Int. j. adv. multidisc. res. stud. 2025; 5(2):527-531

Received: 23-01-2025
Accepted: 03-03-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Hybrid Dielectric (Tube-Rod) Antenna: Design and Analysis for Enhanced Performance at Wide X-Band

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Abstract

This paper discusses developing and analyzing a hybrid (Rod-Tube) dielectric antenna that utilizes Teflon ($\varepsilon_r = 2.2$) as a feeding material. A MATLAB program was used to plot and calculate antenna parameters such as the radiation pattern, half-power beamwidth, maximum power, directivity, and gain. The radiation pattern was analyzed over a frequency range of 8 to 12 GHz; it was too sharp and demonstrated a consistent shape and intensity, which indicates the antenna's wide operational bandwidth within the X-band frequency range. Notably, the side-lobs were suppressed, enhancing the antenna's performance. The antenna exhibited high directivity, and the gain of the antenna was 21.83 dB and 20.8 dB, respectively.

Keywords: Dielectric Antenna, Hybrid Antenna, Directivity, Gain, Radiation Pattern, X-band

Introduction

Dielectric resonator antennas, known for their low profile, lightweight construction, and high-quality factor, have emerged as promising candidates for various applications, including telecommunications, radar, and satellite systems. Among dielectric resonator antennas, dielectric rod and tube antennas have garnered significant attention due to their inherent advantages, such as simple geometries, ease of fabrication, and potential for broadband operation. However, individual rod and tube antennas often exhibit bandwidth, radiation pattern control, and gain limitations. Recent research efforts have explored the concept of hybrid structures that combine the unique characteristics of both rod and tube antennas to overcome these limitations. For instance, [Petosa and Ittipiboon, 2010] [1] demonstrated the potential of integrating rod and tube sections to achieve broader bandwidth, while [Saffold, 2011] explored the impact of tapered transitions between rod and tube sections on antenna performance. Furthermore, [Nalanagula *et al.*, 2022] investigated the use of met-materials to enhance the performance of hybrid dielectric structures, showing promising results in miniaturization and bandwidth enhancement.

The following review discusses microwave hybrid antennas that integrate dielectric tube and rod elements to improve performance in various applications. Dielectric tube antennas, valued for their compact size and high efficiency, provide enhanced impedance matching and bandwidth compared to metallic waveguides, with challenges in frequency response optimization (Liu *et al.*, 2018) [6]. Integrating resonators with dielectric tubes has led to more efficient hybrid designs, especially for millimeter-wave applications (Balanis *et al.*, 2020) [4]. Dielectric rod antennas, known for directional radiation patterns and compactness, benefit from hybridization with other components like metallic patches to improve radiation efficiency and gain (Zhang *et al.*, 2021) [8]. Additionally, using different rod dimensions allows for tailored performance, making them suitable for radar and communication systems (Yang *et al.*, 2019) [7]. Hybrid antenna systems combining dielectric tubes and rods with metallic or other dielectric components enhance bandwidth, gain, and radiation control, offering advantages in miniaturization and multi-frequency operation (He *et al*., 2022; Chen *et al.*, 2021) [5, 9]. These advancements indicate promising directions for developing high-performance antennas for modern microwave and millimeter-wave systems [Balanis, *et al.*, 2020] [4].

This paper focuses on the design of hybrid dielectric (rod-tube) antennas, including their analysis. The aim is to operate the antenna at wide band; X-band (8-12 GHz) was chosen for that. We will examine various parameters of the antenna and its characteristics, such as the dimensions of the rods and tubes, directivity, gain, and overall performance. Additionally, we will analyze the radiation pattern of this hybrid antenna.

Theoretical Design

To create a hybrid design of the antenna, we can combine elements from both formulas. One possible hybrid formula one have to derive the composite formula. From equation (1) the electric field component for (Rod antenna) [Ahmed, 1982] [10] and from equation (2) for (Tube antenna) [Al Taan, 2002] [11] start to Hybrid formula derivation:

$$E_{rod} = \left[\frac{Sin \quad k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,)}{k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,)}\right] Cos(\frac{k_o d}{2} Sin\theta\,) \tag{1}$$

$$E_{tube} = \left[\frac{Sin \quad (\frac{\pi\ell}{\lambda}(1-Cos\theta))}{(\frac{\pi\ell}{\lambda}(1-Cos\theta))}\right] Cos\,(\frac{\pi d}{\lambda} Sin\theta) \tag{2}$$

The radiation from the hybrid dielectric antenna can created as illustrated in Fig 1:

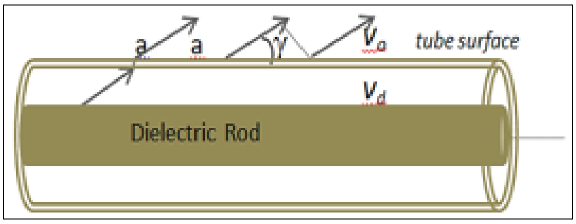


Fig 1: The creation of radiation from hybrid dielectric (Tube –Rod) antenna

We need to find a composite electric field $E_{composite}$ that incorporates both the rod and tube antenna formulas. This can be expressed as: $E_{composite} = \alpha\, E_{rod} + \beta\, E_{tube}$, where α and β are weighting factors that depend on the relative contributions of the rod and tube antennas, [He, 2022] [5].

Substitute the given formulas for E_{rod} and E_{tube} into the composite formula:

$$E = \alpha\left[\frac{Sin \quad (k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta))}{k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta)} Cos\,(\frac{k_o d}{2} Sin\theta)\right] + \beta\left[\frac{Sin \quad (\frac{\pi\ell}{\lambda}(1-Cos\theta))}{(\frac{\pi\ell}{\pi}(1-Cos\theta))} Cos(\frac{\pi d}{\lambda} Sin\theta)\right] \tag{3}$$

To simplify the expression, composite the sine and cosine terms yields the composite formula for the electric field $E_{composite}$:

$$E = \left[\alpha\left[\frac{Sin \quad (k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,))}{k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,)}\right] + \beta\left[\frac{Sin \quad (\frac{\pi\ell}{\lambda}(1-Cos\theta\,))}{(\frac{\pi\ell}{\pi}(1-Cos\theta\,))}\right]\right] Cos(\frac{k_o d}{2} Sin\theta\,) \tag{4}$$

This formula combines the sinusoidal and cosine terms from both the tube and rod antenna formulas, potentially capturing characteristics of both designs. The strategies to reduce side lobes apply the (Tapering Function Modification) T(θ), [Broughton and Kraft, 2020 - Chen and Ott, 2009] [12, 13]:

$$E = T(\theta)\left[\alpha\left[\frac{Sin \quad (k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,))}{k_d \frac{\ell}{2}(1-\frac{1}{\sqrt{\varepsilon_r}}Cos\theta\,)}\right] + \beta\left[\frac{Sin \quad (\frac{\pi\ell}{\lambda}(1-Cos\theta\,))}{(\frac{\pi\ell}{\pi}(1-Cos\theta\,))}\right]\right] Cos\,(\frac{k_o d}{2} Sin\theta\,) \tag{5}$$

Where, T(θ); which is given as one of the following:
Exponential, [Colburn and Hiatt, 1984] [14]: $T(\theta) = n!\, \exp(-k \times \theta^2)$,
Raised Cosine, [Pozar, 2012] [15]: $T(\theta) = 0.5 \times (1 + n!\cos(n!.\pi \times \theta))$, here, $(k = 2\pi/\lambda)$, n=1-3.
Finally, the hybrid (Tube-Rod) antenna can illustrated as in Fig 2:

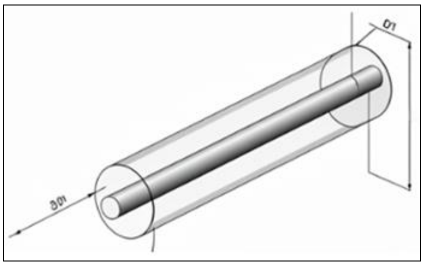


Fig 2: Schematic of the hybrid dielectric (tube–rod) antenna

This hybrid formula combines the characteristics of both dielectric rod and tube antennas, resulting in a unique radiation pattern that utilizes the strengths of each design.

Schematic Description:

1. **Dielectric Rod (central Element):** The core of the antenna is a dielectric rod, typically made from a low-loss material such as Teflon (ε_r=2.2). This dielectric rod guides the electromagnetic waves and determines the primary resonance frequency.
2. **Dielectric Tube (outer Structure):** Surrounding the dielectric rod is a dielectric tube, usually made from the same Teflon material, which enhances the radiation properties. The central dielectric rod supports wave propagation and is responsible for most of the antenna's radiation characteristics.
3. **Feed Point:** This connects the antenna to the transmission line.
4. **Tapering Function:** The tapering function, T(θ, is similar to the Hamming window and helps to reduce side lobes. By incorporating this tapering function, we can adjust the amplitude of the electric field based on the angle θ, effectively reducing side lobes while maintaining the focus on the main lobe.

Generally, dielectric materials with high permittivity are ideal for microwave applications.

The Characteristics of Antenna

A radiation pattern's *Half-Power Beamwidth (HPBW)* measures the angular width of the main lobe where the radiated power drops to half of its maximum value (or -3dB). The HPBW can depend on several factors for hybrid dielectric antennas, such as the antenna's geometry, dielectric materials, and frequency. The beamwidth can be found at ($P_{max}/\sqrt{2}$). where needed, improving efficiency and effectiveness over a range of frequencies.

The directivity: The directivity, D of an antenna is a measure of how concentrated the radiation pattern is in a particular direction compared to an isotropic source. For the Hybrid Dielectric (Tube-Rod) antenna, the directivity formula is derived from the maximum radiation intensity U_{max} and the total radiated power P_{rad} [Saeed and Jazi, 2018] [16]: $D = 4\pi/(\theta_{HPBW})^2$, ……… (6),

θ_{HPBW}, the beam-width of the radiation pattern at half maximum power.

The Gain: The gain, G of an antenna can be calculated using the formula $G = \eta\, D$, ……..(7),

η, is the efficiency of the antenna which is about, ($1< \eta <0.7$).

The Radiated Power: To create a simplified mathematical relationship for the total power radiated from a hybrid antenna, let's use the general formula and put the parts together, $E(\theta, \varphi) = E_o\, f(\theta, \varphi)$, and the density of radiation potential, [Kraus and Marhefka, 2002] [17]: $P(\theta, \varphi)=|E(\theta, \varphi)|^2/2.\ Z_o$, ………(8)

Where Z_o, free wave impedance in the space (about 377 ohms).

Now the total radiated power can be simplified without using integration if we have a directional antenna, the equation can be simplified as: $P_{total}= P_{input}.\ G/ 4\pi$ ……….(9),

Since an antenna cannot convert all the input power into radiated power, the radiated power is less than the input power after taking into account internal losses. This means that if you have an antenna with efficiency η, the radiated power can be calculated by the following equation [Balanis, 2005] [18]:

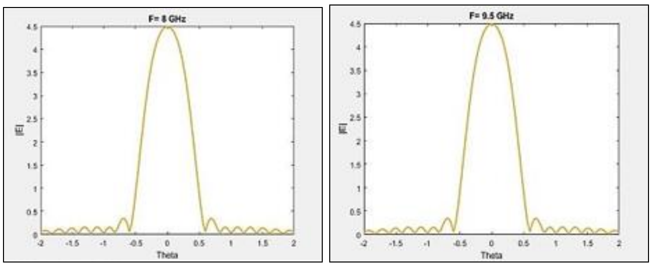
$$P_{total}= \eta\, P_{input} \tag{10}$$

Results and Discussion

A Matlab program was developed to calculate the radiation pattern, half-power beamwidth, P_{max}, directivity (D), and gain (G) of the antenna. The program begins by inputting the following data:

Speed of light, $c=3\times10^8$ m/s, relative permittivity, ε_r =2.2, the antenna length, $l = 5\times\lambda_d$, the diameter of the antenna, $d=1\times\lambda_d$. In this context, λ_o(the wavelength in air) is calculated as λ_o=c/f, and the wavelength in the dielectric is given by $\lambda_d = \lambda_o/\sqrt{\varepsilon_r}$. (see the flowchart in Appendix).

The radiation pattern shown in Fig (3) for different frequencies (8 to 12) GHz.



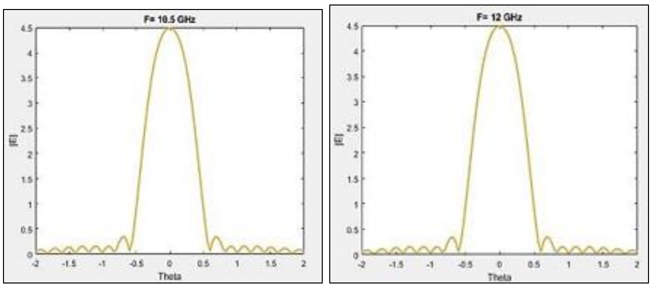


Fig 3: The radiation pattern for different frequencies: a-8, b-9.5, c-10.5, d-12 GHz

Fig (3) shows that the shape and intensity of the radiation pattern did not change with different frequencies. This indicates that the design of the current hybrid antenna has a wide working range within the band-X frequencies. In addition, the side lodes were disappear. Fig (4) shows the 3D radiation pattern at 10 GHz frequency. It shows the design antenna produce a high directivity.

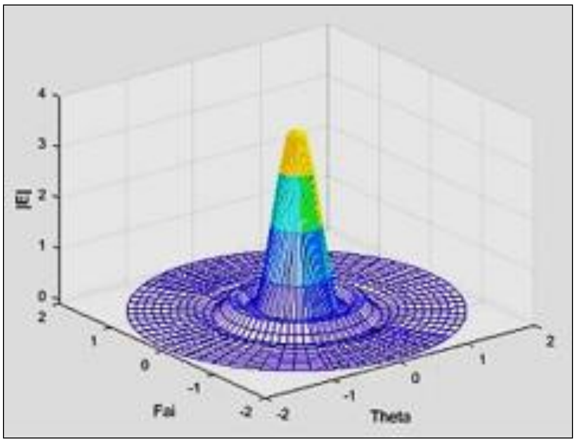


Fig 4: The 3D radiation pattern for hybrid dielectric antenna at 10GHz

The radiation power P_{rad}, also was plotted, as shown in the Fig (5).

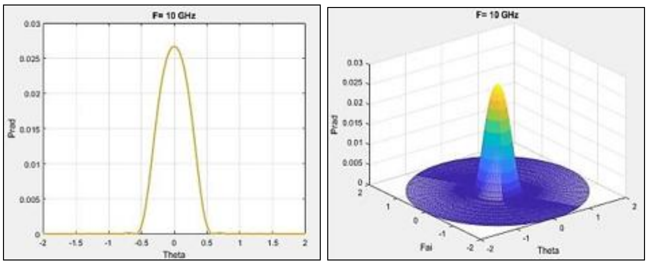


Fig 5: The 2D and 3D radiation power P_{rad} (Watt) for hybrid dielectric antenna at 10GHz

Figures (4 and 5) show that the power is directed in specific directions.
The other results of the antenna characteristics were calculated using equations (6, 7, and 8) as follows:
From Fig (5) as $P_{max}=26\times 10^{6}$ W, the $\theta_{HPBW}=0.52^{o}$. Then D= 152. And, $D_{dB}= 10 \log_{10} (D) = 21.83$ dB.
Now from eq.(7) the gain calculate as($\eta\approx 0.8$) G =121,92. And $G_{dB}= 20.8$ dB.
These results were summarize in the Table (1) bellow:

Table 1: The calculation results for the Hybrid Antenna at 10GHz

	Dimensionless	**In (dB)**
Directivity	152	21.83
Gain	121.9	20.8

The directivity value in decibels, as shown in the table above, indicates a strong concentration of radiated energy in a specific direction. This characteristic allows the antenna to effectively radiate energy over long distances or towards precise targets, making it valuable for applications such as communications, radar, and other systems that require accurate targeting. Additionally, gain is a critical parameter that measures the antenna's ability to amplify signals. A gain of 20.86 dB means that the antenna can significantly enhance the power of received or transmitted signals compared to an isotropic antenna.

Conclusion

The sharp beam structure indicates that the antenna concentrates most of its radiated energy in one direction. This means high signal steering efficiency and reduced interference with other devices. The absence of secondary side lobes indicates an excellent design that reduces wasted energy and improves signal quality in the desired direction. High directivity means the antenna concentrates radiation into a narrow beam, increasing signal strength in that direction. High gain also means that the antenna increases the strength of the transmitted or received signal compared to a reference antenna (such as a dipole antenna). This means a more extended signal range and improved communication quality. Where Teflon was used as an insulating material: As a suitable material for high frequencies, it has low signal loss at high frequencies (such as 10 GHz). This ensures efficient energy transfer within the antenna. It is a material resistant to heat, moisture and chemicals, making it a reliable choice for various environments. Based on these properties, this antenna can be used in many applications, such as improving wireless communication quality and increasing range in Wi-Fi and 5G networks. The radar provides more accurate and clear radar images. Also, more accurate data can be collected from satellites and drones in remote sensing.

Acknowledgment

Researchers pray to Almighty God for mercy on Dr. Rashid Al-Rashed's soul, acknowledging his contributions to microwave physics and antenna engineering.

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