Split ring resonator inspired microstrip filtenna for Ku-band application

Soumya Ranjan Mishra[1,*], Sheeja K. L.[1], Nagendra P. Pathak[2]

1. Department of Electronics and Telecommunication Engineering
Veer Surendra Sai University of Technology, Burla, Odisha, India

2. Department of Electronics and Communication Engineering,
Indian Institute of Technology, Roorkee, India

srmishra.3487@gmail.com

ABSTRACT. This paper reports the design, simulation and characterization of two filtenna structures for Ku-band application. This also presents a comparative study of inductive and capacitive loaded Split Ring Resonator (SRR) in filtenna design. The proposed filtenna structures have the merits of compact size, light weight, low cost and uncomplicated fusion with other planar circuits, in comparison to other circuits. The filtenna structures were simulated with HFSS v.13 software and the results are experimentally verified. The proposed filtenna structures are measured at IIT, Roorkee using FieldFox Microwave Analyzer (N9918A) and anechoic chamber. A good agreement between the simulated and the measured result validates the design. The achieved bandwidth and peak gain of the filtenna structure-I is 3300 MHz and 4.87 dBi respectively for Ku-band. Similarly, the filtenna structure-II resonates at Ku-band with bandwidth 1800 MHz and the peak gain is about 4.8 dBi. The fractional bandwidth possessed by filtenna structure-I and II are 20.62% and 12.77% respectively at resonance. The total build up area of the both proposed structure is about 909.09 mm^2, which is most advantageous feature for ku-band application. It also exhibits low insertion loss and low harmonics at higher frequencies.

RÉSUMÉ. Cet article décrit la conception, la simulation et la caractérisation de deux structures de filtenna pour une application en bande Ku. Il présente également une étude comparative du résonateur à anneau fendu (SRR) à charge inductive et capacitive dans la conception de filtenna.Les structures de filament proposées présentent les avantages d'une fusion compacte, légère, peu coûteuse et simple avec d'autres circuits planaires, par rapport à d'autres circuits.Les structures de filtenna ont été simulées avec le logiciel HFSS v.13 et les résultats ont été vérifiés expérimentalement.Les structures de filtenne proposées sont mesurées à l'IIT, Roorkee à l'aide d'un Analyseur de Micro-ondes FieldFox (N9918A) et d'une chambre anéchoïque.Un bon accord entre le résultat simulé et le résultat mesuré valide la conception.La bande passante et le gain de pointe obtenus pour la structure de filtenna-I sont respectivement de 3300 MHz et 4,87 dBi pour la bande Ku. De même, la structure de filtenna-II résonne en bande Ku avec une bande passantede 1800 MHz et le gain de pointe est d'environ 4,8 dBi.La bande passante *fractionnelle possédée par la structure de filtenna I et II est respectivement de 20,62% et 12,77% à la résonance.La zone de construction totale des deux structures proposées est d'environ 909,09 mm^2, ce qui est la caractéristique la plus populaire pour les applications en bande ku. Il présente également une faible perte d'insertion et de faibles harmoniques à des fréquences plus élevées.*

KEYWORDS: *antenna, filter, filtenna, defected ground structure, split ring resonator, band pass filter.*

MOTS-CLÉS: *antenne, filtre, filtenna, structure du sol defectueuse, resonateur a anneau fendu, filtre passe-bande.*

DOI:10.3166/JESA.20.391-403

1. Introduction

For the sake of low profile, less price, light weight and uncomplicated fusion with RF devices, microstrip patch antenna is widely used and has numerous benefits in wireless communication. At the same time, filter plays a very important role in many RF/microwave, signal processing, mobile communication, Wireless Local areas networks (WLAN), WiMax, and satellite communication and are actively used as a key component for combining, separating, selecting and rejecting frequencies within assigned spectral limits (Chen *et al*., 2014). The wireless communication field having frequencies greater than 10 GHz is experiencing a revolutionary growth in last few decades due to the invention of new wireless products and services operating at higher frequencies (Yu *et al*., 2012). At higher frequencies the system requires larger components like antenna and filter, in addition to other requirements (Tang *et al*., 2016). So focus is on components having a compact module which can perform simultaneously both filtration and radiation. A microstrip patch antenna with in-built filter plays an important role in wireless communication system and this type of structure is referred to as Filtenna.

Etching or intentionally defecting is the best technique to improve or change the performance of any structure, as etched cells are inherently resonant in nature and can be applied to the radiating element and ground plane. The defect in the ground plane disorders the shield current distribution, resulting in modified values of capacitance and inductance of transmission line (Ahn *et al*., 2001). So it can be employed in a filter circuit and in a microstrip antenna. Square head dumbbell shaped DGS (Ahn *et al*., 2001), complementary split ring resonator (CSRR) or inductive loaded SRR DGS (Jahromi *et al*., 2005), U-shaped DGS (Lim *et al*., 2005) and many more varieties of DGS have been used for filter design. Defected ground structure with lumped element in the circuit has been used (Liu *et al*., 2009) for UWB filter design. In last few decades, many filter circuits have been reported using DGS and these reported designs use DGS for different range of frequencies as low-pass, high-pass, band-pass and stop-band filters and catering to various applications in communication systems.

In recent years, filtering antennas where in an antenna adds up with a separate filter is reported in (Chen *et al*., 2013; Wu *et al*., 2011; Chen *et al*., 2014). The filtering characteristics have been obtained mostly by etching or modifying the feed line, resulting in more spurious/insertion loss radiation. Furthermore, the filtering antennas suffer from a drawback of restricted number of bands and high insertion losses produced due to feed line. Moreover, the circuit complexity of these structures increases at higher frequency (Wu *et al*., 2011).

By the virtue of individualistic function, a filtenna is more favorable over conventional filtering antenna. The benefits include reduction in insertion losses which occur when a standard receiving antenna is connected to a filter, suppression of unwanted signals which are out of band and easy interfacing due to compact size and low cost (Tang *et al*., 2016). In recent years, different types of filtennas have been proposed for different band of applications like X-band (Madhav *et al*., 2016), Q-band (Xue *et al*., 2013) and Ku-band (Yu *et al*., 2012; Madhav *et al*., 2016). But the reported designs suffer from a narrow band width, in their respective bands and exhibited significant losses introduced by the integrated filter. Filtenna circuit using Square Capacitive Loaded Loop (CLL) based resonator as a second order filter (Tang *et al*., 2016) exhibited 140 MHz of narrow impedance bandwidth with realized gain 1.15 dBi. Third order Substrate Integrated Waveguide (SIW) inductive window filter was introduced (Yu *et al*., 2012) in filtenna circuits, which has low insertion loss, high power but generates less polarized current. It also reports 1.1 dBi loss in realized gain within the operating band 14.2 GHz to 14.58 GHz. Xue *et al*., 2013 reported a filtenna circuit incorporated with fifth order Substrate Integrated Waveguide (SIW) inductive window filter in feed line with addition of reflector for wireless communication. It exhibits triple bands with variable gain from 4.1dBi to 5.28dBi. Although Split Ring Resonator (SRR) (Barbuto *et al*., 2014) has been used to design a filtering horn antenna resulted a narrow band width. Moreover, non-linear Split Ring Resonator (SRR) was etched on the substrate layer and mounted to the aperture of a horn antenna to achieve power selectivity (Barbuto *et al*., 2015).

This paper focuses on application of Split Ring Resonator (SRR) to obtain the filtering characteristics of structure. Here the idea is to configure uncomplicated and physically viable filtenna structures incorporating Split Ring Resonators. These resonators act as band pass filter without the radiating element. In this paper, design, simulation and measurement of two different type of filtenna structures I and II, have been proposed and compared their performance characteristics. Similar sized rectangular patches acting as radiating element was taken for the proposed structures. Structure-I results in wideband characteristics with peak gain about 4.87dBi at Ku-band. Structure -II also operates at Ku-band with peak gain of 4.8 dBi nearly omni-directional radiation pattern in both E and H planes. Further it is experimentally verified and the measured results agree well with the simulation results in both cases.

This paper organized as follows: section 2 describes the filtenna geometries with their relevant design considerations; section 3 introduces, analyzes the simulated results of designed filter and antenna and section 4 presents the simulated and measured results of the proposed filtenna structures.

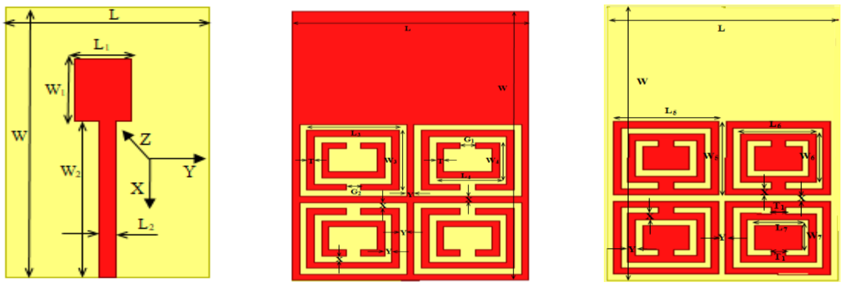
2. Filtenna geometry and design

The proposed microstrip patch filtennas consist of four parts: patch, ground, substrate and the feeding mechanism. Rectangular patch geometry has been considered for the proposed structures with the benefit of easy analysis and effective radiation characteristics (Garg *et al*., 2000). The dimension of the patch is calculated using the following relations (1) and (2), so as to resonate near about 16 GHz.

$$L_1 = C / 2\, f_r\, (\varepsilon_r)^{0.5} \tag{1}$$

$$W_1 = (h\, \lambda_d)^{0.5}\, [\ln(\lambda_d/h) - 1] \tag{2}$$

The parameters L_1 and W_1 indicate length and width of the patch respectively. f_r is the resonant frequency of the antenna when $C=3\times10^8$ m/sec as velocity of light. h denotes thickness of substrate with effective dielectric constant (ε_r). Where $\lambda_d=\lambda_0\,(\varepsilon_r)^{-0.5}$.



(a) *(b)* *(c)*

Figure 1. Proposed Filtenna structures (a) Top view for both structures I and II with design parameters (b) Bottom view of inductively loaded SRR with design parameters (Filtenna structure-I) (c) Bottom view of capacitive loaded SRR with design parameters (Filtenna structure-II). (Red and yellow color refers to copper and substrate layer respectively)

Figure 1 illustrates the proposed filtenna structures-I and II operating at Ku-band. Initially, a rectangular microstrip patch antenna was designed with conventional ground plane (without DGS), as shown in Figure 1(a), so as to operate within the frequency spectrum of Ku-band (12 to 18 GHz). The length, width and thickness of the patch are 6.554mm, 8.65 mm and 0.035mm respectively. In this paper, microstrip line feed technique has been used. The length and width of the strip line are adjusted so as to achieve the characteristics impedance matching of 50Ω. The filter circuit loaded with split ring resonator is designed and then performances are verified. The entire filtenna circuit is implemented on a FR4 (ε_r=4.4, σ=0.02) substrate of dimension (24.05×37.8×1.6) mm^3. A single microstrip feed line (1.8653×21.9) mm^2 is used to excite the antenna. SRRs are placed on bottom of the substrate layer for filter configuration. All the calculated parameters are provided in Table-1. The gap between the SRR contributes to coupling capacitance while the current through the radiating element leads to inductance. Thus it acts as a filter.

The filtering action in case of the proposed filtenna structure-I is obtained by integrating four inductively coupled Split Ring Resonators (SRRs). These resonators are arranged in a 2×2 array on bottom side of substrate below the feed line. The distance between inner and outer rings of SRR represents the capacitance and the area occupied by the length of both rings represents the inductance (Chen *et al*., 2014). It is known that the resonant frequency decreases with increase in the side length of SRR as well as with increase in strip width, whereas increase in gap distance the resonant frequency increases. When the SRR is placed below the feed line stronger coupling can be achieved with negligible change in resonant frequency. This coupled energy keeps the resonant frequency is closer to the pass band. Thus these employed resonators acts as a band pass filter. The resonant frequency of the filter is controlled by adjusting the gap spacing between the annular ends of SRR. Figure 1(a) and (b) shows the top and bottom view of filtenna structure-I respectively. Referring to Saha *et al*., (2011), the design parameters of SRR are calculated using equations, indicated in (3)-(10) and are provided in Table 1.

$$f_0=1/2\pi(L_T C_{eq})^{0.5} \tag{3}$$

$$L_T=0.0002l(2.303\log_{10}(4l/W)-\gamma)\mu H \tag{4}$$

$$l=8a_{ext}-g \tag{5}$$

$$C_{eq}=0.5(C_0-C_g) \tag{6}$$

$$C_0=(4a_{avg}-g)C_{pul} \tag{7}$$

$$a_{avg}=a_{ext}-W-d/2 \tag{8}$$

$$C_{pul}=(\varepsilon_T)^{0.5}(C_0 Z_0)^{-1} \tag{9}$$

$$C_g=(\varepsilon_0 wt)g^{-1} \tag{10}$$

Where

f_0 - Resonant Frequency.

L_T - Equivalent inductance for a rectangular cross section of a single SRR having finite length (l) and width (w).

γ= 2.853, for rectangular geometry SRR.

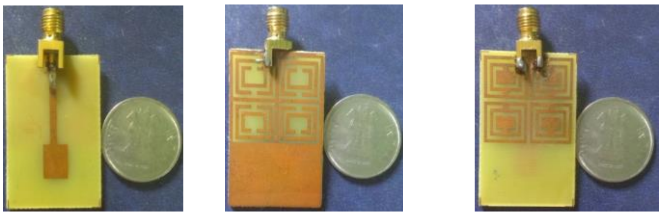
C_{eq} - Equivalent capacitance with series capacitance (C_0) and gap capacitance (C_g).

C_{pul} - Capacitance per unit length.

$Z_0 = 50\Omega$, characteristics impedance.

$C_0 = 3\times10^8$ m/sec, velocity of light.

The filtering action in case of the proposed Filtenna structure-II is obtained by integrating four capacitively loaded Split Ring Resonators (SRRs) arranged in a 2×2 array on bottom side of substrate below the feed line. The design parameters for capacitively loaded SRR for filtenna structure -II are illustrated in Figure 1(c) and the respective values are provided in Table 1. Figure 1(a) and (c) illustrates the top and bottom view of proposed filtenna structure-II respectively. Figure 1 and Table 1 provides the detailed geometry and design specification values respectively. It can be sought that the total build-up area of both proposed structure is 909.09 mm^2, which is an advantageous feature over (Madhav *et al*., 2016; Xue *et al*., 2013; Barbuto *et al*., 2014) especially for Ku- band application.



(a) *(b)* *(c)*

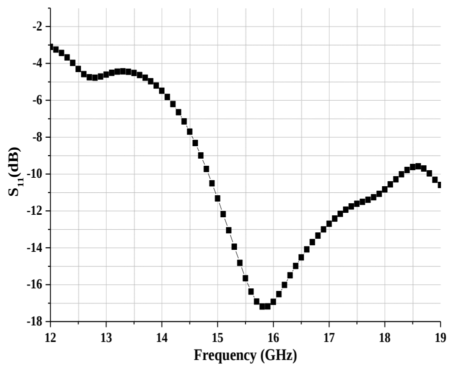
Figure 2. Fabricated Prototype of Proposed filtenna structures using FR4 substrate (a) Top View of both filtenna structure-I and II (b) Bottom view of filtenna structure -I (b) Bottom view of filtenna structure -II

Table 1. Parameters and its values of proposed Filtenna Structure-I and II

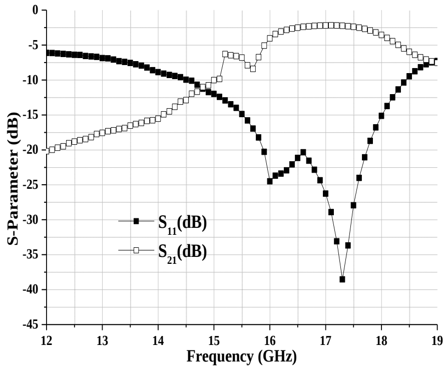
Parameters	Values (mm)	Parameters	Values (mm)
L	24.05	W	37.8
L_1	6.554	W_1	8.65
L_2	1.8653	W_2	21.9
L_3	9.4	W_3	8.4
L_4	6.4	W_4	4.9714
L_5	10.9	W_5	10.114
L_6	7.9	W_6	6.685
L_7	4.9	W_7	3.257
G_1, G_2, T_1	1.5	T	0.75
X	0.85	Y	0.75

3. Simulation results

Figure 1 and 2 shows the simulated models and fabricated prototypes of the designed filtenna structures respectively. Figure 3(a) indicates the simulated S_{11}(dB) (Reflection Co-efficient) of microstrip patch antenna with conventional ground plane (without DGS). The plot clearly indicates that the antenna resonates at 15.9 GHz with a reflection co-efficient of -17.25 dB with impedance bandwidth 3700 MHz. So this structure is considered as a wideband antenna for Ku- band application. Figure 3(b) shows simulated S_{11}(dB) (Reflection Co-efficient) and S_{21}(dB) (Transmission Co-efficient) of the inductively loaded SRR as filter. It indicates the filter resonates about 17.3 GHz with impedance bandwidth of 4000 MHz. Due to DGS, the series inductance of strip line increases. This effective series inductance introduces cut off characteristic at certain frequency. Moreover, the etched gap below the strip line determines capacitance and with increase of gap distance, the effective capacitance decreases moving the attenuation pole towards higher frequency. As we are getting cut off characteristics at certain frequencies due to DGS, so this DGS acts as a filter with some pass bands and stop bands. The filter passes the pass band signals from 14~18.5 GHz for $|S_{11}| \leq -10$ dB and at other frequencies it rejects the signals. These pass band signals excite the radiating element to get required data.



(a)

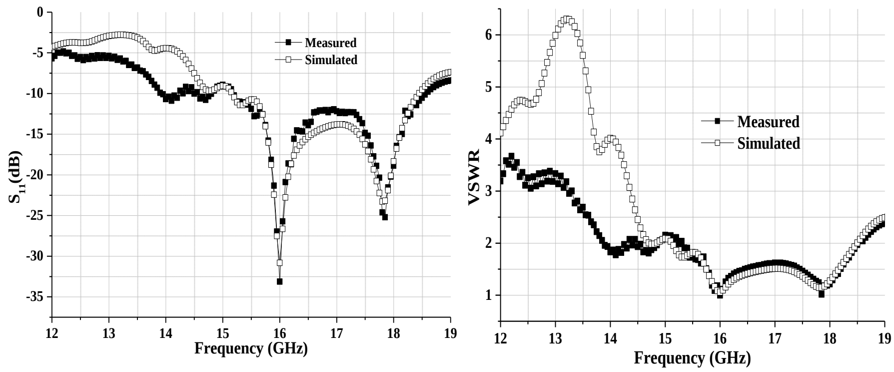


(b)

Figure 3. (a) S_{11}(dB) (Reflection Co-efficient) of the antenna with conventional Ground Plane (without DGS) (b) S-parameter of inductively loaded SRR as filter in Filtenna Structure-I

4. Results and discussion

The S_{11}(dB) (Reflection Co-efficient) and VSWR measurements of the proposed filtennas were done using Fieldfox microwave analyzer (N9918A) at IIT, Roorkee. Figure 4(a) illustrates the measured and simulated S_{11}(dB) of the proposed filtenna structure-I and is found to be in good agreement to each other. There is a good enhancement of return loss about -37 dB found at the pass band due to DGS and can be visualized from Figure 4(a). Due to filter, the working band of the proposed filtenna structure-I is about 15.2~18.5 GHz for $|S_{11}| \leq 10$ dB. The bandwidth and fractional bandwidth of the proposed filtenna structure-I is 3300 MHz, and 20.62% respectively, as transition is found in between 15.2~18.5 GHz for $|S_{11}| \leq 10$ dB. The simulated and measured bandwidth at 16 GHz covers the standards of Ku-band. Thus, this is considered as a wide band filtenna for Ku- band application. So this wide band characteristic is superior over earlier reported filtennas. The VSWR values less than two have been obtained in working band, both in simulated and measured result, as shown in Figure 4(b). It has been observed that, the peak gain of the proposed filtenna structure-I in the working band is about 4.87 dBi, as illustrated in Figure 5. The filtenna possesses higher gain values in the working band as compared to other frequencies.



(a) *(b)*

Figure 4. (a) S_{11}(dB) (b) VSWR of Proposed Filtenna Structure-I

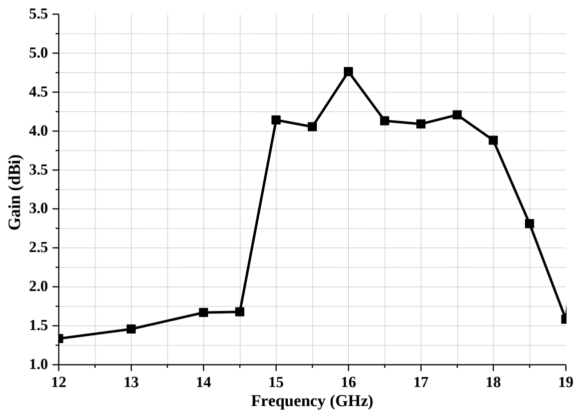
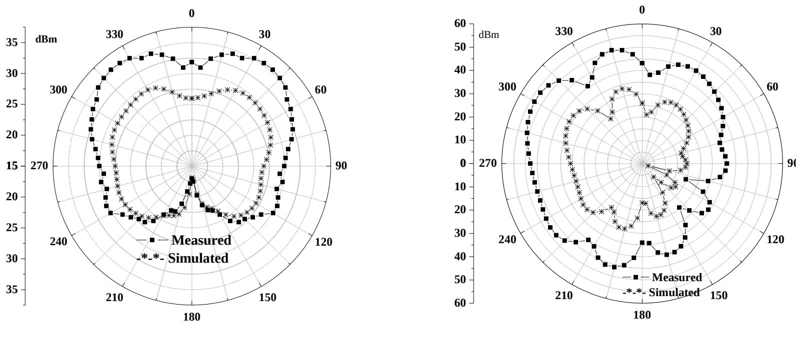


Figure 5. Measured gain of proposed filtenna Structure-I



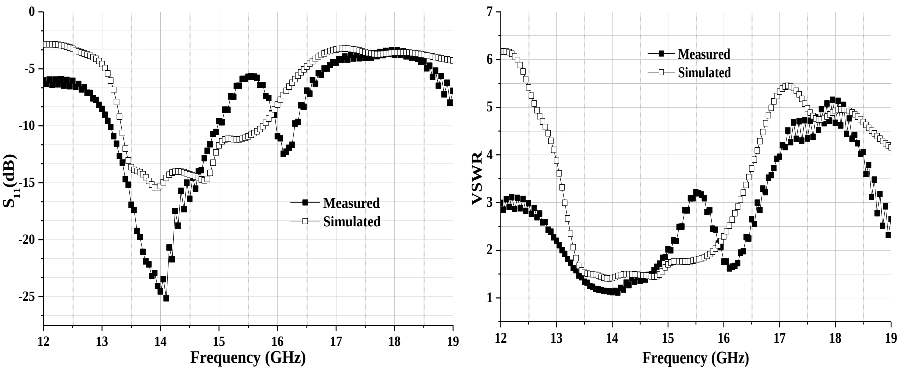
(a) *(b)*

Figure 6 Radiation patterns of proposed filtenna structure -I (a) E-Plane (b) H-Plane at 16 GHz

The radiation patterns were measured by using an anechoic chamber at IIT, Roorkee. Figure 6 (a) and (b) shows the E-plane and H-plane radiation pattern of proposed filtenna structure-I at 16 GHz respectively. This shows a strong correspondence between simulated and measured result. There is a nominal fluctuation of 0-4 dBm and 5-8 dBm found in E-plane and H-plane respectively, between simulated and measured result, keeping same pattern of radiation. These fluctuated values seem negligible. Moreover, the proposed filtenna structure-I keeps same radiation pattern both in simulated and measured result.

The S_{11}(dB) (Reflection Co-efficient) of proposed filtenna structure-II is shown in Figure 7(a). The measured result found superior over simulated result. Due to four capacitively loaded SRR, the proposed filtenna resonates at about 14.1 GHz with reflection coefficient -25 dB. The measured working band of the proposed filtenna structure-II is 13.2~15 GHz for $|S_{11}| \leq 10$ dB. So the bandwidth and fractional bandwidth of the filtenna structure-II is 1800 MHz and 12.77% at 14.1 GHz. As transition is found from 13.2 to15 GHz for $|S_{11}| \leq 10$ dB at center frequency 14.1 GHz and covers standards of Ku-band, the proposed filtenna is referred as a Ku-band filtenna at. So, inductive loaded SRR is a better approach than capacitively loaded SRR in filtenna design. The VSWR values are found convenient, as VSWR of < 2 at in-band frequency, as shown in Figure 7(b). So this can be used in future wireless communication.

The measured gain of proposed filtenna structure-II is illustrated in Figure 8. The measured peak gain of the filtenna is about 4.8 dBi in the working band. The E-plane radiation pattern exhibits omni-directional characteristics at 14 GHz, as illustrated in Figure 9(a). This shows higher values of gain in dBm at different angles of theta as compared to simulated result. Figure 9(b) illustrates simulated and measured H-plane radiation pattern of filtenna structure-II, at 14 GHz. A negligible fluctuation of 5-7 dBm found between simulated and measured result, in H-plane. But there is enhancement of measured gain value as compared to simulated value have been found, keeping same pattern of radiation. So the proposed filtenna may be considered for Ku-band application in future wireless communication. The comparison between the proposed filtenna and other filtennas are presented in Table 2. It can be sought that inductively and capacitively loaded SRR is a better approach in filtenna design for Ku-band application. The merits of the proposed filtennas are low cost, compact size, easy fabrication, less circuit complexity at higher frequency and easy integration with other planar circuits.



(a) *(b)*

Figure 7. (a) S_{11}(dB) (b) VSWR of Proposed Filtenna Structure-II

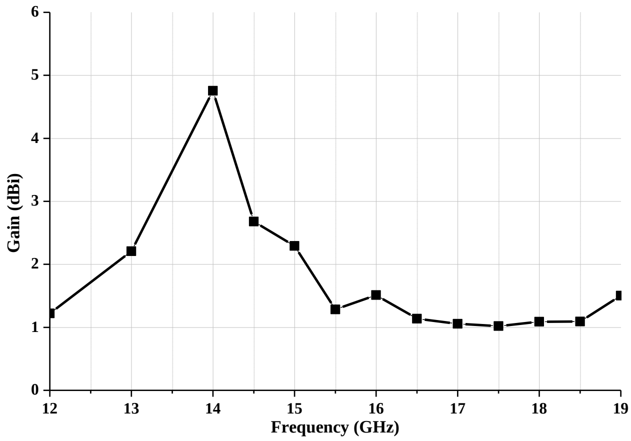
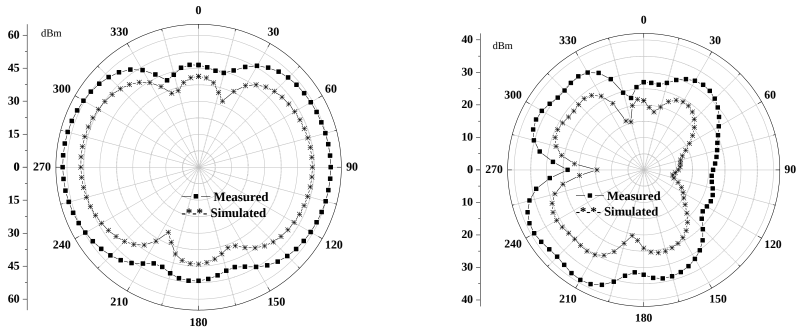


Figure 8. Measured gain of proposed filtenna Structure-II



(a) *(b)*

Figure 9. Radiation patterns of proposed filtenna structure-II at 14 GHz (a) E-Plane (b) H-Plane

Table 2. Comparison between various Filtennas

Ref	Physical Size (mm^2)	Measured Resonant Frequency (GHz)	Measured Bandwidth (MHz)	Fractional Bandwidth (%)	Gain (dBi)
Chen *et al*., 2013	1645	2.4	440	18.34	2.3
Wu *et al*., 2011	1290	2.46	400	16.26	2.41
Chen *et al*., 2014	187.59	5.29	430	8.12	2.5
Tang *et al*., 2016	783	2.36	186	7.89	1.7
Yu *et al*., 2012	1440	14.4	360	2.5	7.8
Xue *et al*., 2013	1452	45.25	3750	8.28	5.34
Present Work	909.09	16	3300	20.62	4.87
		14.1	1800	12.77	4.8

5. Conclusion

Two kinds of microstrip filtenna structures inspired by split ring resonators have been designed, simulated and experimentally characterized. The comparative study and effect of inductive and capacitive SRR have been well explained. There is improvement in performance have been observed mainly due to band pass filter as compared to antenna. Hence it discards use of separate filter circuit in transmitter and receiver for RF communication. Thus the proposed filtenna structures helpful to reduce cost, size of RF subsystem. The presented filtenna structure can be used for

Ku-band application. Reduction of cross polarization and suppression of harmonics would be an important task as a part of future work.

Acknowledgements

The authors would like to thank Mr. Raja Ram, Department of Electronics and Communication Engineering, IIT, Roorkee, India, for providing measurement facilities and assistance at their laboratories towards advancement of this research work.

References

Ahn D., Park J. S., Kim C. S., Kim J., Qian Y., Itoh T. (2001). A Design of low-pass filter using the novel microstrip defected ground structure. *IEEE Trans. on Microwave Theory and Techniques*, Vol. 49, pp. 86-93. http://dx.doi.org/10.1109/22.899965

Barbuto M., Trotta F., Bilotti F., Toscano A. (2014). Horn antennas with integrated notch filters. *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 2, pp. 781-785. http://dx.doi.org/10.1109/TAP.2014.2378269.

Barbuto M., Bilotti F., Toscano A. (2015). Power-selectivity horn Filtenna loaded with a nonlinear SRR. *9th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics - Metamaterials*, Oxford, United Kingdom, pp. 22-24. http://dx.doi.org/10.1109/MetaMaterials.2015.7342586

Chen L., Luo Y.L. (2014). Compact filtering antenna using CRLH resonator and defected ground structure. *Electronics Letters*, Vol. 50, No. 21, pp. 1496-1498. http://dx.doi.org/10.1049/el.2014.2703

Chen X., Zhao F., Yan L., Zhang W. (2013). A compact filtering antenna with flat gain response within the passband. *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, pp. 857-860. http://dx.doi.org/10.1109/LAWP.2013.2271972

Garg R., Bhartia P., Bahl I., Ittipiboon A. (2000). *Microstrip Antenna Design Handbook*, ARTECH HOUSE.

Jahromi M. N., Tayarani M. (2011). Defected ground structure band-stop filter by semi complementary split ring resonators. *IET Microwave Antennas Propagation*, Vol. 5, No. 11, pp. 1386-1391. http://dx.doi.org/10.1049/iet-map.2010.0476

Lim J. S., Kim C. S., Ahn D., Jeong Y. C., Nam S. (2005). Design of low-pass filters using defected ground structure. *IEEE Transactions on Microwave Theory and Techniques*, Vol. 53, No. 8, pp. 2539-2545. http://dx.doi.org/10.1109/tmtt.2005.852765

Liu Y., Liang C.H., Wang Y.J. (2009). Ultra-wideband band-pass filter using hybrid quasi-lumped elements and defected ground structure. *Electronics Letters*, Vol. 45 No. 17, pp. 899-900. http://dx.doi.org/10.1049/el.2009.1364

Madhav B. T. P., Gupta G. S., Rahul M., Lahari O. K., Sameera M. (2016). Linearly polarized microstrip planar Filtenna for X and Ku band communication systems. *Indian Journal of Science and Technology*, Vol. 9, No. 38, pp. 1-5. http://dx.doi.org/10.17485/ijst/2016/v9i38/97115.

Saha C., Siddiqui J. Y., Antar Y. M. M. (2011). Square split ring resonator backed coplanar waveguide for filter applications. *General Assembly and Scientific Symposium*, pp. 1-4. http://dx.doi.org/10.1109/URSIGASS.2011.6050665

Tang M.C., Chen Y., Ziolkowski R. W. (2016). Experimentally validated, planar, wideband, electrically small, monopole Filtennas based on capacitively loaded loop resonators. *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 8, pp. 3353-3360. http://dx.doi.org/10.1109/TAP.2016.2576499

Wu W. J., Yin Y. Z., Zuo S. L., Zhang Z. Y., Xie J. J. (2011). A new compact filter-antenna for modern wireless communication Systems. *IEEE Antennas and Wireless Propagation Letters*, Vol. 10, pp. 1131-1134. http://dx.doi.org/10.1109/LAWP.2011.2171469

Xue Z., Zang Y., Hong W. (2013). Design and Implementation of a Filtenna with wide beam width for Q-band millimeter-wave short range wireless communications. *IEEE Antennas and Wireless Propagation Letters*, Vol. 14, pp. 356-359.

Yu C., Hong W., Kuai Z., Wang H. (2012). Ku-band linearly polarized omnidirectional planar Filtenna. *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, pp. 310-313. http://dx.doi.org/10.1109/TrustCom.2013.279