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Original Article

A Dual-Band Dielectric Resonator Antenna with T-Shaped Ground Plane Slots for Millimeter-Wave Applications

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Abstract *- This paper presents the design and analysis of a dual-band rectangular Dielectric Resonator Antenna (DRA) operating in millimeter-wave frequencies. The dual-band operation is realized by introducing T-shaped holes in the ground plane, enabling the antenna to operate effectively from 29.8 GHz to 31.6 GHz for the lower band and 36.7 GHz to 40.9 GHz for the upper band. Simulated using CST Studio, the antenna features a high-permittivity dielectric material with dimensions of 10 mm × 1.95 mm × 1.00 mm, complemented by Rogers RT/duroid 5880 substrate and a ground plane designed to enhance signal transmission while minimizing interference. The antenna achieved resonance frequencies at 30.6 GHz and 37.8 GHz, with bandwidths of 1.88 GHz (6.12%) for the lower band and 4.18 GHz (10.76%) for the upper band. The antenna achieved return losses of –30.8 dB and –50.3 dB for the respective bands and high gains exceeding 7 dBi, critical for effective Millimeter Wave (mmWave) communications. The antenna efficiency reached 88% and 95% in the lower and upper bands, respectively, with a Voltage Standing Wave Ratio (VSWR) of 1, an indication of excellent impedance matching. The antenna exhibited broadside radiation pattern, making it suitable for applications in satellite and wireless communications, radar systems and 5G technologies.*

Keywords *- DRA, Millimeter wave frequencies, Dual-band, T-shaped ground holes.*

1. Introduction

Over the past three decades, the exponential growth of telecommunications, especially with the evolution of wireless communication, has led to a sharp increase in the amount of data used by an average person [1]. The rise of wireless devices such as the Internet of Vehicles (IoV), e-Health, smart education, smart cities, VR, smart factories have driven advancements in communication networks, with past technologies such as 4G LTE successfully addressing the need for high data rates and throughput. However, for future 5G systems [2] and other wireless applications, millimeter wave (mmWave) communication [3] is emerging as the preferred technology due to its extremely high data rates, large transmission capacity and enhanced security [4]. To maximize these advantages in wireless communication, DRA is the best choice as the radiation medium. The Dielectric Resonator Antenna (DRA) has evolved since the 1950s, when Mei and Southworth proposed dielectric materials for microwave applications [5]. In the 1980s, Luk's cylindrical DRA demonstrated compact size and high efficiency [6]. During the late 1980s and early 1990s, Makimoto and Yamashita developed rectangular DRAs, with enhanced bandwidth and ease of integration [7]. Their work stimulated diverse DRA configurations, such as hemispherical, cylindrical, and conical, in the 1990s, allowing wideband and multiband capabilities for various applications [8]. Numerous studies have since been carried out on DRA feeding techniques, materials, coupling mechanisms, configurations, among others [5]. These investigations have sought to optimize antenna performance metrics, including bandwidth, gain, radiation patterns, and frequency tunability. Despite these advancements in DRA research, limited attention has been given to the realization of dual-band performance in single-element DRAs by incorporating slots into the ground plane. This approach presents a compact, structurally straightforward, and potentially effective strategy for achieving dual resonance without the need for additional radiating elements or complex feeding networks. The Dielectric Resonator Antenna (DRA) has become a favored choice for millimeter-wave communication due to its high radiation efficiency, broad bandwidth, small size, flexibility and cost-effective production. With high radiation efficiency compared to traditional metallic antennas [9], DRAs ensure very good signal transmission across high-frequency networks, making them well-suited to the demands of 5G. Their design flexibility allows for simultaneous multi-band and wideband operation, accommodating the diverse frequency requirements of 5G communication. Furthermore, DRAs are made from low-cost materials, making mass production cost-friendly, hence satisfying the scalability needs of millimeter-wave applications [10]. DRAs can be of circular, triangular or rectangular design [11], but rectangular DRAs are most preferred [12] due to their superior design flexibility. They are defined by three independent geometric dimensions of length, width, and height, giving room for greater freedom of flexibility, allowing optimized designs for specific applications. Compared to cylindrical DRAs, rectangular DRAs offer lower cross-polarisation levels[13], enhancing signal strength and efficiency.

Their compact form factor and capacity to support multiple frequency bands make them ideal for modern communication systems, especially in millimeter wave applications like 5G technology. Current research is primarily focused on developing compact multiband antennas [14] that can accommodate a variety of applications. In dual-band operation, the antenna is designed to resonate and radiate effectively at two distinct frequencies within the mmWave range. This capability is advantageous for applications that need to support multiple frequency bands, such as 5G or radar systems, which often require operation across different channels or bands. Dual-band Dielectric Resonator Antennas (DRAs) that involve multiple DRAs with single feeds have been reported. In [1], a 1 × 4 DRA array operating in lower band of 13.3–19 GHz and upper band of 36.3–40 GHz is presented. It achieved an impressive gain of 10.6 dBi and 14.2 dBi, respectively.

In [15], two cylindrical dielectric resonators were integrated to generate two distinct resonant frequencies at 2.4 and 28 GHz. The realized gains were 6.3 and 12.1 dBi, respectively. In [16], a hybrid ring DRA for C/X/Ku-band communication achieved a dual-band circular polarization over the frequency ranges of 8.22 to 9.53 GHz and 12.29 to 13.71 GHz. The above array systems are complex to design and costly for mass production. Current research is focused majorly on single DRAs that produce dual-band through various feeding methods, such as coaxial probe excitation [2], microstrip slot coupling [3], [17]–[18], and coplanar waveguide (CPW) [19] schemes, successfully achieving dual-band functionality while maintaining compactness and versatility for diverse applications. Another technique that has been reported to have achieved dual-band is multimode excitation [12], where DRAs operating in mmWave frequencies were proposed to operate in the higher-order TE_{115} and TE_{119} modes. In [20], a combination of cross-shaped DRA fed by a U-shaped microstrip power divider achieved dual resonance in the sub-6G band. This approach, however, suffers from increased design complexity, especially impedance matching issues. Shape modification of the DRA is the common method of achieving dual-band radiation. In [21], Isosceles-Right-Triangular DRA achieved a dual bandwidth with high isolation; however, the gain was low. In [18], a compact wide dual-band square DRA achieved resonance at lower frequencies of 8.65 GHz and 11.08 GHz. The gain was also lower under 7dBi. A dual-band stacked Dielectric Resonator Antenna operating in the K/Ka-band is presented in [22]. It featured 10-dB impedance bandwidths above 6%. This stacking complicates the impedance matching and the overall antenna design. Previous research on dual-band DRAs, such as those enlisted above, primarily focused on approaches like shape modification of the DRA, feeding mechanisms, and the use of multiple arrays to achieve dual-band operation. These techniques are complex to design and fabricate, non-compact and potentially inefficient. Employing slots in the ground plane for dual-band radiation offers clear advantages in terms of design simplicity, effective mode excitation, independent band control and compactness. To date, no single-element, single-fed DRA has achieved dual-band radiation in the mmWave range through ground plane modifications, such as the introduction of holes. Moreover, no reported research has demonstrated this approach achieving high gains exceeding 7 dBi in bands, while preserving the typical DRA benefits of high efficiency and compact size.

This paper proposes the introduction of holes in the ground plane of the DRA to achieve high gain, dual-band radiation at mmWave frequencies. The dual resonance is achieved by introducing two T-shaped holes in the ground plane. The slots in the ground plane act as secondary radiators, creating an additional resonant path that contributes to the overall dual-band response of the antenna. The operating frequency of the antenna starts from 29.8 GHz to 31.6 GHz for the lower band while the upper band covers 36.7 GHz-40.9 GHz. The proposed DRA was simulated using CST Studio and various antenna parameters e.g. return loss, gain, radiation pattern, VSWR and efficiency were measured. The proposed antenna can be used in various mmWave applications, including satellite communications, radar systems and 5G.

2. Methodology

The antenna is made up of a dielectric material, substrate and ground plane. The DRA is placed on a ground plane above the substrate as shown in Fig.2. The substrate sits above the feed network consisting of ground plane with T-shaped holes and the feed line. The dielectric material is of high permittivity of 12 and is positioned above the ground plane to excite the dominant mode. The high permittivity results in overall compact size and concentrates the electric fields within the material, resulting in desirable high gain and directivity. The dielectric component is of dimensions 10 mm × 1.95 mm × 1.00 mm and has a low loss tangent of 0.0002. The dimensions of the DRA are given by the equation (1) below [19]:

$$f_0 = \frac{F_c}{2\pi a\sqrt{\varepsilon_r}} \tag{1}$$

Where f_0 is the resonance frequency, F_c is a mode-specific constant, which depends on field distribution and mode geometry of the DRA a is the effective dimension of the DRA, ε_r is the relative permittivity of the dielectric material used. The resonating frequency, f_0, for a rectangular dielectric resonator can be calculated from the following equations [23]:

$$k_x tan\frac{k_x d}{2} = \sqrt{(\varepsilon_r - 1)k_0^2 - k_x^2} \tag{2}$$

Where,

$$k_0 = \frac{2\pi}{\lambda_0} = \frac{2\pi f_0}{c} \tag{3}$$

And

$$k_y = \frac{\pi}{w} \; and \; k_z = \frac{\pi}{b} \tag{4}$$

And

$$k_x^2 + k_y^2 + k_z^2 = \varepsilon_r k_0^2 \tag{5}$$

In this context, k_0 represents the wave number in free space, while K_x, K_y, and K_z refer to the wave numbers in the x, y, and z directions, respectively. By solving these equations iteratively in MATLAB and CST Studio, the finalized dimensions were arrived at, ensuring resonance at the targeted frequencies. The substrate used is the readily available Rogers RT/duroid 5880(tm) of permittivity of 4 and measures 16.60 mm × 13.08 mm × 0.51 mm, designed to provide mechanical stability and support. The ground plane measures 10.36 mm × 9.76 mm. The bottom of the antenna is the feed network consisting of a ground plane with cut-off T shapes connected to a microstrip feedline. The dimensions of the microstrip feedline are 4.78 mm × 1.21 mm and is designed to match the impedance of the antenna system to 50 ohms, while the T-shaped cut-outs are 5.03 mm × 2.51 mm. The dimensions of the slots were obtained through parametric optimization in CST Studio software, varying the length and width to achieve desired impedance matching and dual-band resonance behavior. The flowchart below in Figure 1 summarizes the design process of the antenna.

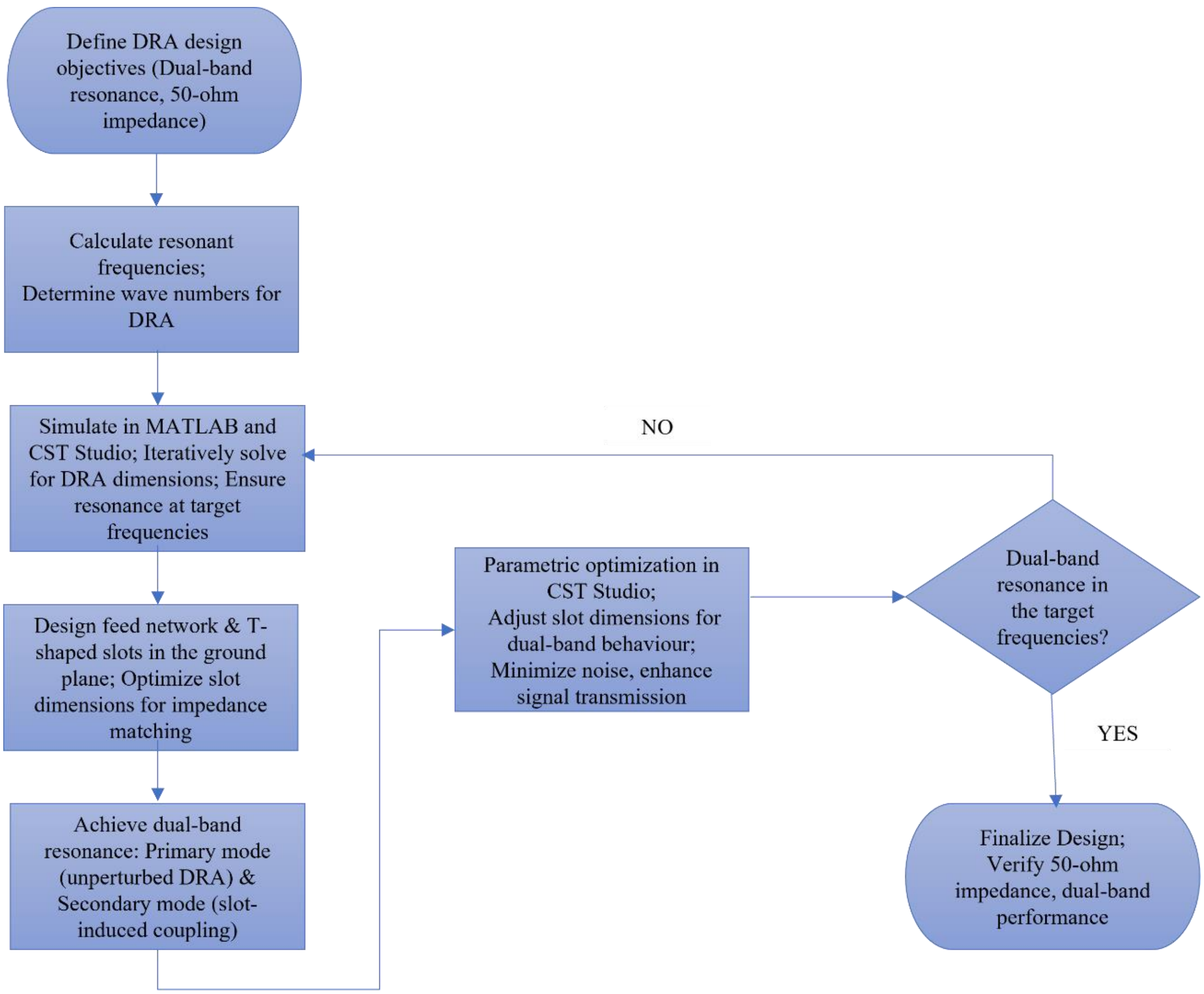

Fig. 1 Flowchart on the design process

The DR is placed above the ground plane to enhance signal transmission while suppressing noise and interference. The T-slots in the bottom feed network make the antenna achieve dual-band radiation. The ground plane slots disrupt current paths, altering the effective permittivity and impedance experienced by the antenna, which shifts resonant frequencies and facilitates mode splitting, thus achieving dual-band excitation [10].

The effective permittivity can be approximated by equation (6) below:

$$\varepsilon_{eff} = \varepsilon_r \left(1 - \frac{V_{holes}}{V_{total}}\right) \tag{6}$$

Where V_{holes} is the volume of the holes and V_{total} is the total volume of the ground plane material. These slots cause a perturbation in the field distribution, yielding two resonant modes [1]: the primary one caused by unperturbed DRA and secondary one due to modified boundary conditions and coupling caused by the slots. The frequency ratio between the two bands can be approximated by equation (7) below:

$$Z_{modified} = Z_0 \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} \tag{7}$$

Where Z_0 is the impedance without slots and μ_{eff} is the effective permeability. Figure 2 illustrates the top view of the design, while Figures 3 and 4 show the bottom and side views of the antenna, respectively.

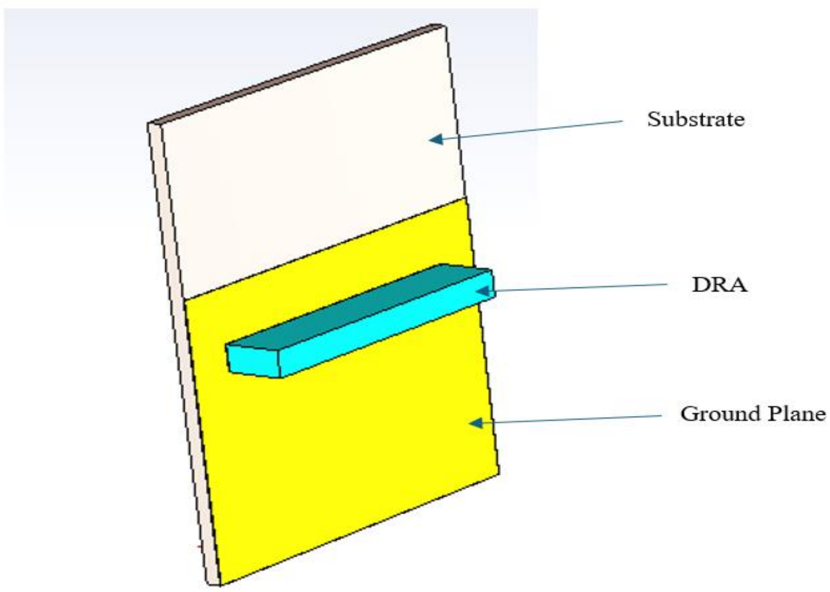

Fig. 2 Top of the DRA

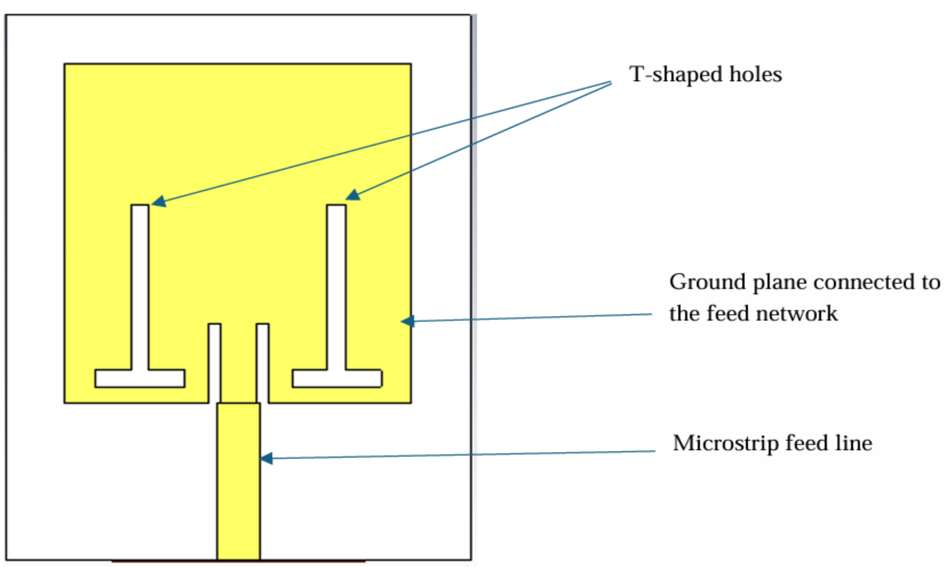

Fig. 3 Bottom of the DRA

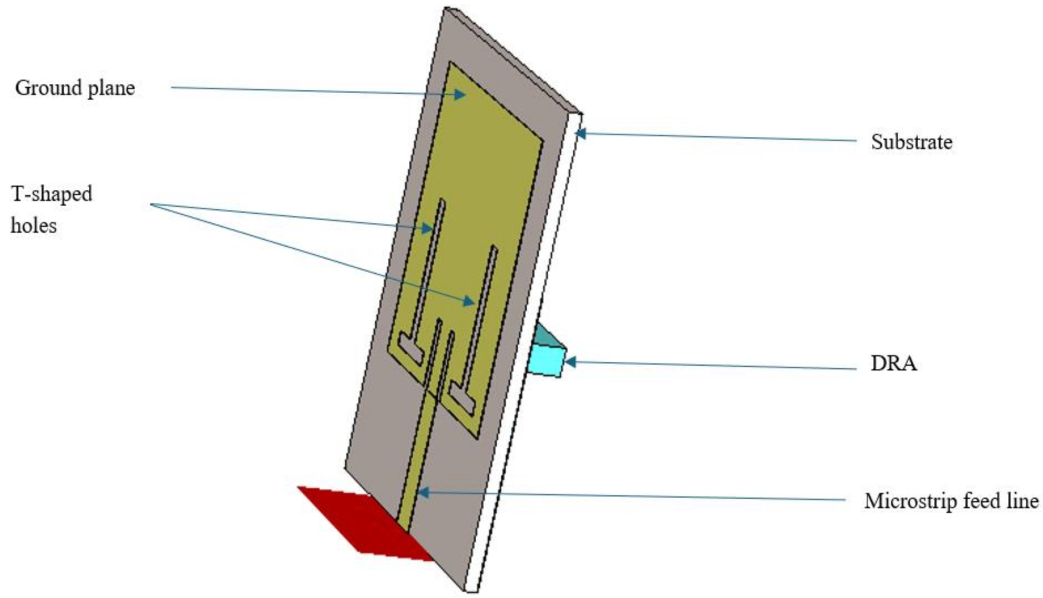

Fig. 4 Side view

3. Results And Analysis

The antenna achieved dual band resonance at 30.6 GHz and 37.8 GHz as shown in Figure 5. The antenna achieved high bandwidth with the lower band being 1.88 GHz, equivalent to 6.12% and that of the upper band is 4.18 GHz, which is an impressive 10.76%. These wide bandwidths can support high data rates and accommodate some of the 5G frequency spectrum. The return loss for the first frequency band is –30.8 dB, while the upper band is –50.3 dB. This is far more excellent compared to [24] which achieved dual-band by stacking two DRAs, achieving return loss of –20 dB and –28 dB in the upper and lower bands respectively. The low return loss shows that most of the input power is radiated, enhancing overall efficiency. This makes the antenna ideal for mmWave communication, where energy efficiency is paramount. Antenna gain is the ratio of the power transmitted or received in the direction of peak radiation compared to the power transmitted or received by an isotropic antenna, which radiates uniformly in all directions. The designed antenna achieved a high gain of above 7 dBi in the resonating frequencies. This high gain is particularly important in mmWave communications, where signals are susceptible to path losses due to their shorter wavelengths. The high gain was achieved due to high efficiency and directivity. The graph below shows the plot of maximum gain versus frequency.

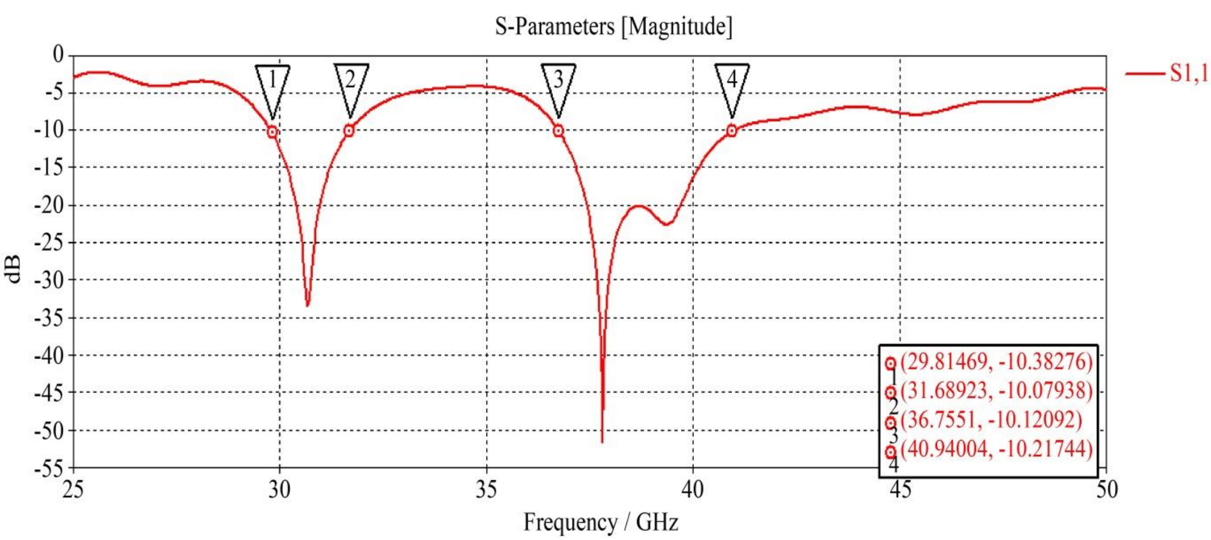

Fig. 5 Return loss Vs. Frequency

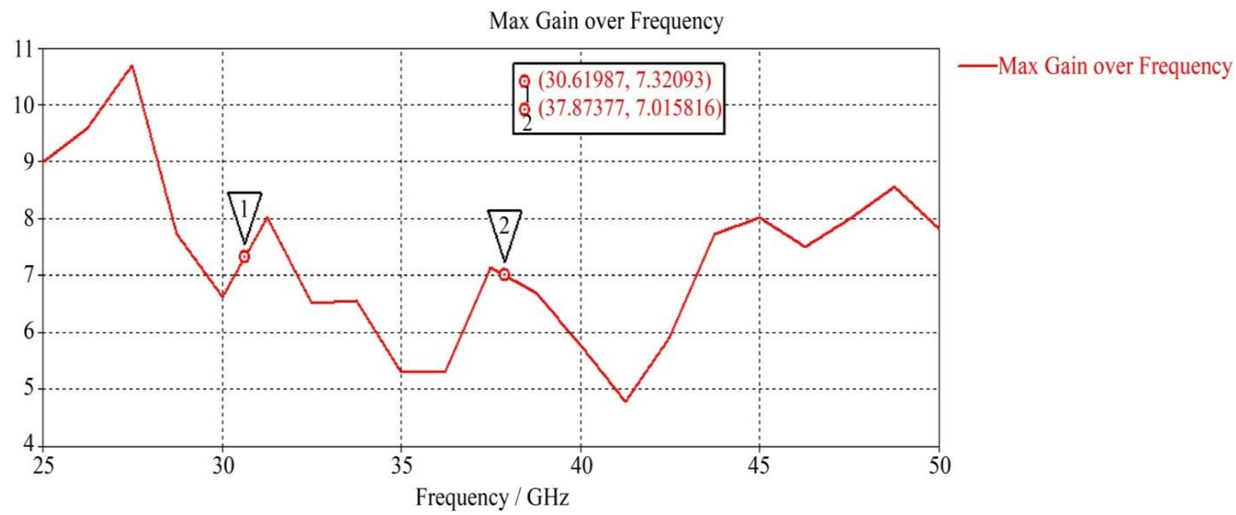

Fig. 6 Max. Gain over frequency

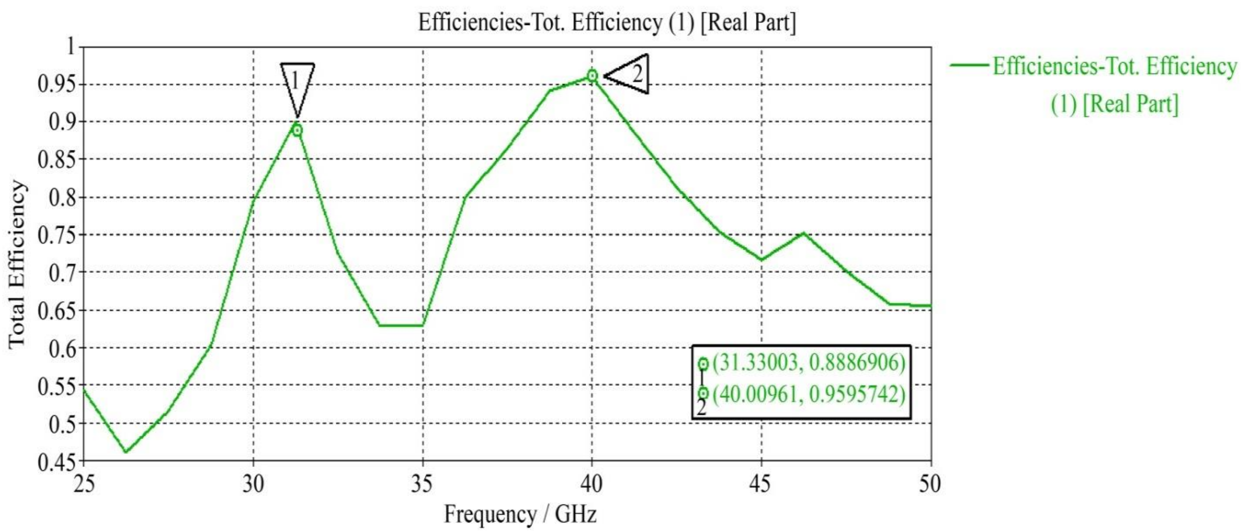

Fig. 7 Total efficiency

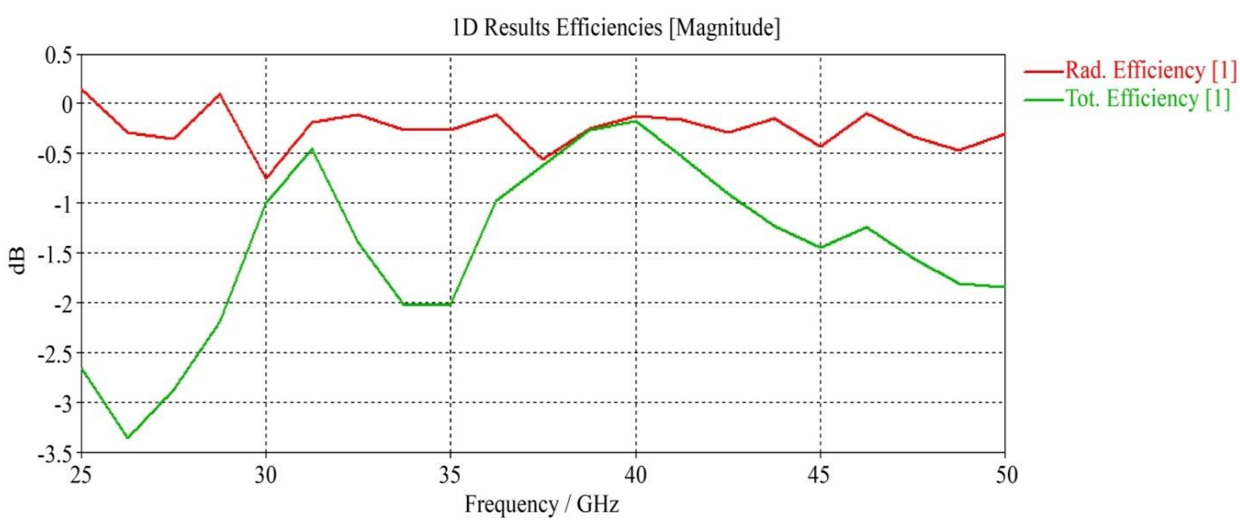

Fig. 8 Radiation efficiency and Total efficiency

Antenna efficiency measures how well an antenna converts input power into radiated electromagnetic energy. Being a DRA, and unlike microstrip patch antennas, the designed antenna does not suffer from significant ohmic losses in conductors, making it attain high efficiencies. The antenna achieved efficiencies of 88% and 95% in the lower and upper frequency bands respectively, outpacing a 1 × 5 array in [25], which achieved 83% and 78% in its lower and bands respectively. The graphs below illustrate the efficiency of the antenna.

The antenna achieved a VSWR of 1 in both bands, as shown in Figure 9 below. This excellent ratio was achieved due to the good impedance match, implying efficient energy radiation and good suppression of reflected power. The designed antenna achieved a broadside radiation pattern. This makes the design ideal for broadcasting, cellular wireless communication and ground-based radar systems. The 2D and 3D radiation patterns of the antenna at the two resonant frequencies are shown below, showing the antenna's radiation properties.

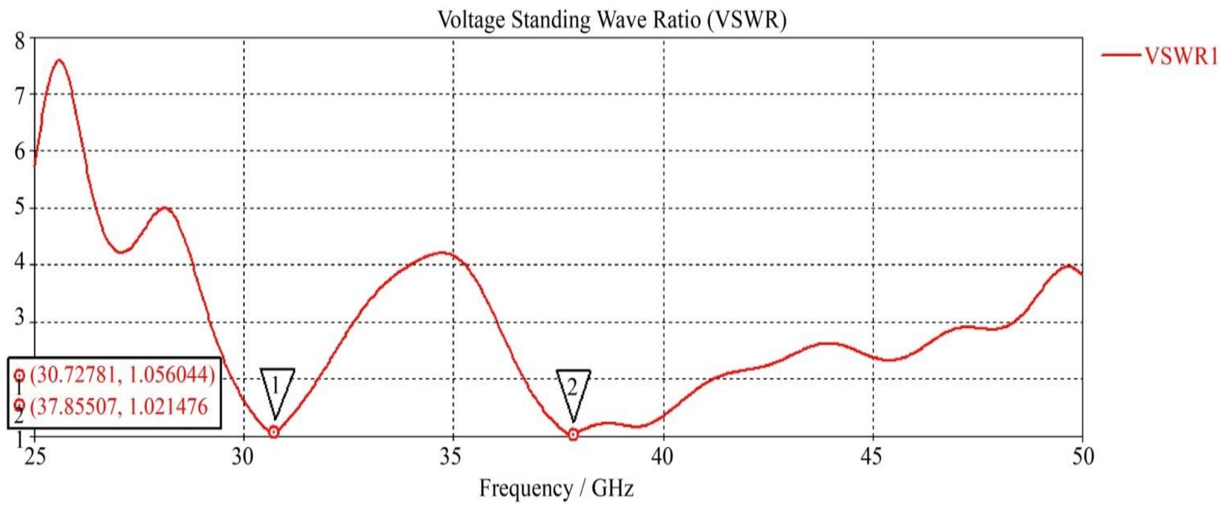

Fig. 9 VSWR

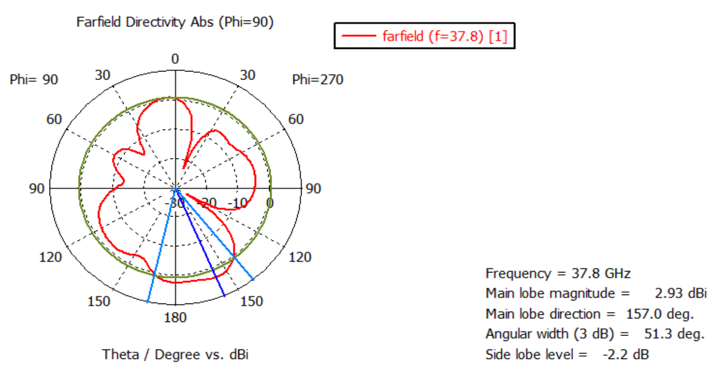

Fig. 10 2D radiation pattern at 37.8GHz

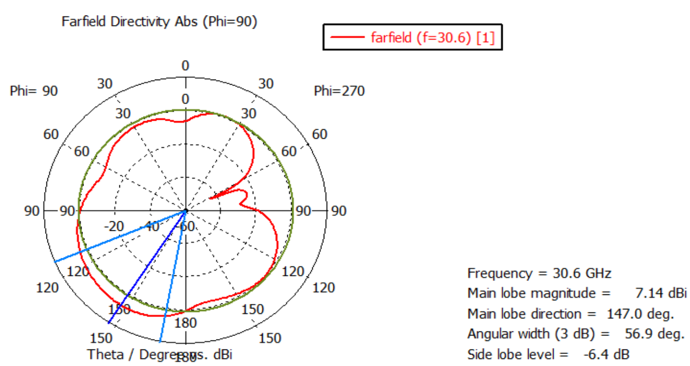

Fig. 11 2D radiation pattern at 30.6GHz

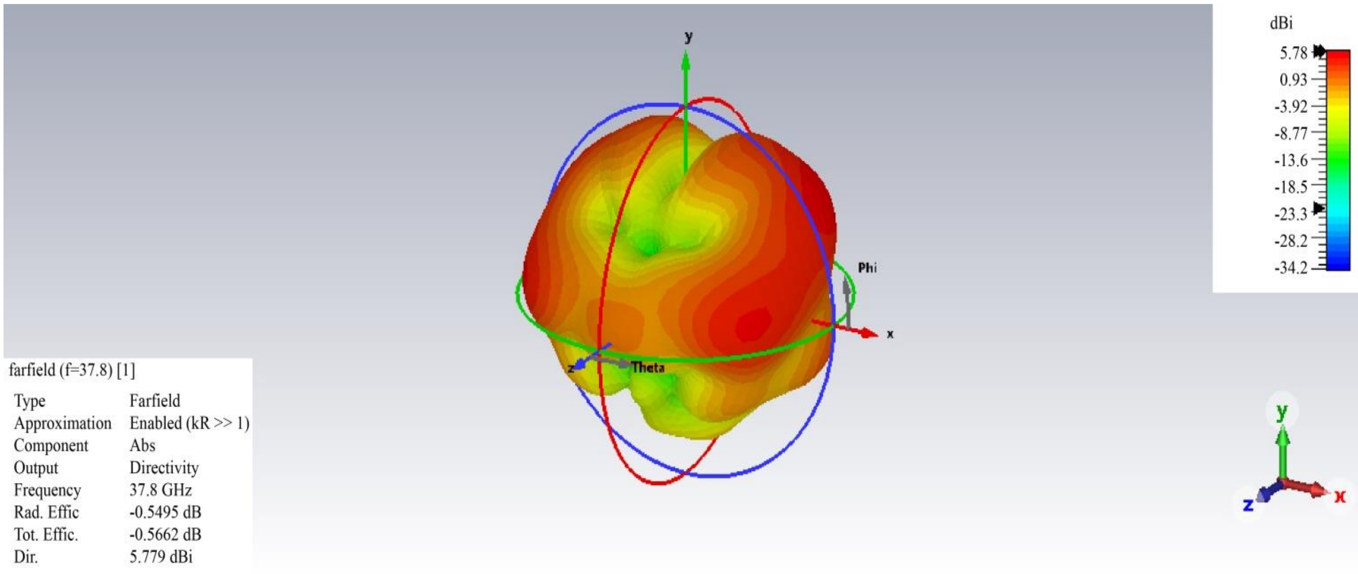

Fig. 12 3D radiation pattern at 37.8 GHz

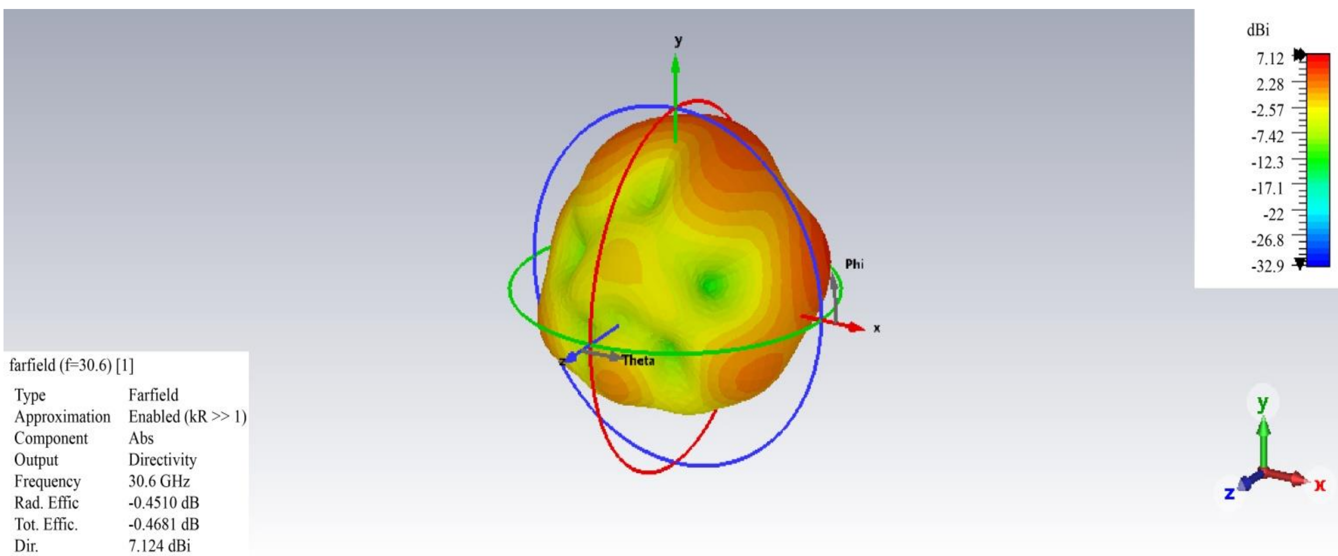

Fig. 13 3D radiation pattern at 30.6 GHz

Table 1 below summarizes the performance metrics of the proposed design.

Table 1. Summary of the antenna's metrics

Parameter	Industry Standard	Proposed Design	Significance
Gain	6-10 dBi	>7 dBi	Critical for overcoming path loss
Return Loss	<-10 dB	<-30 dB	Indication of good impedance matching, maximizing power transferred to the antenna
Efficiency	>80%	>88%	Minimum losses
VSWR	<2	1	Reduced reflected power

While the design achieved impressive performance, further work can be done to improve the individual band Fractional Bandwidth (FBW) and to further improve efficiency in the lower band. Table 2 below presents comparative study between the proposed design and other state-of-the-art dual band DRA designs.

The proposed antenna design stands out from its counterparts due to its superior balance of efficiency, gain, and dual-band performance. This design excels in simplicity, performance and adaptability because of the innovative T-shaped slot design and the choice of materials and proper impedance matching.

Table 2. Comparison with previous dual-band DRA

Reference	Frequency (GHz)	Bandwidth (%)	Gain(dBi)	Efficiency (%)	Dual-band Tech	Antenna configuration
[1]	16.1/38.1	35.3/9.7	10.6/14.2	80/82	Multimode excitation	1 ×4 array
[4]	18.85/31.05	11.4/6.2	6.5/7.8	95/94	Patch and DR integration	1 element
[11]	2.45/5.64	3.3/5.7	3/3.5	>82	Parasitic c-slot	1 element
[17]	5.7/8.1	4.3/5.8	5.8/6	>98	Slot integration	1 element
[20]	3.5/4.85	11.4/6.2	Not stated	Not stated	U-shaped microstrip power divider	1 element
[24]	3.75/28	14.1/11.5	5.9/8	86/90.5	Two radiating structures	1 × 2 array
[25]	28/39	14.11/12.56	6.8/6.4	>80	Integration of strip, slot and DRA	1 × 5 array
Proposed design	**30.6/37.8**	**6.12/10.76**	**8/7**	**88/95**	**T-shaped ground holes**	**1 element**

4. Conclusion

A dual-band DRA operating in the mmWave frequencies has been realized by introducing two T-shaped slots in the ground plane. The antenna resonates at 30.6 GHz and 37.8 GHz with bandwidths of 6.12% and 10.76%. The maximum gains in each of the resonance frequencies are 7.3 dBi and 7 dBi. The antenna can be used in various mmWave wireless applications including 5G, satellite communications, radar systems and IoT devices. Further work can be done to further miniaturize the antenna for compact devices, especially IoT devices, while exploring new materials that could boost gain and efficiency. Additionally, further research can be done on improving dual-band interference and cross-band isolation to increase effectiveness in high-density, multi-frequency setups.

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