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Wideband Ultraminiaturised-Element Frequency Selective Surface Based on Interlocked 2.5-Dimensional Structures

Mingqian Jia, Xiaoxiang He, Yang Yang*, Boyu Hua, Wenxiu Hu, and Xiangyu Qian

Abstract—An approach to synthesizing wideband ultraminiaturised-element frequency selective surface (UMEFSS) based on interlocked 2.5-dimensional (2.5D) structures is proposed. Ultraminiaturisation and wide stopband response can be realized due to compactly staggered arrangement of 2.5D elements. The element size of the proposed UMEFSS is reduced to $0.033\lambda_0 \times 0.033\lambda_0$, and fractional bandwidth attains 99.8%. Stable response is achieved under oblique incidence at different polarisations. The results show a satisfactory consistency between full-wave simulations and experiments.

1. INTRODUCTION

Frequency selective surfaces (FSSs) which have been used for spatial filters, absorbers, polarisation convertors, antenna stealth, etc. are conventionally considered as two-dimensional periodic structures [1–4]. Miniaturised-element FSSs are required so that sufficient elements can be provided to make FSSs act as infinite FSSs when FSSs are applied in limited regions [5].

The concept of 2.5D structures has been put forward to reduce FSS element size thus far. Several FSSs based on 2.5D structures have been proposed. Metallic vias are end loaded to planar elements directly in an early stage [5, 6]. Enlarging length of resonant elements in limited area by knitting vias into metallic lines is a common way to synthesizing miniaturised 2.5D structures. An ultra-wideband FSS based on 2.5D hexagonal ring is proposed in [7]. Metallic segments of hexagonal rings are alternately placed on both sides of a substrate and connected by metallic vias. Yet, the FSS lacks polarisation stability due to its incompletely symmetric structures. Similarly, a miniaturised FSS based on 2.5D square loop is presented in [8]. In [9], two pairs of metallic split rings are printed on both sides of a substrate and connected by metallic vias to form a closed loop. In [10], Hilbert fractals are placed on both sides of a substrate and connected by metallic vias to increase the length of current path. Miniaturisation is normally improved with increased complexity of FSS elements and bandwidth degradation. A 2.5D FSS with narrow bandwidth is presented in [11]. The element size is reduced to $0.03\lambda_0 \times 0.03\lambda_0$, where λ_0 is the free space wavelength of the resonant frequency. Nevertheless, two separate propagation paths are required for different polarisations.

An approach to synthesizing wideband UMEFSS based on interlocked 2.5D structures is proposed in this letter. In stead of enlarging the elongation further, 2.5D elements are integrated efficiently by compactly staggered arrangement. A FSS is simulated and fabricated. The element size is reduced to merely $0.033\lambda_0 \times 0.033\lambda_0$. Furthermore, fractional bandwidth of the FSS is 99.8%. The proposed UMEFSS exhibits wide stopband response with angle and polarisation stability.

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2. FSS DESIGN AND SIMULATIONS

With additional inductances and capacitances provided by metallic vias in 2.5D structures, FSS elements can be miniaturised less or more. Metallic lines on the both sides of a substrate are generally split in 2.5D structures. Other than enlarging elongation of basic element, more elements can be integrated by staggered arrangement. Besides, increasing capacitances between FSS elements can enlarge bandwidth and lower resonant frequency [12, 13]. An increase of capacitances can be easily obtained to realize ultra-miniaturisation and enhanced bandwidth of FSSs by interlocked structures.

A three-dimensional view of the proposed FSS element is presented in Figure 1(a). Basic element of the proposed UMEFSS is a 2.5D closed loop with extra eight metallic vias. As shown in Figure 1(a), segregated by a substrate and connected by metallic vias, two sets of parallel metallic lines are arranged along two orthogonal directions specifically, forming a closed loop. Extra eight vias are introduced to provide additional capacitances without breaking metallic lines on the surface of the substrate. Every metallic via ends with a pair of metallic rings on the substrate for prototype fabrication. Figure 1(b)

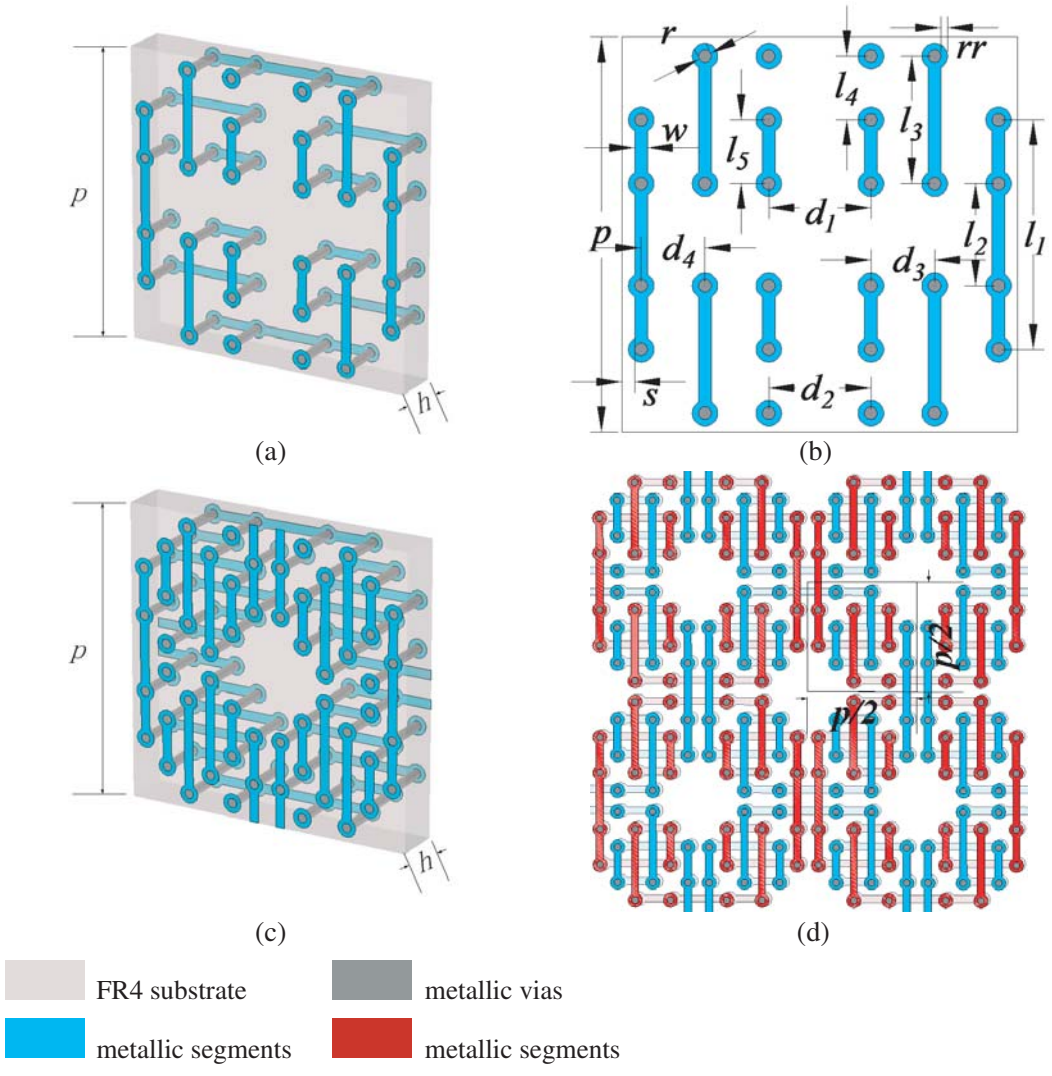

Figure 1. Geometric configuration of the proposed UMEFSS: (a) 3D view of basic element, (b) upper layer of basic element, (c) 3D view of unit cell, (d) 2×2 unit cells of the proposed UMEFSS. ($p = 6.2\,\text{mm}$, $h = 1\,\text{mm}$, $w = r = 0.2\,\text{mm}$, $s = 0.2\,\text{mm}$, $rr = 0.13\,\text{mm}$, $l_1 = 3.6\,\text{mm}$, $l_2 = 1.6\,\text{mm}$, $l_3 = 2\,\text{mm}$, $l_4 = l_5 = 1\,\text{mm}$, $d_1 = d_2 = 1.6\,\text{mm}$, $d_3 = d_4 = 1\,\text{mm}$).

shows metallic segments arranged on the upper layer of the substrate. Metallic segments on both sides of the substrate are arranged in different directions and show the same geometric configuration. It is easy to interlace the elements based on orthometric knitted structures just by panning. The proposed unit cell is depicted in Figure 1(c). Each unit cell contains one complete and four quartered 2.5D elements. Therefore, the equivalent size of an element is half of the unit cell size. Figure 1(d) depicts 2×2 unit cells of the proposed UMEFSS to explain staggered arrangement of the elements. For clarity, different colors are utilized to represent metallic segments of buckled adjant 2.5D elements. As illustrated, an element can coincide with another element of different colors after continuously moving $p/2$ in two orthogonal directions. It can be observed that an element is interwoven with the surrounding four other elements. The proposed FSS uses an FR4 substrate with a relative permittivity of $\varepsilon_r = 4.3$ and a loss tangent of 0.025.

Performed by CST, the simulated transmission coefficients of the FSS without interlocked structures and the proposed UMEFSS are depicted in Figure 2. In the former case, the FSS whose basic elements are arranged in cycles of p along two orthogonal directions is reasonant at 3.1 GHz and fractional bandwidth is 33.4%. Twice as many elements included in an area of equal size, the proposed UMEFSS based on interlocked structures is reasonant at 2.265 GHz and has a wide stopband response from 1.255 GHz to 3.515 GHz with more than 10 dB attenuation. The resonant frequency is reduced by nearly 30%, and fractional bandwidth attains 99.8%. The metallic vias in 2.5D structures provide additional inductances and capacitances. Extra capacitances are introduced between 2.5D elements due to compact arrangement. As illuminated, properties of ultra-miniaturisation and wideband are achieved by staggered arrangement of 2.5D elements.

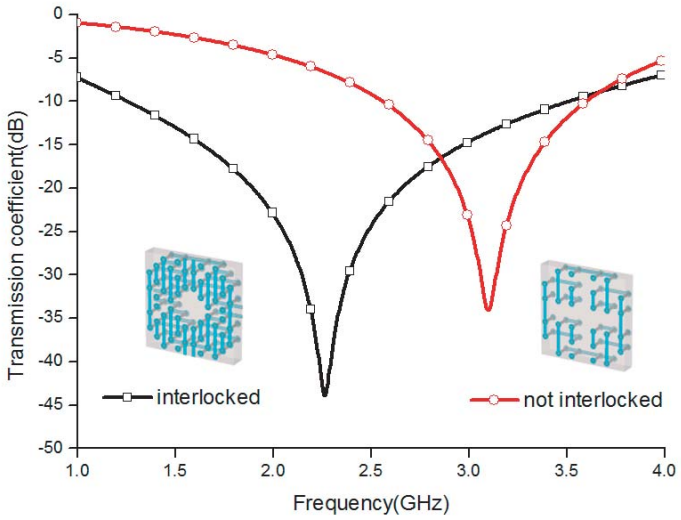

Figure 2. Simulated transmission coefficients of the FSS without interlocked structures and the proposed UMEFSS.

Figure 3 depicts the simulated transmission coefficients with different thicknesses of the substrate. The lengths of metallic vias determined by the thicknesses of the substrate have effect on the resonant frequency. As shown, the resonant frequency shifts down from 2.95 GHz to 1.83 GHz with the value of h changed from 0.5 mm to 1.5 mm. The resonant frequency is lowered by increasing the thickness of the substrate. Besides, the fractional bandwidth maintains about 100%. The operation frequency of the FSS based on 2.5D structures can be altered by changing the substrate thickness without redesigning planar structures. It is effective to further miniaturisation of the proposed element by increasing the substrate thickness of the FSS. The element size of the proposed UMEFSS with 1 mm thickness of the substrate is $0.033\lambda_0 \times 0.033\lambda_0$. As the thickness of the substrate is increased to 1.5 mm, the element size can be reduced to $0.027\lambda_0 \times 0.027\lambda_0$.

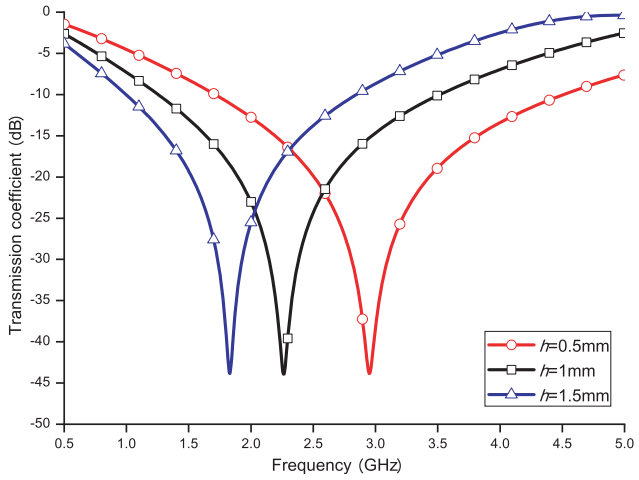

Figure 3. Simulated transmission coefficients of the proposed UMEFSS with different thicknesses of the substrate.

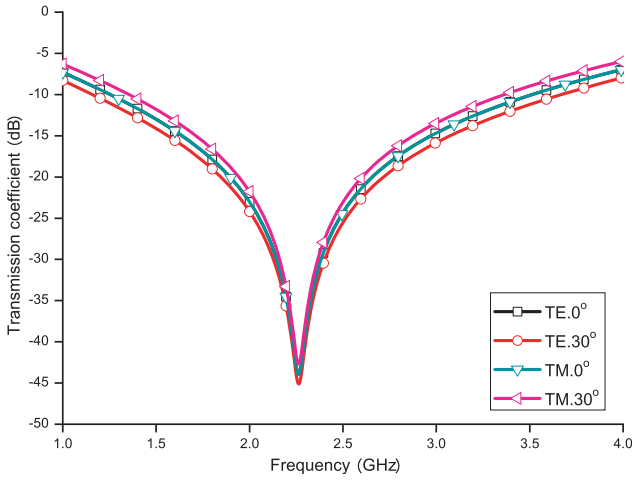

Figure 4. Simulated transmission coefficients of the proposed UMEFSS with different incident angles at different polarisations.

The simulated transmission coefficients of the proposed UMEFSS with different incident angles at different polarisations are illustrated in Figure 4. As shown, the proposed UMEFSS exhibits stable response to oblique incident waves. At 30 incidence, the UMEFSS is resonant at 2.26 GHz/2.265 GHz for transverse electric (TE)/transverse magnetic (TM) mode. The resonant frequency deviation is merely $0.0022f_0$, where f_0 is the resonant frequency.

3. MEASUREMENTS AND COMPARISON

Figure 5(a) shows a photograph of the measurement environment. Figures 5(b) and (c) depict 3×3 unit cells of the fabricated FSS from top and bottom view.

(a) (b) (c)

Figure 5. Photographs of measurement environment and fabricated FSS: (a) measurement environment, (b) 3×3 unit cells of the fabricated FSS (top view), (c) 3×3 unit cells of the fabricated FSS (bottom view).

The test prototype is fabricated with size of 322.4 mm $\times$ 322.4 mm $\times$ 1 mm and consists of 52×52 unit cells. A vector network analyser (Agilent N5230C over frequencies from 300 kHz to 20 GHz) is used. As shown in Figure 5(a), the prototype is fixed in a holder composed of absorbing material in a microwave anechoic chamber. A pair of double-ridged horn antennas operating from 1 to 20 GHz are placed on both sides of the prototype as transmitting and receiving antennas.

Figure 6 shows simulated and measured transmission coefficients of the proposed UMEFSS with different incident angles at different polarisations for a comparison. In spite of discrepancies caused by tolerances of the FSS sample in the fabrication process, favourable agreement is achieved between fullwave simulations and measurements.

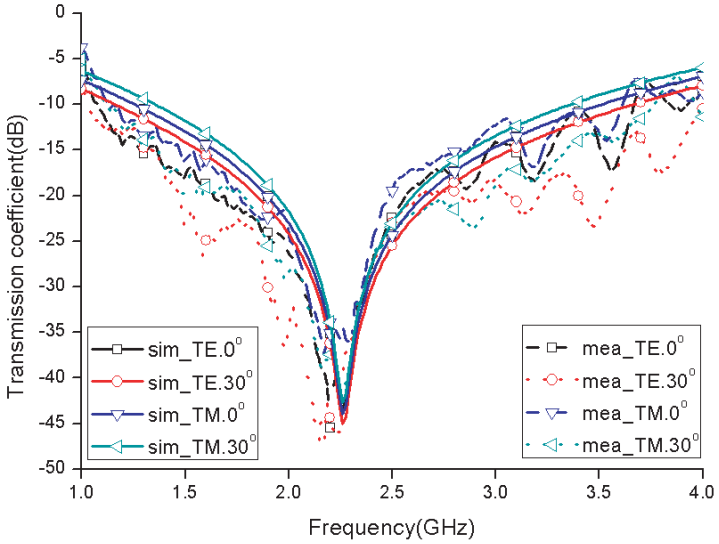

Figure 6. Simulated and measured transmission coefficients of the proposed UMEFSS with different incident angles at different polarisations.

Table 1 gives a comparison of relevant FSSs based on 2.5D closed loop. Compared with ultra-wideband FSS based on 2.5D hexagonal ring in [6], element size of the proposed UMEFSS with thinner substrate is reduced by about 80%. The UMEFSS shows improved stability as a result of ultra-miniaturised symmetric element structure. Compared with other 2.5D FSSs in the table, element size of the proposed UMEFSS is reduced by more than 30% and the UMEFSS shows superior bandwidth performance.

Table 1. Comparison of relevant FSSs based on 2.5D closed loop.

FSS	Substrate thickness (mm)	ε_r	Element size (mm^2)	Fractional bandwith
[7]	1.6	4.3	$0.07\lambda_0 \times 0.08\lambda_0$	121.6%
[8]	1.6	4.4	$0.063\lambda_0 \times 0.063\lambda_0$	79.3%
[9]	1.6	4.4	$0.048\lambda_0 \times 0.048\lambda_0$	21%
[10]	1.6	4.4	$0.041\lambda_0 \times 0.041\lambda_0$	33%
This letter	1	4.3	$0.033\lambda_0 \times 0.033\lambda_0$	99.8%

4. CONCLUSION

An approach to synthesizing wideband UMEFSS is presented in this letter. The approach exploiting interlocked 2.5D structures shows capabilities of ultra-miniaturisation and enhanced bandwidth of FSSs. The proposed UMEFSS provides stable wideband response within a large range of incident angles at different polarisations. The methodology has application value in synthesizing 2.5D miniaturised FSSs with requirement of wideband electromagnetic shielding.

ACKNOWLEDGMENT

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Errata to "Wideband Ultraminiaturised-Element Frequency Selective Surface Based on Interlocked 2.5-Dimensional Structures"

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We would like to do a few corrections to the paper.

1) Page 37, in the fifth line of the abstract, "bandwidth attains 99.8%" is corrected as "bandwidth attains 94.8%".

2) Page 37, in the the fourth line of third paragraph of Section 1, "fractional bandwidth of the FSS is 99.8%" is corrected as "fractional bandwidth of the FSS is 94.8%".

3) Page 39, in the seventh line of the second paragraph, "fractional bandwidth attains 99.8%" is corrected as "fractional bandwidth attains 94.8%".

4) Page 41, in the last row and last column of Table 1, "99.8%" is corrected as "94.8%.

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