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Design of Compact Filtenna Based on Capacitor Loaded Square Ring Resonator for Wireless Applications

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Abstract—This paper proposes and demonstrates a compact integrated filtering antenna built on a square ring resonator coupled with a capacitors loaded microstrip line filter. A microstrip filter module is connected to feeding line of the conventional patch without adding extra space. Thus, the combined configuration possesses radiating and filtering functions simultaneously. The proposed filtenna has a fractional bandwidth (FBW) of 3% at center frequency 2.4 GHz with 2.5 dB of maximum gain. The obtained result shows that the proposed design shows good stopband gain rejection, good selectivity at band edges, and smooth passband gain. Furthermore, the introduced filtenna has advantages of a small size and a simple structure, which makes it ideal for interconnection with different wearable devices operating within 2.4 GHz wireless system range.

1. INTRODUCTION

Bandpass filter and antenna are the main elements in most of the RF front ends, whose performance has a critical effect on system performance. For conventional RF systems, they are generally built independently and linked by a 50 or 75 Ω transmission line, which not only raises system volume but also can degrade its efficiency due to mismatch and additional insertion loss induced by interconnections. Recently, researchers have suggested a kind of co-designed filtering antenna that has antenna and filter functions simultaneously with a small dimensional size to solve this issue [1–4].

The integration process of a filtering antenna is typically divided into two main methods. The first method is called co-design scheme [5–8]. In this approach, filter units and antennas are directly connected by using extra impedance transformers, which inevitably increases the size and introduces extra losses. In addition, replacing the filter with a new configuration inserted in the antenna such an open slot is used in some antenna filtering designs [8–13]. Nevertheless, complex structure and so much parameters optimization process are involved in this design method.

The main and most common technique is to combine the radiated element as the filter's last order resonator or called synthesis approach. The cascading mismatch of filters and antennas may be minimized by air coupling instead of direct coupling between elements [14–22]. The filtering antennas feature small loss and compact volume with no extra circuits to match the impedance. The order of the filters performing the same response could be reduced compared to conventional cascaded design, since the antenna acts not only as a radiator but also as the filter's last resonator. However, most of the filtering antennas suggested in this method often suffered from large size, low frequency selectivity, low gain, or high bandwidth. In [23], lumped capacitors were inserted within the Defected Ground Structure

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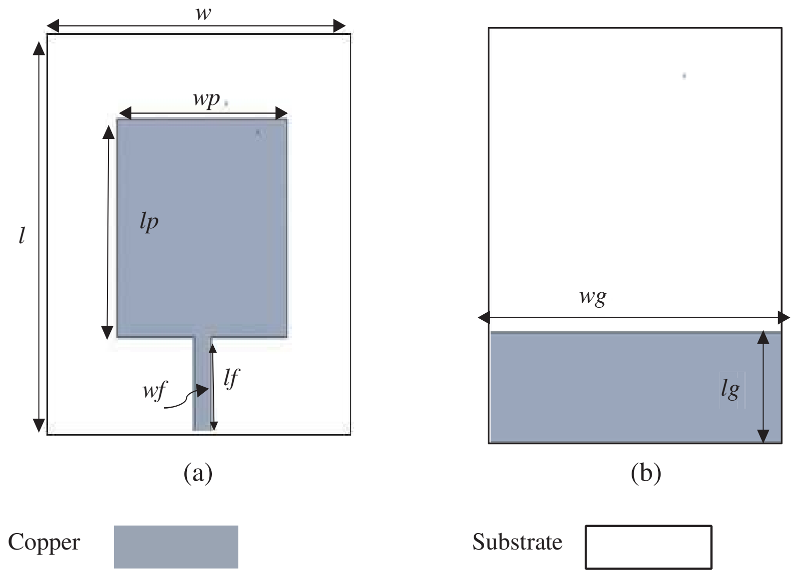
(DGS) resonating slots of filtering antenna ground plane configuration, but at higher frequency with complex design construction.

In this work, a simple structure co-design filtering antenna is developed using the synthesis approach. The filtering antenna consists of asquare ring resonator coupled with a two capacitors loaded microstrip line filter and rectangular patch. For design miniaturization, two lumped capacitors elements are inserted between a ring resonator and microstrip line which drop the total size by 72%. The proposed configuration acts as a bandpass filter at a center frequency of 2.4 GHz with a bandwidth of 100 MHz. It also shows a well-shaped gain response with good skirt selectivity as the traditional bandpass microstrip filter. Due to the aforementioned advantages, the proposed filtenna is a suitable choice for integration in various systems and handheld devices operating at 2.4 GHz band for possible WLAN applications.

2. FILTER-ANTENNA DESIGN

2.1. Antenna Design

A square shaped patch antenna is designed for operation at 2–3 GHz frequency range. The dimensions of the antenna is obtained from the equations reported in [16]. The proposed microstrip patch antenna is shown in Figs. 1(a) and (b). It is built on an FR4 substrate with $er = 4.7$ and thickness $h = 1.6$ mm. The antenna dimensions (in mm) are: the substrate width $w = 45$, length $l = 49$; the patch has width $lp = 31$ and length $wp = 28$; the microstrip feed line has $wf = 3$ and $lf = 15.5$; the partial ground plane has width $wg = 45$ and length $lg = 14$. The antenna simulated result obtained from CST MICROWAVE STUDIO (CST MWS) and measurement result using Network Analyzer (Model: N5242A) from Keysight Technologies are displayed in Fig. 2, and good agreement between both of result is observed.



(a) (b)

Figure 1. The geometries of (a) patch elements and (b) ground plane for the conventional antenna.

2.2. Single Bandpass Filter Design

The development of the bandpass filter starts with implementing a square shape ring resonator after a microstrip line coupled with the square ring is introduced with spacing $g = 0.5$ mm. An L-shape slot is cut in the square ring feed line to suppress the higher unwanted frequencies. The filter unit, designed by using an FR4 substrate with a thickness of 1.6 mm and dielectric constant 4.7, and the optimal value of parameters in (mm) $p = 19.6$, $b = 16$, $m = 3$, $S = 21$, $m = 2$, $w_1 = 2.8$, $e = 11$, is excited via ports 1 and 2 feed line of 50 ohms.

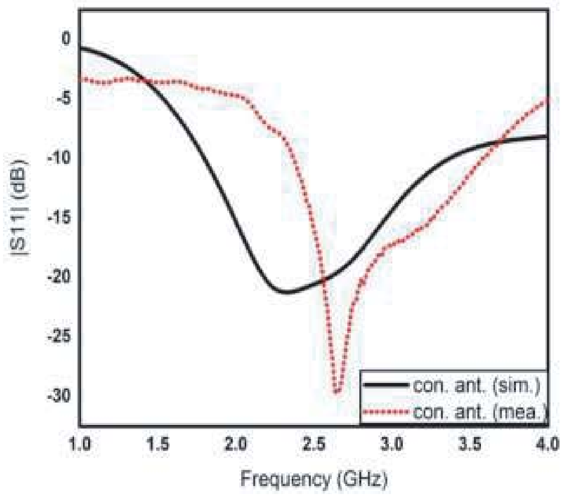


Figure 2. Simulated and measured results of return loss.

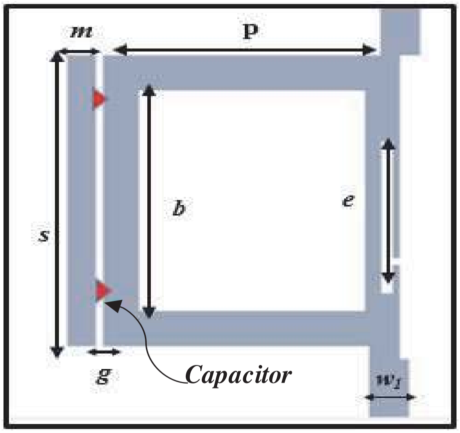


Figure 3. The proposed filter.

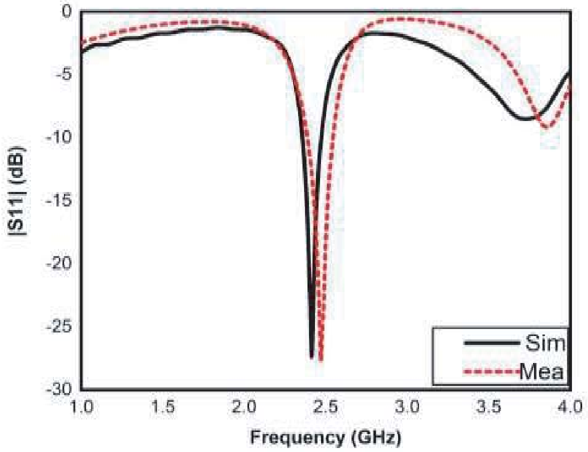


Figure 4. S_{11} simulation and measurement results for the filter.

The filter unit designed with the above dimensions is shown in Fig. 3. Two lumped capacitors have been inserted in the gap between the square resonator and microstrip line for miniaturization purpose. The filter's simulation result obtained from CST MWS and measurement result using Network Analyzer (Model: N5242A) from Keysight Technologies are displayed in Fig. 4, and good agreement between the results is observed.

The current distribution of proposed square resonator filter at 2.4 GHz is presented in Fig. 5. It is found that the current field is focused around the gap between square resonator and microstrip line. Therefore, this region is chosen to insert two lumped capacitors within the gap. The installation of lumped capacitors in the gap improves the effective capacitance and decreases the size of the filter which leads to improving the filter performance by maximizing the energy stored in the resonator.

As displayed in Fig. 6, the filter resonant frequency is operational to the capacitor value (C). The filter has a resonant frequency at 3.7 GHz with no capacitor used, and if two lumped capacitors C are inserted, the resonant frequency shifts to lower value. It is seen that the resonant frequencies is decreased by 45% when two 1 pF capacitors are inserted, so the insertion of a capacitor results in a smaller size. Moreover, the operating bandwidth of the proposed filter is decreased when the lumped capacitors are increased due to rises of the filter quality factor "Q" resulting from the drop of radiation

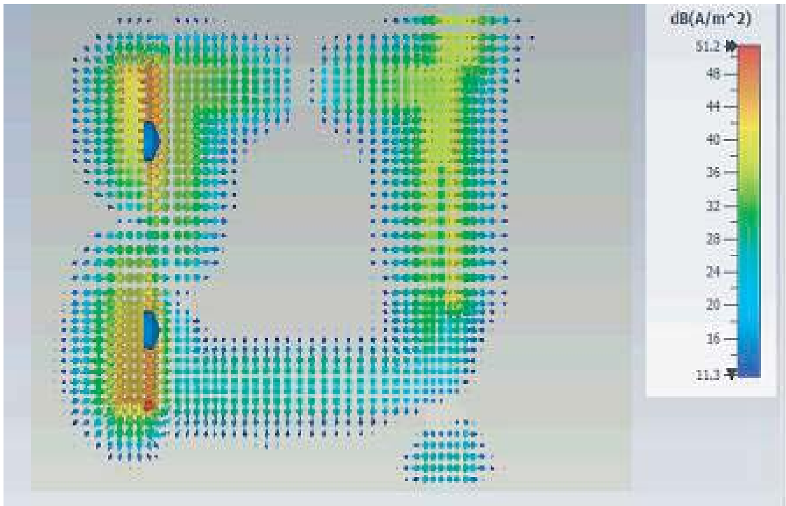


Figure 5. Current distribution for the square resonator filter at 2.4 GHz.

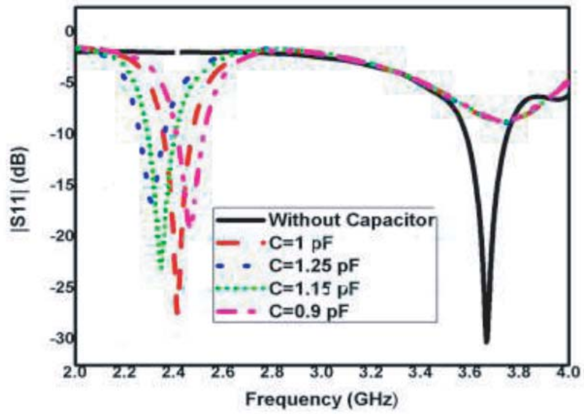


Figure 6. The return loss at various capacitor values for the suggested filter.

loss. It is clear that the chosen capacitor values can be used to tune the filter resonant frequency through different operating bands. For instance, 1 pF value for both capacitors has been selected to adjust the passband from 3.5 GHz (WiMAX) band to lower 2.4 GHz (WLAN) band.

Furthermore, the decrease in resonant frequency has resulted in a reduction of the overall resonator area. Different resonators loaded with different capacitor values by keeping the resonant frequency (f_0) fixed at 2.4 GHz while varying the size of the square resonators are shown in Table 1. With the capacitor value of 1 pF, the effective area is successfully reduced by 72.4%. The proposed filter area is less than 27.6% of that of conventional square resonator operating at the same frequency band.

The proposed 2.4 GHz band pass filter can be modeled by LC equivalent circuit as shown in Fig. 7. The equations used to calculate lumped capacitors and indictors values at resonant frequency of 2.4 GHz can be found in the literature [17]. The values of the lumped elements in Fig. 7 are listed in Table 2.

To achieve optimal performance at 2.4 GHz while sustaining compact filter size, a parametric study for all filter unit parameters is performed, and the optimal value is chosen as stated above. The analysis for two critical parameters (m, s) through filter performance return loss explanation is summarized below.

The effect of microstrip line width 'm' on the resonant frequency is shown in Fig. 8. As can be seen, when microstrip line width is decreased, the resonant frequency is moved toward the lower frequency. The lowering of the resonant frequency is attributed to the enhancement of the coupling as the gap is

Table 1. Capacitively loads square ring resonator characteristics.

C (pF)	p (mm)	Area (mm^2)	Reduction (%)	f_0 (GHz)
0	37.30	1,391	0	2.4
0.25	33.20	1,102	20.8	2.4
0.65	25.4	645	53.7	2.4
1	19.6	384	72.4	2.4

Table 2. Calculated values of the lumped elements in Fig. 7.

LC Circuit	L_1 (nH)	C_1 (pF)	L_2 (nH)	C_2 (pF)
	0.47	9.03	45.17	93.57
	L_3 (nH)	C_3 (pF)	L_4 (nH)	C_4 (pF)
	1.00	4.24	0.47	9.03

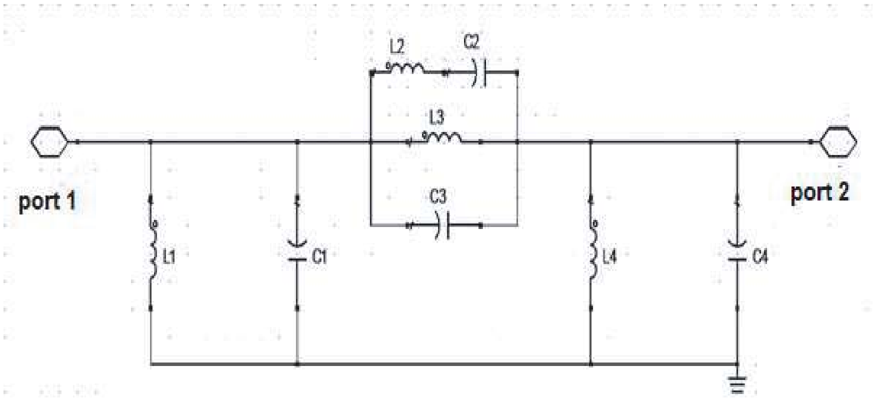


Figure 7. Equivalent circuit model of the proposed filter.

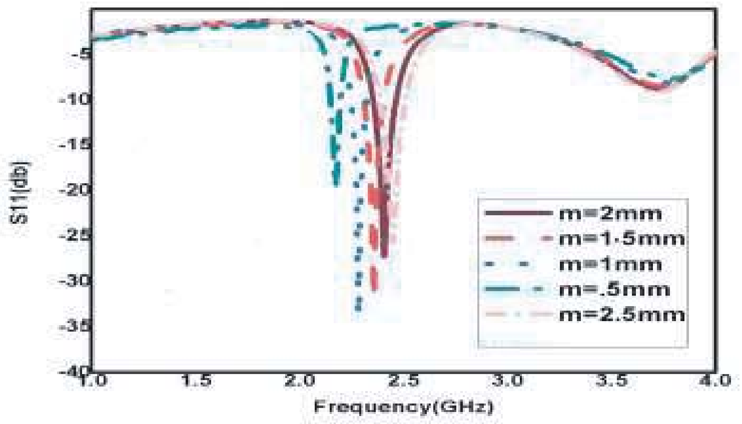


Figure 8. The simulated return loss of different values of (m) microstrip line width.

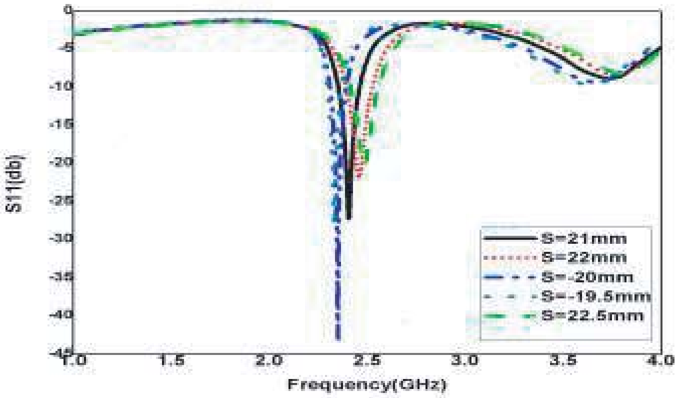


Figure 9. The simulated return loss of different values of (s) microstrip line length.

reduced.

Similarly, the effect of microstrip line length 's' on the resonant frequency is shown in Fig. 9. As can be seen, by varying the length of microstrip line to lower values, the resonant frequency is moved toward lower frequencies. 2 mm and 21 mm are selected as optimal values for 'm' and 's' respectively to provide bandpass response for 2.4 GHz WLAN requirement.

2.3. Integration of Antenna and Filter

The conventional antenna and the compact filter module inserted in the feeding line of the antenna are integrated into a single module as shown in Fig. 10. Because of the compact size of the filter module, this configuration does not require additional space for the integrated filter module. The operating bandwidth for the filtenna is supposed to be around 2.4 GHz, meaning that the antenna and filter are predesigned to have a functioning bandwidth at such operating band. To ensure reasonable filtering performance, the conventional antenna and filter module's structural dimensions have been slightly adjusted in the stage of filtenna co-design.

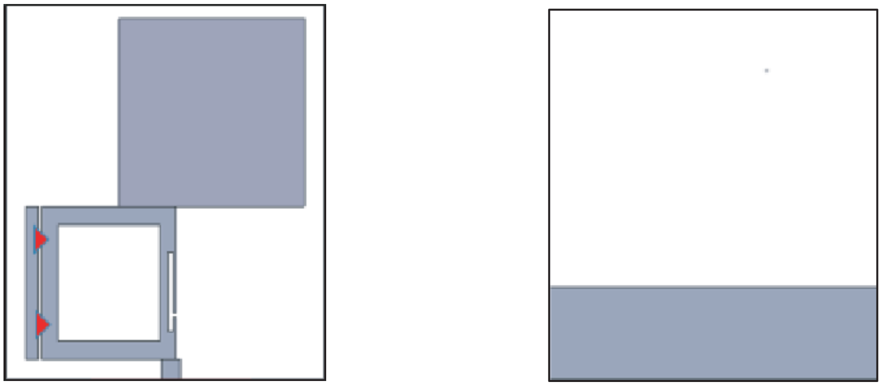

(a) (b)

Figure 10. The structure of the proposed filtenna (a) top view, (b) bottom view.

3. RESULTS, ANALYSIS AND DISCUSSION

The proposed filtering antenna module is fabricated as displayed in Fig. 11. In Fig. 12, the simulation and measurement reflections results for the conventional antenna in the presence and absence of the filter

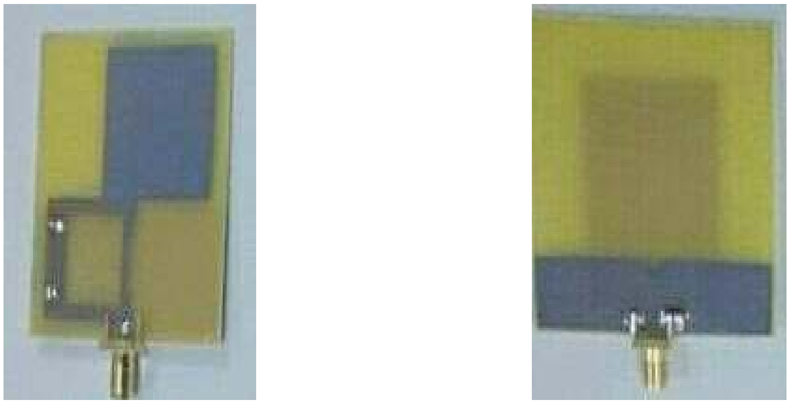

(a) (b)

Figure 11. The photograph of the filtenna prototype (a) top view and (b) bottom view.

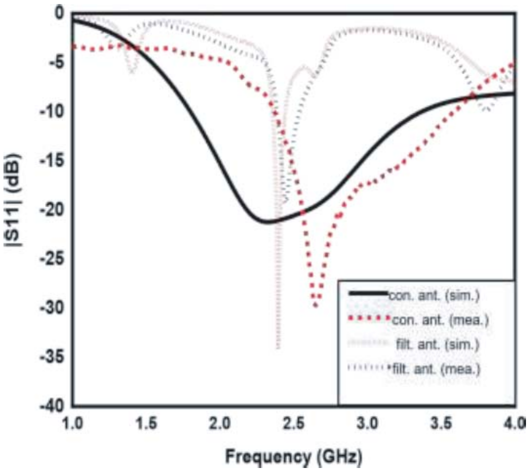


Figure 12. The return Loss (S_{11}), simulation and measurement results for antenna with and without filter.

unit are shown. It can be observed that the filter module bandwidth is 100 MHz which is smaller than impedance bandwidth of the conventional antenna without filter (around 1 GHz). Thus, the bandwidth of the integrated filtenna may be assumed to be determined by the filter unit response.

The measurement result for return loss of the fabricated design is done using Vector Network Analyzer (VNA) (Model: N5242A) from Keysight Technologies to compare with the simulated response. As the proof from the graph shown in Fig. 12, the simulated and measured findings are in reasonable agreement. Any differences in the experimental results may be due to the substrate's manufacturing tolerances and loss tangent. The filtenna has a smaller operating measured bandwidth (around 100 MHz centered at 2.4 GHz) than the traditional antenna attributed to the influence of the integrated filter, which matches the expectations as previously stated.

Figure 13 displays the simulated return loss and realized gain for both the conventional and integrated filtering antenna. The filtering functionality is clearly displayed on the filtering antenna's gain curve. The simulated 3 dB gain bandwidth is around 100 MHz at 2.4 GHz center frequency.

Figure 14 shows the simulated realized gain of the proposed antenna. To prove the filtering functionality for the suggested filtenna, its performance is compared to a traditional patch antenna printed on the same substrata. The suggested antenna displays filtering characteristics with suppressed stopband gain, flat in-band gain, and good skirt selectivity at the edges of the band.

Furthermore, radiation patterns of the conventional antenna and the filtenna at 2.4 GHz

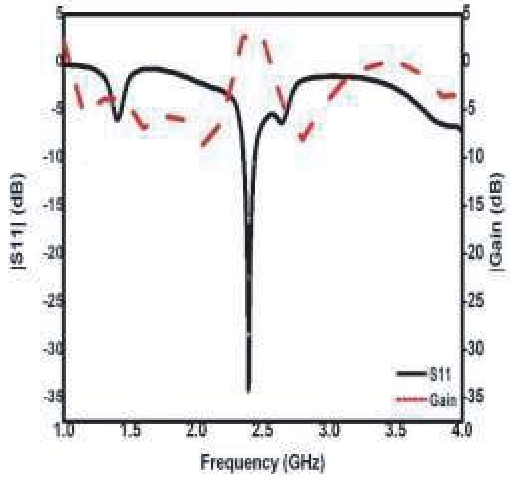


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Figure 13. The Simulated S_{11} and gain of the proposed filter-antenna.

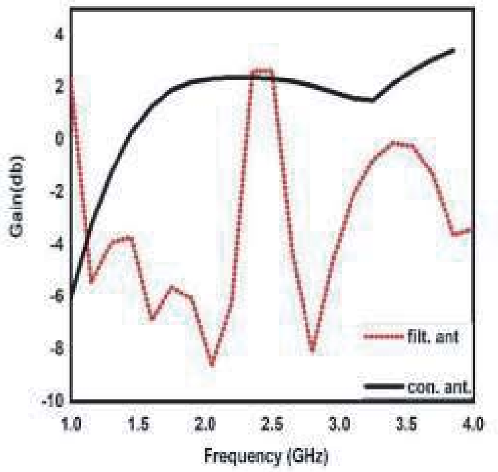
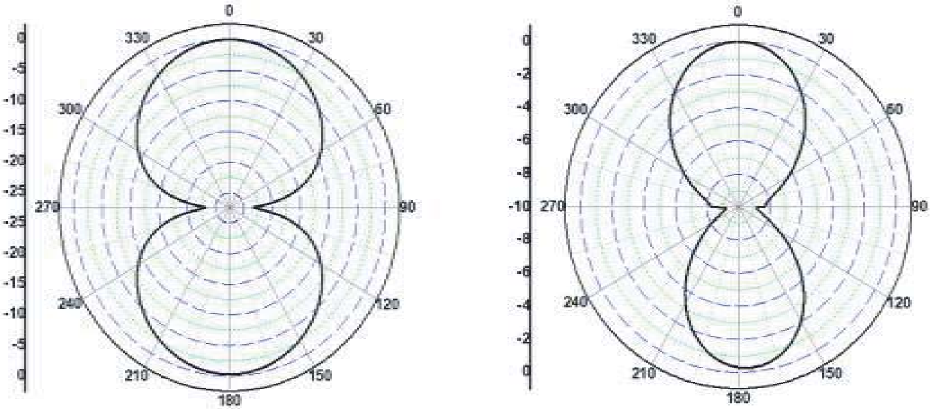
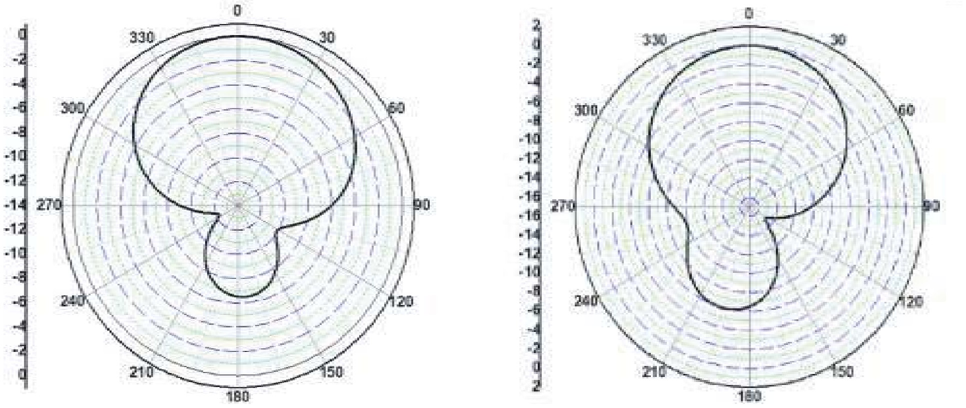


Figure 14. Simulated radiation peak gains for both two antennas.



H-plane E-plane

(a) (b)



H-plane E-plane

(c) (d)

Figure 15. Simulated E- and H-planes patterns at 2.4 GHz (a) and (b) conventional antenna and (c) and (d) filtenna.

performance are studied as shown in Fig. 15. The E- and H-planes radiations for conventional antenna are shown in Figs. 15(a) and (b), respectively, implying an 8-shape radiation pattern.

Similarly, the radiation pattern behavior of proposed filtenna at 2.4 GHz is investigated. The simulated E- and H-plane patterns of the filtering antenna at 2.4 GHz are shown in Figs. 15(c) and (d), respectively. The radiation performance is close to nearly omnidirectional for both planes. It can be seen that the radiation properties stay stable within the working bandwidth. Therefore, the application of the filter unit does not change the characteristics of the radiation.

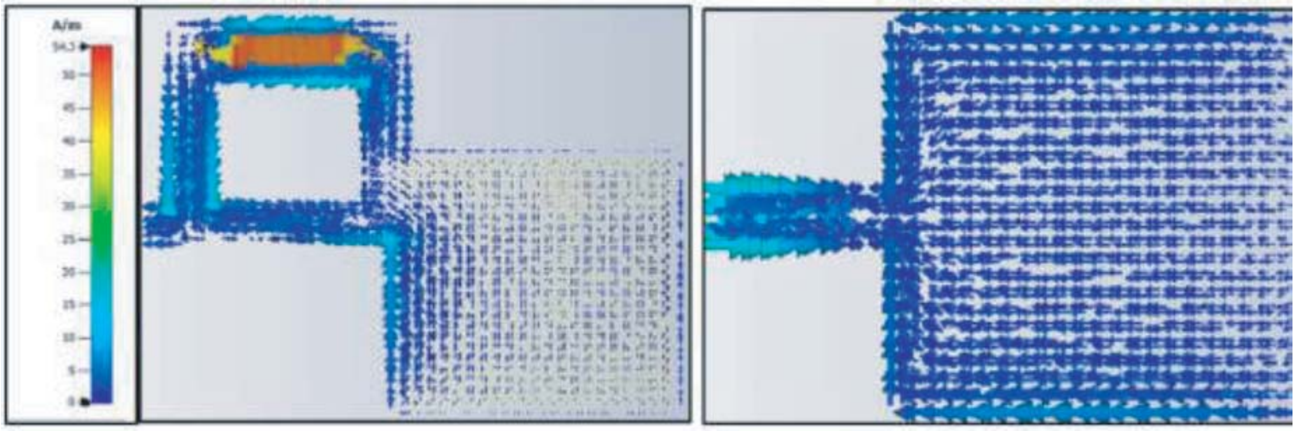
Finally, a comparison of the performance for the filtenna described in this study with previous recorded works is summarized in Table 3, where λ_0 is the free space wavelength at the cut-off frequency (F_0). As can be shown, the filtenna introduced in this study has comparable size, radiation gain, and bandwidth gain.

Table 3. Comparisons of results with previously recorded filtennas.

Ref.	Size ($\lambda_0 \times \lambda_0$)	F_0 (GHz)	FBW (%)	Gain (dB)
8	9.1×0.3	2.4	8.7	1.61
13	0.35×0.24	2.4	16.3	1.31
10	0.36×0.51	2.45; 5.8	4.5; 3.8	−1.8; 1.1
15	0.50×0.35	5.2	9	2.5
17	0.40×0.44	2.4	16.3	2.4
12	0.48×0.30	2	19	5.6
This work	$\mathbf{0.37 \times 0.36}$	**2.4**	**3**	**2.61**

For demonstration of the effectiveness of integration band pass filter with a conventional antenna on rejecting unwanted signals, the current surface distributions for the proposed design with and without integrated band pass filter are investigated. In Fig. 16, and the current distributions for both cases at a frequency of 2.4 GHz are displayed.

As can be observed from Fig. 16(a), in existence of the band pass filter the current is mainly concentrated in the band pass filter area, and insignificant current flow passes to patch, whereas higher level of current passes from the port to the radiating patch in the absence of band pass filter unit as depicted in Fig. 16(b).



(a) (b)

Figure 16. Current distributions of the proposed design at frequency of 2.4 GHz (a) with band pass filter, and (b) without band pass filter.

4. CONCLUSION

This paper proposes and demonstrates a compact integrated filtering antenna built on square ring resonator coupled with a capacitors loaded microstrip line filter. A microstrip filter module is connected to feeding line of the conventional patch without adding extra space. Thus, the combined configuration possessing both radiating and filtering functions simultaneously. The proposed filtenna has an FBW of 3% at center frequency 2.4 GHz with 2.5 dB of maximum gain. Good out-of-band gain rejection, good skirt selectivity at band edges, and flat in-band gain have been observed. Furthermore, the introduced filtenna has advantages of a small size and a simple structure, which makes it ideal for interconnection with different wearable devices operating within 2.4 GHz wireless system range.

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