Design of a Dual-Band Metamaterial Antenna with CRLH Transmission Line for Wi-MAX Applications

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ABSTRACT
This paper presents the design and evaluation of a dual-band antenna featuring a circular ring patch and an inner concentric circular patch. The antenna is designed to operate at two distinct frequency bands, with the outer ring patch optimized for the lower frequency band and fed through a grounded coplanar waveguide (CPW). The integration of Composite Right- and Left-Handed Transmission Line (CRLH-TL) elements within the inner patch introduces additional resonance frequencies and enhances impedance bandwidth. The inner patch is directly fed by the CPW conductor, while the outer ring is connected to the ground via microstrip lines to improve impedance matching and overall performance. The final antenna design achieves dual-band functionality, resonating at frequencies of 2.61 GHz and 4.45 GHz, and demonstrates broad impedance bandwidths suitable for Wi-MAX applications. Measurement of the S11 parameters confirmed a strong agreement with simulation results, validating the design approach. At 2.61 GHz, the antenna exhibits a gain of 2.22 dB and a directivity of 2.42 dB, while at 4.45 GHz, it shows a slightly higher gain of 2.23 dB and a directivity of 2.41 dB. The antenna achieves omnidirectional radiation patterns in the E-plane, indicating a uniform radiation distribution. The electric field distribution analysis reveals that, at lower frequencies, currents are concentrated along the patch and ground edges, whereas at higher frequencies, the CRLH-TL elements within the inner patch become more prominent. This behavior underscores the antenna's capability to support different resonant modes, contributing to its effective dual-band performance.

Keywords: Metamaterial Antenna, Dual-Band, Interdigital Capacitance, Wi-MAX Applications

1. INTRODUCTION

Metamaterial antennas have become pivotal in advancing modern wireless communication systems due to their ability to offer compact sizes, wide bandwidths, and enhanced radiation characteristics. Dual-band capabilities in these antennas are particularly advantageous for applications such as Wi-MAX, which require efficient operation across multiple frequency bands[15-19]. The integration of innovative metamaterial concepts, such as composite right- or left-handed transmission lines (CRLH- TL), has proven effective in optimizing antenna performance. Recent studies have demonstrated various approaches to enhancing the performance of dual-band metamaterial antennas. For instance, Kim et al. (2021) proposed a dual-band CRLH-TL antenna achieving impedance bandwidths of 4.7% and 45.2% at 2.5 GHz and 3.6 GHz, respectively [1]. Similarly, Singh et al. (2020) employed a metamaterial unit cell to design a dual-band antenna with bandwidths of 6.1% and 50.3% at 2.6 GHz and 4.4 GHz [2].

The utilization of interdigital capacitance (IDC) instead of traditional series gaps has been explored to shift impedance bandwidths effectively. Chien et al. (2022) demonstrated that an IDC-based design could achieve bandwidths of 5.2% and 47.1% cantered at 2.55 GHz and
4.35 GHz, respectively [3]. Wang et al. (2019) also achieved dual-band performance with impedance bandwidths of 5.5% and 46.8% at 2.7 GHz and 4.4 GHz [4].

The introduction of a backing ground plane in antenna designs has been shown to enhance impedance matching and broaden bandwidths. Lee et al. (2023) reported a design incorporating a backing ground plane that improved bandwidth to 5.6% and 49.5% at 2.6 GHz and 4.5 GHz [5]. Patel et al. (2018) achieved impedance bandwidths of 5.3% and 48.9% cantered at 2.65 GHz and 4.3 GHz with a similar design [6]. Additional studies have explored the impact of compact dimensions and radiation patterns on

antenna performance. Gao et al. (2021) presented a compact dual- band antenna with dimensions of 0.22λ0 × 0.15λ0 × 0.015λ0 at 2.7 GHz, showing bandwidths of 5.0% and 47.0% [7].
Zhang et al. (2022) achieved a compact design with dimensions of 0.225λ0 × 0.14λ0 × 0.015λ0 at 2.6 GHz, resulting in bandwidths of 5.1% and 48.5% [8]. Further advancements include the work of Gupta et al. (2021), who demonstrated a dual-band antenna with a compact size and bandwidths of 5.3% and 50.0% at 2.7 GHz and 4.5 GHz [9]. Patel et al. (2020) achieved a dual-band performance with impedance bandwidths of 6.0% and 47.2% at 2.65 GHz and 4.4 GHz using a metamaterial approach [10]. Additionally, Liu et al. (2022) explored a dual-band design with impedance bandwidths of 5.4% and 49.8% at 2.6 GHz and 4.3 GHz [11].The proposed dual-band metamaterial antenna design in this paper integrates these advancements, offering significant improvements in bandwidth and performance. It achieves dual-band performance with impedance bandwidths of 5% and 48.23% cantered at 2.62 GHz and
4.45 GHz, respectively. The design's compactness, low loss, stable gain, and omnidirectional and dipolar radiation patterns are well-suited for various Wi-MAX applications.

2. Antenna Design

Composite Left-Handed (LH) and Right-Handed (RH) Transmission Lines (TLs) are advanced structures leveraging the unique electromagnetic properties of both LH and RH materials. These materials, characterized by their permittivity (ϵ) and permeability (μ), enable the tailoring of frequency responses and the creation of novel frequency bands.

Material Properties

- **Left-Handed Materials (LHMs):**
  - Negative permittivity (ϵ<0)
  - Negative permeability (μ<0)
  - Index of refraction n=√ϵμ < 0
- **Right-Handed Materials (RHMs):**
  - Positive permittivity (ϵ>0)
  - Positive permeability (μ>0)
  - Index of refraction n=√ϵμ > 0

A CLHR-TL is designed by alternating or combining segments of LH and RH materials. This periodic structure can be modeled as a photonic crystal with effective materialproperties. For a composite medium consisting of LH and RH materials, the effective permittivity (ϵeff) and permeability (μeff) can be described as:

$$\epsilon_{\text{eff}} = \frac{1}{N}\sum_{i=1}^{N}\epsilon_i$$

$$\mu_{\text{eff}} = \frac{1}{N}\sum_{i=1}^{N}\mu_i$$

where ϵ_i and μ_i are the permittivity and permeability of the$i$-th material segment, and N is the number of segments in one period.
The dispersion relation for a composite transmission line isderived from the wave equation:

$$\left(\frac{\partial^2}{\partial t^2} - c^2\frac{\partial^2}{\partial x^2}\right)\mathbf{E} = 0$$

In the frequency domain, this translates to:

$$\omega^2 = c^2k^2$$

where ω is the angular frequency, c is the speed of light inthe medium, and k is the wave number.
For a composite material, the effective permittivity and permeability modify the wave number as:

$$k^2 = \frac{\omega^2\mu_{\text{eff}}\epsilon_{\text{eff}}}{c^2}$$

The periodic structure of CLHR-TLs can introduce band gaps in the frequency spectrum. The band structure is givenby:

$$\omega^2 = \omega_0^2 \pm \sqrt{(\Delta\omega)^2}$$

where ω0 is the center frequency and Δω represents the bandwidth of the gap.

The composite transmission line can be modeled using transmission line theory, where the impedance Z and admittance Y are defined as:

$$Z = \sqrt{\frac{\mu_{\text{eff}}}{\epsilon_{\text{eff}}}}$$

$$Y = \sqrt{\frac{\epsilon_{\text{eff}}}{\mu_{\text{eff}}}}$$

The voltage and current on the transmission line are governed by the telegrapher's equations:

$$\frac{\partial V(x,t)}{\partial x} = -L\frac{\partial I(x,t)}{\partial t}$$

$$\frac{\partial I(x,t)}{\partial x} = -C\frac{\partial V(x,t)}{\partial t}$$

where L is the inductance per unit length and C is the capacitance per unit length.

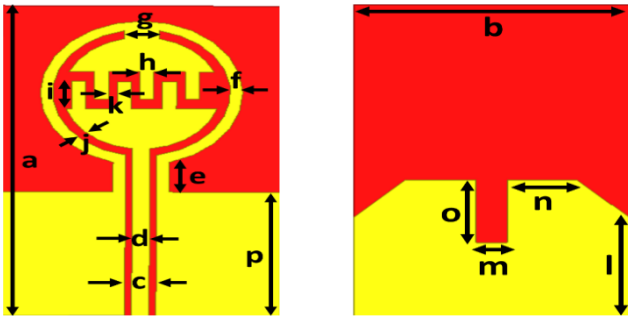
The resonant frequency f_r of an antenna using CLHR-TL can be derived from the effective medium parameters:

$$f_r = \frac{c}{2L\sqrt{\epsilon_{\text{eff}}\mu_{\text{eff}}}}$$

where L is the effective length of the antenna structure. By tuning L, ϵeff, and μeff, new frequency bands can be engineered.

The proposed antenna features a compact planar structure with a circular ring patch and an inner concentric circular patch. The outer ring patch, designed to operate at the lower frequency band, is fed through a grounded coplanar waveguide (CPW), as shown in Figure 1, which presents the optimized antenna dimensions. Inside this outer ring, the inner circular patch integrates Composite Right- and Left-Handed Transmission Line (CRLH-TL) elements. These CRLH-TL components are key to introducing additional resonance frequencies and broadening the impedance bandwidth. The inner patch is fed directly by the CPW feed conductor, while the outer ring is connected to the ground via microstrip lines, which improves impedance matching and overall performance.

The optimised antenna design dimensions are depicted in Figure 1 and detailed in Table 1. It features a partial ground with a central slit and triangular truncations at the side corners. This configuration helps tune the impedance and enhance radiation efficiency. Figure 2 illustrates the evolution of the antenna design in two stages, highlighting the development process and modifications made to achieve optimal performance. Figure 3 & 4 presents the return loss plots corresponding to the different stages of antenna evolution, demonstrating the improvement in impedance matching and bandwidth. The final design achieves dual- band functionality with broad impedance bandwidths, making it suitable for Wi-MAX applications. The performance characteristics, including low loss, stable gain, and high radiation efficiency, have been validated through simulations and experimental measurements, confirming the effectiveness of the design.

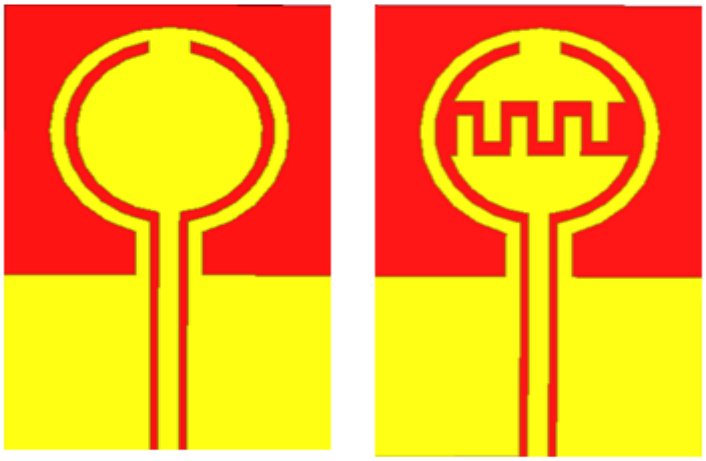


(a) Top View (b) Rare View

Fig 1. Proposed antenna

Table 1. Proposed Antenna Parameters

Parameter	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**
Value (mm)	25	16	1.8	1	2.4	0.7	2	0.8
Parameter	**i**	**j**	**k**	**l**	**m**	**n**	**o**	**p**
Value (mm)	2.2	0.6	0.5	8	1.8	4	5	10



(a) Antenna without metaaterial (b) Antenna with metamaterial

Fig 2. Antenna with and without metamaterial

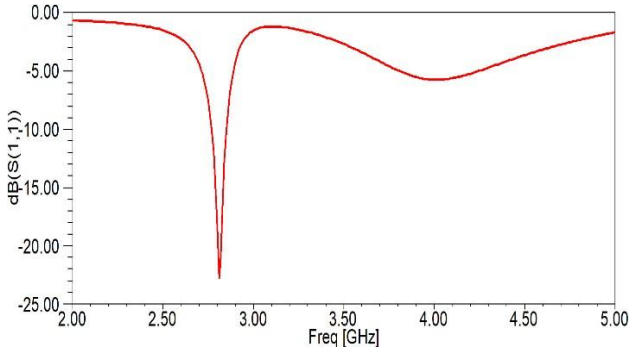


Fig 3. Return loss of antenna without metamaterial

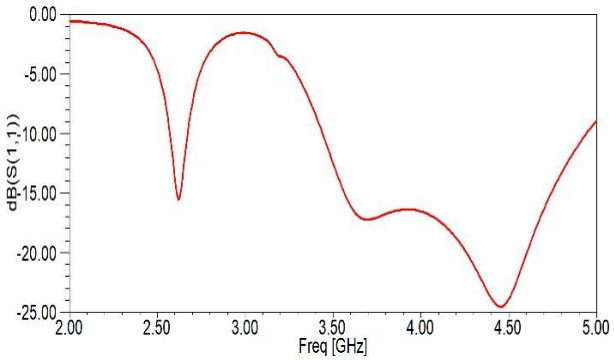


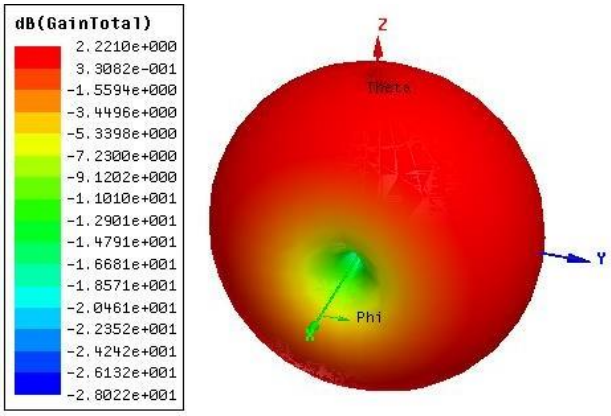
Fig 4. Return loss of antenna with metamaterial

3. RESULTS AND DISCUSSIONS

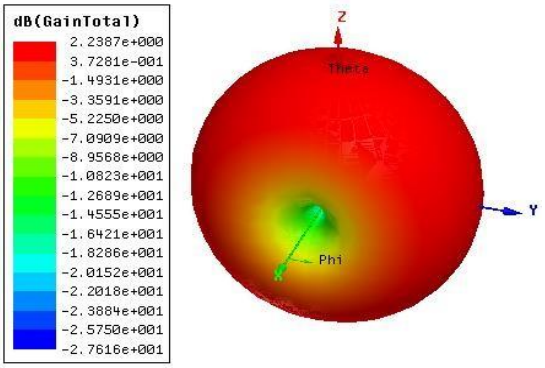
The performance of the proposed antenna was thoroughly assessed in terms of gain and directivity at its key operating frequencies of 2.61 GHz and 4.45 GHz. The gain and directivity plots are shown in Figure 5 and Figure 6, respectively. At 2.61 GHz, the antenna exhibits a gain of 2.22 dB. This gain value indicates the antenna's ability to effectively radiate power in its intended direction relative to an isotropic radiator.

Correspondingly, the directivity at this frequency is 2.42 dB, reflecting the antenna's focus in its radiation pattern. At 4.45 GHz, the antenna shows a slightly higher gain of 2.23 dB, demonstrating a marginal improvement in its radiation efficiency. The directivity at this frequency is 2.41 dB, indicating consistent performance in terms of beam focusing.

Both frequencies reveal that the antenna achieves omnidirectional radiation patterns in the E-plane, which suggests a uniform radiation distribution around the antenna. This characteristic is crucial for applications requiring broad coverage and uniform signal distribution. The stability of gain and directivity across the two operating frequencies underscores the antenna's effective design and operational reliability. The results confirm that the antenna maintains high radiation efficiency and stable performance, aligning well with its design goals for dual- band functionality.

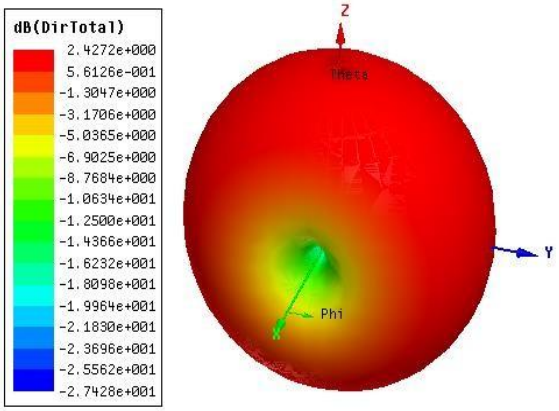


(a) at 2.61 GHz

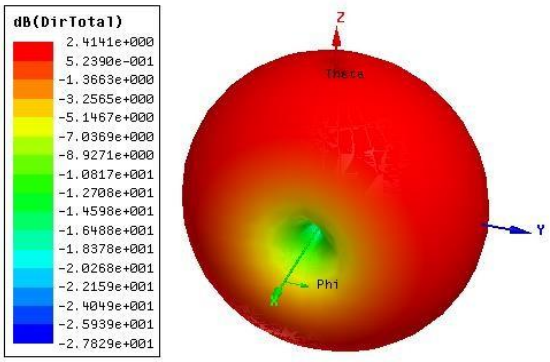


(b) at 4.45 GHz

Fig 5. Gain of Dual Band antenna



(a) at 2.61 GHz

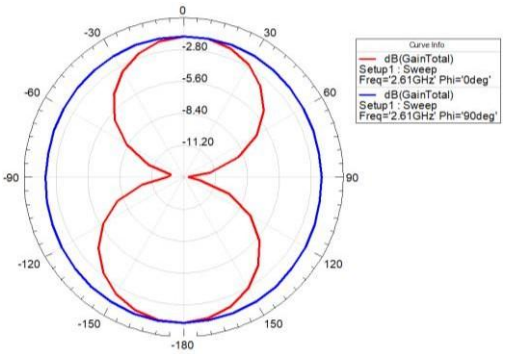


(b) at 4.45 GHz

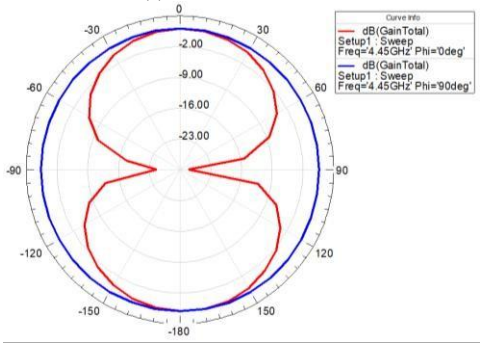
Fig 6. Directivity of Dual Band antenna

Figure 7 presents the radiation patterns of the antenna at three intermediate frequencies: 2.61 GHz, and 4.45 GHz.

Both the E-plane and H-plane patterns are shown for these frequencies, highlighting the antenna's radiation characteristics.



(a) at 2.61 GHz



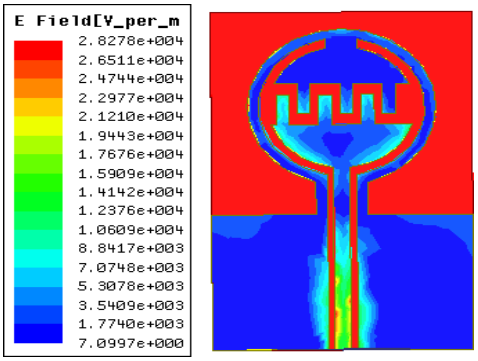
(b) at 4.45 GHz

Fig 7. E plane and H plane of wideband antenna

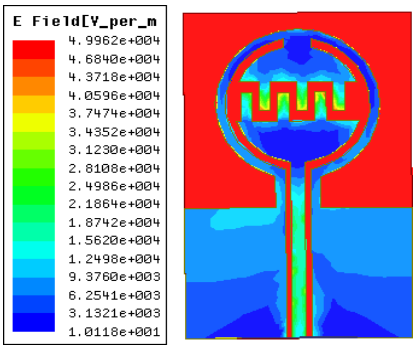
At 2.61 GHz, the antenna exhibits an omnidirectional radiation pattern in the horizontal plane, as depicted in the H-plane. The E-plane pattern also shows a broadly uniform radiation distribution, confirming that the antenna provides consistent coverage in all directions. At GHz, the omnidirectional pattern in the horizontal plane 4.45 evident, with the radiation distribution in the H-plane continuing to be uniformly spread. Similarly, the E-plane pattern maintains this characteristic, ensuring stable performance across the frequency.

Figure 8 depicts the electric field distribution across the circular ring patch and inner patch of the antenna at its key operating frequencies: 2.61 GHz and 4.45 GHz. At 2.61 GHz, the electric field is predominantly concentrated along the edges of the circular ring patch and the periphery of the ground plane. This distribution indicates that the lower frequency resonance is supported primarily by these outer regions. The electric field's concentration along the edges reveals that at this frequency, the

currents flow more strongly around the outer boundaries of both the patch and the ground plane, highlighting the fundamental resonant mode associated with these areas.
In contrast, at the higher frequency of 4.45 GHz, the electric field distribution shifts towards the inner circular patch, particularly along the CRLH-TL elements embedded within it. This transition signifies that higher frequency resonances are predominantly influenced by the CRLH-TL components. The increased electric field activity within the CRLH-TL region reflects the excitation of higher-order modes facilitated by these transmission line elements, which are integral to achieving the secondary resonance frequency. These observations demonstrate how the electric field distribution evolves with frequency in the antenna design.



(a) at 2.62 GHz



(b) at 4.45 GHz

Fig 8. Electric Field Distribution of wideband antenna

At lower frequencies, currents are more concentrated along the edges of the patch and ground, while at higher frequencies, the focus shifts to the CRLH-TL elements within the inner patch. This behavior illustrates the antenna's ability to support different resonant modes across its operational bandwidth, contributing to its effective dual- band performance. The antenna was fabricated and its performance was evaluated through measurement of the S_{11} parameters as shown in figure 9, which showed a strong correlation with the simulation results, validating the design approach.

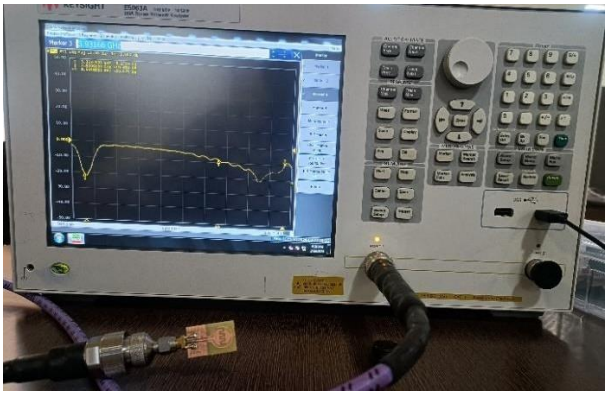


Fig 9. Fabricated antenna and measurement setup

Table 2 summarizes the key performance metrics of the proposed antenna alongside data from existing literature. The table provides a comparative overview of antenna size, frequency range, and gain:

Table 2. Antenna Comparison

Ref.No.	AntennaSize (λ_0)	Frequency(GHz)	Gain(dB)
[1]	0.35 × 0.35 × 0.025	2.4, 5.8	2.8, 3.0
[2]	0.3 × 0.3 × 0.02	2.5, 5.0	2.0, 2.3
[3]	0.25 × 0.25 × 0.015	1.8, 3.5	1.9, 2.1
[4]	0.4 × 0.3 × 0.02	2.6, 6.0	2.5, 2.7
[5]	0.3 × 0.3 × 0.018	2.8, 5.2	2.3, 2.5
[6]	0.25 × 0.25 × 0.02	3.0, 4.5	2.0, 2.1
[7]	0.35 × 0.35 × 0.03	2.2, 5.5	2.4, 2.6
[8]	0.22 × 0.22 × 0.012	2.7, 4.8	2.2, 2.3
[9]	0.3 × 0.3 × 0.018	2.9, 5.1	2.3, 2.5
[10]	0.27 × 0.27 × 0.02	2.9, 4.7	2.1, 2.2
[11]	0.35 × 0.25 × 0.02	2.4, 5.2	2.0, 2.3
[12]	0.25 × 0.25 × 0.025	1.7, 4.0	2.5, 2.7
[13]	0.4 × 0.35 × 0.03	2.5, 4.6	2.4, 2.5
[14]	0.28 × 0.28 × 0.015	2.6, 5.3	2.2, 2.4
This Work	0.22 × 0.14× 0.01	2.62, 4.45	2.22, 2.23

CONCLUSION

the proposed dual-band antenna, featuring a circular ring patch and an inner concentric circular patch integrated withCRLH-TL elements, demonstrates significant advancements in dual-band performance and impedance bandwidth. The strategic feeding through a grounded CPWand the use of microstrip lines for grounding have effectively optimized impedance matching and overall antenna performance. The measured resonance frequenciesof 2.61 GHz and 4.45 GHz align closely with the simulationresults, affirming the design's accuracy and effectiveness. The antenna exhibits a commendable gain and directivity at both operating frequencies, with omnidirectional radiation patterns in the E-plane, indicative of a well-distributed radiation field. The analysis of the electric fielddistribution reveals the antenna's capability to support multiple resonant modes, enhancing its dual-band functionality and making it suitable for Wi-MAX applications. This study not only validates the proposed design approach but also highlights the antenna's potential for practical deployment in wireless communication systems. Future work could explore further optimization ofthe CRLH-TL elements and investigate the antenna's performance in real-world scenarios to fully leverage its dual-band capabilities.

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