An Inkjet-printed Origami-based Frequency Selective Surface with Wide Frequency and Bandwidth Tunability

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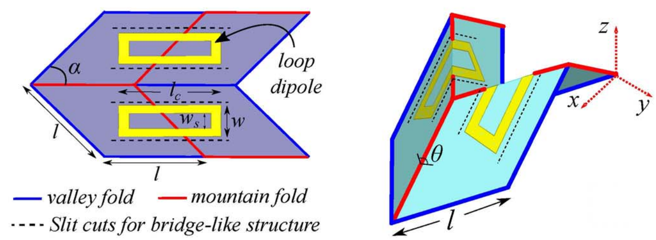
***Abstract*—A state-of-the-art inkjet-printed tunable origami frequency selective surface (FSS) on cellulose paper is presented that can change its resonant frequency as well as its bandwidth by mechanically folding the structure. Special "bridge-like" structures are introduced alongside the conductive traces to increase their flexibility, thereby avoiding breakage during the folding or bending process. The structure also features a wide angle of incidence rejection capability that facilitates it usage to a wide range of applications ranging from smart skins, tunable radome design and reduction in radar cross section of antennas.**

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 including smart skins, absorbers and the 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 changing the electrical properties of the substrate [2], or using electrical components such as varactors or diodes [3] which becomes challenging for larger FSS size because it requires individually biasing each device. These approaches tend to be expensive, labor-intesive and prone to failure in harsh enviroments. Moreover, they offer limited frequency and bandwidth tunability which limits their use in practical applications. Recently, an alternate approach is presented in [4] which realizes a mechanically re-configurable origami-based FSS structure by inkjet-printing dipoles across the foldlines of the origami structure. The frequency response of the FSS structure can be varied by simply changing the folding angle of the origami structure which transforms the flat dipoles into 3D V-shaped structures with reduced electrical length. However, this approach features limited bandwidth tunability and requires multilayer configuration to realize broadband FSS structures.

This paper presents a first-of-its-kind inkjet-printed loop dipole-based origami-FSS on cellulose paper with the resonant elements placed across the foldlines. Unlike the dipole based origami-FSS structure presented in [4], the proposed design features a wide range of frequency and bandwidth tunability with variation in folding angle by offering additional capacitance across the loop structure, thus resulting in dual resonance frequency response.



(a) (b)

Fig. 1: Unit cell of origami FSS in (a) flat state ($\theta = 0^o$) (b) folded state with $l = l_c = 20mm$, $w = 6mm$ and $\alpha = 45^o$

II. Origami FSS Design and Fabrication

The unit cell of the proposed origami-FSS is shown in Fig. 1, which consists of four paralellogram panels (each with the lengths l and an internal angle α) that are connected together along their edges with an inkjet-printed loop dipole resonant element across the mountain foldline to facilitate systematic variation in frequency response with folding angle θ. Two slits are cut along the loop 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 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 loop dipole elements are inkjet-printed across the foldlines using 10 layers of silver nanoparticle (SNP) ink and cured for 2 hrs at 150^{o}C to increase conductivity. One of the key advantages of using cellulose paper is that it absorbs most of the SNP ink making the conductive traces very flexible[5]. Moreover, special "bridge-like" structures are incorporated along the loop-dipole elements to facilitate folding the resonant elements

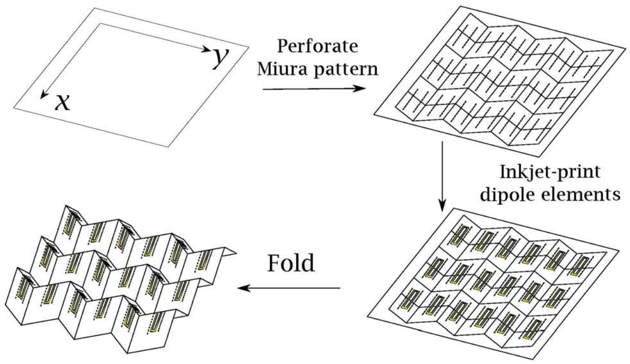


Fig. 2: Fabrication steps to realize origami-FSS

in a smooth cureved fashion along the foldlines rather than a sharp edge 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 which can be automated by using heat sensitive substrates [6] or by using hydro-folding technique[7].

III. Results and discussion

The proposed origami-FSS was designed and simulated in HFSS by using master-slave boundary conditions for the unit cell shown in Fig. 1 to save time and computational resources. The frequency response of the origami-FSS for different values of folding angle θ is shown in Fig. 3 which clearly indicates that as θ is varied from 180^o (flat configuration) to 60^o (folded configuration), the proposed origami-FSS structure transforms its frequency response from a narrow-band FSS structure ($\theta = 180^o$) to broadband ($\theta = 120^o$) and multiband FSS structure ($\theta < 120^o$).

The introduction of extra capacitance across the loop-diple structure at lower values of folding angle θ results in the lower resonance frequency. The effect of variation in loop opening (slot width) w_s is shown in Fig. 4 which clearly shows that as the loop opening is decreased, the frequency response of the FSS structure changes from multi-band/broadband to narrow band. Note that similar response can be realized by integrating a variable lumped component across the loop opening. This feature provides an extra degree of freedom to realize tunable frequency and bandwidth FSS structure.

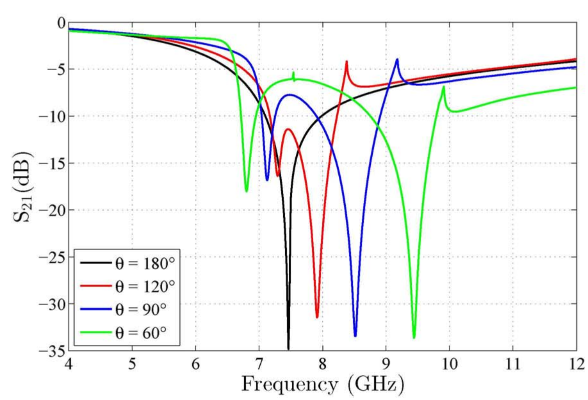


Fig. 3: Frequency response of the Origami-FSS for different values of folding angle θ

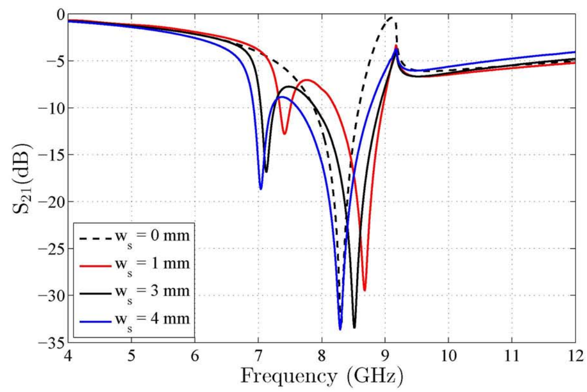


Fig. 4: Frequency response of the Origami-FSS for different values of slot width w_s for $\theta = 90^o$

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 and bandwidth response on-demand by physically folding the structure. The proposed FSS structure features a wide range of frequency tunability and also presents a novel technique for the realization of broadband/multi-band FSS structure by simply changing the geometry of narrow-band resonant elements such as loop-dipoles.

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References

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

[2] T. K. Chang, R. J. Langley, and E. A. Parker, "Frequency selective surfaces on biased ferrite substrates," *Electronics Letters*, vol. 30, no. 15, pp. 1193–1194, Jul 1994.

[3] C. Mias, "Varactor-tunable frequency selective surface with resistive-lumped-element biasing grids," *IEEE Microwave and Wireless Components Letters*, vol. 15, no. 9, pp. 570–572, 2005.

[4] S. A. Nauroze, L. Novelino, M. M. Tentzeris, and G. H. Paulino, "Inkjet-printed "4d" tunable spatial filters using on-demand foldable surfaces," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*, June 2017, pp. 1575–1578.

[5] 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.

[6] G. J. Hayes, Y. Liu, J. Genzer, G. Lazzi, and M. D. Dickey, "Self-folding origami microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 10, pp. 5416–5419, Oct 2014.

[7] C. Guberan, "Hydro-fold," *ECAL/University of Art and Design Lausanne, Renens, Switzerland, http://vimeo. com/39914902*, 2012.