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Design of a Compact Dual-Frequency Microstrip Antenna for Millimeter-Wave Applications

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ABSTRACT

A millimeter-wave (MMW) antenna has been proposed for a current and future wireless application. The proposed model has two resonances at 30.5 GHz and 52.4 GHz. The proposed model has been designed and optimized using a commercial electromagnetic simulator (CST-Studio) and focussed on attaining a return loss rate that is lower than -10 dB. The proposed MMW models were built on a small thick Rogers Substrate (RT-5880) with h = 0.508 mm for the thickness, relative permittivity of $\varepsilon r = 2.2$ and $\tan\delta = 0.0009$ for the loss tangent. In order to assure reliability, mobility and high efficiency, the proposed antenna has a small size, low profile and straightforward design structure. It can be employed for a variety of MMW applications e.g. wireless personal area network (WPAN) and 5G applications in some countries e.g. Colombia and Mexico. The proposed model has a moderate gain of 3 - 7 dBi at resonance frequencies of 30.5 GHz and 52.4 GHz, which is one of the unique characteristics of the proposed antenna. The impedance bandwidth is between 28.7 Ghz and 32.6 GHz, equalling to 3.9 GHz, and 49.7 - 56.2 GHz, which then is equal to 6.5 GHz respectively for the proposed model, and satisfying efficiency of about 75 % and 87 % as calculated by CST-Studio, and a VSWR equal to 1. All of these positive results are more than enough to satisfy the needs of MMW wireless applications.

1. Introduction

Microstrip patch antenna for millimeter-wave (MMW) communication systems has paid notable attention for meeting many requirements for present and future applications. These applications were represented by radars, security scanners, short-range wireless networks, higher band 5G networks and many other applications.

Compared to conventional 2.4 GHz or 5 GHz bands, the MMW license-free bands have unique features. These features place the suggested design at the top of the market for high bandwidth commercial wireless networks [1]. Countries all over the world have taken note of the 60 GHz radio license-free since it has shown to be valuable and high-quality [1-3].

Moreover, depending on the magnitude (5-30 dB/km) of the carrier frequency, the atmospheric conditions and common building materials [4,5], the signal can withstand an attenuation level of up

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to 20 dB in free space. There are several emerging 60 GHz standards, such as Wireless HD [6], the IEEE multi-gigabit mm wave 802.15.3c standards [6,7] and the standard ECMA-387 for high rate 60 GHz [8], that are popular for short-range wireless personal area networking (WPAN).

For MMW applications like radars, security scanners, short-range wireless networks and higher band 5G networks, there is a need for a small antenna size with a wideband and better antenna beam forming to achieve the needs of the MMW applications WPAN [9] and 5G applications in some countries e.g. Colombia and Mexico, which is planned for licensed use [10]. Therefore, the planar multiband antenna structures microstrip (MS), coplanar waveguide (CPW) and stripline (SL) have become very popular antennas due to their compact sizes, low cost, less weight and ease of installation with the current microwave wireless devices as compared to the conventional wire antennas (helical, yagi-Uda and spiral) [11-18].

Also, plenty of interest has been received in designing an efficient microstrip patch antenna (MPA) module to achieve the desired characteristics within the effective operating frequency of MMW systems [11-13]. In addition, the MS antenna configuration has superior advantages over the other planar structures of antennas, including easy fabrication and excellent compatibility with modern microwave circuits [11].

The design of the dual frequency MPA, which resonates at 30.5 GHz and 52.4 GHz, is presented in this study. There are various shapes available for the patches, e.g. elliptical, square, pentagonal, octagonal, circular ring, rectangular and etc. The rectangular form was selected because it has more benefits than other MS designs [19,20]. It is simple to perform fabrication analysis and performance prediction.

The proposed model has a rectangular shape with four edge slots in the patch's corners, this model also has a Defected Ground Structure (DGS), which is made up of an elliptical-shaped slot in the ground. In MS antennas, DGS and slots were used for the enhancement of gain and bandwidth, as a common example, they used some slots in the patch radiators [14]. Also, it has been used for higher mode harmonic suppression, mutual coupling between elements and to improve the characteristics of the MS antenna radiation [21]. Changing the current distribution on the ground because of the DGS is for improving the gain and the bandwidth of the proposed MPA. The model resonates at a dual band of frequencies of 30.5 GHz and 52.4 GHz with a fractional bandwidth of 12.7 % and 12 %, respectively, with a gain of 3.8 dBi and 6.6 dBi, the efficiency was 75 % and 87 % as calculated by the commercial electromagnetic simulator (CST-Studio), while VSWR approximately equal to 1.

In general, antennas with wide beam widths typically have low gain and antennas with narrow beam widths tend to have higher gain, so low gain and narrow bandwidth are the main limitations of MPA [22]. So, some techniques were presented in designing MS patches such as tapering techniques and DGS, to overcome these limitations.

The challenges of bandwidth against gain, efficiency and compact size were handled in this design, resulting in approved bandwidth combined with a good gain in this bandwidth as well as the antenna's small size, which is smaller than conventional patch antennas e.g. the ones which are proposed at [12] and [23].

2. Methodology

The CST-Studio was used for antenna parameter design and analysis. This simulation software was applied to display the analysis results in this study.

By selecting the dielectric constant ε_r, the width of the patch w_p and the length of the patch l_p, all the calculations have been done using the formulae given below [15]. The width of the patch w_p was determined using the Eq. (1),

$$w_p = \frac{c}{2f_r} X \sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

where, w_p = width of the patch, c = speed of light ($3*10^8$ m/s), f_r = resonant frequency and ε_r= dielectric constant of substrate. The effective dielectric constant ε_{reff} was determined by Eq. (2),

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1 + 12\frac{h}{W}]^{-0.5} \quad (2)$$

where, ε_{reff} = effective dielectric constant and h = thickness of substrate. The length of the patch was calculated as in Eq. (3),

$$l_p = L_{eff} - 2\Delta L \quad (3)$$

where, l_p = the physical length of the patch, L_{eff} = the effective length or the distance between the radiating edge and ΔL = fringing field. The effective length, L_{eff} was produced as in Eq. (4),

$$l_{eff} = \frac{c}{2f_r x\sqrt{\varepsilon_{reff}}} \quad (4)$$

The fringing ΔL was calculated as in Eq. (5),

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{\varepsilon_{reff}-0.258(\frac{W}{h}+0.8)} \quad (5)$$

2.1 Design of the antenna

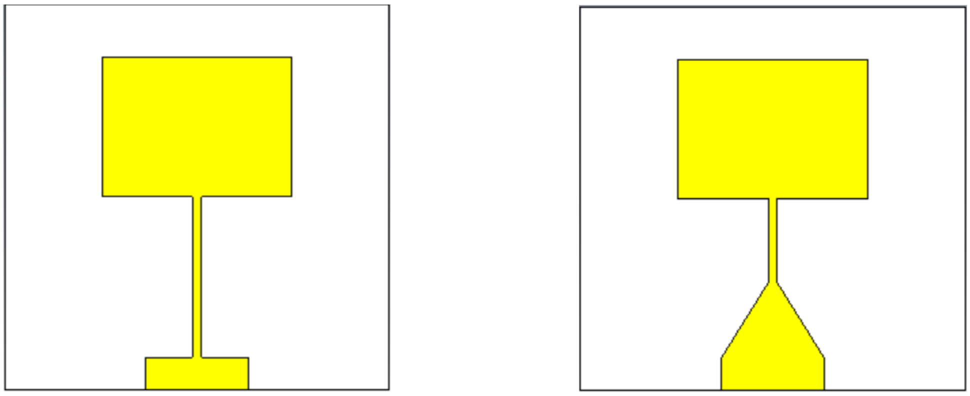
A substrate with a height of 0.508 mm from RT Duriod 5880 was used to simulate the suggested antenna design. The substrate was chosen due to its great performance, mechanical strength, light weight and ease of supply.

Applying the antenna to resonate at the desired dual frequency, which is about equivalent to 30 GHz and 52 GHz, requires using Eq. (1) to determine the patch's width, which is equal to 3.2 mm and equations (3), (4), (5) and (6) to determine the patch's length, which is equal to 2.15 mm.

The first design after mathematical calculations, and after adjusting the feeding port to 50 ohm with a feedline base length l_b of 0.5 mm and a feedline length l_f of 3 mm, is as shown in Figure 1 (a).

Using the tapering techniques for enhancing matched impedance is as shown in Figure 1 (b) after initial calculations to have a length of tapering l_t equal to 1.8 mm.

The final optimized design after final calculations is shown in Figure 2 with an optimized taper length l_{to} of 2.8 mm and this design will be adapted to achieve the final proposed model.



(a) (b)

Fig. 1. (a) First design with adjusted 50 ohm feeding port and (b) Second design with tapering feedline

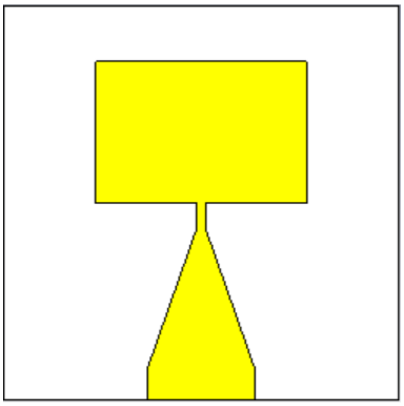


Fig. 2. The optimized design after final calculations

Before reaching the desired results of this work, two models were designed with the same main dimensions as the current proposed model, these two models were an initial step to reach the final results of the current proposed dual band model [24], except that the first model didn't have the DGS and the four edge slots as shown in Figure 3, while the second model has the four edge slots with different slots' dimensions and without DGS as shown in Figure 4.

The first previously proposed model covers a single frequency of 39.7 GHz with a gain of 6.6 dBi, an efficiency of 73.8 %, a VSWR equal to 1 and a fractional bandwidth of 6.8 %, while the second previously proposed model covers a single frequency 43 GHz with a gain of 6.6 dBi, efficiency of 78 %, a VSWR equal to 1 and a fractional bandwidth equal to 7.2 % [24].

Figure 5 shows the first model after fabrication and due to the compactness of the design, there were some difficulties in measurements because of lack of compatible connector to the compact design (the connector was wider than the width of the designed model).

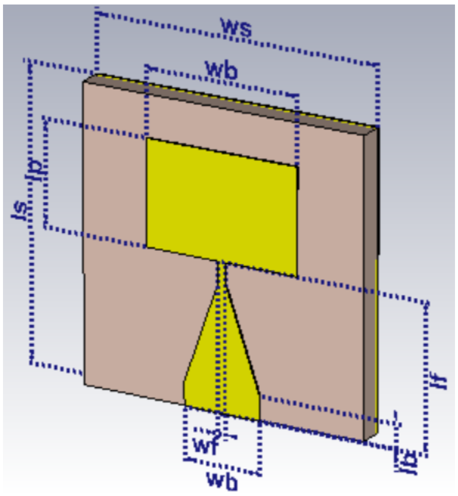


Fig. 3. First model without corner slots

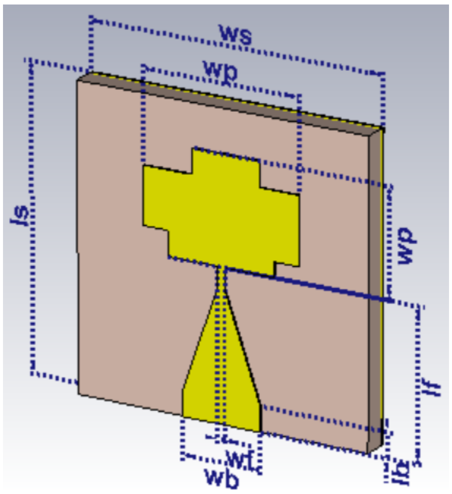


Fig. 4. Second model without DGS

Fig. 5. First model after fabrication

According to Figure 6, the suggested antenna comprises of three layers, which are a ground, a dielectric and a patch layer. Both the ground and the patch layers were comprised of copper as a conducting lossy material. After final optimization, the main proposed MMW patch antenna is depicted in isometric form in Figure 7. The rectangular patch had a length of l_p and a width of w_p . It was designed on an RT 5880 substrate with relative permittivity ε_r, loss tangent tanδ of value 0.0009 and thickness h. The substrate had a width w_s and a length l_s. The antenna was fed through a slot of length l_b and width w_b. The tapering of the transmission line had a length l_t to improve the matching of the impedance between the transmission line and the patch, which then improved bandwidth and gain respectively. DGS was utilised to further improve gain, bandwidth and impedance.

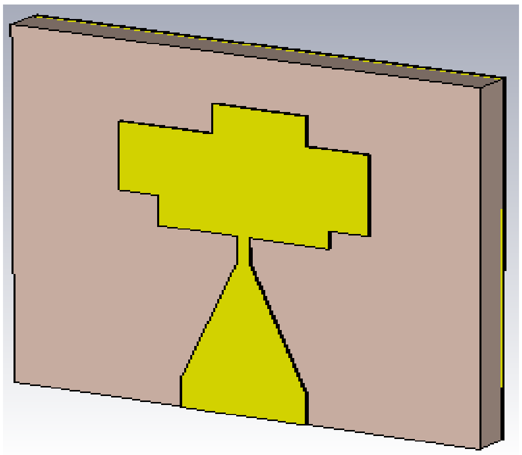


Fig. 6. Proposed model isometric front view

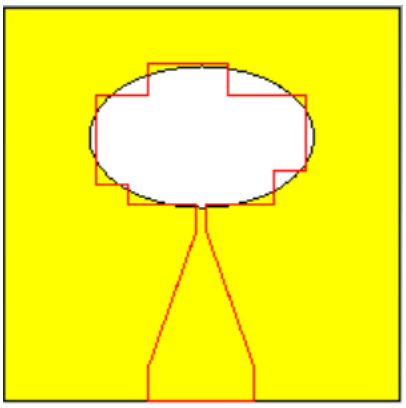


Fig. 7. Proposed model back view

The optimized desirable parameters for the model are provided in Table 1 after the optimization of the parameters was completed in the CST-Studio to acquire the desired frequencies.

For the current dual band proposed model, Figure 8 shows the geometric view of the antenna, which had dimensions of 0.6 λ_o x 0.6 λ_o, while Figure 9 shows the elliptical defected ground structure geometry and position.

Table 1
Antenna parameters

Symbol	Parameter	Dimensions (mm)
w_s	Substrate width, & ground width	6
l_s	Substrate length, & ground length	6
w_p	Width of patch	3.2
l_p	Length of patch	2.15
w_f	Feed Width	0.145
l_f	Feed Length	3
h	Substrate higth	0.508
ε_r	Dielectric Constant	2.2
w_b	Feedline base width	1.613
l_b	Feedline base length	0.5
l_t	Taper length before optimization	1.8
l_{to}	Taper length after optimization	2.8
t	Ground and patch thickness	0.035
w_{cpr}	Upper right slot width	0.8
w_{cpl}	Upper left slot width	1.2
l_{cpu}	Upper slot length	0.5
l_{cpr}	Lower right slot length	0.3
l_{cpl}	Lower left slot length	0.5
w_{cpll}	Lower slot width	0.5
R_u	U radius of DGS	3.4
R_v	V radius of DGS	2.2

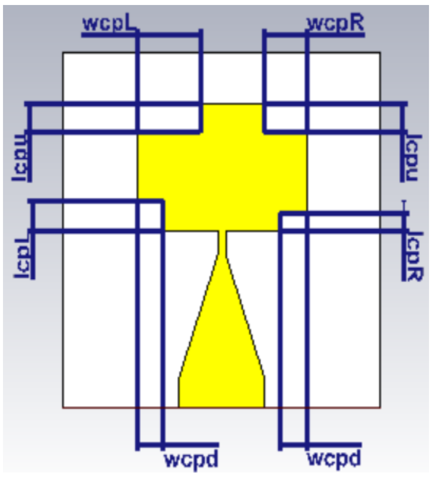


Figure 8. Geometric view of the proposed patch antenna.

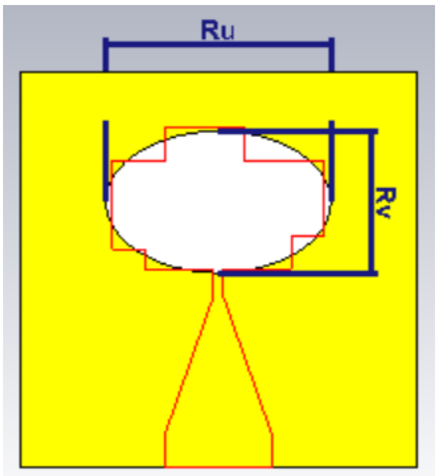


Figure 9. Geometric view of the elliptical defected ground structure

3. Results and Discussion

The below results were measured using the CST-Studio in which the calculated results were return loss, bandwidth, gain, efficiency, VSWR, current distribution and radiation pattern.

Figure 10 shows the return loss of the initial designs. Curves (a) and (b) show the return loss during the steps of optimization and curve (c) shows the return loss after final optimization of the first initial model, while Figure 11 shows the return loss of the first and second initial model after adding the four edge slots.

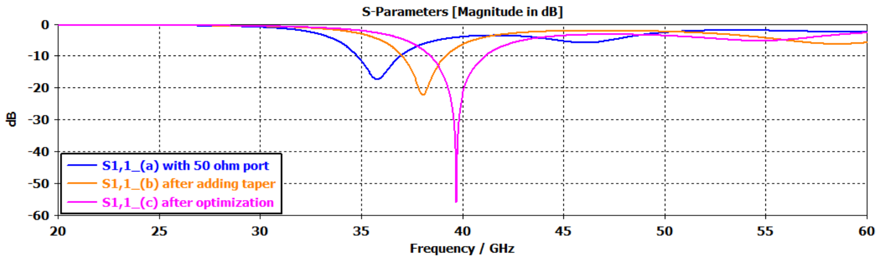


Fig. 10. Return loss of the initial designs

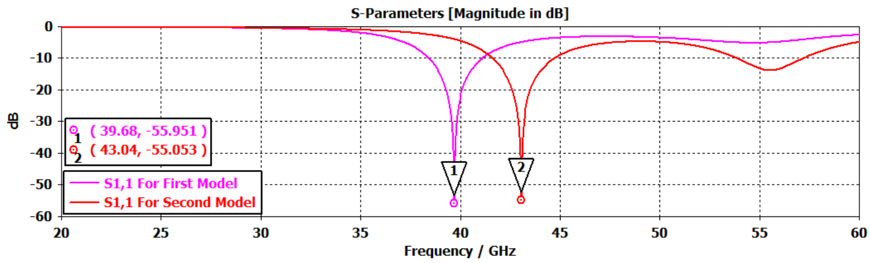
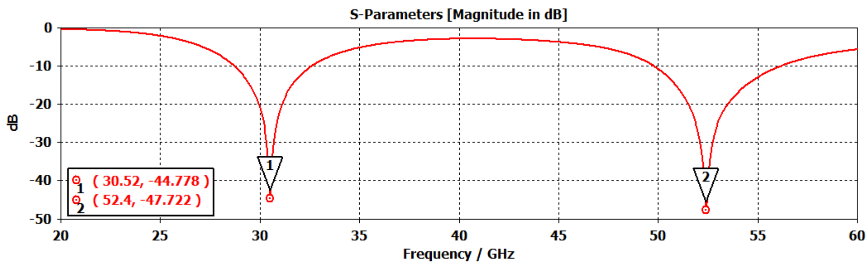


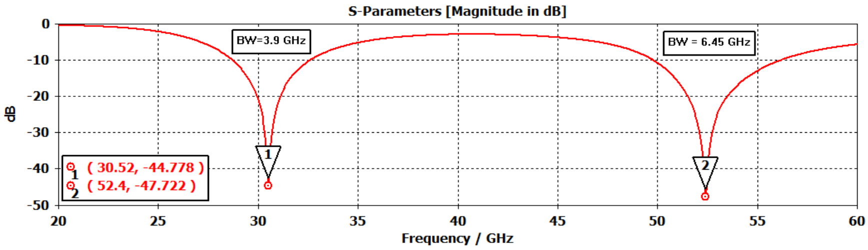
Fig. 11. Return loss of the first and second proposed models

Figure 12 however depicts the simulation results for the recently dual band proposed model. Figures 12 (a) and (b) depict the return loss and bandwidth of the suggested design. These values for the return loss were -44 dB and -47 dB, respectively. The proposed design achieved an adequate bandwidth between 28.7 GHz and 32.6 GHz, which was equal to 3.9 GHz for the first resonant frequency, and 49.7 - 56.2 GHz, which was equal to 6.4 GHz for the second resonant frequency.

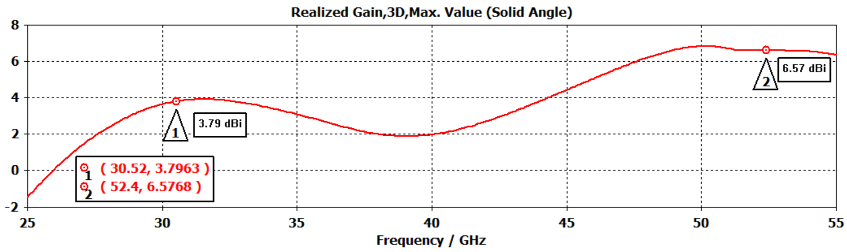
In Figure 12 (c), the suggested antenna offered a gain of 3.8 dBi for the first resonant frequency and 6.6 dBi for the second resonant frequency with a consistent directional radiation pattern. Figure 12 (d) shows a very sufficient efficient proposed model, which was equal to 75 % and 86.8 %, respectively. Figure 12 (e) then shows the proposed design that had an accurate optimal VSWR value of 1 at the resonant frequency of 30.5 GHz and 52.4 GHz.



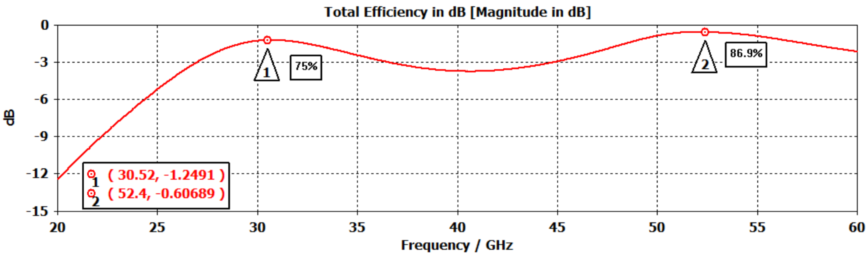
(a) Return loss for the proposed model



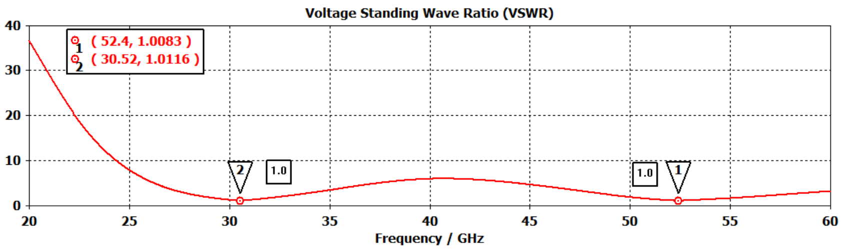
(b) Bandwidth for the proposed model



(c) Gain for the proposed model



(d) Efficiency of the proposed model

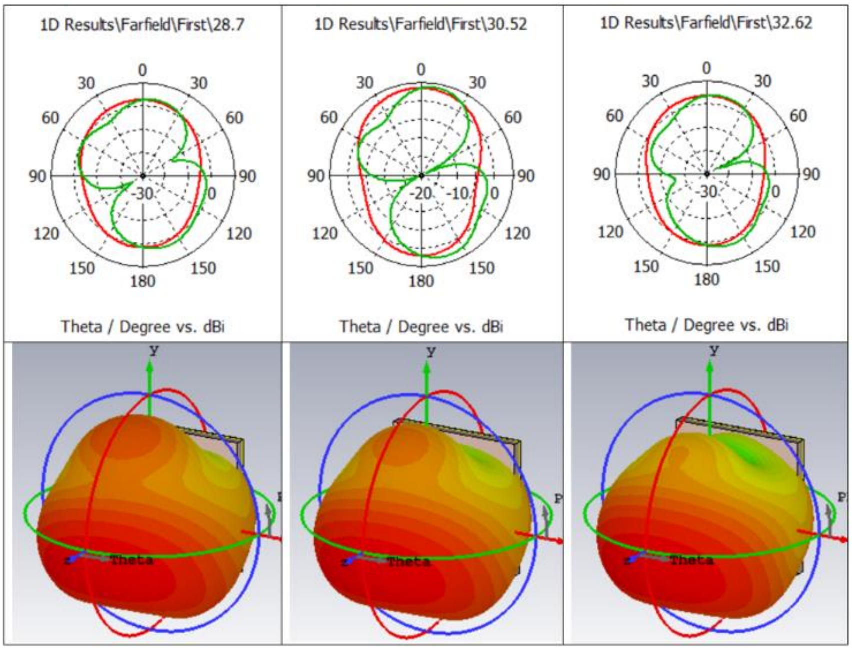


(a) VSWR of the proposed model

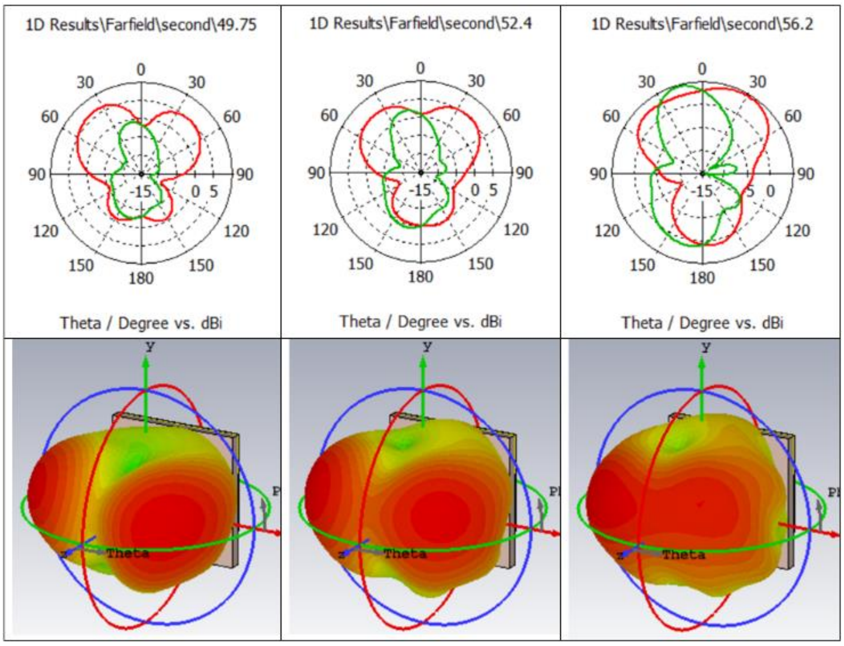
Fig. 12. Simulated results at CST

Figure 13 (a) depicts the suggested design's steady, uniform and omni-directional radiation pattern. Furthermore, it displays the 3D pattern of the suggested model as well as both situations of Phi 0 degree and Phi 90 degree.

Figure 13 (b) shows a uniform directional radiation pattern with very smooth radiation where all beams were equally in the same wide directional position, which indicated increased spectral efficiency.



(a) The proposed antenna’s 30.5 GHz pattern

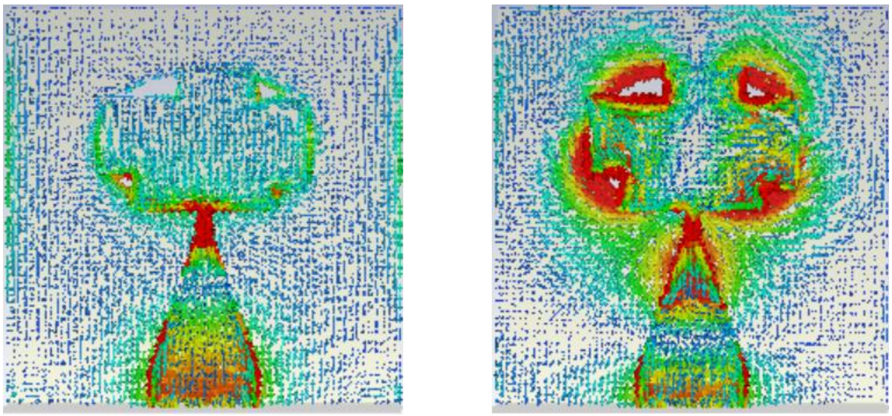


(b) The proposed antenna’s 52.4 GHz pattern

Fig. 13. Polar and 3D radiation pattern for the whole bandwidth of the proposed model

Generally, it can be seen clearly in both cases where Phi is 0 degree and Phi is 90 degrees. The antenna exhibits a stable radiation pattern with no back and side lobes in the range of the proposed targeted resonant frequencies.

The surface current distribution at 30.5 GHz is shown in Figure 14 (a), while Figure 14 (b) depicts the current distribution along the patch at 52.4 GHz. It can be seen that the current density was high on the feed line at both frequencies, while on the outer edge of the rectangular patch antenna was at frequency 52.4 GHz.


(a) (b)
Fig. 14. Current distribution along the patch (a) 30.5 GHz and (b) 52.4 GHz

5. Conclusions

A dual frequency compact-sized MMW high-efficiency and high-gain MPA were presented. Using the RT Duriod 5880 substrate, the design and analysis of the model of MPA were simulated. A tapering fed line structure was designed to improve the matched impedance to enhance the gain, while using DGS for bandwidth, gain and efficiency enhancement. The proposed model resonates at 30.5 GHz and 52.4 GHz with gain of 3.9 dBi and 6.6 dBi, respectively, which is suitable for MMW applications in many countries e.g. WPAN and 5G applications in some countries e.g. Colombia and Mexico. The proposed models have an impedance bandwidth of 3.9 GHz and 6.5 GHz for both frequencies. A good agreement can be obtained due to the model's efficiency, which was around 75 and 87 %, respectively for both resonance frequencies.

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