Fully Inkjet-printed Tunable Hybrid *n-Ri*pple *M*iura (n-RiM) Frequency Selective Surfaces

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***Abstract*—A first-of-its-kind fully inkjet-printed tunable hybrid n-ripple Miura (n-RiM) frequency selective surface (FSS) is presented that combines the advantages of n-RiM FSS structures (i.e. ultra wideband frequency & bandwidth tunability) and traditional Miura-FSS (i.e. ability to form multilayer FSS structures without mechanical support). They also feature high angle of incidence rejection, making them suitable for wide range of terrestrial and outer-space wireless communication applications.**

I. Introduction

Traditional frequency selective surfaces (FSSs) lack tunability which limits their use in practical applications. That is why numerous tunability mechanisms have been proposed in the last two decades that change the electromagnetic filtering response of FSS by using complex (non-linear) electronic components, integrated MEMS structures or specialized substrates. However, these techniques are laborious, expensive, power hungry and offer limited tunability.

Recently, an origami-inspired approach has been proposed in [1][2][3] that realizes wideband tunable FSS structures by inkjet-printing dipole elements on foldlines of Miura-Ori tessellation. The tunability is realized by physically changing the shape of dipole elements from a flat to an (electrically-small) inverted V-shaped dipole using mechanical actuation. These Miura-FSS structures can also be extended to multi-layer configuration without using any specialized frames or inter-layer substrates that are required in traditional multi-layer FSS structures to maintain desired inter-layer distance [3].

The tunability range of Miura-FSS structure is typically determined by coupling between the edges of inverted V-dipole that can be improved by inkjet-printing dipole over multiple (n) foldlines - **n-Ri**pple **M**iura (n-RiM) [2]. However, relative planar nature of these structures (as compared to Miura-FSS structures) makes them unsuitable for multi-layer configurations as they would require specialized mechanical support to maintain desired inter-layer distance.

This paper introduces a novel fully inkjet-printed hybrid n-RiM FSS structure on cellulose substrate that combines the advantages of both single-layer Miura and n-RiM FSS structure by inkjet-printing dipoles over multiple Miura-ori structures with different dimensions. The proposed design features wideband tunability and good angle of incidence rejection for different folding angles.

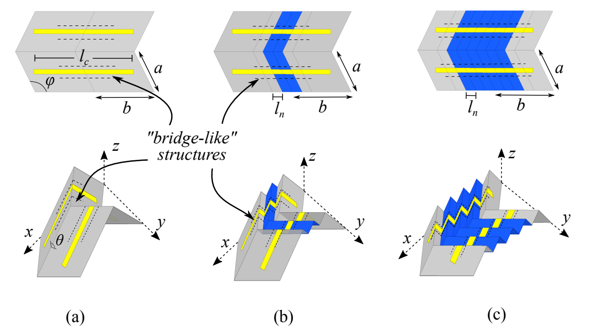

Fig. 1: Unit cell of (a) Miura (b) 3-RiM (c) 5-RiM FSS structure in flat (top) and folded (bottom) configuration. a=20mm, b=30mm, ϕ=75^o, l_c=50mm and l_s=5mm.

II. Hybrid n-RiM FSS Design and Fabrication

The unit cell of traditional Miura-FSS consists of four parallelogram that are connected together along the edges with each resonant (dipole) elements inkjet-printed across a single foldline as shown in Fig. 1(a). However, the dipole spans *n* Miura cells for hybrid n-RiM FSS structure (Fig. 1b & c). Therefore, it bends in a meander-line fashion as the folding angle θ is varied resulting in relatively wider frequency tunability as compared to conventional Miura-FSS due to additional capacitance introduced at each fold of the dipole [2]. It is important to note here that unlike n-RiM FSS structure, the proposed FSS structure is not planar. Therefore, multi-layer configuration can be realized by simply overlapping two or more layers with an inter-layer distance without using any specialize mechanical support [3]. The slit cuts along dipole elements form "bridge-like" structures allowing them to maintain high conductivity during bending process [1].

The proposed structure was fabricated by first perforating the n-RiM pattern on cellulose paper and then inkjet-printing dipoles along the foldlines using ten layers of silver nano-particle ink and cured for 1.5 hrs to realize highly flexible conductive traces that are embedded into the substrate [2]. Finally, the structure is folded manually that can be easily be automated by 3D-printed or heat-sensitive substrates [4]. Note that inkjet-printing facilitates accurate, on-demand and rapid fabrication of these highly flexible origami-inspired RF structure upto mm-wave frequency regime with the ability to be scaled-to-large-numbers easily. On the other hand, such

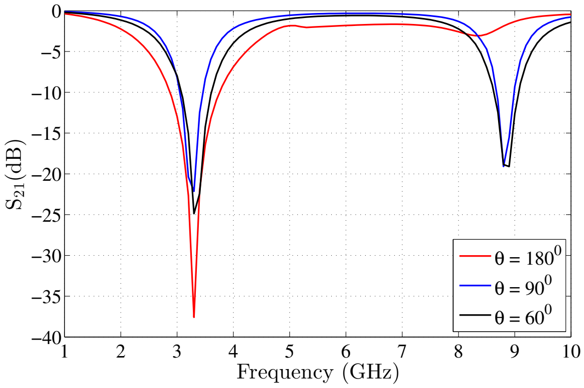

Fig. 2: Frequency response of Miura-FSS structure for different values of folding angle θ.

features are almost impossible to realize using traditional subtractive manufacturing technologies.

III. Results and Discussion

The proposed origami-inspired FSS structures were designed and simulated in HFSS using master/slave boundary conditions and Floquet port excitation using single unit cells. The frequency response of traditional Miura-FSS structure for different values of folding angle (θ) is shown in Fig. 2 which shows negligible variation in resonance frequency. This is typically observed when dipole size is comparable to the total length of the Miura unit cell that exhibits low mutual coupling at the open ends of the inverted V-dipole in folded Miura-FSS configuration. The peaks at higher frequency values corresponds to excitation of higher-order mode in the Miura-FSS structure [5]. The tunable range can be increased to almost 220% by using hybrid 5-RiM FSS structure as shown in Fig. 3. However, further improvement is not possible for higher n values as shown in Fig. 4 because for the given length of the dipole element, it does not introduce any additional folds along its length. The proposed structure also features wide angle of incidence rejection as shown in Fig. 5.

IV. Conclusions

This paper introduces a novel origami-inspired hybrid n-RiM FSS structure with dipoles elements that can be easily

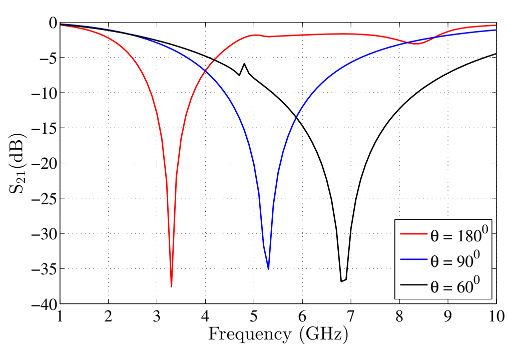

Fig. 3: Frequency response of 5-RiM FSS structure for different values of folding angle θ.

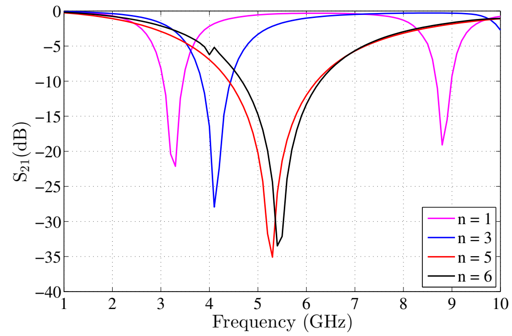

Fig. 4: Frequency response of n-RiM FSS structure for different number of ripples (n) with θ=90^o.

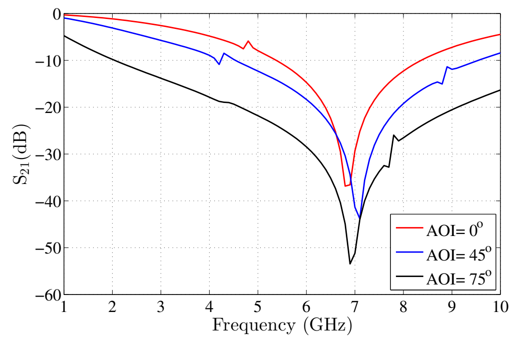

Fig. 5: Frequency response of 5-RiM FSS structure for different values of angle of incidence with θ=60^o.

extended to multi-layer configurations without use of any additional mechanical support and features upto 220% tunable frequency range as opposed to 15% and 145% of traditional Miura and n-RiM FSS structures respectively. It also solves the inherent problem with single-layer Miura-FSS structures that features minimal tunability when dipole length is comparable to its unit cell by using ripple-Miura topology.

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References

[1] 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.

[2] S. A. Nauroze, A. Eid, and M. M. Tentzeris, "n-rim: A paradigm shift in the realization of fully inkjet-printed broadband tunable fss using origami structures," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*, June 2018, pp. 51–54.

[3] S. A. Nauroze, L. S. Novelino, M. M. Tentzeris, and G. H. Paulino, "Continuous-range tunable multilayer frequency-selective surfaces using origami and inkjet printing," *Proceedings of the National Academy of Sciences*, vol. 115, no. 52, pp. 13 210–13 215, 2018. [Online]. Available: https://www.pnas.org/content/115/52/13210

[4] 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.

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