Double Square Loop FSS with Slots for Closer Band Spacing at Oblique Incidence

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***Abstract*—This paper proposes a modified nested double square loop Frequency Selective Surface (FSS) in order to achieve a higher FSS packing density. By introducing slots to a conventional square loop, a longer electrical length of the FSS and a lower ratio of l/λ can be accomplished. The optimized FSS prototype provides a maximum attenuation of more than 30 dB alongside with 270 MHz and 690 MHz bandwidth for the lower and upper resonant frequencies, respectively. Furthermore, the proposed structure also offers a stable frequency response for both TE and TM modes at normal and oblique incidence, up to 45°. The measured and simulated results are shown to be in a very good agreement with each other.**

Keywords—fractal; frequency selective surface (FSS); spatial filter; square loop

I. Introduction

Frequency Selective Surfaces (FSSs) have been widely employed in the microwave system designs such as dichroic reflector [1], antenna radomes [2] and spatial filters [3]. There is a large volume of published studies describing techniques to optimize FSS geometry to ensure that the structure is capable to provide multi resonance behavior with a higher packing density without compromising the angular stability [4]. There are various compact structures that were proposed in literature either as a bandstop or bandpass filter [5]-[7]. In this paper, a nested double square loop FSS is proposed with dual-band stop behavior. The proposed structure is initially designed in which the outer and inner loops attenuate GSM signals at 900 MHz and 1800 MHz bands, respectively [8]. By extending the capability of the structure to cover the IMT2000 frequency band, the inner square loop is further optimized to attenuate both signals at 1800 MHz and 2100 MHz bands. In order to provide closer band spacing between the lower and the upper resonant frequencies which are contributed by the outer and the inner loops, space restriction has become the main concern because the inner loop is nested inside the outer loop. Thus, the slots are introduced only for the inner loop while geometry of the outer loop is remained the same. By doing this, the upper transmission null can be shifted towards the lower transmission null. The details of the FSS geometry design is described in Section II. The approach to provide closer band spacing by optimizing the slots on the inner square loop is explained in Section III. This is followed by the performance of the modified FSS at oblique incidence in Section IV.

II. FSS Geometry Design

FSS element type is generally designed based on specific criteria such as operating bandwidth requirement and frequency response stability under various angles of incidence and polarizations. Previous studies revealed that the square loop element offers an excellent performance in terms of the bandwidth and angular stability [9]. The double square loop FSS is printed on 1.6 mm thick FR-4 lossy substrate (ε_r=4.3) with the periodicity, l_s of the unit cell equal to 46.2 mm. The length, l_1 and the width, w_1 of the outer loop are 44.2 mm and 1 mm, respectively. The length of the inner loop, l_2 is 38 mm while the width, w_2 is 4 mm. The stability of transmission frequency response and size reduction of the unit cell can be improved by convoluting the FSS element [5]. Therefore, by using similar approach, further optimization of the square loop element is done by introducing slots, defined by s and f parameters as illustrated in Fig. 1. The electromagnetic performance of the FSS is performed numerically in frequency domain solver by using Computer Simulation Technology (CST) Microwave Studio software.

III. Slots and Higher FSS Packing Density

Fig. 2 shows the simulated transmission frequency responses for conventional square loop where f and s are both equal to 0 mm and the proposed structure where f = 3 mm and s = 16 mm. At normal incidence, the lower resonant frequency, f_{r1} and the upper resonant frequency, f_{r2} are 920 MHz and 2070 MHz, respectively. By using the same periodicity, rectangular slots are introduced to the inner loop. Table 1 lists various values of s and f parameters and illustrates their effects on resonant frequencies alongside with the ratio of l/λ.

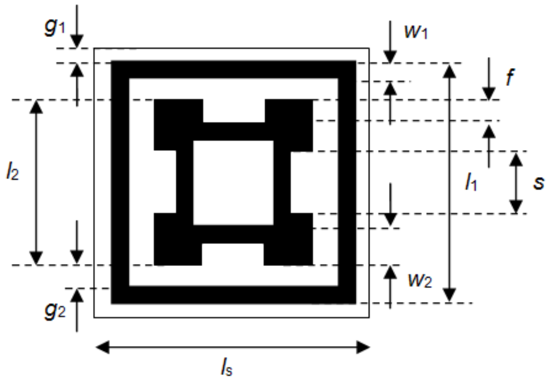


Fig. 1. Unit cell of modified square loop FSS, l_s=46.2 mm, l_1=44.2 mm, l_2=38 mm, w_1=1.0 mm, w_2=4.0 mm, g_1=1 mm, g_2=2.1 mm, s=16 mm, f=3 mm.

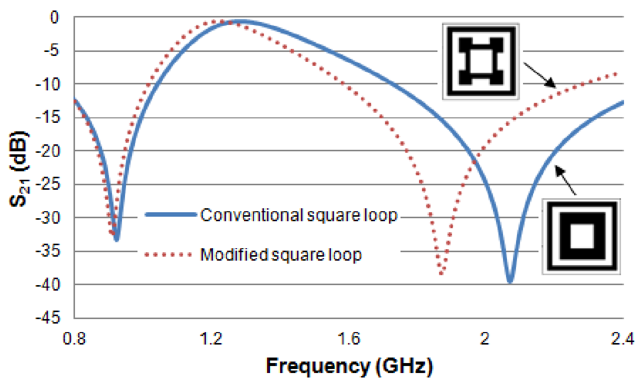


Fig. 2. Simulated transmission frequency responses of conventional square loop and modified square loop FSSs at normal incidence.

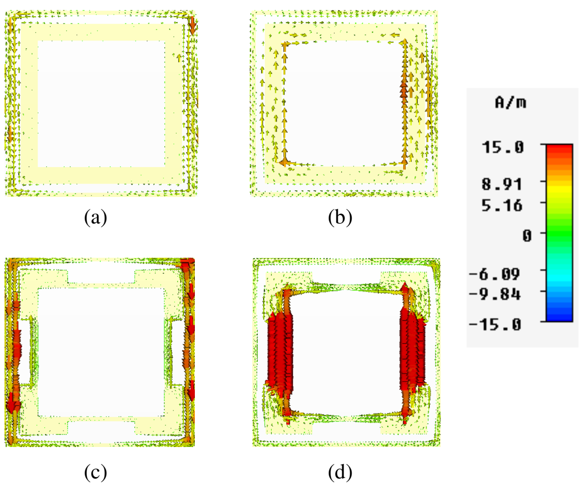


Fig. 3. Surface current of conventional square loop at (a) f_{r1} and (b) f_{r2} and modified square loop at (c) f_{r1} and (d) f_{r2}.

TABLE I. MODIFIED SQUARE LOOP FSS WITH DIFFERENT PARAMETERS

Parameter		f_{r1} (MHz)	f_{r2} (MHz)	f_{r1}/f_{r2}	l_1/λ_1	l_2/λ_2
f	s					
0	0	920	2070	0.444	0.136	0.262
1	8	920	2050	0.449	0.136	0.260
1	16	890	2050	0.434	0.131	0.260
1	24	890	2050	0.434	0.131	0.260
2	8	890	2020	0.441	0.131	0.256
2	16	900	1990	0.452	0.133	0.252
2	24	900	1990	0.452	0.133	0.252
3	8	920	1920	0.479	0.136	0.243
3	16	910	1870	0.487	0.134	0.237
3	24	910	1870	0.487	0.134	0.237

TABLE II. MODIFIED SQUARE LOOP FSS UNDER VARIOUS ANGLES OF INCIDENCE

Polarization (θ°)	f_{r1} (MHz)	f_{r2} (MHz)	-10 dB bandwidth for f_{r1} (%)	-10 dB bandwidth for f_{r2} (%)
TE (0)	910	1870	29.7	36.9
TE (15)	910	1870	29.7	36.4
TE (30)	920	1860	31.5	35.5
TE (45)	940	1890	34.0	37.0
TM (0)	910	1870	28.9	37.2
TM (15)	910	1870	28.6	35.8
TM (30)	930	1870	24.7	32.6
TM (45)	950	1920	20.0	27.1

The ratio of l/λ defines the relative of the loop length to the wavelength specified at the resonant frequency. This indicates that the FSS has a higher packing density if the value of l/λ reduces. The upper resonant frequency slightly decreases by 20 MHz when f = 1 mm and s = 8 mm while the lower resonant frequency remains the same as compared to the conventional square loop. In general, the variation of f_{r1} is not that much since the slots are introduced only for the inner loop which corresponds to f_{r2}. As the value of f increases from 1 mm to 3 mm and s remains constant as 8 mm, it can be seen that f_{r2} decreases by 130 MHz. Likewise, f_{r2} can be further reduced to 1870 MHz when the values of f and s increase up to 3 mm and 16 mm. This provides the minimum value of l/λ and indicates the maximum packing density that can be offered by this structure. In general, the reduction of f_{r2} is significant when f = 3 mm, as it is capable to provide a longer electrical length to the inner loop which can be clearly illustrated by the surface current density as in Fig.3. The maximum surface current of the conventional square loop is 50.9 A/m for f_{r1} and 16.4 A/m for f_{r2}. By introducing slots to the inner loop, the current density on the loops for f_{r1} and f_{r2} increases to 80 A/m and 39.6 A/m, respectively.

IV. PERFORMANCE AT OBLIQUE INCIDENCE

It is shown that the optimum slot dimensions is when f = 3 mm and s = 16 mm, as it offers the lowest value of l_2/λ_2. Therefore, further investigations on the FSS performance at oblique incidence is performed using this optimum dimensions. Table II shows the details of the resonant frequencies and bandwidth of the modified square loop under various angles of incidence and polarizations. At normal incidence, the lower and upper resonant frequencies for TE and TM polarizations are 910 MHz and 1870 MHz, respectively.

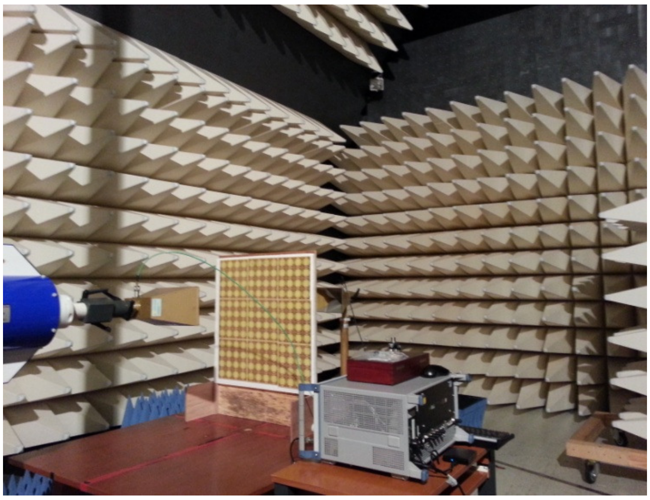
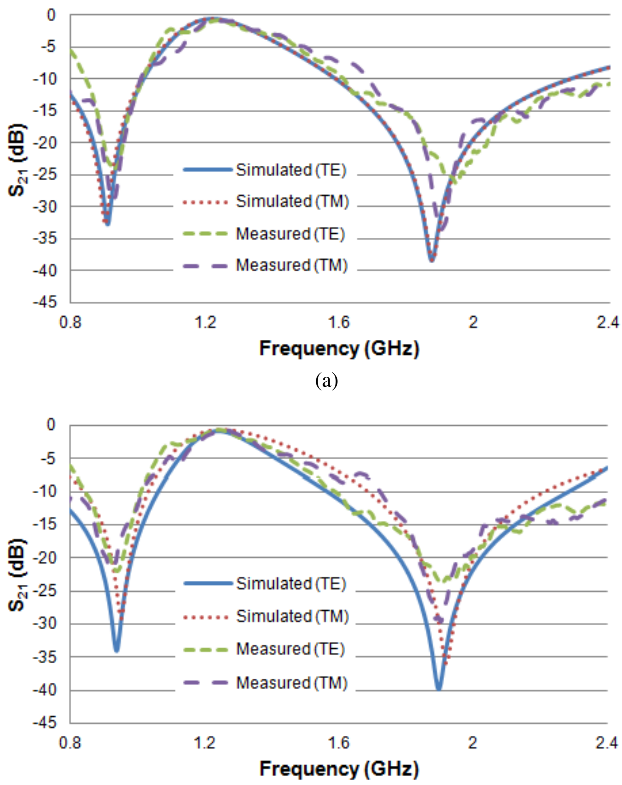


Fig. 4. Measurement setup.



(a)

(b)

Fig. 5. Simulated and measured transmission frequency responses at (a) θ=0° and (b) θ=45°.

As the angle of incidence increases up to 45°, f_{r1} increases by 3.3% while f_{r2} increases by 1.1%, relative to the resonant frequency at normal incidence for TE polarization. Similarly, for TM polarization, f_{r1} and f_{r2} increase by 4.4% and 2.7%, respectively. This proves that the dual polarized structure is relatively insensitive to signal impinges at oblique incidence. For TE polarization, the bandwidth at normal incidence is 29.7% for f_{r1} and 36.9% for f_{r2}. As the angle of incidence increases up to 45°, the bandwidth for f_{r1} and f_{r2} increases to 34% and 37%, respectively. On the contrary, for TM polarization, the bandwidth reduces from 28.9% to 20% for f_{r1} while for f_{r2} the bandwidth decreases from 37.2% to 27.1%.

The measurement setup was performed in the anechoic chamber which consists of two 15 dB horn antennas for transmitting and receiving, network analyzer and fabricated FSS as shown in Fig. 4. The fabricated FSS was positioned in the middle between the two antennas that were separated about 1 mm away. The measured transmission frequency responses under various angles of incidence for both polarizations are compared to the simulated results in Fig. 5. In general, it can be seen that the measured results are in a very good agreement with the simulated results. The small deviation appears in the measured results is due to the scattering of the signals from the environment.

V. Conclusion

The performance of the modified nested double square loop FSS is demonstrated. The proposed structure reduces the resonant frequency by 9.7% as compared to the conventional square loop FSS. The size reduction is achieved without compromising the angular stability of the FSS. The designed FSS can be used to attenuate signals operating at GSM900, GSM 1800 and IMT2000 frequency bands while transmitting other microwave signals. The measured results are shown to be in a very good agreement with the simulated results. Our future work will be extended to further reduce the unit cell dimensions of the FSS.

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