Design of a High Gain Bandwidth Improved Aperture Antenna Using a Frequency Selective Surface

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Abstract **─** In this paper a wideband, high-gain, and compact design of an aperture antenna has been proposed. In the proposed antenna a patch type frequency selective surface (FSS) as a superstrate has been placed in front of a rectangular aperture, mounted to a conducting ground plane. The proposed simple 3×3 patch type FSS has considerably enhanced the antenna performance, including the gain and the bandwidth concurrently. The proposed structure has been simulated to validate the obtained results. The maximum gain of 16.03 dB and 3-dB gain bandwidth of 19.7% (14.25–17.35 GHz) has been achieved.

Index Terms **─** Frequency Selective Surface (FSS), Partially Reflecting Surface (PRS), Resonant Cavity Antenna (RCA).

I. INTRODUCTION

Waveguide antennas are high efficiency, high polarization purity, and high power handling antennas with good return loss, but the gain of these antennas are low. By adding partially reflecting surface (PRS) in front of the feeding aperture and parallel to the ground plane at suitable distance, directivity and gain of this type of antennas are enhanced. Trentini in 1956 [1] for the first time has introduced these types of antenna and has been investigated later in [2-4] and many other literatures. In these structures, a resonating cavity consisting of conducting ground plane and partially reflecting surface (PRS) as superstrate has been formed to provide electromagnetic wave multi-reflected between these two planes. The electromagnetic wave is leaked to broadside from the superstrate and realized directive and high gain beam. The distance between these two planes should be such that the maximum number of these beams that are leaked from superstrate be in a same direction.

PRS can be made of simple unprinted high permittivity dielectric material [5], [6]. In unprinted dielectric PRSs as a superstrate, most important factor is permittivity. The higher permittivity, allow the higher gain and directivity but increase losses and fabrication cost. The printed PRS is more useful and it has more parameters for optimization. The PRSs may be array of simple square shape FSS [7] or special pattern over dielectric [8]. Also, using two or more layers of PRSs, enhance the gain and the directivity more efficiently, but 3-dB gain bandwidth is decreased. The resonant frequency of each PRS may be designed so that to enhance 3-dB gain bandwidth, but it increases fabrication cost and complexity [9], [10]. In [11], two layers of dielectrics and three layers of metal slabs are laminated to form a more compact size of PRS. The other way for using more compact and efficient structure is double side printed circuit board (PCB) [12], [13]. In [14], meta-material is used as a ground plane for more compact size of the antenna, but charts show weak input impedance and 3-dB gain bandwidth. In [15], horizontally polarized antenna for ultra wideband operation has been presented, so that the antenna maximum achievable gain has been increased, and also the bandwidth has been improved significantly. In [16], novel shape of FSS has been investigated. FSS can also be used for multiband applications [17].

Unprinted dielectrics have a simple structure but usually high cost, that in high frequencies have high power losses. Some techniques are used to enhance the maximum gain, but the antenna bandwidth is not desirable in the given frequency range. So, it is aimed to have an antenna which has advantages of improved 3-dB gain bandwidth and wide band impedance bandwidth in the same time.

In this paper, we investigate an antenna with easy structure that improved 3-dB gain bandwidth, maximum gain and the impedance bandwidth concurrently. A rectangular aperture mounted on a conducting ground plane has been used to feed antenna as primary radiating source. A FSS has been placed above the aperture at the distance of free space half wavelength at the design frequency. The FSS is composed of 3×3 square metal patches laminated on inside of FR4 dielectric slab. The proposed antenna has provided high gain, wide 3-dB gain bandwidth and wideband features in a compact design. Waveguide aperture antenna is widely used in millimeter wave and communication systems that

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provide high gain specification. This kind of antenna can be fabricated to conform to the desired surface, so it is often used in aircraft applications.

II. ANALYSIS AND PHYSICAL INSIGHT

Figure 1 shows a resonant cavity antenna which is formed between FSS and the ground planes. The ray analysis can be used to describe the resonance frequency in terms of the cavity height. This way is approximate because it ignores edge effect, and it investigates the dominant mode of radiation between two planes. The ray is multi-reflected between these two planes and leaked out from superstrate.

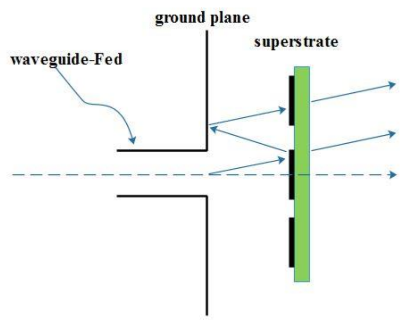


Fig. 1. Resonant cavity antenna formed between FSS and the ground plane.

The resonant height of the cavity or distance between superstrate and ground plane can be obtained as [18]:

$$s_d = \left(\frac{\psi_0}{2\pi} - 0.5\right)\frac{\lambda}{2} + n\frac{\lambda}{2}, \quad (1)$$

where s_d is the cavity height, ψ_0 is the angle of reflection coefficient of the FSS, λ is wavelength of designed frequency at free space, and n is an integer number. In this work for $\lambda = 19.35\ mm$ $(f_0 = 15.5\ GHz)$, $\psi_0 = -43.8°$, n=2, s_d is equal to 13.3 mm that is in good agreement with s_d=11 mm, which is used in the simulation to compensate the capacitive loading effect of the FSS.

Also the gain and bandwidth of antenna can be obtained using the following formulas:

$$G = \frac{1+\rho}{1-\rho}, \quad (2)$$

$$BW = \left(\frac{\lambda}{2\pi s_d}\right)\frac{1-\rho}{\rho^{0.5}}, \quad (3)$$

where G is the relative maximum gain, BW is the bandwidth, and ρ is reflection coefficient magnitude.

An alternative procedure to obtain the design parameters of the proposed antenna can be performed using transmission line equivalent model. Figure 2 shows the transmission line equivalent model of the proposed antenna. The model is composed of two transmission line sections. To maximize the radiation field of the proposed antenna, the impedance seen just after FSS should be infinity. Moreover, FSS as superstrate can be modeled as a LC circuit. Hence, it is straight forward to optimize the structure in terms of unit cell dimensions and cavity height to achieve the goal of maximum radiation.

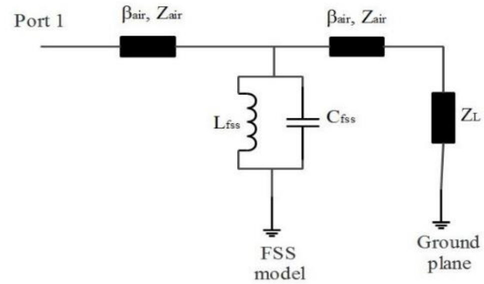
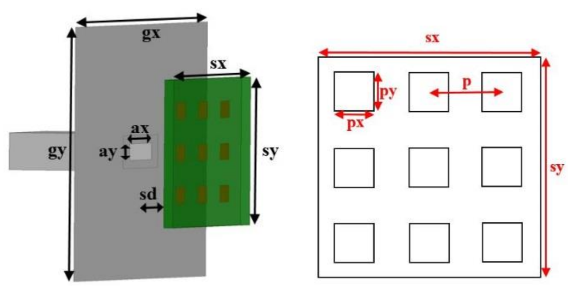


Fig. 2. Circuit model for the proposed antenna.

III. DESIGN AND SIMULATION

A. The proposed antenna configuration

The proposed antenna configuration has been shown in Fig. 3. The proposed antenna is composed of a rectangular aperture mounted on a conductive ground plane along with a FSS as superstrate. FSS in made of 3×3 arrays of square metal patches which is printed on inside surface of FR4 dielectric slab. Feeding waveguide is WR62 with dimensions of 7.9×15.8 mm. The FSS is symmetrically located in front of the aperture at the free space half-wavelength distance at the design frequency.



(a) (b)

Fig. 3. The proposed antenna configuration: (a) three dimensional view, and (b) FSS structure.

Rectangular aperture (slot) with dimension of a_x and a_y in the center of conductive ground plane of dimensions $g_x \times g_y$, acts as primary radiating exciting source. Electric permittivity of FR4 dielectric is 4.41.

B. Design steps

Step 1: The design frequency of $f_0 = 15.5\ GHz$ is considered, corresponding to $\lambda_0 = 19.35\ mm$ free space wave length. So, the cavity height is about $\lambda_0/2$. Figure 4 shows the gain of the aperture antenna with unprinted dielectric slab for a set of cavity height. It can be concluded that the maximum gain occurs at approximately

$\lambda_0/2$, so that, with increasing the value of s_d, maximum gain occurs at lower frequencies. Moreover, 3-dB gain bandwidth and maximum gain is nearly the same for various parameters of s_d. According to the design consideration, s_d=11 mm ($0.57\lambda_0$) is selected for superstrate height.

Step 2: Figure 5 shows the reflection coefficient of the aperture antenna with and without slot. The antenna aperture size has negligible effect on the antenna gain specifications, but can improve the reflection coefficient. The proposed antenna without slot has a resonant at 16.5 GHz, but week bandwidth at frequencies less than 15.5 GHz. So, the aperture size of a_x=10 mm and a_y=4 mm is applied to the proposed antenna, where a WR62 waveguide aperture (15.8 mm×7.9 mm) at the center of a 60 mm×60 mm ($3.1\lambda_0 \times 3.1\lambda_0$) conductive ground plane is used as primary radiating source.

Step 3: Figures 6 (a), (b) and (c) show the gain, the reflection coefficient and E-plane radiation pattern of the proposed antenna for various values of patch size, in the frequency range. These figures show that increasing of patch dimensions improve maximum gain, but disturb the bandwidth, especially in lower frequencies. So, there should be a tradeoff between the antenna gain and its input impedance bandwidth. Hence, the values of p_x=p_y=4 mm ($0.21\lambda_0$) are the best choice to improve the maximum gain and the bandwidth. In this case, return loss is less than 10 dB and the gain is optimized. Also it shows that using metal patches printed dielectric slab instead of standalone dielectric increase maximum gain and 3 dB gain bandwidth.

Step 4: The other factor which has significant effect on the antenna features is the patch element distance, namely, p. Fig. 7 depicts the gain, the reflection coefficient and E-plane radiation pattern in accordance with p. Decreasing of p parameter is negligibly increased maximum gain and more effectively improve 3-dB gain bandwidth. But p parameter influence on bandwidth, and there is a tradeoff between both gain and bandwidth performance. So, in this design, p=10 mm ($0.52\lambda_0$) is considered as the best value.

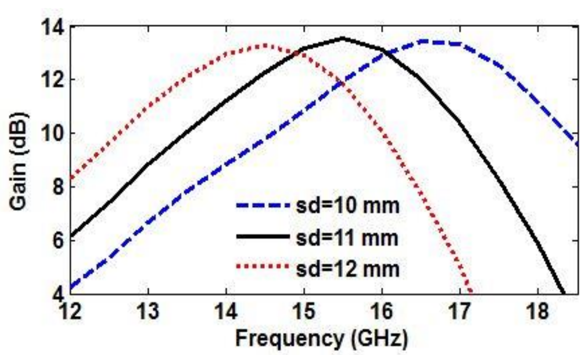


Fig. 4. Gain of the aperture antenna with unprinted dielectric for a set of cavity height.

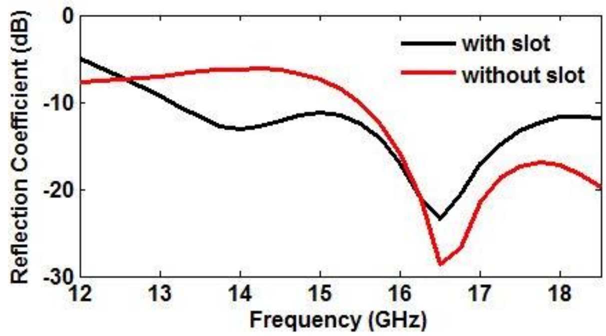


Fig. 5. Reflection coefficient of the aperture antenna with and without slot.

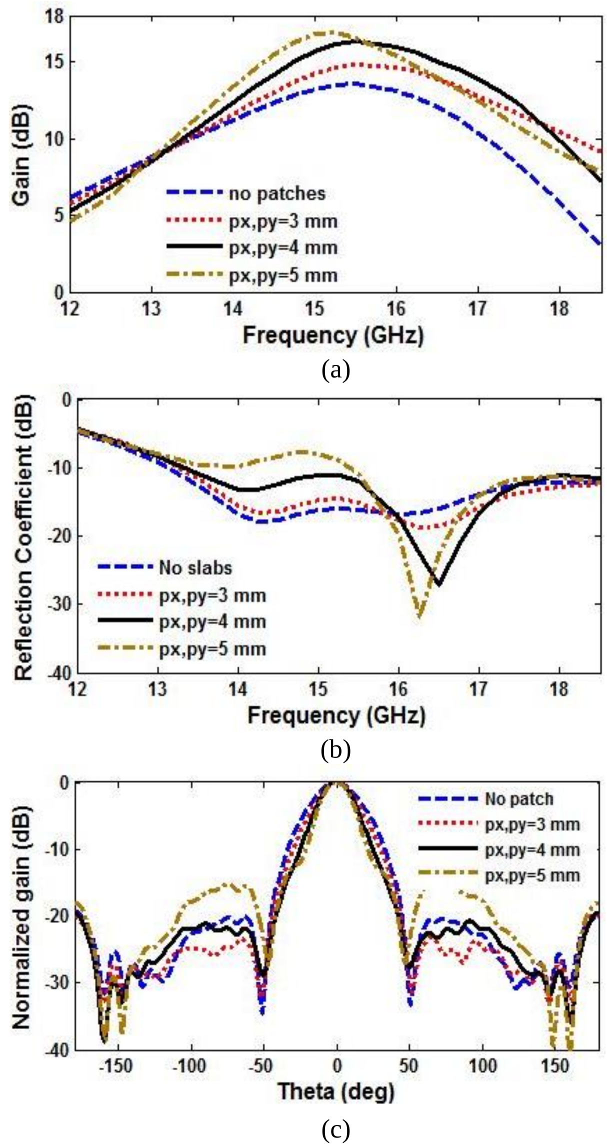


Fig. 6. (a) Gain, (b) reflection coefficient, and (c) E-plane radiation pattern of the proposed antenna with various metal patches size.

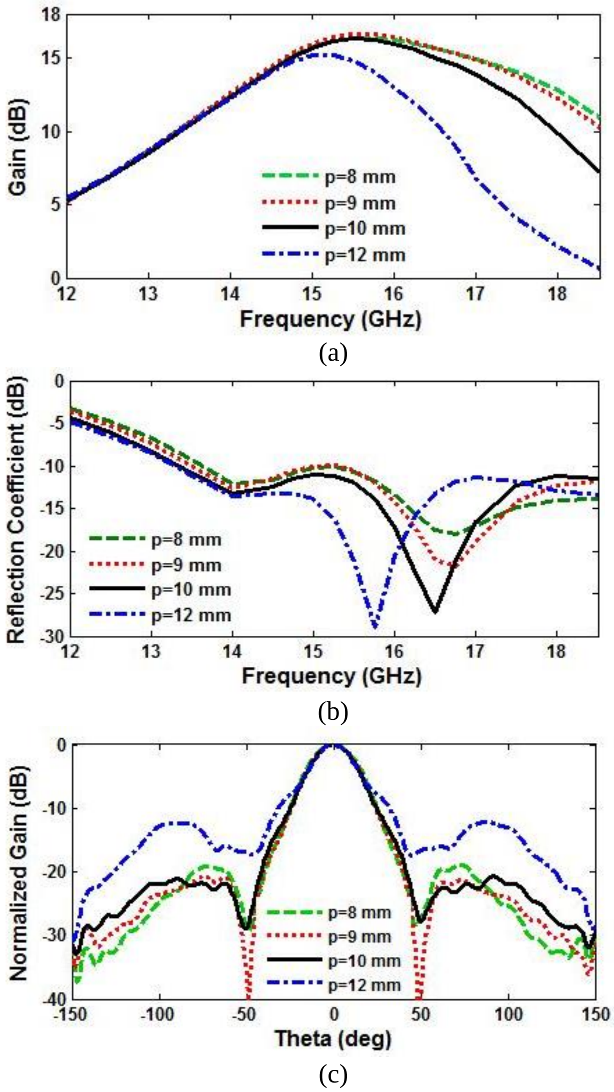


Fig. 7. (a) Gain, (b) reflection coefficient, and (c) E-plane radiation pattern of the proposed antenna with various metal patches distance.

When the patch size increases, stronger current on FSS as the main radiating surface, produce higher gain, but deteriorates input impedance matching. Our target is to increase the maximum gain until the reflection coefficient is less than 10 dB.

Step 5: Figures 8 (a), (b) and (c), show the gain, reflection coefficient and the E-plane radiation plane of the proposed antenna in terms of superstrate size, respectively. It is obvious that significant variations in the antenna performance are noticed. It can be deduced that increasing superstrate size up to 35 mm improves the maximum gain and 3-dB gain bandwidth, and then decreases beyond 35 mm. The bandwidth is also improved with increasing of the superstrate size up to 35 mm and then stands approximately constant for more than 35 mm. Therefore, the superstrate size of 35 mm ($1.81\lambda_0$) has the best maximum gain, however in all of the cases it's approximately constant. Also for s_x=s_y=35 mm, the bandwidth of the proposed antenna has a better performance compared to other values. Then it is considered as an optimum value in the design process.

Step 6: Similar parametric study lead to g_x=60 mm ($3.10\lambda_0$) as the optimum value for size of ground plane.

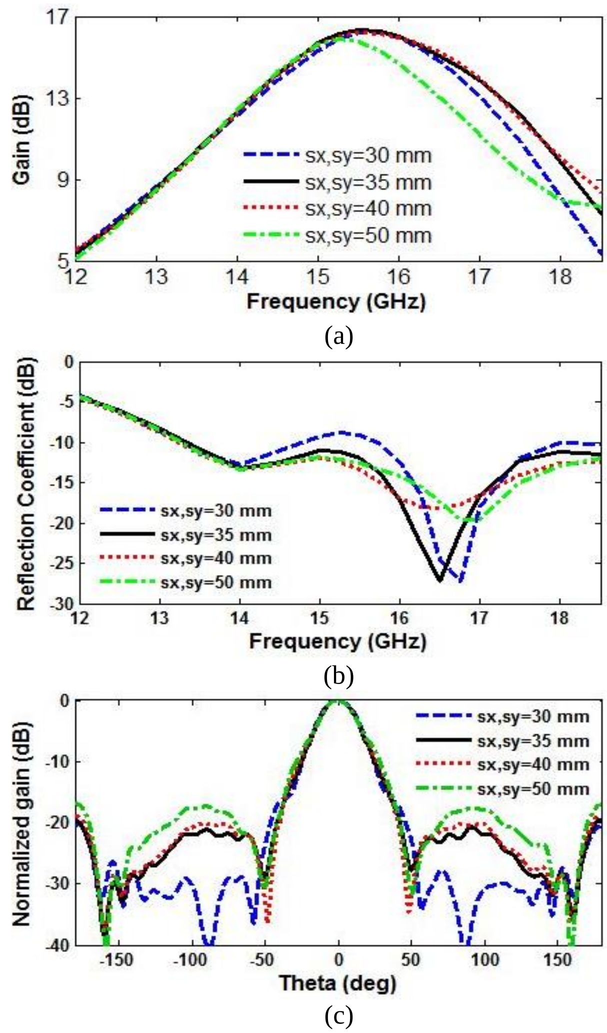


Fig. 8. (a) Gain, (b) reflection coefficient, and (c) E-plane radiation pattern of the proposed antenna with various superstrate sizes.

C. Simulation results and comparison

After determining the optimum design values, the proposed antenna is simulated using HFSS. The proposed antenna has a maximum gain of 16.03 dB at 15.5 GHz, 29.9% (13.42-18.13 GHz), high gain bandwidth (bandwidth with gain more than 10 dB), and 19.7% (14.25-17.35 GHz) of 3-dB gain bandwidth, with good bandwidth in the frequency range (absolute value of return loss greater than 10 dB). Furthermore, this structure uses single layer of FR4 dielectric with one side printed FSS as a superstrate, so it is realized cheaper and fabricated easier compared to similar ones.

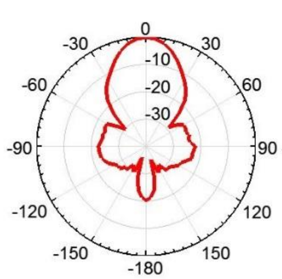
In Table 1, recent related works have been compared. The proposed antenna has improved the antenna performance in terms of (i) maximum gain, (ii) 3-dB gain bandwidth, (iii) high gain bandwidth and, (iv) impedance bandwidth, maintaining low cost and easy fabrication process. These features, occurring simultaneously, are not available in the presented ones in Table 1.

Table 1: A comparison study between the proposed antenna and earlier major available works

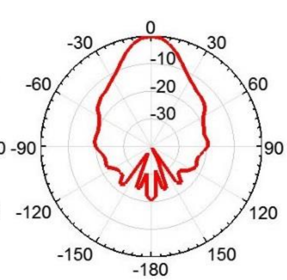
Reference	Max Gain (dB)	3-dB Gain Bandwidth (%)	High Gain Bandwidth (%)
[5]	16	18.75 Exactly: 12.5	Exactly: 19
[6]	16.95	16.25	Exactly: 29
[7]	20.07	Exactly: 2.5	Exactly: 5.5
[8]	12.1	17.2% bandwidth	Exactly: 12
[9]	20	15 Exactly: 9	-
[10]	19.0	16	Exactly: 22
[11]	9.0	Bandwidth: 65	-
[12]	12.2	12.3	Exactly: 10
[13]	18.4 16.2	6.4 12.6	Exactly: 18.5 Exactly: 23
[14]	19.2	1.8 Exactly: 1.0	5.5 Exactly: 3.5
[15]	9.0	Exactly: 100	-
[16]	13.93	-	-
[17]	11.1	Multiband application	
The proposed antenna	16.03	19.7	29.9

Figures 9 (a), (b) shows the radiation pattern of E- and H-plane of the proposed antenna at frequency design of 15.5 GHz. Side lobe and back lobe levels are 22.6 dB and 20.2 dB, respectively. Figures 10 (a), (b) show the gain and the reflection coefficient of the proposed antenna compared with main WR62.

Finally, the optimization has been done for 7×7 and 9×9 arrays of patches. Figures 11 (a), (b) show the gain and the reflection coefficient for the case.

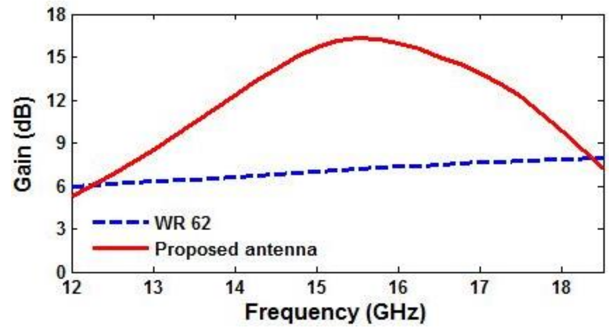


(a)

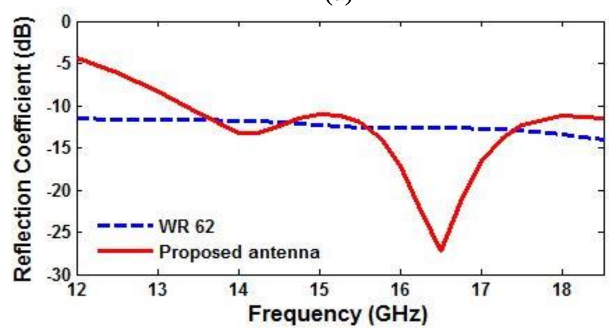


(b)

Fig. 10. (a) E-plane and (b) H-plane radiation pattern of the proposed antenna at 15.5 GHz.

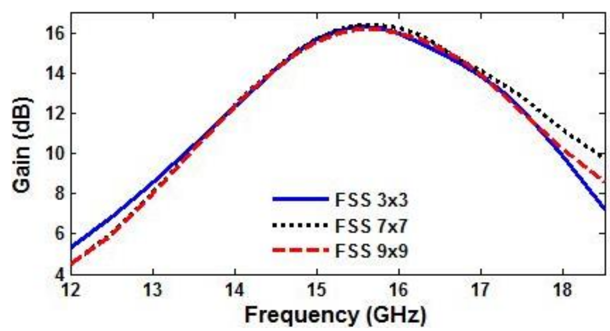


(a)

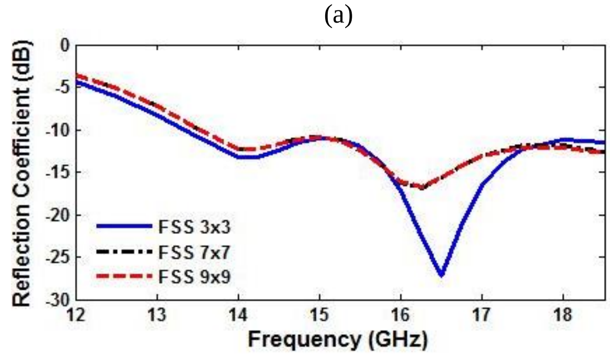


(b)

Fig. 10. (a) Gain and (b) reflection coefficient of the proposed antenna compared to WR62.



(a)



(b)

Fig. 11. (a) Gain and (b) reflection coefficient of the proposed antenna for 3×3, 7×7 and 9×9 arrays of patches.

The results confirm that the number of patches has negligible effect on the antenna performance.

IV. FULL METAL STRUCTURE

In the proposed antenna, printed FR4 dielectric is used for easy and cheap fabrication. This structure also can be considered without dielectric material. In this case superstrate is composed of 3×3 arrays of metal patches, which it is placed above the aperture using foam. In this case, the design parameters are obtained as a_x=11 mm (0.57λ_0), a_y=6 mm (0.31λ_0), p_x=p_y=7.5 mm (0.39λ_0), p=12 mm (0.62λ_0), s_d=12 mm (0.62λ_0), g_x=g_y=50 mm (2.58λ_0). Table 2 shows the design parameters of full metal antenna compared with the FSS with standalone dielectric. It shows that the same result can be obtained with full metal structure.

Table 2: A comparison study between the proposed antenna and its full metal structure counterpart

Antenna Characteristic	FSS with Dielectric	FSS without Dielectric
Max gain (dB)	16.03	16.20
Bandwidth (GHz)	13.14 and above	12.68 and above
3-dB gain bandwidth	3.10 GHz (19.7%)	2.52 GHz (17.0%)
High gain bandwidth	4.71 GHz (29.9%)	4.38 GHz (28.5%)
Side lobe level (dB)	22.6	17.1
Back lobe level(dB)	20.2	19.8

V. CONCLUSION

In this paper, a waveguide fed aperture antenna with a FSS as superstrate is proposed. The proposed antenna is composed of aperture mounted on an extended conducting ground plane, together with a FSS as a superstrate, which is located over the aperture. FSS is composed of common and cheap FR4 with 1.6 mm thickness, which 3×3 array of metal patches that is printed on inside surface of dielectric slab. The proposed antenna has a maximum gain of 16.03 dB at 15.5 GHz, and 29.9% (13.42-18.13 GHz) high gain bandwidth, and 19.7% (14.25-17.35 GHz) of 3-dB gain bandwidth. Moreover, full metal structure with a FSS composed of 3×3 array of metal patches is investigated and the same result has been obtained. The full metal structure antenna have a maximum gain of 16.20 dB at 15.5 GHz, and 28.5% (13.64-18.17 GHz) high gain bandwidth, and 17.0% (14.44-17.12 GHz) of 3 dB gain bandwidth. The proposed antennas have been simulated using HFSS to verify the results.

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