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Abstract: A novel element provides reflection band ratios as low as 1.1. It is derived from the double square but is less demanding on printing definition. Together, the two elements offer increased flexibility in frequency selective surface design for close band applications. Substrate loss effects are also discussed.

Frequency selective surfaces (FSSs) using the double square loop patch element shown in Fig. 1a have transmission frequency responses with two main reflection nulls at frequencies f_{r1} and f_{r2} , on either side of a mid-range transmission band. These nulls correspond to resonances of the inner and outer squares. Varying the relative sizes of the two square components is a convenient way of altering the spacing of the reflection bands. FSSs based on the square loop [1] have been used over a wide range of frequencies, from microwave to submillimetre wavelengths [2], and have proved useful in separating moderately spaced components of multiband signals. The band ratio f_{r2}/f_{r1} can be set to exceed a factor of 2 but if the design requirement is to separate much closer bands an immediate problem arises. The dimensions of the inner square subelement rapidly approach those of the outer, leading to fabrication problems in etching very narrow gaps between the two squares and in practice limiting the reflection band ratio to ~ 1.4 .

A possible solution might be to place the subelements in different but very close planes, separated by a very thin dielectric film, but fabrication of such structures is difficult, relatively expensive and much less practical at short wavelengths. An alternative approach is to fold the inner square, giving it a correspondingly greater resonant length, generating the convoluted double square structure shown in Fig. 1b. Highly folded geometries, such as the convoluted dipole [3], have been used to derive arrays with very greatly reduced unit cell sizes for use at long wavelengths or on highly curved surfaces, and to increase the separation of the useable reflection bands from the grating lobe

region. The same principle is used in this Letter to design a single layer FSS capable of providing close band spacings.

The plane wave transmission frequency responses of a range of double square FSSs and the convoluted variant have been computed using a standard Floquet modal analysis. The basis functions used to represent the currents induced in the conductors were subsectional (rooftop) modes [4]. Fig. 2 gives a comparison of some of these results with experimental values, to validate the software. It contrasts the computed transmission response with measurements made in a plane wave chamber at normal incidence over the frequency range 8 to 12GHz, for a convoluted double square FSS. The array periodicity p was 6.0mm, with $D_1 = 5.6^\circ$ in Fig. 1b and $D_2 = 4.8$ mm. The clearance g was 0.2mm. The agreement is close. The measured band ratio f_{r1}/f_{r2} is 1.2 and the predicted value differs by only 3% from this. It should be noted, though, that there is a significant loss in the transmission band between the two reflection bands, at about 10.3GHz. The array was printed on a dielectric substrate 0.03mm thick with $\epsilon_r = 3.0$, but with a high loss tangent, ~ 0.02 . The software shows that this loss is absorptive and not a mismatch loss. It falls below 0.5 dB when the loss tangent is 0.005, and would almost vanish for a lossless substrate. High-quality substrate materials are therefore required in applications using the close band spacings that these FSSs offer the same periodicity $p = 10$ mm, and with the same external element length $D_1 = 9.4$ mm (Fig. 1), which generates FSS with the first main resonance at about 6GHz. The supporting substrate was again 0.03mm thick and $\epsilon_r = 3.0$. The dimensions D_2 of the internal subelement were varied to alter the clearances g between the inner and outer squares. The results are given for a set of six designs, in which g ranges from 0.2 to 1.5mm. The width of the conductors W_1 and W_2 was equal to the smallest of these spacings, 0.2mm. In the convoluted double square (CDS) the stub on each side had dimensions $G = 0.6$ mm with the length $H = 3.0$ mm.

As might be expected, the first resonant frequency f_{r1} is practically independent of the inner square dimension D_2 , especially for the double square element (DSL), whereas the second resonant frequency increases with increasing conductor clearance.

The ratio f_{r2}/f_{r1} varies from ~ 1.4 to 2.3 for the double square, but is significantly less for the convoluted designs. For those elements, the second reflection null merges with the first for design 1 where the clearance g is 0.2mm , but for the higher values the ratio is in the range 1.1 to 1.4 . These values are quite stable to the angle of wave incidence to beyond 30° . Between them therefore, the two designs cover a useful sequence of band separations. But to achieve the value of 1.4 , the double square requires the small 0.2mm clearance and demands much more accurate etching to achieve the required line definition, whereas in the convoluted design g is much wider i.e. 1.5mm .

Table 1 also gives values for the fractional widths of the reflection bands. They refer to the -10dB levels. Generally the widths for the double square are slightly greater except for design 1 where the two nulls have merged in the case of the convoluted square, and for both elements the first null is wider than the second. The values are almost independent of g for the double square, but for the convoluted design the first null steadily widens while the second narrows as g is increased. Overall, the bandwidths for the latter element range from -10 to 25% , a capability which is typical of single layer resonant element FSS. We conclude, therefore, that this new convoluted geometry offers enhanced flexibility in the design of FSS for close band separation, but high quality substrate materials must be used.

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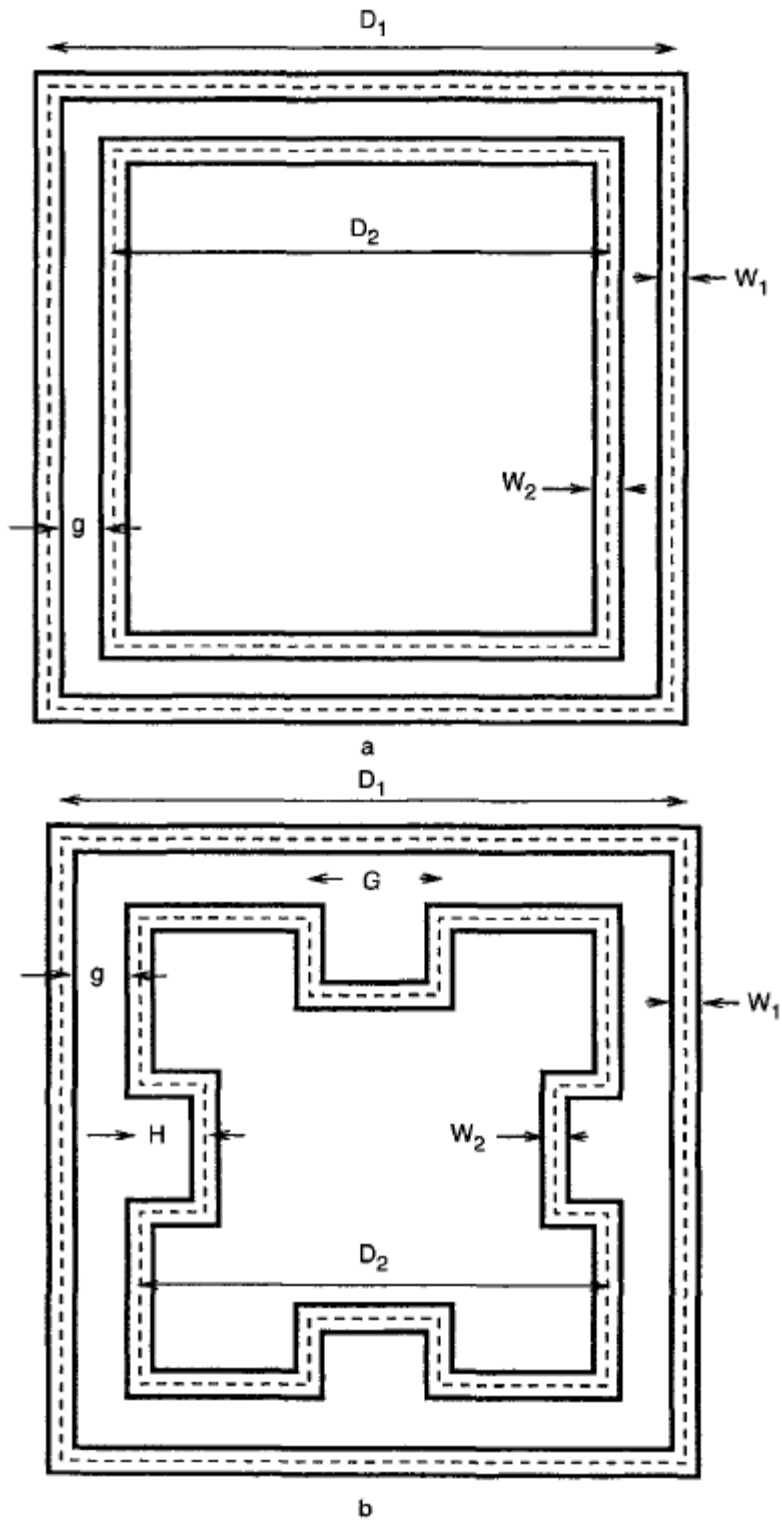


Fig. 1 Element geometry

g = clearance parameter

a Double square loop (DSL)

b Convoluted double square (CDS)

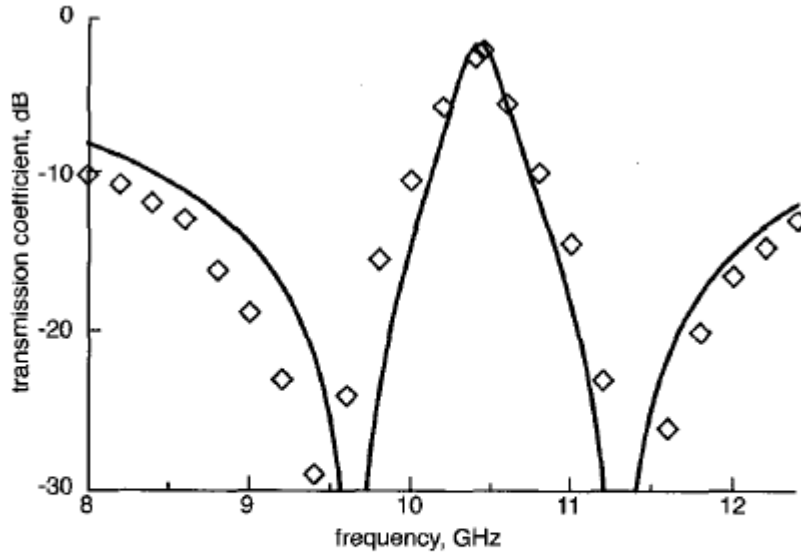


Fig. 2 Plane wave transmission response of convoluted double square loop FSS at normal incidence

Reflection band ratio is 1.2
 — computed response
 ◇ measured values

Table 1: Computed reflection band parameters of six double square loop (DSL) and convoluted double square (CDSL) FSS arrays

No.	Clearance g [mm]	Resonant frequencies				Band ratio		Fractional bandwidth			
		f_{r1} [GHz]		f_{r2} [GHz]		f_{r2}/f_{r1}		$\Delta f_{r1}/f_{r1}$		$\Delta f_{r2}/f_{r2}$	
		DSL	CDSL	DSL	CDSL	DSL	CDSL	DSL	CDSL	DSL	CDSL
1	0.2	6.1	6.0	8.7	—	1.4	—	0.25	0.33	0.13	—
2	0.4	6.1	6.0	9.5	6.5	1.6	1.1	0.25	0.17	0.14	0.14
3	0.6	6.1	6.0	10.2	6.9	1.7	1.15	0.25	0.18	0.16	0.14
4	0.8	6.1	6.0	11.0	7.2	1.8	1.2	0.25	0.21	0.16	0.11
5	1.0	6.1	6.0	11.9	7.4	1.9	1.2	0.25	0.21	0.15	0.11
6	1.5	6.1	6.1	14.3	9.0	2.3	1.45	0.26	0.23	0.14	0.08

Table 1 shows performance data for a set of FSSs. The elements were closely packed on a square array lattice, always with