



DESIGN AND ELECTROMAGNETIC ANALYSIS OF A HIGH-GAIN DUAL-BAND MICROSTRIP FILTENNA AT 26/29 GHz BASED ON COUPLED RECTANGULAR RESONATORS

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ABSTRACT

This article describes the design and electromagnetic evaluation of a high-gain dual-band microstrip filtenna operating at 26 and 29 GHz. The proposed filtenna solution employs coupled rectangular resonators embedded in a planar configuration to ensure both filtering and transmission. Dual-band operation is achieved over the 25–31 GHz range, with reflection coefficients below -30 dB at both resonant frequencies. A transmission coefficient (S₂₁) of approximately -2 to -3 dB in the passbands validates the filtering behavior. The filtenna ensures constant direct radiation with a maximum gain of approximately 10.58 dB at both operating frequencies, making it suitable for millimeter wave wireless applications in the 26/29 GHz bands.



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I. INTRODUCTION

The rapid development of millimeter-wave (mmWave) wireless communication systems has spurred research into compact, high-performance radio frequency (RF) front-end components. In particular, the 26 GHz and 29 GHz frequency bands have been identified as key candidates for fifth-generation (5G) RF2 applications due to their ability to handle high data transfer rates, low latency, and improved spectral efficiency. However, antenna devices operating in the millimeter-wave spectrum face numerous challenges, including increased propagation loss, stringent size requirements, and the imperative of high selectivity and enhanced radiation stability [1], [2]. In traditional RF front-end architectures, filtering and transmission tasks are commonly assigned to separate components: bandpass filters and antennas. While this approach offers considerable design flexibility, it inevitably leads to greater circuit complexity, higher insertion losses, and increased system size, particularly at millimeter-wave frequencies [3], [4]. To overcome these limitations, the concept of a filter antenna, often referred to as a "filtenna," has proven to be an effective solution. Filtennas, which combine filtering and radiation functions within a single structure, reduce the number of components, minimize interconnect losses, and possess inherent frequency selectivity. These characteristics make them attractive for compact and integrated wireless systems [5]. Microstrip filtennas have attracted considerable interest due to their planar architecture, thin profile, ease of integration, and compatibility with modern RF circuits [6-8]. The literature describes several methods for implementing filtering in microstrip antennas, including the use of defected ground structure (DGS), open and shorted stubs, parasitic elements, and resonant slots [9], [10]. These methods promote increased bandwidth, harmonic suppression, and optimal impedance matching while maintaining satisfactory radiation characteristics. However, many of the designs discussed emphasize single-band operation or offer limited gain and low out-of-band attenuation, particularly in the millimeter wave range. To overcome these obstacles, coupled resonator filtenna configurations were considered a potentially advantageous option. The use of various resonant elements with controlled electromagnetic coupling makes it possible to produce multiple resonance modes while offering dual-band or multi-band functionality in a compact form factor [11]. Rectangular resonators, in particular, are of interest due to their simple geometry, predictable resonance behavior, and easy integration into microstrip circuits. The interaction between neighboring resonators promotes improved frequency selectivity and superior control of the filter response, while also contributing to radiation [12]. This article presents the design and electromagnetic analysis of a high-gain, dual-band microstrip filtenna operating at 26 GHz and 29 GHz, based on coupled rectangular resonators.

The proposed antenna utilizes controlled coupling between the rectangular resonators to produce two separate resonance modes, enabling dual-band operation in the 25–31 GHz range. Unlike traditional antenna solutions, the proposed structure inherently exhibits filtering behavior, as demonstrated by its scattering parameters, while maintaining stable directional characteristics. A detailed electromagnetic analysis was performed to gain a deeper understanding of the proposed filtenna. The study of scattering parameters confirmed the two-band filtering response, while examination of the electric and magnetic field distributions provided insights into resonance generation, interaction effects, and frequency selectivity. Furthermore, analyses of radiation properties such as gain, directivity, and radiation patterns were conducted to demonstrate the proposed filter's suitability for high-frequency wireless applications. The remainder of this paper is organized as follows. Section 2 presents the theoretical operating principle of the proposed microstrip filtenna, including its electromagnetic behavior and resonant mechanism. Section 3 describes the filtenna configuration and design methodology. Section 4 discusses the simulated results and performance analysis. Finally, Section 5 concludes the paper.

II. OPERATING PRINCIPLE OF THE PROPOSED MICROSTRIP FILTENNA

II.1 CONCEPT OF INTEGRATED FILTERING RADIATION

A microstrip filtenna combines the characteristics of a bandpass filter and a radiating element in a single configuration plane [13]. Unlike conventional antennas followed by external filters, frequency selectivity in a filter is efficiently achieved through resonant elements that also participate in radiation. Consequently, the filtenna exhibits a controlled bandwidth response, strong out-of-band suppression, and efficient radiation within the desired frequency bands. In the proposed design, the filtering behavior is realized by a set of coupled rectangular resonators integrated into a microstrip configuration. These resonators act as distributed electromagnetic elements that store electric and magnetic energy and radiate selectively at their resonant frequencies. The interaction between adjacent resonators produces multiple resonant modes, enabling dual-band operation without increasing the overall footprint.

II.2 RESONANT MECHANISM OF RECTANGULAR MICROSTRIP RESONATORS

Each rectangular resonator can be modeled as a half-wavelength microstrip resonator operating in its fundamental mode. The resonance condition of an isolated rectangular microstrip resonator can be approximated by [8]:

$$f_r = \frac{c}{2L_{eff}\sqrt{\epsilon_{eff}}} \quad (1)$$

Where:

c is the speed of light in free space,

L_{eff} is the effective resonator length including fringing fields, and

ϵ_{eff} is the effective dielectric constant of the substrate.

By properly selecting the dimensions of the rectangular resonators, resonances are introduced around 26 GHz and 29 GHz, corresponding to the two operating bands of the proposed filtenna. However, dual-band operation is not achieved by isolated resonators alone, but rather through electromagnetic coupling between adjacent resonant elements.

II.3 COUPLING EFFECT AND DUAL-BAND FORMATION

When rectangular resonators are placed in close proximity, electromagnetic coupling occurs through overlapping electric and magnetic fields. This coupling can be described using coupled-resonator theory, where the interaction between resonators leads to the splitting of resonant modes into distinct frequencies. For two coupled resonators, the resonant frequencies can be expressed as [14]:

$$f_{\pm} = f_0\sqrt{1 \pm k} \quad (2)$$

Where:

f_0 is the uncoupled resonant frequency

k is the coupling coefficient determined by the physical separation and geometry of the resonators.

In the proposed filtenna, the coupling between the rectangular resonators generates two dominant resonant modes, which are responsible for the observed resonances at 26 GHz and 29 GHz. This controlled coupling mechanism directly results in the dual-band filtering response, as confirmed by the deep minima in the reflection coefficient.

II.4 FIELD DISTRIBUTION ANALYSIS AND PHYSICAL INTERPRETATION

Analysis of the distribution of electric and magnetic fields clarifies the mode of action of the proposed filtenna. At resonant frequencies, a strong electric field concentrates in the rectangular resonators, indicating capacitive energy storage and validating their function as major resonant elements. However, the magnetic field propagates primarily along the narrow microbands that connect the resonators, thus illustrating inductive coupling and energy transmission between neighboring elements. This complementary distribution of electric and magnetic fields justifies the liquid crystal-based interpretation and confirms that the resonators provide both frequency selection and radiation. Furthermore, the spatial distribution of the fields differs between the two resonance frequencies, suggesting the activation of distinct resonance modes that underlie the bi-band response.

Unlike conventional bandpass filters, where transmitted energy is delivered to a matched load, the proposed filtenna radiates a significant portion of the energy within the passbands [14]. This explains the observed transmission coefficient behavior, where moderate attenuation within the passband is inherent to the radiation mechanism rather than indicative of excessive losses. Consequently, the proposed structure exhibits a combined filtering and radiating response, characterized by: strong impedance matching at the resonant frequencies, inherent suppression of out-of-band signals, stable and directive radiation at 26 GHz and 29 GHz. This integrated behavior confirms the suitability of the proposed coupled-resonator-based microstrip filtenna for compact millimeter-wave wireless systems.

III. FILTENNA CONFIGURATION AND EQUIVALENT CIRCUIT INTERPRETATION

III.1 GEOMETRY OF THE PROPOSED MICROSTRIP FILTENNA

The proposed microstrip filtenna is implemented on an FR4 substrate with an overall dimension of 23 mm × 10 mm and a substrate thickness of 0.254 mm. The filtenna topology consists of three identical rectangular resonators connected in series through narrow microstrip sections, forming a compact and planar integrated filtering-radiating structure. Each rectangular resonator has physical dimensions of 3.28 mm × 3.47 mm, which are carefully selected to support resonant modes in the millimeter-wave frequency range. The identical sizing of the resonators ensures a controlled and predictable electromagnetic coupling along the series configuration, while the spacing between adjacent elements governs the strength of interaction and mode splitting. The equations below will let us know how we can calculate the dimensions of the rectangular patch [9].

$$W = \frac{c}{2f} * \sqrt{\frac{2}{\epsilon_r + 1}} \quad (3)$$

$$L = \frac{c}{2f} \left(\frac{\epsilon_r + 1}{2} - \frac{\epsilon_r - 1}{2} \sqrt{1 + 12 \frac{h}{w}} \right)^{-\frac{1}{2}} - 2\Delta L \quad (4)$$

The narrow microstrip sections providing the interconnections function as impedance conversion devices and introduce an additional inductive load, essential for impedance matching and frequency selectivity. Consequently, the overall structure operates as a distributed resonant system rather than a traditional single-element antenna.

Table 1: Antenna parameters.

Parameters		Values (mm)
Substrate	A	23
	B	10
Patch	C	3.28
	D	3.47
	E	1
	F	4.27
	G	0.54
	H	0.6
	I	0.25

Source: Authors, (2026).

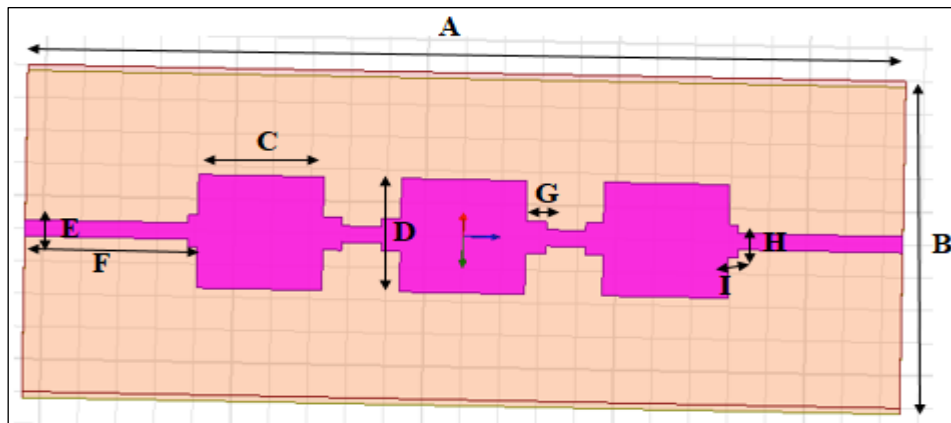


Figure 1: Proposed microstrip filtenna.

Source: Authors, (2026).

III.2 EQUIVALENT RLC CIRCUIT INTERPRETATION

To provide a clear physical insight into the operating mechanism of the proposed filtenna, an equivalent RLC circuit interpretation is employed. The filtenna can be modeled as a series-coupled resonant network, where each rectangular resonator is represented by a parallel RLC branch. In this interpretation:

The equivalent inductance (L) arises from the surface current paths flowing along the rectangular patches and the narrow microstrip interconnections, the equivalent capacitance (C) is mainly attributed to the strong electric field confinement over the rectangular resonators and across the coupling gaps, the equivalent resistance (R) represents the combined effect of conductor losses, dielectric losses of the FR4 substrate, and radiation losses [15]. The suggested filtenna can be viewed as a series-coupled resonant network, where each rectangular resonator is represented by a resonant parallel RLC branch. From this perspective, the resonant behavior of each rectangular element can be approximated by the classical resonance condition for a parallel RLC circuit, formulated as follows:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

The input impedance of a parallel RLC resonator is given by:

$$Z(w) = \left(\frac{1}{R} + jwC + \frac{1}{jwL} \right)^{-1} \quad (6)$$

At the resonance condition:

$$W_r = \frac{1}{\sqrt{LC}} \quad (7)$$

In this context, the impedance tends to be essentially resistive, ensuring ideal impedance matching and pronounced minima in the reflection coefficient at 26 and 29 GHz. Furthermore, since the suggested structure operates as a filter antenna, the transmitted power is deliberately shared between filtering and transmission. The power conservation equation describes this behavior [15].

$$|S_{11}|^2 + |S_{21}|^2 + P_{rad} = 1 \quad (8)$$

Where P_{rad} denotes the radiated power. As a result, the moderate values of S_{21} observed within the passbands are not indicative of losses but rather confirm the effective radiation mechanism of the filtenna.

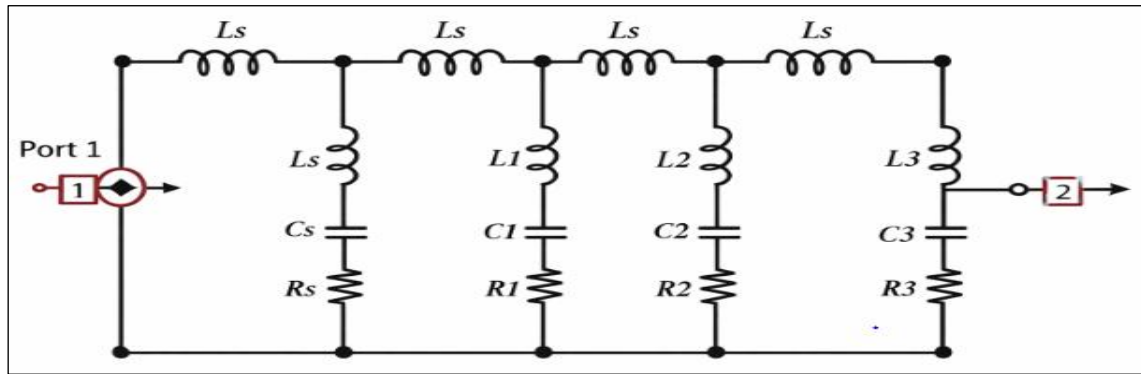


Figure 2: Equivalent RLC circuit of the microstrip filtenna.

Source: Authors, (2026).

Due to the series coupling between the three rectangular resonators, an additional reactive load is introduced, which modifies the inductance and effective capacitance of the resonant paths. This interaction excites two dominant resonant modes, corresponding to the dual-band operation observed at 26 GHz and 29 GHz. The filtenna distributed radiation mechanism is simulated by increasing radiation resistances along the resonant path, thus reflecting the gradual radiation of the structure. It should be emphasized that the proposed equivalent RLC circuit provides a qualitative and physical interpretation of the filter's behavior, rather than a precise extraction of parameters using discrete elements. However, the model adequately explains the impedance matching, mode separation, and filter-radiation integration characteristics recorded in the electromagnetic simulation results. The quality factor Q is a key parameter that characterizes the energy storage capability of the resonant elements in the proposed filtenna. It quantifies the ratio between the stored electromagnetic energy and the energy dissipated through radiation and losses per cycle. For an equivalent RLC resonator, the unloaded quality factor is expressed as [13]:

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}} \quad (9)$$

Alternatively, the quality factor can be extracted from the frequency response using the -3 dB bandwidth method:

$$Q = \frac{f_r}{BW_{-3dB}} \quad (10)$$

BW_{-3dB} denotes the bandwidth measured at half-power points. In the proposed filtenna, the use of three coupled rectangular resonators amplifies the effective quality factor by increasing energy retention within the structure, while maintaining controlled emission. This phenomenon is manifested by distinct resonance features at 26 GHz and 29 GHz, thus confirming the filtering performance of the antenna-filter combination. The moderate Q factor, resulting from the balance between stored and emitted energy, is ideal for the operation of the filter antenna since it ensures adequate selectivity without excessively compromising the operational bandwidth.

IV. RESULTS AND DISCUSSION

IV.1 SCATTERING PARAMETERS ANALYSIS

Figure 3 illustrates the simulated reflection and transmission coefficients of the proposed filter. The reflection coefficient shows two resonances, located at 26 GHz and 29 GHz, thus confirming dual-band operation. For both frequencies, the reflection coefficient S_{11} remains below -10 dB, indicating good impedance matching in the operating bands. At 26 GHz, the minimum value of S_{11} reaches approximately -31 dB, while at 29 GHz it remains below -28 dB, indicating excellent impedance matching at both resonant frequencies. These deep reflection nulls confirm the effective excitation of the resonant modes generated by the series-coupled rectangular resonators and validate the resonance mechanism predicted by the equivalent RLC model discussed in Section 3. The transmission coefficient S_{21} reveals controlled bandwidth behavior, exhibiting moderate attenuation at the resonance frequencies. Unlike traditional filters, the proposed structure operates as a filtenna, in which a portion of the guided energy is deliberately emitted. Thus, the observed insertion levels do not indicate losses but rather demonstrate the integration of filtering and radiation mechanisms within a single structure. The transmission coefficient S_{21} shows passband responses around the two operating frequencies, with insertion levels of approximately -2 dB at 26 GHz and -2.5 dB at 29 GHz. Unlike conventional microwave filters, where low insertion loss is the primary objective, the proposed structure operates as a filtenna, in which part of the input power is intentionally radiated into free space.

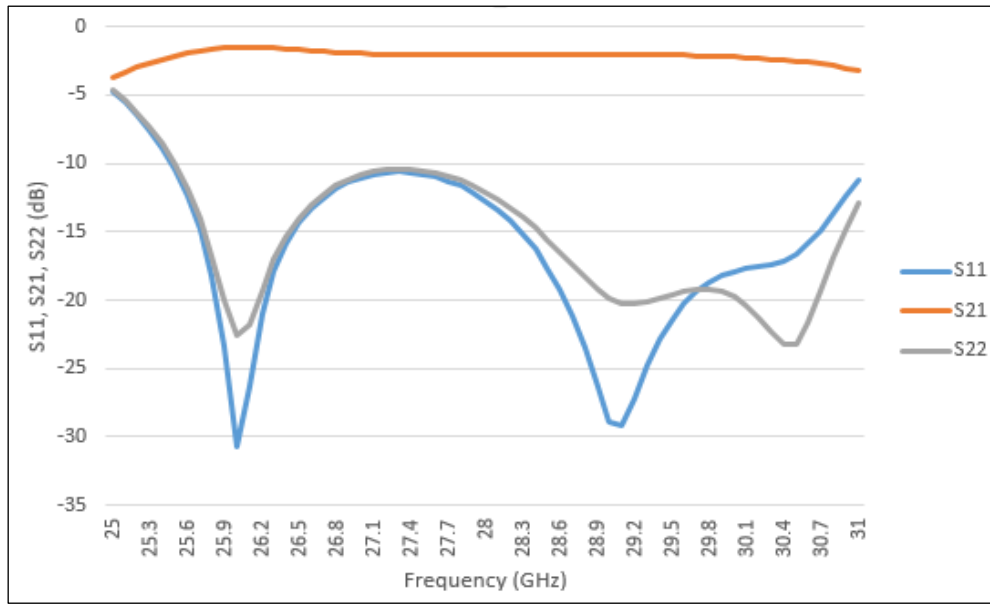


Figure 3: Reflection and transmission coefficients of the proposed filtenna.

Source: Authors, (2026).

IV.2 ELECTRIC AND MAGNETIC FIELD DISTRIBUTIONS

The electric and magnetic field distributions of the proposed filter at resonant frequencies are examined to understand the filtering and radiation processes. Figure 4 shows the electric field strength, while Figure 5 depicts the distribution of the associated magnetic field on the upper metallic layer. According to Figure 4, the maximum amplitude of the electric field reaches approximately 5.7×10^4 V/m. High electric field concentrations are observed primarily at the edges of the rectangular resonators and along the small interconnecting sections. These areas coincide with regions of intense leakage, confirming the predominantly capacitive nature of the resonators. The effect of electromagnetic coupling, which leads to the excitation of various resonance modes and the associated dual-band response, is highlighted by the uneven distribution of the field between the three resonators. Figure 5 shows that the magnetic field reaches an approximate maximum amplitude of 2.6×10^2 A/m. High magnetic field strengths are concentrated mainly on the feed line and the connections between the resonators, indicating a significant surface current. This behavior confirms the inductive quality of the narrow microstrip sections, which are of paramount importance in controlling the resonance frequencies and the intensity of the coupling between neighboring resonators. The simultaneous existence of strong electric and magnetic fields within the resonator structure illustrates efficient energy storage and controlled power transmission. Furthermore, the spatial superposition of the intense E and H fields confirms that a portion of the guided energy is indeed transformed into radiation in free space, which explains the moderate transmission rates observed in the S_{21} response. Overall, the field distributions, along with their specific amplitudes, clearly demonstrate the resonance, coupling, and radiation mechanisms that govern the operation of the suggested dual-band microstrip filtenna.

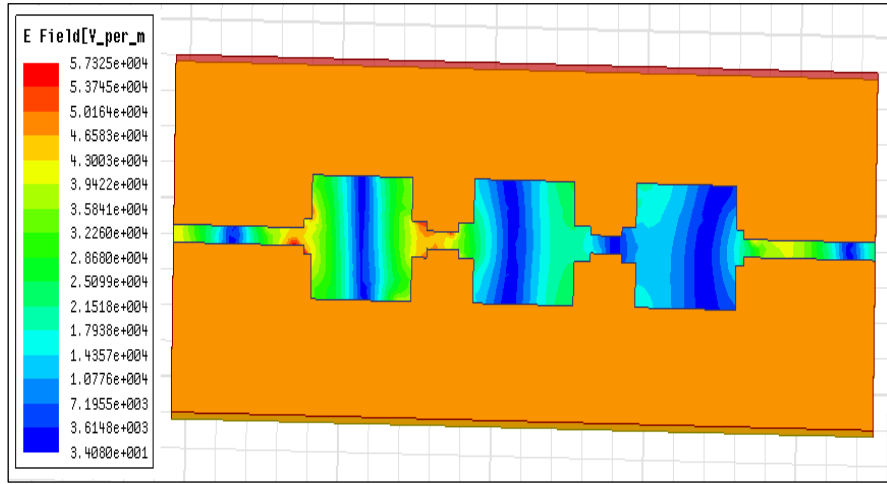


Figure 4: Electric fields of the proposed filtenna.

Source: Authors, (2026).

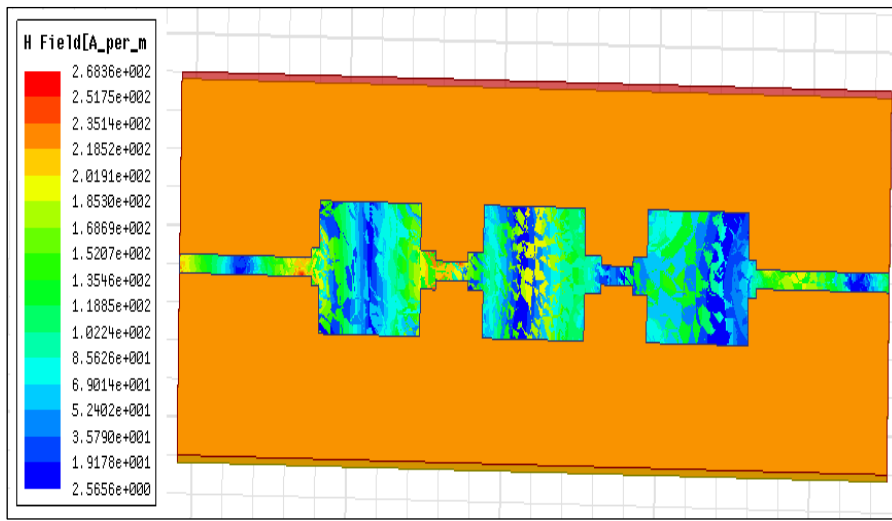


Figure 5: Magnetic fields of the proposed filtenna.

Source: Authors, (2026).

IV.3 GAIN AND RADIATION CHARACTERISTICS

The radiation performance of the proposed filtenna is evaluated in terms of realized gain and directivity at the operating frequencies of 26 GHz and 29 GHz, as illustrated in Figure 6 and Figure 7. Simulations indicate that the filter achieves a maximum gain of approximately 10.5 dBi across all frequency ranges. Over the tested frequency range, this gain remains stable, exhibiting only slight fluctuations between the two resonant frequencies, thus confirming stable radiation behavior. Despite the compact structure, this significant gain is achieved, demonstrating the effectiveness of combining filtering and radiation in a single planar topology. Directivity reaches a peak of approximately 10.8 dBi, indicating excellent focusing of the emitted power in the principal radiation direction. The small difference between the direct and achieved gain confirms minimal dissipation losses and efficient radiation, even when using an FR4 substrate at millimeter frequencies. The three-dimensional radiation patterns show a consistent main lobe, minimal back radiation, and no significant distortion across either frequency band. This behavior illustrates the scattered radiation pattern of the filtenna, where each rectangular resonator contributes to the total radiation, resulting in higher gain than a standard isolated patch antenna. Overall, the gain and radiation properties indicate that the suggested configuration operates effectively as a high-gain filtenna, providing both frequency selectivity and directional radiation. These attributes make this design a suitable choice for millimeter-wave 5G applications, where compactness, high gain, and integrated filtering are critical requirements. Therefore, the efficiency was calculated using the following formulas [12].

$$G_{lin} = 10^{G(dB)/10} \quad (11)$$

$$D_{lin} = 10^{D(dB)/10} \quad (12)$$

G_{lin} and D_{lin} are respectively linear gain and linear directivity

$$G_{lin} = 10^{\frac{G(dB)}{10}} = 10^{\frac{10.5}{10}} = 11.22$$

$$D_{lin} = 10^{D(dB)/10} = 10^{10.8/10} = 12.02$$

Then we have the efficiency:

$$\eta = \frac{G_{lin}}{D_{lin}} \quad (13)$$

$$\eta = \frac{11.22}{12.02} = 0.93 = 93\%$$

Based on the simulated gain and directivity values, the radiation efficiency is estimated to be approximately 93% confirming that most of the input power is effectively converted into radiated energy.

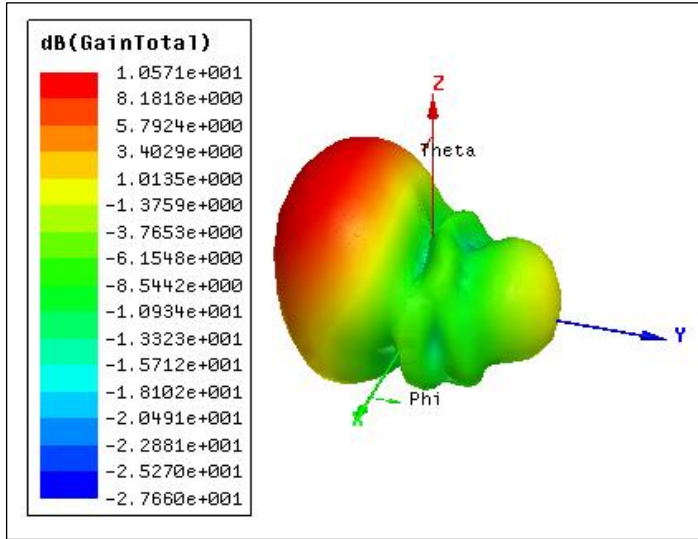


Figure 6: Gain of the proposed filtenna.
Source: Authors, (2026).

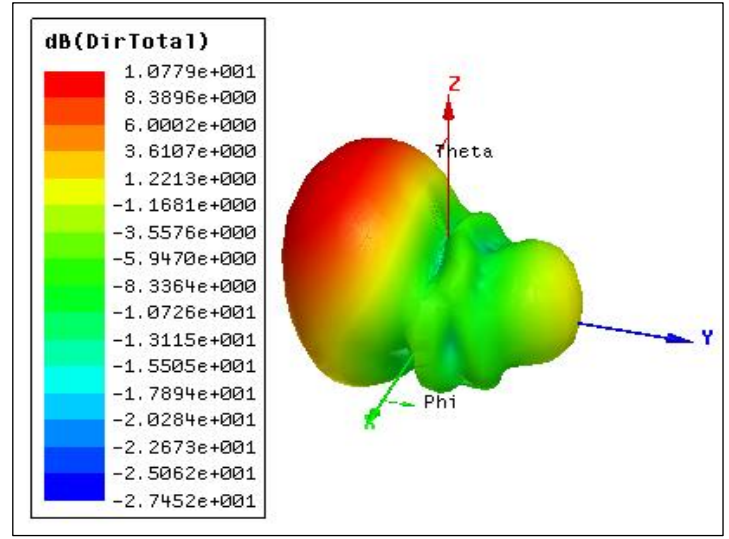


Figure 7: Directivity of the proposed filtenna.
Source: Authors, (2026).

The three-dimensional radiation patterns exhibit a stable main lobe with low back radiation and consistent beam shape across both operating bands. The distributed radiation mechanism provided by the series-coupled rectangular resonators contributes to the enhanced gain and high efficiency. Overall, the radiation characteristics demonstrate that the proposed design operates as a high-efficiency, high-gain filtenna suitable for 5G millimeter-wave applications.

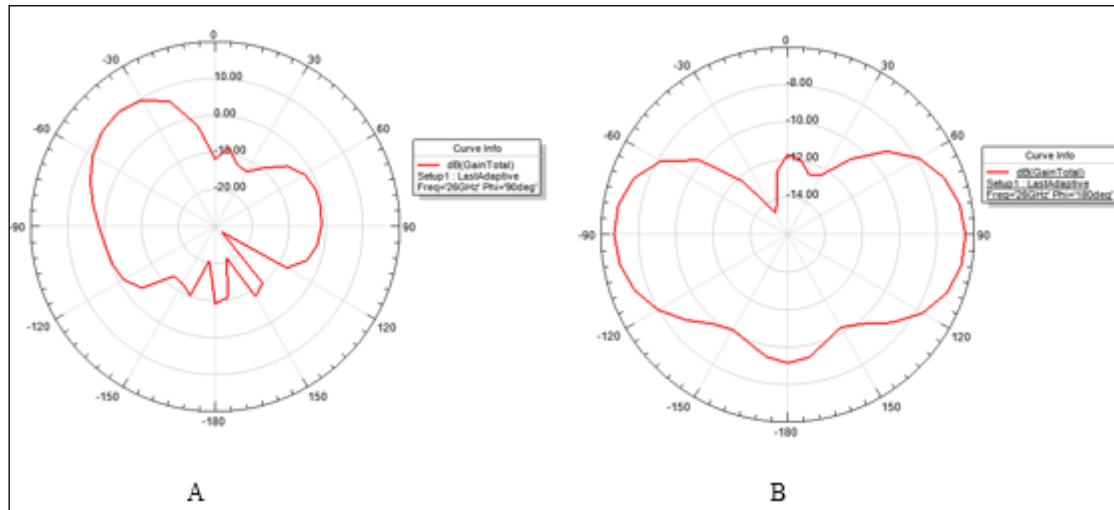


Figure 8: Radiation pattern A (Phi=90 degrees) and B (Phi=180 degrees).
Source: Authors, (2026).

Table 2: Comparison with other works.

Work	Frequency (GHz)	Susbtrate	Size (mm x mm)	Peak gain (dB)	Efficiency (%)
[3]	15 – 18	FR4	90 x 90	4.87	NA
[5]	1.9 – 3.56	Rogers TMM4	25 x 35	2.26	60
[6]	26 – 29	FR4	60 x 70	4.5	N/A
[10]	12	FR4	50 x 40	4.8	67
[12]	3.6	FR4	26 x 60	2.5	
This work	26 - 29	FR4	23 x 10	10.58	93

Source: Authors, (2026).

V. CONCLUSION

This article discusses the design and analysis of a compact dual-band microstrip filtenna, based on series-coupled rectangular resonators, for 5G millimeter-wave applications. The proposed structure incorporates filtering and radiation functions in a separate planar topology, eliminating the need for external RF filters and reducing the overall device complexity. The filtenna operates 26 GHz and 29 GHz, ensuring effective impedance matching with a reflection coefficient below -30 dB and controlled transmission properties. The physical behavior of the structure was clarified using an equivalent RLC resonator model, which accurately depicts the dual-band response derived from capacitive coupling and inductive current paths between neighboring. Compared with recently reported filtenna designs, the proposed structure offers higher gain, superior efficiency, and a more compact footprint, making it a promising candidate for 5G millimeter-wave front-end modules. Future work will focus on experimental validation and extension toward array-based filtenna configurations for beam-steering applications.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Touko Tcheutou Stephane Borel.
Methodology: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Investigation: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Discussion of results: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Writing – Original Draft: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Writing – Review and Editing: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Resources: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Supervision: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.
Approval of the final text: Touko Tcheutou Stephane Borel, and Rashmi Priyadarshini.

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