Double-Sided Bowtie Antenna Array for Ku/K Band Applications and Performance Study of Controlling Ground Plane

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Abstract

For having adapted to the various national spectral regulatory authorities, it is preferred to have a design of antenna that can be easily modified to be compatible with the different requirements. To fulfill the demand, a double-sided bowtie antenna operating within K and Ku band is investigated in this project. This antenna consists of two modified bow-tie structures patched on opposite sides of the substrate, where the lower one acts as a ground plane. It is composed on TSM- DS3M substrate and has dimensions of 17.8 x 14.2 x 0.51 mm3. The partial ground plan shows significant effects on antenna characteristics such as radiation pattern and bandwidth. This model can also work for different wideband technology because the percentage bandwidth can be easily switched from 26.995% to 71.84% by changing the length of the partial ground plane. Overall system performance of this model is improved by investigating different array configurations. Four and eight elements array have been designed in this research. The output characteristics of the array, such as radiation pattern, return loss, and peak realized gain are studied along with the single antenna parameters.

INTRODUCTION:

The interest for high-speed point to point microwave link is very significant in upcoming 5G technologies. As the current commercial spectrum is getting increasingly crowded, mobile operators and ISP need more and more bandwidth [1]. They are looking for new spectrum allocation that will reduce their cost for wireless backhaul. In this regard, mm-wave frequency range has become an excellent candidate for this backhaul connection for the cellular tower that will be the backbone of the 5G system [2]. As most of the devices are still working on the sub 6 GHz range, this will be more resistant to interference. The beam-width in this spectrum range is limited to just a few degrees. The narrow beam has the benefit of not interfering with co-located and densely populated links around it. The beam steering characteristic of the arrays makes it suitable for maintaining good coverage while also allowing the control on the direction of the main beam by phasing the excitations in the linear array [3]. However, this spectrum range has some drawbacks- it is subject to high atmospheric attenuation, and the path loss is very high. Various types of antennas have been reported for cellular towers and mobile devices that are working in these bands [4]–[7]. However, these antennas are not flexible in terms of directivity, bandwidth, and radiation pattern.

To fulfill the demand of this technology, a double-sided bowtie (DSBT) antenna operating in K and Ku band have been investigated in this letter. This antenna consists of two homogenous perfect electric conductors patched on both sides of the substrate, where the lower one acts as a ground plane. There is an additional rectangular conductor in the bottom that merges with the ground plane for mainly improving the gain characteristics of the antenna. The structure is called the partial ground plane. The study includes the development of DSBT antenna model, antenna simulation, and analysis of results based on various outputs of the simulation tool from ANSYS HFSS. Then, the procedure is extended to design different array configurations for higher gain and beam steering nature.

DESIGN AND ANALYSIS OF DSBT ANTENNA:

Single Element Design

The initial goal is to determine the dimensions of the DSBT antenna model to obtain the optimal performance at 17.5 GHz. In this work, parametric study for various dimensions is conducted to design the DSBT antenna. The optimized design of the top and ground plane of this antenna are shown in Figure 1(a) and 1(b), respectively. Later, this design was fabricated using an LPKF milling machine. Figure 1(c) shows the antenna prototype.

In order to choose the substrate, various features such as relative permittivity, dielectric loss tangent, and thickness of the material are considered. In the initial design, Rogers RO-3203 with properties of relative permittivity 3.02, dielectric loss tangent 0.0016, and thickness of 0.5 mm is chosen as the substrate after a thorough investigation on some laminations with different thicknesses and values of relative permittivity. However, TSM-DS3M, which has very similar properties with RO-3203, was used for the final prototype. Better antenna performance was obtained with this substrate. There are occasions where a different ratio of width to length are required because of space limitations, or to change the input impedance.

This version of the bowtie antenna is designed by investigating the performance properties of the model. The patch designs, having various width to length ratios, were optimized. The values of the design parameters are given in Table 1.

Performance analysis of the single antenna

In this section, at first, the effects of the partial ground plane on the radiation pattern, impedance bandwidth, and gain have been investigated. In the simulation results, it is seen that changing the length of the partial ground (Lg) affects the gain value. From Figure 2, it is seen that at 17.5 GHz, the maximum value of the gain is increasing from 4.2 dB to 4.9 dB for the change of the partial ground from 0.7 mm to 4.4 mm.

This change of the L_G also has a very significant effect on the radiation pattern and bandwidth. In Figures 3-7, the effects of L_g parameter on the radiation pattern are shown. It is seen that for a small value of the length of the partial ground plane, the radiation pattern is almost omnidirectional (Figure 3 and Figure 4). However, when the length of the partial ground is being increased gradually, this omnidirectional characteristic is lost and instead, for the larger partial ground plane, the antenna shows a directional pattern (Figure 5, Figure 6, and Figure 7). The front to back ratio of this directional antenna is higher than 10 dB.

Figure 8 shows the simulation results of the return loss (S11) for the different length of the partial ground. The operating frequency shifts between 15 to 20 GHz. The antenna has been designed initially for operating at 17.5 GHz, and as illustrated, the covered bandwidth for this frequency is 4.6 GHz. For the lower value of L_g, it is seen that bandwidth is significantly higher. For instance, when the length of the partial ground is 0.7 mm, the resonance frequency shifted to 19.48 GHz, and the bandwidth is 8.7 GHz. When $L_g$value increases to 1.5mm, the center of the resonance goes to 19.58 GHz, and the bandwidth becomes 15.18 GHz. Due to the operating limitations of the network analyzer, the design with L_g=4.4mm has been chosen, and this model was built using RO-3203 substrate. The fabricated antenna was tested using an Agilent PNA- L N5230C network analyzer. There were differences between simulated and measured results.

The reason is accounted for ED copper cladding type, which is not very suitable for high-frequency operations like Ku band applications. Therefore, the substrate is changed to TSM-DS3M with properties of relative permittivity 2.94±0.05, dielectric loss tangent 0.0011, and a thickness of 0.51 mm for the fabrication purpose. This ultra-low profile (ULP) copper is also electrodeposited, but has a smoother surface, resulting in lower insertion loss at high frequency, where the skin effect is the dominant factor in the loss equation. As seen in Figure 9, the measured return loss is compatible with the simulation. The bandwidth becomes slightly narrower than the simulated result, and there is a small dip at 15.8 GHz. One possible reason can be soldering effect that might bring some differences.

DESIGN AND ANALYSIS OF 1X4 ELEMENTS ARRAY:

1x4 Elements Array Design

To improve the overall system performance of the antenna, various array configurations have been investigated. First, 1x4 element array has been designed with a single power excitation for each radiating element. The distance between the radiating structures is chosen as 13.35mm with an electrical distance of 0.75λ at 17.5GHz. Later, the top four radiating elements are connected to a corporate-fed network, which is basically a 1x4 power divider. This feed network has a single input port and multiple feed lines that constitute the output ports. This configuration is shown in Figure 10. All the bowties in the ground plane are terminated in the partial ground plane. The parameters for feed networks are designed and optimized in HFSS circuit to make it work as a 50-ohm transmission line at 17.5 GHz, and then push excitation of this power divider is used to empower each element of the array. The values of the parameters are listed in Table 2. Figure 11 shows the geometric structures of the array along with the fabricated antenna.

Performance Analysis of 1x4 Elements Array

The S-parameters of the individual fed 1x4 element array is shown in Figure 12. It can be seen that the bandwidth of the four-elements array covers from 14.9 to 19.4 GHz. It shows that the mutual coupling between the antenna element is lower than -20 dB. It implies that there is not much interference among the array elements.

The electric field distribution of the corporate fed array in Figure 13 also shows that the individual radiating elements are not affecting each other significantly.

In Figure 14, the return loss for both simulated and fabricated 1x4 element corporate-fed array is given. In simulation, the antenna array works in the band from 15 to 19.2 GHz and in measured result, it covers the frequency from 12.49 to 18 GHz. It is seen that the resonance frequency slightly moves from 17.5 to 17.28GHz. This may happen because of the extended ground plane. The bandwidth is very close to the single element antenna.

Figure 15 shows that for both individual and corporate fed antenna array, the peak realized gain is around 10dB in the entire operating frequency. At center frequency 17.5 GHz, the peak realized gain is 11.59 dB for the individual fed array. On the other hand, for corporate fed, it is 10.34 dB at 17.5 GHz.

1. **DESIGN AND ANALYSIS OF 1X8 ELEMENTS ARRAY:**
2. 1x8 Elements Array Design

At first, an array has been designed with an individual power excitation for eight radiating elements that are patched in parallel to cover 17.5 GHz operating frequency. In this linear phased array, the distance between the radiating structures is optimized as 13.35mm with an electrical size of 0.75λ at 17.5GHz. Following this design, a corporate feed network is designed for empowering the whole array with a single port. The configuration of the 1x8 elements corporate fed array is shown in Figure 16.

Performance Analysis of 1x8 Elements Array

Figure 17 shows the return loss and mutual coupling for the 1x8 element individual fed array. The return loss is 21.7574dB at 17.5 GHz and the mutual coupling is less than -20dB that means there is a good isolation between the array elements. The operating frequency of the antenna array with $|s_{11}| < -10$dB is 15.2 to 19.3 GHz.

Figure 18 depicts the variations of peak realized gain in the operating frequency range for both individual and corporate fed antenna array. In the operation region, the peak gain is stable, and the average value is more than 12dB.

The designed antenna array shows a very good beam steering characteristic. For 0^o, progressive phase shift of $\pm80^o$ and $\pm160^o$, Figure 19 depicts the illustration for the beam steering phenomena of the array respectively. The main beam is scanning up to a maximum of $\pm77°$ based on the progressive phase shift. The 3D directional beam is also shown in this figure for 0^o phase shift. Table 3 shows the proposed arrays in comparison with antenna arrays from the literature. It is observed that the proposed designs achieve high gain values within a broad bandwidth. Also, the array has low mutual coupling in a compact size.

CONCLUSION:

A small size DSBT antenna has been proposed in this research, which is promising for microwave link, radar and future 5G technology. The antenna array is operating at Ku and K band frequency which ensures the flexibility for improving the efficiency and gain as per the requirement of the radar application and microwave link. In the ground plane analysis, it is seen that this model can work for a technology that needs high bandwidth. Besides, the controlled radiation pattern made this antenna suitable for future WPAN and WBAN technology with high throughput in data transfer. At present UWB monopole antenna is very popular in WPAN/WBAN technology, and from the analysis shown above, it can be easily said that the directional feature of this antenna model can be a very good alternative for this technology.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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Table 1 The optimized dimensions of the designed antenna

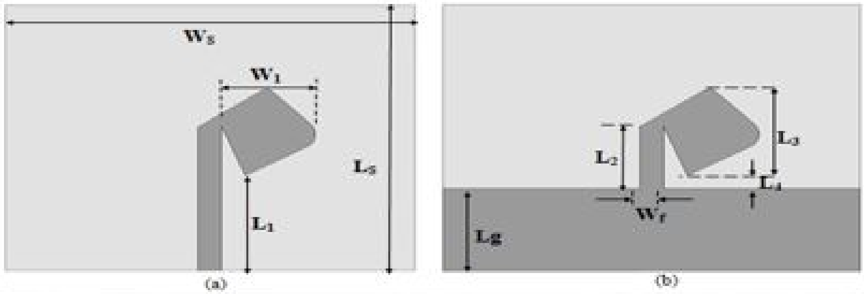
Parameter	W_S	L_S	W_f	W_1	L_G	L_1	L_2	L_3	L_4
Value(mm)	17.8	14.2	0.8	3.2	4.4	5.1	3.3	4.6	0.7

Table 2 The optimized dimensions of the corporate feed network and 1x4 elements array

Parameter	W	W2	P	P2	W_a	L_a
Value(mm)	1.1334	0.52587	1.427	1.427	53.4	22.389

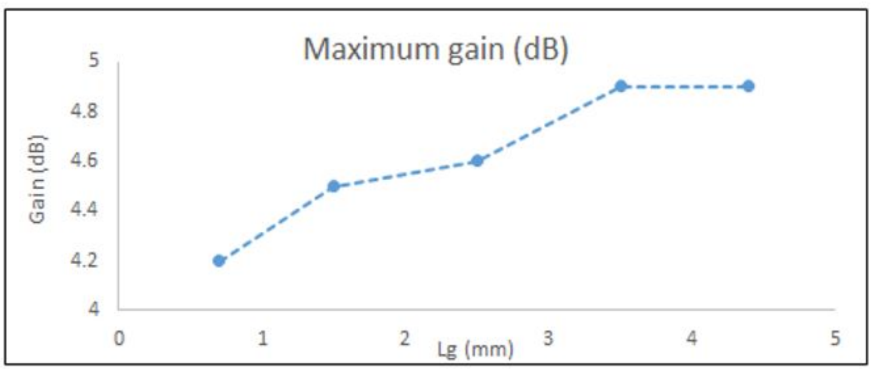
Table 3 Performance comparison of this work with other antennas

Ref.	Dimensions (mm^3)	Bandwidth (GHz)	Max. Gain (dBi)	Unit Cell Combi-nation	No. of Elements
[8]	100x80x1.57	4.68-5.24	9.5	1x4	4
[9]	180x60x13.524	2.26-2.54	9.6	1x4	4
[10]	90x90x0.8	7.9-9.5	8.7	3x3	6
[11]	25x20x0.8	40-45	7.3	12x10	22
[12]	60x30x11.27	6-8	10.21	3x3	6
[13]	26.6x19.4x2.77	12.5-15.2	8.51	2x2+1	5
This work	71.2x14.2x0.5	15-19.2	11.87	1x4	4
This work	106.8x14.2x0.5	15.2-19.3	13.8	1x8	8

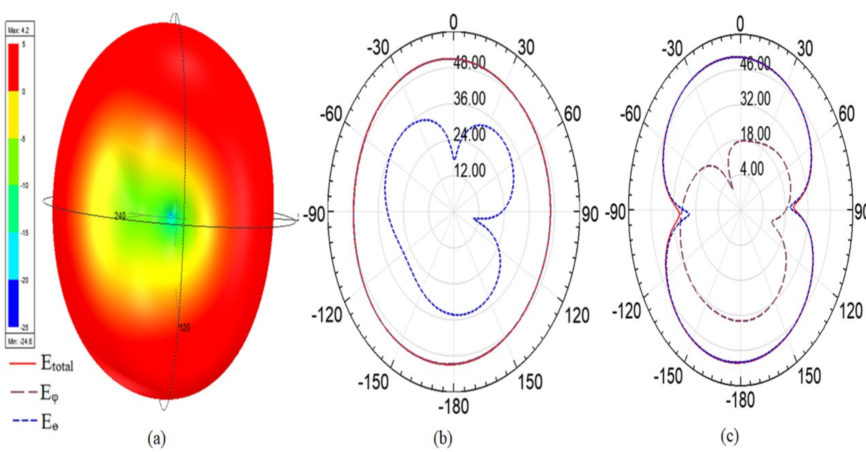


Ws
W1
Ls
L1
(a)
L2
L3
L4
Wf
Lg
(b)

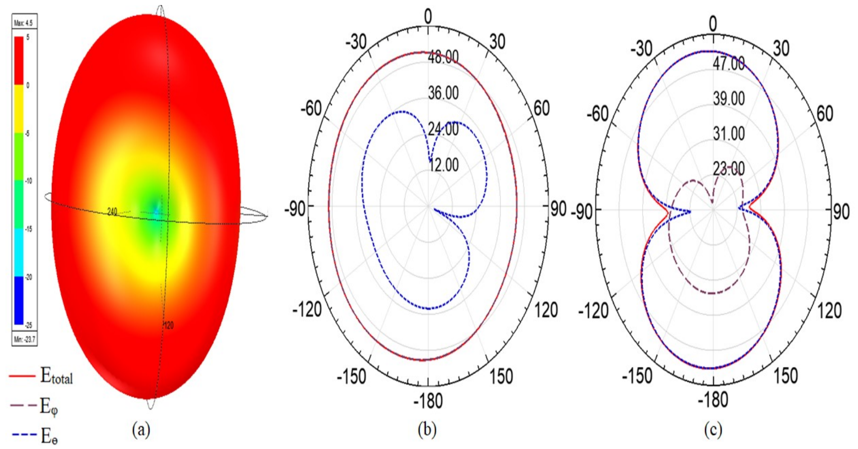
Top Plane
Ground Plane

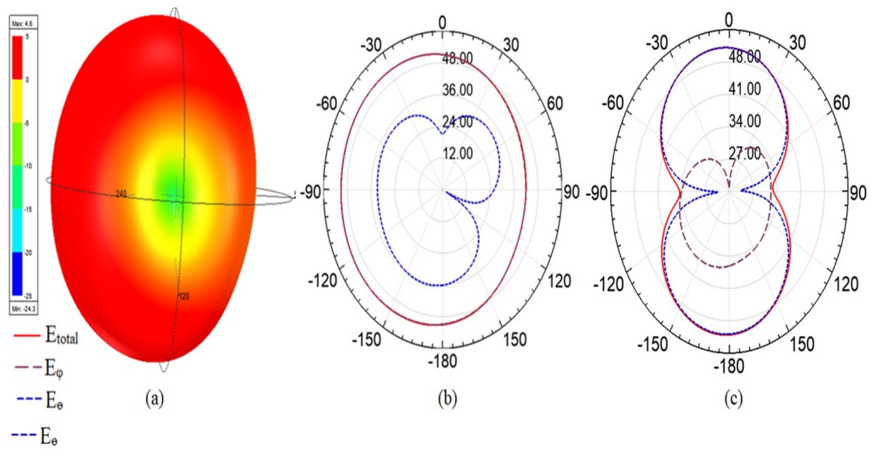


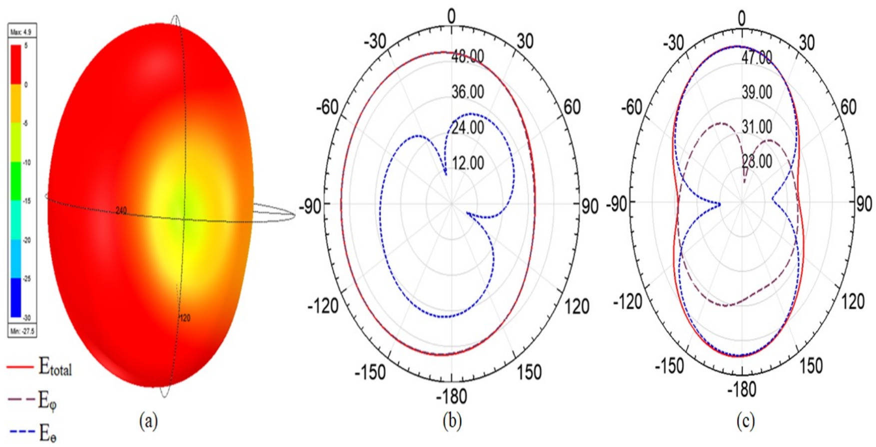
Maximum gain (dB)
Gain (dB)
Lg (mm)
5
4.8
4.6
4.4
4.2
4
0
1
2
3
4
5

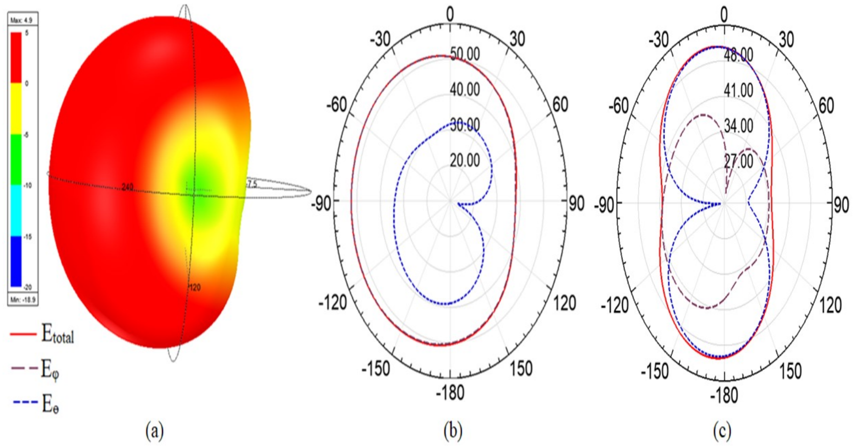


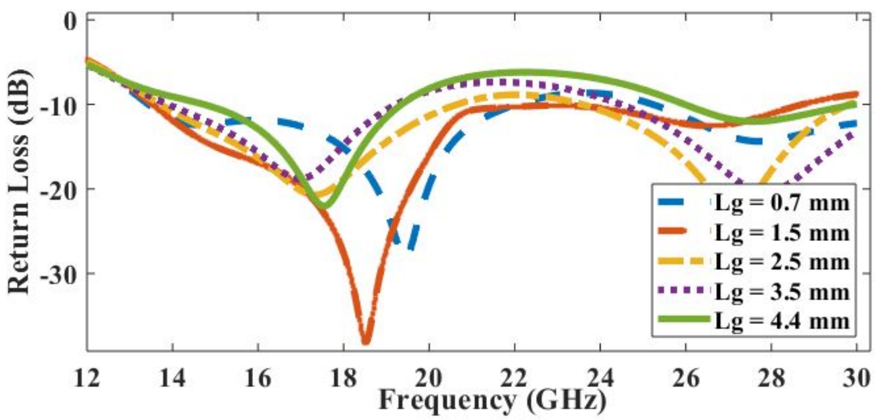
Etotal
Eφ
Eθ
(a)
(b)
(c)

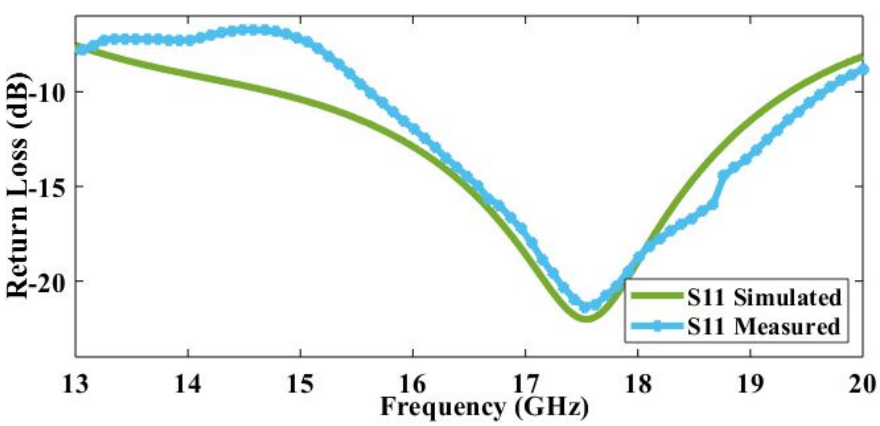

Max: 4.5
Min: -23.7
Etotal
Eφ
Eθ
48.00
36.00
24.00
12.00
47.00
39.00
31.00
23.00
(a)
(b)
(c)

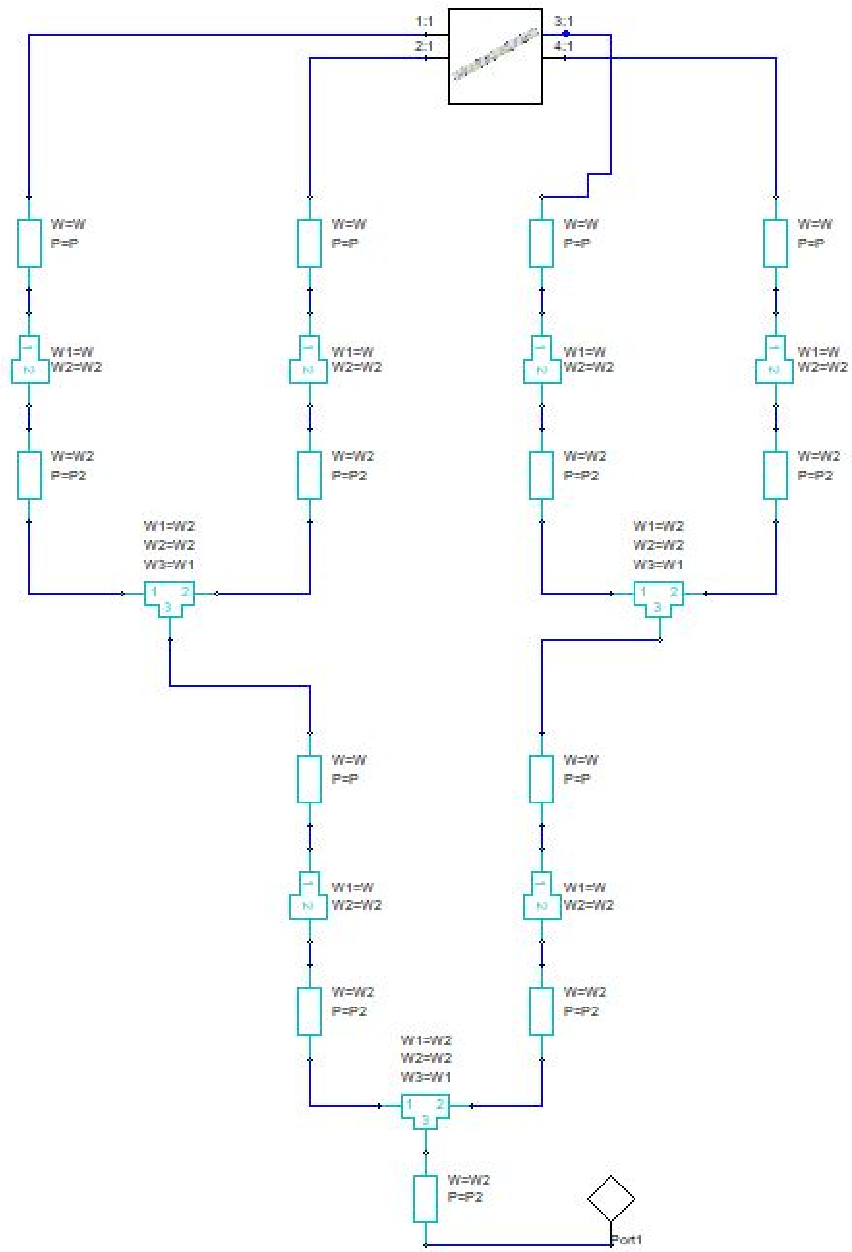

Max: 4.6
Min: -24.3
Etotal
Eφ
Eθ
Eθ
48.00
36.00
24.00
12.00
48.00
41.00
34.00
27.00
(a)
(b)
(c)

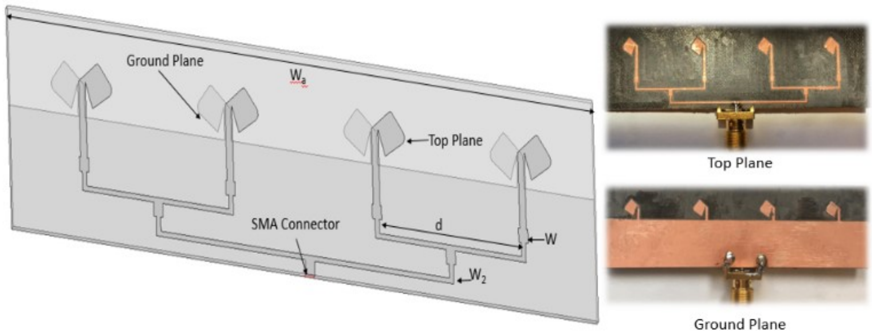

Max: 4.9
Min: -27.5
Etotal
Eφ
Eθ
48.00
36.00
24.00
12.00
47.00
39.00
31.00
28.00
(a)
(b)
(c)

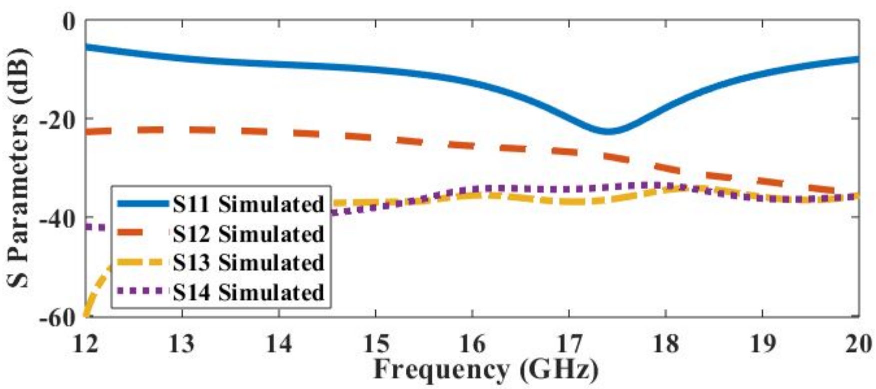

E_total
E_φ
E_θ
0
30
60
90
120
150
-180
-150
-120
-90
-60
-30
50.00
40.00
30.00
20.00
48.00
41.00
34.00
27.00
(a)
(b)
(c)

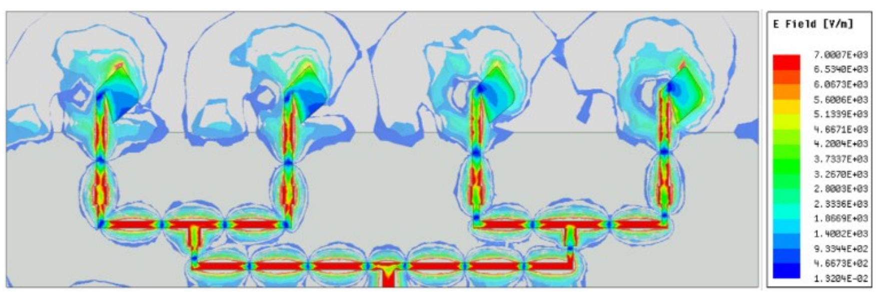

Return Loss (dB)
0
-10
-20
-30
Frequency (GHz)
12
14
16
18
20
22
24
26
28
30
Lg = 0.7 mm
Lg = 1.5 mm
Lg = 2.5 mm
Lg = 3.5 mm
Lg = 4.4 mm

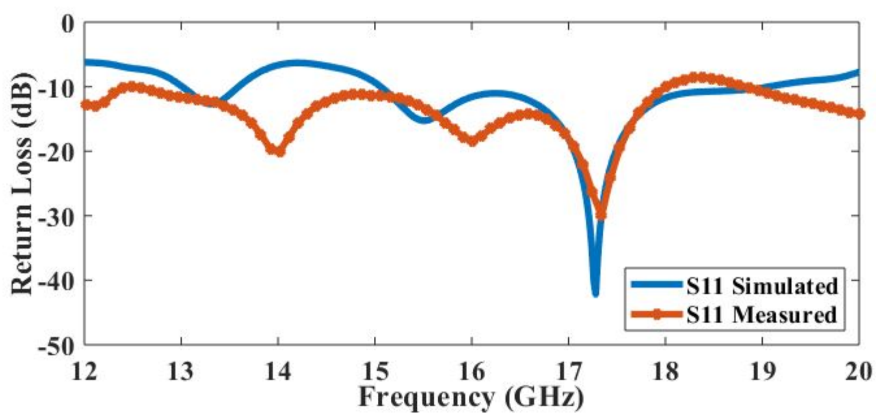

Return Loss (dB)
-10
-15
-20
Frequency (GHz)
13
14
15
16
17
18
19
20
S11 Simulated
S11 Measured

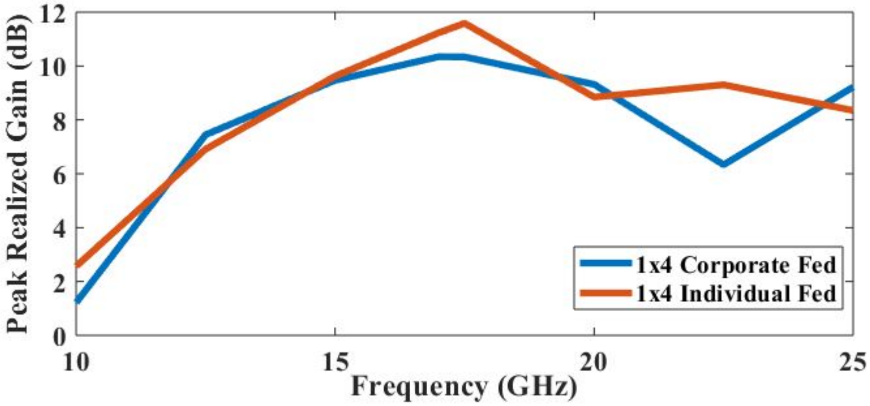

1:1
2:1
3:1
4:1
W=W
P=P
W1=W
W2=W2
W=W2
P=P2
W1=W2
W2=W2
W3=W1
Port1


Ground Plane
Top Plane
SMA Connector
d
W
Top Plane
Ground Plane

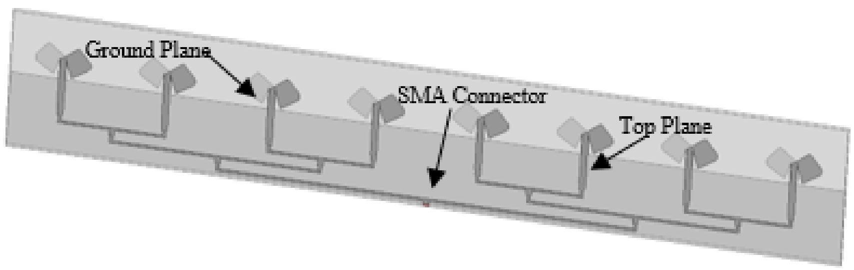

S Parameters (dB)
Frequency (GHz)
S11 Simulated
S12 Simulated
S13 Simulated
S14 Simulated


E Field [V/m]

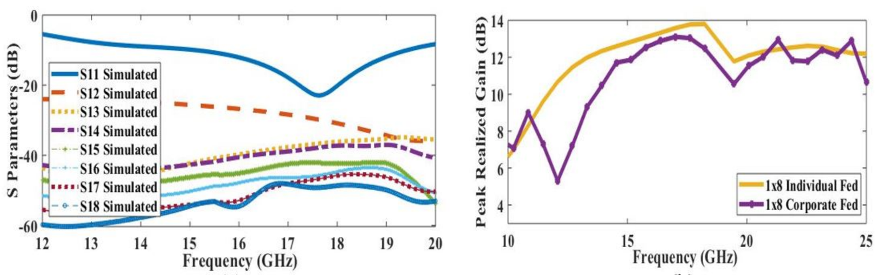

Return Loss (dB)
Frequency (GHz)
S11 Simulated
S11 Measured



Peak Realized Gain (dB)
Frequency (GHz)
1x4 Corporate Fed
1x4 Individual Fed

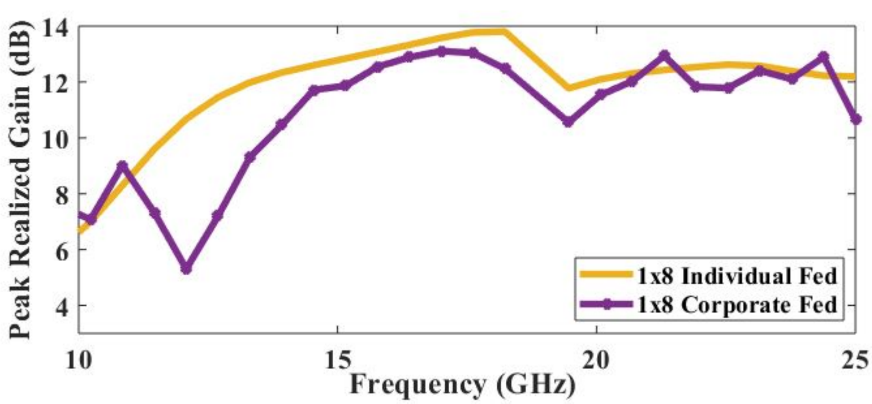


Ground Plane
SMA Connector
Top Plane

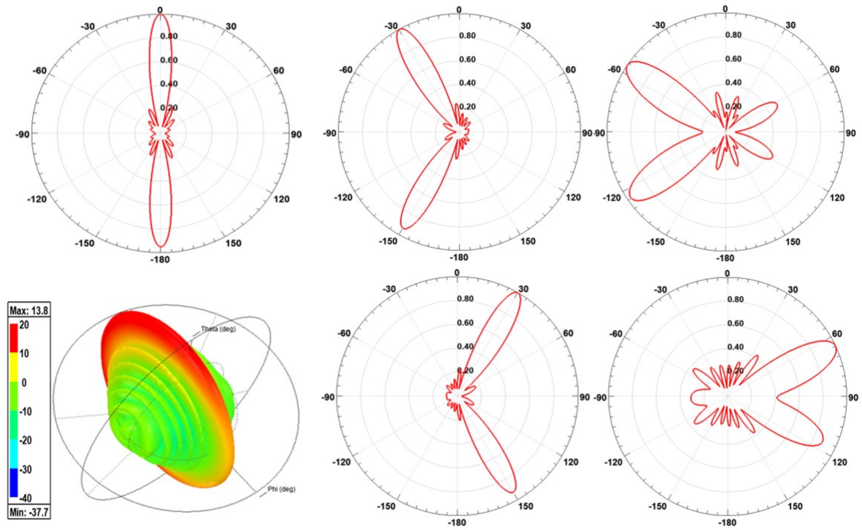


S Parameters (dB)
Frequency (GHz)
S11 Simulated
S12 Simulated
S13 Simulated
S14 Simulated
S15 Simulated
S16 Simulated
S17 Simulated
S18 Simulated
Peak Realized Gain (dB)
1x8 Individual Fed
1x8 Corporate Fed

(a) (b)



Peak Realized Gain (dB)
Frequency (GHz)
1x8 Individual Fed
1x8 Corporate Fed


Max: 13.8
20
10
0
-10
-20
-30
-40
Min: -37.7
Theta (deg)
Phi (deg)