A metasurface radar for steering ultrasonic guided waves

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\textbf{ABSTRACT}

This article presents a new metasurface made of shape memory alloy (SMA) unit cells for steering ultrasonic guided waves in desired emitting directions. The philosophy behind the controllable wave steering performance of the metamaterial system resides in the tunability of its stopband. Such a tunable feature originates from the reversible dramatic variation of the elastic modulus of the shape memory element under the thermal loads. The research starts with the investigation of the adjustable bandgap behavior of the metastructure at different statuses from the scrutiny of the wave dispersive characteristics. Additionally, a systematic parametric study is carried out to unfold the bandgap evolution principle by changing the SMA stub height. Subsequently, numerical modeling of the wave steering behavior is performed by shifting the stopband of one sector within the unit-cell-ring away from the excitation frequency. The wavefield images associated with the wave directionality plots demonstrate that the thermally-activated metasurface area can open up a transmission path for the ultrasonic waves, while the rest portion will not allow guided waves to penetrate. By rotating the designated sector, the metamaterial structure could work like a wave emission radar, realizing the steerable unidirectional wave radiation from a single piezoelectric transducer. In the end, the targeting phenomena are validated by the Scanning Laser Doppler Vibrometry (SLDV) experimental tests. The proposed active metasurface system with the controllable ultrasonic wave interrogating capability may find its application for directional guided wavefield generation in future Structural Health Monitoring (SHM) and Nondestructive Evaluation (NDE) systems.

1. Introduction

Guided waves have been extensively investigated as a powerful tool for structural sensing attributed to their preferential features, such as the long propagation distance associated with little energy attenuation and high sensitivity to various damage types [1–3]. Control of guided wave energy is of great interest for enhancing the performance of guided wave based Structural Health Monitoring (SHM) system [4–6]. The directionality of guided wave generation may benefit the structural sensing purpose by allowing better detection and localization of the damage sites, creating desirable orientational sensitivity. Thus, the unidirectional wave emission approaches are attracting increasing attentions [7].

To date, a variety of investigations have been performed for searching the controllable-directionality beam emanation methods. One category originates from the wave generation mechanism itself on the directional wave transmitter design. Phased arrays of
piezoelectric discs could feature the directive radiation by imposing a time delay between consecutive excitation elements [8]. Furthermore, Salas and Cesnik proposed the Composite Long-range Variable-direction Emitting Radar (CLoVER) transducer, which could utilize individual wedge-shaped piezoelectric fiber composite sectors to interrogate the structure along a particular direction from the central location [9]. Senesi and Ruzzene presented another novel spiral Frequency Selective Acoustic Transducer (FSAT), which could perform directional guided wave generation through the frequency sweeping methodologies combined with the wave-number analysis [10]. The aforementioned creative sensor designs exhibited highly efficient performance on the directional wave emission.

In addition to the steerable-direction transducer designs, another category of the unidirectional wave emission methods takes advantage of the peculiar wave control capabilities of the elastic metamaterials. Elastic metamaterials refer to a family of artificially designed microstructural system with the bizarre and fantastic features beyond the natural materials. The metastructural system could work at the subwavelength scale with the local resonant response. Monopolar, bipolar, and quadrupolar local resonances have been proved to be the essential wave mechanisms to enable the abnormal effective properties of the metamaterial unit cells, i.e., negative bulk modulus [11–14], negative mass density [15–17], and negative shear modulus [18,19], respectively. These novel behaviors could render numerous appealing applications for elastic wavefield manipulation. Versatile attractive applications have been demonstrated, including, but not limited to waveguiding [20–24], focusing [5, 25], anomalous refraction [26,27], and cloaking [28–30]. Profited from the peculiar and valuable characteristics, the directional beam steering would be highly feasible via the metasystem’s modulation. Semperlotti et al. designed an anisotropic resonant metamaterial with flat equi-frequency contours to control the wave propagation unidirectionally [7]. Zhu et al. proposed a metalens using the principle of the acoustic drop-channel. By tuning the frequency of excitation, waves could be manipulated propagating along the designated orientation [31]. In addition, the directional flexural wave transmission was also demonstrated in a two-dimensional array of kirigami-decorated plate. The anisotropic effective mass densities in x and y directions supported the propagation of subwavelength flexural waves in one direction, while forming evanescent waves that decayed exponentially along another orientation [32]. They all could achieve the wave controlling functionalities by means of a single transducer and possess a finer angular resolution of the elastic wave emission compared with the directional transducer designs. Unfortunately, these metastructural systems could not allow the active tailoring of the wave interrogation along arbitrary directions. The passive metamaterial designs usually encounter the difficulties of featuring the controllable dynamic properties, once the unit cells have been fabricated. Such inherent shortcomings would considerably limit their adaptiveness for various applications. Nevertheless, the active metamaterials outperform the conventional ones for their tunable characteristics by incorporating the smart materials (shape memory alloys/polymers [33–39], piezoelectric materials [40–43], dielectric/electrorheological elastomers [22,44], and magnetic media [45–49]) via applying the external controllable activations (thermal, electrical, and magnetic stimuli). They are drawing burgeoning attentions over recent decades due to their superb capabilities for highly flexible wave manipulation.

Shape memory alloy (SMA) has been investigated as a desirable candidate for achieving active metamaterials. SMA refers to a special class of energy transduction material, processing the unique thermo-mechanical behaviors [50]. The mechanism behind the unique properties of nitinol, the most typical SMA, resides in the phase transformation between the martensite at low temperature with a relatively lower elastic modulus and the austenite at high temperature with a higher modulus. The crystallographic structure evolution induced by the varying temperature will render a dramatic stiffness change and shape morphing of the SMA. Such a fascinating phenomenon provides the feasibility for designing an SMA-constituted metamaterial whose natural properties can be highly adjustable, which would facilitate the controllable wave manipulation. Pioneer investigations have been performed towards adopting the SMAs as the active metastructural components. Ruzzene et al. had demonstrated the practicability of controlling wave propagation in periodic composite rods using the shape memory inserts as early as 2000 [33]. Sousa et al. proposed a metamaterial beam with the SMA resonators. The underlying martensitic phase and austenitic phase transformation for a sufficient temperature change enabled a significant shift of bandgap and bandwidth increase [36]. Chuang et al. designed a series of two-way-curved/flat-curved SMA structures. They perceived that the 2nd and 3rd bandgaps could be lowered and widened when the SMAs were thermally activated [34]. It was also reported that the controllable stopband behavior switched between Bragg scattering and local resonance mechanisms could be successfully attained [35]. The authors’ previous research has also numerically and experimentally demonstrated the effectiveness of the stubbed SMA metasurface design on the tunable ultrasonic elastic wave manipulation through a one-dimensional unit-cell-chain model [51]. Nonetheless, the investigations towards controlling the multimodal plate guided waves via the SMA structures are still limited. Additionally, the steerable directional ultrasonic wavefield generation approaches through the active SMA metamaterial designs are likewise absent.

This paper puts forward a new tunable metasurface to realize the adaptive directional manipulation of ultrasonic guided waves. SMAs are employed as the active elements in the unit cells. The elastic waves can be steered for emitting a unidirectional wavefield from a single piezoelectric transducer via the proposed metastructural systems. The investigation starts with the numerical scrutiny of the adjustable stopband behavior of the SMA pillarated unit cells over their dual-phase states. It further systematically explores the bandgap evolution patterns by varying the microstructural geometric parameters. Taking advantage of the tunability of the bandgap, the principle of the directional wave scanning phenomenon is illuminated via an elaborated unit-cell-ring model. Subsequently, the wavefield images as well as the quantitative wave directionality plots of the metamaterial radar are illustrated through harmonic analysis to demonstrate the unidirectional wave propagation. In the end, the full-region propagating wavefields inside the metamaterial plate are experimentally depicted by the Scanning Laser Doppler Vibrometry (SLDV) tests to validate and demonstrate the unidirectional wave emission performance.
2. Shape memory alloy metamaterial with tunable band behaviors

This section presents the systematic investigation of the metamaterial unit cell design. The stopband development and shifting phenomena associated with the crystal phase transformation of the SMA elements are appreciably exhibited. Additionally, a systematic parametric study on the SMA cylinder height unfolds the bandgap evolution trends, demonstrating the geometric sensitivity of the band features of the proposed metastructure.

2.1. Unit cell configurations and their band features

Fig. 1(a) illustrates the schematic diagram of the proposed SMA metamaterial unit cell structure. It is comprised of an SMA cylinder directly deposited on a 1-mm thick aluminum substrate plate. The height and radius of the pillar are 9 mm and 1.75 mm, respectively. The lattice constant of the unit cell is set to be 5 mm. It should be noticed that the spatial arrangement of the stubbed resonators would not affect the dynamic responses of the metamaterial system [52], which supports the annulus arrangement of the unit cells in the metamaterial ultrasonic radar prototype in Section 3. The material properties used for the unit cells are the following: Young’s modulus $E_{Al} = 70$ GPa; Poisson’s ratio $\nu_{Al} = 0.33$; $\nu_{SMA} = 0.33$; density $\rho_{Al} = 2700$ kg/m$^3$; $\rho_{SMA} = 6400$ kg/m$^3$. The phase transformation between martensitic and austenitic state of the SMAs due to the temperature variation can be numerically simulated by changing the elastic moduli of the pillars [36]. The stiffness of the martensitic structure was estimated to be 30 GPa, whereas the elastic constant of the austenite was designated to be 70 GPa (the values were provided by SuZhou Chuan Mao Materials Co., Ltd., the manufacturer of the SMAs in the experimental validation section). Bloch-Floquet periodic boundary condition was employed on the lateral surfaces of the unit cell using the finite element modeling (FEM) software package ANSYS 15.0 as presented in Fig. 1(b). Consequently, the ideal frequency-wavenumber domain dispersion characteristics of the elastic waves propagating through the infinite metasurface plate could be derived.

The tunable band structures of the metastructural system at different phases are displayed in Fig. 2. Fig. 2(a) displays the band
characteristic of the martensitic metastructure. The lowest three dispersive modes were labelled as stub mode 1, stub mode 2, and stub mode 3, respectively. Stub mode 2 exhibits a typical shear horizontal vibrational characteristic. On the other hand, stub mode 1 and stub mode 3 present the complicated coupling motions between the stub and the plate. As the representative cases, three mode shape images at point \( \alpha, \beta, \gamma \) on the three propagative dispersion curves are illuminated in Fig. 2(c) to clarify their natures. It is apparent that a complete stopband is opened up ranging from 50.44 - 68.30 kHz. The ultrasonic guided waves cannot pass through the metamaterial area within the corresponding frequency scope. Taking the frequency at the center of the band range (59 kHz) as an example, the ratios between the propagating fundamental Lamb-wave wavelengths in the pristine aluminum plate and the lattice constant of unit cell are 2.52 and 18.34 for A0 mode and S0 mode, respectively, demonstrating a subwavelength working regime of the metamaterial system. Moreover, it is perceptible that a selective, stub mode 1 and 2 bandgap is also formed at the relative low frequency covering 10.54 to 15.95 kHz. Only mode 3 is allowed to transmit within this frequency scope. However, the scrutiny of band 3 reveals that it exhibits the complicated coupling features, containing both longitudinal and flexural vibrational components. In this circumstance, neither of the two fundamental Lamb modes in the plate can be completely suppressed, except for the SH guided mode. Whereas, our previous investigation has demonstrated the intriguing selective Lamb mode phenomenon by a symmetrical, double-stub setup [53]. On the other hand, Fig. 2(b) portrays the dispersion relation of the unit cell system in the austenitic phase. The bandgap shifted upwards to a higher frequency range from 71.20 - 99.07 kHz as a result of the larger elastic modulus of transformed austenitic status of the SMA. Under such a circumstance, the proportion between the wavelength of the A0 (S0) Lamb wave mode and the unit cell dimension is 2.08 (12.76) at 85 kHz, still within sub-wavelength control range. The scrutiny of the vibrational motions of the martensitic stub in Fig. 2(d) unfolds that the complete bandgap is contributed by the longitudinal and shear horizontal stub modes, with the degenerate anti-resonance \( \delta (\epsilon) \) followed by the corresponding resonance \( \delta' (\epsilon') \). It should be noted that for mode \( \delta \), the wave vector resides along the \( \Gamma M \) direction. The diagonal-orientation vibration of pillar in the square lattice demonstrates a longitudinal characteristic. Such results of the band features depict the prominent stopband developing and tuning capabilities of the proposed SMA pillar metamaterial. Furthermore, it is foreseeable that, by delicately tailoring the wave excitation frequency and microstructural states in the metamaterial plate, the wave energy could be steered precisely. This mechanism provides the feasibility to actively control the wave propagation via the SMA unit cell design with thermal load controls.

### 2.2. Parametric study on the SMA cylinder geometric influence

The geometric parameters of the unit cell structure would significantly influence the performance of the metamaterial system. An in-depth understanding of the stopband evolution trend would benefit the attainment of an optimized design. As a demonstrative investigation, a parametric study towards the SMA stub height was performed. The height of the SMA cylinder was varied from 5 to 14 mm. Fig. 3(a) portrays the first bandgap location as a function of the SMA stub height for martensitic and austenitic systems. The markers denote the upper/lower bounds of the stopbands. Fig. 3(b) presents the variation characteristics of the first stopband width. It can be concluded that the band moves to a dramatically lower frequency region with the increment of the cylinder height. At the same time, the bandwidth tends to be noticeably narrower. The downwards movement phenomenon of the stopbands as a result of geometric parameter change can be interpreted as follows. The theoretical vibration mechanics depicts that the local resonant behaviors of a structure can be evaluated by \( \omega = (k/m)^{1/2} \), where \( \omega \) refers to the natural frequency, \( k \) represents the spring constant, and \( m \) indicates the mass. With the increment of the height of the SMA resonator, its effective stiffness \( k \) will become more flexible. Simultaneously, the effective mass \( m \) will increase. As a consequence, the resonance performance is shifted to a lower frequency range credited to the superimposed effect, giving rise to the significant decrease of the stopband. In accordance with the bandgap evolution principle, a
preferable design parameter can be selected catering to the targeting controllable frequency coverage. A 9 mm height SMA stub can render the common ultrasonic scope in SHM applications and was finally chosen as the preferential design to demonstrate the controllable wave manipulation capability of the proposed active metamaterial.

3. Numerical demonstration of the controllable unidirectional guided wave emission phenomenon

This section investigates the guided wave emission performance of a unit-cell-ring layout via FEM harmonic analysis to demonstrate the excellent wave manipulation capability of the SMA metamaterial system. The wavefield images and the directionality plots will illuminate the successful attainment of the selective unidirectional wave emission of the proposed adaptive metamaterial radar.

3.1. Configuration of the ultrasonic radar and conceptual rationale

The schematic plot and the zoom-in details of the proposed metasurface system are displayed in Fig. 4 (a) and (b). The SMA metasurface radar was constructed by depositing 180 stubbed unit cells on an aluminum plate which were delicately arranged in an annular pattern. The inner circle of the metasurface area has a radius of $r_1 = 30$ mm and that of the outer circle is $r_2 = 50$ mm. It should be noticed that the change of the internal and external radii of the metasurface area will influence the stopband band effectiveness on account of the variation of the stub depositing ratio and radial unit-cell number. Moreover, the alteration of the radii will also affect the unit-cell distance and resolution along the hoop-direction, which may significantly affect the wave energy transmission and thoroughness of wave-cell interaction. It is safely deducible that a meta ring structure with more unit cells along the radial direction and denser hoop-direction layout would provide a better directionality performance. The circumferential metamaterial surfaces were partitioned into 12 controllable sectors with the azimuthal resolution of 30°. Another annular-shaped aluminum plate area with the inner and outer radius of 55 mm and 100 mm served as the wavefield demonstration region, for the purpose of observing the directional wave propagation phenomenon. A piezoelectric wafer transducer with a size of $D\times 0.2$ mm was bonded at the center of the metamaterial area to generate omnidirectional symmetric and antisymmetric guided wave modes. Non-reflective boundaries were implemented surrounding the numerical setup to absorb the boundary reflections. The band structures presented in Fig. 2 have revealed that two non-overlapping stopbands can be developed and distinguished for the metamaterial system at the two SMA crystallographic structure states. As a consequence, when the excitation frequency falls within the stopband scope of the martensitic structures (room-temperature sectors), meanwhile, outside that of the austenitic surfaces (heating sectors), the elastic wave energy can only penetrate through the austenitic state sectors and emit from the particularly selected wave transmission gates. In a word, the directionality of the wave emission could be flexibly accomplished through delicately controlling the austenitic phase transformation inside the designated metasurface sectors via the thermal stimuli.

3.2. Controllable unidirectional wave transmission characteristics

To demonstrate the target unidirectional wave transmission phenomenon, as an illustrative case study, the crystallographic structures of the SMA stubs located within the 0–30° sector were transformed from the room-temperature state (martensitic phase) to heating state (austenitic phase). Fig. 4(c) displays the displacement frequency spectra of the metamaterial plate at the two selected representative sensing points #1 and #2, aiming at searching for an appropriate guided wave excitation frequency. It is obvious that, at 68 kHz, the ultrasonic elastic wave propagation prevails along the austenitic sector (large amplitude at point #1). On the other hand, it is nearly quenched in the martensitic metamaterial area (small response at point #2). As a consequence, 68 kHz can serve as an eligible candidate working frequency to demonstrate the directivity feature of the transmitted wavefield.

Subsequently, in order to provide an intuitive perspective of the directionally steered wave propagation, the equivalent stress...
wavefield of the metamaterial plate for the aforementioned case is illuminated in Fig. 5 (a), when the guided waves are excited at 68 kHz. It can be clearly observed that the wave energy propagates along the designated direction. Some inevitable wave leakage phenomena may arise from the edge effects of the metamaterial sectors.

Moreover, to further quantitatively evaluate the unidirectional wave emitting effectiveness, the steady-state out-of-plane displacement responses were extracted along the circular sensing line to portray the wave amplitude distribution transmitted through the metamaterial ultrasonic radar. It should be noted that the detailed wave directionality profiles may change slightly with the radius variation of the circular sensing line considering the wave energy attenuation as well as some wave interference effects (may appear as side-lobes in the directivity plots). However, the major wave directive emitting phenomenon and the orientational distinction would not be affected much, as evidently demonstrated in Fig. 5. The obtained directionality plot of the wavefield is exhibited in Fig. 6 (a).
using the polar coordinate. The inserted blue roundlets in the graph depict the shape memory alloy pillars in the martensitic phase, while the brown ones indicate the austenitic unit cells. It is apparent that the displacement response is constrained in the emitting region covering 0°–30° with negligible penetrations along other orientations. Thus, the austenitic sector opens up a transmission path for the ultrasonic guided waves, presenting an excellent resolution for the wave directionality control.

Additionally, in order to demonstrate the capability of the metasurface radar to fulfill a full-circumference directional beam radiation, five more cases with varieties of emitting angles were numerically simulated, covering a semi-circle tunable region (due to the centrosymmetric characteristic of the metamaterial radar). Fig. 5 (b)-(f) illustrate the equivalent stress nephograms of the metasurface plate at 68 kHz with the austenitic phase transformation taking place in the SMA sectors of 30°–60°, 60°–90°, 90°–120°, 120°–150°, and 150°–180°, respectively. It can be observed that the controllable wave transmissions with arbitrary azimuths were achieved. Likewise, Fig. 6 (b)-(f) present the wave directionality plots of the metamaterial radar corresponding to Fig. 5 (b)-(f), respectively. The ultrasonic beam can be swept over a full field coverage. Such an SMA metastructural design may provide a new paradigm for selective unidirectional elastic wave emission from a single omnidirectional wave source.

4. Experimental verification of the scanning radar phenomenon

Experimental demonstration will be delivered in this section to substantiate the controllable unidirectional wave manipulating capability of the proposed metamaterial radar. Selective and scanning wave emission phenomena will be presented through the wavefield visualization using the Scanning Laser Doppler Vibrometry (SLDV) measurements.

4.1. Experimental setup

In order to validate the numerical results of the controllable wave steering effect, the SLDV tests were carried out to visualize the wavefield propagating inside the metamaterial plate [54]. Fig. 7 illuminates the experimental setup and zoom-in details of the metamaterial plate. An annular array of SMA unit cells was deposited on the aluminum substrate, encircling the central piezo wafer. Damping clay was implemented surrounding the plate to eliminate the boundary reflections. The laser scanning area was coated by the reflective tape to enhance the intensity of planar surface reflection. A physical black arrow marker was drawn on the plate to indicate the orientational layout of the tested specimen. Six fan-shaped heating patches were attached on the opposite side of the plate underneath the SMA microstructural area, covering a half-round controllable region in all. They were loaded by the DC power supply and served as the thermal sources to trigger and control the phase evolution of the SMA cylinders (Fig. 7 (c)). The SMA was tailored with the transformation temperature around 55 °C (provided by SuZhou Chuan Mao Materials Co., Ltd.). It would sufficiently transform into austenitic phase from martensitic structure above such a temperature, considering no external mechanical loads were exerted on the pillars. The temperature contour images were captured by the infrared thermometry to monitor the working temperature and ensure the full accomplishment of the austenitic transition. During the experimental test, a 50-count Hanning window modulated sine tone burst was generated by the Keysight 33500B arbitrary function generator. The excitation waveform was further amplified to 100 Vpp by the Krohn-hite 7602 M wideband power amplifier and was applied on the circular piezo wafer. Elastic waves generated by the piezoelectric transducer would propagate omnidirectionally into the metamaterial surfaces and undergo the substructural interactions with the unit cells. Thereafter, the wavefield outside the metamaterial region would be picked up by the SLDV, post-processed by the Polytec system, and showcased as the visualized wavefield images. The effectiveness of unidirectional wave propagation would be experimentally demonstrated at 68 kHz, at which the displacement wavefield along austenitic metasurface path exhibited a notable response, while that within the martensitic area was suppressed in our numerical prediction (Fig. 4 (c)). Additionally, it should be noted that experimental validation would be performed merely over a semi-circle coverage as the demonstrative verification due to the...
centrosymmetric feature of the metasurface system.

4.2. Transmitted wavefield of SMA ultrasonic radar

Six rounds of tests were carried out to demonstrate the wave steering characteristics of the SMA ultrasonic radar. The heating patches underneath the metamaterial area covering 0–30°, 30–60°, 60–90°, 90–120°, 120–150°, and 150–180° were activated in turns. Fig. 8 presents the temporal-domain snapshots of the propagating wavefields imaged by the SLDV system. The insets illustrated in the figure show the experimental wavefield images and the infrared images of the metamaterial plate with the corresponding sectors under thermal activation. Fig. 9 displays the experimental wave directionality plots of the metamaterial ultrasonic radar with the corresponding sectors under thermal activation.
figures portray the infrared images of the thermally-stimulated metasurface areas in each scenario. The highlighted temperatures in the callout textboxes were recorded by the infrared measurement system (the dark yellow roundlet represents the circular piezo wafer; it should be noticed that the highest temperature over the metamaterial plate may not happen at the central location of the heating zones; the heating zone central temperatures are given by the call-out textbox). It can be observed that the elevated temperature area mainly localized within the controlled ranges, albeit of some inevitable thermal dissipation attributed to the heat conduction effect, illuminating the candidate wave passing tunnels. Indeed, the wave velocity fields identify that the ultrasonic waves propagated through the designated paths with negligible leakage along other orientations, rendering an excellent consistence with the heating zones. By activating the thermal patches in sequence, multiple wave emission directions were attained as shown up in Fig. 8(a)-(f). Fig. 9 displays the experimentally derived directionality graphs. It can be also distinguished that the elastic waves were manipulated to propagate along the targeting orientations, corroborating with the numerical simulations. The slight discrepancies between the numerical observation and experimental results may have arisen from the material property deviations, heating zone inaccuracies, influence of the bonding layers, and the thermoelastic behaviors. Nevertheless, the directional guided wave emission paths can be explicitly discerned, demonstrating the effectiveness of the controllable wave steering phenomena of the metamaterials system from the practical perspective. The presented SMA metasurface radar provides a new and alternative approach to achieve the steerable unidirectional ultrasonic guided wave emission by utilizing a single piezoelectric wafer transducer. It possesses the potential capability to send the ultrasonic interrogating wave energy into a preferential direction. The directional sensitivity of guided wave based structural sensing systems would be dramatically increased, which may benefit the precise damage localization and identification in future SHM and NDE applications.

5. Concluding remarks and suggestions for future work

This article innovatively put forward a new metamaterial radar to achieve the steerable unidirectional ultrasonic guided wave emission. The radar consists of a series of SMA stubbed microstructures arranged in a ring fashion. The dramatic elastic modulus variation of the SMA pillars under the thermal loads provided the feasibility to actively control the guided wavefield. The research began with the numerical investigation of the stopband development as well as the band structure shifting phenomena of the metamaterial system by adopting the elastic stiffness of the SMA stubs at their corresponding crystallographic material statuses. It was found that a change from martensite to austenite phase rendered a much higher frequency and wider range bandgap. Subsequently, a series of systematic parametric studies were carried out on the geometry influence. It was found that the stopband showed a lower frequency and narrower bandgap trend with the increment of the SMA cylinder height. In addition, a demonstrative unit-cell-ring model was elaborately designed. The tunable and directional wave emission phenomena were demonstrated by shifting the bandgaps of the designated sectors away from the excitation frequency to form the wave transmission channels. The wavefield images associated with the quantitative directionality plots indicated the successful attainment of the controllable unidirectional wave manipulation. In the end, the SLDV experimental tests further substantiated the fabulous directive wave control capability of the proposed SMA metamaterial radar from a practical perspective. The experimental measurements agreed well with the numerical predictions. Such a novel tunable metasurface radar concept puts forward an alternative approach to achieving the steerable ultrasonic guided wave emission by utilizing a single piezoelectric wafer transducer. It provides an enabling method for the next generation unidirectional wave generation facilities, which may find the promising application potential for future SHM and NDE purposes.

CRediT authorship contribution statement

Yihao Song: Writing – original draft, Writing – review & editing. Yanfeng Shen: Methodology, Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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