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Design of A Circular Tapered Dielectric Rod Antenna for Sub-Thz Applications

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Abstract: - In this paper a circular tapered dielectric rod antenna has been designed for sub-terahertz (sub-THz) frequency range. The antenna is designed on a Polypropylene ER182_substrate with dimensions of 0.563mm x 0.563mm x 12.51mm. The advantages of this antenna include compactness, low loss characteristics, and ultra-wide bandwidth. The design considerations for sub-THz dielectric antennas, specifically addressing substrate selection and dielectric properties, geometric design parameters, feeding techniques, and polarization considerations. These design considerations have a significant impact on the performance and radiation characteristics of the antenna. The results obtained clearly show that the designed antenna meets all the requirements over the entire frequency band.

Keywords: Full-wave, EM modelling, design, circular rod dielectric, antenna, sub-THz.

I. INTRODUCTION

Invented in 1939 [1], the dielectric rod antenna, also known as the "poly-rod," is recognized as a specific kind of "surface wave" antenna, where electromagnetic energy passes through the interior and exterior of the rod before radiating at the rod's surface discontinuity. Their electrically lengthy dimensions also give them the name travelling-wave antennas. These antennas are suitable for ultra-wideband applications such as earth-penetrating radars because they often achieve excellent gain over a wide bandwidth. In addition, dielectric rods are popular because to their good polarization purity, low radar cross-section, and low side lobe levels.

Dielectric-rod antennas, also known as Polyrod antennas, have gained significant attention as surface-wave antennas due to their advantageous characteristics. Their compact size and light weight make them particularly well-suited for the millimeter-wave range, while their compatibility with dielectric waveguides enables a wide range of applications. As highlighted by [2], dielectric-rod antennas offer various configurations, typically featuring tapered dielectric-rods with rectangular or circular cross-sections. This document focuses on a specific dielectric-rod antenna with a circular cross-section and a sectional taper. The antenna is fed using an air-filled waveguide, further enhancing its performance and versatility. In this work, we delve into the design, operation, and potential applications of this particular dielectric-rod antenna configuration.

Dielectric rods with a circular cross section can attain a broad bandwidth and offer design flexibility to generate the appropriate radiation pattern. They can be simply and affordably produced with generally available dielectric materials. The side lobe level can be controlled and bandwidth enhanced via taper of the circular cross section, as detailed in, for example, [3]. However, the unavoidable emergence of higher-order modes hinders these rod antennas at higher frequencies. When the diameter of the rod exceeds the guided wavelength., higher-order modes become active, which deteriorates the polarization and pattern. A dielectric rod antenna with ultra-wide bandwidth was created by using electromagnetic absorbers and enclosures in combination with a broadband feed, as demonstrated in [4] to get over this restriction. Furthermore, a broader bandwidth design utilizing several rod

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sections was reported in reference [5]. The dielectric rod antenna's optimal wave transmission and radiation were optimized for each component in this design.

The suggested antenna design, which makes use of a standard circular tapered dielectric rod antenna, is seen in Figure 1. This construction satisfies the 6 G criteria and is appropriate for the Sub-THz frequency band. The feed structure is a waveguide, which allows for maximum power transfer. The suggested antenna is simple to fabricate and has a regular, compact structure.

1. The reflection amplitude of the antenna is primarily determined by the circular waveguide matching, which makes it insensitive to the material and size of the dielectric rod. This simplifies the design process.

2. The dielectric rod can also be constructed with a lengthy structure and a very uniform surface amplitude distribution to obtain high gain.

3. A stable radiation pattern at the end of the line is produced by the antenna's continued moderate phase constant over a broad bandwidth.

4. The 2D and 3D radiation patterns across the antenna's frequency range show how well the suggested construction absorbs undesired energy. This characteristic makes it easier to design and produce the antenna and guarantees a high gain, steady emission pattern throughout a large bandwidth.

The electromagnetic simulation of the antenna under investigation was performed using the commercially available CST-MWS 2024 simulator. The CST-MWS simulator is a dedicated tool for 3D electromagnetic simulation of high frequency structures. It is based on a combination of the perfect boundary approximation (PBA) method and the finite integral method (FIT).

II. Design concept

2.1. Background

Dielectric rod antennas, commonly referred to as polyrod antennas, belong to the category of surface wave antennas. These antennas offer the advantages of compact size and light weight, making them particularly suitable for millimeter-wave applications. In addition, their compatibility with dielectric waveguides opens up a wide range of applications The dielectric rod antenna can be configured in a variety of ways, often with a conical shape with either a rectangular or circular cross section. In the case of a circular cross section, the antenna discussed in this text incorporates a sectional taper. The antenna is also fed by an air-filled waveguide [2].

2.2. Design Considerations

Designing efficient sub-THz dielectric antennas requires careful consideration of various factors to achieve optimal performance. This section discusses key design considerations that significantly impact the antenna's performance in the sub-THz frequency range. These considerations include substrate selection, dielectric properties, geometrical design parameters, feeding techniques, and polarization considerations.

a) Substrate Selection and Dielectric Properties

The choice of substrate material in sub-THz dielectric antenna design is important because it affects the antenna’s performance. The substrate should have a high dielectric constant (ε_r) to enhance the radiation efficiency and achieve compact antenna designs. Dielectric materials with very low loss tangent (tan $\delta \approx 0$) are preferred to minimize energy losses and improve antenna performance. Materials such as composite materials have also been explored for efficient radiation characteristics in the THz spectrum [6].

Polypropylene polymer (ER182) is a promising material for fabricating circular tapered dielectric rod antennas for sub-THz applications. This polymer is known for its extremely low dielectric losses, which has minimal losses with a $\tan\delta = 0.008$ and a relative permittivity of $\varepsilon_r = 2.47$.

This choice is motivated by polypropylene's low dielectric constant and loss tangent, which are favorable for efficient signal transmission at sub-THz frequencies. However, polypropylene's mechanical properties and thermal stability must be considered during fabrication. Additionally, material homogeneity and a smooth surface finish are crucial for optimal performance. Proper impedance matching is also essential to ensure efficient power transfer in the antenna design is also essential to ensure efficient power transfer in the antenna design [7].

b) Physical Description

The considered dielectric rod antenna has a circular cross-section. The cross section is tapered as shown in the figure below. (Fig. 1).

This particular configuration employs the concept of sectional taper, where the dielectric rod consists of different sections, each characterized by its unique linear taper (Fig. 2).

Specifically, the rod has four sections, each of which serves a different purpose. First, the matching section is located within the circular feed waveguide and provides a seamless transition from the waveguide to the waveguide port. Second, the base or feed taper bridges the gap between the waveguide port and the straight section of the dielectric rod. Finally, the nose or end taper plays a critical role in mitigating reflection by facilitating the smooth transition of surface waves to free space waves. By using these different sections and their corresponding tapers, the dielectric rod antenna optimizes its performance and minimizes any undesirable effects caused by wave transitions.

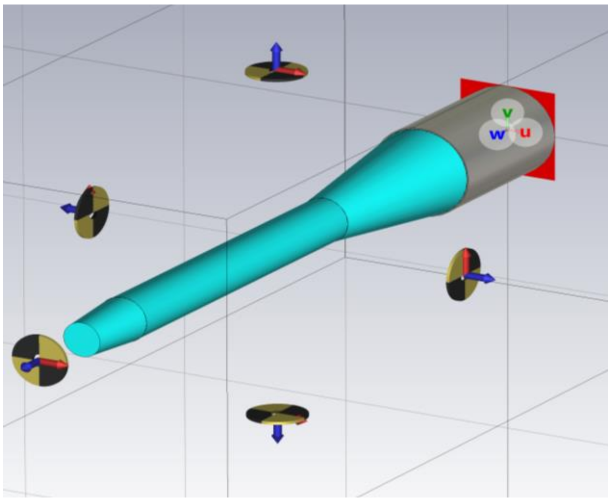

Figure 1. Circular tapered dielectric rod antenna.

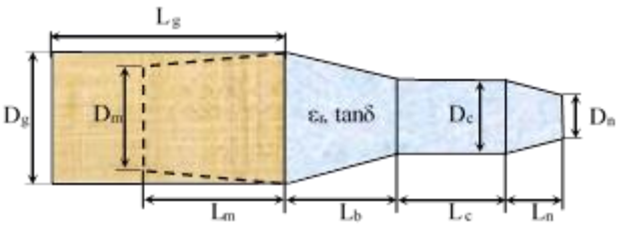

Figure 2. Side view of a dielectric-rod antenna.

c) Feed Method

The feeding technique employed in sub-THz dielectric antennas is crucial for achieving efficient power transfer and impedance matching. Common feeding techniques include microstrip feed, aperture coupling, proximity coupling, and probe feeding. The selection of the appropriate feeding technique depends on the antenna geometry, desired impedance, and radiation characteristics [6].

Not all of the power is connected to the surface wave when a dielectric-rod antenna is fed by a waveguide. At the waveguide aperture, the power that is not connected to the surface wave is directly radiated [8].

In this study, waveguides are used to feed circular tapered dielectric-rod antennas. A tapered dielectric transition needs to be put into the feeding waveguide in order to act as an impedance match between the dielectric rod and the air-filled waveguide. In a perfect excitation, only the dominant mode would propagate along the rod, as assumed by this analysis. As a result, there's a chance that the outcomes won't exactly match those from real feeding methods. This approach works with feeding strategies including slots, magnetic ring currents, and circular waveguides that effectively excite the HE_{11}^{y} mode [9].

2.3. Operation Mechanism

The operating mechanism involves the use of a feed waveguide to transfer a portion of the input power to create a surface wave. This surface wave propagates along a dielectric structure with minimal reflection. As it travels along the dielectric structure, the surface wave undergoes a transformation from a tightly confined wave, primarily confined within the dielectric region, to a wave that propagates freely in space. This transformation process was observed by [2].

In the case of the circular tapered dielectric rod antenna, different sections perform different functions. The matching section provides an impedance match between the air-filled waveguide and the dielectric rod, facilitating efficient power transfer. The base or feed taper helps increase excitation efficiency by establishing the surface wave.

The surface wave then continuously radiates energy as it progresses along the straight section. To prevent unwanted reflections of the surface wave

caused by sudden changes, the nose or terminal taper is used to reduce such reflections. Schwering et al. highlighted the importance of these individual sections in their research.

2.4. Physical parameters of the dielectric rod antenna

In our work, a waveguide feeds the antenna, which is positioned atop a circular waveguide. The waveguide's dimensions can coincide with the frequency and be the same as those of the bottom plane. The bottom plane's dimension is smaller than the waveguide's corresponding frequency in our configuration. As a result, the substrate beneath the antennas needs to be composed of the same dielectric material. An array of identical rods, each constructed like a single antenna, could represent the antenna's design in this case.

As an alternative to obtaining a complex numerical solution, a simple semi-analytical formulation of the volume integral issue is obtained. The scattering problem is solved by simulating the tapered zone using the staircase approximation [10].

Each portion is modeled as a thin planar radiating cylinder with local radius R(r) and thickness dz. Based on the previous assumption, the total field $\vec{E}$ in the tapered region is estimated using local mode theory. To estimate J_{eq} in each part, the total electric field in the rod's core portion is utilized.

On the other hand, the geometrical design parameters of a dielectric antenna directly influence its radiation characteristics and impedance matching. Key parameters include the shape, size, and configuration of the antenna structure. The resonant mode of the dielectric material and the desired radiation pattern determine these parameters. Optimizing the geometrical design parameters enables achieving the desired radiation properties, such as high gain, directive radiation patterns, and wide bandwidth [6].

The dimensions of the antenna were calculated using the model described in [10,11]. It is important to note that the calculations are optimized for a center frequency f_0=360GHz and a poly-rod with a total length of $L \cong 14\lambda_0$. The physical characteristics of the circular dielectric conical rod antenna are listed in table 1.

Tab. 1. Physical parameters of the dielectric rod antenna.

Name	Description	Value	Name	Description	Value
F_0	Centre frequency	360 GHz	D_n	Nose diameter	221.7 µm
D_g	Waveguide diameter	562.9 µm	L_n	Nose length	416.4 µm
L_g	Waveguide length	916.0 µm	ε_r	Dielectric's relative permittivity	2.47
L_b	Base taper length	2.319 mm	tanδ	Dielectric's loss tangent	0.008

D_m	Matching section's base diameter	110.9 µm	X	Device X-dimension	562.9 µm
L_m	Matching section length	832.8 µm	Y	Device Y-dimension	562.9 µm
D_c	Centre diameter	291.7 µm	Z	Device Z-dimension	12.51 mm
L_c	Centre length	8.860 mm			

III. OBTAINED RESULTS

The proposed antenna is designed and simulated using CST Microwave studio software. In the proposed design the performance enhancement of antenna parameters is subject only to the geometric design of the antenna.

3.1. Reflection coefficient

The reflection coefficient and VSWR results are shown in figures 3 and 4 respectively. The plots show the results for designed antenna with a 2.47 relative dielectric constant substrate.

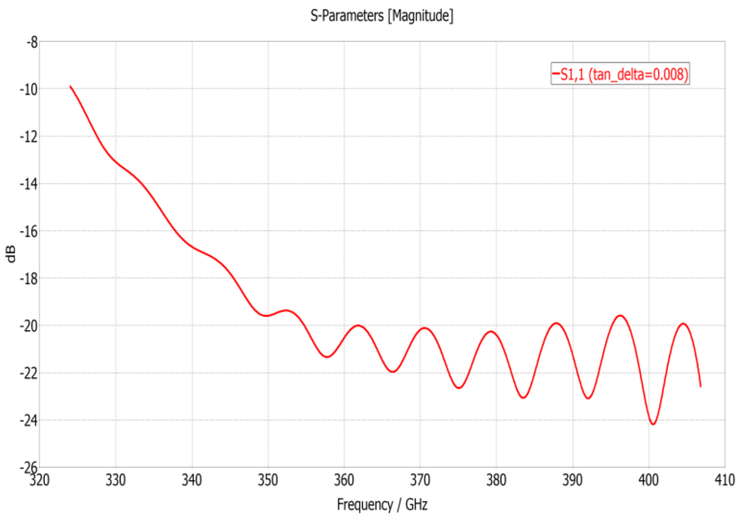

Figure 3. Reflection coefficient as a function of frequency.

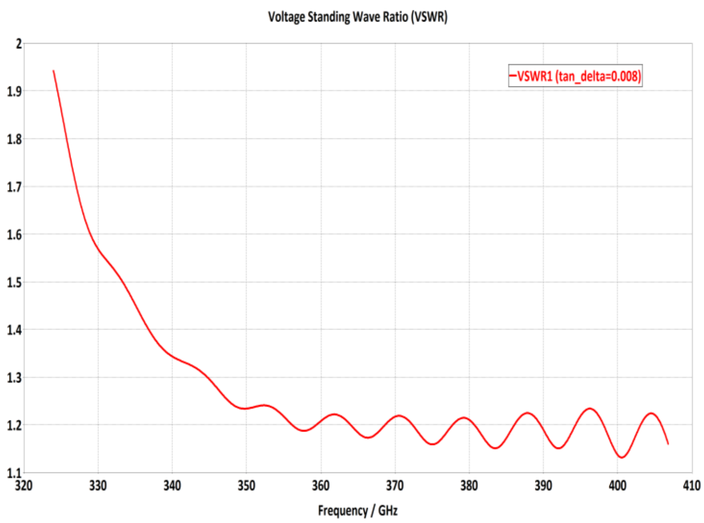

Figure 4. VSWR as a function of frequency.

It can see that the reflection coefficient decreases with frequency, it starts with the value of S_{11}=-10.00dB at the frequency f=324.23GHz and reaches its minimum value at the frequency 402.50GHz, where S_{11}=-24.18dB, which corresponds to a better adaptation. Beyond this frequency, S_{11} begins to increase, which is explained by the higher-order mode becoming excited. Typically, the circular tapered dielectric rod antenna has an S_{11} Bandwidth more than 21.74% (the band is almost UWB).

The VSWR results confirm those of S_{11}. Antenna matching begins at f=324GHz (VSWR<2) and improves with frequency, reaching perfect matching at f=400.50 GHz with VSWR=1.13. Beyond this frequency, the VSWR value increases for the same reasons discussed in the previous paragraph.

The impedance bandwidth of dielectric rod antennas can be quite wide, provided that the matching section within the waveguide is sufficiently long. According to Schwering et al. [2], the length of the matching section should range between $1.5\lambda_0$ and $2.5\lambda_0$; however, it has been observed that shorter lengths can also provide adequate matching. In our case study, we opted for a matching length of $L_m = \lambda_0$. It is clear that the designed antenna exhibits good matching over an ultra-wideband.

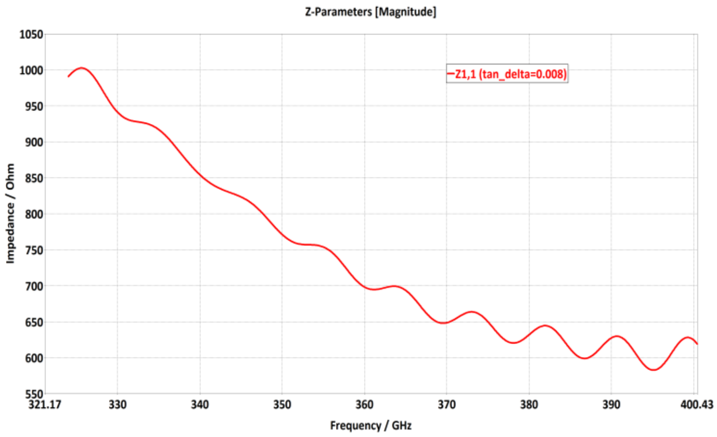

Figure 5. Antenna impedance as a function of frequency.

3.2. *Radiation pattern*

The antenna's 2D and 3D radiation patterns at frequency f_0 and its surrounding are shown in the figures 7 to 14.

A low VSWR indicates a well-matched antenna, but it does not guarantee even power distribution. Radiation pattern results provide a better answer to this question.

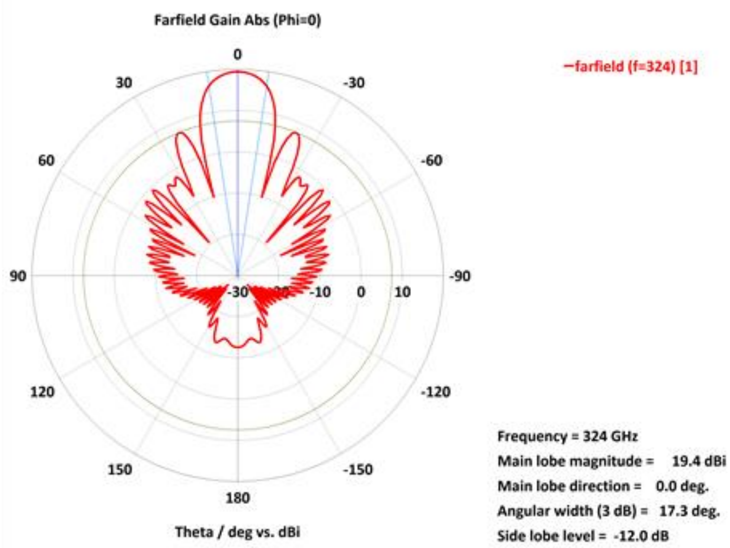

Figure 7. 2D Radiation pattern at 324 GHz.

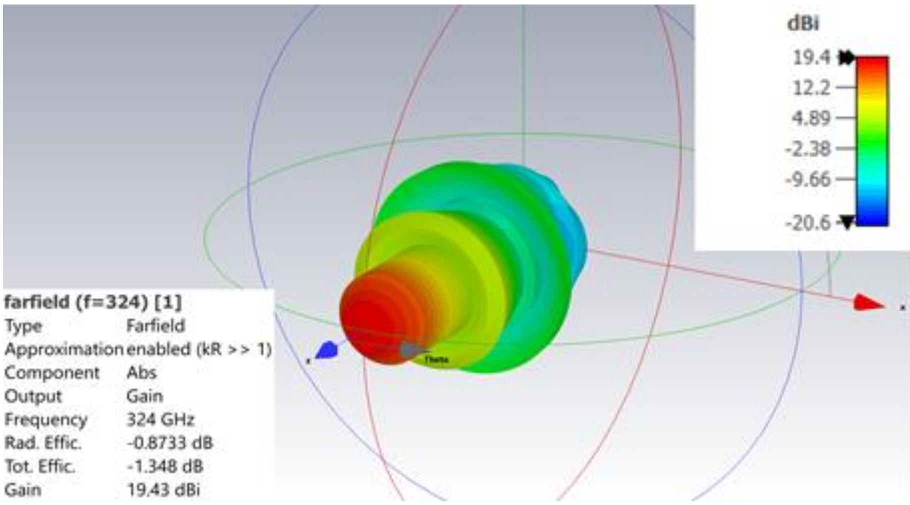

Figure 8. 3D Radiation pattern at 324 GHz.

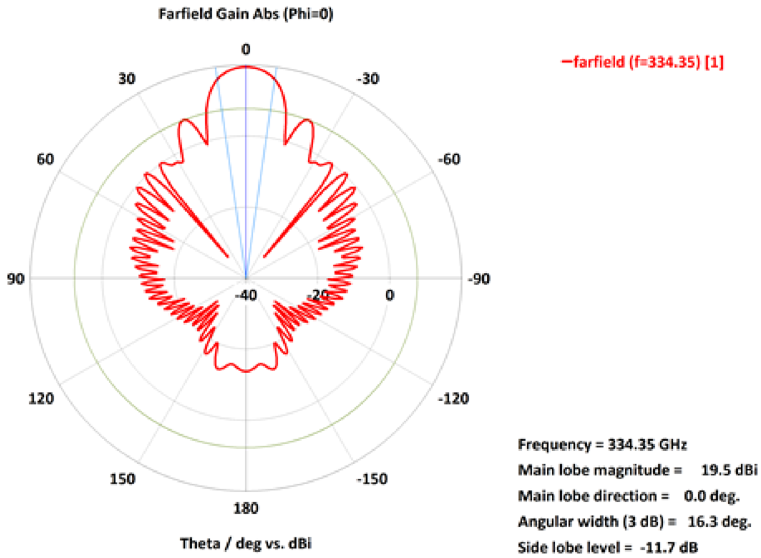

Figure 9. 2D Radiation pattern at 334.35 GHz.

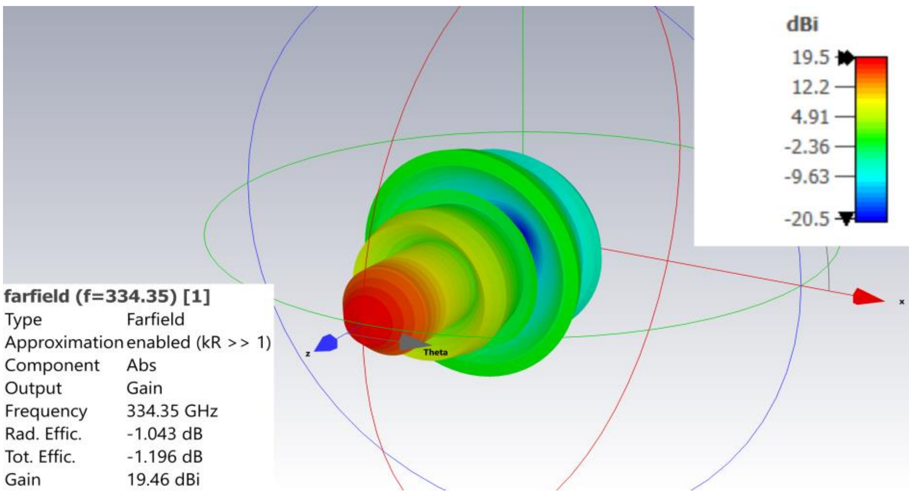

Figure 10. 3D Radiation pattern at 334.35 GHz.

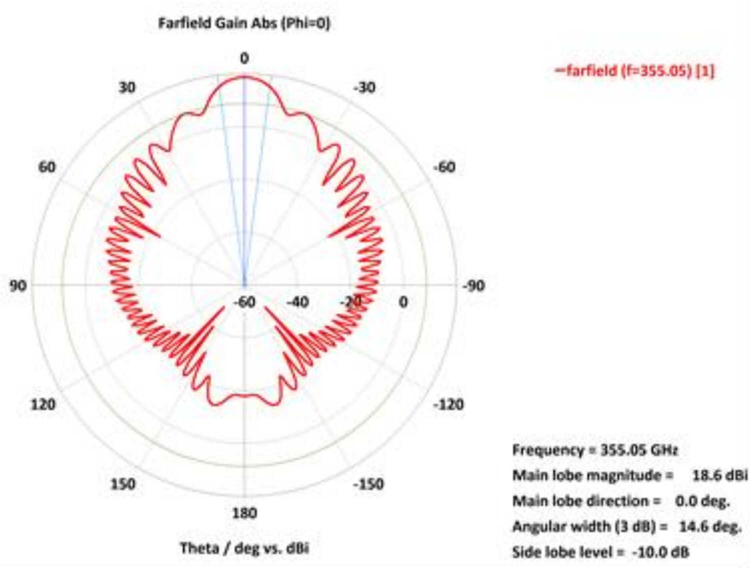

Figure 11. 2D Radiation patterns at 355.05 GHz.

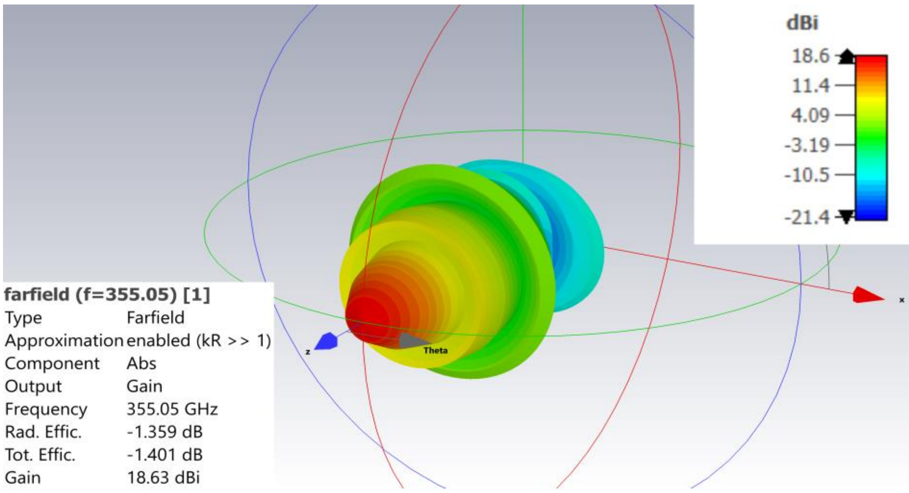

Figure 12. 3D Radiation pattern at 355.05 GHz.

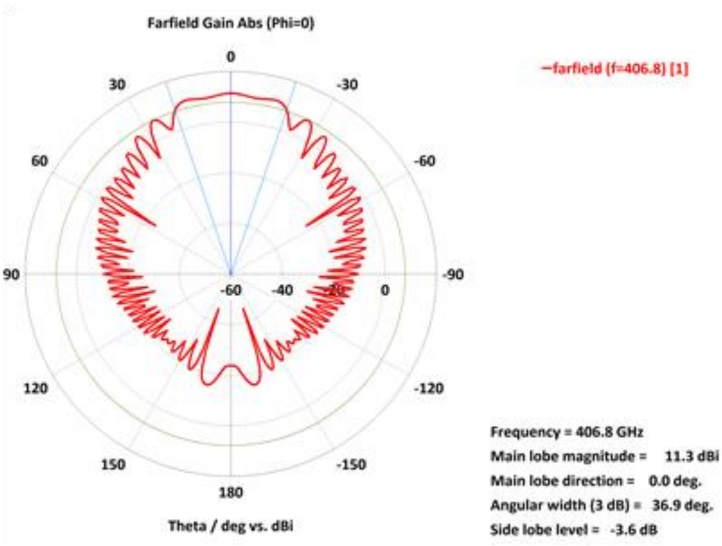

Figure 13. 2D Radiation pattern at 406.8 GHz.

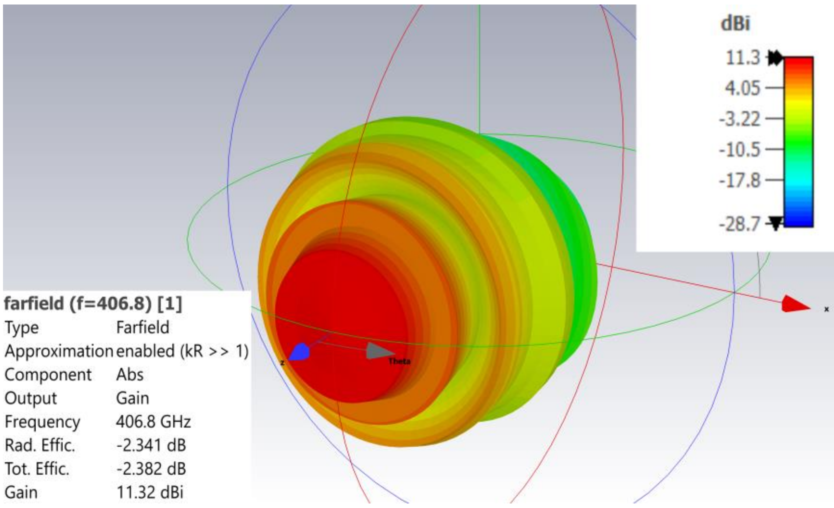

Figure 14. 3D Radiation patterns at 406.8 GHz.

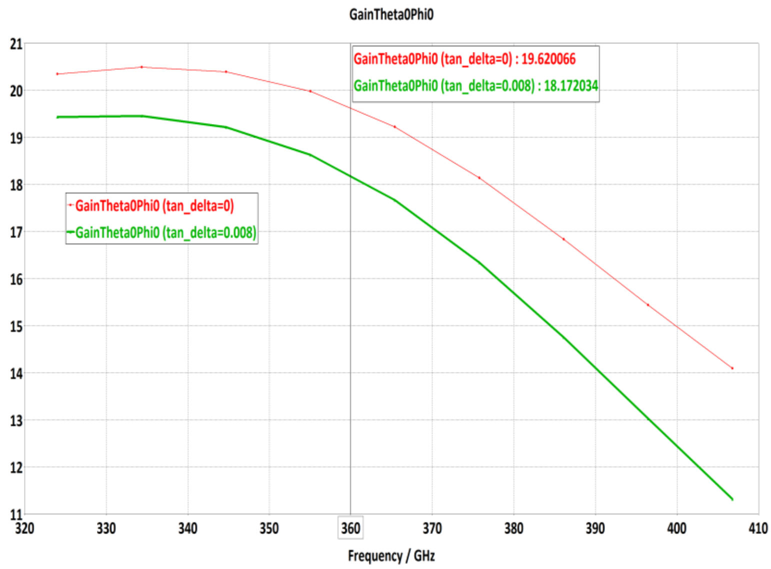

Figure 15. Total gain variation of the dielectric rod antenna.

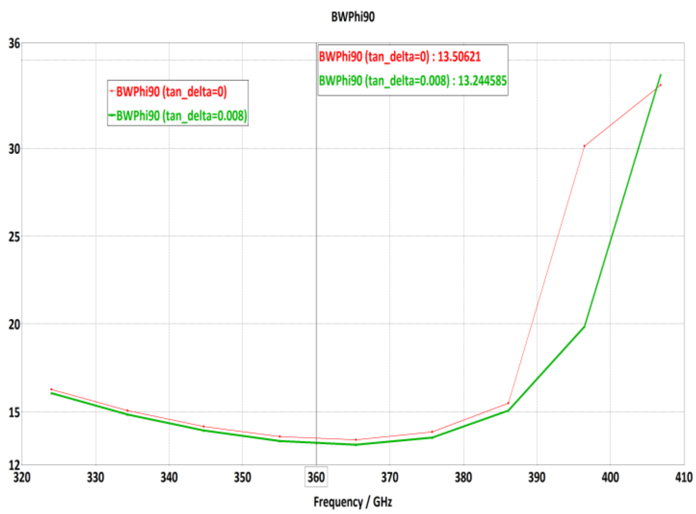

Figure 16. Beamwidth variation of the dielectric rod antenna.

Figures 7 through 16 illustrate that the antenna gain reaches maximum values between frequencies 324 GHz and 337 GHz, slightly exceeding 19.40 dB. Beyond this range, the gain begins to decrease but remains significant up to 362 GHz, where it is still above 18 dB across the entire band. From this central frequency, the gain continues to decrease more noticeably, reaching 11.32 dB at 406.8 GHz. However, at this frequency, the antenna still exhibits a broad beamwidth of 36.9°, which remains desirable for certain applications.

The results obtained indicate that the antenna radiates efficiently over a wide bandwidth, with substantial gain across most of the band (324 GHz–406.8 GHz) and very low side lobe levels within the same range. These findings are summarized in Table 2.

TABLE **2**. Radiation characteristics of the dielectric rod antenna.

Frequency (GHz)	**Magnitude of main lobe (dB)**	**Minimum beam width at half power (In degrees)**	**Side lobe level (dB)**
324.00	19.43	17.3	-12.0
334.35	19.46	16.3	11.7
355.05	18.63	14.6°	-10.0
360.00	18.70	13.25	-09.5
365.40	17.70	14.1°	-08.5
386.10	14.75	15.0°	-04.8
391.45	13.03	20.2°	-02.7
406.80	11.32	36.9°	-03.6

3.3. Gain Performance

At the frequency of 360 GHz (centre frequency), for the antenna designed with length $L \approx 14\lambda_0$, the antenna demonstrates high directivity, achieving a gain of 19.62 dB in the ideal lossless case ($\tan\delta = 0$) and 18.17 dB in the lossy case ($\tan\delta = 0.008$). The antenna maintains a beamwidth of 13.5°, aligning with Zuker's law [15]:

$$G = p\frac{L}{\lambda_0} \quad \text{with } p=7\ (L>8\lambda_0), \tag{1}$$

$$BW_{HP} = 55\sqrt{\frac{\lambda_0}{L}} \tag{2}$$

The frequency response of the gain highlights the impact of dielectric loss ($\tan\delta$), showing that even with slight material losses, the antenna maintains satisfactory performance over a wide frequency range. This level of directivity and narrow beamwidth is suitable for high-frequency applications, where efficient energy focusing and minimal side lobes are critical.

The significant decrease in gain beyond 360 GHz can be attributed to the level of radiated power losses in the dielectric, as illustrated in figure 17.

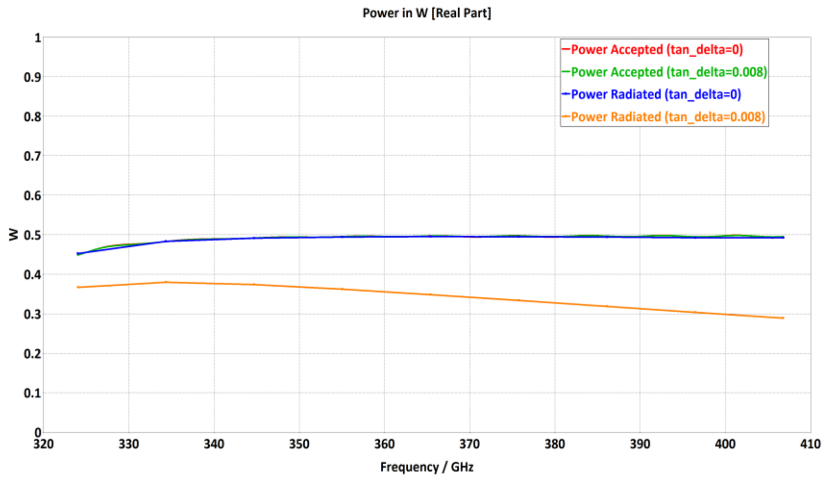

Figure 17. Power accepted and radiated.

IV. CONCLUSION

An ultra-wideband circular tapered dielectric rod antenna intended for Sub-THz applications is described here. The antenna features dual polarization, a symmetrical design, low side lobes, and a high gain. The antenna's exceptional performance over the 324GHz–406.8GHz spectrum is confirmed by the 2D and 3D findings, which show a maximum gain of 19.46dB, side lobes of -12 dB, and a reflection coefficient of -10dB to -24.18dB. Because of the well-matched waveguide feed section, pattern degradation is not a hindrance to the antenna's operation. This produces a dual-polarized, symmetrical-pattern, high-gain antenna with a broad bandwidth and good radiation efficiency. The antenna structure is reasonably priced and easy to assemble. It can be used as a reflector feed or a near-field probe.

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