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Research Paper

Design of a compact single-band, dual-mode microstrip filtering antenna with a high suppression stopband and a good band-edge selectivity for WiMAX applications

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ABSTRACT

A design of compact filtering antenna which is suitable for modern wireless communication is proposed in this paper. This project is based on the integration of a microstrip monopole patch antenna and a bandpass filter, which has two dual-mode four-sided open-loop resonant circuits and a single feed line. This design involves a couple of square open-loop resonators, which can create a pair of transmissions by zeros, and this method significantly boosts the design's selectivity. As a confirmation of the hypothesis, For WiMAX applications, and a filtering antenna technique have been explored, which operates in the 5.8 GHz range. By using CST Microwave Studio Suite simulator software Technology. The low-cost FR-4 substrate material has been used to fabricate the filtering antenna prototype. According to the filter synthesis approach. In addition to radiating, the monopole patch antenna serves as a final resonator. This design shows good agreement between measured results and simulation results.

1. Introduction

With these attractive properties such as low profile, lightweight, compact size, and easy to fabricate, microstrip filters and antennas are demanded in modern wireless announcements in the ISM regularity band 5.8 GHz [1]. Antennas are the furthest part of microwave wireless communication, where signals are exchanged without any risks or harmful to human health and the environment [2]. The microwave circuit miniaturization is one of the important challenges faced by the researchers on the RF/Microwave front ends design [3,4].It is essential to establish an antenna technique that will have the ability to filter out unwanted signals out of the antenna passband, to avoid interferences with the neighboring frequency bands[5]. Antennas and filters are important parts of many wireless systems' front end. Traditionally, these gadgets are designed using a variety of methods, frequently by experts in their respective fields. It is presumed that these devices' input and/or output ports have a 50-ohm interface. Additionally, it is believed that following a cascaded connection, the impedance matching would be maintained by keeping the 50 Ohm interface. In actuality, mismatches and losses from connectivity are introduced by the connection between devices, particularly when the components have differing bandwidths [2].The integration of filtering and radiating element functions in one module is one of the efficient ways to miniaturize the overall circuit size [6]. In contemporary RF and microwave systems, the integration of a bandpass filter (BPF) with a patch antenna has grown in popularity as a design strategy. Along with increasing the antenna's bandwidth, this integration has other benefits like decreased size, minimal insertion loss, and frequency selectivity. The main design principles and how this integration increases bandwidth are explained below. Furthermore, the matching condition is necessary and sufficient for the two circuits joining to provide combined input/output resistances to the joining port [7]. As it concerns, after the designing of the first circuit, the second one can be coordinated to its terminal impedance. The furthermost popular solution to alleviate the interference of the various frequency bands, another method has been found. Adding filtering characteristics to the antenna will make it have a particular frequency-selective response [8]. The filtering antenna reduces pre-filtering needs and improves the system's noise performance [9]. Numerous filtering antennas have been developed utilizing a filter synthesis technique, as shown in reference [10]. The synthesis approach is employed to generate a co-design filtering antenna basic structure [11]. The filtering antenna comprises a square ring resonator, two micro-strip line filters loaded with capacitors, and a rectangular shape patch. Double lumped capacitor components are sandwiched between a micro-strip line and a ring resonator, which obtained a 72% decrease in overall size. The suggested arrangement works as a band range pass filter, with a bandwidth that has 100 MHz and a 2.4 GHz central frequency. It features a well-defined gain response and excellent skirt selectivity, much like a standard band range pass micro-strip filter. Because of the previously mentioned benefits, the suggested filter is an excellent candidate for inclusion in a wide range of offered systems and portable operation devices in the 2.4 GHz band for future applications of WLAN. In [7], to create high-selectivity filtering, a printed circuit antenna that ends in a crescent-shaped stub is coupled with a small, sharp printed circuit filter. The resulting filtering exactly covers about the 5G mid-band frequency that has a range of $3.6 - 3.8\ GHz$ while rejecting any frequencies outside of the defined range. To achieve structural compactness, the suggested antenna is electromagnetically connected to half of the structure of an existing filter. With this method, the antenna serves as the band range pass filter's final resonator of the bandpass filter [12].

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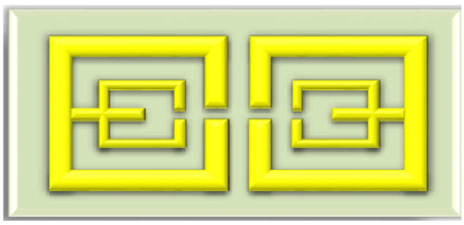
Nomenclature

CST	Computer simulation technology software	fr	Patch antenna's resonance frequency
WiMX	Worldwide Interoperability for Microwave Access	h	Dielectric substrate thickness
$FR-4$	Flame Retardant 4 (glass epoxy laminate)	S	Coupling space
BPF	Bandpass Filter	S_{11}, S_2	Scattering parameters
WLAN	Wireless Local Area Network	Z_o	Characteristic impedance
GHz	Giga Hertz	*VSWR*	Voltage Standing Wave Ratio
MHz	Mega Hertz		
f_1, ...	Band edge frequencies	*Greek Symbols*	
ISM	Industrial, Scientific, and Medical Band Frequencies	ε_{re}	Effective dielectric constant
$M12$	Coupling coefficient	ε_r	Dielectric constant
Qext	External quality factor	λ_g	Guided wavelength
Ql	Loaded quality factor	θ	Electric length
Qr	Radiation quality factor	$J_{n,\ n+1}$	Admittance inverters
c	Light speed	$B(\omega)$	The equivalent susceptance of the resonator

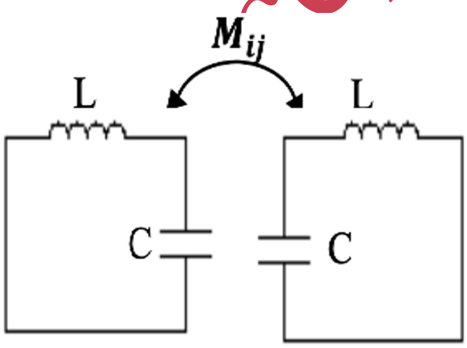
This paper presents a design of a compact single-band, dual-mode square open-loop filtering antenna that has a high out-of-band suppression and relatively good frequency-selective response. This design employs two identically connected dual-mode square open-loop resonators and a square monopole patch antenna. The analogous circuit for the filtering antenna is identical to the bandpass filter prototype; however, the antenna can be configured with the filter response [11–13]. The filtering antenna is developed and built to function within the ISM frequency band of 5.659 GHz to 6.077 GHz. The filtering antenna circuit is built, simulated, and optimized using the CST Microwave Studio Simulator Suite software.

2. Design of Filtering Antenna

The two identical dual-mode square open-loop resonators shown in Fig.1 with their equivalent circuit are magnetically coupled. The coupling coefficient of these resonators can be computed from the two split resonant frequencies. f_1 and f_2. The frequency f_1 represents the first resonant frequency of the first resonator and f_2 represents the second resonant frequency of the second resonator [14, 15].



(a) Resonator constructions.



(b) The equivalent circuits.

Figure 1. Two open-loop, dual-mode square resonators are present.

The external quality factor Q_ex A filtering antenna is a measurement of how quickly energy radiates into the free space from the patch antenna construction or the resonator. It is essential in establishing the filtering antenna's bandwidth and selectivity. This idea is primarily used for radiating systems and antennas that display resonant behavior, but it is taken from classical resonator theory. The coupling coefficient of the resonators and the external quality factor are shown in Figs. 2 and 3, respectively.

$$f(x) = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \tag{1}$$

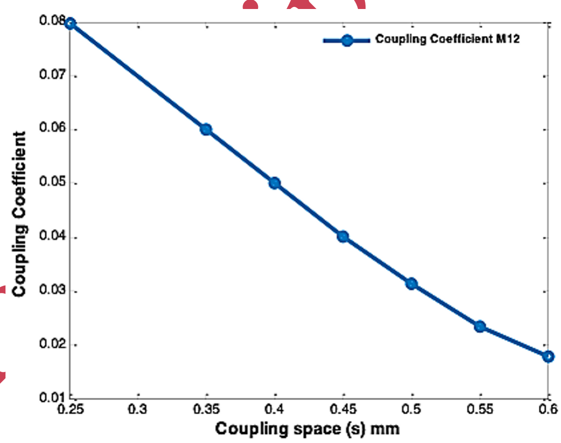


Figure 2. Coupling coefficient of the resonators as a function of the coupling distance (S).

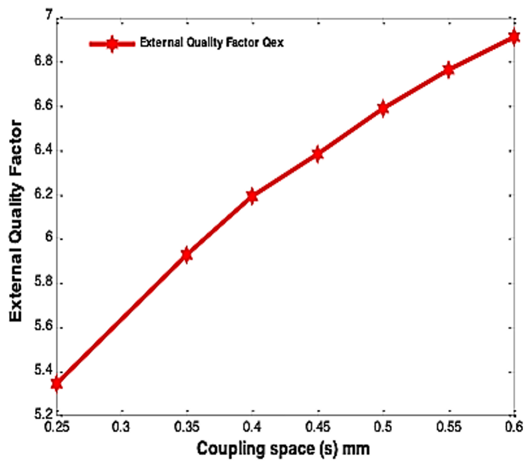


Figure 3. The filtering antenna's external quality factor as a function of coupling spacing (s).

$$Q_{ex} = \frac{f_o}{B.W} \tag{2}$$

$$Q_r = \frac{c\sqrt{\varepsilon_{re}}}{4\ f_r\ h} \tag{3}$$

$$Q_l = \frac{1}{\frac{1}{Q_{ex}} + \frac{1}{Q_r}} \tag{4}$$

The efficiency with which a resonant antenna radiates energy into free space about the total energy contained inside the antenna construction is measured by the radiating quality factor, when describing antennas that exhibit resonant behavior, such filtering antennas or antennas integrated with resonator circuits are especially helpful. A filtering antenna's loaded quality factor, which takes into consideration all energy loss processes, is a representation of the system's overall quality factor. It incorporates the contributions from external coupling, radiative losses, and non-radiative losses (such as ohmic or dielectric losses). The antenna's selectivity and bandwidth are directly impacted by XXXXXXXL. The filtering antenna resonator's external quality factor Q_ex and the factor for radiation quality Q_r A rectangular monopole antenna can be evaluated as [16, 17]: The relationship of these quality factors represents the loaded quality factor and can be expressed as [18]: The values of the external quality factor, the radiation quality factor, the loaded quality factor, and the coupling coefficient are stated in Table 1. The strength of interaction (coupling) between two resonators is quantified by the coupling coefficient, or XXXXXX. It defines the energy transfer between resonators and is directly affected by the coupling space or their physical separation. Fig. 2 shows the relationship between the coupling coefficient of the resonators and the coupling space (S) of these resonators. In resonator-based systems, such as filtering antennas, the coupling gap between resonators is a critical component in determining the quality factor (Q). The bandwidth and energy distribution among resonators is directly impacted by the coupling between them, which also affects the overall system quality factor (XXXXXX) and the external quality factor (XXXXXX). The main connection and justification for how coupling space influences the quality factor as above shown in Fig. 3.

Table 1. The values of quality factors and the coupling coefficient of the filtering antenna.

Q_{ex}	Q_r	Q_L	M_{12}
07.01100	14.13000	04.68600	00.01832

Transmission lines that feed resonators and are connected by capacitance or inductance make up the microwave model of a coupling resonant circuit with feeder lines. Impedance matching, transmission efficiency, and bandwidth are all impacted by the scattering parameters (XXXXXXX) that are determined by this model. For applications such as filtering antennas, it is essential to properly tune the coupling space, resonator parameters, and feeder lines to achieve optimal performance. Coupled resonant circuits are used in microwave engineering to create antennas, resonators, and filters. These circuits illustrate the process of electromagnetic coupling, which transfers energy between two or more resonators. Distributed-element models or lumped-element equivalents can be used to simulate the behavior of coupled resonators. An outline of a linked resonant circuit's microwave model is shown in Fig. 4. The microwave model of the coupling resonant circuit with the feeder line at the two ends [19, 20]. This model uses the admittance inverters. The admittance inverter is a two-port network that has a unique characteristic at all frequencies. J_01 is the section that couples the feed line to the resonator, $Y()$ is the resonator's admittance and J_12 is the coupling part between resonators [21].

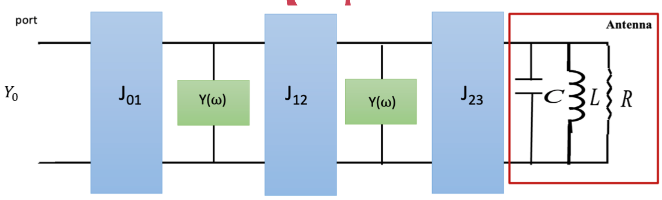


Figure 4. A microwave circuit model with a filter-antenna and inverter admittance (J-Inverters).

$$Y(\omega) = G_0 + jB(\omega) \tag{5}$$

G_o is the equivalent conductance of the resonators and $B(\omega)$ is the equivalent susceptance of the resonator.

$$\begin{aligned} B(\omega) &= \pm\sqrt{(G_o + J_{12}^2 Z_o)^2 + J_{12}^2} \\ B(\omega_1) &= -\sqrt{(G_o + J_{12}^2 Z_o)^2 + J_{12}^2} \\ B(\omega_2) &= -\sqrt{(G_o + J_{23}^2 Z_o)^2 + J_{12}^2} \end{aligned} \tag{6}$$

The admittance inverters of the microwave model of the offered filtering antenna explained in Fig. 4 can be calculated as [22, 23].

$$\begin{aligned} \frac{J_{o1}}{Y_o} &= \sqrt{\frac{\pi\, FBW}{2\, g_o\, g_1}} \\ \frac{J_{i,i+1}}{Y_o} &= \sqrt{\frac{\pi\, FBW}{2\, g_i\, g_{i+1}}} \quad For\ i = 1,\ 2,\ \ldots .\ n \\ \frac{J_{n,n+1}}{Y_o} &= \sqrt{\frac{\pi\, FBW}{2\, g_n\, g_{n+1}}} \end{aligned} \tag{7}$$

In a filtering antenna, the guided wavelength (XXXXXXXXX) represents the wavelength of the wave as it passes through the transmission or resonant structure of the antenna. The wavelength is shorter than the free-space wavelength as a result of the effective permittivity of the substance. To achieve the desired filtering and radiation properties, this parameter is essential for calculating the size, resonance conditions, and coupling behavior of filtering antennas. The guided wavelength of the filtering antenna design $(_g)$ is given as [24]: One of the common substrate materials used in printed circuit boards (PCBs) is FR-4 (Flame Retardant 4). It is made of woven fiberglass fabric that has been treated with epoxy resin, giving it superior electrical, mechanical, and thermal qualities. The following are the main attributes and specs of FR-4 material; High-frequency, high-temperature, and ultra-low-loss applications may require higher-grade materials, but FR-4 is valued for its mix of cost, durability, and electrical qualities.

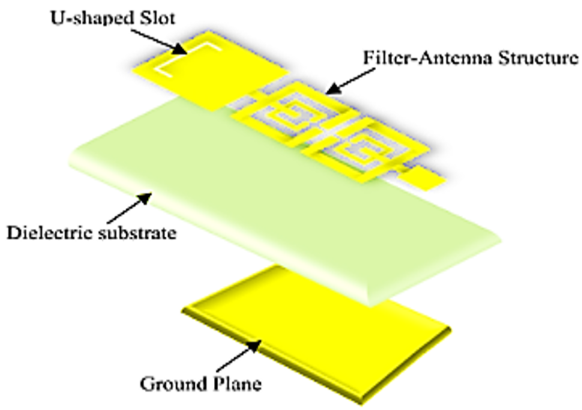


Figure 5. A 3-D view of the filtering antenna structure.

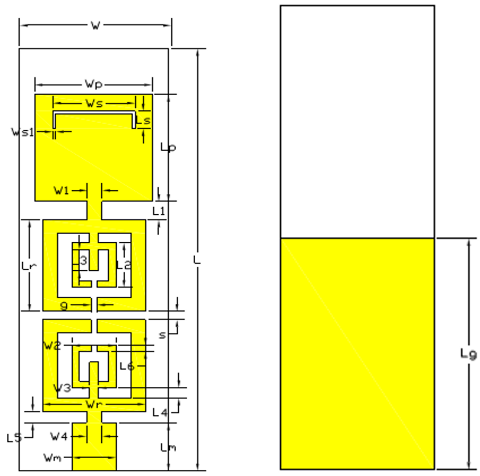
The filtering antenna is fabricated on $(FR-4)$ substrate material together with a dielectric-constant $_r = 4.3$ and the value thickness $h = 1.6\ mm$, while the effective dielectric constant ε_{ref} and characteristic impedance Z_o are provided as [25, 26]: The guided wavelength establishes a relationship between the electrical length XXXXXX and the physical length L. The wave's propagation in the medium is determined by its electrical length, which is typically longer than the physical length in structures with higher effective permittivity. The relation between the electrical length (phase length) θ (rad.) and the physical length l (mm) is given in Equation (11). According to Eqn. (11), any physical length of a microstrip transmission line can be found if its electrical length is known [27]. Fig. 5 displays the filtering antenna structure in three dimensions.

$$Y_g = \frac{300}{f(GHz)\sqrt{\varepsilon_{re}}} \tag{8}$$

$$\varepsilon_{ref} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\left(1 + 12\frac{h}{W}\right)^{-0.5} + 0.04\left(1 - \left(\frac{W}{h}\right)^2\right)\right] \tag{9}$$

$$Z_o = \frac{60}{\sqrt{\varepsilon_{re}}}\ln\left(8\frac{h}{W} + 0.25\frac{W}{h}\right)\Omega \tag{10}$$

$$\theta = \frac{2\pi}{\lambda_\theta} l \tag{11}$$



(a) Top view. (b) Bottom view.

Figure 6. Filtering antenna circuit design.

The dual-mode, single-band microstrip filtering antenna architecture is shown in Fig.6, and Table 2 contains the optimal parameters of the circuit.

Table 2. Optimal design parameters of the proposed filtering antenna.

Parameters	$Unit/mm$	Parameters	$Unit/mm$	Parameters	$Unit/mm$
W	10.1	W_r	07.0	L_4	00.80
W_p	08.0	W_{s1}	00.2	L_5	00.90
W_1	01.0	L	31.3	L_6	00.50
W_2	03.0	L_p	08.0	L_m	03.60
W_3	00.6	L_s	01.3	L_r	06.80
W_4	01.1	L_1	01.4	g	00.40
W_5	05.6	L_2	03.3	s	00.60
W_m	03.0	L_3	01.6	L_g	15.65

3. Results and Discussion

The comparison results of the S11-parameter which used the filtering antenna with the traditional monopole patch antenna models are shown in Fig.7, it is obvious that the integration of the bandpass filter with the patch-antenna has improved the bandwidth of the conventional monopole patch antenna of about 20%, also improved the suppression of the unwanted frequency component outside the passband, which in turn improves the selectivity of the filtering antenna. On the other hand, the size of the conventional monopole patch antenna has been reduced to about 60%. The comparison results of the presented filtering antenna model and the conventional monopole patch antenna are stated in Table 3.

Table 3. Comparison results between the conventional monopole patch antenna and the filtering antenna design.

Parameter	Filtering antenna	Monopole patch antenna
10-dB B.W (GHz)	0.4245	0.3384
Circuit size $(W \times L)\ mm^2$	10.1×31.3	55.96×73.8

Table 4. The comparison between the measured and simulated results of the presented filtering antenna design.

Parameter	Measured	Simulated
$f_o(GHz)$	5.779	5.8
FBW	14.77%	14.226 %
Gain (dB)	3.488	3.91
External quality factor Q_ex	6.77	7.011
Coupling coefficient M_12	0.024	0.01832
VSWR	1.11	1.06

In a filtering antenna, the coupling space between two resonators is crucial for managing the energy transfer between resonators, which has a direct impact on the scattering parameters (S-parameters). The behavior of signals at the antenna's input and output ports, specifically concerning transmission and reflection, is described by the scattering parameters. These S-parameters are essential for a filtering antenna to guarantee minimal loss, frequency selectivity, and appropriate impedance matching. Fig. 8 shows how the coupling distance (S) between the resonators affects the response of the filtering antenna. From Fig. 8 the scattering parameter S11 parameter strongly depends on the coupling spacing (S) of the two resonators and increases with increasing (S) even up to a maximum value and then decreases as the coupling between the resonators becomes weak.Fig. 9 displays the comparison of the simulated and measured S11 parameters of the suggested filtering antenna. It is easy to understand from the Figure above that there is no significant difference between the simulated S11 parameter and the measured S11 parameter. Fig. 10 displays the comparison of the simulated and measured findings for the filtering antenna gain. The comparison results between the simulated and measured values of the overall filtering antenna design are shown in Table 4.

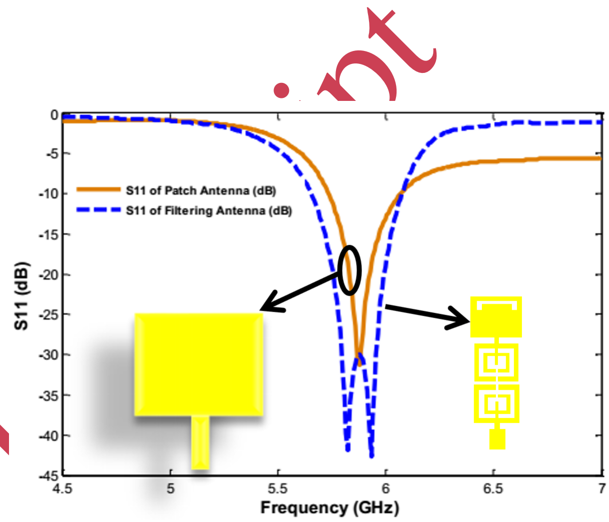


Figure 7. Comparison of the S11 - parameter between the filtering antenna and traditional patch antenna.

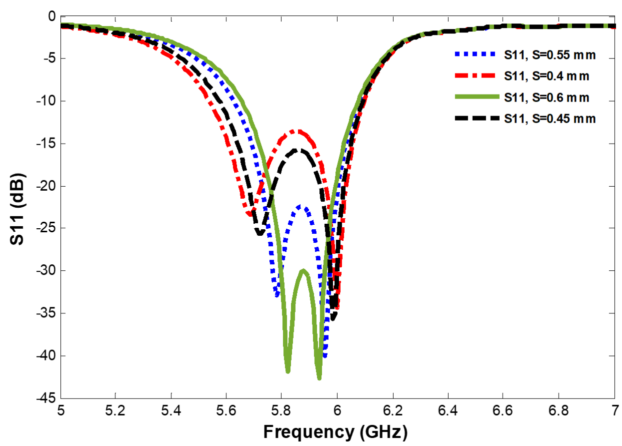


Figure 8. The filtering antenna's S11 parameter for a variable coupling spacing (s).

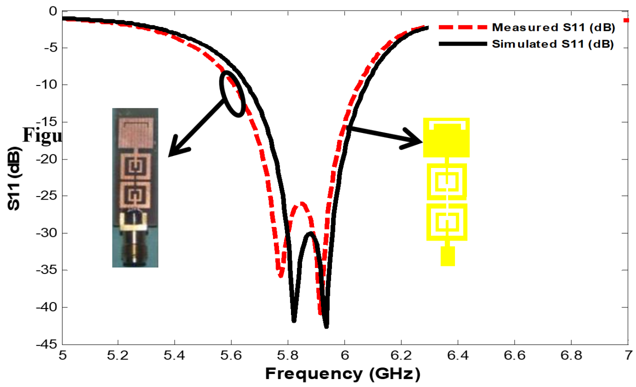


Figure 9. Simulated and measured S11-parameter of filtering antenna design.

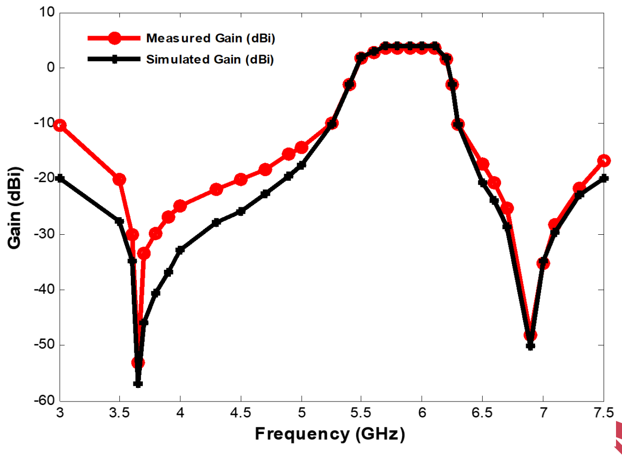


Figure 10. Filtering antenna simulated and measured gain.

One of the important performance statistics for assessing the impedance matching between a source, transmission line, and load (such as an antenna) is the Voltage Standing Wave Ratio (VSWR). Achieving a good VSWR is essential for filtering antennas, which incorporate filtering capabilities into the radiating structure, in order to guarantee correct signal transmission with little power loss. The suggested filtering antenna design's Voltage Standing Wave Ratio (VSWR), as calculated and observed, is displayed in Fig. 11. The proposed filtering antenna operates in the range of Industrial, Scientific, and Medical (ISM) bands, suitable for WiMAX mobile applications 802.16e. So, the value of simulated VSWR is (1.06) and for measured VSWR is (1.11), this is a good indicator of the matching between the filter and the antenna and clear evidence of the quality of the design.

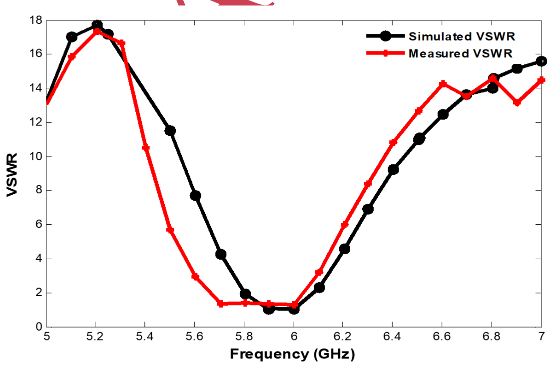
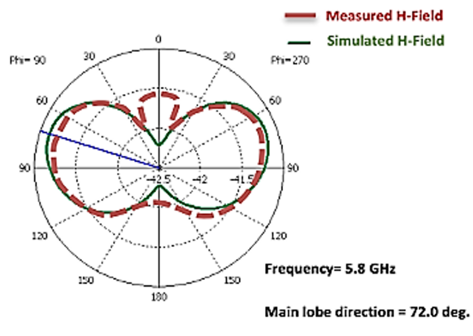
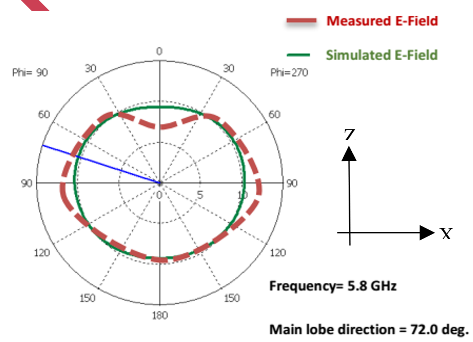


Figure 11. Simulated and measured VSWR of the filtering antenna.

An antenna's far-field area is where the angular field distribution stabilizes and electromagnetic waves radiate outward. The far-field characteristics of a filtering antenna, which combines radiating and filtering elements, are crucial for determining how effectively and selectively the antenna emits or receives signals in the targeted frequency range. When the angular field distribution is independent of the distance from the antenna, the far-field zone starts. Filtering antennas have far-field radiation patterns that are focused and frequency-selective, which guarantees. Effective signal delivery that is limited to the intended frequency range. Through the use of integrated filtering, out-of-band signals cause very little interference. Depending on the design, directed or omnidirectional patterns with low side lobes and maximum gain. Filtering antennas are therefore ideal for uses such as wireless communication (Wi-Fi, 5G), where interference reduction and selective transmission are essential.Simulated and measured far-fields of the filtration antenna are illustrated in Fig. 12. The simulated and measured results show acceptable agreement, therefore it give a good impression of the design quality and accuracy. The photograph of the front view and back view of the fabricated filtering antenna design is shown in Fig. 13.



(a) xxxxxx.



(b) xxxxx.

Figure 12. XXXXXXXXXXXXXXXXXXXXXXXX.

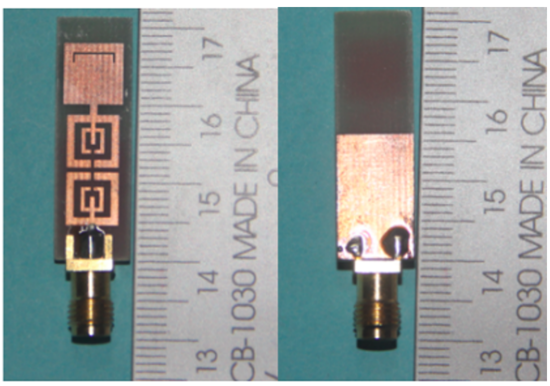


Figure 13. A photograph showing the single-band, dual-mode filtering antenna in construction (a) top perspective ; (b) bottom perspective.

4. Conclusion

This article presents the construction of a single-band with dual-mode filtering antenna operating in the range of Industrial, Scientific, and Medical

(ISM) bands, suitable for WiMAX applications. Compared with the traditional monopole patch antenna, the filtering antenna has a much more reduction in size of about 60 %. By changing the distance (S) between the resonators, one can regulate the return loss and therefore the filtering antenna's performance. Simulated and measured findings show good gain and impedance-matching performance. The filtering antenna was designed and built using FR-4 substrate material, which has a thickness of 1.6 mm and a dielectric constant of 4.3. The performance of a conventional monopole patch antenna is enhanced by the incorporation of a bandpass filter. Good agreement between simulated and measured results, an indicator of design quality, is demonstrated by the research findings.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

Funding source

This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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