A Novel Fully Inkjet Printed Dual-Polarization Broadband Tuneable FSS Using Origami "Eggbox" Structure

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***Abstract* — A dual polarization 'eggbox'-inspired frequency selective surface with cross-conductive elements that can change the frequency response of two orthogonal linear polarizations is demonstrated for the first time in this article. The additional degree of freedom from the dual-mode metamaterial in combination with the 'eggbox' origami structure which exploits the symmetrical planes of the metamaterial leads to an unprecedented re-configurability performance compared to traditional Miura-Ori based structures which have fewer degrees of control.**

***Keywords* — dual-polarization, eggbox, frequency selective surface (FSS), inkjet-printing, origami, tunable filters.**

I. Introduction

A Frequency Selective Surface (FSS) is a periodic structure of 2D elements in a repeatable configuration exhibiting frequency filtering properties. In particular, a band-stop FSS is an array of conducting elements that prohibit electromagnetic waves at the resonant frequency, while letting the non-resonant frequencies go through. The shapes of the conductive elements can come in variety of shapes including dipole, cross-dipole, and the circular patch [1].

Recently, origami inspired structures has seen increased adoption in microwave components. Origami-inspired microwave designs featuring unprecedented capabilities for deployability and continuous-range tunability have enabled drastic improvements in the performance of devices such as antennas, sensors, and frequency selective surfaces (FSS) [2-4].

One of the most common origami inspired element used in FSS design is Miura-Ori structure, which can achieve a frequency band tunability by changing the electrical length or inter-element coupling. The Miura structure is based upon a periodic foldable element and has demonstrated an effective tuning of the operation frequency band by integrating flat dipoles along the foldlines of the Miura. The Miura enables side-ways compression from one side, with the distance between the flat dipoles changing and thereby altering the bandwidth.

An alternative periodic origami design is the eggbox structure, consisting of discrete Voss surfaces with a bidirectionally flat-foldable planar quadrilateral mesh [5]. The eggbox, in comparison to the Miura, can be compressed from two directions, opening new tuning possibilities including multiband frequency tuning and wider range of tuning. This paper presents a novel dual-polarization bandstop 3D FSS based on the eggbox origami structure, which demonstrates tunability on both polarizations that perpendicular to each other and much wider tunable frequency range than traditional Miura-Ori based structures.

II. Eggbox FSS Design

A. "Eggbox" Structure

Often with origami-based foldable electronic metamaterials and FSS's, a Miura-Ori structure has been employed due to its inherent easier fabrication. The single direction foldable feature of the Miura-Ori structure enables configurability of the placement of elements perpendicular to the folding axis to maintain a constant pitch of the elements. While this enables precise positioning by maintaining constant interspacing of elements along that axis, it also removes a degree of freedom in the tuning parameters of an FSS device. A structure which features additional degrees of freedom is the so-called 'eggbox' origami structure [6]. While the structure cannot be fabricated out of a single continuous planar sheet of substrate, the bidirectional symmetry adds an additional degree of freedom which can effectively realize FSS structures along two orthogonal linear polarizations.

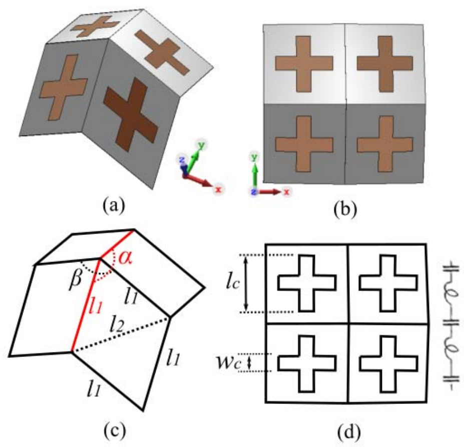

Fig. 1. Eggbox unit cell design: (a) 3D perspective view; (b) 3D top view; (c) folding angle α=β=111°, length l1=l2=20mm (d) equivalent circuit and conductor dimension l_c=15mm, w_c=3.5mm.

The design of the unit cell shown in Fig. 1 has been inspired by the origami eggbox pattern that can be folded both vertically and horizontally [5]. The dimension of the structure is defined by two lengths l_1 and l_2. The folding angle along y axis and x axis is defined by α and β. When the eggbox is not folded, α and β can be calculated by (1):

$$\alpha = \beta = \theta_0 = 2 \times \arccos(\sqrt{\left(1 - \frac{l_2^2}{2l_1^2}\right)}) \quad (1)$$

When eggbox is folded, the relationship between the two folding angles can be calculated by (2):

$$\beta = 2 \times \arccos\left(\left(\frac{1}{cos\frac{\alpha}{2}}\right) \times \left(1 - \frac{l_2^2}{2l_1^2}\right)\right) \quad (2)$$

The side wall of the eggbox unit cell is printed with crossed resonating elements with the equivalent circuit shown in Fig. 1(d). The dimension of the elements are defined by conductor length l_c and conductor width w_c.

B. 6X6 Eggbox FSS Design

As a proof-of-concept demonstrator, a 6X6 "eggbox" FSS with crossed resonating elements is employed in this work. The centre frequency is designed at 7.5GHz. The length of the FSS can be folded from 170mm(α=β=θ) down to 60mm(α/β=0.4θ). The design takes advantage of the bidirectional symmetry of the eggbox.

When folding along the x-axis (as shown in Fig. 2), the decreased equivalent inductance of the horizontally faced branches, increase the resonant frequency of the horizontally polarized waves. The increased equivalent capacitance of the vertically faced branches, decrease the resonant frequency of the vertically polarized waves. Fold along y-axis will in contrast decrease the horizontally polarized frequency and increase vertically polarized frequency. Consequently, this FSS can tune the frequency range from both directions.

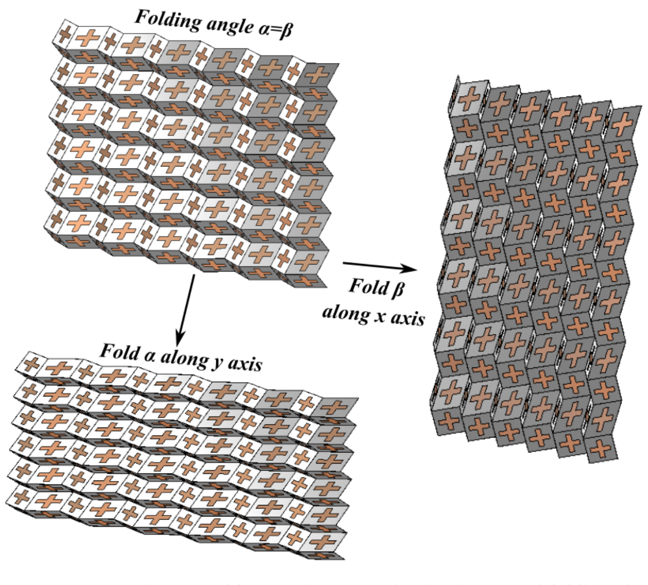

Fig. 2. 6 x 6 Eggbox Tunable FSS demonstrating bi-directional folding along both the x and y axis.

C. Fabrication

Unlike the Miura structure, the eggbox cannot be fabricated out of a single planar dielectric sheet. Therefore, to realize the eggbox, alternative fabrication approaches need to be considered. While 3D printing has been employed to create arbitrary shapes which have been metalized for pre-folded origami-based metamaterials in the past [3-4], inkjet printing of silver nanoparticle inks on planar substrates have demonstrated rapid and reliable results, with fewer fabrication steps [4,7]. Therefore, a fabrication architecture which utilizes cuts and folds of individual FSS elements which are then adhered together, can easily enable an end-user reconfigurability of the total number of elements and size of the FSS device.

The eggbox FSS prototype consists of a 6x6 array of individual cells. The structure was fabricated out of cellulose paper (ε_r = 3.4, tanδ = 0.01), which inherently absorbs the conductive ink. First, a folding pattern for the individual eggbox cell was designed in a 2D CAD software. The 2D drawing accounts for the conductive traces, the folds, and an additional polygon to glue the edges that enable linking of the elements together, as seen in Fig. 3, that can be easily printed with an office laserjet printer. In our approach, the 2D perforate eggbox pattern on paper was fabricated, the sheet was used layout is printed, the sheet is used as the substrate for the silver nanoparticle ink (SNP). A Dimatix DMP-2831 was used to align to the previously printed layout, and deposit ten layers of Suntronic EMD5730 SNP ink (Sigma-Aldrich) on the surface of the cellulose paper. After printing, the substrate was thermally cured at 140° C for 1 hour to sinter the silver nanoparticles and increase the conductivity. Finally, to realize the eggbox 6x6 matrix, each folded structure was attached together by 3M General Purpose Super Glue. The entirety of the 6x6 matrix of elements can be seen in Fig. 4, with an approximate length and width of 170mm x 170mm in its uncompressed folded state.

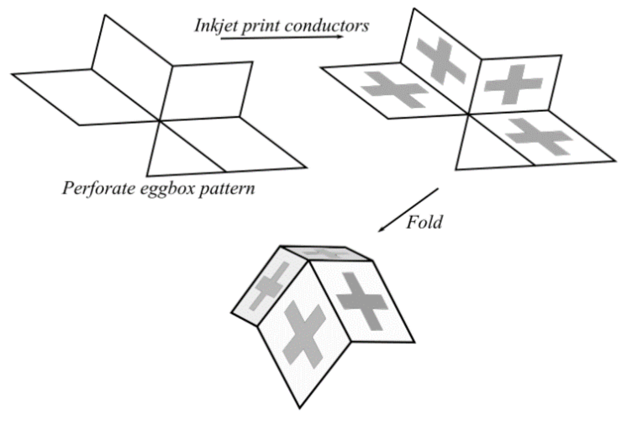

Fig. 3. Three-step additive fabricated process for the fabrication of the eggbox-enabled FSS unit cell

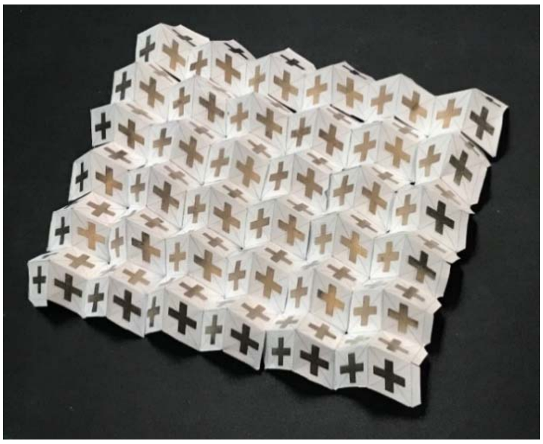

Fig. 4. Fabricated prototype of the 6x6 eggbox metamaterial array.

III. Simulation and Measurement Results

The proposed eggbox FSS was simulated in CST Studio Suite 2019 frequency domain solver with unit cell boundary condition and Floquet port excitation, which enables simulation of a singular FSS element and extrapolates to an infinite sheet. In order to measure the fabricated prototype, two horn antennas (A-INFOMW LB-20245-SF) was placed equidistant with 1.5 meter spacing, with the results measured on an Anritsu MS46522B VNA set to measure from 6 GHz to 9 GHz. The 6x6 eggbox structure is put equidistant between the horn antennas. The eggbox structure was compressed for different angles α and β, and the length and width of the eggbox after various compressions enables determination of the fold angles α and β, which are then compared to the simulated results.

Fig. 5. Measurement setup for for the characterization of the eggbox FSS prototype.

A. *Measurement Results*

The simulated and measured insertion loss of the eggbox FSS for horizontal polarization (along x axis) is shown in Fig. 6. From this figure, the resonant frequency of the metamaterial shifts higher as the folding angle β decreases. This is due to the reduced effective length of the horizontal branch of the cross element due to folding, which in turn causes a reduction of the inductance. On the other hand, the resonate frequency of the origami meta-material shifts lower as the folding angle α decreases. The result of this is due to the folding along the y axis reducing the gap between the horizontal components of the metamaterial, leading to an increased capacitance that reduces the resonant frequency.

The vertical polarization response is demonstration in Fig. 7. In this scenario, as the folding angle of β decreases, the frequency reduces due to the increase capacitance. If the folding angle α is reduced, the frequency of the resonant response increases due to a reduced inductance.

Note that the amount of frequency shifting varies depending on the folding direction and polarization. For example, it can be seen that the folding angle β has an increased impact to the response of the system along the horizontal polarization. Similarly, along the folding angle α has a larger impact of the response in the vertical polarization along the y-axis.

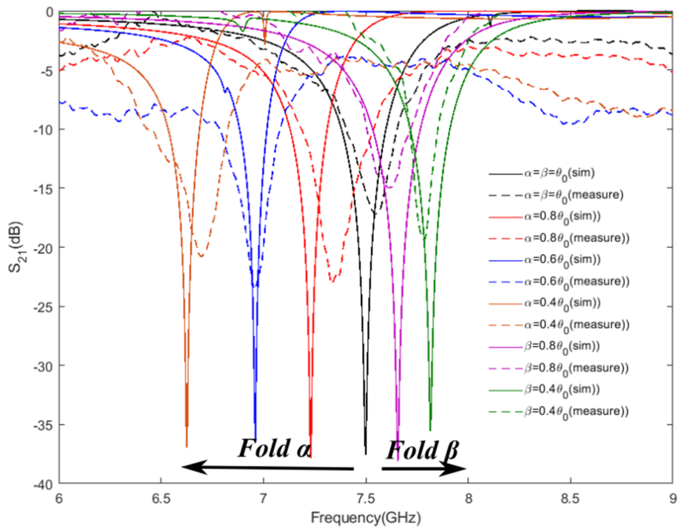

Fig. 6. Horizontal (x-axis) polarization simulation and measurement results

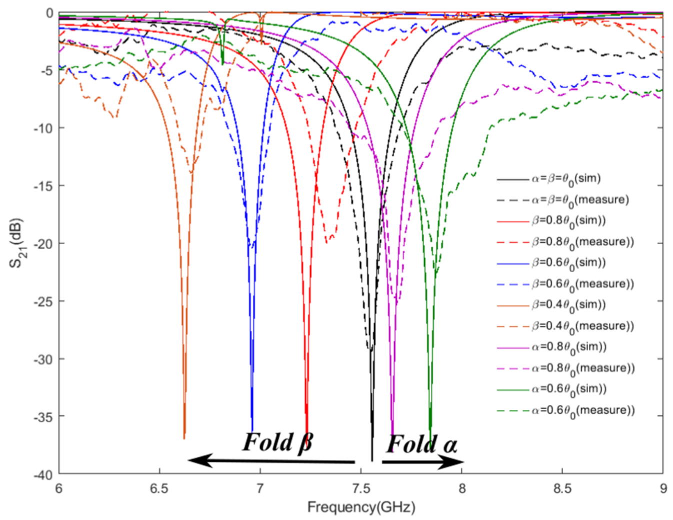

Fig. 7. Vertical (y-axis) polarization simulation and measurement results

Table 1. Performance comparison of typical origami inspired FSS

Work	Type	Pattern	Freq Tenable Range	Polarization
[8]	Miura	Dipole	12.8%	Linear
[3]	Miura	Cross	9.5%	Dual-linear
This work	Eggbox	Cross	17%	Dual-linear Dual-tunable

IV. CONCLUSION

A novel eggbox-based origami metamaterial FSS is demonstrated for the first time, allowing bidirectional configurability of the frequency band pass filter of a FSS device. The measured results show a wide range of control, with different sensitivities of response depending on the folding angle axis, enabling precise control of the frequency response of both horizontal and vertical linear polarizations. The fabrication of individual cells without the use of active devices enables easy scalability by allowing many individual elements to be fabricated and then assembled in any desired configurability. The design enables geometrical configurations with the potential of ultrawideband tuneable FSSs for 5G and mm-wave applications.

ACKNOWLEDGMENT

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