Shape-morphing polymers for tunable frequency selective surfaces and reflectarray elements

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***Abstract*— This work presents a route to rapidly configuring electromagnetic metamaterials and elements such as reflectarrays from a generic 'blank'. The concept is based upon the thermal-shrinkage properties of prestrained polystyrene (PPS), which is utilized in two distinct designs: In the first, an array of resonant split rings is printed upon a sheet of PPS. It is shown that heating to near the glass transition temperature of the sheet can controllably shrink the entire structure, thereby tuning its spectral transmission or reflection. A second application is to make coupled resonant elements, one of which is placed on a hinge of PPS that can be deformed via optical illumination, providing an optical route to tuning the resonance. This kind of element can show a large range of phase shifts in the reflected radiation, and opens the door to the creation of optically configurable reflectarrays.**

***Keywords*— shape-morphing, microwave, kirigami, metamaterial, reconfigurable**

I. INTRODUCTION

Electromagnetic metamaterials have revolutionised the design of antennas, superscatterers, reflectarrays and many other electromagnetic components over the last decade. Currently however, once a material is designed and fabricated, its properties are fixed - unless each unit cell is fitted with a complex array of electronics, which adds significant weight, bulk and cost. An interesting alternative to this has been the use of photoactive components to optically tune the behaviour of an array[1], which negates the need for complicated circuitry, but still requires the use of a projector. A family of materials that could be fabricated as a 'blank', and then readily altered in situ, would therefore have a myriad of applications.

One route to achieve this is the use of shape-morphing materials. These materials will alter their geometries in a controlled way on the application of a stimulus, typically heat, light or moisture, although others are available[2]. An everyday example of a shape-morphing material is prestrained polystyrene (PPS), which is commonly used as a hobbyist material (known as "shrinky-dinks", or "shrinkles"). Through the application of kirigami techniques, this material has demonstrated the capacity to form complex 3D structures from a folded sheet on the application of light or heat due to its extreme shrink factor[3].

In this paper, we demonstrate the potential of prestrained polystyrene to create rapidly tuneable components via two practical examples. In the first case simply by shrinking a frequency selective surface (FSS) via heating in order to alter its resonant frequency, and in the second by controllably tuning the resonance of individual elements via optical illumination, which is the first step to creating rapidly configurable reflectarrays.

II. THERMALLY CONFIGURABLE FREQUENCY-SELECTIVE SURFACES

A simple demonstrator to introduce the concept of heat-shrinking materials is to simply print a frequency selective surface upon a sheet of PPS and demonstrate that the heat-induced change in the geometry of the sheet alters the resonant frequency. This is shown in Fig. 1: a square array of split rings are printed on an A4 sheet of PPS using conductive silver ink applied through a machined latex stencil. Silver ink is advantageous compared to solid metal, due to its flexibility, and it was found that a continuous silver layer was maintained for each element at every level of shrinkage explored. The samples were placed in an oven at around the glass transition temperature for differing times: Table 1 shows the times and heat conditions for each sample. As can be seen in Fig. 1a, the longer the sample is in the oven, the greater the shrinkage – Array 5 is reduced to nearly a third of its original size. As the silver ink is able to compress with the PPS, the resonant elements shrink with the sample. Fig. 1b shows the transmission (s21) of the samples measured in an anechoic chamber between two horn antennas; the shrinkage can be seen to produce a blueshift of the resonances of the split-rings, which can be controlled by the conditions under which they were heated.

This demonstrates the potential of PPS and shape-morphing processes to create easily configurable electromagnetic components. However, there are a number of drawbacks to this design – it can be seen that the deformation is not entirely even across the samples, probably due to inconsistencies in the PPS and in the ink deposition for the resonant elements. To get around this, Cui et al have shown that it is possible to finely control the deformation of PPS by affixing it to non-shrinking elements[4]. This could be used in future to even out the samples. Another drawback here is the fact that since the entire sample shrinks, the interaction with incident radiation is weaker, resulting in a smaller dip in S21 for larger shrinkages. To overcome this, it would be better to have elements that could be tuned without significantly diminishing their size, and/or interaction strength with incident radiation.

TABLE I. RAW DATA FOR THERMALLY TUNED FSS'S

	Time in oven (s)	Oven Temp (ºC)	Time*temp (x10^4)	% original size	Resonance shift (GHz)
Array 1	0	0	0	100	0
Array 2	90	110	0.99	86.4	0.23
Array 3	120	115	2.76	62.1	0.62
Array 4	900	115	10.35	41.7	1.28
Array 5	1320	100	13.2	35	1.37

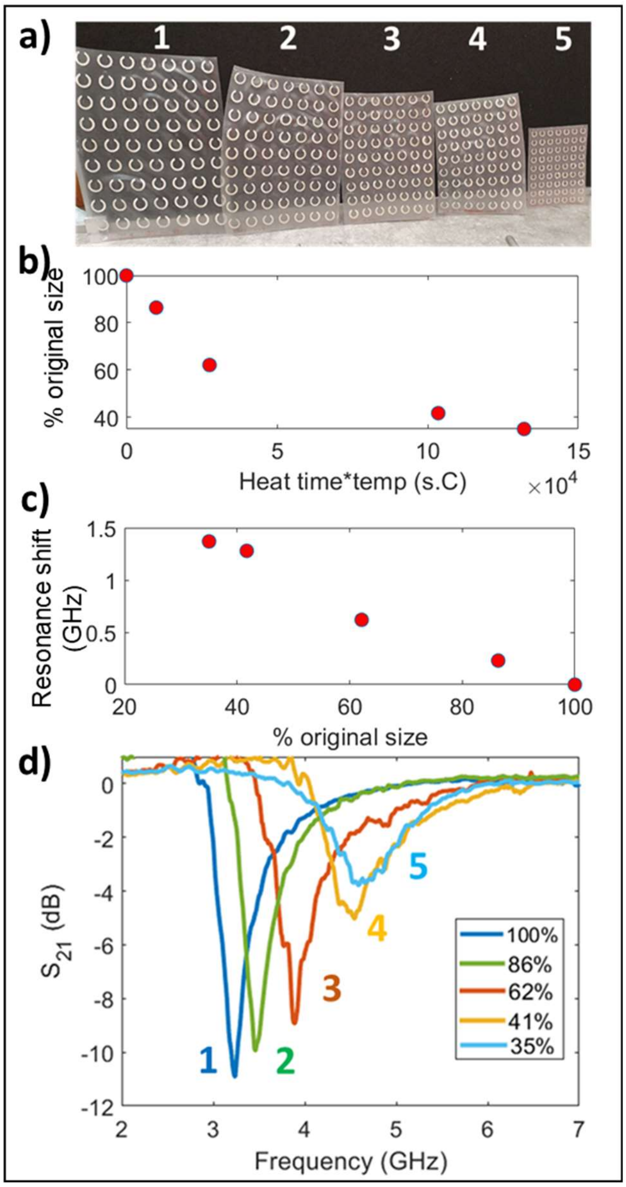

Fig. 1. Thermally tunable frequency selective surfaces made from PPS. a) shows the five arrays after heating and shrinking in an oven. b) shows ths the effect on heat & time on the size of the array, and c) shows the effect of the size on the resonance frequency. In d) the measured transmission (S21) spectra for the 5 arrays are shown.

III. OPTICALLY CONFIGURARABLE RESONATORS

One route to achieve this is to use the impressive thermal shrinking of PPS to create a bilayer actuator, which can be used to tune an electromagnetic response without reducing the size of the entire sample. The basic principle of this is shown in Fig. 2 : a section of prestrained polystyrene is marked with black ink where a bend is desired and then the entire sample is illuminated with optical or infrared radiation. The incident radiation is absorbed strongly in the inked area, and weakly elsewhere, leading to localised heating near the ink. As polystyrene is a very poor thermal conductor, this heat is localised to one side of the sample even for quite thin sheets. Once this area reaches the glass transition temperature it starts to shrink, whereas the opposite face does not, which creates a significant bending of the sample. This bending can be controlled via the time and power of the incident radiation.

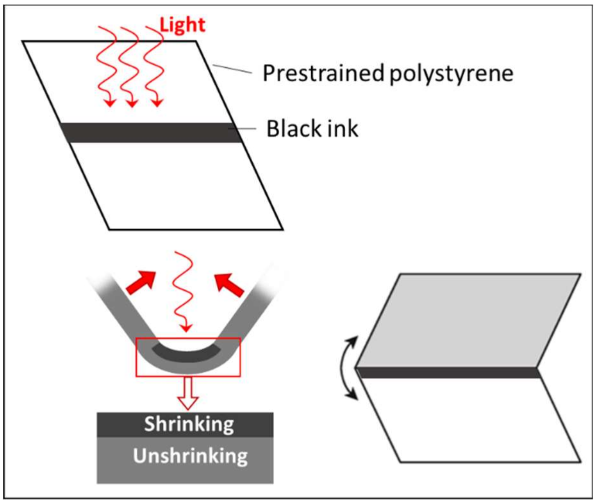

Fig. 2. The principle of photothermal actuation using prestrained polystyrene.

A method for using this to control the electromagnetic properties of a metamaterial is shown in Fig. 3. A dimer of coupled Jerusalem crosses (CJC's) is selected as the resonant element, with one cross attached to a hinge ending in an inked strip, so the entire cross will hinge away from its partner when irradiated, which will alter the resonance conditions of the system. CJC's are a good choice as they have two strong resonances nearby to each other (Fig. 3d), one of which is highly sensitive to the coupling between the two elements, and hence moving them apart will alter the resonant conditions and the associated reflected phase significantly (Fig. 3e).

The samples were manufactured as before using silver ink applied through a stencil onto a pre-cut PPS sheet, with carbon ink applied at the hinge. To actuate the samples, they are in placed on a hot-plate at 85C and illuminated via a 20W white LED lamp, set with the front panel 10 cm above the sample. As shown in figures 3b&c, the differing illumination times resulted in different bending of the hinge. Fig. 3d shows the forward scattering (RCS) of the CJC's, measured using methods described previously[5], [6]. These results demonstrate how the bending impacts the resonances of the CJC's: When the sample is flat there are two distinct peaks present in the RCS. However, when the sample is illuminated leading to bending and separation of the crosses, the peaks move together, until at 50 degrees bending, only one strong peak is visible.

This technique has obvious advantages compared with shrinking the entire structure, but beyond creating a simple frequency selective surface, this system shows the potential to make readily-manufacturable reflectarrays. A CJC array could be illuminated by a projector with a selective light intensity distribution chosen to cause a different deformation at different CJC pixels. This would in turn create a phase gradient across the array that could be used to achieve effects such as non-specular reflection, lensing etc. Fig. 3e shows a COMSOL simulation of the reflected phase from a CJC pair as a function of bend angle. The frequency is taken at the central frequency of the two resonances of a CJC above a metal ground plane, which demonstrates close to a 2π phase change about the resonance, which is a required condition for constructing high-quality reflectarrays[7].

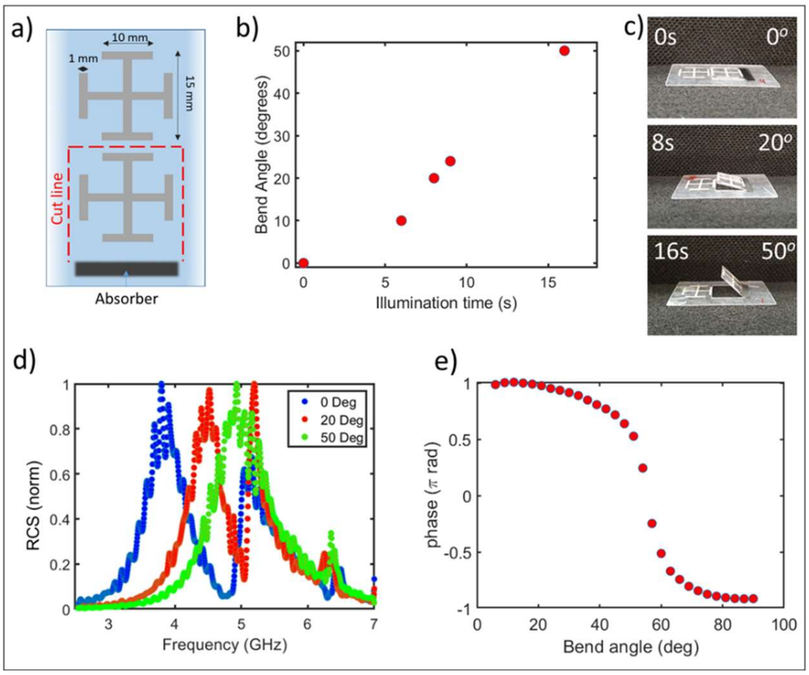

Fig. 3. a) Design for an optically configurable CJC resonator unit cell. b) The bend angle of the hinge vs the illumination time – flat and bent samples are shown in c). d) shows the normalised forward scattering spectra (RCS) for three of the measured samples. The reflected phase change achievable at a point between the resonances for a similar system when a metal ground plane is added is shown in e).

IV. Conclusions

This paper demonstrates the potential for prestrained polymer sheets to create rapidly configurable electromagnetic components that could be easily configured on-site from a mass-produced 'blank' to suit a desired application. Thermally tunable frequency selective surfaces, and optically tunable resonant elements have been demonstrated. Whilst there remain many questions to address, these show the potential to form the building blocks of an optically configurable reflectarray, which could reduce installation and fabrication costs of such systems.

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References

[1] X. G. Zhang et al., "An optically driven digital metasurface for programming electromagnetic functions," Nat. Electron. 2020 33, vol. 3, no. 3, pp. 165–171, Mar. 2020.

[2] H. Ko and A. Javey, "Smart Actuators and Adhesives for Reconfigurable Matter," Acc. Chem. Res., vol. 50, no. 4, pp. 691–702, Apr. 2017.

[3] Q. Zhang et al., "Origami and kirigami inspired self-folding for programming three-dimensional shape shifting of polymer sheets with light," Extrem. Mech. Lett., vol. 11, pp. 111–120, Feb. 2017.

[4] J. Cui, F. R. Poblete, Y. Zhu, J. Cui, F. R. Poblete, and Y. Zhu, "Origami/Kirigami-Guided Morphing of Composite Sheets," Adv. Funct. Mater., vol. 28, no. 44, p. 1802768, Oct. 2018.

[5] A. W. Powell, A. P. Hibbins, and J. R. Sambles, "Multiband superbackscattering via mode superposition in a single dielectric particle," Appl. Phys. Lett., vol. 118, no. 25, p. 251107, Jun. 2021.

[6] A. W. Powell, M. Mrnka, A. P. Hibbins, and J. Roy Sambles, "Superscattering and Directive Antennas via Mode Superposition in Subwavelength Core-Shell Meta-Atoms," Photonics 2022, Vol. 9, Page 6, vol. 9, no. 1, p. 6, Dec. 2021.

[7] J. Huang and J. Encinar, Reflectarray Antennas. John Wiley & Sons, 2007.