Design of higher gain 1×4 cylindrical dielectric resonator antenna for mm-wave base stations

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ABSTRACT

In this work, a cylindrical-shaped dielectric resonator antenna (DRA) with four elements is designed and presented at 28 GHz for millimeter-wave applications. The microstrip line is designed to excite the dielectric resonator (DR) with a relative permittivity of 8.3, and then the proposed single cylindrical DR antenna has been mounted on a FR4-Epoxy substrate with a relative permittivity of 4.4 and a thickness of 1.8 mm. However, the optimized single element was used to create a particular array for improving the gain and achieving the required antenna performance. The resulting antenna enabled a response range for the reflection coefficient from 26.8 GHz to 30.6 GHz, which covers the operational frequency. This allows for a maximum gain of 19.07 dB, an impedance bandwidth of 3.8 GHz, and a total efficiency of 80.62%, meeting the requirements for millimeter-wave and fifth-generation applications.

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1. INTRODUCTION

The latest cellular communication systems require an efficient antenna that is capable of supporting high data rates, wider bandwidths, and high frequencies as part of their wireless communication system [1]. To accommodate these requirements, it is necessary to design a system covering different frequency bands. One of the most talked-about wireless standards is 5G technology with higher carrier frequencies [2]. Due to the implementation of 5G in recent years, antenna designers must also address other concerns of modern devices, such as increased data rate, wide bandwidth, and high gain [3], [4]. Additionally, the antennas to be deployed in the base stations must be highly efficient to minimize losses and maximize the transmitted power.

In order to comply with the features required to deploy the antennas in base station applications, numerous recent designs have been published in the literature. A T-shaped antenna is presented in [5]. The design could be scaled or optimized for base station applications but would yield low gain compared to the traveling antennas. Raheel *et al*. [6] proposed a dual-band microstrip-fed antenna; even though the antenna operates in multiple bands, the gain for the available radiating aperture is low. A modified phased array approach is shown in reference [7]. The scanning loss is close to 4 dB, which makes it unsuitable for base station applications. A wide-band antenna operating frequency of 28 GHz for 5G applications is presented by Kamal *et al*. [8], showing that the pattern integrity across the band is poor. Even though the antenna presented in [9] is compact, the gain and pattern integrity are compromised. A high-efficiency antenna system with multi-polarization is proposed in [10]. It is designed on an expensive substrate with multiple fabrication technologies. Wideband antennas with lower gains are presented in other works [11], [12].

Because the 5G data rates are 1 GBPS for upload and around 100 GBPS for download, to accommodate the tremendous data rates of the current world, it is necessary to take into account the values of its various parameters. However, a high-gain array cylindrical dielectric resonator (CDR) antenna is constructed and optimized to operate in the 5G frequency band, supporting the dielectric resonator (DR) as the main radiator element for many advantages, including easy design and excitation, simple fabrication methods, wider impedance bandwidth, high radiation efficiency, and flexibility in designing and analyzing the results to achieve our coverage requirements [13]. First, a single CDR antenna is proposed. A suitable microstrip connector is used to feed the antenna through the transformer, with dimensions of L_f and W_f. This single element was developed in order to create a 1×4 array antenna fed with a common corporate feed. The development of antennas aims to meet the data rate requirements of the modern world. In the proposed array, the focus is mainly on the improvement of the gain. The HFSS software is used to simulate the proposed structure for its simplicity and precision. The single element antenna resonates at around 28 GHz. The impedance was mached appropriately to minimize the power loss due to an impedance mismatch, as seen in Figure 1. Next, the single element is extended to four elements to improve the gain of the antenna further. Using corporate feeding. However, the proposed array antenna resonates at 28 GHz with $|S_{11}|\leq$-20 dB achieving a high gain and impedance matching of 50 Ω.

Finally, we briefly mention the main aim of this work and highlight the principal conclusions. As far as possible, the objective of this work was to design and create an appropriate array of CDR antennas with four elements that could be easily simulated with good performance in terms of gain, bandwidth, directivity, and radiation efficiency for achieving the requirements of 5G data rates in the modern world. For 5G base station applications, the desired antenna characteristics of the dominant mode are relatively preserved compared to those given in the literature. This approach allows us to enhance the gain of our antenna since it concentrates solely on optimizing the parameters of the single DRA along with its feeding mechanism, all while maintaining the original shape of the DRA and avoiding unnecessary complexities in its structure. Additionally, the significance of the $HEM_{11\delta}$ mode is emphasized due to its desirable broadside radiation characteristics [14].

2. RESULTS AND DISCUSSION

2.1. Signal element configuration

The design for an array DRA was developed after an investigation of a single element. However, in the first design trial, a single DRA is designed with an inset feeding for the millimeter band. A cylindrical shape is chosen for all proposed structures of DR antennas with a relative permittivity of 8.3 and dimensions of R_{DR} (radius) and h_{DR} (height). These two parameters are carefully selected to ensure that the single element operates at its fundamental resonant frequency, as well as the rectangular patch with dimensions of W and L that are used for the proposed structures. All conductors within the design are constructed using FR4-Epoxy substrate material, with a uniform thickness of 1.8 mm. The substrate possesses a relative permittivity of 4.4 and its dimensions are specified as 10×10×1.8 mm³ (L_s×W_s×h_s). Based on the analytical theory of the DRA design developed by Petosa [15], the studied single element consists mostly of dimensioning the DR which is usually cylindrical, noting that other shapes with a specified mode of excitation have already been considered [16]. The antenna parameters, namely the patch width (W) and length (L), are determined by employing the following equations for calculation purposes [17].

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

In the given equations, "f_o" represents the resonant frequency, "c" denotes the velocity of light in free space (c=3×10^8 ms^{-1}), and ε_r is the relative permittivity. The length L of the rectangular patch is usually in the range of 0.333 λ_o to 0.5 λ_o [18]. Where "λ_o" represents the free-space wavelength, it is worth noting that the length of the patch is slightly less than half-wavelength due to the fringing effect. The length is defined as (2):

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

where ΔL represents the length extension caused by the fringing field effect and ε_{eff} is the effective dielectric constant. These two parameters are calculated by applying (3) [17]:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)((w/h)+0.264)}{(\varepsilon_{eff}-0.258)((w/h)+0.8)} \quad \text{where} \quad \varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\left(\frac{w}{h}\right)\right)^{1/2} \tag{3}$$

In our published work [19], [20], we presented a thorough discussion demonstrating the feasibility of designing a microstrip patch antenna for wireless applications. To further optimize the performance of the suggested structure, two rectangular slots have been incorporated into the patch. These slots are used to adapt the antenna characteristics, enhancing parameters such as antenna gain, bandwidth, and efficiency. Besides, in order to show the effect of DR at a frequency of around 28 GHz, we printed another cylindrical-shaped dielectric material which is a DR with a small size on the rectangular patch. The dimensions of the cylindrical DR are noted as R_{DR} and h_{DR} are carefully selected to ensure resonance at the fundamental resonating frequency mentioned. Additionally, a microstrip feed line is used to feed the DR because of its easier method of excitation. However, to enhance the performance of the suggested array and achieve high gain and a large bandwidth, several approaches can be considered. We start by dimensioning the dielectric element to resonate in the $HEM_{11\delta}$ mode at a frequency of 28 GHz. Based on the results of Petosa [15] who have worked on the enhancement bandwidth performance of DR antennas for wideband applications, we consider the radius R_{DR} and we can find the value of h_{DR} by using the following mathematical formulation for resonant frequency f_o [21]. The obtained parameter values are given in Table 1 and the geometry of a single cylindrical DR antenna is shown in Figure 1.

$$f_{0,HEM_{11\delta}} = \frac{6.321c}{2\pi R_{DR}\sqrt{\varepsilon_{r,eff}+2}}\left\{0.02\left(\frac{R_{DR}}{2h_{eff}}\right)^2 + 0.36\left(\frac{R_{DR}}{2h_{eff}}\right) + 0.27\right\} \tag{4}$$

where h_{eff} represents the effective height of the DR, $\varepsilon_{r,eff}$ is the effective permittivity of the proposed CDR which can be determined as (5) [22]:

$$\varepsilon_{r,eff} = h_{eff}/\left(\frac{h_{DR}}{\varepsilon_D} + \frac{h_s}{\varepsilon_r}\right) \text{ where } h_{eff} = h_s + h_{DR} \tag{5}$$

Table 1. Dimensions of the proposed single antenna element

Symbol	Parameters	Dimensions (mm)
Ls	Substrate length	10
Ws	Substrate width	10
L	Length of patch	3.02
W	Substrate height	3.26
hs	Length of line	1.8
L_f	Length of line	4.8
W_f	With of line	1
R_{DR}	Radius of DR	1.33
h_{DR}	Height of DR	1.6

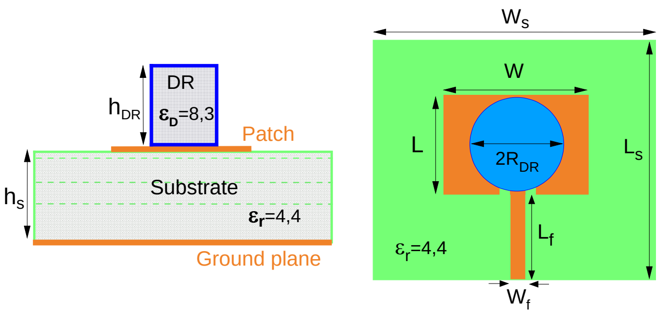


Figure 1. The schematic of the proposed single element cylindrical DR antenna: side view and top view

To ensure the accuracy of the operating frequency, a simulation of the electric field pattern at 28 GHz is conducted for the single element. The modes $HEM_{11\delta}$ and $HEM_{12\delta}$ are characterized by their electromagnetic field configurations inside the structure. These modes refer to specific resonance modes in a cylindrical cavity or waveguide. However, the $HEM_{11\delta}$ mode is considered the fundamental mode compared to the $HEM_{12\delta}$ mode which is often related to symmetry and the simplest and most stable electromagnetic field configuration for a cylindrical cavity as well as the $HEM_{11\delta}$ mode has a simpler field distribution with only one radial variation, making it the lowest energy and most stable mode for this geometry. Hence, the choice of the fundamental mode depends on the geometry of the cavity, the symmetry of the electromagnetic field sought and the specific conditions of the application, but in general, the $HEM_{11\delta}$ mode is considered as the basic mode for an open cylindrical cavity due to its simplicity and stability [14]. The results are depicted in Figure 2, showing the field patterns in the x-z and y-z planes. From this Figure, it can be observed that the cylindrical shape of the antenna generates the $HEM_{11\delta}$ mode. The microstrip line feed induces this mode, functioning as a magnetic dipole [23]. Besides, the $HEM_{11\delta}$ mode refers to the mode in which there is one magnetic field maximum along the radius and one along the height, while the electric field is predominantly in the azimuthal direction. The resonance of the $HEM_{11\delta}$ mode can also be confirmed mathematically by using (5). Figure 3 depict the gain vs frequency and the broadside E-field radiation patterns of the single element at operating frequency in the x-z and y-z planes respectively of the single DR antenna through Ansoft HFSS simulation software.

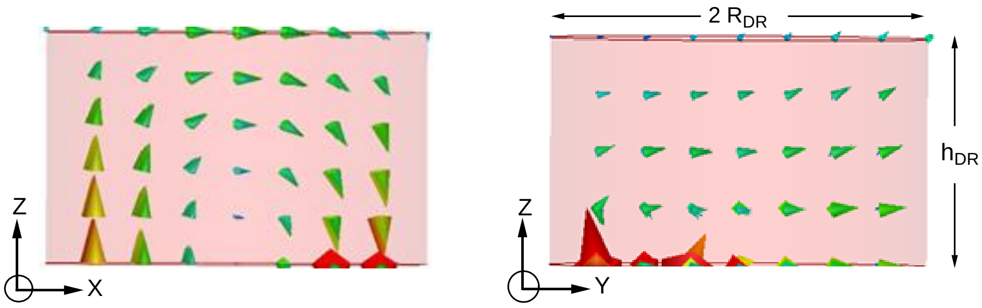


Figure 2. Electric field distribution over y-z plane and x-z plane

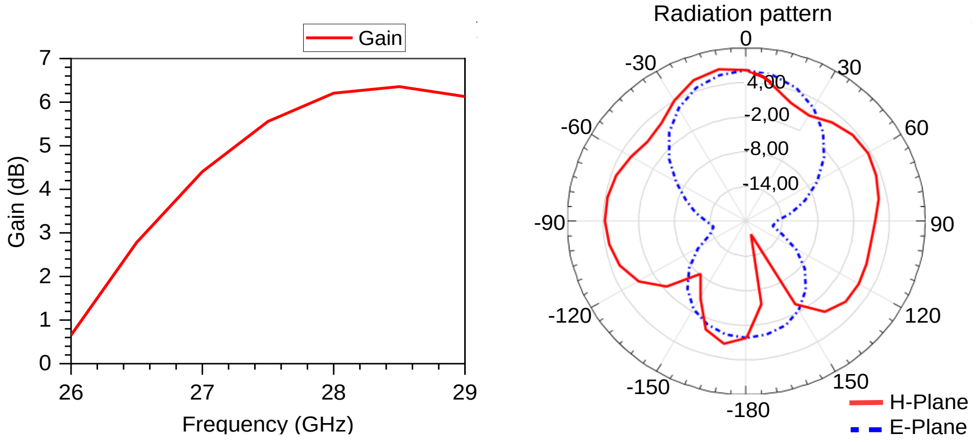


Figure 3. Simulated results of single element, gain vs frequency (left) and farfield e-field pattern in x-z and y-z planes (right)

2.2. Antenna array design

In order to better understand the role of the proposed antenna, we were able to construct an array with four elements. Each element is equally spaced from the adjacent one; the ground and substrate planes are uniform. However, it should be noted that the feed lines play a crucial role in achieving impedance matching for an antenna. As illustrated in Figure 4, quarter-wave transformers are employed to supply the four elements equally in order to achieve equal power distribution. Typically, a single element has relatively broad radiation, and each element has a low gain and a narrow bandwidth. However, many wireless applications require an antenna with good performance characteristics, such as high gain and a large bandwidth. These can be accomplished by creating an assembly of radiating elements that is formed as an array [24]. Therefore, an array antenna configuration is devised where four identical radiating elements are connected in parallel via a microstrip line that is appropriately adapted to 50 Ω. This arrangement forms the basis of the array structure. The development of the proposed array aims to cater to the increasing need for performance considerations that take frequency into account, as well as achieving a high gain with significant bandwidth for fifth-generation applications. Based on Lu and Leung [25], the performance of a DR array antenna depends on the dimension of the DR, number of elements, feed arrangement, mode of operation, and geometry. In this part, the parametric studies conducted on the linear CDR array antenna are presented and discussed in this section in order to achieve good antenna performance.

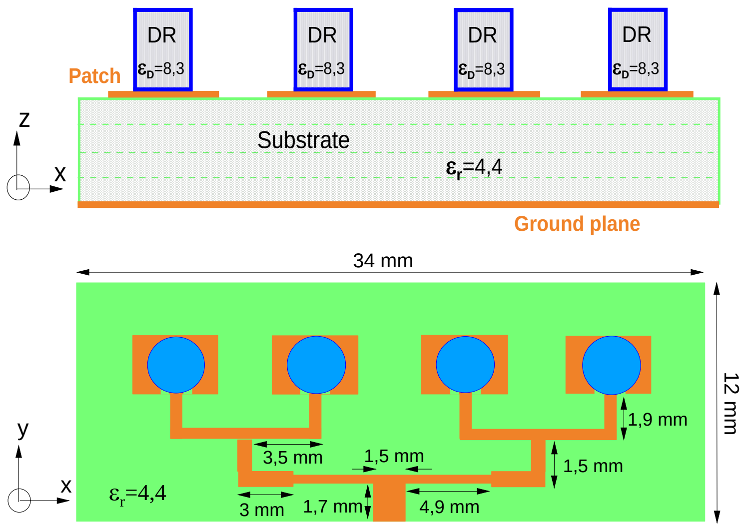


Figure 4. Top view (x-z plane) and side view (x-y plane) of the proposed antenna array

The proposed 1×4 cylindrical DR antenna array was simulated using Ansoft HFSS, utilizing the finite element method in the frequency domain, as detailed in [26]. As shown in Figure 5, the antenna resonates at 25 GHz, 28 GHz, and 33 GHz frequencies, with S_{11} values of -18.67, -30.24 and -19.53 dB respectively. Three bands are obtained, covering frequencies: the first is from 24.8 GHz to 26.2 GHz, the second is from 26.84 GHz to 30.61 GHz, and the third is from 32.45 GHz to 33.65 GHz, all determined at -10 dB. The fractional impedances that indicate the degree of capacitance of the antenna are respectively (6.1%), (13.5%) and (3.12%). The simulated results of the S_{11} and impedance bandwidth for the proposed array are shown in Figure 5(a). While the results of two other important parameters considered for analyzing the performance of the proposed array are also presented, they are gain and directivity.

Total efficiency in antenna systems involves converting input power into radiated electromagnetic energy. Using epoxy FR-4 substrates can yield high efficiency in antennas under specific conditions due to their electrical insulation properties and cost-effectiveness. Key factors affecting efficiency include frequency matching, antenna type, construction quality, substrate size and thickness, and dielectric properties. Despite challenges such as dielectric absorption losses and some material limitations, it is indeed possible to achieve high efficiency using the FR-4 substrate through precise design, meticulous tuning, and an understanding of the specific properties and limitations of the substrate. Figure 5(b) shows the variation of the simulated radiation efficiency of the proposed 1×4 cylindrical DR antenna array versus theta. A maximum efficiency of 80.62% has been achieved.

An antenna usually has a gain it is expected to have at its operating frequency, and a usable bandwidth determined by some minimum gain. This is often 3 dB lower than the peak gain. In this case, the gain bandwidth is defined as the range of gain that is within 3 dB of the peak. Alternatively, the gain bandwidth is the bandwidth for which the gain is higher than some set level. Figure 5(c) shows the variation in signal amplitude gain with respect to frequency. As can be seen, the value of this parameter has a higher value at the operating frequency (28 GHz) which is 19.07 dB and a 3 dB gain bandwidth of 17.85%. Compared with the gain of a single element, in the array an exact 12.8 dB increment of gain is achieved, and the bandwidth achievement has increased to 13%.

To assess the credibility and analyze the utilized array antenna, we performed the design and simulation of the identical structure using CST Microwave Studio software which employs the finite integration technique (FIT), was utilized for the numerical analysis of the structure. Figure 5(d) depicts the simulated reflection coefficients S_{11} that were produced from both simulation tools. These results show good S_{11} values, as well as a bandwidth of 3.8 GHz. The minor disparity observed in the simulated results between HFSS and CST can be attributed to the distinct numerical techniques employed by the two software platforms.

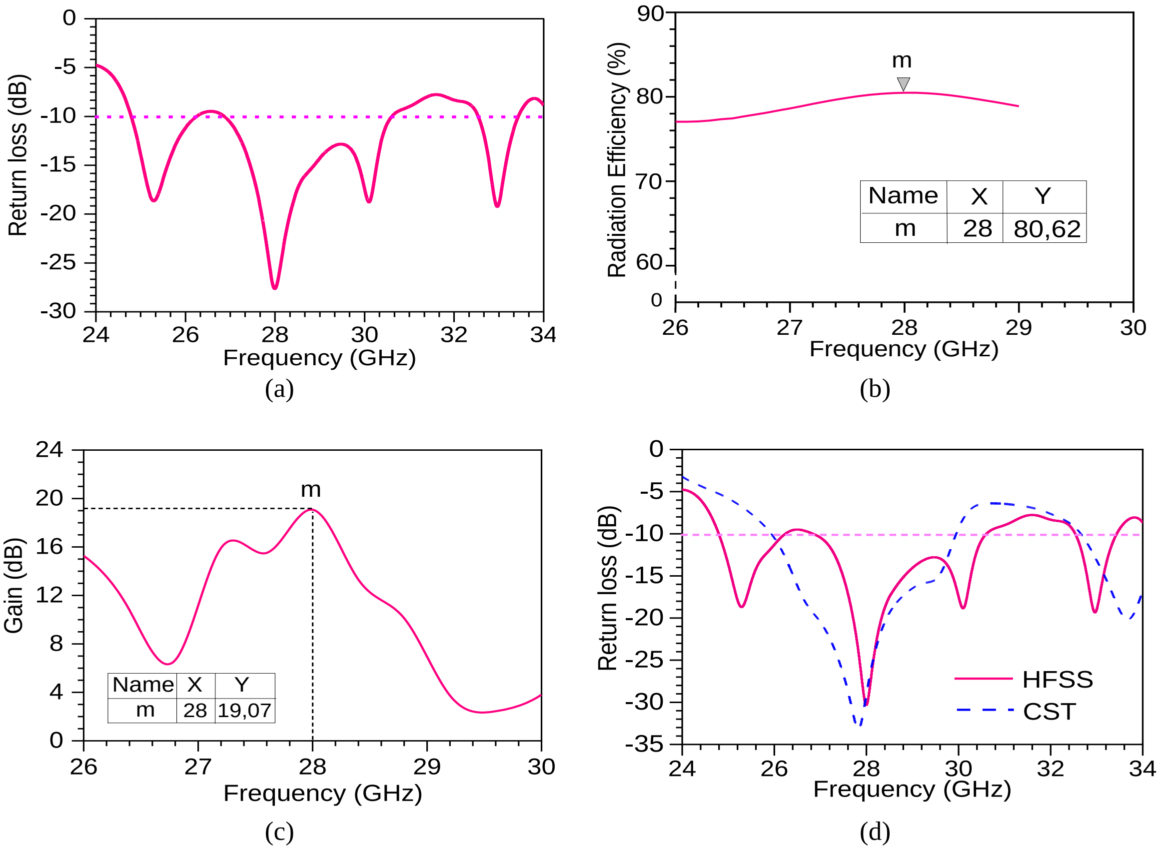


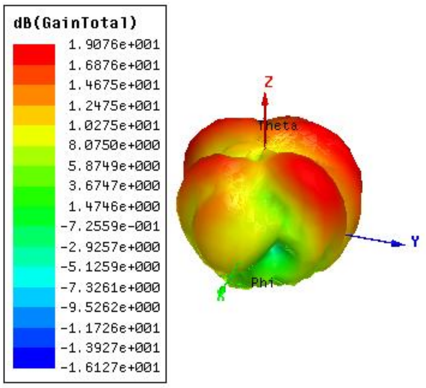
Figure 5. Simulated resultas of the proposed antenna array: (a) return loss, (b) radiation efficiency, (c) gain vs frequency, and (d) return loss using HFSS and CST

To check the importance and validity of the obtained simulation results, we perform an extensive comparison between the performance of our proposed antenna array and that of other antenna designs presented in the literature [6], [8], [27]–[30]. This significant comparison takes into account parameters such as antenna gain, bandwidth and efficiency. As depicted in Table 2, our simulated value of gain is 19.07 dB, bandwidth is 3.77 GHz, and efficiency is 80.62%. However, in the literature the obtained results are lower than our obtained values. Concluding that better performance is observed in the proposed array which gives a good gain and a large impedance bandwidth as well as a high efficiency compared to those obtained in the literature. As a result, the cylindrical DR and properties used in our proposed array offer better performance in terms of the antenna parameters. Besides, these results indicate that the proposed design exhibits a high-performance antenna, making it a promising candidate for 5G applications.

Table 2. Antenna performance comparison

Reference	Frequency (GHz)	Gain (dB)	Bandwidth (GHz)	Efficiency (%)	Element
[6]	28 and 38	7.9	0.84, 1.28	90	4
[8]	28	10.71	3	90	4
[27]	28	9.57	2.8	-	4
[28]	28	14.9	1.15	79	9
[29]	29	5	2	80	9
[30]	30	12.1	2.1	-	4
[31]	28	4.07	2	92	4
Our work	28	19.07	3.77	80.62	4

Figure 6 show the simulated three-dimensional polar coordinate gain and 2D radiation pattern of the proposed array. We can find that the maximum gain of the designed antenna is 19.07. It is apparent from the observations that the effect of the CDR with a permittivity of 8.3 on the microstrip patch antenna array is an important process in the three-dimensional plots. Besides, it is noticed that almost all of the back radiation emitted from the antenna back side is reflected on the front side, focusing the radiation and increasing the maximum achievable gain for wireless communication.



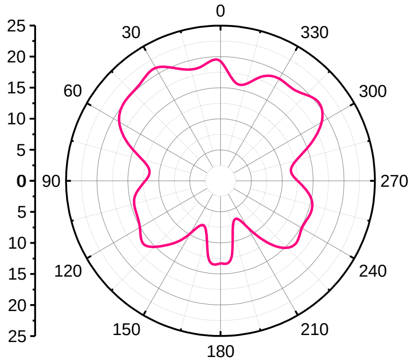


Figure 6. Polar coordinate three dimensions: gain (left) and 2D radiation pattern of the proposed array (right)

3. CONCLUSION

In this study, a basic CDR antenna and a 1×4 array are designed and simulated for base station usage in the fifth-generation frequency band. The antenna utilizes a microstrip line feeding structure and is arranged in a linear array configuration. At the desired frequencies, the antenna achieves a reflection coefficient of -30 dB and an impedance bandwidth exceeding 3.8 GHz, making it suitable for millimeter-wave applications. Moreover, the simulated radiation pattern exhibits broad coverage across the bandwidth, with a high gain value of 19.07 dB and a radiation efficiency of 80.62%. Hence, these qualities can meet the requirements for 5G applications.

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