Design of a Compact Microstrip Filtenna for Miniaturized Devices to Access Internet of Things Using Long Term Evolution

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ABSTRACT A filtenna, or filtering antenna, has both radiation and filtering functions and is an important module for the RF front-end of wireless devices. The main function of a filtering antenna is to filter out out-of-band interferences from adjacent bands. In this paper, the design of a compact coplanar microstrip filtering antenna in 2.6 GHz band is presented. The antenna is designed for the miniaturized devices for city connectivity to access internet of things (IoT) services over 2.6 GHz long-term evolution (LTE) gateways. The filtering antenna is designed using hairpin band-pass filter integrated with semi-circular microstrip antenna. Filtering antenna is designed by computer simulation technology (CST) software and measurements are performed by a vector network analyzer. Good impedance matching in 2.6 GHz band is obtained for the filtering antenna by choosing appropriate dimensions of the hairpin band-pass filter. A comparison between the semi-circular patch filtering antenna and a circular patch filtering antenna is also presented here. The simulated 10 dB return loss bandwidth of the semi-circular filtering antenna is 4.65%, with a maximum gain of 1.9 dB. Measured and simulated results agree well for the semi-circular filtenna.

INDEX TERMS Compact, internet of things, hairpin band-pass filter, microstrip filtenna, semi-circular patch, circular patch.

I. INTRODUCTION AND RELATED WORK

THE internet of things (IoT) provide network connections to different devices and sensors called “things” [1]. The IoT devices are connected to the gateways using wireless networks of GSM/Wi-Fi/3G/LTE/4G/5G. Cities have a wide range of IoT connectivity starting from the outdoors to the basements of the indoors and therefore signal strengths ranges from very good to very poor. It is found that the performance of 2.6GHz band LTE has higher capacity than the lower band of 800MHz for city coverage in varying signal strength conditions [2]. To handle smart indoor cameras and cloud-based automated access control systems, like, mobile apps, personalized key cards, key fobs, and mobile phone links, very small compact all-coplanar antenna systems are most attractive. A filtering antenna or filtenna radiates and functions for a desired frequency band while rejecting out-of-band interferences [3]. There are several approaches to design microwave filters for RF front-end [4, 5]. The design of filtering antenna, that is, antenna integrated with filter, is application specific. For miniaturized devices, most suitable antenna is planar microstrip antenna which in its simplest form is a metallic radiating patch, etched on a dielectric substrate backed by a ground plane and using a microstrip antenna, multiple frequency, polarization diversity and reconfigurability can be achieved very easily. There are several approaches of in-band filtering for RF front end [6-10] having their advantages and disadvantages. In [6], the non-uniform filter synthesis and amplifier-based active antenna is used for the application to wireless local area network (WLAN). In [7], a short-ended coupled line on ceramic technology is used for filter design to use at the base station for high power handling capability. A dual microstrip line low-pass (LPF) filter is proposed in [8] with characteristics of wide stop-band and sharp roll-off rate. Slotted-patch microstrip resonator and quasi-fractal patch are used in [9] for the design of microstrip filter. In [10], a programmable filter with an adaptive folder is used to improve the jamming suppression quality over a wide frequency band of RF front-end. For practical applications, filtering antenna design is application specific [11-15]. The flatter gain response within the passband of a filtenna of fan-shaped radiator with defected ground structure (DGS) is achieved in [11] using Butterworth band-pass filter. In [12] a filtenna of high gain is reported using a U-slot loaded driven patch and a stacked shorted patch. A compact filter antenna, using a folded open loop resonator band-pass filter and a varactor diode loaded patch, is designed in [13]. A low-profile polarization diversity filtenna design is reported in [14] where the antenna is fed by a custom-designed coupling probe. A duplex filtenna, using substrate integrated waveguide (SIW) and two vias, is designed [15] to enhance the selectivity of the passband with impedance bandwidth of 4.2% at 9 GHz band. Design of a dual circularly polarized cavity backed filtenna using SIW technology is reported in [16] where operating bandwidth of 12% is achieved at 10 GHz band. In [17], a vertically integrated full duplex filtering antenna with SIW cavity, is designed which has measured realized gain of 4.36 dBi and impedance bandwidth of 3.2% at 4 GHz band. The design of the filtenna, reported in [18], used a circular radiator with coplanar feed, shorting stubs and defected ground structure (DGS) to achieve fractional impedance bandwidth of 20.34% with a peak realization gain of 1.88 dBi. To design a compact dual band filtenna [19], a shorted slot-loaded patch is used with coupled lines and DGS to obtain best impedance matching with high gain. Some reports are available, particularly, on the antenna or filtering antenna design for IoT and LTE applications [20-23]. A frequency reconfigurable filtering antenna is designed [20] using hairpin filter and p-i-n diode switch to operate at 2.47 GHz, 3.42 GHz, 7.18 GHz, 8.4 GHz and 12.14 GHz for IoT services. A duplexer-based reconfigurable filtering antenna is designed [21] to operate at 29/20 GHz satellite services for IoT communications using microstrip patch, p-i-n diode switch and hairpin filter. In [22], electromagnetic bandgap (EBG) structure is used to design textile antenna to operate at the millimeter wave frequency of 26 GHz where reduced specific absorption rate (SAR) and high gain of 8.65 dBi are achieved. Slot-loaded quarter-wave monopole and filtering stubs are used to design frequency-reconfigurable filtering antenna for the multiple wireless applications including 4G LTE [23].

From the previous related works, it is found that most of the reported filtering antennas have design complexity and many of those are not coplanar and compact systems. In many reports, at out-of-band frequencies, the return loss is not minimum to minimize interferences from the notching frequencies. Also, very few reports are available to on the design of filtenna for IoT over 2.6 GHz band LTE networks.

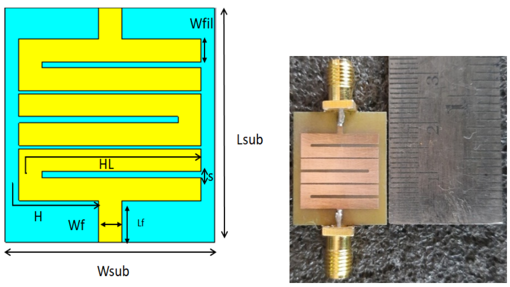
In this paper, the design of a microstrip filtering antenna incorporating hairpin filter with a semi-circular microstrip antenna is reported. The filtering antenna is very compact and is proposed for the application to very small home appliances to access IoT services over 2.6 GHz LTE gateway. The design of this filtering antenna is very simple, compact and coplanar antenna system with hairpin band-pass filters. The filtenna is fabricated on FR4 substrate with dielectric constant (ε_r) of 4.4, loss tangent (tanδ) of 0.0025 and height (h) of 0.8 mm. The filtenna is simulated by CST software and measured by an MS2037C vector network analyzer to validate the simulated results. Anechoic chamber is used to measure the radiation characteristics of the filtenna. Dimensions of the semi-circular filtenna are 40 mmX40 mm ($0.35\lambda_0 X 0.35\lambda_0$ at 2.6 GHz band).

After introduction and related work in Section 1, the design of hairpin band-pass filter is described in Section 2. Simulated results for hairpin band-pass filter are validated by measurements. Design and measurements of the semi-circular filtering antenna are presented along with their performance comparison in Section 3. The simulated and measured results for the circular patch filtering antenna and their comparison with those of the semi-circular filtering antenna are presented in Section 4. The conclusion and the future extension of this research work are described in Section 5.

II. DESIGN OF MICROSTRIP HAIRPIN FILTER

Due to their compact size and easy design, microstrip hairpin filters are among the most popular band-pass filters [24-26]. These filters are made of a U-shaped structure that is created by folding the half-wavelength resonators of parallel-coupled filters. Coupling between the lines of the resonators can be reduced by folding the lines [4, 5]. In hairpin filter structures, tapped and coupled line inputs are mostly used. The tapped line input takes up less space in the integrated form compared to the coupled-line input. The design of a hairpin filter requires an equal ripple low-pass prototype. Each resonator is modeled as an inductor-capacitor pair. Two resonators couple at $m_{i,\, i+1}$. Q_1 and Q_n are the input and output quality factors. The dimensions and spacing of the hairpin filter can be estimated using the quality factor and coupling coefficient [4, 5]

The 3rd order hairpin-line filter, it is considered that the fractional bandwidth (FBW) is 20% = 0.2 with mid-band frequency (f_0) of 2.61 GHz and passband ripples of 0.5dB. The low-pass prototype parameters and cutoff frequency are computed according to the design procedure given in [4, 5]. For a normalized low-pass cutoff frequency of $\Omega_c = 1$, the suggested low-pass prototype elements are $g_0 = g_4 = 1$, $g_1 = 1.402$, $g_2 = 0.707$, and $g_3 = 1.984$. Where, g_0, g_1, g_2,....g_{n+1} are the normalized low-pass components. The line width [4, 5] of the hairpin resonators is 1.5 mm, resulting in Z_r=59 Ohm and the separation between the two arms is 0.6mm. At mid-band frequency f_0=2.61 GHz, the hairpin resonator's length *Hl* is 15.25 mm. The calculated values [4, 5] are $m_{1,2} = m_{2,3} = 0.184$ and Q_1= 5.158. As a result, the spacing between the resonators is 0.2 mm, as calculated using the coupling coefficient. The filter is built with tapped line input and output. The characteristic impedance of the tapped line is Z_0=50 Ohms. As a result, the width of the tapped line is 1.23 mm. The tapping location (H) is 10.5 mm. Fig. 1 depicts a simulated and fabricated prototype of the microstrip hairpin filter design. Full Wave EM simulation CST MWS is used to construct hairpin filters.

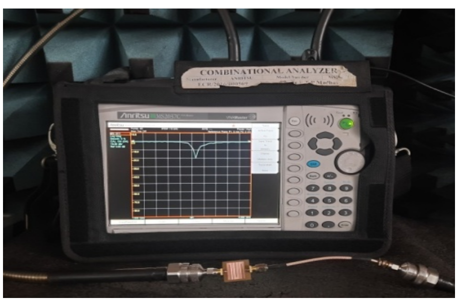


(a) Simulated (b) Fabricated

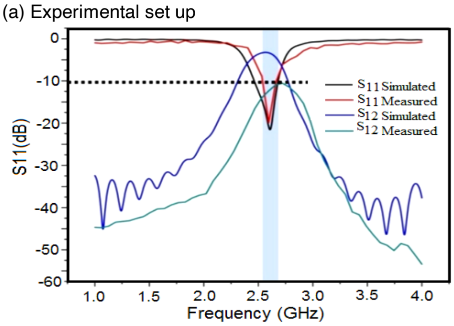
FIGURE 1. Hairpin filter

The dimensions of the hairpin filter of Fig. 1 are: Lsub=22 mm, Wsub=20 mm, H=10.5 mm, HL=15.25 mm, Wfil=2.2 mm, Wf=1.23 mm, Lf=4 mm and S=0.2 mm

The Simulated designs are fabricated and measured using an MS2037C vector network analyzer.The experimental setup and results for S_{11} and S_{12} of the designed hairpin filter are shown in Fig. 2.



(a) Experimental set up



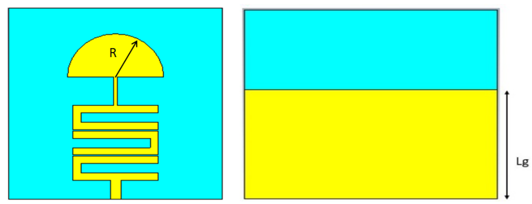
(b) Simulated and measured results

FIGURE 2. Experimental set up and results for hairpin filter

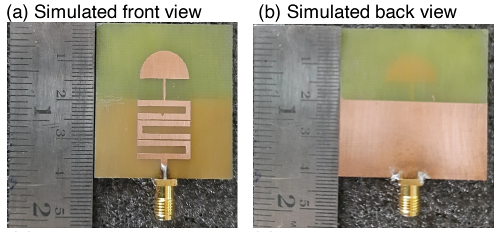
Simulated bandwidth of the hairpin band-pass filter is 220 MHz (2.46 GHz - 2.68 GHz) whereas the measured bandwidth is 150 MHz (2.53 GHz - 2.68 GHz).

III. DESIGN OF COMPACT FILTENNA USING SEMI-CIRCULAR PATCH

To design a filtenna of semi-circular patch at 2.6 GHz band, first the the dimensions of a filtenna of circular patch antenna is determined. Then taking the half dimension of the circular patch and by parameteric studies, the final dimensions of the filtenna of semi-circular patch are determined. The radius of the circular patch [27, 28] is evaluated and optimized to 6mm using the calculations above. The semi-circular-shaped patch is designed after removing half of the part from the circular patch. After parametric studies, the radius of the semi-circular shaped patch is found to be 7.45 mm to achieve better results. The same FR4 substrate with partial ground is used. The final dimensions of the filtenna of semi-circular patch are: radius, R =7.45 mm and Lg=20.2 mm with the dimensions of the hairpin filter of Fig. 3; Lsub=22 mm, Wsub=20 mm, H=10.5 mm, HL=15.25 mm, Wfil=2.2 mm, Wf=1.23 mm, Lf=4 mm and S=0.2 mm. The simulated and fabricated prototypes of the Semi- circular patch filtering antenna are depicted in Fig. 3.



(a) Simulated front view (b) Simulated back view



(a) Fabricated front view (b) Fabricated back view

FIGURE 3. Diagrams of the microstrip filtenna

The parametric study to obtain the dimension of the semi-circular patch is shown in Fig. 4. The minimum S_{11} value is -28 dB for radius of 7.45 mm. For other values of radius, resonance frequency shifts far from the required band.

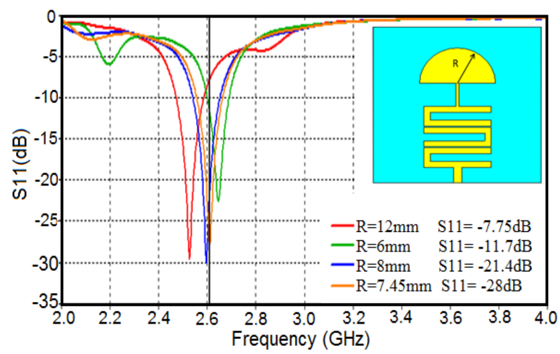
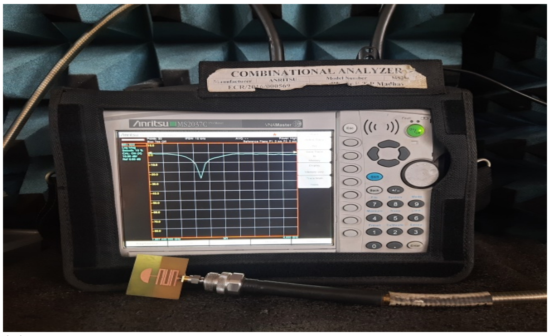
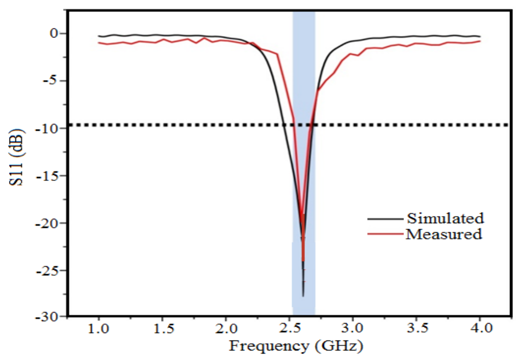


FIGURE 4. Parametric study for the semi-circular microstrip filtenna

The simulated and measured return loss plots for the semi-circular patch filtering antenna is shown in Fig. 5. The simulated resonance frequency of the antenna is 2.61 GHz with return loss of -28 dB whereas the measured resonance frequency is 2.60 GHz with a return loss value of -27 dB. The bandwidth offered by both simulated and measured antennas is almost the same, that is, 110 MHz (2.55 GHz - 2.66 GHz) and 102 MHz (2.55 GHz - 2.66 GHz).



(a) Measurement set up



(a) Measured and simulated results

FIGURE 5. Measurement set up and results of the microstrip filtenna

Fig. 6 depicts the simulated and measured gain plots of the semi-circular patch filtering antenna.The measured gain for the filtering antenna design is very close to the simulated gain. The maximum simulated gain of the filtenna is 1.9 dB and the measured gain is 1.7 dB.

Fig. 7 shows the radiation patterns at 2.61 GHz for semi-circular filtenna. The measured results agree with the simulated patterns very well.

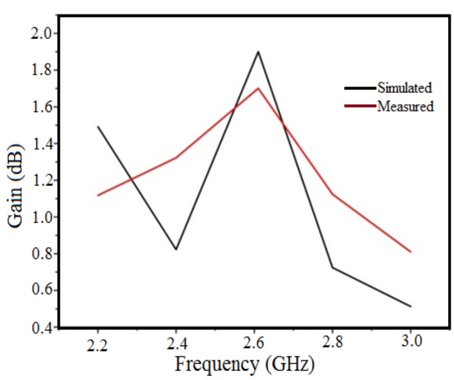
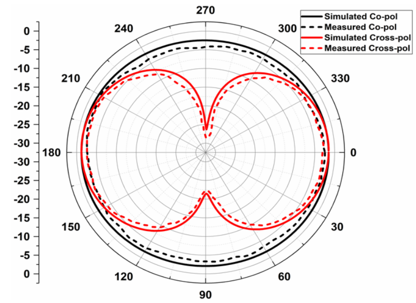
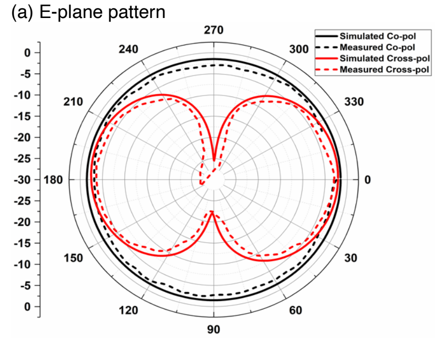


FIGURE 6. Measured and simulated gains of the microstrip filtenna



(a) E-plane pattern



(b) H-plane pattern

FIGURE 7. Radiation patterns of the microstrip filtenna

The simulated and measured results for the semi-circular microstrip filtering antennas are compared with published results [23, 29, 30, 31] in Table I.

TABLE I. Performance comparison of the microstrip filtenna

References	Type of filtering antenna	Frequency band (GHz)	10dB return loss bandwidth (MHz)	Gain (dB)
Ref [23]	Slot-loaded quarter-wave monopole and filtering stubs	2.45	370	2.0
Ref [29]	Square-ring patch coupled with capacitor-loaded planar line filter	2.4	72	2.5
Ref [30]	Multilayered filtenna on grooved ground plane	2.6	70	2.2
Ref [31]	Printed antenna with a cresent shaped stub and electromagnetically coupled with a band-pass filter	3.7	240	2.9
This paper	Semi-circular filtenna with coplanar hairpin filter	2.6	121(simulated) 150(measured)	1.9 (simulated) 1.7 (measured)

The design of filtering antenna in [23], [29, [30] and [31] are difficult and the systems are not coplanar. In [30] and [31], bandwidths are very less. The semi-circular filtering antenna, proposed in this paper is a coplanar system and easy to design. The filtenna has moderate gain and bandwidth for the miniaturized devices for the access to 2.6 GHz IoT connectivity over LTE.

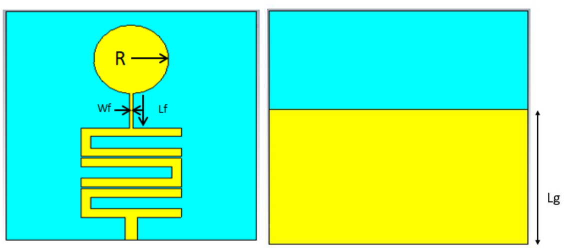
IV. DESIGN OF FILTENNA USING CIRCULAR PATCH

The radius of the circular patch is evaluated [27, 28] and optimized to 6 mm. The circular-shaped patch is integrated with a hairpin filter and microstrip feed line using the same dielectric substrate as semi-circular filtenna. The width and length of microstrip feed line are obtained after a number of simulations considering different lines and widths of the feed line to obtain the best matching in terms of reflection coefficient. The simulated and fabricated prototype of the circular filtering antenna is depicted in Fig. 8.

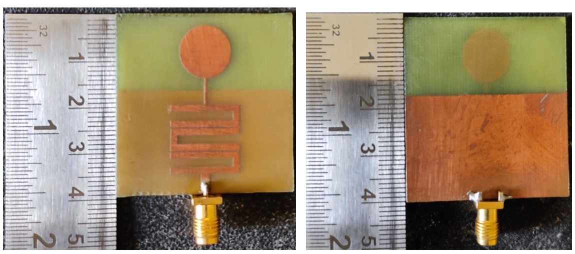
The length of the partial ground was also tuned a little to achieve better-operating results and the final dimensions of the circular filtering antenna are: R=6 mm, Wf=0.6 mm, Lf=4 mm and Lg=22.9 mm.

The radius of the circular patch is 6 mm and the ground plane is dimension is 22.9 mm for the circular patch filtering antenna which are found from the parametric studies. The parametric studies for the ground plane dimension for the simulated circular patch filtering antenna is shown in Fig. 9.

The return loss plot of the simulated and measured circular patch filtenna is shown in Fig. 10. Both the simulated and fabricated antennas resonate at 2.61 GHz with return loss values of -46dB and -37dB respectively. The bandwidths obtained in simulation and measurement are 121 MHz (2.54 GHz - 2.67 GHz) and 150 MHz (2.53 GHz - 2.68 GHz) respectively.



(A) Simulated front view (B) Simulated back view



(C) Fabricated front view (D) Fabricated back view

FIGURE 8. Simulated and fabricated diagrams of the circular filtering antenna

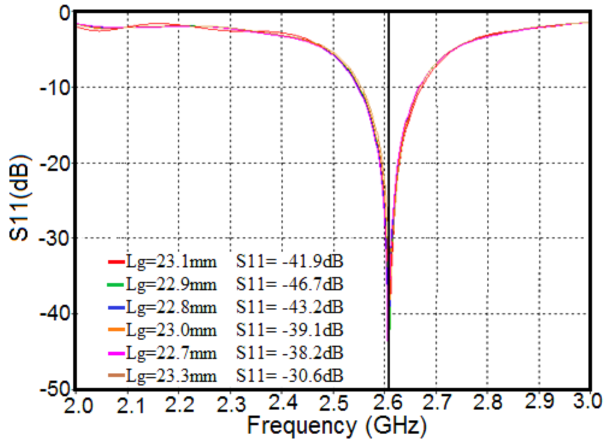
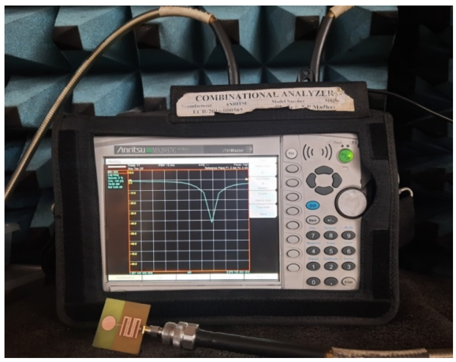
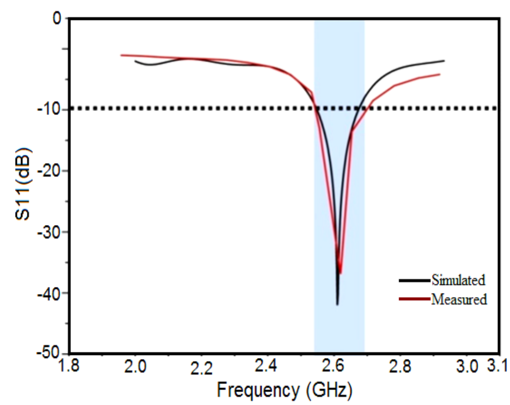


FIGURE 9. Parametric study for the ground plane dimension of microstrip circular filtering antenna

Fig. 11 compares the measured and simulated gains of the microstrip circular filtering antenna. The maximum simulated gain of the circular filtering antenna is 1.78 dB at 2.61 GHz, while the measured gain is 1.66 dB.



(A) Measurement set up



(B) Simulated and measured results

FIGURE 10. Measurement set up and results for the microstrip circular filtering antenna

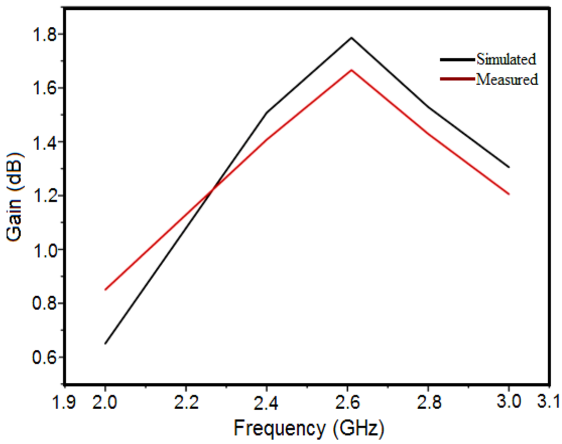
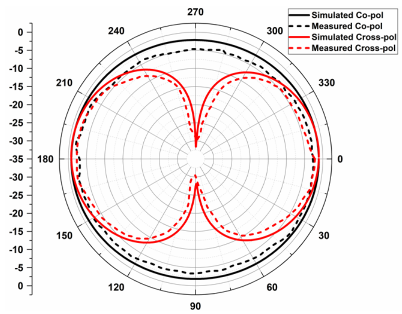
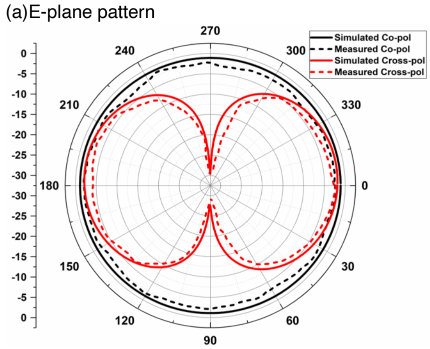


FIGURE 11. Simulated and measured gains of microstrip circular filtering antenna

Fig. 12 depicts the simulated and measured radiation patterns in two principal planes at 2.61 GHz for circular filtering antenna. The measured results agree with the simulated patterns very well.



(a)E-plane pattern



(a)H-plane pattern

FIGURE 12. Simulated and measured radiation patterns of microstrip circular filtering antenna

The Performance of semi-circular microstrip filtenna is compared with that with a circular microstrip filtenna in Table II.

TABLE II. Performance comparison semi-circular and circular microstrip filtering antennas (S-simulated, M-measured)

Filtenna Module	Center frequency (GHz)	S11 (dB)	10dB return loss bandwidth (MHz)	Gain (dB)	Patch Size (mm²)
Semi-circular patch filtenna	2.61 (S) 2.61 (M)	-28(S) -27(M)	121 (S) 150 (M)	1.9 (S) 1.7(M)	56.55
Circular patch filtenna	2.61 (S) 2.61 (M)	-46(S) -37(M)	121(S) 150(M)	1.78 (S) 1.66(M)	113.1

Good impedance matching is obtained for the circular patch filtenna compared to that of the semi-circular filtenna. The size of the semi-circular patch is half that of the circular patch, that is, the filtenna using semi-circular patch is very compact.

V. CONCLUSION

A compact filtenna is designed for the miniaturized devices to access IoT services over LTE networks. The filter is coplanar with the semi-circular patch antenna having defected ground structure and reduces the design complexity. The measured and simulated results agree well. The filtenna has moderate gain and omnidirectional radiation pattern. At the out-of-band frequencies, the achieved return losses are very low which minimizes the undesired radiation caused by the notching frequencies. A comparison between semi-circular patch filtenna and circular patch filtenna is also presented. Small differences between the experimental and simulated results are for the imperfections in microstrip filtenna fabrication. This research work will be extended in future to design multiple frequency microstrip band-pass filtering antennas to operate at different frequency bands used in Wi-Fi, WiMAX, WLAN, LTE for IoT services.

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