Advances in Aircraft and Spacecraft Science, *Vol. 12, No. 1 (2025) 45-57*
https://doi.org/10.12989/aas.2025.12.1.045

Analyses of a cylindrical dielectric resonator antenna for 28 GHz applications

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(Received August 26, 2024, Revised February 21, 2025, Accepted February 26, 2025)

Abstract. The current work presents a novel cylindrical dielectric resonator (CDR) antenna geometry operating at 28 GHz for fifth-generation wireless communication networks (5G). Because of its high radiating power factor, the used dielectric resonator is regarded as a promising new candidate in the field of antennas. The CDR antenna is made up of a FR4 Epoxy Resin substrate with a relative permittivity of 4.4 and a height of 1.8 mm, to which we added a dielectric resonator with a relative permittivity of 8.3, a height of 1.5 mm and a radius of 1.34 mm and it fed by a single microstrip line. The designed antenna geometry was simulated and optimized with the electromagnetic solver HFSS, and the results were validated with the CST microwave studio software. The results allowed us to obtain an antenna radiation at the desired frequency of 28 GHz with an interesting return loss value, a good radiation pattern, a high gain, a large bandwidth and a high directivity. As a result, this antenna is suitable for a wide range of wireless satellite applications.

Keywords: CDR antenna; directivity; gain; operating frequency; return loss

1. Introduction

Nowadays, scientific researchers and wireless system designers are focusing their efforts on fifth-generation wireless communication systems that can bring efficient use of available bandwidth while maintaining high speeds at frequencies ranging from 3 GHz to 300 GHz (Sallehuddin *et al*. 2018, Dwivedi *et al*. 2020). Resonator antennas (RA) provided an intriguing solution to achieve these requirements; they have been the subject of extensive research and have gained great interest in academia and industry. Therefore, dielectric resonator antennas (DRA) are being extensively researched due to their appealing characteristics such as small size, simple geometry structure, high radiation efficiency, ease of excitations, and a high dielectric constant that makes antenna designs more flexible (Saed and Yadla 2006, Petosa 2007, Rezaei *et al*. 2006).

It is known that the dielectric substrate with a metallic motif on the top surface is an example of a dielectric resonator that has diverse shapes that can be used in portions of large fields such as rectangular (McAllister and Long 1983, Sreekantan 2009), cylindrical (Long *et al*. 1983), spherical and hemispherical (McAllister and Long 1984), equilateral triangular (Lo *et al*. 1999), and half split cylindrical (Mongia 1989), and they can be excited in a number of ways, such as by

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http://www.techno-press.org/?journal=aas&subpage=7 ISSN: 2287-528X (Print), 2287-5271 (Online)

microstrip lines (Kranenburg and Long 1988), coaxial probes (Neshati and Wu 2000), and slots (Kishk 1995).

Numerous studies have demonstrated that selecting a particular dielectric resonator may result in a radiating element that is suited for wireless applications. In order to achieve high performance, Lui *et al.* (2018) proposed a different design known as S-shaped DR antenna for 5G mobile systems. In 2018, Maity *et al.* designed a cylindrical dielectric omnidirectional antenna for wideband radiation, while Bahreini *et al.* (2019) designed a unique triangular DR antenna with a broadside radiation pattern for communications of the fifth generation. Due to the increasing demand for high-performance antennas gigahertz applications (Ballav *et al.* 2018, Isernia and Morabito 2013), the proposed cylindrical dielectric resonator antenna design could be employed as a basic contender for advanced communications requirements in future. The DR is a new kind of antenna because of its good performance, wide bandwidth and high gain antenna. Besides, the dielectric permittivity is also the sensitive parameter in the evaluation of the antenna, as a conventional dielectric material with dielectric constant less than 20 (ε_r<20) and very low loss tangent (tan δ<0.001) were used for carrying out DR antenna operating at microwaves frequencies. In our design, we have selected the marble material as a DR with a dielectric constant of 8.3 because of its several advantages. However, Material selection in antenna design, especially for 5G applications using dielectric resonators, must consider key performance factors such as dielectric properties, thermal stability, manufacturing compatibility, and cost. A material with a high dielectric constant (ε_r) enables compact designs, but excessively high values can narrow bandwidth or increase sensitivity to fabrication tolerances. Low dielectric loss is crucial for achieving high efficiency, especially in millimeter-wave bands, and if significant loss is present, alternatives exist. Additionally, the material should be easy to fabricate and compatible, particularly for consumer-grade 5G applications.

In this paper, we present a novel designed cylindrical dielectric resonator antenna (CDRA) for wireless application based on addition of the CDR with specific dimensions to the rectangular patch in order to show its effect on the performance of the novel designed antenna. The simulations were performed using two simulator software-based 3D antenna which are Ansoft HFSS and CST. The obtained results have shown a good wide bandwidth and a significant gain. Taking into account the demand of fifth generation (5G), the CDR antenna is considered as a suitable design for the 28 GHz frequency which could be applied for 5G communication.

2. Results and discussion

2.1 Substrates selection

For designing a suitable and a good antenna performance, it is important to choose the appropriate physical material. Key material properties include relative permittivity (ε_r), dielectric loss tangent (tan δ) and substrate thickness (t), all of which must be carefully selected. The relative permittivity determines the size of the antenna, with higher values enabling miniaturization by reducing the wavelength inside the substrate (Yun 2013). However, to guarantee high network performance and wide bandwidth, the tan δ should have a low value (Anandkumar 2020). In order to achieve this objective, in this study we have chosen the FR4 Epoxy substrate and Marble dielectric resonator as material for designing the proposed antenna.

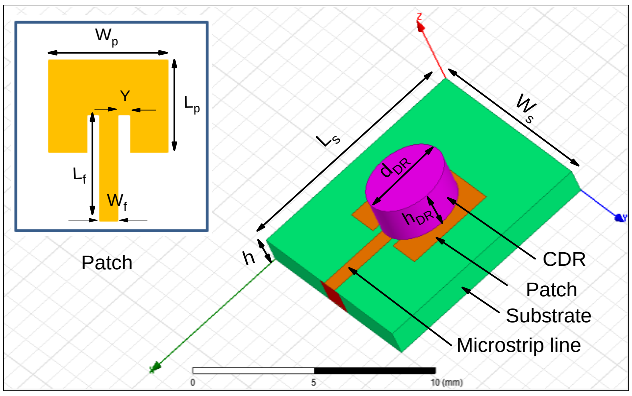


Fig. 1 Schematic representation of the proposed antenna geometry generated by the HFSS software

2.2 Antenna design and configuration

This section describes a novel configuration of a cylindrical DR antenna based on a marble resonator ε_m=8.3 as following: (i) the FR4 Epoxy material, has a dielectric constant of 4.4, a thickness of 1.8 mm and dimensions of 10×10×1.8 mm^3 ($L \times W \times h$), has been selected as the substrate. (ii) A plane created using copper (annealed copper) with a thickness of 35 μm and the same dimensions as the substrate that used as the ground plane of this design. (iii) We have imprinted a rectangular radiating element (patch) with precise dimensions on the surface of this substrate. The scheme of the configuration view of the applied geometry is depicted in Fig. 1. Another material, a cylindrical DR that may enhance the antenna performance with higher efficiency, is printed on the rectangle radiating element in order to study the impact of the unique characteristics of the developed antenna. Additionally, as shown in Fig. 1, a 50 Ω microstrip feed line with dimensions of 4.8 mm in width and 1 mm in length is used to excite the antenna.

2.2.1 Calculation of patch parameters

The parameters defending the used patch have been calculated using the theoretical formulas given below. We first determined the width (*Wp*) parameter of the rectangular patch that is defined as (Bouzakraoui *et al*. 2017, Garg *et al*. 2001).

$$W = \frac{c}{2 f_o \sqrt{(\varepsilon_r + 1)/2}} \tag{1}$$

where c is the speed of light in empty space (3.10^8 m.s^{-1}), f_0 is the resonance frequency and ε_r is the relative permittivity of the substrate. The length (*Lp*) of the rectangular patch element is then calculated by using the following relationship (Bouzakraoui *et al*. 2017, Ravi *et al*. 2023)

$$L_p = \frac{c}{2 f_o \sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{2}$$

In which the fringing length ΔL of the patch rectangular antenna and the effective dielectric constant ε_{eff} of a microstrip line which represents the mixed dielectric constant of substrate and air are calculated using the following expressions

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (3)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-1/2} \quad (4)$$

By using the aforementioned equations, we carried out the antenna design based on the Ansoft High Frequency Structure Simulator (HFSS) software because of its familiar Microsoft Windows graphical user interface and its high-performance in full wave electromagnetic (EM). In our published works (El Hasnaoui and Mazri 2022, El Hasnaoui *et al.* 2022, El Hasnaoui and Mazri 2024), we have presented a detailed discussion showing that a microstrip patch antenna with rectangular slots can be designed for wireless applications. For this reason and to enhance the performance of the proposed antenna, two rectangular slots have been inserted on the radiating element (Fig. 1). In order to obtain the resonant frequency at 28 GHz, we added a cylindrical DR with small size on the rectangular patch structure. The dimensions of the small cylindrical noted by d_D and h_D are chosen in such a way that it operates in the mentioned fundamental resonating frequency, and a microstrip feed line is used for feeding the DR due to its simpler mode of excitation.

2.2.2 Calculation of DRA parameter (h_D)

The basic $HEM_{11\delta}$ mode the formula given in Eq. (5) (Mongia *et al.* 1994) is used to calculate the h_D.
where f_0 is the operating frequency, *RD* is the radius of the cylindrical dielectric resonator, and *c* is the speed of light.

$$f_{0,HEM_{11\delta}} = \frac{6.321c}{2\pi R_D\sqrt{\varepsilon_m+2}}\left\{0.27+0.36\left(\frac{R_D}{2h_D}\right)+0.02\left(\frac{R_D}{2h_D}\right)^2\right\} \quad (5)$$

The Eq. (5) is converted to the following equation

$$0.02\left(\frac{R_D}{2h_D}\right)^2+0.36\left(\frac{R_D}{2h_D}\right)+0.27 = \frac{2\pi f_0 R_D\sqrt{\varepsilon_m+2}}{6.321c} \quad (6)$$

then by considering $\left(\frac{R_D}{2h_D}\right)$ as "X", the Eq. (6) can be written as

$$0.02X^2+0.36X+0.27 = \frac{2\pi f_0 R_D\sqrt{\varepsilon_m+2}}{6.321c} \quad (7)$$

The resolution of this equation leads to the X value of 0.422 and $h_D=R_D/2\times6.6324$. The estimated value of the dielectric resonator h_{DR} in the fundamental mode is found to be 1.6 mm. The calculated design parameters (L,W) and ($R_D=d_D/2$, h_D) of the rectangular patch and the cylindrical DR are depicted in Table 1.

2.3 Simulation processes

The procedure of the design methodology of the patch antenna which has been adopted is based on the addition of the DR with suitable dimensions at the level of the radiating element for showing its performance in terms of return loss (S_{11}), gain, directivity, and radiation pattern around

Table 1 Physical parameters of the proposed patch antenna

Parameters	Descriptions	Dimensions (mm)
Ls	Substrate length	10
Ws	Substrate width	10
L_P	Length of patch	3.02
W	Width of patch	3.26
h	Substrate height	1.8
L_f	Length of line	4.8
W_f	With of line	1
Y	Rectangular slot	0.4
R_D	Radius of dielectric resonator	1.33
h_D	Height of dielectric resonator	1.6

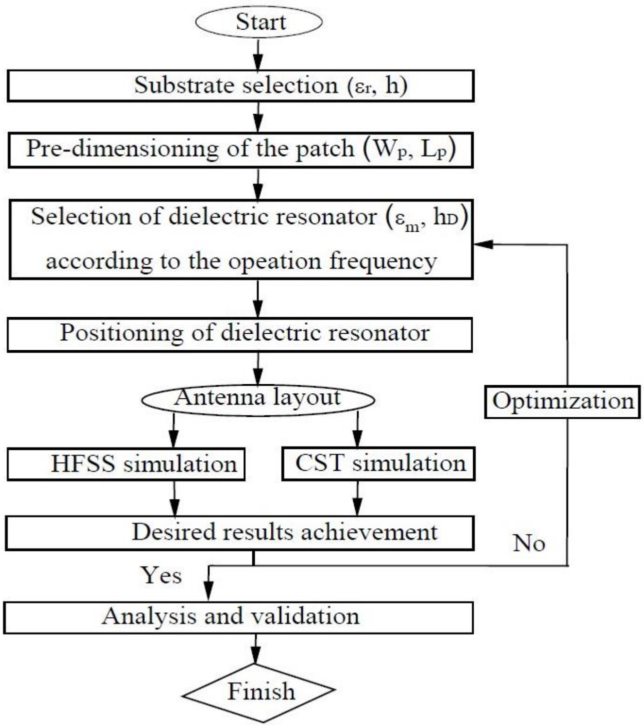


Fig. 2 Scheme of antenna design flow char

the operating frequency of 28 GHz. The thickness (h) and relative permittivity (ε_r) of the substrate are selected in accordance with the desert design based on the appropriate application of the antenna. In order to validate the obtained antenna, the simulation was then performed using the two types of software, HFSS and CST, in accordance with the flowchart of the subsequent simulation, as shown in Fig. 2. However, the HFSS and CST Studio Suite are two leading electromagnetic simulation tools used for antenna design, RF components, and microwave applications. HFSS is based on the Finite Element Method (FEM) and is well-known for its

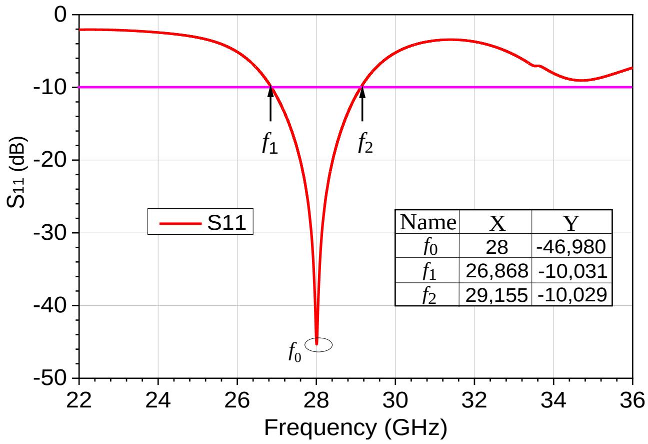


Fig. 3 Frequency dependent return loss of designed cylindrical DR antenna. The inset Table illustrates the values of the resonate frequency, f_o, and the frequencies limits of the range bandwidth coordinates

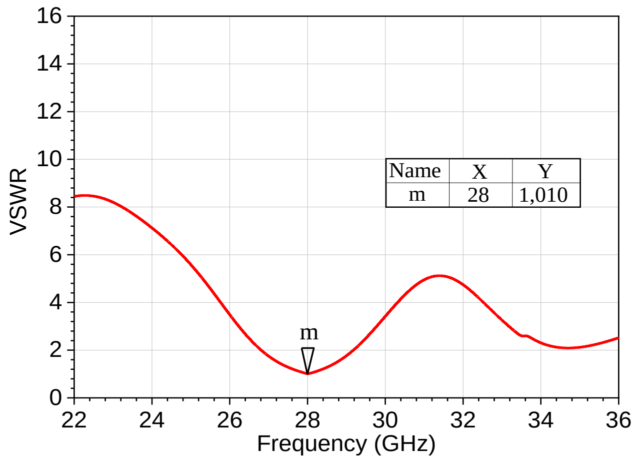
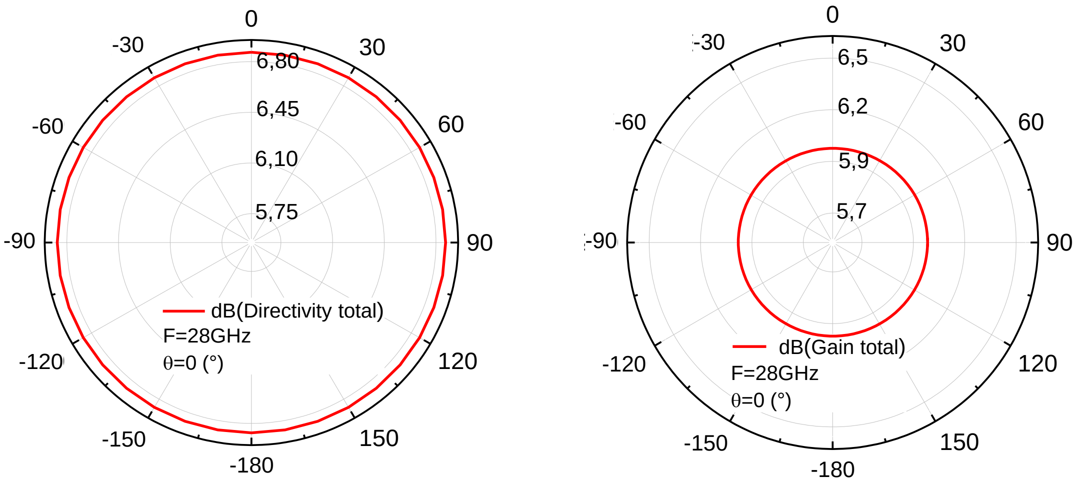


Fig. 4 Frequency dependent VSWR of designed cylindrical DR antenna using HFSS. The resonant frequency and its corresponding VSWR are given in the inserted Table

adaptive meshing capabilities, which automatically refine tetrahedral meshes based on error estimation. It supports complex material properties, including surface roughness models, and offers radiation. While CST is based on the Finite Integration Technique (FIT) and offers multiple solvers, including time-domain, frequency-domain, and eigenmode solvers. It supports frequency-dependent, anisotropic, and dispersive materials, with meshing strategies that include hexahedral and tetrahedral meshes, along with adaptive mesh refinement for accuracy.

2.4 Results and analysis

The return loss, whose value should be less than -10 dB, is the most crucial parameter that permits determining the ratio of the amplitudes related to the incident and reflected waves, this parameter is primarily affected by impedance matching, which depends on the resonator



(a) Directivity (b) Antenna gain

Fig. 5 Peak representation: Directivity and antenna gain

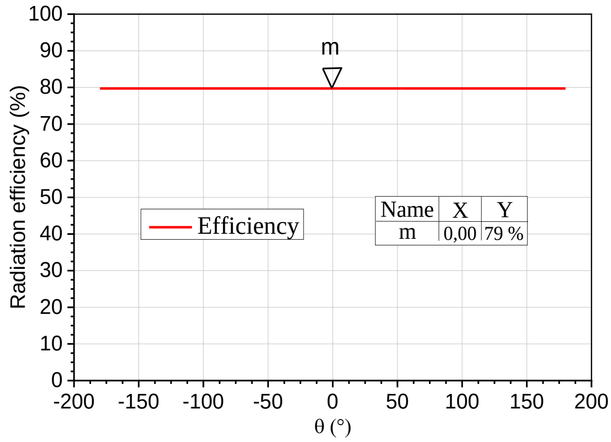


Fig. 6 Total efficiency for the proposed cylindrical DR antenna

dimensions, substrate properties, and antenna geometry. A well-matched impedance (close to 50 Ω) minimizes reflection and improves performance. The evolution of the simulated reflection coefficient (S_{11}) as a function of frequency is shown in Fig. 3. It is evident that the antenna resonates at 28 GHz that corresponds to the maximum value of the $|S_{11}|$ that is 47.49 dB giving an impedance bandwidth, below -10 dB, of 2.25 GHz (26.86-29.11 GHz), making it suitable for new wireless applications (26-28 GHz for 5G mmWave).

Several works have shown that the VSWR is an important parameter demonstrating the matching of the antenna, which indicates impedance matching quality, is influenced by the feed network and resonator design, with a well-optimized structure ensuring a value below 2 for efficient power transfer. For our case, the value of VSWR obtained by the simulation approach at the frequency of 28 GHz is equal to 1.01 (Fig. 4), proving the good adaptation between the radiating element and transmission line of our novel designed antenna. This value, representing

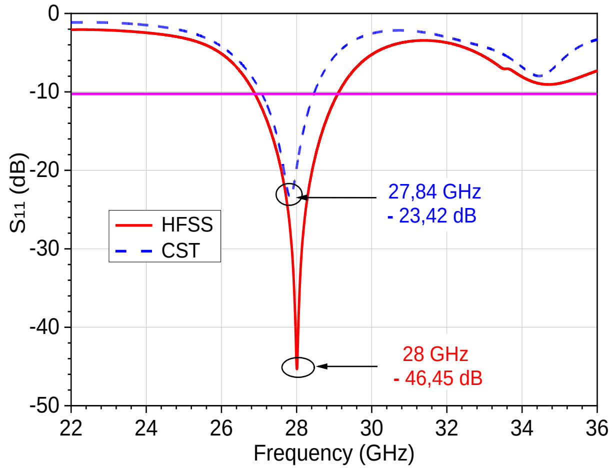


Fig. 7 S_{11} reflection parameter for the simulated structure of the dielectric resonator antenna on HFSS and CST software

optimal conditions, ensures maximum power transfer between transmitter and antenna for many applications such as 5G communication and WLAN/WiMAX applications. Additionally, we examined the antenna performance at the same frequency to determine the values of directivity and gain. The results are 7.63 and 6.63 dB, respectively (Fig. 5). These achievements are reasonable regarding their important applications in satellite and terrestrial microwave applications. Fig. 6 shows their matching radiation efficiency which measures the ratio of radiated to input power, is impacted by material losses, surface waves, and impedance matching. Reducing conductive and dielectric losses while optimizing the resonator placement enhances overall efficiency. These factors collectively determine the performance of the proposed antenna in the millimeter-wave 5G frequency band. At the resonance frequency, it can be seen that the proposed design has a high radiation efficiency of 79%.

2.5 Comparison and validation

For further examining and validating the effects of the dielectric resonator on the performance antenna, the proposed structure is resimulated at a frequency of 28 GHz using alternative software that uses the finite element method as a numerical analysis, namely the CST Microwave Studio (MWS) simulation tool. Although many simulation results of the suggested cylindrical DR antenna are examined using this software in terms of return loss, gain, directivity, voltage standing wave ratio, and bandwidth. The discussions and conclusions are as follows:

i) The magnitude of the reflection coefficient (S_{11}) corresponding to the two softwares, CST and HFSS, which gives the high-performance value (Naik 2021) are depicted in Fig. 7, we observed that the reflection coefficient values are nearly equal, and allowed the impedance bandwidth of 2.3 GHz for HFSS and 1.7 GHz for CST.

ii) The frequency dependence of the typical VSWR that was simulated by the two softwares of the proposed antenna is shown in Fig. 8. As can be observed, the values of VSWR correspond to the two peaks at 28 GHz are 1.01 and 1.14, respectively. These values range from 1 to 2, suggesting that they are approaching the most efficient VSWR value of 1, which indicates that the

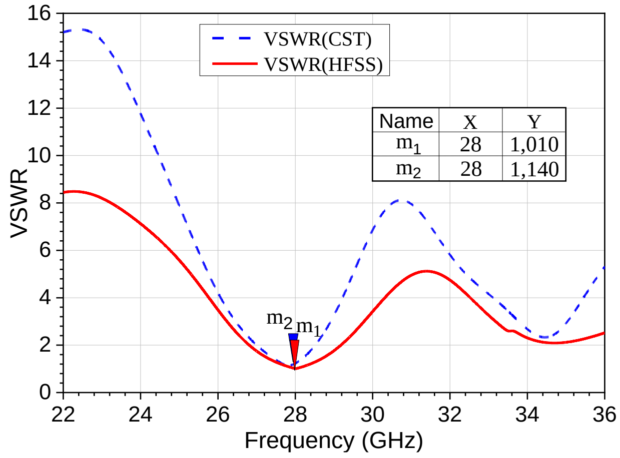


Fig. 8 Total efficiency for the proposed cylindrical DR antenna

Table 2 The obtained values of the proposed antenna characteristics using the three FR-4 Glass Epoxy substrates

Antenna performance parameters	HFSS software	CST software
Resonant frequency (GHz)	28	27.84
Return loss (dB)	- 46.25	- 23.42
Gain (dB)	6.63	4.5
Directivity (dB)	7.62	5.9
Bandwidth (GHz)	2.3	1.7
VSWR	1.01	1.14
Efficiency (%)	79	72

designed antenna may attain the best performance possible for the operating band as determined by Pozar (1986), Arumugam *et al.* (2022). Thus, it allows the maximum power transfer between the antenna and the transmitter to operate efficiently for many wireless satellite applications.

iii) In Table 2 we summarize the comparison of the antenna performance parameters of the designed structure which are gain, directivity, VSWR, and impedance bandwidth, showing no significant differences.

The difference in the results obtained from the two software tools, as presented in Table 2, can be attributed to several factors. First, the simulation algorithms and solvers employed by each software may differ, such as the use of Finite Element Method (FEM), Method of Moments (MoM), or Finite Difference Time Domain (FDTD), each of which has varying accuracy and error propagation. Additionally, the meshing process, including mesh density and quality, plays a crucial role, as finer meshes typically yield more accurate results but require greater computational resources. Variations in the definition of boundary conditions, such as Perfectly Matched Layers (PML) or periodic boundaries, can also impact the simulated electromagnetic environment. Discrepancies in material property definitions, including permittivity, permeability, and conductivity, may lead to differing outcomes.

The 2D far-field radiation patterns were simulated in a normalized azimuth plane $E(x\text{-}y)$ and elevation plane $H(x\text{-}z)$ in the range of frequency from 26.8 to 29.5 GHz with a step value of 100

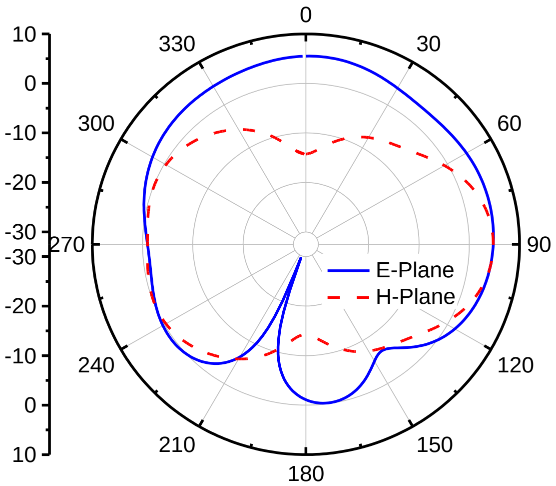
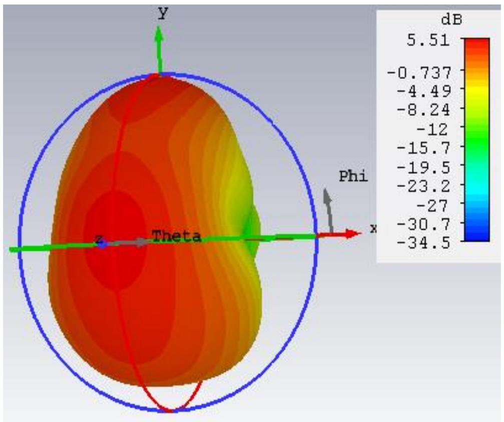
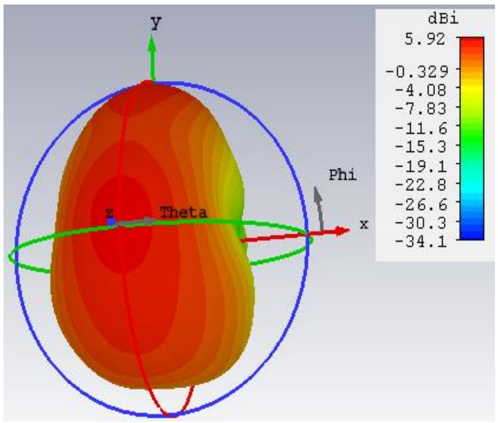


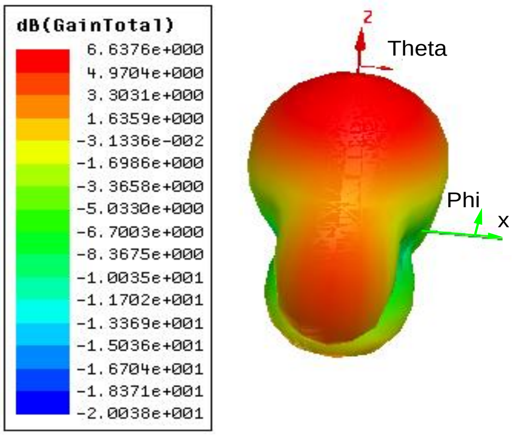
Fig. 9 Simulated radiation patterns in the *E* plane for ϕ=0° (solid line) and in the *H* plane for ϕ=90° (dotted line) of the proposed antenna



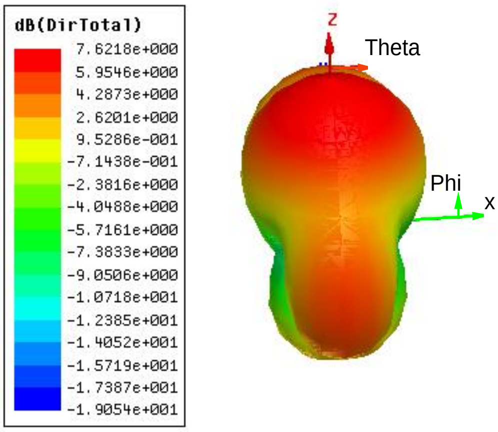
(a) Gain in CST



(b) Directivity in CST



(c) Gain in HFSS



(c) Directivity in HFSS

Fig. 10 Gain and directivity radiation pattern in 3D in CST and HFSS software

Table 3 Comparatives characteristics of different substrate and of performance for 5G applications at 28 GHz

Ref. No.	DRA Shape	Frequency (GHz)	Return Loss (dB)	DRA Dimensions (mm×mm×mm)	Bandwidth (GHz)	Gain (dB)
[28]	Cylindrical	28	-44.83	0.91 × 11.54	-	4.39
[33]	Trapezoidal	26	-28.56	2.9 × 3.4 × 2.6	2	3.98
[34]	Rectangular	26	-38	2.9 × 2.6 × 1.4	3.6	6.2
[35]	Rectangular	28	-41	5.9 × 7.5 × 2.54	1.35	12
Proposed	Cylindrical	28	-46.45	1.6 × 2.66	2.3	6.63

MHz, the obtained results are shown in Fig. 9. As seen, the proposed antenna exhibits a large bandwidth, a nearly constant gain, and a low cross-polarization in both planes. However, the antenna radiates mostly in a broadside direction. In Fig. 10, we present the simulated three-dimensional (3D) radiation patterns using CST and HFSS softwares by taking into account the antenna directivity and gain. The maximum antipodal radiations have been achieved with a gain and directivity of about 6 and 7 dB, respectively. In addition, these 3D radiation patterns showed only one main lobe that radiates from the front of the antenna, indicating the achievement of good radiation from the designed antenna.

In order to check the concept of the design, a comparison with some of the recently published works at the resonance frequency (El Hasnaoui and Mazri 2022, Abinash *et al.* 2022, Gaya *et al.* 2022, Zhang *et al*. 2019), antenna dimensions, impedance bandwidth, gain, and other metrics is illustrated in Table 3. We observed that the proposed antenna has small dimensions, a higher gain and a large impedance bandwidth compared to those of the given references. Besides, the examined antenna shows a minimum reflection coefficient compared to those reported in Table 3, indicating that our proposed design gives a pretty good performance antenna that may satisfy the requirements of new wireless applications which is the primary motivation of this study.

5. Conclusions

In this work, an effort has been made to design and analyse a novel cylindrical dielectric resonator antenna based on the microstrip line fed. The parameters of the studied antenna are optimized at the operating frequency of 28 GHz due to its important application on the standard for millimeter waveband and 5G applications. The simulation results of the designed antenna with FR4-Epoxy substrate material and marble as a dielectric resonator have allowed good performance in terms of return loss, gain, directivity, voltage standing wave ratio and impedance bandwidth, concluding that the selection of patch dimensions and dielectric resonator are a key feature to achieve a fruitful application in wireless communication for the fifth generation.

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