Inkjet-printed "4D" Tunable Spatial Filters Using On-demand Foldable Surfaces

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***Abstract*—A state-of-the-art fully inkjet-printed tunable frequency selective surface on cellulose paper is presented, which uses a Miura origami structure for an on-demand linear variation in inter-element distance and the effective length of the resonant dipole elements, resulting in an observable shift in the operational frequency of the structure. The dipole elements are placed on the foldlines along with special "bridge-like" structures to realize first-of-its-kind truly flexible conductive traces over sharp bends. Simulation and measurement results show that the Miura-FSS can be tuned to a wide range of frequencies and features a large angle of incidence rejection.**

***Index Terms*—Frequency selective surface (FSS), origami, Miura, tunable filters, inkjet-printing, cellulose paper, oblique incidence .**

I. Introduction

Filters play an important part in the design of almost any RF and electronic module. Their spatial counterparts are Frequency Selective Surfaces (FSSs), which typically comprise of a 2D-array of periodic resonant structures on a thin substrate that can filter electromagnetic waves based on their frequencies. FSS have found many applications ranging from security, smart skins, metamaterials, absorbers to the design of radomes to reduce the antenna radar cross-section outside their operating frequency range [1].

However, one of the key disadvantages of conventional FSS is that they are unable to re-configure or tune their frequency response according to their environment. Therefore, a significant amount of research and development has been done in the design of re-configurable FSS in the past couple of years. These techniques usually involve changing the electrical properties of the substrate [2], the geometry of FSS structure or the use of electrical components such as varactors or diodes [3] [4] that can change the flow of current between the FSS elements [5]. An alternate approach for designing a re-configurable FSS has been presented in [6], which uses chemically etched (from copper tape) cross-dipole FSS-elements that were placed manually on every facet of the origami structure. The frequency response of the FSS is then tuned by folding the origami, however, this design had a number of drawbacks. For example, manual placement of the resonant elements would make the design hard to replicate and inconsistent throughout the FSS structure. Secondly, copper tape is prone to peel off with humidity and temperature. Thirdly, the FSS featured a narrow angle of incidence rejection which limits its usage in practical applications.

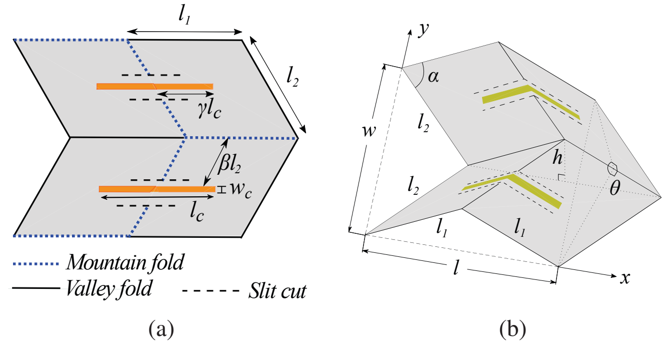

Fig. 1: Unit cell of Miura FSS in (a) flat state ($\theta = 180^o$) (b) folded state with $l_1 = l_2 = 20mm$, $\alpha = 45^o$, $\beta = \gamma = 0.5$, $l_c = 20mm$ and $w_c = 2mm$.

This paper presents a first-of-its-kind fully inkjet-printed 4D tunable FSS, using Miura origami structure on cellulose paper and dipole resonant elements. The dipole elements are inkjet-printed on the foldlines to demonstrate a rugged realization of flexible resonant elements at sharp edges. The flexibility of the inkjet-printed dipoles is further increased by placing special "bridge-like" structures along the dipoles. The designs are simulated and measured to evaluate the performance of the structure with respect to angle of incidence and folding.

II. Miura-shaped FSS with dipole elements

The behavior of an FSS is primarily determined by the shape of its resonant elements which can be broadly categorized either as open or closed [1]. The simplest examples of an open-shaped FSS and closed-shaped FSS are dipoles and loops, respectively, that resonate when their size is comparable to $\lambda/2$, where λ is the wavelength of the operating frequency [1]. Furthermore, both open and closed shaped FSS structures have complementary structures that determine the resulting filter type. For example, while a dipole FSS would act as a first-order bandstop filter, its complementary design (a slot FSS) would act an a bandpass filter which can be electrically modeled as an LC network connected in series or across the transmission line. Typically, FSS elements are printed or etched on a thin substrate that shifts resonant frequency by a factor of $\sqrt{(\epsilon_r + 1)/2}$. However, the effect of the substrate

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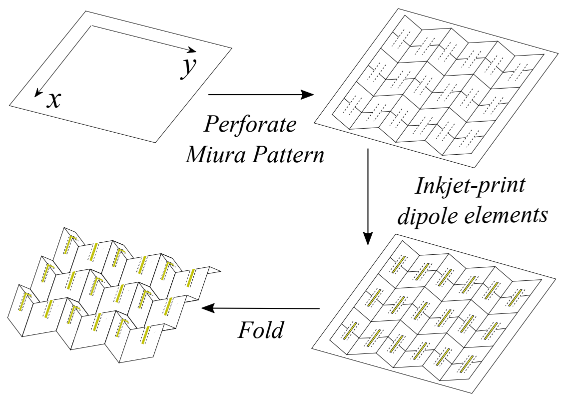


Fig. 2: Fabrication process for single-layer Miura FSS.

can be ignored if its thickness is very small compared to the operating wavelength (usually much less than $\lambda/10$).

In this paper, a 2D-periodic array of simple dipole elements, that are inkjet-printed across the foldlines of a Miura origami structure, are used to realize a first-order tunable spatial filter. A Miura is fundamentally a developable surface - that is, it can be realized by folding a flat sheet along the foldlines (in the form of mountains and valleys) without stretching or compressing the sheet, which facilitates the packaging of large flat structures into smaller areas. A study of mechanical properties of the Miura is presented in [7], [8], [9]. The Miura folding pattern also allows us to systematically vary the effective length and spacing between each dipole element by stretching or compressing the Miura structure, thereby changing on-the-fly the FSS frequency response.

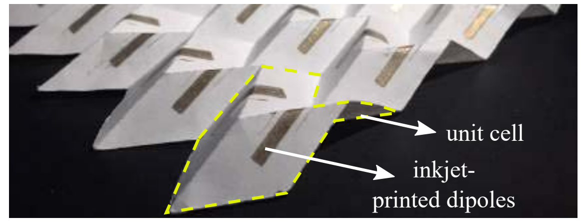
A typical Miura unit cell with inkjet-printed dipoles over the mountain folds is shown in Fig. 1b which consists of four parallelograms (each with length l_1, l_2 and an internal angle α) that are connected to each other along the edges. The folding behavior is depicted by changing the angle θ or equivalently lengths w or l that are related to each other by [9]:

$$\begin{aligned} l &= 2l_1\zeta \\ w &= 2l_2\xi \\ h &= l_1\zeta\tan\alpha\cos(\theta/2) \end{aligned} \tag{1}$$

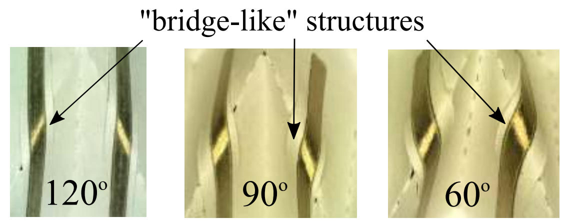
where,

$$\begin{aligned} \zeta &= \cos\alpha(1-\xi^2)^{-1/2} \\ \xi &= \sin\alpha\sin(\theta/2) \end{aligned} \tag{2}$$

It is important to note here that any type of FSS element could be used to implement tunable spatial filters, however, dipole elements are used here due to their simplicity and ease of implementation that facilitates the full understanding of the FSS frequency response variation with respect to the kinematics of Miura structure. Moreover, by placing the dipoles over the mountain folds, it also helps to demonstrate the first-of-its-kind efficient implementation of truly flexible FSS resonant elements across sharp folded structures, such as the foldlines.



(a)



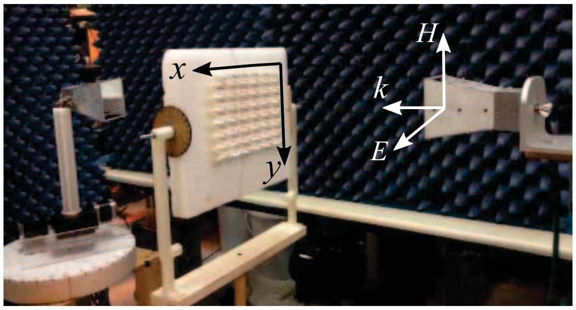
(b)

Fig. 3: (a) Fabricated single-layer Miura FSS in folded state (b) close-up of dipole elements with different folding angle θ.

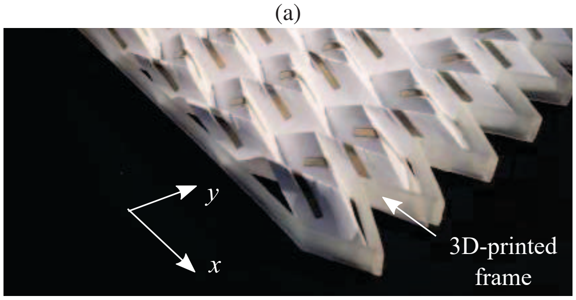
The fabrication process for tunable FSS is shown in Fig. 2. First, the outline of the Miura pattern is perforated on $110\mu m$ thick cellulose paper. Then, the dipole elements are inkjet-printed across the foldlines of each Miura cell by using 10 layers of silver nanoparticle ink and sintered at 150^oC for 2 hours. The cellulose paper is used because it absorbs the silver ink, thereby making the traces very flexible [10]. The flexibility of the traces is further enhanced by using a "bridge-like" structure along the traces which is realized by making small slits along the edges of the resonant elements as shown in Fig. 3b. This allows the conductive traces to fold in a curvature rather than a sharp edge, thus avoiding breakage and cracking. Finally, the inkjet-printed Miura FSS is cut out and folded manually. The folding mechanism could be automated by using hydrofolding techniques [11] or using a temperature sensitive drafting paper [12]. A closeup picture of the fabricated prototype is shown in Fig. 3a. It is interesting to note that the slits along the dipole elements (that form a "bridge-like" structure) prevent the dipoles to bend sharply along the foldlines even at θ=60^o that adds an extra degree of flexibility to the conductive traces. The behavior of the dipoles with respect to different values of the folding angle (θ) is shown in Fig. 3b.

III. Simulation and Measurement Results

Single-layer Miura FSS was designed and simulated using HFSS. In order to exploit the periodic nature of the Miura-FSS structure, master-slave boundary conditions with Floquet port excitation were used to simulate the unit cells, thereby saving time and computational resources. The simulation results were then verified using the measurement setup shown in Fig. 4a which consists of a fabricated Miura-FSS placed in the middle of two horn antennas at line-of-sight to each other. Moreover,



(a)



(b)

Fig. 4: (a) Measurement setup (b) 3D-printed frame to uniformly fold Miura-FSS structure at a given folding angle θ (frame for $\theta = 90^o$ is shown here).

three 3D-printed frames were used to hold the FSS at different folding angles (θ=$60^o, 90^o, 120^o$) and to ensure all unit cells in the Miura-FSS structure are folded at the same folding angle (θ) as shown in Fig. 4b.

The simulated and measured insertion loss (S_{21}) of a single-layer Miura-FSS with respect to different values of the folding angle (θ) is shown in Fig. 5 which clearly indicates a systematic shift in FSS frequency response due to folding and a strong agreement between simulated, measured and theoretical results. Since the Miura-FSS is realized on paper substrate

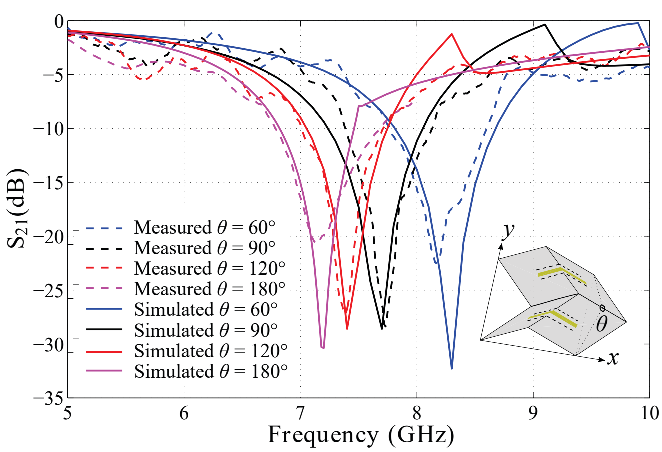


Fig. 5: Frequency response of single-layer Miura-FSS with different values of folding angle θ.

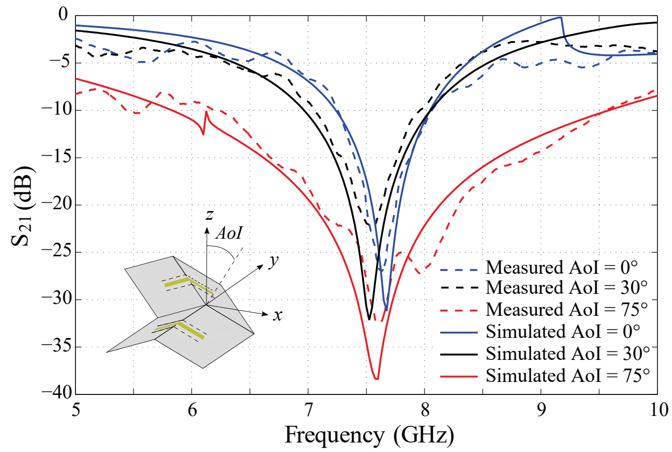


Fig. 6: Frequency response of single-layer folded ($\theta = 90^o$) Miura-FSS with different values of angle of incidence.

with thickness relatively small as compared to operational wavelength, the dielectric effects and losses can be ignored. For example, a completely flat Miura-FSS ($\theta = 180^o$) with 20mm long dipole elements resonates at 7.5GHz (with $\epsilon_r = 1$). In our case, we observed a slight shift in resonant frequency which is primarily due to the spreading of ink on the porous cellulose paper substrate which causes the length of printed dipoles to be increased by 0.3mm on each side, resulting in printed dipoles with length of 20.6mm that corresponds to a resonant frequency of around 7.2GHz which matches very closely to the theoretical, simulated and experimental results.

Similarly, Fig. 6 shows a very high angle of incidence (AoI) rejection for a folded Miura-FSS, which is not usually true for a conventional dipole-based FSS [1]. Moreover, the percentage bandwidth also increases significantly for higher values of AoI. This is mainly because at lower values of theta (i.e. when the Miura is compressed), the dipoles bend in a way to form an inverted V-shaped 3D structure which improves the AoI rejection performance and increases the percentage bandwidth of the overall Miura-FSS. The preliminary experimental results show that AoI rejection can be further increased for higher-order filters using a multilayer configuration. Moreover, the future work would involve investigation of origami [13] and kirigami-based structures [14] that can possibly lead to realization of more novel FSS structures.

IV. Conclusion

This paper presents a detailed design and analysis of a state-of-the-art fully inkjet-printed 4D tunable frequency selective surface (FSS) on cellulose paper using a Miura-origami structure. The frequency response of the FSS is varied on-demand by physically folding the Miura structure. Furthermore, the performance of the Miura-FSS was found to be much superior to conventional 2D dipole-FSS in terms of angle of incidence rejection and reconfigurability. The simulation and measurement results show a good agreement with the theoretical values.

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