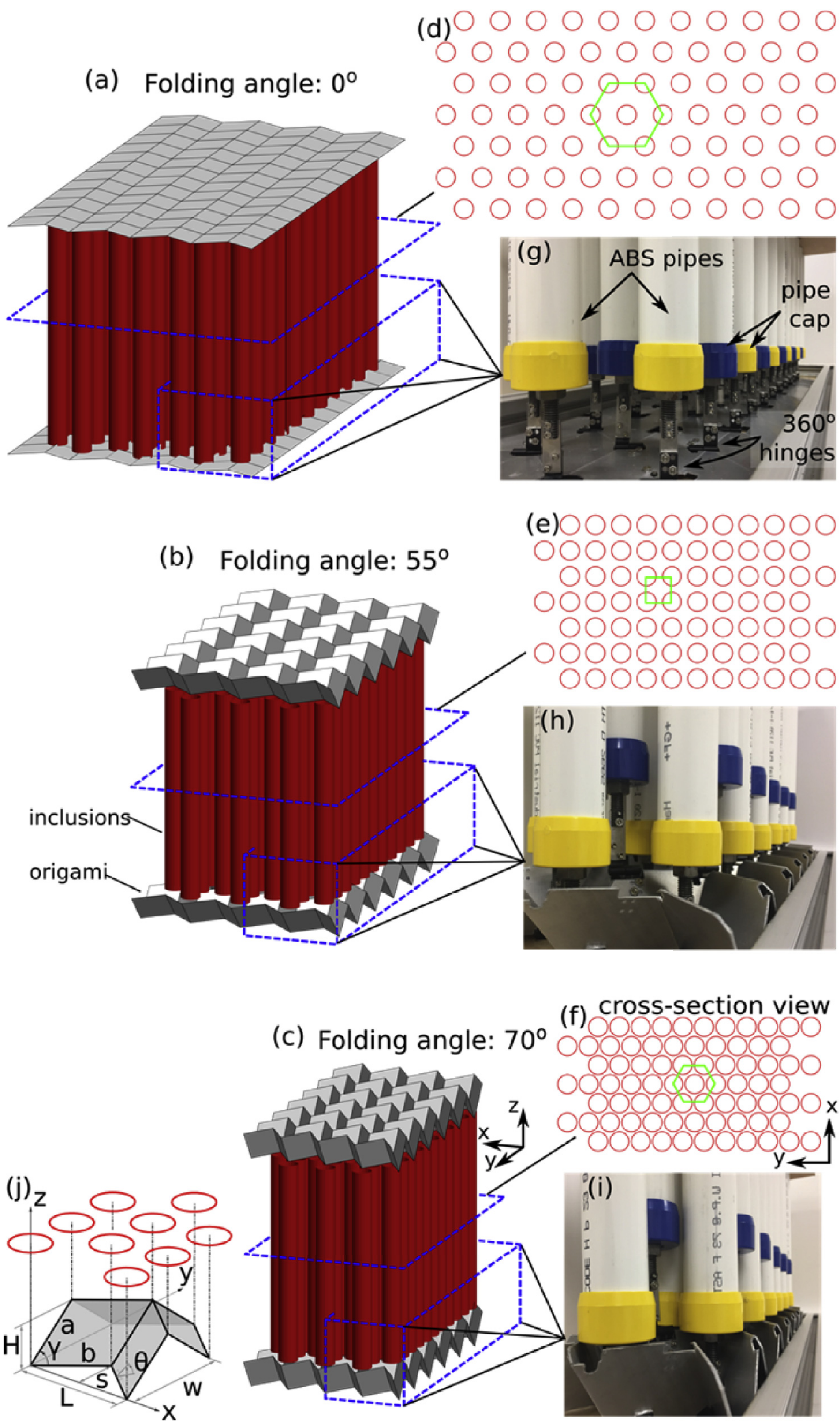
Fig. 2(c and d) are the dispersion diagrams of origami phononic structure with waveguide at two folding configurations, 55° and 70° respectively. In order to find the waveguide modes (modes with localized wave functions inside the waveguide), we need to compare the band structure diagrams in Fig. 2(c and d) with that of perfectly periodic origami phononic structures without a waveguide [12]. For the purpose of comparison, we extract complete bandgaps and mark them as red dashed-dot rectangular regions in Fig. 2(c and d). It can be clearly seen that some modes, marked by large red dots, are formed inside the spectral region where a bandgap is predicted for perfectly periodic case. Based on [1,8,22,23], these observations suggest that the modes inside the red rectangle have localized wave functions inside the waveguide.

3.2. Numerical investigation via COMSOL simulations on finite structures

In order to validate the spectral properties and localization phenomena of waveguide modes, we perform numerical simulations on a finite origami phononic structure using the acoustic-structural numerical analysis package COMSOL. 2D cross-section profiles used for simulations are given in Fig. 3(a and b); where we show waveguide with complex-geometry that is being studied. As stated before, the periodicity around the waveguide is changed when the folding angle is varied and this effect can be clearly seen in Fig. 3(a and b), where (a), (b) correspond to 55° and 70° folding configuration respectively.

In this COMSOL model, plane incident wave is excited at the bottom of the simulation domain (in front of the origami structure) while a line receiver is placed at a distance of 1[cm] behind the origami structure. The receiver measures the pressure and evaluates the sound pressure level (SPL, in dB) along the y-direction. The outer boundaries of the simulation domain are provided with radiation boundary conditions to absorb any reflections.

Frequency domain analysis is performed across the frequency range of interest and contour maps of SPL are plotted in Fig. 3(c–f); where (c), (d) are results of SPL across the width of the structure at the output of waveguide at 55° and 70° respectively and (e), (f) are zoomed in spectral regions where waveguiding is predicted to happen via band structure analysis (given in Fig. 2(c and d)). From the zoomed-in plots, it can be observed that the SPL is localized around the output of the waveguide indicating that the sound energy is guided through the complex-shaped waveguide. It can further be noticed that the spectral region where waveguiding occurs is different for different configurations, indicating that the waveguide frequency can be tuned via changing the folding angle. Moreover, since the periodicity around the waveguide shifted between different Bravais-lattice types, in this case from a square to a hexagon, we have achieved significant adaptation in waveguide frequency (waveguide frequency doubled for the example case considered here).


(a) Folding angle: 0°
(b) Folding angle: 55°
(c) Folding angle: 70°
(d)
(e)
(f) cross-section view
(g)
ABS pipes
pipe cap
360° hinges
(h)
(i)
(j)
inclusions
origami
z
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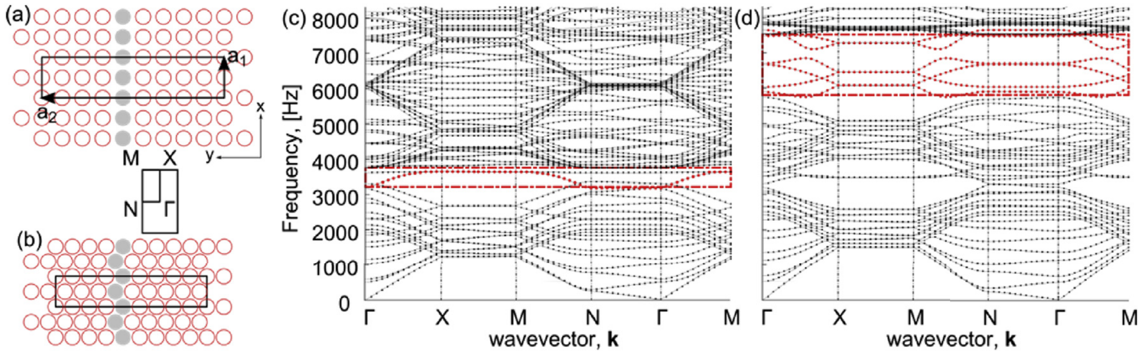

Fig. 2. Cross-section profiles of origami phononic structure in different folding configurations (a) 55° and (b) 70° with straight-geometry waveguide. (c,d) are corresponding bandgap structures evaluated via plane wave expansion method, assuming that origami phononic structure is made from periodic repetitions of rectangular super-cell and lattice vectors as given in (a,b). The modes represented by red dots in (c,d) have localized modeshape with sound energy confined inside the waveguide; drastic variation in spectral location of localized modes in (c) and (d) indicate that the waveguide can be tuned to different frequency wave propagation via changing the folding angle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Material properties of host and inclusion.

Material properties	PVC	Air
Density, (ρ), [Kg/m^3]	1.56 × 103	1.3
Longitudinal speed of sound (c_l) [m/s]	2395	340

4. Experimental investigation

4.1. Test setup

An experiment has been set up to validate the waveguide tuning. Top and side views of the origami phononic structure at 55° and 70° folding configurations are shown in Fig. 4 and the corresponding close-up views of the origami sheet are given in Fig. 1(h–i). A total of five unit-vertices (as shown in Fig. 1j) are combined along y-direction to create the experimental setup shown in Fig. 4. 1 ¼ [in] PVC pipes with outer radius of 0.0211[m] are chosen as inclusion and 0.05[in] thick aluminum sheets are water jet cut to form facets of origami sheet (geometric parameters are provided in Section II). Different facets are connected together by ultra-high molecular weight polythene adhesive tape to form the origami sheet and inclusions are attached to the vertices of the origami sheet via 360° friction hinges; one end of hinge is attached to the origami sheet while the other end is attached to a pipe cap, as shown in Fig. 1(h–i). PVC pipes are inserted in the caps that move as per the trajectory of origami vertices during the folding process. To hold the origami structure in a given folding configuration, stencils corresponding to the spatial distribution of inclusions are carved out using laser on masonite boards and are slipped onto the pipes as shown in Fig. 4. Based on the geometric parameters of the test setup, a maximum folding angle of 71° is possible before the closed packing condition of inclusions is reached.

The experiments are performed on the origami structure at 55° and 70° folding configurations and two sets of tests are performed on each configuration, (a) with waveguide (Fig. 4(b,d,f,h)) and (b) without waveguide (Fig. 4(a,c,e,g)) – the results from these sets will be compared to demonstrate waveguiding phenomena. Unlike the numerical model (sec. 3.2) where a complex wave guide shape is studied, here in the test setup, waveguiding will be shown in a simple straight geometry. Since the goal of this test setup is to demonstrate that folding can be used as a means to tune the waveguide frequency, studying a simple waveguide geometry is sufficient to prove the concept.

As before, waveguide is formed by removing inclusions (at spatial location marked by green circles in Fig. 4(b,f)) and it can be seen that as the folding angle is changed from 55° to 70°, the periodicity around the waveguide is shifted from a square to hexagon. As a guide to the eye and for better legibility, lattice topology of the two folding configurations are marked by green polygons in top views of the origami structure without waveguide (Fig. 4(a,e)). The incident wave is produced by a horn which is placed at an angle such that the incident wave (represented by red arrow in Fig. 4) makes an angle of 45° with respect to the x-axis. To record the pressure, a microphone is located at the center of the origami structure in the y-direction (which also coincides with the y-coordinate of the output of the waveguide) and behind the origami structure at distance of 2[cm].

Fig. 1. Lattice reconfiguration in origami phononic structure. (a–c) are illustrations of origami structure at different folding angles i.e. at (a) 0°, (b) 55° and (c) 70° respectively and (g–i) are corresponding views of fabricated test-setup. (d–f) are the cross-section profiles displaying the spatial distribution of cylindrical inclusions attached on top of origami vertices; green polygons are drawn to identify lattice topologies and it can be seen that lattice transforms between square and hexagonal lattices during folding operation. (j) is a close up view of origami unit-vertex showing various geometric parameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

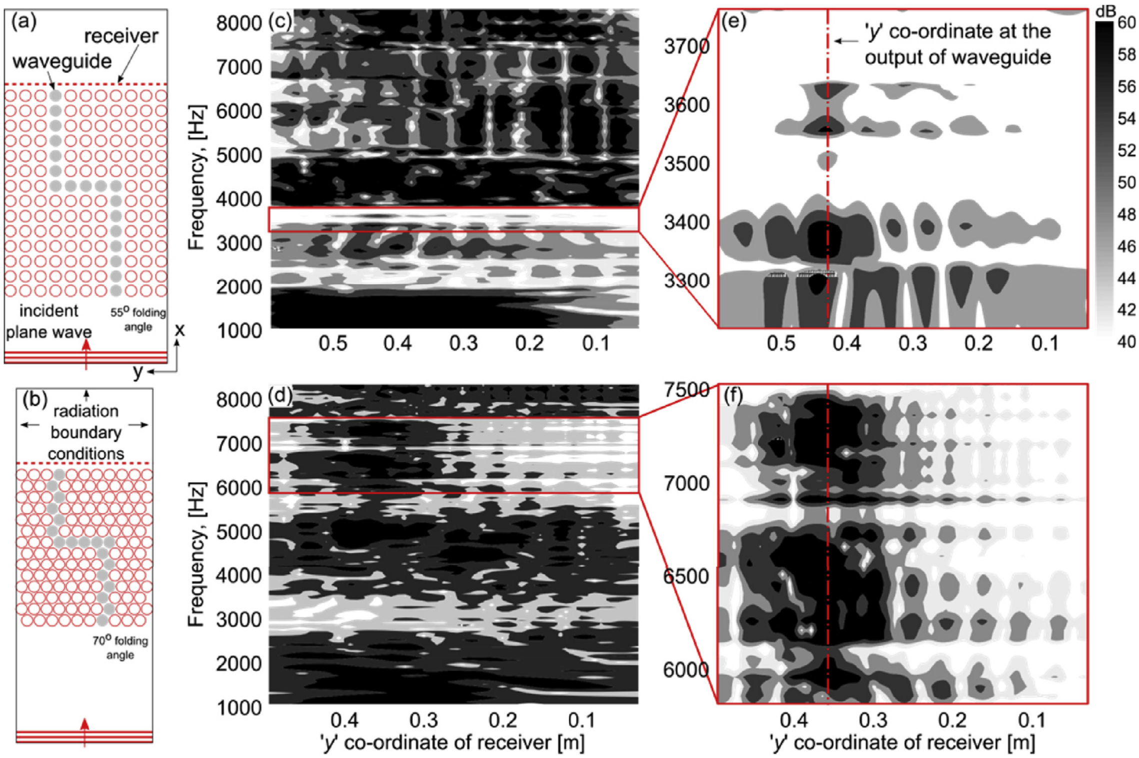

Fig. 3. Numerical acoustics simulations are performed on cross-section profile of origami phononic structure with complex-geometry waveguide; where (a), (b) are COMSOL models correspond to folding configurations at 55° and 70° respectively. Thick solid lines and arrow direction at the bottom of (a,b) represent the incident plane wave and outer boundaries are provided with radiation boundary conditions to reduce reflections. (c,d) are corresponding contour maps of sound pressure level (SPL, in dB) along line-receiver that is positioned at the output of waveguides across the width of structure (marked as horizontal dashed line in (a,b)) and (e,f) are zoomed in spectral regions of contour maps.

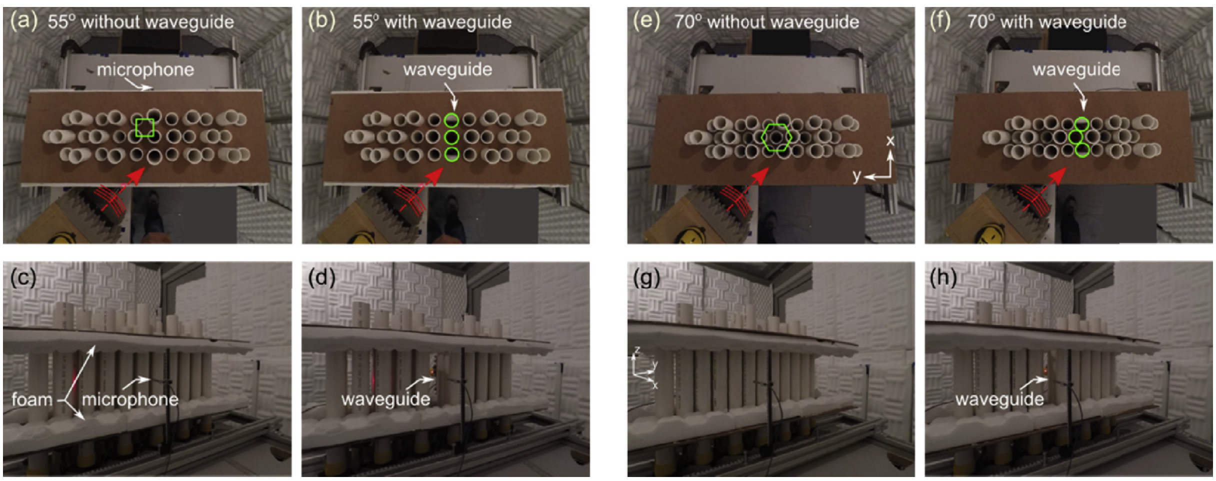

Fig. 4. Experimental setup of origami phononic structure with and without waveguide in different folding configurations. (a,e) and (c,g) are top and oblique views of origami structure without waveguide at 55° and 70° folding angle (where transformation in lattice topologies between square and hexagon can be seen via green polygons in top views), while (b,f) and (d,h) are corresponding of origami structure views with a straight-waveguide (where waveguide is formed by removing inclusions at locations represented by green circles in top views). The red arrow in top view indicates the direction of incident wave generated from the horn and the location of the microphone to measure the pressure at the output of waveguide can be seen in the bottom panels. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.2. Results and discussions

The SPL spectra of transmission is calculated, as the ratio of pressure measured by microphone to the reference pressure 20e-6[Pa], for the cases with and without waveguide and are given in Fig. 5(a,b). Firstly for the case without waveguide (green

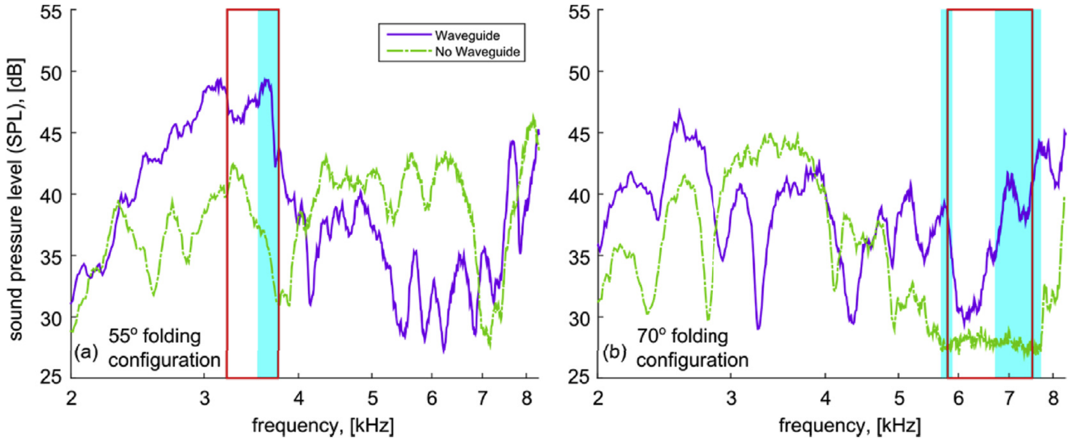

Fig. 5. (a,b) Sound pressure level (SPL, in dB) spectra of origami structure at (a) 55° and (b) 70° folding configurations. Green dash-dot and purple solid curves in (a,b) represent spectra recorded by the microphone positioned at the same location without and with waveguide respectively. The red rectangle represents the spectral region predicted by band structure analysis, where waveguiding is possible. Blue shaded spectral regions are areas with lowest transmission in origami structures for the case with no waveguide combined with high transmission in the presence of a waveguide. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

dash-dot curves in Fig. 5(a,b)), it should be noticed that there are regions of very low transmission at spectral locations that are coincident with complete bandgaps regions (represented by red rectangle) of origami phononic structure without waveguide. Now for the case with waveguide (purple solid curve in Fig. 5(a,b)), the transmission measured at the output of the waveguide is substantially increased inside the red rectangle compared to the case without waveguide – as predicted by simulation results in Figs. 2–3 – indicating that the wave energy is confined and propagating through the waveguide; these regions are highlighted as light blue shaded rectangular regions. Finally, it can be clearly seen that the spectral region where wave guiding occurs is drastically shifted by changing the folding configuration. Overall, these experimental results validate the analytical and numerical predictions and corroborate the findings that, folding in origami structures can be used as a means to drastically tune the waveguide frequencies. These results also provide us confidence to use the analytical and numerical 2D models to gain insights into the dynamics of wave propagation in origami phononic structures with waveguides.

5. Conclusion

In this research, we proposed a novel phononic structure based on origami architecture that can shift between different Bravais-lattice types for tunable waveguiding. Analytical and numerical simulation are performed on 2D models with simple and complex waveguide to predict the spectral range of waveguiding and also to demonstrate that the waveguide frequency can be drastically tuned via folding. Further, experimental investigation revealed that the spectral range of waveguiding can indeed be tuned and the results matched very well with theoretical findings.

Overall, this practical and scalable origami phononic structure with tunable waveguiding will be useful in various applications such as filters, multiplexers, de-multiplexers, energy harvesting, fluid sensors and structural health monitoring. Apart from tunable waveguiding features, being a scalable geometry, origami phononic structures can be used to manipulate waves across the spectrum, such as from low-frequency sound waves to hypersonic waves. In addition, this architecture could also be a primary candidate for fabricating phoxonic crystals with tunable waveguides where interactions between photons and phonons can be studied. Lastly, since the folding operation is a one-degree-of-freedom mechanism, the waveguide tuning can be achieved with minimum actuation effort and these features can be found useful in practical applications.

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