Front-to-Back Ratio Enhancement of an Aperture-stacked patch antenna by an Improved circular slots and New Reflector element.

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Abstract. In this paper, we investigate an aperture-stacked patch microstrip antenna with three slots in a circular shape that feeds the antenna in order to have an improvement in its performance. The structure optimized and analyzed in this study has an upper substrate of foam dielectric material with a thickness of 0.254 mm and a dielectric constant of 1, a lower substrate of rogers RT3003 with a thickness of 0.5 mm and a loss tangent of 0.001. A cost-effective technique of improving the front-to-back ratio used in this work is to install a reflector which take shape like an aperture-stacked, printed on a thin dielectric layer (0.254 mm) with a dielectric constant of 4.4 and a loss tangent of 0.025. As a result of using the proposed reflector to increase the directivity, the front-to-back ratio of the proposed antenna improved by about 10 dB. With 7.79 dB and matching S11 -40 dB, the structure provides an intriguing gain value.

1. Introduction

An antenna is a tool for transmission and reception electromagnetic waves. This process can be done using the same antenna or using one for transmission and the other for reception. One of the most widely used antennas is the microstrip antenna technology, which became established in the late 1970s. By the beginning of 1980s, basic microstrip antenna elements and arrays had a good foundation in terms of design and modeling. and researchers were focusing on increasing antenna performance attributes (e.g., radiation, matching, bandwidth …) and expanding the technology's applicability.
The inherently narrow bandwidths and low directivity limited Microstrip patch antennas although they were a lot of appealing features like low cost, and low profile, facility of solid-state device integration. Previous research attempted to correct these flaws which have yielded significant results. In order to achieve larger bandwidths, shaped slots and electromagnetically coupled patches have been used, while so as to achieve higher directivities parasitic patches or high permittivity substrates have been used [1][2]. The majority of previous attempts, on the other hand, were aimed at improving either bandwidth or directivity. To increase the patch antenna's versatility, it would be advantageous to improve their gain and directivity through of front to back ratio at the same time [3].
A multi-layer microstrip patch antenna configuration can be employed to obtain higher directivity performance [4]. The top side of a microstrip antenna is a metal conducting patch that can be printed on a thin grounded dielectric surface known as the substrate. A single radiating element can be fed through coaxial line, microstrip line, or electro-magnetic coupling in the simplest situations [5]. The slotted power shown in Figure 1 is a much more interesting and practical method of powering the multi-layer antenna.

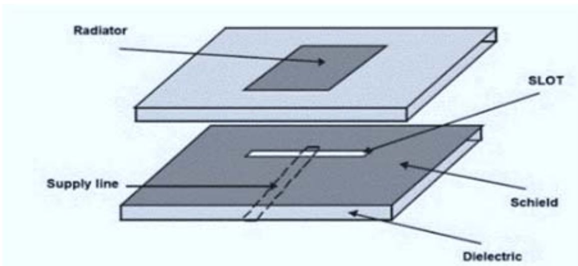


Fig1. Aperture coupling.

Patch antennas are made up of a dielectric substrate on an optically planar ground plane and a radiating element on the other side of the substrate, which is made up of conducting materials [1]. In this paper the goal is on matching enhancement technique of a multilayer patch antenna for Satellite applications. In order to enhance the directivity, antenna losses are contained by controlling those slots feeding which can have a significant impact on the matching, bandwidth for a given permittivity and thickness of the substrate. In this work, to improve the radiation characteristics of the slot excited patch antenna, a new shielding plane was placed behind the antenna, this method eliminates any unnecessary radiation in the back and improve the front-to-back ratio.

2. Aperture Coupled Patch Antenna Design

The aperture coupled feed technique is used in this paper in order to take advantage of the benefits of this type of antenna and improve the defects. The ground plane separates the radiating patch and the microstrip feed line in this technique. A slot or an aperture in the ground plane is used to connect the patch to the feed line. Microstrip feed line is placed on the bottom side of the lower substrate and is connected to the radiating patch via a slot in the ground plane [2]. This feeds technique possesses several advantages over other feeding methods, we cite that the most interesting in terms of realization is the separation of the feed line from the radiating element to avoid parasitic radiation generated by the feed line [7]. These antennas are more advantageous in arrays since the feed and phase shifting circuits are electrically isolated from the patch antennas.

2.1 Antenna Parameters

The bottom substrate is usually made of a high dielectric constant material, while the top substrate is made of a thick low dielectric constant material [3]. Aperture coupling [6] is also useful for fabricating antennas with two or more dielectric layers; however, the resonant frequency must be determined which is dependent on the layers used in the antenna [4]. The substrate's Dielectric constant (ε_r), its operating frequency (f_r), and the height of the substrate (h) from the ground plane are the three design parameters of a microstrip antenna, and they affect the patch's dimensions, radiation pattern, return loss, and other parameters [3]. The problem of effective dielectric constant of multilayer structures for antenna applications has been studied by a number of researchers [4,5,11], to obtain expressions for the effective filing fractions and effective dielectric constant. In this work we have based on Wheeler's [8] transformation from the physical z plane to the complex flux-potential g plane ($g = u + jv$), these areas are depicted in Figure 2. The ratio of the area occupied by each individual dielectric in the g plane defines the degree of filling or filling fraction q_i of each of the dielectric materials S_i (i=1,2,3…) and the entire area of the cross section S_c. (1) – (3) are Svacina's filling fraction q equations, with q_1 and q_2 equal to the effective filling fractions of the substrate dielectric (relative permittivity ε_{r1}), and dielectric material above the superstrate (relative permittivity ε_{r2}), respectively.

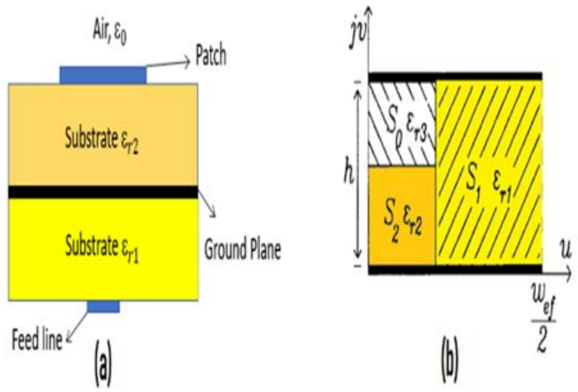


Fig 2. (a) Section of the under-review microstrip antenna structure, (b) Approximately how dielectric materials are distributed between parallel plates, as shown in [9] and [10].

$$q_1 = \frac{S_1}{S_C} = 1 - \frac{h}{2w_{ef}} \ln\left(\frac{\pi}{h} w_{ef} - 1\right) \quad (1)$$

$$q_2 = \frac{S_2}{S_C} = 1 - q_1 - \frac{1}{2}\frac{h - v_c}{w_{ef}} \times \ln\left[\pi \frac{w_{ef}}{h} \frac{\cos\left(\frac{v_c \pi}{2 h}\right)}{\pi\left(\frac{h_2}{h} - \frac{1}{2}\right) + \frac{v_c \pi}{2 h}} + \sin\left(\frac{v_c}{2}\frac{\pi}{h}\right)\right] \quad (2)$$

the effective line width taken from [18] is

$$w_{ef} = w + \frac{2h}{\pi} \ln\left[17.08\left(\frac{w}{2h} + 0.92\right)\right] \quad (3)$$

and the quantity v_c is

$$v_c = \frac{2\pi}{\pi} \tan^{-1}\left[\frac{\pi}{\frac{\pi}{2}\frac{w_{ef}}{h} - 2}\left(\frac{h_2}{h} - 1\right)\right] \quad (4)$$

The effective permittivity of the wide microstrip line is calculated by [9] and [10] using the approximate capacitance of an equivalent parallel-plate structure with the filling fractions arranged as shown in Figure 2.

$$\varepsilon_{eff} = \varepsilon_{r1} q_1 + \varepsilon_{r2} \frac{(1 - q_1)^2}{\varepsilon_{r2}(1 - q_1 - q_2) + q_2} \quad (5)$$

The resonant frequency of a rectangular microstrip antenna is given by [1]:

$$f_r = \frac{c}{2(L + 2\Delta L)\sqrt{\varepsilon_{eff}}} \quad (6)$$

The starting of the calculation has been made to have a resonance frequency at 28 GHZ, and for the bottom substrate is rogers RT3003 with 0.5 mm thickness with dielectric constant of 3 and loss tangent equal to 0.001, for this design, the top substrate is made of dielectric foam with a thickness of 0.254 mm and a dielectric constant of (εr=1). For the calculation of the basic antenna elements (width, length, feed line) we have used the formulas that are already published on the work [11]. Aperture coupling is a non-contact feeding mechanism that has been studied to overcome problems related to matching, directivity and stray radiation from the feed lines [12]. A general schematic diagram of this ASP (aperture-stacked patch) microstrip antenna is shown in Figure 3.

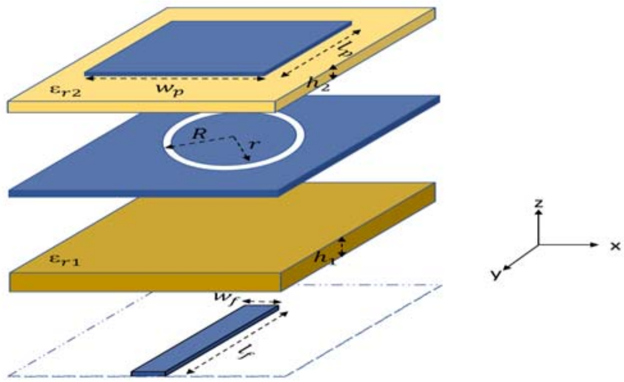


Fig 3. ASP (aperture-stacked patch) microstrip antenna designed with circle slot, The dimensions are $l_p = 5.43\ mm$, $w_p = 4.83\ mm$, $h_1 = 0.5\ mm$, $h_2 = 0.254\ mm$, $w_f = 0.58\ mm$, $l_f = 7.147mm$, $\varepsilon_{r1} = 3$, ε_{r2} =1.

2.2 The Aperture Slot Proposed

Design of the proposed antenna consists of circular slot in the ground plane; it was designed by an outer radius R and an inner radius r, their centre is midpoint of the ground plan. The circle slot was studied by the effect of changing the deference between outer and inner radius (ΔR=R-r) in order to have a good current flow on the surface. The optimization procedure used here begins with a random set of antenna parameters. It is possible to start with a known solution, but we prefer to start with purely random parameters to avoid biasing the solution. CST Microwave Studio is used to simulate the proposed antenna, and the simulated results are obtained, the Table 1 shows the results of different radius value.

Table 1. Effect of changing the deference between outer and inner radius (ΔR=R-r)

ΔR (MM)	$f_r(GHz)$	ε_{eff}	$w_{ef}\ (mm)$	*S11(dB)*
0.08	NA	-	-	NA
0.1	26.8	4.1431	6.72	-14
0.12	27.2	3.9534	6.45	-12
0.14	26.4	4.3176	6.86	-21
0.16	27.4	3.7856	6.34	-23
0.18	28.9	3.0648	5.92	-13
0.2	28	3.2012	6.02	-19
0.22	28.6	2.8721	5.34	-17
0.24	NA	-	-	NA
0.26	29.2	2.3952	5.02	-16
0.28	NA	-	-	NA

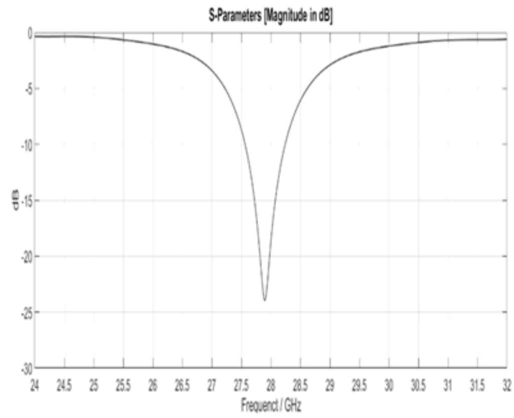


Fig 4. Return loss response of the antenna with ΔR= 0.2 mm.

2.3 Optimization Approach

In order to optimize the obtained result, we choose to improve the coupling slot by increasing the number of circles, with the same radius difference (ΔR). The figure 5 shows the summary of the parametric study that we have done to have a result well matching to the frequency we want (28 GHz). The parametric study carried out clearly shows the number of circles effective to matching the antenna to have a good surface current flow, the use of only one circle of opening is not sufficient to have a good antenna adaptation. As well as the increase in the number of circles is not always effective as an example two and four circles. On the other hand, the use of three circles presents an acceptable result at the level of adaptation and at the level of the surface current. The number of circles cannot be increased more than four due to the global antenna size and the parameters for calculating this size [13].

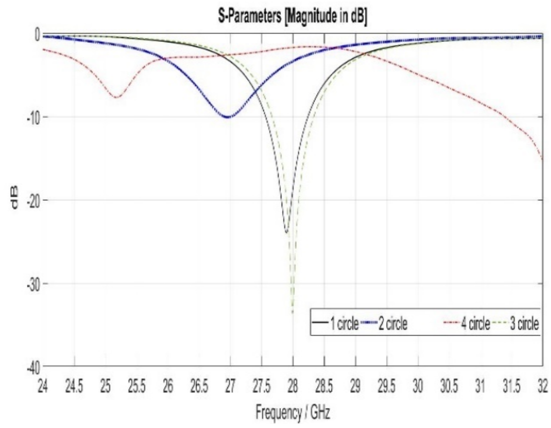
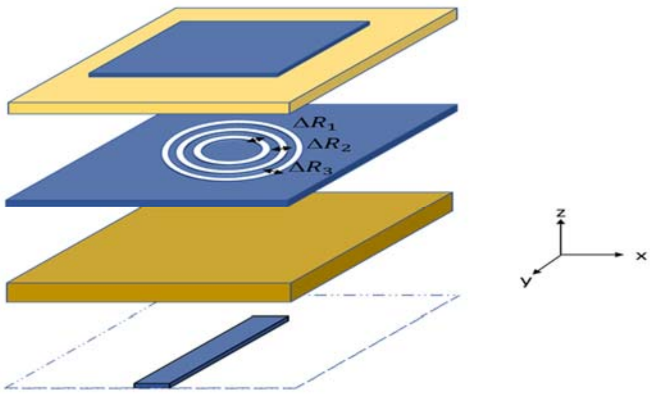
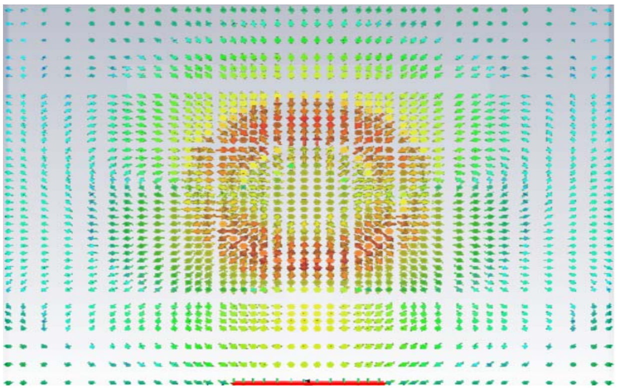


Fig 5. Return loss variations of antenna in different aperture circles.

The figure 6 (a) shows a general schematic of the aperture-coupled patch antenna with three slot couplings in the form of circles with equal slot widths ΔR. The current surface shown in Figure 6 (b), it is important to note that the current flow has been well distributed over the constructed slots which guarantees to get increased antenna performance and minimized losses caused by slots.



(a)



(b)

Fig 6. (a) General schematic of the antenna with three slot couplings in the form of circles, (b) Current distribution through the slots

3. Backward directed radiation reduction techniques

In this section we study technique to reduce the backward directed radiation for proposed microstrip antenna. We proposed and experimentally verified the simple technique of using a microstrip patch antenna element directly behind the microstrip line that fed aperture which acts as a reflector to substantially decrease radiation from an aperture coupled antenna. It is worth nothing that both the suggested reflector patch and the traditional radiating/directive patch utilise a similar ground plane.

We need also to mention the reflector element principal of operation is not as similar as the mechanism used in [14.15] for reflect array's led printed antennas. Reflected arrays like traditional reflectors depend on far-field results to attain the desired properties. A near field interaction between the excitation slot and the reflector patch in the printed reflector element achieved the desired far-field cancellation of the radiated fields.

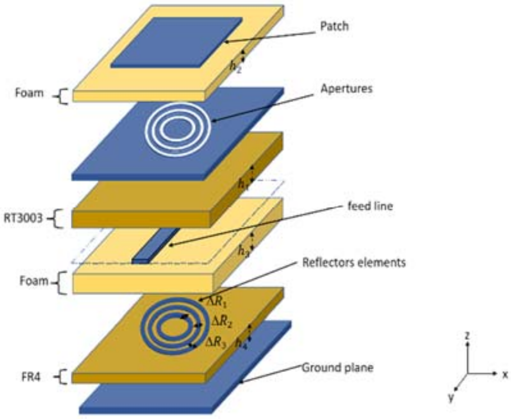


Fig 7. Aperture stacked patch antenna with reflectors patch elements.

We show a schematic diagram of a proposed ASP antenna with a reflector element in Figure 7 which consists of a reflector plate in the form of circles reflecting the shape of the aperture in the ground plan. So as to ensure that the surface wave losses related with this structure have been decreased. A low dielectric constant laminate of thickness h3 separated the reflector microstrip patch. As shown in Figure 7, a thin dielectric layer (h_4=0.254 mm) is utilised to etch the conductor of the reflector patch with dielectric constant of 4.4 and loss tangent equal to 0.025. The dielectric material that divides the feed-line and the reflector can be different thicknesses, however, it is usually electrically thick (greater than $0.1\lambda_0$, where λ_0 is the wavelength corresponding to the center frequency within the antenna's operation band). Therefore, direct coupling between this patch and the feed line is minimal.

Several parameters can be altered to reduce backward directed radiation. The relative phase between the slot and the reflectors patch controls the radius of the patch, whereas the radius of the patch and the distance between the slot and the reflectors control the relative magnitudes. This latter variation makes intuitive sense since the distance between the slot and the reflector patch increases the power coupled to this patch is expected to decrease resulting in the change in relative magnitude. Variating the radius of the reflector patch will provide the finer phase control required to provide effective field cancellation because there are only a few foam thicknesses compatible with the Ka-band frequency range. We have chosen to fix the radius of the reflectors in this work. Figure 8 shows the effect of varying the parameter (h_3) of substrate thicknesses on the Front to Back ratio performance for proposed antenna incorporating reflector elements.

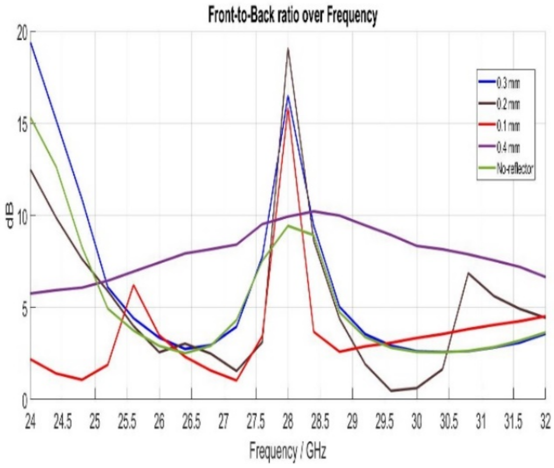


Fig 8. Effect of substrate thickness (h_3) for Reflector Patch on Front-to-back Ratio.

As can be seen from Figure 8, the more spacer thickness increases, the more F/B ratio ameliorates until it reaches certain point where its performance starts to degrade. In this experiment increasing the thickness (h_3) improves F/B ratio until a value of 0.4 mm where at the ratio degrade for the proposed antenna, we selected h_3 = 0.2 mm with 19.92 dB.

4. Antenna performances

In this section, we study the performance of the proposed antenna with reduced back radiation, which we show the antenna efficiency at the front to back ratio, gain, directivity and matching at 28 GHz.
A matching analysis for the designed patch antenna by using the reflector elements is presented in Figure 9 It can be observed that the center frequency is kept when we use technique to reduce the backward directed radiation. The addition of reflector elements affects mostly on the bandwidth but also the desired frequency is kept and well matched.

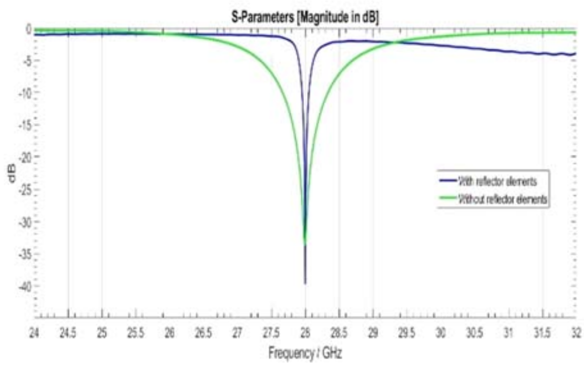
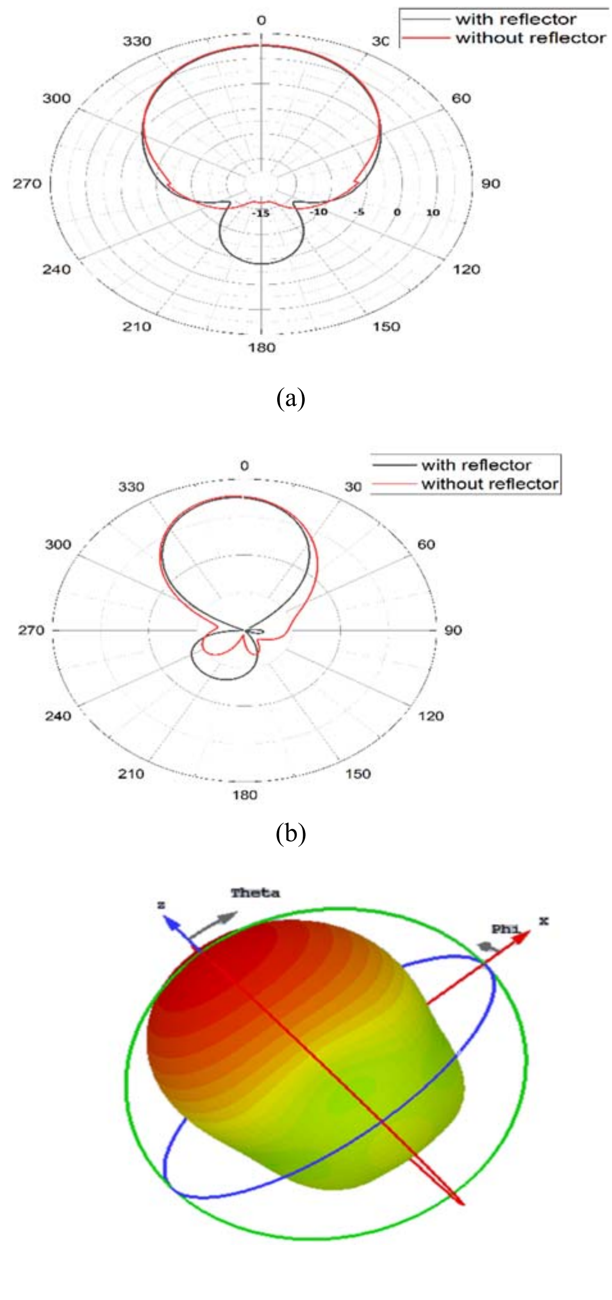


Fig 9. Reflection coefficient simulated with and without reflector elements.

Figures 10 (a), (b), and (c) demonstrate how adding a reflector element to the proposed ASP microstrip antenna reduces field radiation in the antenna's back half plane. The reduction in total power radiated into the antenna's rear hemisphere is visible across the entire impedance bandwidth, emphasizing the technique's matching ability. The most significant field cancellation occurs near backfire (180°), which is especially noticeable in the E-plane. The total radiated power has increased in the forward hemisphere of the H-plane, and the indentations in the pattern that have been smoothed over. The measurement of the radiated fields had a few minor alignment issues.



(a)

(b)

(c)

Fig 10. Radiation pattern of the proposed antenna at 28 GHz (expressed in dB). (a) E-Plane. (b) H-Plane. (c) 3D radiation pattern.

The gain with or without reflector, both are presenting the figure 11 which show us that there is no big change among them except some increase when we used the reflector. The antenna gives an interesting gain value with 7.79 dB. For the directivity the figure 12 shows an interesting increase with the reflector, which is normal due to the reduction of the total radiated power in the rear hemisphere of the antenna, which underlines the ability to increase the directivity by this technique.

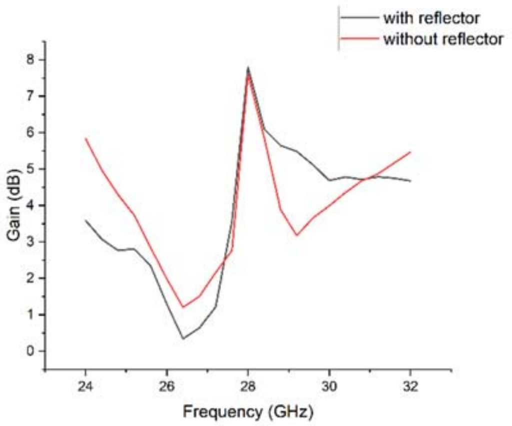


Fig 11. Comparison of gain antenna with and without reflector

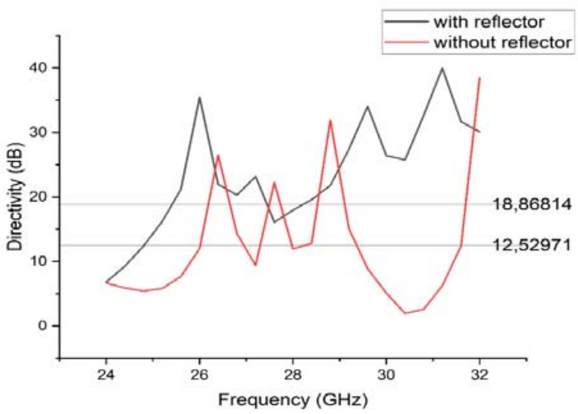


Fig 12. Comparison of directivity antenna with and without reflector

In order to validate the results obtained, a comparative study was carried out which compared the work carried out with previous research. The table illustrates the specification and performances of this comparison that shows the interest of the results obtained at the different levels matching, directivity, gain and F-to-B ratio.

Table 2. Comparisons between the proposed antenna and other works.

Ref	Resonance Frequency (GHz)	Matching at resonance Frequency (dB)	Gain (dB)	F-to-B ratio (dB)
[16]	6	< -25	3.5	8.2
[17]	1.7-2.7	<-35	7.5	18.6-25
[18]	10.5	<-25	7.6	15
[19]	30	<-30	5	20
[20]	3.4	<-30	8	9.4
This work	28	<-40	7.9	19.92

5. Conclusion

Design and characterization of an aperture-stacked patch microstrip antenna with reflector elements is presented in this paper. By an optimization approach, a new slot aperture has been used to have a good surface current flow at resonance frequency (28 GHz). In the same way, a study was carried out to improve the antenna performance in order to concentrate the radiation power and eliminate the power radiated in the rear hemisphere of the antenna, which is shown in the results presented in the different parameters. As a result, the improvement of the front-to-back ratio of a patch antenna was studied and simulated by an improvement of more than 10 dB. The antenna has a good frequency matching at 28 GHz <-40 dB and has an average gain of 7.79 dB. without forgetting to mention the increase in directivity caused by the improvement of the front-to-back ratio up to 18.8 dB and proved by the radiation plane E and H. The proposed antenna is a real contender for uses in low-profile, high directivity, and high gain satellite systems and high-resolution microwave radar.

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