An Inkjet-printed Tunable Origami Frequency Selective Surface on Cellulose Paper

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***Abstract*—A state-of-the-art inkjet-printed tunable origami frequency selective surface (FSS) on cellulose paper is presented that can change its resonant frequency by mechanically folding the structure. Special "bridge-like" structures are introduced along the conductive traces to increase their flexibility, thereby avoiding breakage during folding or bending process. The bandwidth of the overall structure is almost doubled by using a one-of-a-kind multilayer approach which does not require any supporting structures or extra substrate between FSS layers.**

I. INTRODUCTION

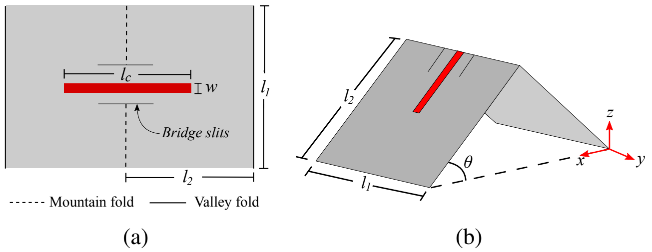
Frequency selective surfaces (FSS) typically comprise of 2D-periodic arrays of resonant elements on thin dielectric substrates that can filter out certain electromagnetic waves based on their frequency. They have found many applications such as smart skins, absorbers and design of radomes to reduce the antenna radar cross-section outside its operating frequency range [1].

The recent development of numerous wireless and communication systems has attracted a lot of interest in tunable FSS that can change their frequency response with change in external environment. Typically this is achieved by use of varactors or diodes [2] which becomes challenging for larger FSS size because it requires individually biasing each device. An alternate approach is presented in [3] which uses chemically etched conductive resonant elements (from copper tape) that are manually placed on every facet of a mechanically re-configurable origami structure to tune the resonant frequency of the FSS. However, this process is not repeatable and lacks consistency due to the manual placement of the resonant elements and due to the fact that the copper tape is prone to peel off with changes in humidity or temperature.

This paper presents a first-of-its-kind inkjet-printed multilayer dipole-based origami-FSS on cellulose paper with the resonant elements placed across the foldlines. Since a dipole typically resonates when its effective length is in the order of $\lambda/2$ (where λ is the wavelength of the operating frequency), the operating frequency of the origami-FSS is changed by mechanically folding the origami-FSS along the foldlines. The bandwidth of the FSS is increased by using multilayer configuration.

II. ORIGAMI FSS DESIGN AND FABRICATION

The unit cell of the proposed origami-FSS is shown in Fig. 1, which consists of two rectangular panels (each with the lengths l_1 and l_2) that are connected together at the edges with an inkjet-printed dipole resonant element across the mountain foldline. Two slits are cut along the dipole element to realize a "bridge-like" structure that increases the flexibility of the conductive traces and minimizes the risk of cracking while while bending or folding the FSS structure. The effective length of the dipoles is changed by varying the folding angle θ from 0^o (flat FSS) to 90^o (completely folded FSS).



(a) (b)

Fig. 1: Unit cell of origami FSS in (a) flat state ($\theta = 0^o$) (b) folded state with $l_1 = l_2 = 20mm$, $l_c = 20mm$ and $w = 1mm$

It is important to note that the simple dipole elements are chosen due their simplicity, ease of implementation and to fully understand the behavior of the origami-FSS with respect to its folding variations. However, they can be replaced by any complex-shaped resonant element to realize an FSS with the desired frequency response. Moreover, the dipoles are inkjet-printed along the foldline to demonstrate first-of-its-kind truly flexible FSS structures.

The fabrication process of the proposed tunable origami-FSS on 110μm thick cellulose paper is shown in Fig. 2. First, the foldlines and the slits for "bridge-like" structures are perforated on the cellulose paper. Then, the dipole elements are inkjet-printed across the foldlines using 10 layers of silver nanoparticle (SNP) ink and cured for 2 hrs at 150°C. One of the key advantage of using cellulose paper is that it absorbs most of the SNP ink making the conductive traces very flexible[4]. Moreover, the "bridge-like" structures are used here to avoid sharp edges at higher values of θ, thereby further enhancing the overall flexibility of the conductive traces. Finally, the whole structure is manually folded along the foldlines to realize the proposed origami-FSS.

Whereas the operating frequency of the single-layer

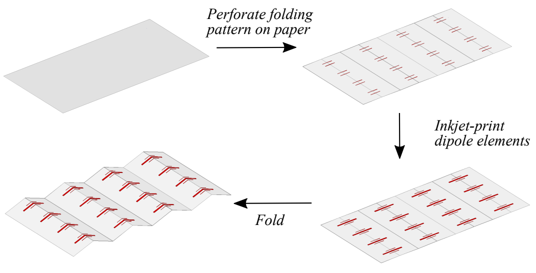
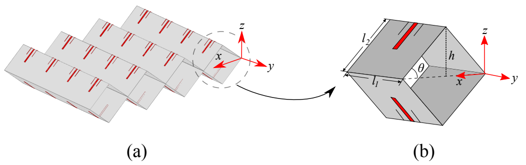


Fig. 2: Fabrication steps to realize origami-FSS

origami-FSS is tuned by varying the folding angle θ, the bandwidth of the structure can be enhanced by using multi-layer origami-FSS structures as shown in Fig. 3. It should be noted here that the proposed multi-layer origami-FSS has an inherent separation between each FSS layer at higher folding angles; something that is impossible to achieve in conventional multi-layer FSS structures that require physical separation (in the order of $\lambda/2$ [1]) between FSS layers using specialized frames or inserting thick substrate between each layer, thus providing origami-FSS a unique advantage of tuning both frequency and the bandwidth of the structure by using multi-layer configuration and varying the folding angle.



(a) (b)

Fig. 3: (a) Double layer Origami-FSS and (b) its unit cell

III. Results and Discussion

The single-layer and double-layer origami-FSS were designed and simulated using HFSS. In order to save time and computational resources the unit cells shown in Fig. 1 and Fig. 3b are simulated with master-slave boundary conditions with Floquet port excitation.

The frequency response of the single-layer origami-FSS with respect to variation in folding angle θ is shown in Fig. 4. The simulated results clearly indicate that the insertion loss (S_{21}) of the single-layer is a strong function of the θ. However, since the distance between the dipole elements decreases only along x-axis during folding, the decrease in percentage bandwidth and insertion loss can be noticed at higher values of θ due to the coupling effect.

Similarly, the simulated insertion loss for the double-layer origami-FSS is shown in Fig. 5 which shows a significant increase in percentage bandwidth as compared to single-layer origami-FSS. For example, the percentage bandwidth for $\theta = 60^o$ increases from 5.58% for single-layer origami-FSS to 11.16% for double-layer origami-FSS. The poor performance of the origami-FSS at $\theta = 20^o$ is due to the resultant decrease in inter-layer distance (2*h), which becomes lower than $\lambda/2$ resulting in an unwanted coupling effect between the two layers that is evident with the appearance of second peak at higher frequency.

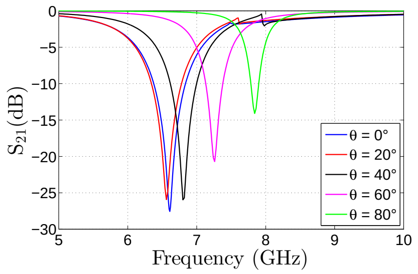


Fig. 4: Frequency response of the single-layer Origami-FSS for different values of folding angle θ

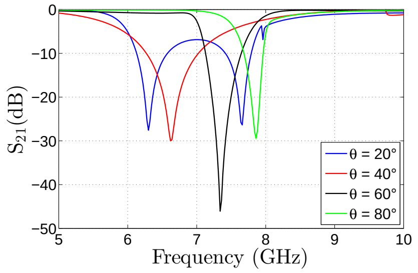


Fig. 5: Frequency response of the double-layer Origami-FSS for different values of folding angle θ

IV. Conclusion

This paper presents a detailed fabrication, design and analysis of a state-of-the-art felxible inkjet-printed tunable origami-FSS on cellulose paper that can vary its resonant frequency on-demand by physically folding the structure along the foldlines. A novel multilayer FSS approach is also presented which features a significant increase in percentage bandwidth of the FSS. The simulation results show a strong agreement to the theoretical values.

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References

[1] B. A. Munk, "Frequency selective surfaces theory and design. john wiley&sons," 2000.

[2] J. A. Bossard, D. H. Werner, T. S. Mayer, and R. P. Drupp, "A novel design methodology for reconfigurable frequency selective surfaces using genetic algorithms," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 4, pp. 1390–1400, April 2005.

[3] K. Fuchi, J. Tang, B. Crowgey, A. R. Diaz, E. J. Rothwell, and R. O. Ouedraogo, "Origami tunable frequency selective surfaces," *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 473–475, 2012.

[4] S. A. Nauroze, J. Hester, W. Su, and M. M. Tentzeris, "Inkjet-printed substrate integrated waveguides (siw) with "drill-less" vias on paper substrates," in *Microwave Symposium (IMS), 2016 IEEE MTT-S International*. IEEE, 2016, pp. 1–4.