

Reconfiguration of Electromagnetic Metasurfaces Using Tunable Shape Morphing Structures

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Abstract—Reconfigurable metamaterials and metasurfaces are of interest for a variety of functionalities for next-generation communications and sensing. However, electronically controlling large arrays is difficult, and traditional PCB technology has limited capabilities for conforming to curved surfaces. We demonstrate the use of novel magnetically reconfigurable shape morphing structures for metasurface applications. The reconfiguration is performed using a quasi-DC magnetic field, which decouples the electrical control problem from the electromagnetic design. In addition, the magnetic composite is flexible and can conform to various shapes. We have previously demonstrated the use of these structures for reconfigurable on-off filters. We also demonstrate fully wrapped conformability to cylindrical shapes.

Index Terms—metamaterials, metasurfaces, magnetic polymer, conformal metasurfaces.

I. INTRODUCTION

Metasurfaces are a class of planar periodic structures that have been investigated for a variety of electromagnetic (EM) functions, including filtering [1], polarization control [2], beamforming [3], and cloaking [4], among others. To make such systems reconfigurable for next-generation communications and sensing, electrically switched or tuned elements are used, such as PIN diodes, varactors, or MEMS switches. However, the bias lines required to actuate such devices must be carefully designed and routed to have minimal impact on electromagnetic performance. It becomes more difficult to route these lines for large arrays. One alternative is mechanical reconfiguration, wherein the physical structure can be altered [5], [6]. Additionally, it is desirable for metasurfaces to be able to conform to non-planar shapes and structures. The applications may demand that these metasurfaces are mounted onto curved structures such as aircraft fuselages. However, the conformability of most standard PCB technology is limited.

To address these limitations, we propose the use of novel magnetically actuated, shape morphing materials for reconfigurable metasurface applications. The concept is broadly illustrated in Fig. 1. When no magnetic field is present, the unit cells take on a deployed, unfolded shape. When a magnetic field is applied, the unit cells contract into the folded state. A conductive pattern can be designed on the unit cell such that the two magnetically actuated states exhibit unique desired electromagnetic properties. Because the shape morphing material is flexible, it can also conform to a wide

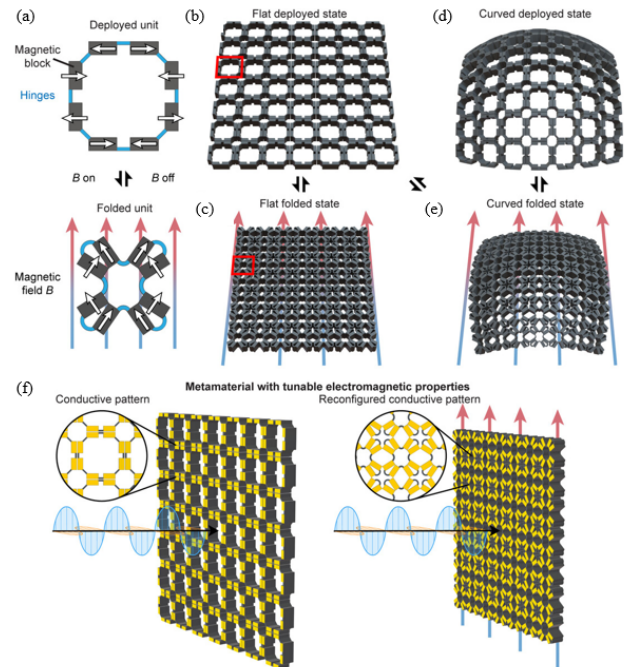


Fig. 1. Magnetically reconfigurable metasurface concept. (a) Unit cell in deployed and folded states. Full arrays in deployed (b) and folded (c) states for a flat configuration. Full arrays in deployed (d) and folded (e) states for a curved, conformal configuration. (f) Metallized array in deployed and folded states [7].

range of shapes. We have presented our preliminary results for reconfigurable metasurface filters based on this technology [7]. We have extended the work on the shape morphing structure towards bilayer metamaterials with global area preservation [8].

In Section II, details are provided about the shape morphing structure itself, originally presented in [7]. We present reconfigurable EM metasurfaces based on the technology in Section III, including on-off filters [7] and fully wrapping conformal structures. Section IV concludes the paper.

II. SHAPE MORPHING STRUCTURE

The shape morphing unit cell is comprised of eight magnetic blocks joined around the perimeter by thin hinges, as illustrated in Fig. 1 [7]. The unit cell is fabricated as one piece by creating a mixture with a commercial silicone material and hard-magnetic NdFeB particles, which is cured

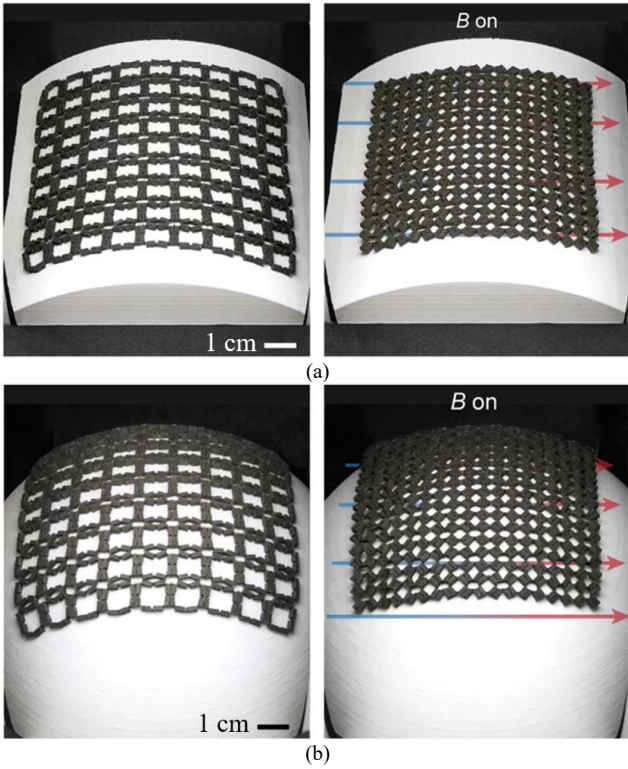


Fig. 2. Experimental demonstrations of magnetically actuated shape-morphing structures conforming to (a) cylindrical and (b) spherical substrates [7].

in a mold. The percent volume of NdFeB particles can be tuned to adjust the magnetic and mechanical properties of the structure. The magnetic blocks are then magnetized with the orientations shown in Fig. 1(a). The unit cells take on the deployed state when no magnetic field is present. The magnetic blocks are magnetized such that they rotate into the folded orientation when actuated by a static external magnetic field. Following the removal of the applied magnetic field, the metamaterial returns to the deployed state due to the stress caused in the structure by the field. Alternatively, a magnetic field can be applied in the reverse direction to promote morphing back to the deployed state.

Full arrays are fabricated by assembling the magnetized unit cells together using an adhesive. Due to the flexibility of the magnetic polymer, these arrays can conform to various shapes, as demonstrated in Fig. 2 [7]. The shape morphing is exhibited despite the curvature of the underlying structure. As such, these materials are a promising candidate for conformal metasurfaces. For these experiments, a pair of single-axis Helmholtz coils were used to generate a homogeneous magnetic field of 60 mT. A magnetic field of 15 mT in the reverse direction assists morphing back into the deployed state. The switching time is less than one second.

III. MAGNETICALLY RECONFIGURABLE METASURFACES

The magnetic blocks provide an area that can be metallized to realize a desired electromagnetic response for each state of the unit cell, as shown in Fig. 1(f). The metallic patterns may be realized by laser etching copper tape. As a

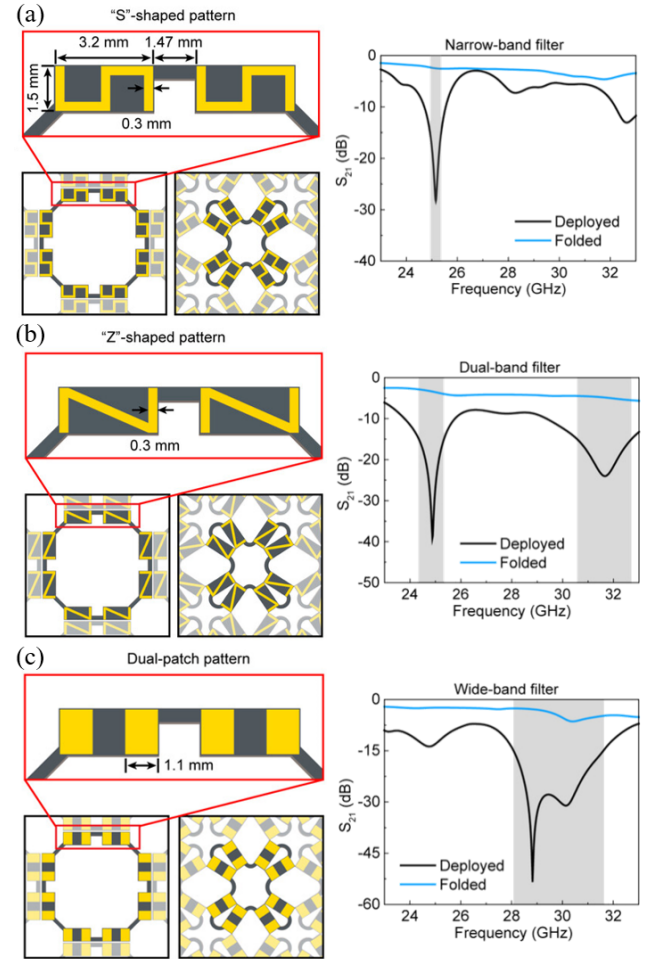


Fig. 3. Infinite-array simulation results for various patterns on the first-generation metamaterial. (a) “S”-shaped pattern with narrowband filtering. (b) “Z”-shaped pattern with dual-band filtering. (c) Dual-patch pattern with wide-band filtering [7].

demonstration of the technology, we have designed various on-off filters [7].

A. Filtering Metasurfaces

The unit cells for the filtering metasurfaces were designed in an infinite array environment using Floquet ports. The three filter designs are shown in Fig. 3 [7] with the simulated unit cell response. The narrow-band filter design uses “S”-shaped patterns on the magnetic blocks. The length of the line adds inductance, while the bends and the coupling between adjacent “S” patterns add capacitance. At 25.1 GHz, the inductance and capacitance of the unit cell resonate and reject the incident wave. The bandwidth (where $S_{21} < -15$ dB) is narrow, covering 24.9–25.3 GHz. In the folded state, the capacitance is altered due to the change in coupling between “S” elements. As a result, the resonance frequency shifts out of band and the metasurface passes the entire 23–33 GHz band with < 5 dB of insertion loss. The “Z”-shaped pattern behaves similarly, but there are two resonances, resulting in a dual-band filter. The stopbands are at 24.4–25.4 GHz and 30.7–32.7 GHz, respectively. Finally, the dual-patch pattern has two

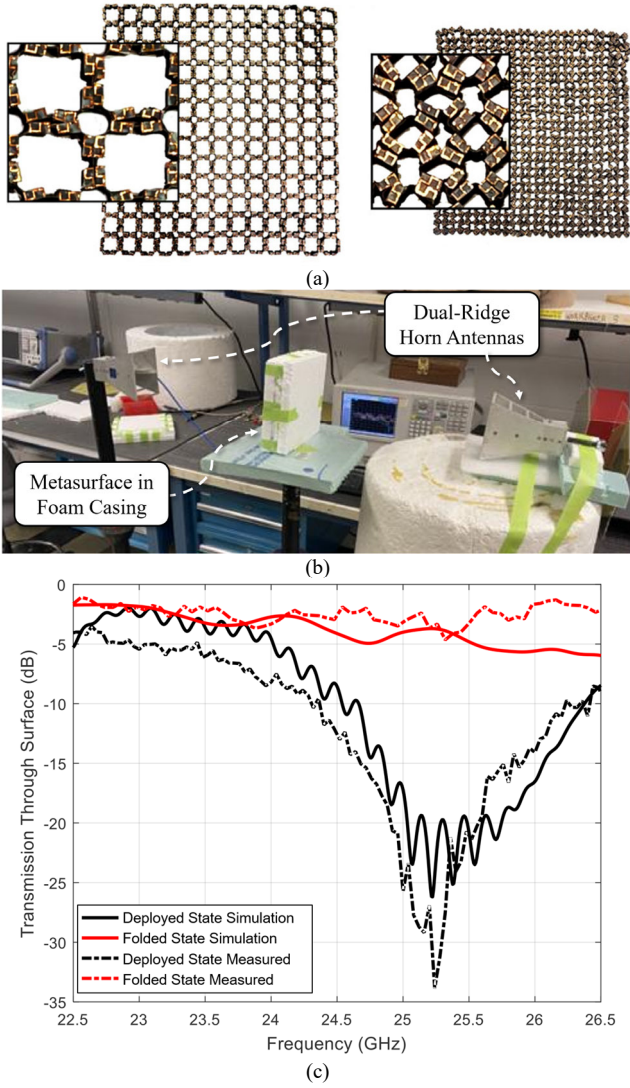


Fig. 4. (a) Images of the deployed and folded shape memory polymer based metasurfaces [7]. (b) Image of the test setup using two dual-ridge horn antennas. The metasurface is encased in foam for structural stability. (c) Measured and simulated transmission data for the deployed and folded states.

closely spaced resonances, resulting in a wide stopband at 28.1–31.6 GHz.

The narrow-band design was selected for fabrication and testing. A finite array with the “S”-shaped patterning was constructed using the assembly procedure described in Section II. To approximate the behavior of an infinite array, the transmission characteristic of the fabricated metasurface was tested using a pair of dual-ridge horn antennas. It was found that an array size of 13×13 was suitable for this experiment. Because the metal housings for the Helmholtz coils would cause undesired effects in the measurement setup, an alternative shape-memory polymer was used to fabricate the arrays. The polymer can be “frozen” in the folded or deployed state, permitting each configuration of the metasurface to be tested without requiring the external magnetic field.

The arrays and test results are shown in Fig. 4. The experimental results are compared with a finite array

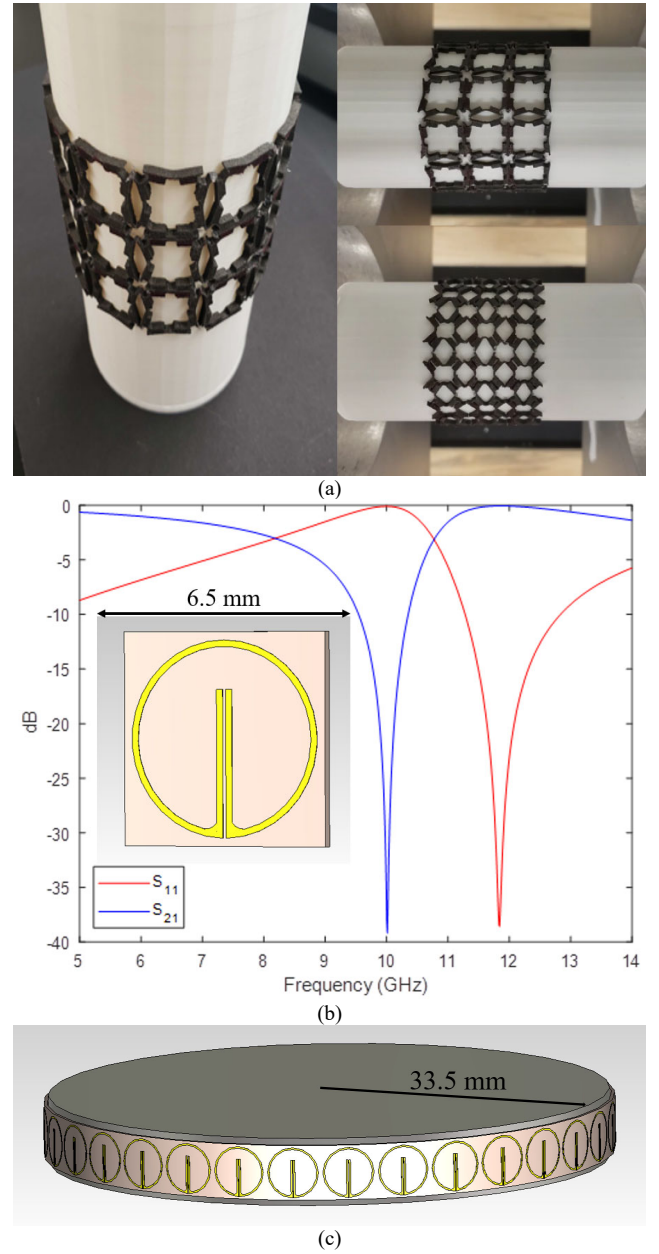


Fig. 5. (a) Demonstration of fully wrapping the magnetically reconfigurable unit cell from [8] around a 67 mm diameter cylinder. The unit cells can be arrayed along the length of the cylinder, and the shape morphing properties are intact. (b) Infinite array simulation results for a subwavelength ($\sim \lambda/5$) SRR unit cell with a resonance at 10 GHz. (c) Illustration of the unit cell fully wrapped around a cylinder mimicking the structure in (a).

simulation conducted with CST Microwave Studio. The experiment and simulation show similar trends with each other and with the infinite array simulation. The measured array’s stopband in the deployed state is 24.6–25.7 GHz. In the folded state, the array passes the entire measured band with < 5 dB of insertion loss. Some deviation of the measurement result from the simulation is expected due to geometrical variations of the magnetic structure in the finite array. The results validate the reconfigurable filter design and

pave a path towards further development of magnetically actuated shape morphing metasurfaces.

B. Fully Wrapped Conformal Metasurfaces

The morphing metasurfaces are able to conform beyond the open boundary topographies, as seen in Fig. 2, and can be utilized to completely surround a given structure. Placing the magnetically reconfiguring cells around a structure allows for control over the electromagnetic response from all directions. Moreover, the reconfigurability provided by these structures enables additional features such as frequency tunability, polarization control, or responses to variation in incident angle for objects fully enclosed by the metasurfaces, such as small vehicles.

The unpatterned unit cells from [8] can be wrapped around a cylindrical shape without degradation to the shape morphing performance, as shown in Fig. 5(a). The unit cells can be arrayed along the length of the 67 mm diameter cylinder. We propose to wrap layers of the reconfigurable metasurface with tuned electromagnetic parameters around a cylindrical object. Simulation results are shown for an infinite planar array of split ring resonator (SRR) unit cells in Fig. 5(b). For the SRR with a side length of 6.5 mm, a resonance appears at 10 GHz with a 10 dB bandwidth of 800 MHz. The SRR has a unit cell width of approximately $\lambda/5$, making the electrically small SRR suitable for mounting onto the magnetic blocks in the unit cell of the shape morphing structure. Fig 5(c) illustrates fully wrapping 32 SRR unit cells around a 67 mm diameter cylinder. We plan to present the fabrication and testing results for a fully wrapped conformal metasurface at the meeting.

IV. CONCLUSION

We have demonstrated reconfigurable metasurfaces with filtering capabilities based on a novel shape morphing structure. The structure is fabricated from a polymer mixed with hard magnetic particles, then magnetized to morph into the desired shape under an applied magnetic field. Due to the flexibility of the magnetic polymer, the shape morphing structure can conform to various shapes. We demonstrated a narrow-band on-off filter using this technology. We have shown the shape morphing material to fully wrap around cylindrical structures and will present additional fabrication and measurement results at the conference.

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