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Key words: Convoluted array elements, FSS, bandwidth enhancement, miniaturisation.

Abstract: The interweaving of abjacent convoluted elements of crossed dipoles is shown to give reductions in operating frequencies of almost 15 times for single layer surfaces. The frequency stability with oblique incidence is observed to be significantly better than for simple crossed dipoles. At normal incidence the fractional reflection band width increases to more than 60% and the common bandwidth for oblique incidence upto 45º is 46%.

Introduction: Although Frequency Selective Surfaces have been applied at microwave frequencies for several decades, their use at civil mobile bands is much more recent. One of the barriers to FSS application at frequencies in the WLAN bands (2.4GHz and 5.5GHz) and below is the requirement for the individual array elements to be of large physical size (approaching one half wavelength) in order for them to be resonant. Unfortunately, large element sizes and large periodicities lead to problems, including difficulties in conforming to curved surfaces. Also, when backed by a closely spaced ground plane, FSS form what are known as High Impedance Surfaces (HIS) [1], which can reduce back scatter and improve gain when used as ground planes for antennas. If the element size is sufficiently reduced, it becomes possible to implement HIS at mobile bands for use in handsets [2].

The term ‘convoluted’ in the context of printed rf structures was first used in [3] to describe a class of complex array elements which exhibit long wavelength resonances in a surface with small periodicity. It was noted that the use of convoluted FSS elements improved the angular stability of the frequency responses of the surface, moving the operating bands away from the grating region which is determined by the periodicity of the array. The idea was developed further in [4], where the element configurations included sequences of Hilbert space filling curves and also in [5], which introduced a scheme for convolving crossed dipoles. There have been many papers published since, including [6] which applied interwoven convoluted structures to high impedance surfaces and most recently, [7] which extends the concept of element interweaving to obtain small size elements with enhanced bandwidths.

In this letter we present single layer interwoven element designs based on those of [5] which exhibit operating frequencies lower by a factor of almost 15 than those of simple crossed dipole arrays with the same periodicty and with bandwidths similar to those reported in [7].

Interwoven Convoluted Elements: A consequence of reducing element size is often a corresponding reduction in the widths of the reflection bands in patch element arrays, as noted in [7]. This is a distinct advantage for some low frequency applications, but the use of interweaving as proposed in [6] can reverse this trend as the element size is no longer constrained to lie within a single periodic cell of the surface.

All the surfaces discussed here are single layer, and the convoluted element that is the subject of this letter is shown in Fig.1a , with no interweaving. The convoluted crossed dipole of Fig.1a is modified to interweave with its neighbours and the various stages of this process are indicated in Fig.1b. A square lattice with a periodicity p of 10.8mm was used for the design. The surfaces were simulated using periodic boundaries around a single cell in CST Microwave Studio. Conductor widths and gaps were no smaller than 0.2mm which would enable fabrication by wet etching. No dielectric substrate was included in the simulations, though its effect on FSS response is well understood [8], and can lead to a further reduction in resonant frequencies. For single finger interweaving, only the finger labled 1 is present. For full interweaving all fingers up to and including 7 are included. Table 1 summarises the results of adding 0 to 7 interwoven fingers and compares their transmission parameters with a benchmark surface consisting of a simple unconvoluted cross dipole FSS based on the same lattice. The bandwidth here is the width of the reflection band measured between the -10dB points on the computed transmission/frequency response.

Normal incidence: The table shows that for the unconvoluted dipoles, the lattice size at the resonant frequency f_r is nearly half of one wavelength and convoluting the element according to Fig.1a increases the electrical length of the cell by more than 5 times. Figure 2 illustrates that adding up to 4 interwoven fingers continues this trend, but at a slower rate. The resonant wavelength λ_r continues to increase for 5-7 finger interweaving, though the trend is less marked. Full interweaving increases λ_r by a factor of 14.8 times compared with the unconvoluted crossed dipole arrays. In contrast to the small reflection bandwidths around f_r reported for interwoven elements in [6], the fractional bandwidth increases with interweaving, until at 7 fingers, it is over 5 times wider than that of an unconvoluted crossed dipole array. The band edge ratio is the frequency ratio of the -10dB and -0.5dB points on the transmission curve. Figure 3 shows this curve is symmetrical for elements with no interweaving, but the high bandwidths for the interwoven cases are due to the increasingly slow roll off on the leading (low frequency) edge.

Oblique incidence: The angular stability of the transmission response tends to improve as the periodocity becomes small with respect to wavelength [3]. This is confirmed in Table 1 which shows the frequency of the benchmark unconvoluted crossed dipoles varies (in opposite directions) by 7.9 and 3.7% for TE and TM 45° incidence respectively. Convoluting the dipoles causes the frequency stablility to improve radically for both TE and TM incidence with no further significant change noted for the interwoven elements. Generally, the TE bandwidth increases with respect to normal incidence for convoluted dipoles while the TM bandwidth decreases, as is typically the case with patch elements. The frequency stability of the convoluted elements means that the bandwidth common to the 3 states of incidence is equal to that of the TM band, and should be compared with the common bandwidth of benchmark unconvolued crossed dipoles, which is 0%.

For comparison, the surfaces reported in [7] offer λ_r / p of 13.4 and a fractional bandwidth of 64%.

Conclusions: The convoluted interwoven crossed dipole FSS elements presented in this paper offer a reduction of almost 15 times in operating frequency compared with non-convoluted elements, with a relection bandwidth of more than 63% at normal incidence, together with excellent frequency stablity and a common bandwidth no smaller than that available to TM incidence at 45°. In addition to its implications for the design of electromagnetic screens, this magnitude of size reduction makes the application of High Impedance Surfaces (HIS) viable for antennas on handset mounted platforms where there is a requirement of between 3 and 8 rows of HIS elements around the antenna to gain an artifical magnetic conductor effect.

The cost of producing such significant element size reductions by convolution on a single layer surface is the high resolution required in the mask [4]. The interwoven convoluted elements presented here have conductor spacings of 0.2mm, the minimum acceptable resolution for a conventional wet etching process typically used for FSS fabrication. Small gaps are required to keep equivalent surface capacitance high, which reduces the transmission frequencies and improves the bandwidth for a given periodicity. The high band edge ratios in Fig 3 for the most closely interwoven elements are similar to those for superdense dipole arrays. How to reduce them is described in reference 9.

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List of Figure Captions:

Figure 1: (a) Convoluted FSS crossed dipole element introduced in [5] (b) Interwoven fingers of convoluted element.

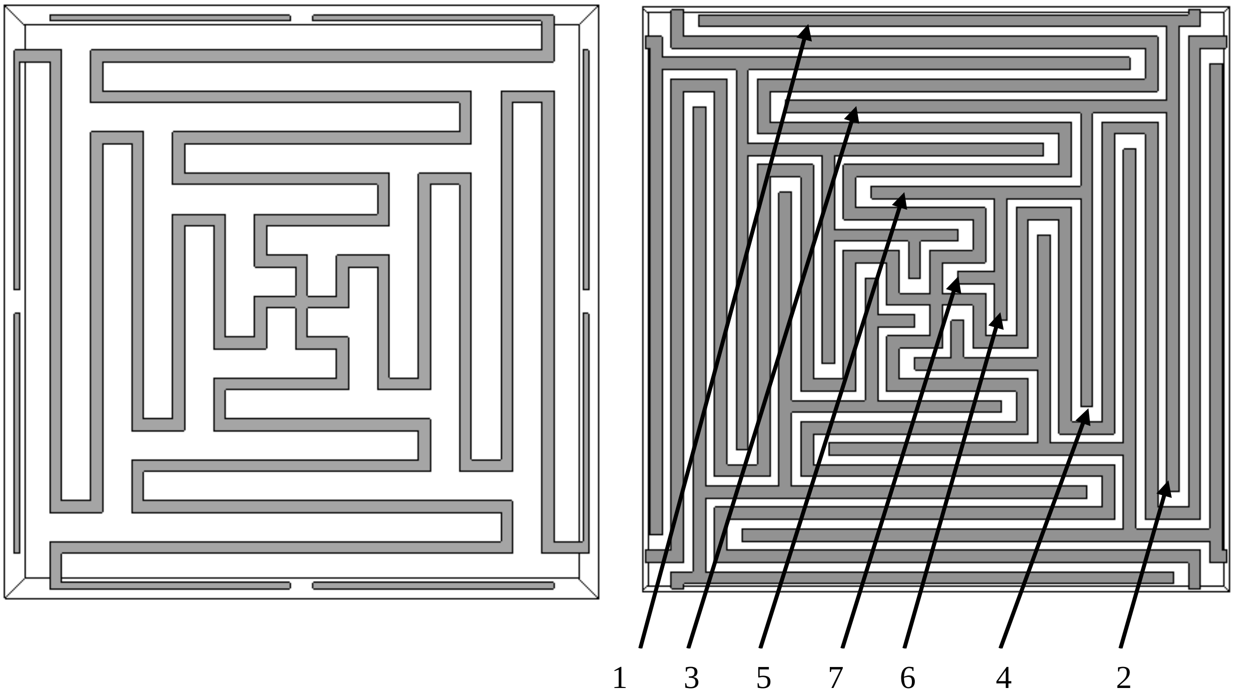
Figure 2: Variation of resonant frequency, f_r and fractional reflection bandwidth vs. the extent of interweaving between adjacent elements.

Figure 3: Band edge ratio for the leading and trailing edges of the interwoven convoluted element transmission reponse.

List of Table captions:

Table 1: Comparison of frequency and bandwidth for FSS designs based on a square lattice with perodicity p of 10.8mm.

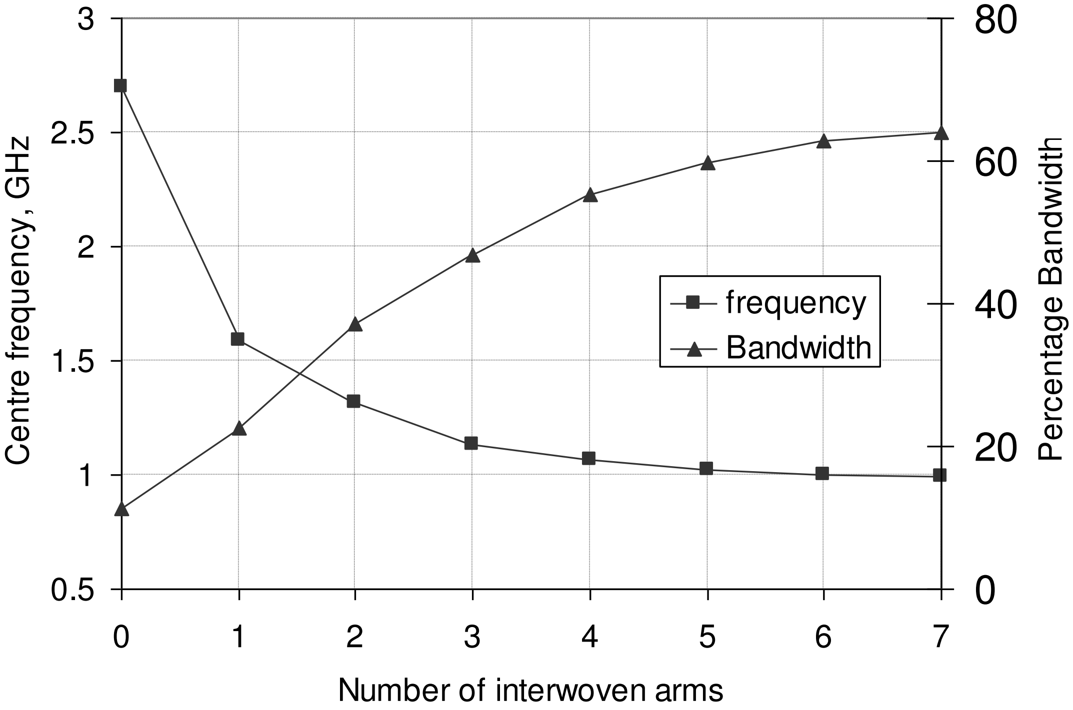
Figure 1:



a

b

Figure 2.


Centre frequency, GHz
3
2.5
2
1.5
1
0.5
80
60
40
20
0
Percentage Bandwidth
0
1
2
3
4
5
6
7
Number of interwoven arms
frequency
Bandwidth

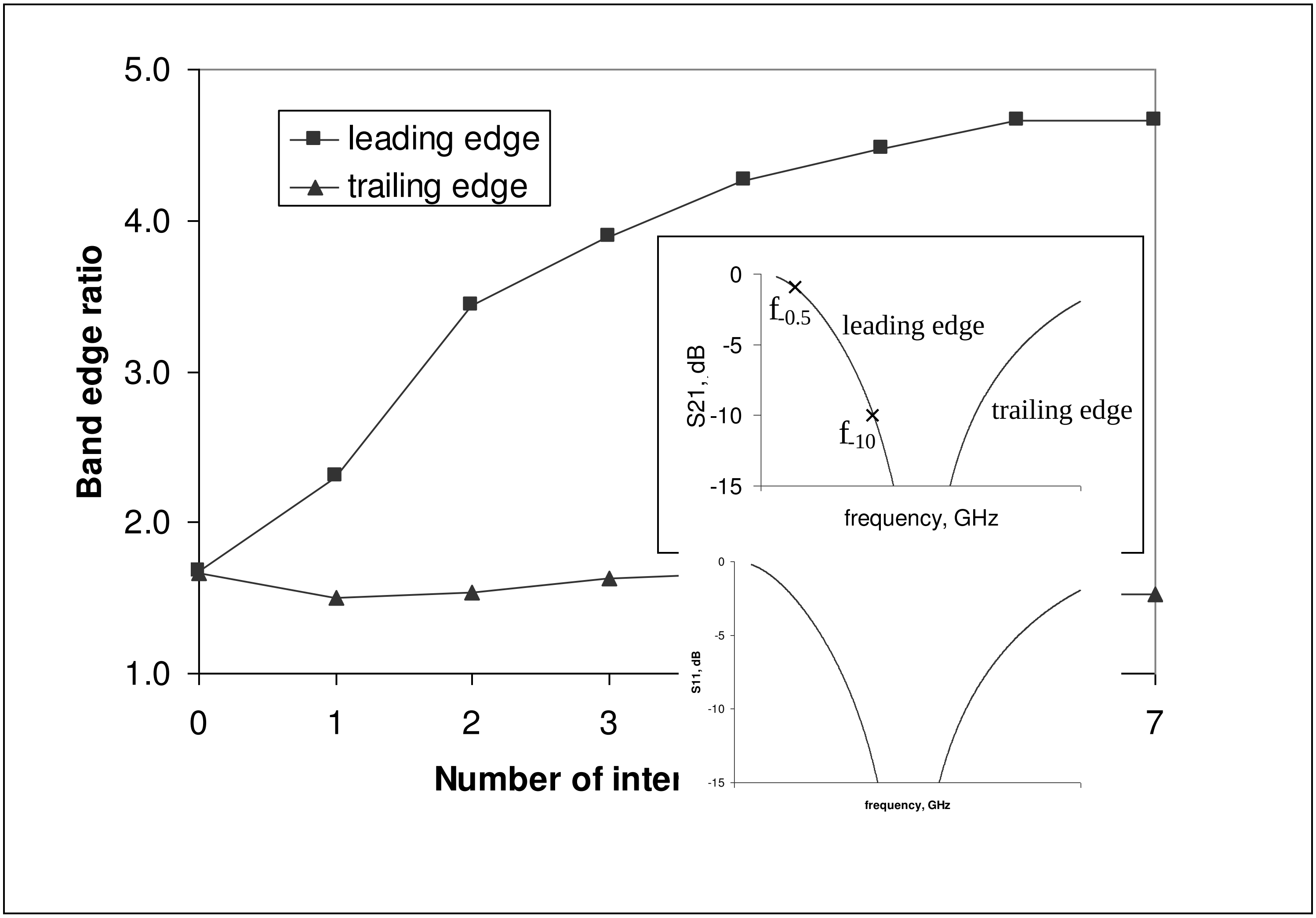

5.0
4.0
3.0
2.0
1.0
Band edge ratio
0
1
2
3
7
Number of inte
leading edge
trailing edge
0
-5
-10
-15
S21, dB
$f_{0.5}$
f_{10}
leading edge
trailing edge
frequency, GHz
0
-5
-10
-15
S11, dB
frequency, GHz

Table 1:

	f_r, GHz	λ_r / p	Frequency Shift, %		Fractional Bandwidth, %			Common Bandwidth, %
Incidence	Normal	Normal	TE45	TM45	Normal	TE45	TM45	
Unconvoluted crossed dipoles	14.7	1.88	-7.9	3.7	12	11	7.7	0
Fig.1a, 0 interweaving	2.67	10.4	-0.1	-0.2	11	16	7.9	7.9
Fig.1b, 1 finger interweaving	1.61	17.2	1.2	0.1	24	33	17	17.2
Fig.1b, 2 finger interweaving	1.38	20.2	-0.9	-0.1	36	39	25.1	25.1
Fig.1b, 3 finger interweaving	1.13	24.6	-0.4	0.0	50	60	36.0	36.0
Fig.1b, 4 finger interweaving	1.09	25.5	-0.1	-0.1	55	74	39	39
Fig.1b, 5 finger interweaving	1.03	27.0	-0.4	-0.2	61	82	43	43
Fig.1b, 6 finger interweaving	1.01	27.6	0.6	-0.2	62	84	45	45
Fig.1b, 7 finger interweaving	1.00	27.8	0.2	-0.2	63	85	46	46