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doi:10.15199/48.2024.10.18

A Comparative Analysis of the Impact of Circular, Square and Hexagonal Frequency Selective Surfaces on the Performance of a 10GHz Microstrip Patch Antenna

Abstract--- *The search for better techniques for microstrip patch antenna improvement is a continuous process as long as these antennas continue to find application in devices. By way of simulation, periodic frequency selective surfaces (FSSs) of circular, hexagonal and square were each designed at 10GHz and individually combined with a 10GHz microstrip antenna and the corresponding behaviours were observed. The FSSs designed improved the directivity, gain and efficiency of the antenna. The combination was done in two configurations; the antenna placed in front of the FSSs and the antenna placed behind the FSSs. For the antenna in front of the FSSs' configuration, while the bandwidth decreased for all, the circular and hexagonal FSSs gave better frequency stability. For the antenna positioned behind the FSSs, at near but below the half wavelength (15mm) distances, the results were better than the previous arrangement. When the FSSs were positioned in front of the antenna, they gave good results between 14.5mm and 13.0mm air gap distance. In this configuration, all of the FSSs were able to improve the performance of the antenna, but the circular FSS, when used between 14.0mm and 14.4mm, gave the best overall result because all of its parameters saw some improvement, especially at 14.0mm. For new researchers in the area of frequency-selective surface microstrip antenna, this work can serve as a guide. Also, a choice of the type of FSS (circular, square, or hexagonal) that best suits one's 10GHz design needs is possible from the comparison data provided.*

Streszczenie *--- Poszukiwanie lepszych technik ulepszania anten mikropaskowych jest procesem ciągłym, dopóki anteny te znajdują zastosowanie w urządzeniach. W drodze symulacji zaprojektowano okresowe powierzchnie selektywne częstotliwościowo (FSS) o kształcie okrągłym, sześciokątnym i kwadratowym na częstotliwość 10 GHz i indywidualnie połączono z anteną mikropaskową 10 GHz i zaobserwowano odpowiednie zachowania. Zaprojektowane systemy FSS poprawiły kierunkowość, zysk i wydajność anteny. Połączenie zostało wykonane w dwóch konfiguracjach; antena umieszczona przed FSS i antena umieszczona za FSS. W przypadku anteny przed konfiguracją FSS, podczas gdy szerokość pasma zmniejszyła się dla wszystkich, okrągłe i sześciokątne FSS dały lepszą stabilność częstotliwości. W przypadku anteny umieszczonej za FSS, w odległości bliskiej, ale mniejszej od połowy długości fali (15 mm), wyniki były lepsze niż w poprzednim ustawieniu. Kiedy FSS zostały umieszczone przed anteną, dały dobre wyniki w odległości między 14,5 mm a 13,0 mm szczeliny powietrznej. W tej konfiguracji wszystkie FSS były w stanie poprawić wydajność anteny, ale okrągły FSS, używany w zakresie od 14,0 mm do 14,4 mm, miał najlepszy ogólny wynik, ponieważ wszystkie jego parametry uległy pewnej poprawie, zwłaszcza przy 14,0 mm . Dla nowych naukowców zajmujących się selektywną częstotliwościowo powierzchniową anteną mikropaskową praca ta może służyć jako przewodnik. Na podstawie dostarczonych danych porównawczych możliwy jest również wybór typu FSS (okrągły, kwadratowy lub sześciokątny), który najlepiej odpowiada potrzebom projektowym 10 GHz. (****Analiza porównawcza wpływu powierzchni selektywnych częstotliwościowo o kształcie koła, kwadratu i sześciokąta na wydajność anteny mikropaskowej 10 GHz****)*

Keywords: Microstrip antenna, frequency selective surfaces, hexagonal FSS, square FSS, circular FSS, bandwidth.
Słowa kluczowe: Antena mikropaskowa, powierzchnie selektywne częstotliwościowo, sześciokątny FSS, kwadratowy FSS, okrągły FSS.

I. Introduction

A microstrip patch antenna is created by employing a microstrip technology to etch out a patch of conductive material on a dielectric of a printed circuit board [1]. This type of antenna is easy and cheap to fabricate, it has low volume and weight and can be integrated easily into devices. Among other disadvantages, these types of antennas are also known to have narrow bandwidth, poor gain, low directivity and poor power handling capabilities [2]. Diverse attempts have been made to improve on some of these lapses including but not limited to various forms of substrate thicknesses and material types, various antenna feeding techniques and the use of parasitic elements such as; various ground plane types, different reflectors, directors and filters [3]. Microstrip antennas may have some drawbacks but their usefulness outweighs their shortcomings and that is why they have widespread use in mobile communication devices, satellite communications, radar, medical and several other wireless communication applications.

One of the procedures for improving the drawbacks of microstrip patch antennas is the use of parasitic elements such as Frequency selective surfaces (FSSs). FSSs are periodic structures with spatial filter characteristics that offer transmission and reflection properties by altering the electromagnetic waves that impinge on their surfaces. They have been shown to enhance a patch antenna's bandwidth, gain, and return losses [4], [5].

This work attempts to design and simulate, using Computer Simulation Technology (CST) microwave studio software, three different basic frequency selective surfaces of periodic nature of circular, square, and hexagonal configurations all resonating at 10GHz and combining each one of them separately with a 10GHz rectangular microstrip antenna to observe the resultant effects of each on the antenna's properties.

II. FSSs design

Three (3) basic frequency selective surfaces (FSS) were designed in circular, square and hexagonal forms. From the fact that an FSS reaches resonance when the loop element's circumference (perimeter) approaches a full wavelength [6], we then try to find the perimeters of the figures. Where wavelength,

(1) $\lambda = \frac{3X10^8 m/s}{10X10^9 Hz}$=30mm

There is no general rule to determine the internal radius. The thicker the width, the higher the frequency and vice versa. The designer keeps varying internal radius size till resonance is attained. For compactness, the smallest attainable resonant rings/loops sizes at 10 GHz were adopted for each FSS. Their various designed dimensions with S_{11} parameters are shown in Figures 1-9. Figure 1 and Figure 2 illustrate the circular ring unit cell and full circular periodic structure, respectively. Figure 4 and Figure 5 illustrate the square unit cell and full square periodic structure, respectively. Figure 7 and Figure 8 illustrate the hexagonal unit cell and full hexagonal periodic structure, respectively. Figure 3,6 and 9 show the S-parameters for unit cell circular, unit cell square and unit cell hexagonal ring, respectively. Table 1 shows the parameters of the substrate used.

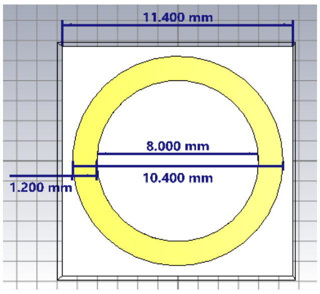


Fig 1. Circular ring unit cell

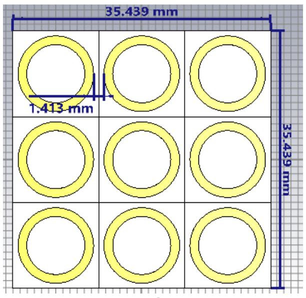


Fig. 2. Full Circular Ring Periodic Structure

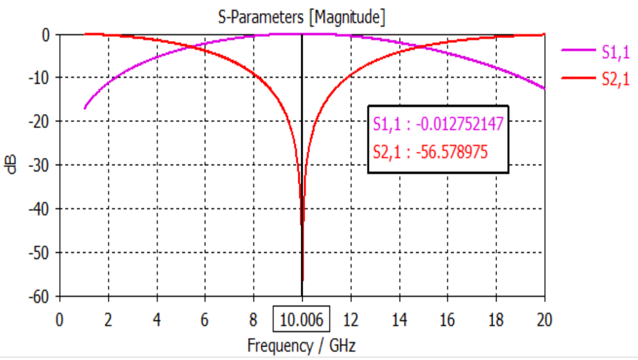


Fig. 3. Circular ring FSS unit cell S-Parameters

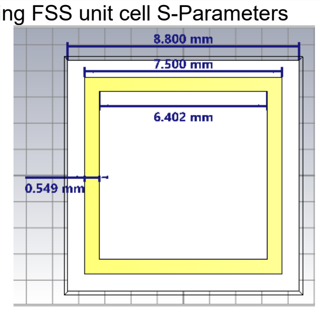
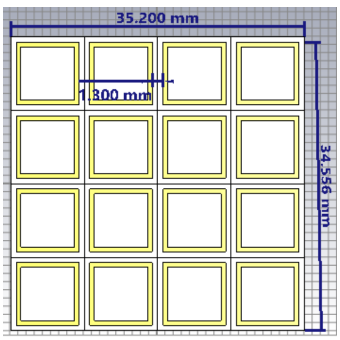


Fig. 4. Square unit cell



Fig, 5. Full square periodic structure

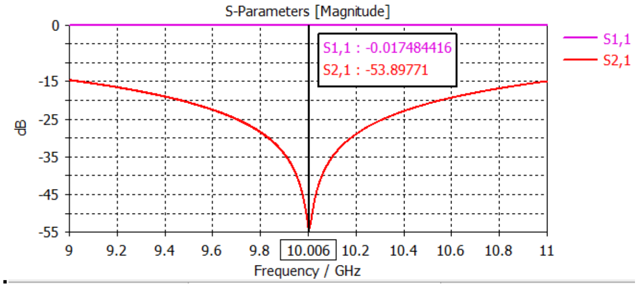


Fig. 6. Square FSS unit cell S-Parameters

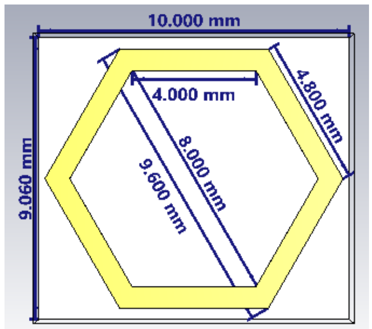


Fig. 7. Hexagonal unit cell

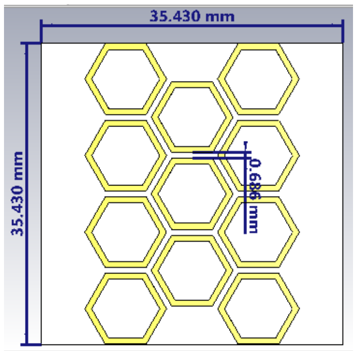


Fig. 8. Full hexagonal periodic structure

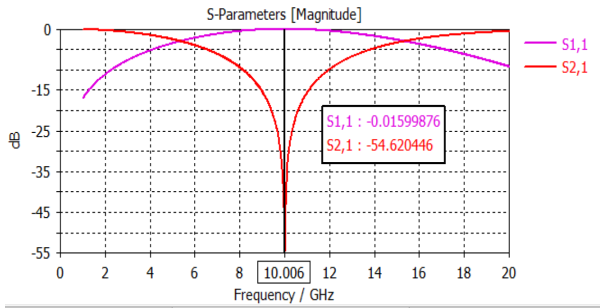


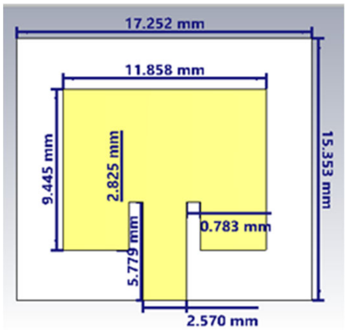
Fig. 9. Hexagonal ring unit cell S-Parameters

Table 1 Substrate Properties

Rogers RT5870 Dielectric Constant (εr)	Substrate thickness, h (mm)	Loss tangent (tan δ)	Metallization (copper)
2.33	0.938	0.0012	35 μm

III. 10GHZ antenna and properties

A rectangular microstrip patch antenna operating in the X-band region of the radio frequency spectrum with a resonant frequency of 10GHz was designed and simulated with properties summarised in Table 2. Figure 10 shows the dimensions and Figure 11 shows its S_{11} plot.



Fig/ 10. 10GHz Antenna

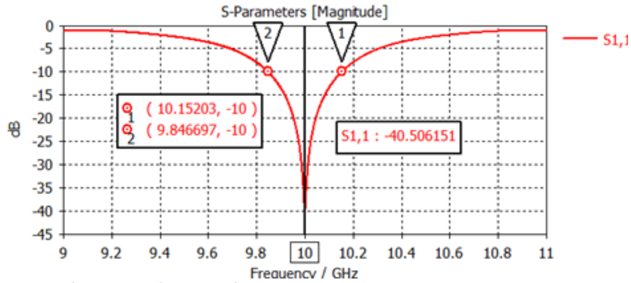


Fig. 11. S_{11} Plot of the 10Ghz Antenna

Table 2 Summary of the 10GHz Antenna Properties

	d(mm)	fc(GHz)	S11(dB)	%Efficiency		Dir. (dBi)	RGain (dBi)	BW (GHz)
				Rd.	Tot.			
Antenna		10	-40.506	69.98	69.97	6.86	5.314	0.305333
Antenna with square FSS	14.1	9.832	-53.412	68.1	60.6	8.81	6.64	0.303995

Where; d=air gab ; fc= centre frequency; S11= reflection coefficient Rd.=radiated efficiency ; Tot. = total efficiency Dir.=directivity; RGain=realised gain; BW=bandwidth

Table 3 Summary of the Performance of the 10GHz Antenna with FSS behind

it	d(mm)	f_c(GHz)	S_{11}(dB)	%Efficiency		Dir. (dBi)	RGain (dBi)	BW (GHz)
				Rd.	**Tot.**			
Antenna		10	-40.506	69.98	69.97	6.86	5.314	0.305333
Antenna with plain PCB	0.5	9.976	-31.896	70.64	69.16	8.23	6.71	0.296601
	1.5	9.978	-32.98	69.89	68.52	8.11	6.55	0.298643
Antenna with Circular FSS	0.5	10.004	-27.964	69.29	68.95	8.63	7.078	0.296756
	1.5	10.008	-27.50	68.13	67.61	8.52	6.85	0.297361
Antenna with Square FSS	0.5	9.976	-30.40	74.78	73.11	9.19	7.92	0.287777
	1.5	9.98	-31.27	68.51	67.11	8.47	6.81	0.284837
Antenna with Hexagonal FSS	0.5	10.008	-26.22	74.83	74.22	7.19	5.92	0.29454
	1.5	10.008	-24.30	71.30	70.06	8.01	6.53	0.290869

Table 4 Summary of the 10.15GHz Antenna Properties

f_c(GHz)	S_{11}(dB)	%Eff.		Dir.(dBi)	RGain(dBi)	BW(GHz)
		Rd.	Tot.			
10.15	-55.08	68.43	55.63	6.91	4.91	0.302328

Table 5 Performance of the 10.15GHz Antenna with Circular FSS Placed in Front of it

d(mm)	f_c(GHz)	S_{11}(dB)	%Efficiency		Dir.(dBi)	RGain(dBi)	BW(GHz)
			Rd.	Tot.			
14.8	10.01	-19.96	68.09	67.03	8.66	6.95	0.340839
14.4	10.006	-25.70	69.43	69.04	8.79	7.2	0.32664
14.2	10.002	-31.818	70.13	70.0	8.85	7.31	0.317214
14.1	10.002	-35.503	70.45	70.41	8.88	7.36	0.31149
14.0	10.004	-50.29	70.46	70.31	8.94	7.42	0.305445
13.8	10.006	-30.425	70.91	70.63	8.99	7.51	0.293466
13.6	10.008	-24.629	71.57	70.99	9.05	7.59	0.279042
13.4	10.01	-21.25	71.98	71.00	9.11	7.66	0.264214
13.2	10.014	-18.734	72.53	70.89	9.16	7.72	0.246747
13.0	10.018	-16.87	72.73	70.34	9.21	7.75	0.2293
Antenna	10.15	-55.08	68.43	55.63	6.91	4.91	0.302328

Table 6 Performance of the 10.15GHz Antenna with Square FSS Placed in Front of it

d(mm)	f_c(GHz)	S_{11}(dB)	**%Efficiency**		Dir.(dBi)	RGain(dBi)	BW(GHz)
			Rd.	**Tot.**			
14.8	10.002	-18.64	66.92	65.92	8.66	6.86	0.345494
14.2	9.994	-27.18	68.83	68.3	8.86	7.23	0.324817
14.0	9.994	-35.26	69.44	69.00	8.93	7.34	0.314673
13.8	9.994	-39.85	70.00	69.60	8.99	7.44	0.303031
13.6	9.998	-28.46	70.57	70.32	9.05	7.53	0.29021
13.4	10.00	-23.64	71.08	70.78	9.11	7.61	0.2757
13.2	10.004	-20.43	71.20	70.41	9.19	7.68	0.25957
13.0	10.01	-18.19	71.63	70.00	9.24	7.73	0.242807
Antenna	10.15	-55.08	68.43	55.63	6.91	4.91	0.302328

Table 7 Performance of the 10.15GHz Antenna with Hexagonal FSS Placed in front of it

d(mm)	f_c(GHz)	S_{11}(dB)	%Efficiency		Dir.(dBi)	RGain(dBi)	BW(GHz)
			Rd.	Tot.			
14.2	9.988	-24.9425	69.65	68.65	6.9	5.31	0.32799
14.0	9.99	-31.0074	70.04	69.32	7.03	5.48	0.32267
13.8	9.99	-60.96	70.67	69.99	7.1	5.59	0.311409
13.6	9.992	-31.15	71.26	70.66	7.17	5.7	0.29872
13.4	9.996	-24.99	71.84	71.33	7.24	5.79	0.28465
13.2	9.998	-21.41	72.38	71.72	7.3	5.87	0.269211
13.1	10	-20.05	72.60	71.89	7.33	5.9	0.260988
13.0	10.002	-18.88	72.85	71.82	7.37	5.93	0.252413
Antenna	10.15	-55.08	68.43	55.63	6.91	4.91	0.302328

IV. 10GHZ antenna placed in front of FSS

The 10GHz antenna was positioned in front of the circular FSS periodic structure at some distances as shown in the Figure 12 to observe the effect on the antenna properties. The process was repeated for the square and hexagonal FSSs as well as a plain PCB board with only copper ground. The results are shown in the Table 3 below.

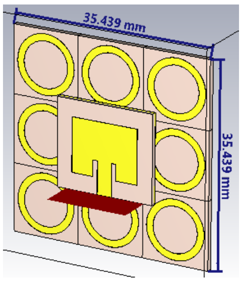


Fig 12. Antenna in front of circular FSS

From Table 3, it could be seen that a plain PCB exhibits reflection abilities capable of improving some of the characteristics of a microstrip antenna, such as gain and directivity. It can also be observed that the circular and hexagonal rings FSS offer greater frequency stability than square FSS when operating behind the antenna. Furthermore, square FSS offered better gain and directivity improvement though shifting the resonant frequency lower. Both plain and square FSSs lowered the resonant frequency when placed behind the antenna.

All the FSS structures improve the antenna characteristics better than plain PCB. Additionally, both the FSS and plain PCBs impacted negatively on the bandwidth of the antenna. Conclusively, the lower air gap (separation) of 0.5mm gave better results.

V. FSS placed in front of the 10.15GHZ antennaA

With the antenna and square FSS combination, at distance of 14.1mm close to half wavelength(15mm) apart [7], resonance was observed but the resonant frequency shifted to 9.832GHz instead of 10GHz as shown in Figure 13. Figure 14 illustrates the distance of 14.1mm. This gave similar results with circular and hexagonal FSS periodic structures.

The deviation from the 10GHz observed when combined with FSS cannot be tolerated. There was the need to design another antenna since the first resonates at 9.832GHz when combined with the FSS instead of the expected 10GHz. With continuous varying of the physical dimensions of the antenna and some re-simulations, while keeping the 14.1mm separation constant, 10.15GHz was discovered. Figure 15 shows the final dimension at 10.15GHz. At 10.15GHz, the combination of the two structures resonated at 10GHz. This also gave similar results for the circular and hexagonal periodic structures as well and so the 10.15GHz antenna was adopted for use. Table 4 summarizes the 10.15GHz antenna properties.

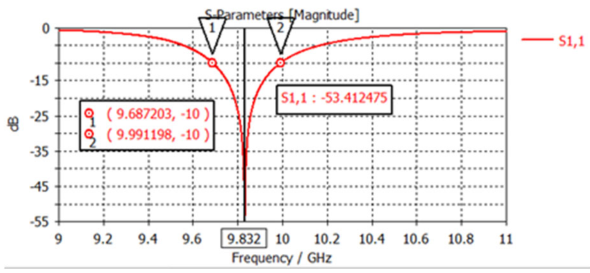


Fig. 13 S_{11} Plot of the 10GHz Antenna with Square FSS at 14.1mm apart

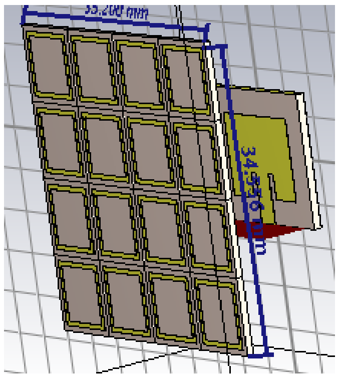


Fig 14. Antenna behind the Square FSS 14.1mm apart

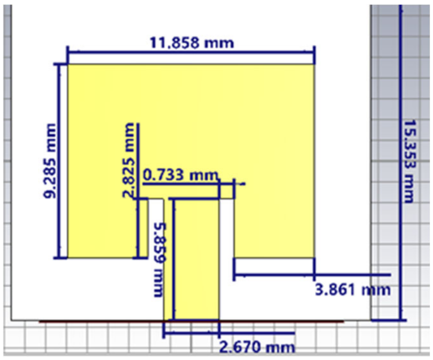


Fig 15 Dimensions of the Adjusted antenna at 10.15GHz

VI. Antenna with FSS AT distances close to half wavelength

The FSSs were positioned in front of the antenna to maximise the reflection property of the loops [8] [9]. All three FSSs were examined by placing them at different distances close to the antennas' half wavelength and the properties were recorded. The graphs/plots presented in Figures 16 to 20 are for the circular FSS/Antenna combination at a distance that gave a resonance closest to

10GHz and every other distance has its results/properties presented in the combined Table 5. Square and Hexagonal FSSs antenna combinations have similar plots with their results only, presented in Tables 6 and 7, respectively.

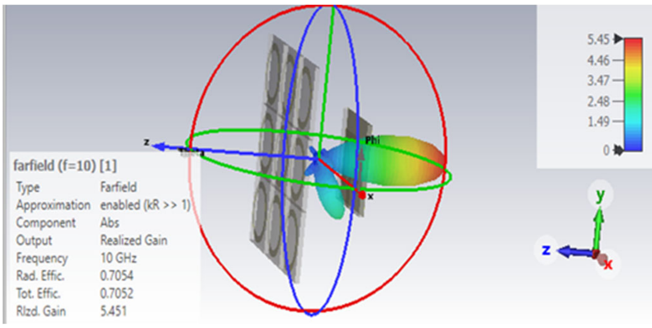


Fig. 16. Realised Gain of the Circular Loop FSS and the Antenna in Linear Scale

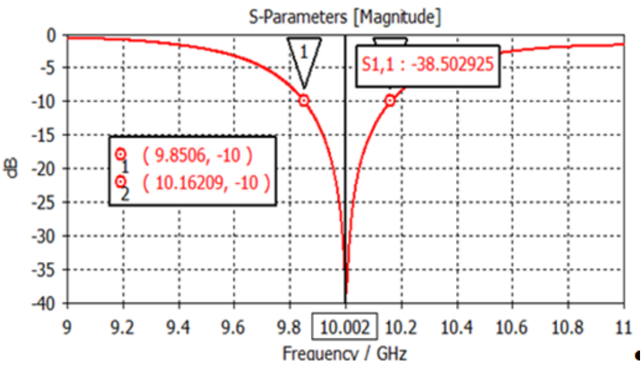


Fig. 17. S_{11} Plot of the Antenna with FSS at 14.1mm Apart

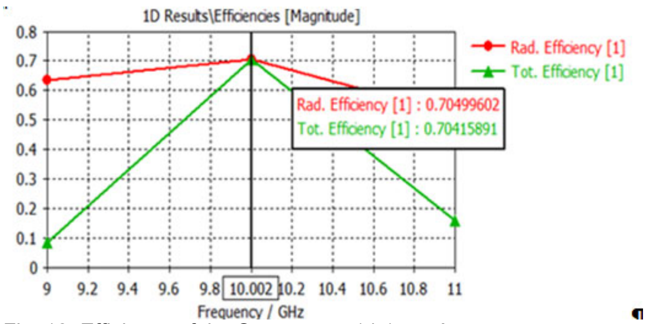


Fig. 18. Efficiency of the Structure at 14.1mm Apart

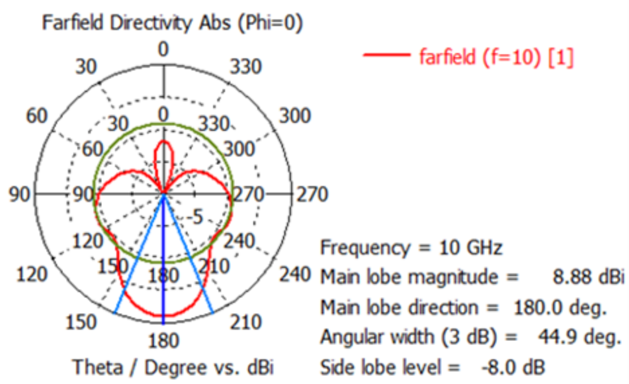
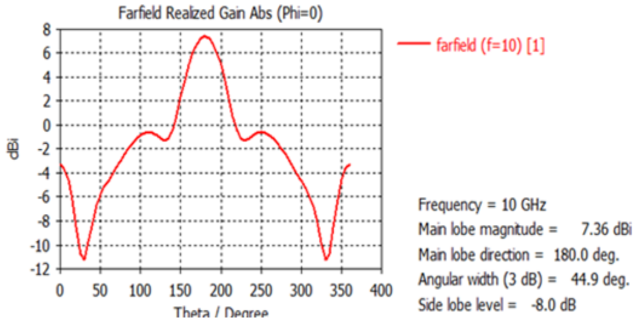


Fig. 19. Directivity of the Structure at 14.1mm Apart



Fig/ 20 Realised Gain of the Structure at 14.1mm Apart

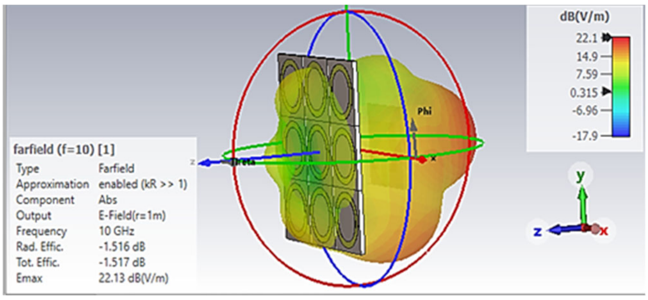


Fig. 21 E-field of the Structure at 14.1mm Apart

I. Research outcome

When the three FSSs and a plain PCB were placed at 0.5mm behind the 10GHz antenna as shown in Table 3, there was an improvement in the antenna's directivity and gain. The plain PCB and the square FSS showed a drop in the centre frequency while the circular and the hexagonal had a high degree of frequency stability. In all the arrangements, there was a drop in the bandwidth.

The FSSs were later placed in front of the antenna as initially conceived and better results than the previous cases were obtained as shown in Tables 5 to 7 for circular, square and hexagonal FSSs, respectively. The results were mostly better at distances close but below the half wavelength (15mm). They all function best between 14.5mm and 13.0mm when the FSS is placed in front of the antennas. All of the FSSs were able to enhance the performance of the antenna in this configuration, but the circular FSS, when employed between 14.0mm and 14.4mm, had the best overall result since all of its parameters saw some degree of enhancement, particularly at 14.0mm. The square FSS arrangement showed greater frequency stability, while the hexagonal FSS had the least overall performance.

II. Results summary

A microstrip antenna whose properties of directivity, gain efficiency and bandwidth were enhanced when paired with frequency-selective surfaces. Three (3) basic frequency selective surfaces (FSSs) of circular, hexagonal and square loops were designed with the FSSs intended for use as 10GHz reflectors when placed in front of the antenna but the option of placing the FSSs behind the antenna was also investigated.

The FSSs proved useful when placed behind the antenna for performance improvement. The circular and hexagonal FSS showed better frequency stability but all the FSSs impacted negatively on the bandwidth.

When the FSSs were placed in front of the antenna, the qualities of the antenna were improved by all the FSSs depending on the distance around the half-free space wavelength(14.5mm-13mm). This arrangement gave better results than when the FSSs are positioned behind the antenna. The efficiency of all three possible combinations is best when the air gap is between 14mm and 13mm. Also, all the FSSs were able to improve the performance of the antenna but the circular FSS gave a better performance than the others when used between 14.0mm and 14.4mm as all the tabulated properties witnessed some degree of improvement. Even though the square presents more frequency stability, the hexagonal FSS gave the least overall performance.

III. Significance of the work

Microstrip antenna properties; gain, directivity, efficiency and bandwidth were improved using simple FSS designs. Also, this work can serve as a model and learning tool for new researchers in the field of microstrip antenna design using frequency-selective surfaces. Finally, from the comparison data made available, one can decide on the type of FSS (circular, square or hexagonal) that best suits his/her 10GHz design need.

ACKNOWLEDGEMENT

The authors would like to thank all who contributed toward making this research successful. The authors wish to express their gratitude to Research Management Center (RMC), Universiti Teknologi Malaysia for the financial support and advice for this project (UTMFR Grant with reference no Q.J130000.2551.21H64 or PY/2019/01958).

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