Miniaturized Cavity Backed Substrate Integrated Waveguide Antenna with Enhanced Gain for Ka-Band Application

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Abstract

In this graft, first a low profile cavity-backed (CB) substrate integrated waveguide (SIW) antenna design with planar configuration and unidirectional pattern, functioning in Ka-band is designed. The structure has a rectangular slot in the ground plane. In the first case the length of the antenna is kept at half the wavelength and in the next design, the length is kept equal to the wavelength, and then the results are compared. Gain of the antenna gets enhanced by increasing the dimensions of the antenna. In CST microwave studio, the performances of both the antennas are studied in terms like antennas have the impedance bandwidth of (S11 < -10 dB) of 0.780 GHz (780 MHz) (2.5%), while that of the array is (S11 < -10 dB) of 0.446 GHz (446 MHz) (1.5%) mainly due to tradeoff between bandwidth and gain; maximum directivity of 6.32 dBi and 9.456 dBi, realized gain (IEEE) of 5.5196 dBi and 8.847 dBi, overall efficiency of 92% and 81% respectively, with high front to back ratio (FTBR) and unidirectional radiation patterns in both the designs. This antenna can be applicable in satellite communications high resolution data transmission, close-ranging targeting radars on military aircrafts etc.

Keywords: SIW (substrate integrated waveguide), FTBR (front-to-back ratio), gain, impedance bandwidth, mm (millimeter), CB (cavity backed)

1. Introduction

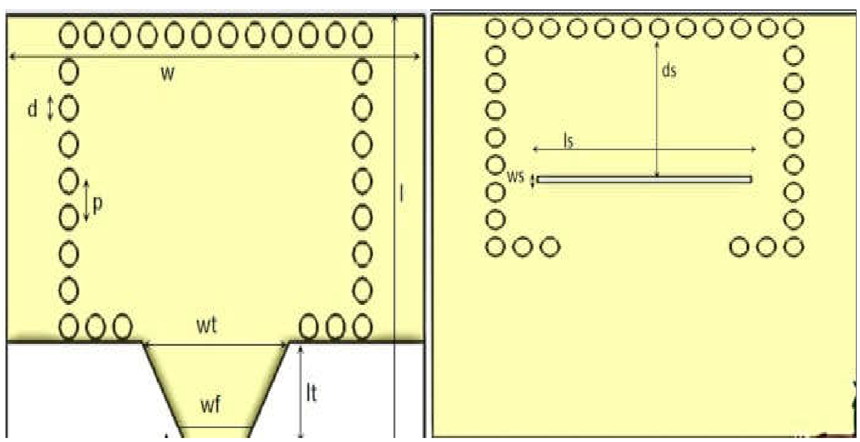
The growing request for high speed and enhanced performance communications systems are working as the driving forces for persuasive researchers to develop more proficient and improved active and passive structures. Ka-band has been considered as efficient for Fifth-generation (5G) wireless transmissions at high speed. Arrays tend to provide us with better performances, either in terms of gain or bandwidth, but at the cost of increased cross-section. For implementing such structures at mm wave transmissions, substrate integrated waveguides (SIW) are most sought after, which possess the aids of waveguides as well as microstrip antennas like high power operations, low cost, easy to fabricate etc.

Substrate integrated waveguides (SIW) consists of vertical holes named vias. It is similar to dielectric filled waveguide [1-2]. Vias and the two conducting plates blocks unwanted radiations permitting only TE_{mn} modes and opposing TM_{mn} modes, due to absence of continuous magnetic field [3].

Here, a conservative rectangular slot is scraped in ground plane enforcing the antenna to radiate in TE_{10}, which is dominant mode. The dimension of slot is kept at half of wavelength. Preference is given to taper feed, to feed the antenna, for good matching and better results, as suggested by many authors.

Until now we have witnessed the arrays implemented as replicated same structure using power dividers. Here, rather than replicating the structure differently, we have increased the length of the structure, thus widening the design vertically instead of horizontally. The slot in the ground is replicated with same half wavelength, as in the original design. Hence it can be called a virtual array as we are able to get increased gain. Thus, we are not supposed to incorporate power dividers, which prevent the structure from being more bulky and complex. First the simple structure is designed to work in Ka-band with length of the radiator being half the wavelength. When the desired results are obtained, the length of the antenna is increased to one wavelength. At this stage, we get the enhanced gain of the antenna.

2. Design procedure



(a) (b)

Figure 1. Geometry of the Intended Aerial (a) Front View (b) Back View.

The intended aerial is as shown in figure 1. The slot is present on the ground plane as shown in figure 1(b). All geometrical dimensions are registered in table 1. The SIW cavity is designed complying with design rules keeping in mind the minimum leakage and losses [4-5]. The precious works of authors is studied to determine the dimensions of the cavity working in Ka-band.

Using the range of lower and higher frequencies respectively as shown, in which a conventional waveguide will work as

$$f_{low}=1.25fc \quad (1)$$

$$f_{high}=1.89fc \quad (2)$$

the cutoff frequency will be 21.4 GHz. The broad side dimension is found from

$$a= \frac{c}{2f_c\sqrt{\epsilon_r}} \tag{3}$$

c = speed of light, ϵ_r= relative permittivity, f_c = cutoff frequency
The width of equivalent SIW which now works as a dielectric filled waveguide is found using

$$a_{equ} = \frac{a}{\sqrt{\epsilon_r}} \tag{4}$$

Center-to-center space between the vias walls is given as

$$a_{c-c}=a_{equ} + \frac{d^2}{0.95p} \tag{5}$$

"d" = diameter of a via , "p" = spacing between two neighboring vias. Where,

$$d<p\leq 2d \tag{6}$$

$$0.05<(\frac{p}{\lambda_c}) < 0.25 \tag{7}$$

λ_c = cutoff wavelength .

Achieving impedance matching for minimum reflections, technique of taper feed is used. Techniques like modified taper feed, coaxial feed, inset feed etc. are also prominent. Here, taper feed which work like a transformer matches port feed impedance with that of cavity, whose feed width can be derived from [6-7] as

$$W_t = \frac{c}{2f_c\sqrt{(\epsilon_r+1)/2}} \tag{8}$$

and, the feed width at the port end can be approximated as 0.4 times opening of patch [8].

$$\frac{W_f}{a_{equ}} \sim 0.4 \tag{9}$$

W_t = width at the feed end, a_{equ} = opening of the patch.

The length of the taper is given by

$$l_t = \frac{n\lambda_g}{4} \qquad n=1,2,3\ldots\ldots \tag{10}$$

Rogers/RT Duroid 5880 having ϵ_r = 2.2, loss tangent 0.0009. All the variables of the proposed aerial are listed in table 1.

Table 1. Parameters of Design Proposed

d = 0.50	ds = 3.79	h = 0.787	t = 0.035
lt = 2.36	ls = 3.50	p = 0.715	l = 9.33
wf = 1.80	ws = 7.00	wt = 3.75	w = 7.00

All lengths are in mm.

3. Results and comparisons

For the antenna so designed, the length of the patch is kept nearest to half of the wavelength, as some extra length was required to accommodate the required number of vias in the structure. The waveguide with the cutoff frequency of 21.4 GHz works in the frequency range of 26.8 GHz to 40.5 GHz. So, the cutoff wavelength comes out to be 9.45 mm. Next, to design the pseudo array, the length of the patch is doubled, keeping the same width and increasing the number of vias, optimizing the parameters and obtaining the results.

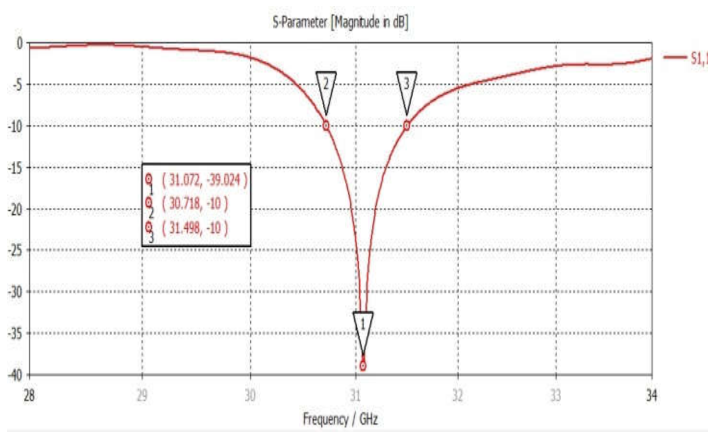
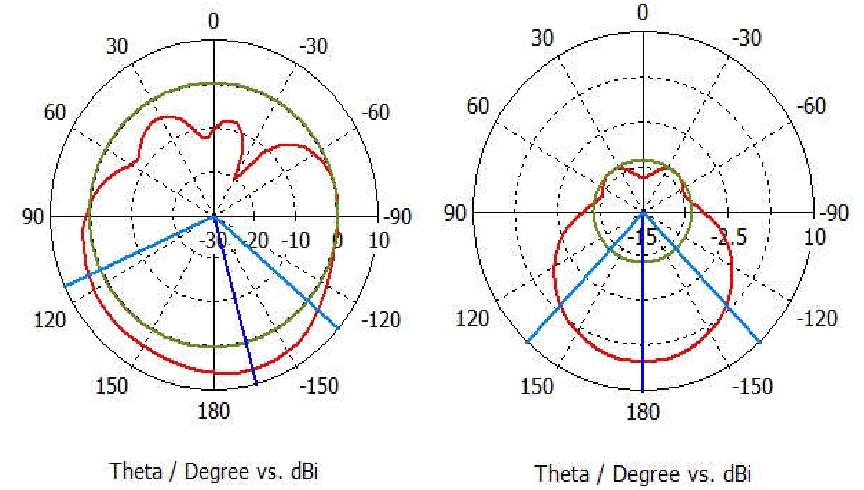


Figure 2. Simulated S11 of the Proposed Antenna.

Here, no power dividers are employed, rather, the power is fed to the structure in the same manner as done in the first element. An appreciable impedance matching is achieved. Taking in account the dielectric and conductor losses, S-parameter is plotted in figure 2. It is evident from the figure, that resonance arises at 31.072 GHz and the antenna is operational over the bandwidth of 780 MHz which shows the antenna performs decently in this regard. Generally SIW antennas show narrow-band performances, which is a drawback, but, it is a good bandwidth to achieve.



E-Plane H-Plane
Figure 3. Simulated Radiation Patterns in Different Cut Planes at 31.072 GHz.

Both, E-plane (ϕ = 90°) and H-plane (ϕ = 0°) radiations are presented in figure 3, which depicts the unidirectional behavior [8].
A satisfactory front-to-back ratio is attained which is around 12.2, which verifies the unidirectional pattern, which can be seen in figure 4.

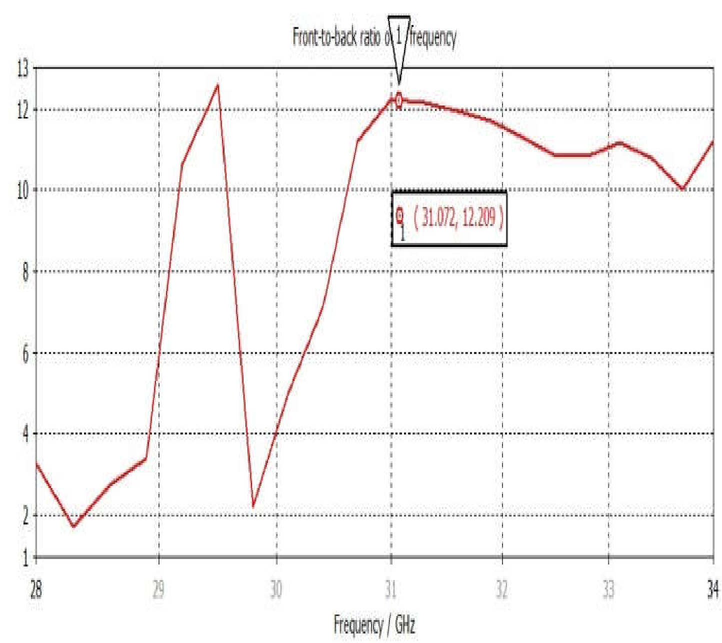


Figure 4. Simulated Front-to-Back Ratio.

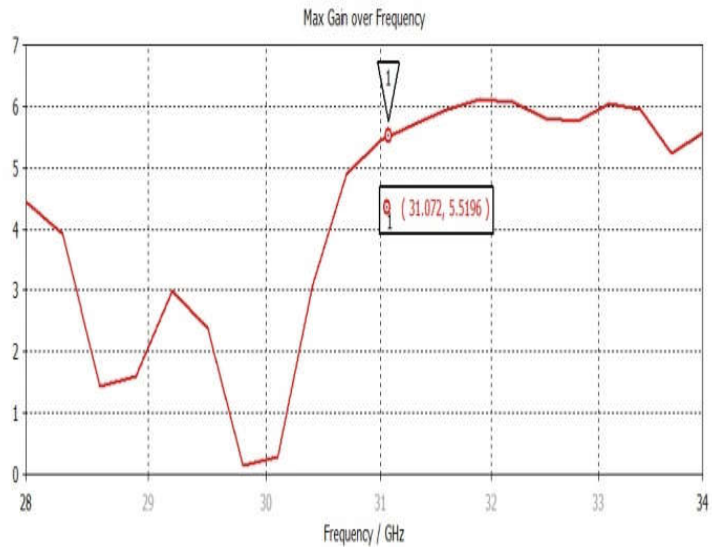
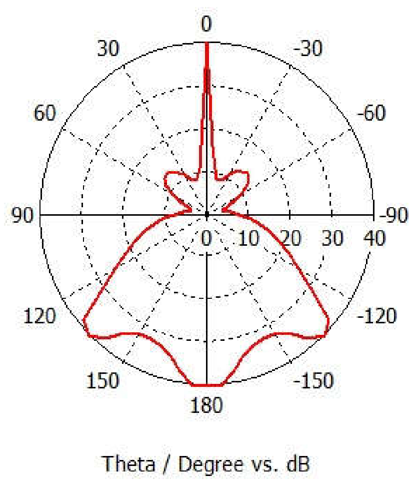
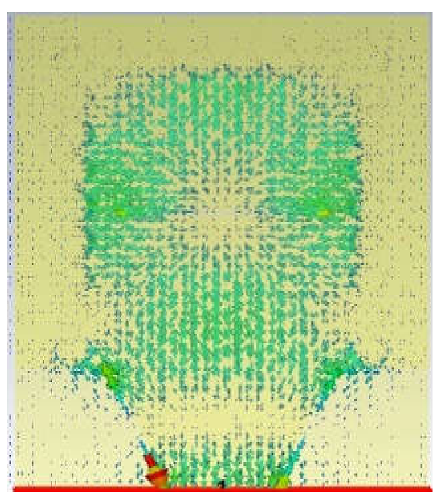


Figure 5. Simulated Gain.

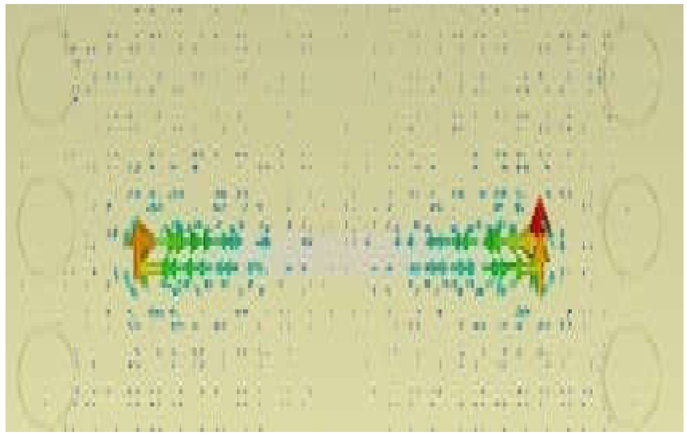
A realized gain of 5.51 dBi is achieved by the antenna as seen in figure 5.

Figure 6(a) presents the axial ratio implicating antenna being horizontally polarized while 6(b) and 6(c) gives the distribution of current along the structure and slot respectively. Current being distributed evenly within boundaries of vias along the antenna can be seen. The current is not allowed to cross the virtual wall being created by the vias. Electric fields within the slot gets cancelled as the direction of flow of current is opposite along the boundaries [9].





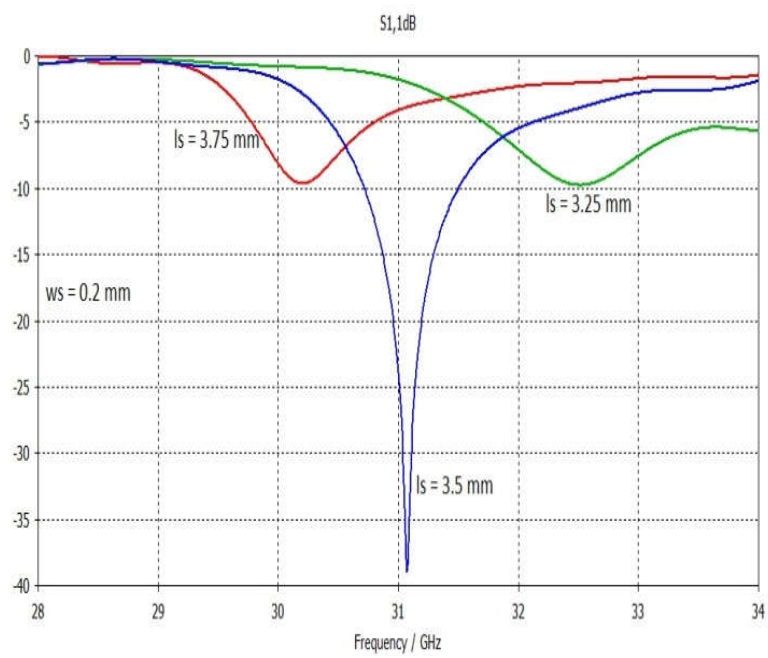
(a) **(b)**



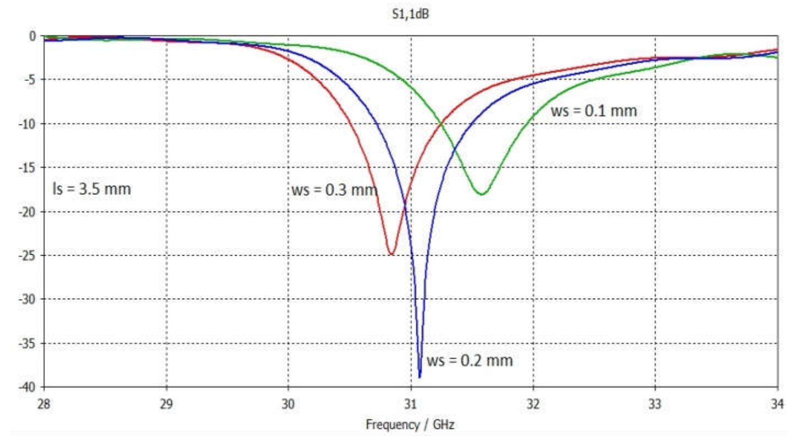
(c)

Figure 6. Simulated (a) Axial Ratio (b) Surface Current and (c) Surface Current through the Slot.

Figure 7 presents the variation in the performance with respect to the parameters of the slot, where in (a) width of the slot is kept constant and in (b) length is kept constant and optimization is performed.



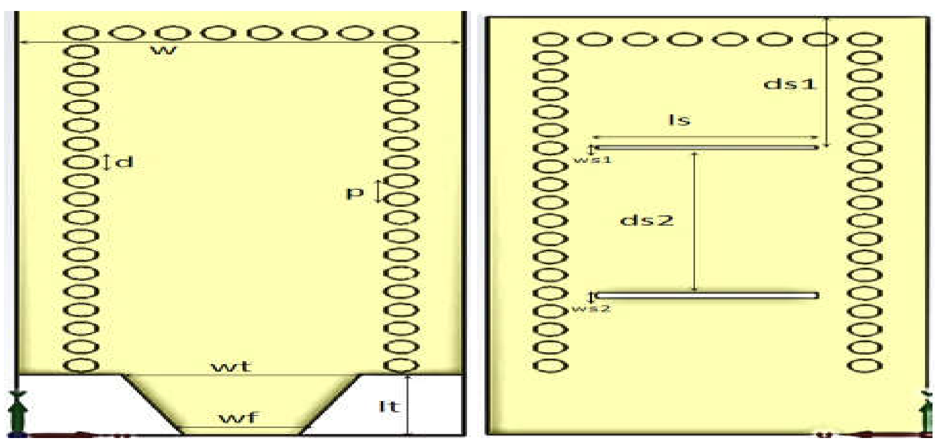
(a)



(b)

Figure 7. Parametric Study of Slot (a) Width and (b) Length constant.

The virtual array so designed is shown in figure 8. The slot in the ground plane is repeated but the width of the slot is changed, that is, reduced to get the desired radiation pattern. All the dimensions of the design are listed in table 2



(a) (b)

Figure 8. Geometry of the Proposed Aerial Array (a) Front View (b) Back View.

Table 2. Parameters of Design Proposed of Virtual Array

d = 0.50	ds1 = 5.11	ds2 = 5.385	lt = 2.36
ls = 3.50	p = 0.715	l = 16.48	wf = 1.80
ws1 = 0.10	ws2 = 0.20	wt = 3.75	w = 7.00

All lengths are in mm.

The results of the design with increased length are as shown. As it is visible in the figure 9 that the frequency of operation has shifted slightly from 31.072 GHz to 30.916 GHz, but the antenna is covering this frequency also in its working range which provide us with bandwidth around 446 MHz. The shift of the peak is mainly because the dimensions of the antenna have been changed [10]. Figure 10 shows the E-plane which shows the direction of maximum radiation giving us the angular 3dB width of around 44 degrees. From H-plane, giving the direction of magnetic field and E-plane we can observe that the antenna is radiation is from its back.

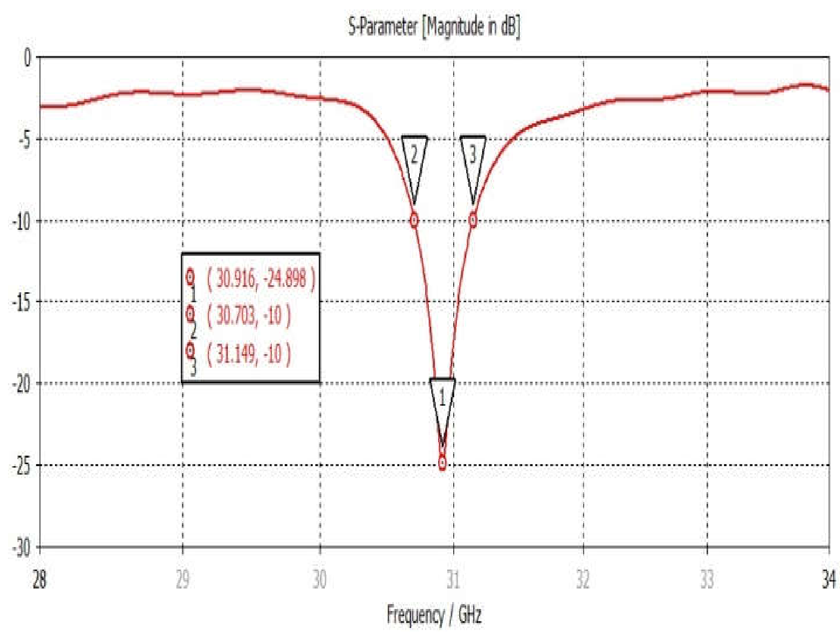
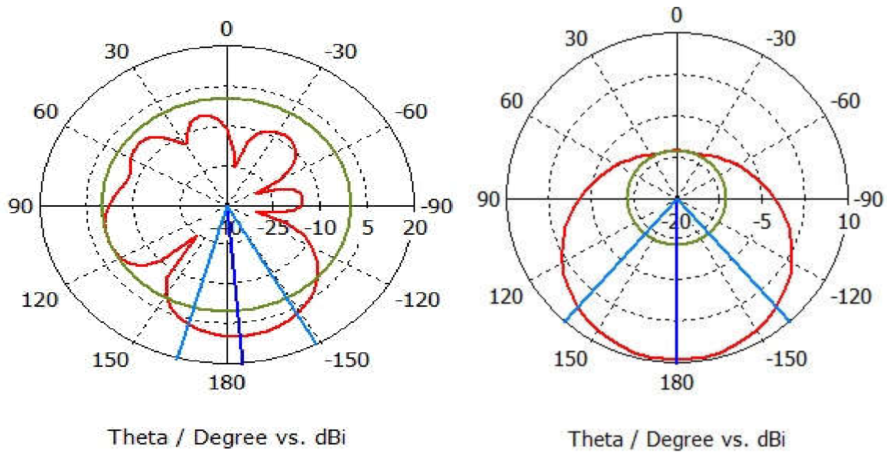


Figure 9. Simulated S11 of the Proposed Aerial Virtual Array.



E-Plane **H-Plane**

Figure 10. Simulated Radiation Patterns in Different Cut Planes at 30.916 GHz.

Figure 11. Simulated Front-to-Back Ratio.

The strength of the fields can be estimated from the given front-to-back ratio as given in figure 11, which is around 16. Figure 12 shows the desired result of the work where we are getting a gain of around 8.847 dBi where in the former design we were getting a gain of 5.519 dBi.

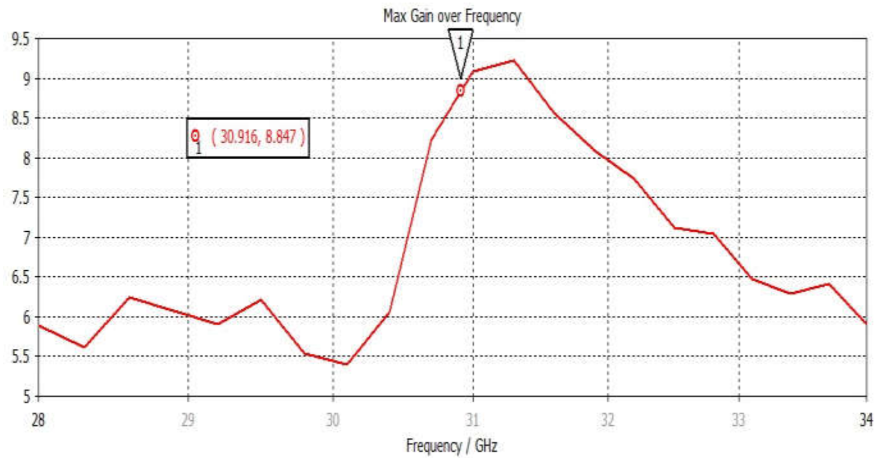
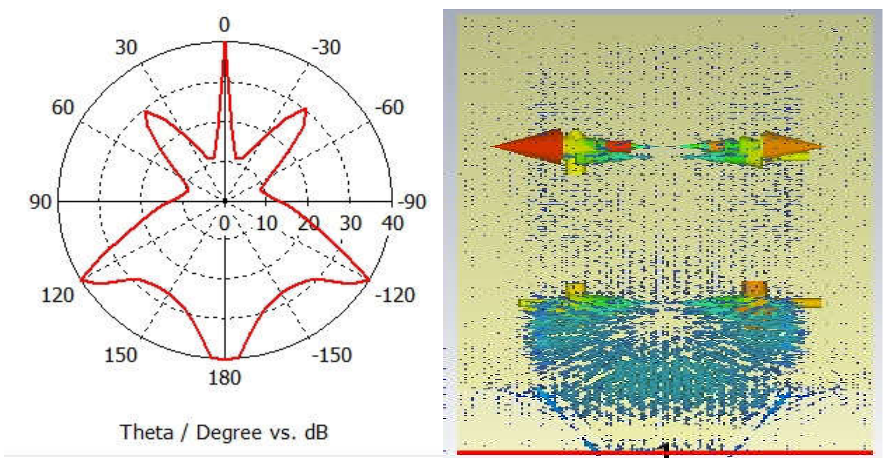
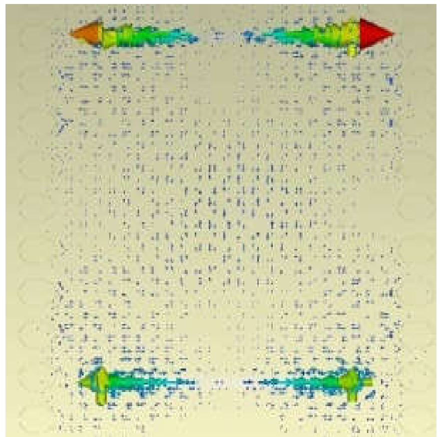


Figure 12. Simulated Gain.

Due to this behavior of the antenna it is called as virtual array since it does not employed any power dividers and antenna is well operating in almost same frequency range. Figure 13 shows the axial ratio, showing horizontal polarization, and the current distribution through patch and the slots. Here we can notice that it is accommodating two cycles of the signal in comparison to the former structure as shown in figure 6(b), where it is accommodating only one cycle. Thus, there is a shift in mode of operation occurs due to which a shift in peak of the frequency occurs.



(a) (b)



(c)
Figure 13. Simulated (a) Axial Ratio (b) Surface Current and (c) Surface Current through the Slots.

4. Conclusion

The compactness of both the designs can be determined from their dimensions of 9.33 mm X 7.00 mm in case of former and 16.48 mm X 7.00 mm in case of latter. Both antennas have unidirectional pattern. Rogers RT/ Duroid 5880 is selected for both the designs as it has low variations and higher performance at higher frequencies. Thus we have achieved enhanced gain of a low profile antenna by replicating the structure vertically without any extra connections like power dividers. Both the antennas are working in Ka-band having good performance characteristics.

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