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Investigations on Dual Band Filtering Antenna for Wireless Applications

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ABSTRACT

The paper delineates a unique dual-band filtering antenna that integrates filtering and radiation properties into a single module employing a defective ground structure. The role of a filtering antenna is to remove out-of-band interference from adjacent frequency bands. The proposed configuration consists of a rectangular defective ground structure embedded in the ground plane, along with a filter (designed as a square open loop resonator (SOLR)), and an antenna (designed as an H-shaped radiating element) connected through a coupled line on the substrate's opposite side. The recommended filtenna dimensions are 30 mm × 34 mm × 1.6 mm, functioning at 2.4 GHz and 7.2 GHz. A return loss $|S_{11}| < 10$ dB occurs at the working frequencies. The H-shaped radiator enables dual-band functionality, and narrowband performance at specified frequencies is achieved by modifying the dimensions of the designed SOLR bandpass filter. Integrating a filter with the antenna element limits the bandwidth to 0.21 GHz, spanning from 2.32 GHz to 2.54 GHz, centered at 2.4 GHz, making it highly suitable for wireless applications. The high-frequency resonance attained at 7.2 GHz (6.46 – 7.56 GHz) is widely employed in short-range radar systems and wireless data communications. Stable gain (> 2 dBi) and radiation patterns are achieved at low and high operating frequencies. The design undergoes simulation, fabrication, and measurement. The validated results strongly correlate, suggesting that the proposed filtering antenna is appropriate for diverse wireless applications.

Keywords: Filtering antenna; Dual-band; Defective ground structure; 5G applications; H-shaped radiating element

NOMENCLATURE

FILTENNA	: Filtering Antenna
DGS	: Defected Ground Structure
CST	: Computer Simulation Technology
VSWR	: Voltage Standing Wave Ratio
PEC	: Perfect Electric Conductor
SOLR	: Square Open Loop Resonator

1. INTRODUCTION

Current wireless communication technology is increasingly reliant on frequencies below 6 GHz, which are essential for numerous applications, including WLAN (Wireless Local Area Network), WiMAX (Worldwide Interoperability for Microwave Access), GPS (Global Positioning System), and Bluetooth. This phenomenon stimulates the advancement of novel wireless devices and services. Antennas and filters are fundamental components of every system for transmission and reception. A filtering antenna (sometimes termed filtenna) combines these features into one compact device and presents several benefits, including reduced complexity, lower costs, smaller size, and enhanced filtering and radiation characteristics[1-2]. However, integrating antennas and filters can introduce challenges such as mismatch and insertion losses. These complexities present a significant challenge for filtenna designers aiming to maintain optimal performance for antenna and filter functions simultaneously[3].

In the last few decades, many techniques have been used to develop filtering antennas, and few were listed[4-25]. The reported works were designed for different applications in different microwave frequency bands, such as S, C, X, Ku, and Ka. A filter feeding network[4] connected by metallic pins along with patch, square loop resonator, γ shaped radiator integrated by using a coupled line[5], monopole filtering antenna using multimode resonators[6], chebyshev filter patch antenna with orthogonal polarisation[7] , U-shaped patches with multi stub feedline[8], interdigital capacitor (acting as band pass filter) along with meander lines and rectangular patches with coplanar waveguide feeding[9], γ shaped antenna with dumbbell shaped resonator[10], slotted ground plane and tuning stubs[11], interdigital structure with quasi yagi antenna[12], monopole antenna with stub loaded multimode resonators[13], T shaped resonator with inset coupling structure[14], square patch with stepped feedline and metal vias[15], rectangular and U shaped patches with two coupling slots etched on the ground plane[16], DGS (defected ground plane) with E shaped patch acting as radiating element[17], loading slots

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on patch radiator[18], using double U shaped DGS[19] (serving as filter) with radiating patch, coplanar waveguide fed with semi fractal UWB (Ultra Wide Band) antenna[20], half wavelength open circuit resonator[21], butterworth band pass filter along with fan shaped defected ground structure[22], capacitively loaded loop band pass filter with crescent shaped planar monopole structure[23], quasi microstrip antenna with capacitive feeding structure[24], substrate integrated suspended line concept[25], modified feedline with monopole radiating element backed by AMC[26], hairpin bandpass filter integrated with semicircular microstrip antenna[27], SIW resonator based duplex filtenna[28] were used to design various filtering antennas suited for wireless, low sub 6 GHz, LTE (Long Term Evolution), MIMO (Multiple Input Multiple Output), ISM (Industrial Scientific and Medical) band applications. However, the major pitfalls in the aforementioned techniques include complexity in design[4,26,28], requirement of more circuit area[6,8], limited working bandwidth[8], and fabrication complexity[17,25-26].

This study introduces a novel dual band filtering antenna designed for optimal performance across the C and X bands, tailored explicitly for 5G applications. The filtenna design incorporates a filter, coupled line, and an H-shaped radiating element, all within a compact footprint of 30 mm × 34 mm × 1.6 mm. The research demonstrates strong agreement between simulated and measured results, showing excellent return loss, effective rejection of out-of-band frequencies, and stable radiation patterns. The article is organized as follows: Section 2 provides a detailed account of the filtenna design process, Section 3 validates the findings, and Section 4 offers the concluding remarks. The uniqueness and innovation of this design are highlighted by its compact size, manufacturing versatility, simplified complexity, stable antenna performance, and robust out-of-band rejection capabilities within the designated frequency bands. Table 1 illustrates the analysis of the proposed design and earlier existing designs.

The primary contributions and novelty of the design are stated as follows:

Size: The filtering antenna is designed to be 30 mm × 34 mm, occupying a less PCB area of 1020 mm^2 than other literary works[6,8].

Materials used/Ease of fabrication: Using FR-4 as a substrate reduces fabrication costs and provides good technical advantages. Additionally, FR-4 is a readily accessible dielectric material.

Complexity reduction: The structure uses a simple square open loop resonator acting as the filter which is connected to the H-shaped radiating element through a quarter wavelength coupled line with a rectangular defective ground structure compared to other cited works[4,11,13] which uses complex structures.

Dual-band operation and multiple applications: The suggested structure functions in dual-band with narrow band operation at 2.4 GHz (ISM band) and 7.2 GHz, enabling its employment in various applications optimised for C and X bands, mainly intended for wireless applications.

Impedance matching: The VSWR values are ≤ 2, indicating that the antenna perfectly matches the feed port and provides excellent impedance matching. In comparison to the referenced works[6,8,11,13,19], the proposed design concurrently fulfills multiple objectives required for wireless applications including overall size, while most of the cited works[6,8,11,13,19] require a larger footprint area, fabrication flexibility[6,8,26,28] as FR-4, PEC are readily available materials at affordable costs, to attain complexity reduction in the design an innovative half wavelength SOLR is connected through a coupled line to H shaped radiating element while most of cited works[11,13] uses complex structures, stable antenna characteristics are obtained for the proposed design within the operating band.

2. PROPOSED ANTENNA DESIGN WITH FILTERING CAPABILITIES

2.1 Design Procedure for Filtering Antenna

A filtering antenna integrates filtering and radiation properties into a single module which addresses

Table 1. Comparison to prior existing designs

Ref	Antenna Size (in λ_0^2 (mm^2))	Filtering antenna technique used	Working frequency (GHz)	Impedance bandwidth (GHz)	Return loss $\|S_{11}\|$ (dB)	Intended application	Fabrication complexity
[6]	1 × 0.48	Multimode resonators with monopole antenna	2.4, 5.2, 6.5	0.2, 0.4, 0.2	< 10	S, C bands	Complex
[8]	0.63 × 0.51	U shaped patches+ multi stub microstrip feedline	1.9, 2.6	0.04, 0.05	40, 30	LTE, MIMO	Complex
[11]	0.4 × 0.42	Slotted ground plane+ tuning stubs+ L shaped MMW element inside ground	5.2, 28	0.3, 0.5	20	Microwave and MMW bands	Moderate
[13]	0.65 × 0.3	Stub loaded multimode resonators + monopole antenna	3.23, 5.65	1.5, 0.75	10	S, C bands	Moderate
[19]	1 × 0.64	DU-DGS	11.57, 17.87	0.7, 1.8	23, 28	X, Ku bands	Moderate
This work	0.24 × 0.27	Square loop resonator, H shaped radiating element connected by coupled line	2.4, 7.2	0.21, 1.08	23, 42	C and X bands	Simple

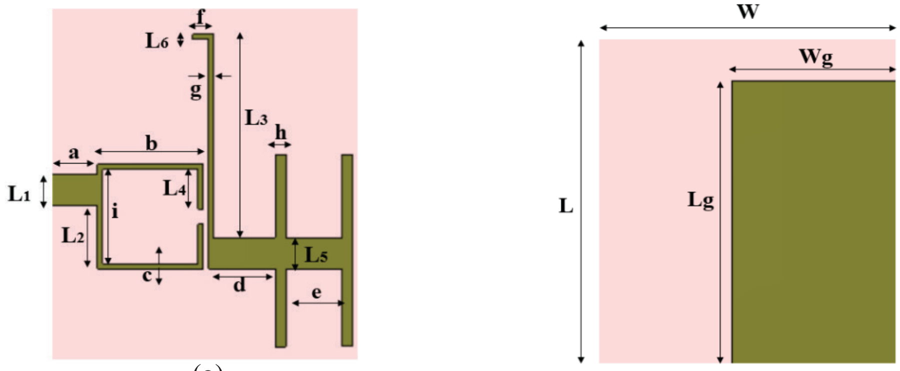

Figure 1. (a)Top; and (b) Bottom view geometry of the suggested prototype.

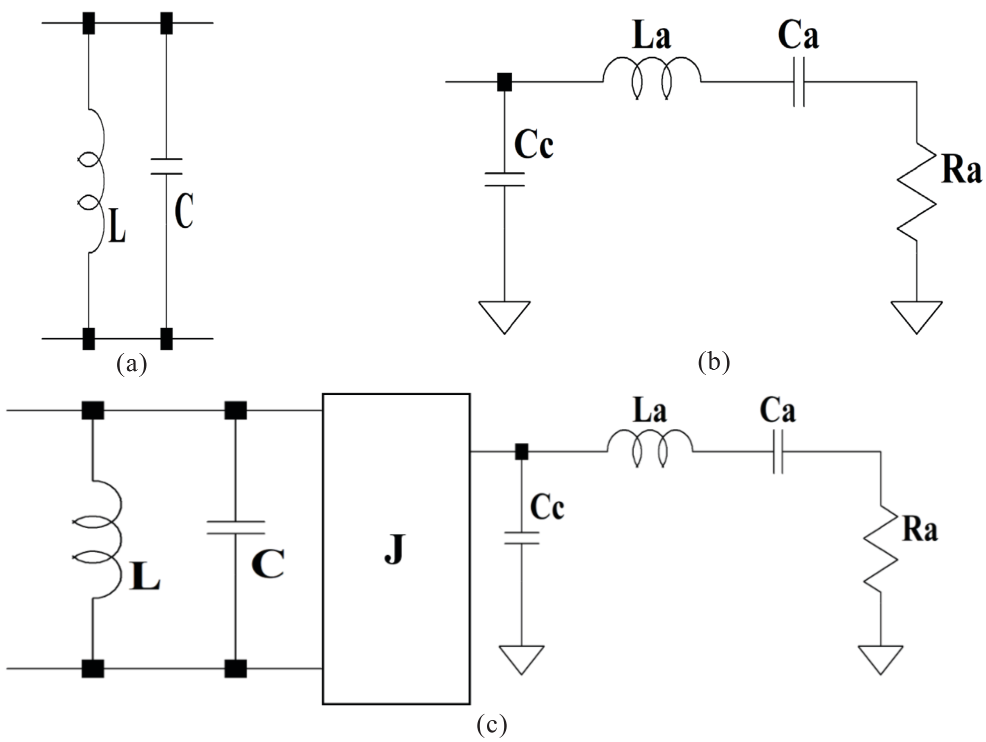

Figure 2. (a) Circuit modelling of square open loop resonator; (b) Circuit modelling of the H shaped radiator; and (c) Circuit modelling of the proposed filtering antenna.

Table 2. Optimised filtering antenna dimensions

Parameters	Size (mm)
$L/W/L_g/W_g$	34/30/29.3/17
$a/b/c/d/e/f/g/h/i/j/k/L_1/ L_2/ L_3/L_4/ L_5/ L_6$	5/10.1/0.5/6.35/5.35/2/0.5/1.25/9.10/1.5/0.55/2.45/6.1/19.7/3.8/3/0.5

challenges such as frequency selectivity, minimizing cost, size, efficiency and performance that traditional antenna setups face. The role of a filtering antenna is to remove the out-of-band interference from the adjacent frequency bands. In contrast, a traditional antenna design consists of interference from the adjacent bands without any frequency selectivity feature and to ensure that only desired frequency band is processed, external filters are required. The proposed H shaped radiating element is integrated with a half wavelength square open loop resonator through a quarter wavelength coupled line and the entire design is microstrip line fed by 50 Ω. Figure 1 represents the suggested filtering antenna in its front and rear views. The optimised filtenna dimensions are outlined in Table 2. The overall dimensions of the suggested filtenna are given by 30 mm × 34 mm. The height of the substrate is choosen as 1.6 mm. Flame Retardant epoxy 4 resin with ε_r of 4.3, tan δ value of 0.02 is used as the material for substrate. Ground plane and remaining components are designed using perfect electric conductor material (PEC). The entire design is carried out using the electromagnetic simulation tool CST microwave studio software.

The accuracy of the findings relies on the input parameters provided to the CST software tool such as ε_r and tan δ of the dielectric material as well as the alignment of different layers. The input parameters required for the flame retardant 4 material used in the antenna design are well established in the software. Additionally, the simulation's precision is influenced by different factors such as type of the solver involved based on the simulation model needs. The number of mesh cells, port definitions also play a significant role in determining simulation results. Nevertheless, errors can be effectively minimized with a solid understanding of the software. Figure 2(a) represents the equivalent circuit modelling of the half wavelength square open loop resonator governed by a parallel LC circuit whose L =2.74 nH and C = 3.03 pF. Figure 2(b) represents the circuit modelling of the proposed H shaped radiator (R_a represents the radiation resistance of the radiator, L_a, C_a represents the equivalent inductance and capacitance of the radiating element, C_c accounts for the mutual capacitance). An antenna equivalent circuit is defined by the impedance properties of the radiator, represented by the resistive, inductive, and capacitive components.

The losses in the antenna systems, encompassing ohmic and radiation losses, are denoted by the resistor. The energy in the magnetic field around the antenna is denoted by the inductor, which is directly proportional to the current traversing the conductors. The energy stored in the electric field between closely spaced antenna components, such as conductors, is denoted by the capacitor. The components influence the surface current distribution, with inductance facilitating large currents, capacitance associated with potential differences, and resistance dissipating energy, affecting antenna efficiency, bandwidth, and impedance matching. This model optimizes the radiator to a quarter wavelength to enhance signal transmission and reception, maximizing current at operational bands, facilitating bidirectional and omnidirectional radiation characteristics through harmonizing energy storage and dissipation. The resonance condition of a circuit is determined by using the Eqn. (1).

$$f = 1 / 2\pi\sqrt{L_a C_a} \tag{1}$$

The circuit elements values of the proposed radiator design are R_a = 50 Ω (for impedance matching), C_a =1 pF, C_c = 13.26 pF (which accounts for mutual capacitance), La = 4.42 nH (for 2.4 GHz) and La = 0.49 nH (for 7.2 GHz). The entire circuit modelling of the proposed filtering antenna is represented in Fig. 2(c) (where J represents the coupled line admittance inverter of quarter wavelength). The suggested design exhibits consistent and stable S_{11} values within the operational bandwidth, as well as effective suppression of out-of-band signals.

2.2 Filter Design

Microstrip square open loop resonators are considered for the design of band pass filters. From Fig. 3 it can be observed that two open loop square resonators constitute the design of band pass filter each of half wavelength at 2.4 GHz. The 50 Ω microstrip line feeding technique is utilized to provide a signal to both resonators. The overall dimensions of the filter are 30 mm × 34 mm and it shares the same ground plane as that of the radiating element. The substrate height is measured as 1.6 mm. The total length of each resonator is 42 mm as obtained from the Eqn. (2). The pass band is obtained at 2.4 GHz with a transmission coefficient of -4 dB.

$$l = \frac{\lambda g}{2} = \frac{c}{2 f_r \sqrt{\in_{eff}}} \tag{2}$$

guide wavelength is denoted by λg, working frequency is denoted by f_r, velocity of light in open space is denoted by *c,* effective dielectric constant is denoted by $\in_{eff}$ whose value can be computed from Eqn. (3) using 4.3 as $\in_r$ value.

$$\in_{eff} = \frac{\in_r + 1}{2} + \frac{\in_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{3}$$

where, h denotes substrate height, W denotes substrate width, $\in_r$ represents the dielectric constant of the dielectric material. The working frequency of the filter is modified by varying the length, width and the gap between the resonators. The integration of such type of resonator by replacing the second resonator with the dual band operated H shaped antenna known as filtenna where the H shaped radiator is responsible for the dual band operation and narrow band operation at the working

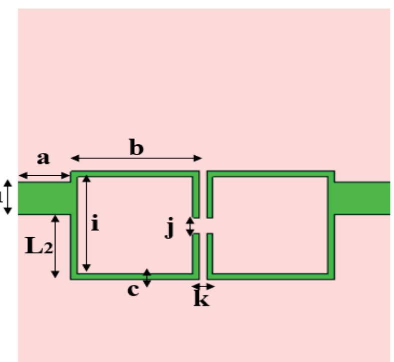

Figure 3. Filter design of the filtenna.

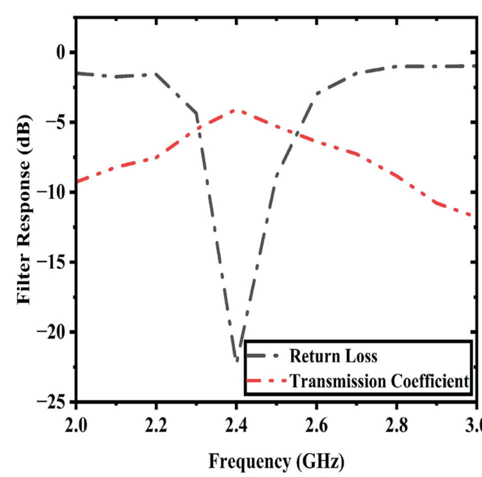

Figure 4. Filter response of the presented filtenna.

frequencies is achieved by the designed square open loop resonator band pass filter. The presence of filter with the antenna element reduces the bandwidth to 0.21 GHz (2.32

- 2.54 GHz centered at 2.4 GHz), making it well suited for wireless applications. The high frequency resonance obtained at 7.2 GHz (6.46 GHz – 7.56 GHz) is widely used by short range radars and wireless data transmissions. The transmission (S_{12}) and reflection coefficients (S_{11}) of the designed resonator are illustrated in Fig. 4.

2.3 Parametric Analysis of the Filtenna

For improving the return loss, the study of the design is carried out and analysed using different substrates such a FR-4, Taconic, RT Duroid 5880, 5870 having the dielectric constant values 4.3, 2.2, 2.2, 2.33 and loss tangent values of 0.02, 0.0009, 0.0012, 0.0006 respectively. The dimensions of the substrate are kept constant. From Fig. 5(a) it can be observed that FR-4 offers good return loss in working and non-working bands. For better reflection coefficient, impedance bandwidth and suppression of harmonics defected ground plane technique is used. The Lg and Wg of the defected ground plane are varied keeping the remaining dimensions constant for improving the above said parameters. It can be observed from the Fig. 5(b) that 29.3 mm and 17 mm are the optimised dimensions for the

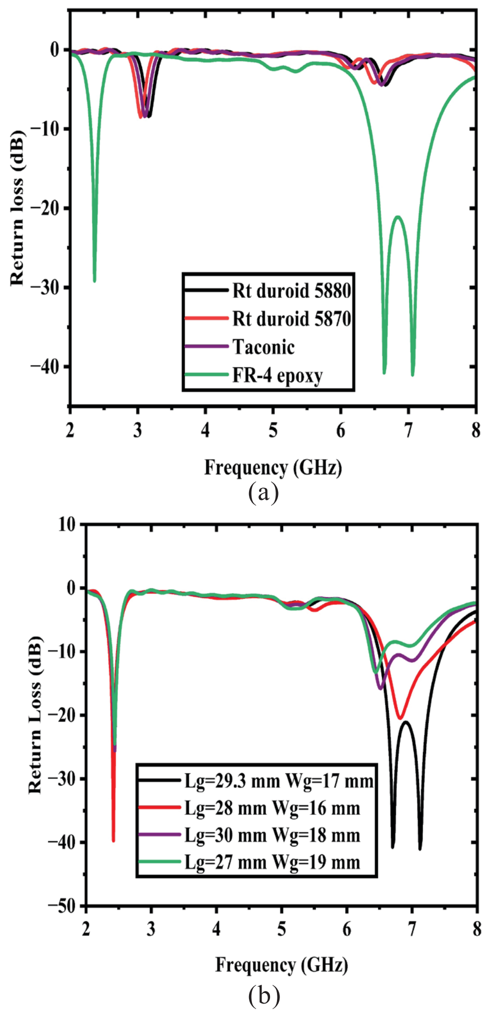

Figure 5. (a) Parametric analysis using different substrates; and (b) Parametric analysis varying length and width of the ground plane.

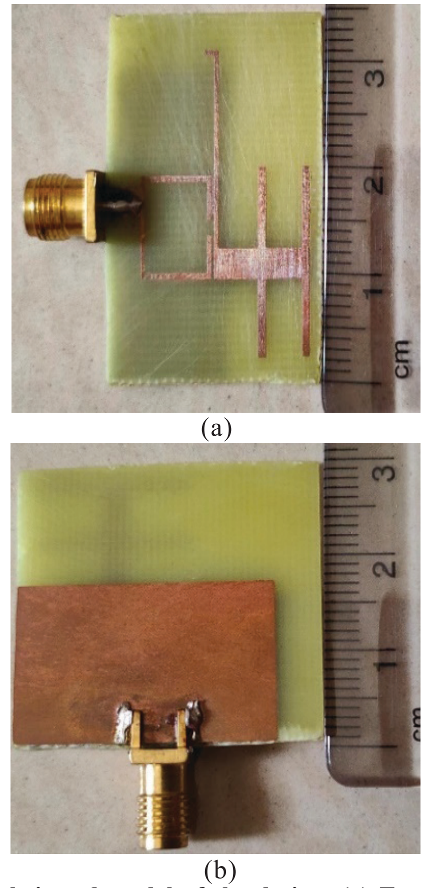

Figure 6. Fabricated model of the design, (a) Top view; and (b) Rear view.

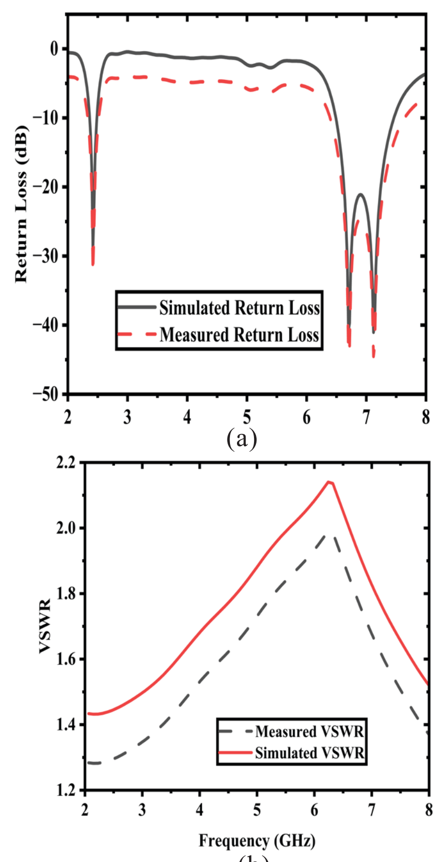

Figure 7. (a) S parameters; and (b) VSWR of the suggested design.

ground plane producing satisfactory performance of the filtering antenna at the working bands.

3. RESULTS VALIDATION

3.1 S Parameters and VSWR

The developed prototype of the suggested structure is depicted in Fig. 6, featuring both the front and rear views. The fabricated design is validated for S parameter response using vector network analyser (Anritsu MS2037C). The accuracy and precision of the measurement depends on proper handling of RF cables and connectors, soldering, interconnections between different systems, proper calibration before measurement using vector network analyser. Figure 7(a) illustrates the computed and assessed return loss parameter values at the working frequencies. The slight disparities among the actual and validated results

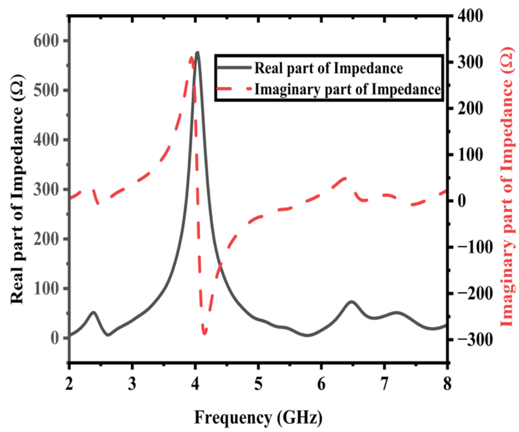

Figure 8. Impedance of the suggested design.

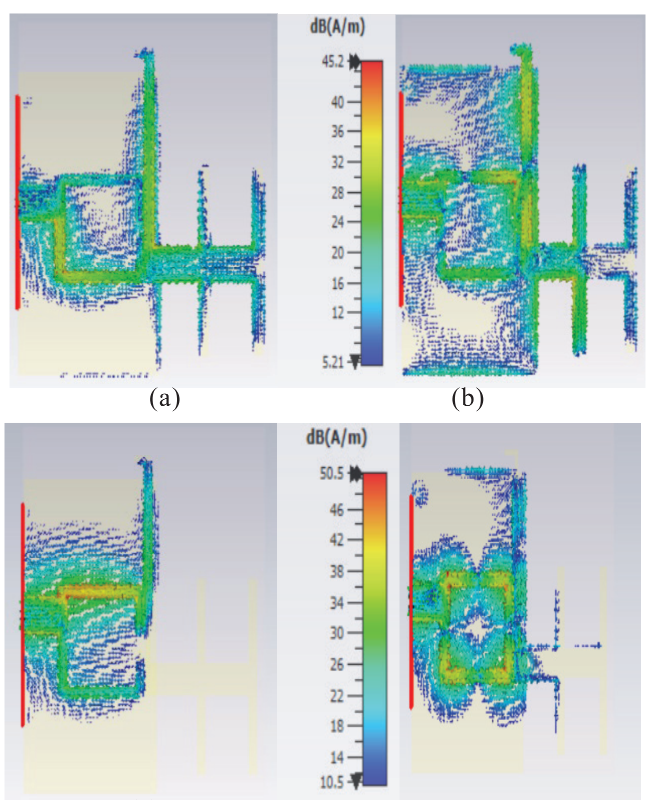

Figure 9. Surface currents of the filtenna at (a) 2.4 GHz; (b) 7.2 GHz; (c) 3 GHz; and (d) 10 GHz.

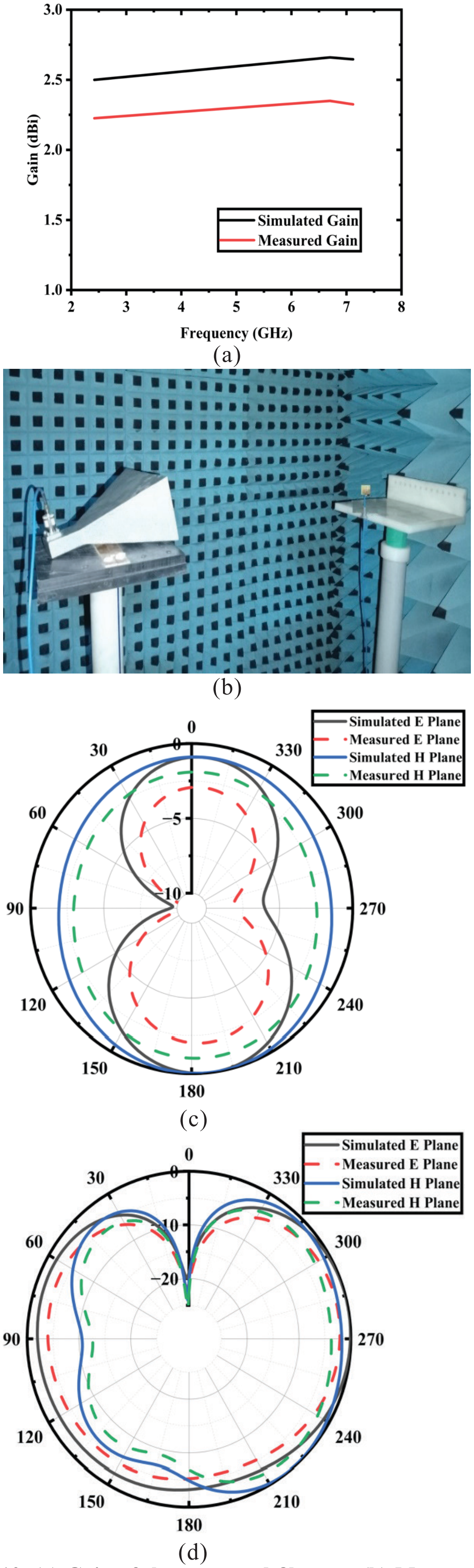

Figure 10. (a) Gain of the suggested filtenna; (b) Measurement setup for computing radiation pattern; (c)Far field patterns of the suggested filtenna at 2.4 GHz; and (d) 7.2 GHz.

can be attributed to the fabrication tolerances, soldering and calibration errors. As can be seen simulated $|S_{11}|$ of 23, 42 dB are produced at the working frequencies of 2.4 GHz, 7.2 GHz and measured $|S_{11}|$ values are also < 10 dB with minor deviation from simulated results. The computed and assessed VSWR as displayed in Fig. 7(b) is < 2 which indicates that the proposed design is perfectly matched to the feed port. The computed and assessed impedance bandwidths are around 0.2 GHz at 2.4 GHz and 1 GHz at 7.2 GHz. The real and reactive part of the impedance of the proposed design is close to the ideal values (50 Ω and 0 Ω respectively) as seen from the Fig. 8.

3.2 Surface Current Aanalysis

The surface currents for the suggested filtenna are illustrated in the Fig. 9(a), (b), (c), (d). At working bands (Fig. 9(a), (b)), it is apparent that the surface currents are distributed on the square loop resonator as well as on the radiating element. The current flows from resonator to radiating element through the coupled line and radiates through antenna into free space. At the non-working bands (Fig. 9(c),(d)), the surface currents are confined more to the resonator itself which indicate that resonator plays a key role in the process of filtering and less current is concentrated around the radiating element.

3.3 Gain and Radiation Patterns

The gain of the presented filtenna is illustrated in Fig. 10(a). The actual and validated gain at the working bands is > 2 dBi. The gain has been measured in a reflection free anechoic chamber by choosing a reference antenna usually a horn antenna whose gain and frequency range of operation are known accurately. The antenna under test (AUT) for which gain is to be found is placed at a far field distance. In the reference antenna the input is provided from a signal generator and frequency, amplitude values are set. Now the reference antenna radiates the signal and AUT receives the signal. The received power is calculated by using the spectrum analyser. Later, using the Friis transmission equation, the gain of the receiving antenna is determined (the cable losses are taken into account).

The radiation measurement setup for the proposed design is outlined in the Fig. 10(b). Figure 10(c), 10(d) displays the E and H plane patterns, both simulated and observed, at the working frequencies. At lower frequency of 2.4 GHz the pattern is bidirectional in E plane and omnidirectional in H plane. At the resonant frequency of 7.2 GHz an omnidirectional plot is obtained in both the planes. The disparity in radiation patterns at different frequencies can be ascribed to far-field patterns influenced by the design size relative to the wavelength. The defected ground structure affects the configuration and positioning of lobes and nulls, resulting in alterations to the pattern's characteristics. A minor disagreement exists between the measured results and the electromagnetic simulation outcomes, attributable to motor movements during antenna rotation, connecting issues across various systems (including probe influence and RF connectors), and the movement of RF cables.

4. CONCLUSIONS

The current study introduces innovative dual-band filtenna for optimal performance for various wireless applications. Two operational bands with return loss < -10 dB are generated simultaneously using a defective ground structure, resonator and antenna connected through a coupled line. The out of band frequencies are rejected completely. Consistent gain and radiation patterns are also achieved. The strong congruence between the actual and validated results shows that the suggested design is suitable for wireless applications.

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