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Popup Tunable Frequency Selective Surfaces for Strain Sensing

Shaghayegh Soltani*, Paul S. Taylor, Edward A. Parker, John C. Batchelor**
School of Engineering and Digital Arts, University of Kent, Canterbury, Kent, CT2 7NT, UK.
** Student Member, IEEE*
*** Senior Member, IEEE*

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Abstract—A 3D popup frequency selective surface (FSS) is presented that can be tuned by the amount of strain due to mechanical loading in its elastomeric substrate. The proposed FSS structure comprises periodic two-dimensional (2D) crossed dipoles attached to the substrate at selective bonding sites. Strain release in the substrate induces compressive stress in the attached FSS, converting it to a 3D periodic pattern. With the out of plane displacement, the interaction with the incident field and mutual interactions between the elements are altered, resulting in a resonant frequency shift and a more stable response regarding the incident angles from 0º to 45º. A design of popup FSS structure is introduced for strain sensing applications. The potential sensor can measure up to 50% strain in the substrate by frequency down-shift from 3.1 GHz to 2.4 GHz. Multiphysics Finite Element Method (FEM) modeling of the mechanical and RF simulation was in good correlation with the experimental data and demonstrates the potential of these structures as sensors.

Index Terms— Compressive stress, Frequency selective surface, multiphysics simulation, strain.

I. INTRODUCTION

Frequency selective surfaces (FSS) also called spatial filters are periodic arrangements of metal patches or perforated metal screen elements usually on a dielectric substrate. These repetitive structures can modify the incident electromagnetic radiation by completely or partially transmitting (pass-band) or reflecting (stop-band) depending on the nature of the array element [1]. Low profile, tunability, dual polarization, angular stability and easy fabrication route are among the desired properties of FSSs. However, achieving all these characteristics has been a challenge for FSS designers. To date various attempts have been made to design electronically or mechanically tunable FSS structures [2-7]. For example, the authors of [2] proposed a dual layer FSS layout loaded with variable capacitors to adjust the resonant frequency. Furthermore, an FSS structure consists of periodic square loop slots and PIN diodes connected to a separate biasing circuit was introduced in [3], which exhibits tunable operation. Although electronic tuning has many benefits, it suffers from several disadvantages, especially for large area FSSs, as it requires lots of controlling lumped elements for each unit cell as well as bias circuits to ensure RF/DC isolation. Other researchers [4-6] obtained tunability by integrating stimuli-responsive substrates such as liquid crystals and ferrites into the FSS structures. In this way, a resonant frequency shift was achieved by changing the electrical properties of the substrate in exposure to external excitation. Mechanical tunability was also proposed in [7] where rotation of each 3D unit cells was controlled using a shaft connected to a motor. However, the reported method suffers complex fabrication routes.

An alternative approach for tuning FSS layouts is introduced in this letter, based on stretch/release of the embedded substrate due to external stimuli such as force or temperature changes to convert a 2D unit cell to a 3D one in a popup-like fashion. This method provides higher degree of stretchability and can detect wider range of strain compared to the other FSS-based sensors in the literature [8, 9].

Recently, more attention has focused on 3D FSS designs as they can offer more frequency stability for different incident angles and polarization [10]. However, most designs encounter difficulties in implementation and fabrication, as current 3D direct print technology can be expensive and slow. The popup technique introduces a simple 3D indirect fabrication route for any shape and type of materials, based on mechanical deformation of the soft substrate. According to this technique, two ends of a 2D precursor are strongly bonded to the pre-strained substrate, while the other parts are free on the substrate [11]. Following the complete release of the substrate, the 2D precursor goes under compression and buckles up. Our proposed FSS design operates between two planar and fully buckled states in response to environmental stimuli such as strain, which lends itself well for sensing application. It can measure up to 50% strain by frequency shift in the range of 2.4 GHz to 3.1 GHz. Moreover, as it starts buckling, it provides more stable frequency response for incident angles up to 45º. This letter is organized as follows; Section II describes the design and simulation procedure. Section III analyzes the numerical and experimental results and Section IV concludes the paper.

II. DESIGN AND WORKING PRINCIPLE

A. Geometry of the Unit Cell

The unit cell of the proposed FSS structure, when flat consists of

Corresponding author: Shaghayegh Soltani (ss969@kent.ac.uk).

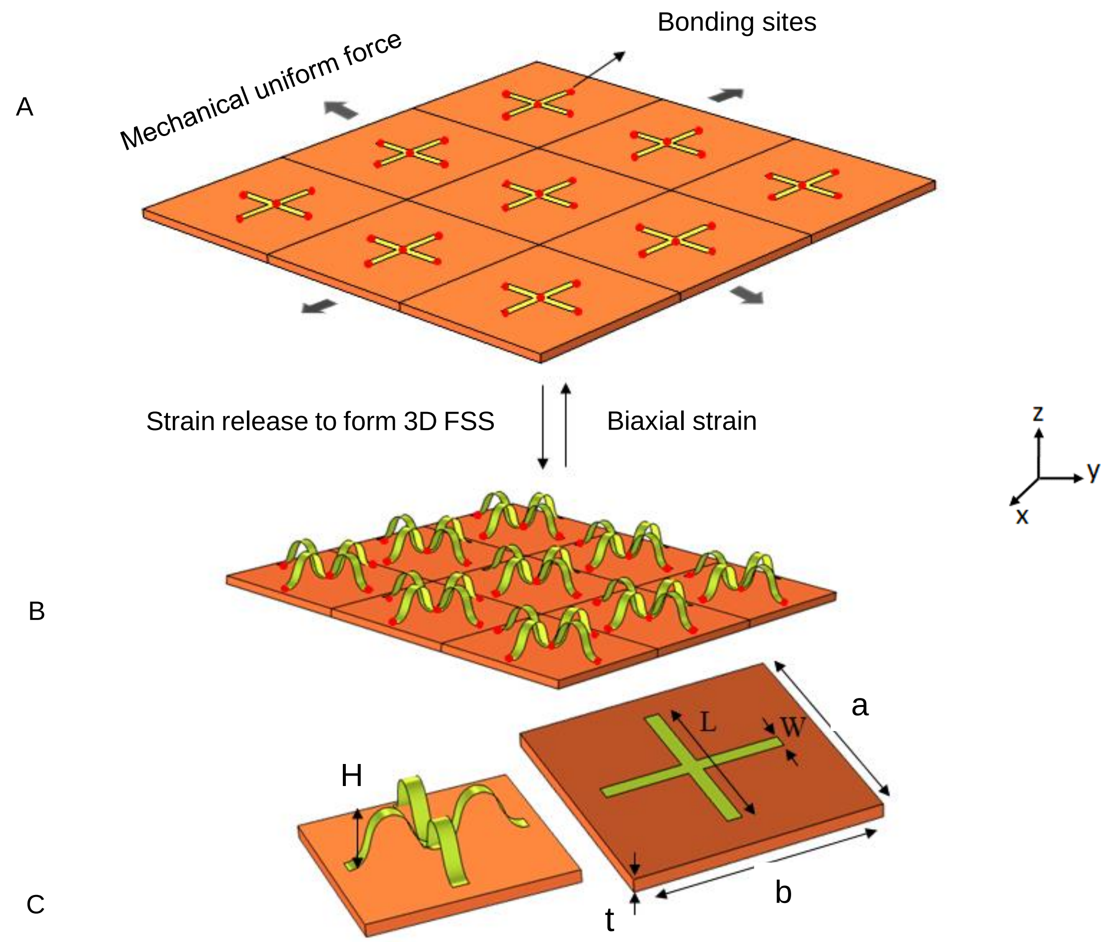


Fig. 1. Popup formation procedure of the FSS structure. A) Elastomeric substrate is under strain (2D unit cells), B) Substrate is relaxed and 3D unit cells are formed due to the induced compressive force, C) Geometry parameters of each unit cell.

Table 1. Parameters for the designed FSS

Parameters	***a***	***b***	***L***	***W***	***t***
Dimensions(mm)	68.2	68.2	54	2	0.46

2D crossed dipoles as shown in Fig. 1. The cell is repeated periodically along two directions $\hat{x}$ and $\hat{y}$ with periodicity a and b. All geometrical dimensions are presented in Table I.

The substrate is made of Silicone rubber with a commercial name of Dragon Skin [12] with relative permittivity of 1.8 and conductivity of 0.004 S/m and thickness of 1 mm. The metallic patterns are made up of 35 µm-thick copper foil.

B. Fabrication Procedure

The fabrication began with cutting a copper sheet (Cu, 35 µm) into the desired shape using a cutting machine (Cricut Explore Air TM 2). The next step involved transferring the precursors onto a pre-stretched elastomer substrate (Dragon Skin, Smooth on). A commercial adhesive (Super Glue, Loctite Company) dispended at desired bonding sites. There are some techniques reported in the literature for an almost perfect bonding [13-15]. However, here our aim was the simplicity of the fabrication, while receiving sufficient loading cycles. Slowly releasing of the pre-stain initiates the assembly process. The proposed design was a 3×3 array on an elastomeric substrate. For mechanical stability, the sample was backed with a 12 mm thick sheet of Polystyrene foam ($\varepsilon_r = 1.04$).

C. Simulation Procedure

Multiphysics simulation using COMSOL V. 5.4 [16] has been performed to analyze the proposed structure. The simulation procedure is divided into three steps.

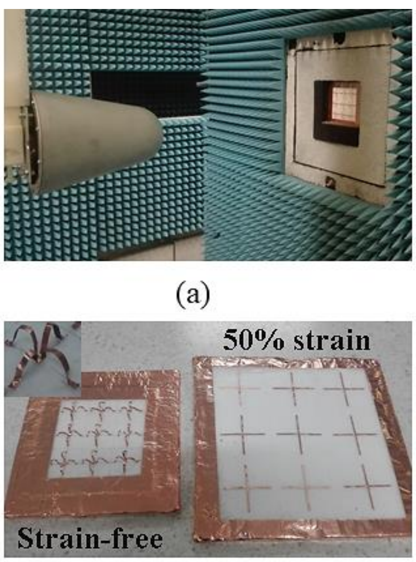
Step one: Full-wave electromagnetic simulation of the flat FSS unit cell using the RF module, at 2.45 GHz. The finite element method was adopted to determine the functionality under different incident angles for both TE and TM polarizations. Adaptive meshing convergence was used and for simplicity and time, all metal strips were modeled imposing a transition boundary condition with prescribed thickness. The geometry of the unit cell in flat state was optimized through parameter sweep in order to resonate at 2.45 GHz.

Step two: Mechanics simulation using the structural mechanics module to model the unit cell deformation for up to 50% strain in the substrate. The elastomeric substrate was modeled as a solid element with Young's modulus of 166 [kPa], Poisson's ratio of 0.49 and mass density of 927 kg/m^3. Copper precursors were modeled by shell elements with prescribed thickness. The load ramping method was adopted to model nonlinear buckling. This method ensures the solution convergence by gradually increasing the applied load and using the solution of each step as the initial value for the following step.

Step three: Full-wave electromagnetics simulation of the deformed unit cell (corresponding to 0 to 50 % deformation) obtained from step two on the relaxed substrate to recalculate the transmission responses under various incident conditions.

III. RESULTS AND DISCUSSION

Measurement were carried out using two Rohde and Schwarz HL050 log periodic antennas at 0.6 m from a 3×3 m^2 absorbing panel containing the FSS and a Hewlett Packard 8722ES VNA for transmission system. The absorbing panel was loaded with a rotatable screen, thus allowing for angular measurement. To ensure consistency in the test, the system was calibrated before each measurement. Fig. 2 shows the prototypes and the experimental set- up. A unit cell of the proposed FSS design was illuminated by a normal plane wave, first with electric field polarized along the x-axis and the propagation vector along the z-axis (TE polarization) and next with electric field polarized along the y-axis and the same direction of propagation vector (TM polarization). A resonant frequency is clearly seen near 2.45 GHz for the flat state (50% strain in the elastomeric substrate). Tuning the FSS is accomplished by changing the strain value in the substrate and a resonance is seen at a higher frequency, around 3.1 GHz for a relaxed substrate (0% strain).



(b)

Fig. 2. (a) Experimental set-up, (b) FSS prototypes. The right hand side sample has been undergone 50% strain in its elastomeric substrate and the left hand side sample is strain free.

Fig. 3 shows the resonant frequency shift of the FSS structure at normal incidence and for TM polarization as a function of equi-biaxial strain values in the elastomeric substrate. This frequency shift is mainly due to two effects after buckling. First, the induced compressive force causes the flat copper precursor to deform out of plane and expand into the third dimension. This out of plane displacement (which is specified by H in Fig. 1) leads to a gap between the substrate and the conductors and thus a change in effective permittivity felt by the crossed dipole patterns. Moreover, the buckled shape is observed to be electrically small viewed from the above. This can be understood by considering current cancellation between opposite conductors after buckling, Fig. 4.

The second reason for the observed resonant frequency shift is the fact that by relaxing the elastomeric substrate from its 50% stretched state, the inter-element spacing or periodicity of the FSS structure changes bi-axially and this factor affects the frequency response and causes a shift.

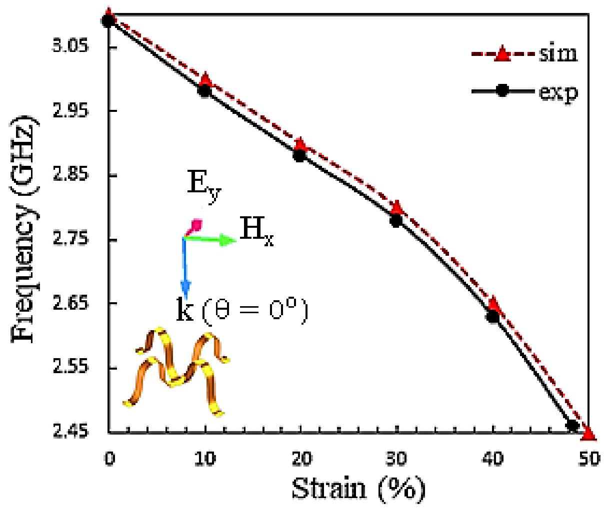


Fig. 3. Numerical and experimental results for resonant frequency shift vs strain values in the elastomeric substrate for normal incidence and TM polarization.

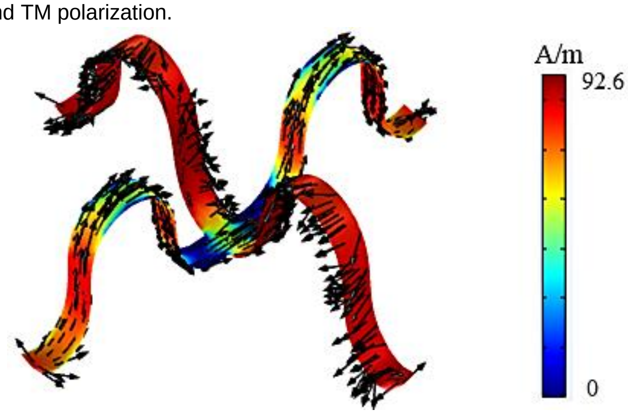


Fig. 4. Surface current (A/m) on the buckled crossed dipole. The currents flow in opposite directions on adjacent vertical arms and have cancelling effect leading the structure to be electrically smaller than the actual physical size.

To investigate the stability of the proposed FSS design with regard to angle of incidence, the performance of the structure has been evaluated for oblique incidences. Therefore, the originally z-directed propagation vector was rotated at angles of $\theta = 0^\circ, 15^\circ, 30^\circ$ and 45° from the z-axis. In order to perform a thorough comparison between the stability of the flat FSS and the popup one, two types of structure are investigated. The first structures are strain free 3D FSS layouts after 10%, 20%, 30%, 40% and 50% strain release in the substrate and the second structures are scaled versions of the flat FSS, with the same periodicity as the first series. The purpose of choosing these two structures is to keep the periodicity factor the same and then compare the stability of 2D and 3D unit cells. Fig. 5 demonstrates the improved stability of the popup FSS for TM polarization in comparison to the flat counterpart. Fig. 6 shows the transmission responses vs frequency for different angles of incidence and TE polarization.

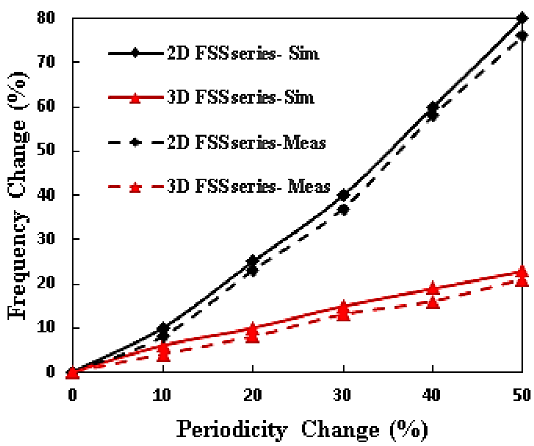


Fig. 5. A comparison between an FSS structure with 3D buckled crossed dipole unit cell and similar flat counterparts with equal periodicity in terms of stability.

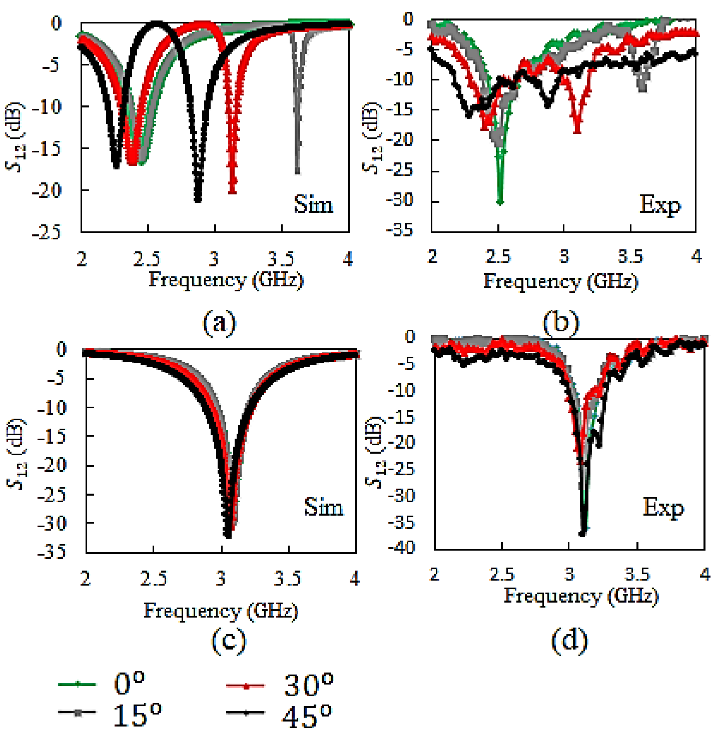


Fig. 6. Numerical and experimental results for TE incidence at four angles of 0°, 15°, 30° and 45°. (a) 50% strain in the elastomeric substrate (simulation), (b) 50% strain in the elastomeric substrate (experiment), (c) strain-free elastomeric substrate (simulation), (d) strain-free elastomeric substrate (experiment).

IV. CONCLUSION

The design and assembly of a 3D popup FSS structure based on a compressive buckling is briefly presented. The proposed FSS design can detect 0 to 50% strain in its elastomeric support by resonant frequency change in the range of 2.45 to 3.1 GHz. This popup design provides a good level of stability and compared to any other 3D FSS deigns reported in the literature which are fabricated using direct routes such as 3D printing, the proposed layout is fabricated indirectly via simple and cost-effective way of stretch and release. This design has a potential in sensing applications such as temperature where an environmental change causes a strain variation in the embedded substrate. Therefore, future research will focus on integration of the designed popup FSS with smart polymers.

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