Thermally reconfigurable helical shape memory alloy–based metamaterial

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This paper presents our investigation and experimental validation of a thermally reconfigurable shape memory alloy (SMA)-based metamaterial with the offered degree of freedom of SMA mechanical features. The metamaterial unit cell consists of a two-way helical SMA acting as the resonator element and a cartridge heater for controlling the excitation temperature of the helical SMA. Experimental results of electrical control of the cartridge heater's excitation temperature show that as the temperature increases from room temperature (25°C) to approximately 92°C—corresponding to input DC voltages of 0 and 4 V, respectively—the metamaterial structure acts as a switchable absorber with an absorptivity of 97.2% and a reflector with a reflectivity of 89.4% at 7.13 GHz. Additionally, it deforms to its initial state as the temperature decreases to room temperature.

Introduction: Metamaterials are artificial electromagnetic structures with a strong ability to control electromagnetic waves. Over the past decades, metamaterials have received considerable attention and have become an important research topic because of their unusual properties, which are not exhibited by materials found in nature. Therefore, the concept of metamaterials has shown several remarkable phenomena and applications such as negative refractive indices [1], invisibility cloaking [2], superlensing [3] and analogue computing [4]. Most metamaterials reported thus far are passive; that is, their functions are fixed after fabrication [5, 6]. Some metamaterials are designed such that their functions change with a change in the polarisation of the incident electromagnetic wave. However, this feature is difficult to achieve practically, because the polarisation of the incident electromagnetic wave is essentially fixed. Therefore, a tunable metamaterial whose function can change under a fixed polarisation of the incident wave is considered the best option for practical applications.

Active reconfigurable metamaterials have practical applicability because they have multifunctionality without requiring additional fabrication [7, 8]. Several technologies have been proposed to achieve reconfigurability and tunability in these materials. For instance, varactors, p-i-n diodes and transistors have been used for achieving high tuning speed or for real-time applications [9]. Microfluidic technology has also been proposed to tune the states of metamaterials. Continuous frequency and phase tuning can be achieved via control of the movement of liquid droplets in tubes. However, the reconfiguration speed of these technologies is insufficient. The advancement of material technology has recently spurred research interest in artificial muscles with various actuation mechanisms, for example, shape memory polymers (SMPs) or shape memory alloys (SMAs) [10, 11]. In previous designs of smart material (SMP or SMA) based mechanical metamaterials, external excitation sources such as electric heaters were widely used to change the operating states of the metamaterials. However, this technique is inadequate to control due to the far distance of the heater control, and it is also unreliable in practical applications.

In this work, we experimentally realise a reconfigurable metamaterial using a helical SMA with the two-way shape memory effect. In contrast to the conventional design that uses external temperature excitation, our proposed design incorporates a cartridge heater in the metamaterial unit cell to electrically control the excitation temperature of the helical SMA. Experimental results of electrical control of the cartridge heater's excitation temperature show that the metamaterial structure functions as a switchable absorber and reflector as the temperature increases from room temperature (25°C) to approximately 92°C and also that it deforms to its initial state as the temperature decreases to room temperature.

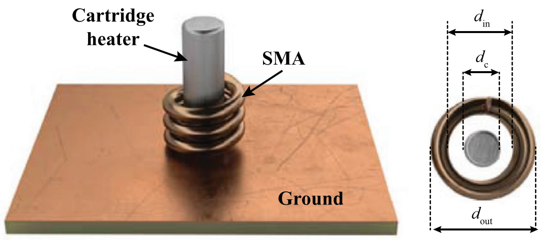


Fig. 1 *Schematic illustration of viewing geometry of thermally reconfigurable helical-SMA-based metamaterial*

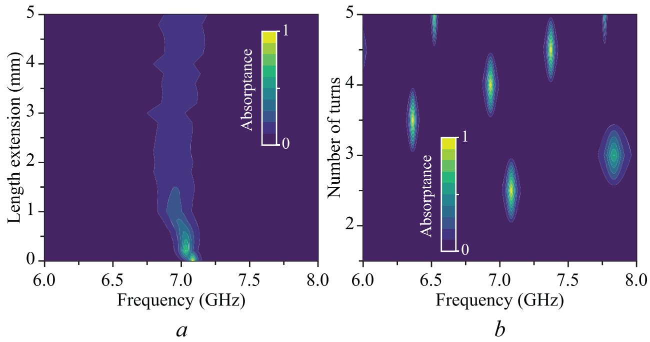
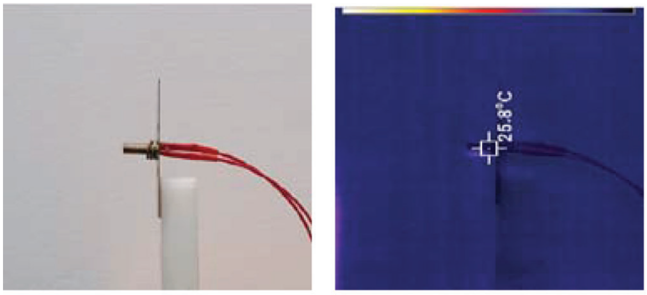


Fig. 2 *Numerical simulation results of thermally reconfigurable metamaterial under variation of two different parameters of SMA. (a) Length extension of SMA from 0 to 5 mm with step size of 0.2 mm. (b) Variation of number of SMA turns from 1.5 to 5 with step size of 0.5 when coil radius and pitch are 4.3 mm and 1.8 mm, respectively*

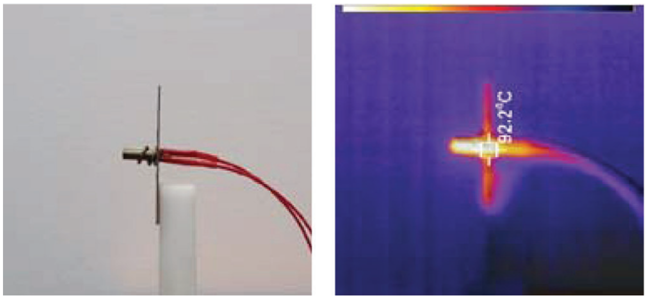
Thermally reconfigurable metamaterial: The schematic geometry of the proposed thermally reconfigurable metamaterial is illustrated in Figure 1. The unit cell of the metamaterial structure comprises a two-way helical SMA acting as a resonator element and a cartridge heater loaded inside the SMA to electrically control the excitation temperature of the helical SMA. The loading of the cartridge heater inside the SMA can be advantageous for individual control of the unit-cell elements for future extension design. The physical dimensions of the proposed structure are as follows: $d_{out} = 10.4$ mm, $d_{in} = 6.8$ mm, $d_c = 6$ mm, $h = 5$ mm and $h_c = 20$ mm; here, d_{out}, d_{in} and h denote the outer and inner diameters and height, respectively, of the helical SMA in the initial state; and d_c and h_c denote the diameter and height, respectively, of the cartridge heater.

We performed a full-wave electromagnetic simulation using the Ansys HFSS (high-frequency simulation software) simulator to demonstrate the electromagnetic functionality of the design. The simulation model of the two-way helical SMA was generated on the basis of the geometry shown in Figure 1. A parametric study of the helical SMA was conducted under two different conditions to investigate the effects of its extended length and number of coil turns. It should be noted that the extended length of the SMA is obtained under application of heat corresponding to the input voltage applied to the cartridge heater. The numerical simulation results of the proposed thermally reconfigurable metamaterial are shown in Figure 2. The structure behaved as an absorber with an absorptivity of 98% at 7.08 GHz in the initial state (zero extension) and as a reflector at the extended length of the SMA (see Figure 2a). As observed from Figure 2b, the design can be realised as an absorber at different coils turns. However, for our proposed design, we selected the minimum number of turns at which the structure behaved as an absorber at 7.08 GHz, which was 2.5.

Fabrication and experimental measurement: To experimentally validate the electromagnetic functionality of the proposed design, we fabricated a prototype of the thermally reconfigurable metamaterial, as shown in Figure 3. The experimental measurements of the fabricated prototype were performed in a waveguide environment. The waveguide (no. HD-70WCA2.92K, frequency range of 5.38–8.17 GHz) was procured from Fairview Microwave, Inc. Before measuring the electromagnetic



a



b

Fig. 3 *Photograph of fabricated prototype (left) and its corresponding thermal image (right) at different input DC voltages. (a) 0 V. (b) 4 V*

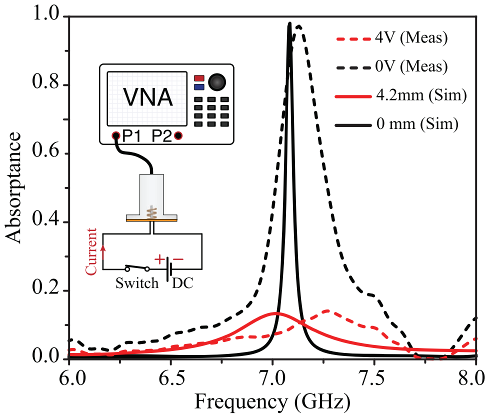


Fig. 4 *Comparison of numerically simulated and measured absorptivities and reflectivities of the proposed structure at input voltages of 0 and 4 V corresponding to extended SMA lengths of 0 and 4.2 mm, respectively*

response of the structure, we examined the effect of the helical SMA at different input voltages of 0 and 4 V, as shown in Figure 3. As observed from the thermal image in Figure 3, the extended length of the helical SMA increased to approximately 4.2 mm when the input voltage was at 4 V (which corresponded to approximately a 92°C temperature). This helical SMA has a two-way memory; therefore, it can self-recover to its original shape (Figure 3a) when the temperature is decreased to room temperature. Next, we measured the electromagnetic functionality of the fabricated prototype, wherein the rectangular waveguide was connected to an Agilent E5071C vector network analyzer (VNA). Comparison of the simulated absorptivity and measured absorptivity of the structure (Figure 4) revealed good agreement between the simulation and measurement results. The prototype behaved as an absorber with an absorptivity of 97.2% at 7.15 GHz and 0 V. In contrast, it behaved as a reflector over the entire incident frequency range at 4 V with a reflectivity of 89.4% at 7.15 GHz.

Conclusion: This study demonstrated the design, realisation and measurement of a thermally reconfigurable helical-SMA-based metamaterial in the microwave frequency region. The proposed metamaterial was designed to include a cartridge heater for electrical control of the excitation temperature of the helical SMA. For experimental validation of the proposed concept, a prototype metamaterial structure was fabricated and tested in a waveguide environment. Good agreement was found between the simulated and measured results of the electromagnetic functionality of the prototype structure. At zero input voltage, the structure behaved as an absorber with an absorptivity of 97.2% at 7.15 GHz. At a high input voltage of 4 V, the structure behaved as a reflector, whereby it reflected all frequencies of the incident wave with a reflectivity of 89.4% at 7.15 GHz. Since the proposed concept was demonstrated in the waveguide, this concept can also be extended to the realisation of an individually controllable thermal metamaterial on a larger scale.

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Conflict of interest: The authors declare no conflict of interest.

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