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Design and Simulation of a Compact Filtenna for 5G Mid-Band Applications

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Abstract

In order to provide an efficient, low cost, and small size radiating structure that passes a certain frequency band with negligible amount of interference, the combination of filters and antennas is proposed to form a single element called filtenna. This paper presents a filtenna element with compact size that can radiates in the 5G mid-band frequency range (3.6-3.8 GHz) and perfectly rejects all the frequencies outside this range. The filtenna is composed of a printed circuit antenna that is terminated with a crescent shaped stub that is coupled electromagnetically with a miniaturized sharp band-pass filter. The simulation results show a filtenna reflection coefficient with a reduced value within the intended 5G band and with high values along the other unwanted frequencies. Moreover, the structure has an omnidirectional pattern with reasonable gain value within the band of interest, and this makes the antenna very suitable for portable 5G devices.

KEYWORDS: band-pass, dual-band, filter, filtenna, monopole antenna.

I. INTRODUCTION

With the development of the wireless communication and to achieved large wireless data connection, an antenna is presented as a device that provides a transition between guided electromagnetic waves in wires and electromagnetic waves in free space (transmitting and receiving EM waves) in a prescribed manner [1]. The antenna may be in variety of shapes and sizes by which the frequency band and its EM radiation is determined, such as half elliptic patch [2], hexagon slotted circular monopole antenna [3], 9-shaped monopole antenna [4], star shaped antenna [5], dumbbell-shaped slot antenna [6]. Each shape can be used for different applications like Single- band [7], [8], dual band [9], [10], [11], and single-dual band [12], [13].

However, given the nature of most bands and extent interferers, antennas need a tight controller to suppress the interference and to eliminate the unwanted signals where other system exists. The filter is a special device whose distinguishing feature provides a complete or partial suppression of some aspects of the signal, that is, the removal of some undesired frequencies or frequency bands. It is modified to cover the intended rang by using many techniques of stub- loaded multiple mode resonator [14], hairpin filter based on accurate impedance-transforming tapped feeds [15], and stepped-impedance resonator (SIR) dual-band band pass filter (BPF) with selectivity-enhancement cells [16].

By referring to the fact that antenna elements are resonators themselves, the filter can be moved and combined within the antenna in single model. This combination (Filter + antenna) achieves many important advantages of wide bandwidth, small electrical size, and an improved performance for frequency selectivity. There are several technics to give filtering antenna, of two edge-coupled filters and two hairpin filters [17], a C-shaped narrow band resonator and an E-shaped wideband resonator [18], and custom- designed coupling probe structures [19], a pair of parasitic elements and pair of slits [20]. This new filtering antenna combination is called Filtenna.

In this paper, a compact and sharp printed circuit filter is combined with a printed circuit antenna that is terminated with a crescent shaped stub to form a filtenna with large selectivity. The resulted filtenna perfectly covers the 5G mid-band that occupies the frequency range 3.6-3.8 GHz and perfectly rejects all the frequencies outside the intended range of frequencies. Half of the structure of an already designed filter is coupled electromagnetically to the proposed antenna to attain the compactness in the structure. The simulation results verify the perfect frequency coverage for the 5G mid-band applications in term of the reflection coefficient and transmission coefficient. In addition, the results also show an omnidirectional radiation pattern with reasonable gain value.

II. FILTENNA DESIGN

The design of the proposed filtenna is described in this section. The main design goals are: inserting a filtering element that determines the operation frequency range of the antenna with high selectivity, providing a flat gain, and providing good radiation pattern characteristics.

A. *Filter Design:*

The design structure consists of two-square Capacitively Loaded Loop (CLL) Based band pass filter similar to that presented in [21]. The composite design is depicted in Fig. 1. It is printed on a Rogers RT5880 substrate with dielectric constant (ε_r) of 2.2, a loss tangent (δ) of 0.009 and thickness (h) of 0.8 mm, and full ground. The following formula estimates the electrical length of the CCL-based filter with respect to the center frequency to the required pass band [22]:

$$l = \frac{\lambda_g}{2} = \frac{c}{2 * f_c \sqrt{\varepsilon_{reff}}} \qquad (1)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_{r-1}}{2} \left[1 + 12 \frac{h}{W_p}\right]^{-1/2} \qquad (2)$$

where λ_g is the guided wavelength, ε_{reff} is the effective dielectric constant, W_p is the patch width. Therefore, the overall length of the L element is equal to (35.7 mm).

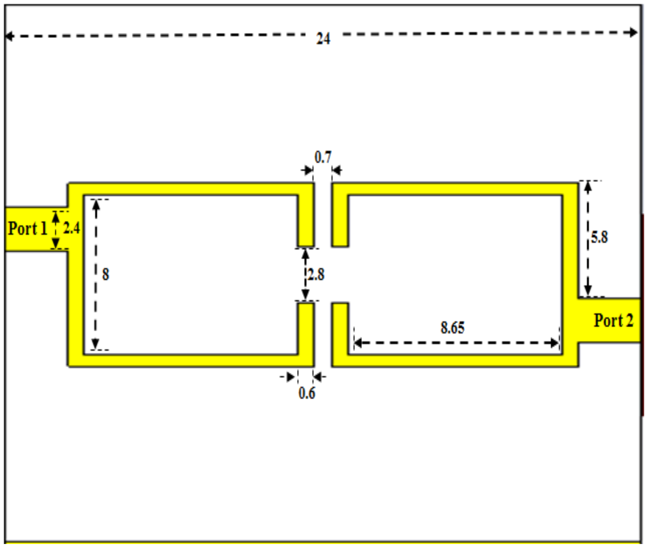


Fig.1. Geometry of the CCLs-based filter (all dimensions are in mm).

In Fig.2, the performance of the designed filter is shown. The $| S_{11} | < -10$dB coverage includes two resonant frequencies at 3.6GHz and 3.75 GHz and covers the frequency range from 3.6GHz to 3.82 GHz.

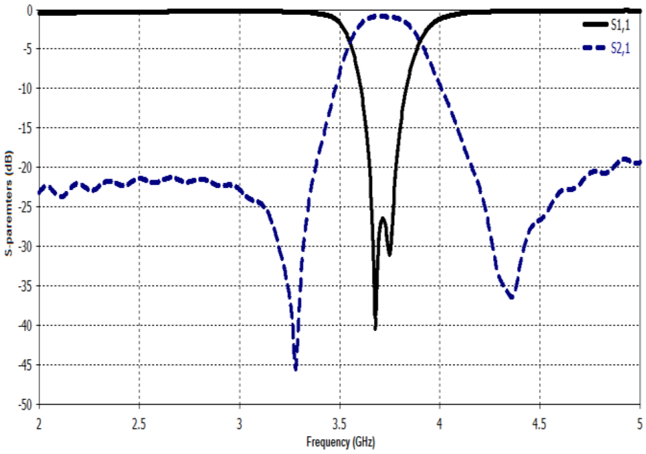


Fig. 2. Simulated of S-parameters of CCLs-based

B. *Filtenna Design:*

The design starts with a circular monopole antenna, then it is modified to moon shaped radiating antenna at 3.7 GHz with radius of (R). By replacing the second half of the CLL-based filter with antenna as a parasitic element, the proposed filtenna is presented. As mentioned earlier, the dielectric substrate of the proposed filtenna is Rogers RT5880 substrate with dielectric constant (ε_r) of 2.2, a loss tangent (δ) of 0.009 and thickness (h) of 0.8mm , and overall size 27 mm*24.2 mm as demonstrated in Fig. 3. It is fed by a 50 Ω microstrip feed line whose characteristic impedance is given by the following formula [1]:

$$Z_c = \frac{120\pi}{\sqrt{\varepsilon_{reff}} \left[\frac{W_f}{h} + 1.393 + 0.667\, ln\left(\frac{W_f}{h} + 1.444\right) \right]} \qquad (3)$$

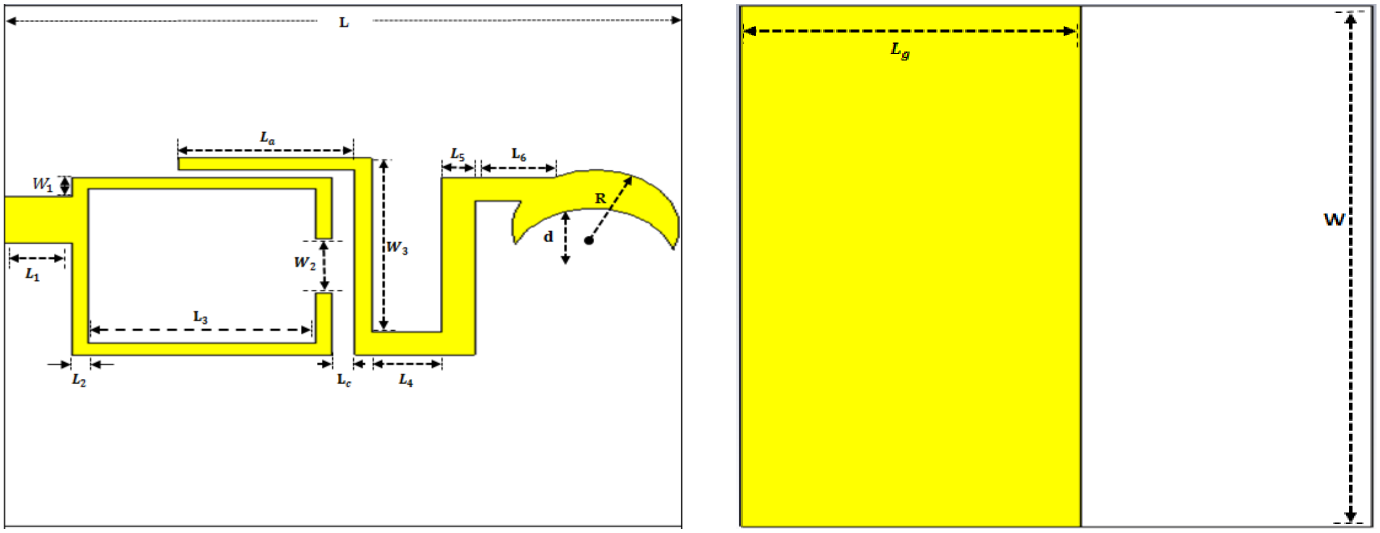
where W_f denotes the width of the feed line, and h is the height of the substrate. The electrical length of the monopole antenna with respect to the center frequency [22]:

$$l = \frac{\lambda_g}{4} = \frac{c}{2 * f_c \sqrt{\varepsilon_{re}}} \qquad (4)$$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} \qquad (5)$$

ε_{re} is the effective dielectric constant of monopole antenna.

The optimized parameters of the proposed filtenna are given in Table I.



(a) (b)

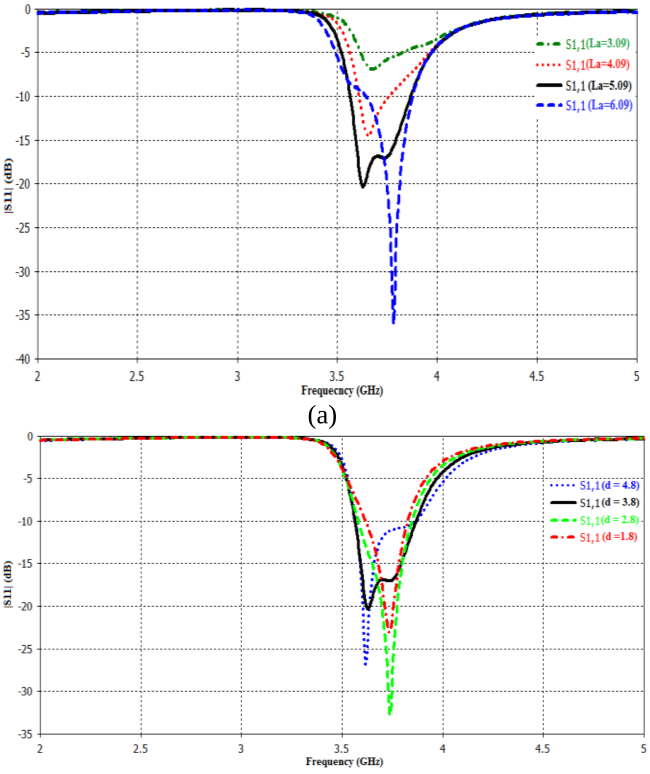
Fig. 3. Geometry of the proposed filtenna. (a) Top view (b) Back view

TABLE I
The Optimized Design Parameters of the Presented Filtenna.

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	24.2	L_5	1.2
W	27	L_6	3.05
L_g	13	L_a	5.09
R	3	d	3.8
L_1	3.6	L_c	0.72
L_2	0.6	W_1	1
L_3	8.09	W_2	2.8
L_4	2.49	W_3	9

III. PARAMETRIC STUDY

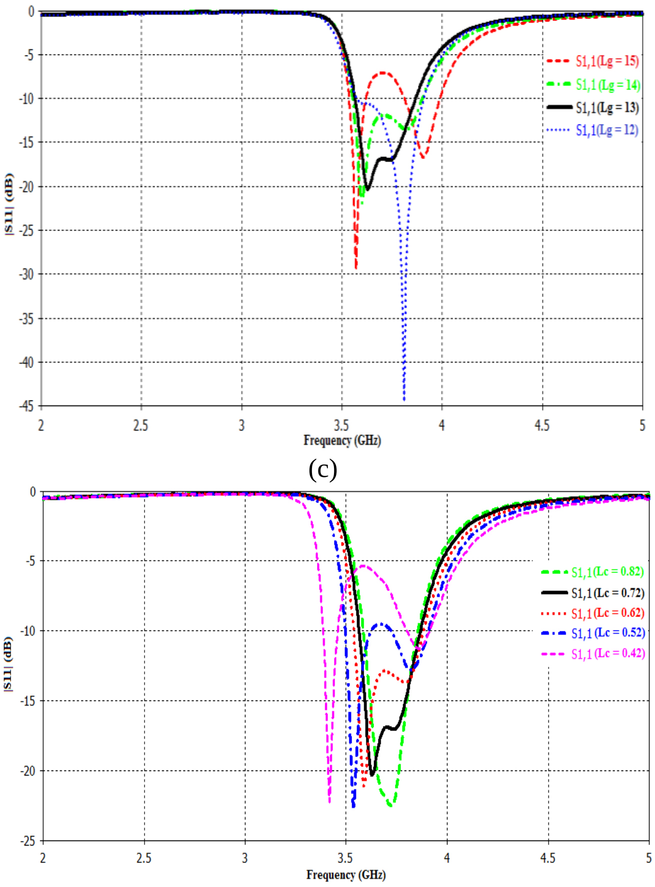
In this section, the effects of different fundamental parameters (L_a, L_g , L_c , and d) on the filtenna reflection coefficient are shown in Figs. 4 (a) through (d). In Figs 4(a) and (b), the reflection coefficient characteristics of the filtenna can be tuned by modifying the position of the resonant frequencies. The values of L_a = 5.09mm and d = 3.8mm provides the suitable locations of the resonant frequencies so that the intended 5G mid-band is covered perfectly. In addition, the change in L_a dramatically affects the filtenna matching and the bandwidth, while the variation of d just influences the bandwidth. It is observed from Figs. 4 (c) and (d) that the bandwidth and impedance-matching characteristics of the filtenna at both resonant frequencies are strongly dependent on the value of $L_g$andL_c. L_g= 13mm and L_c= 0.72mm are so suitable to set the filtenna reflection coefficient below -10 dB with better impedance matching along the desired frequency range (3.56GHz to 3.8GHz).All optimized parameters are obtained using the CST Microwave Studio software [23].



(a)

(b)

Fig.4. Antenna reflection coefficient for the moon shaped filtenna at (a) d=3.8mm, L_g =13mm, L_c=0.72mm, and different values of L_a, (b) L_a =6mm, L_g =13mm , L_c= 0.72mm, and different values of d, (c) L_a =6mm d=3.8mm, L_c =0.72mm, and different values of L_g, and (d) d=3.8mm, L_a =6mm, L_g =13mm, and different values of L_c.



(c)

(d)

Fig.4. Continued.

IV. SIMULATION RESULTS

The simulated reflection coefficients of the antenna with and without filter are shown in Fig.5. The proposed antenna has a bandwidth of 3.7 GHz (from 3.36 GHz to 4.2GHz). The fitenna (antenna with filter) shows dual resonant frequencies at 3.63GHz and 3.75 GHz, respectively. Two resonance frequencies are close to each other so that they show a broad bandwidth characteristic from 3.56GHz to 3.8GHz. It effectively suppresses the unwanted signals out of the 5G mid-band. It is clear that the CCL-base filter can be modified as a filtenna by which it is followed by an antenna having resonant frequency that encompasses with the pass band of the filter.

In Fig. 6, the current distribution of the filtenna is shown in order to understand the radiation mechanism at each resonant frequency. It is clear that the current is mainly concentrated over all antenna arms and the top part of CLL element at 3.7GHz as shown in Fig. 6. (a). On the other hand, Fig. 6(b) exhibits that the current is concentrated around the filter arms at 3.86 GHz, and a negligible amount at the antenna because the frequency 3.86GHz is outside the bandwidth of the proposed filtenna. In other words, outside the frequency coverage of the filtenna, the energy is stored within the filter rather than radiating via the antenna.

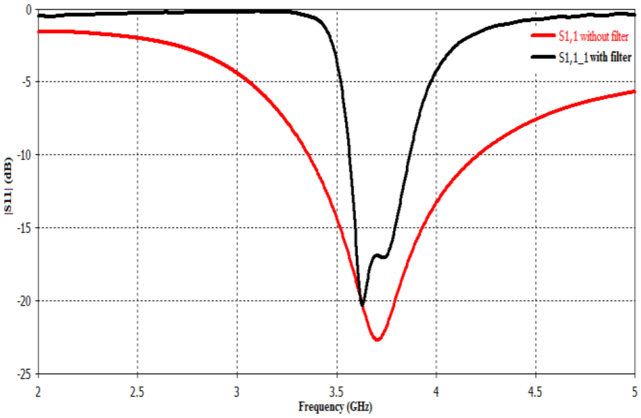
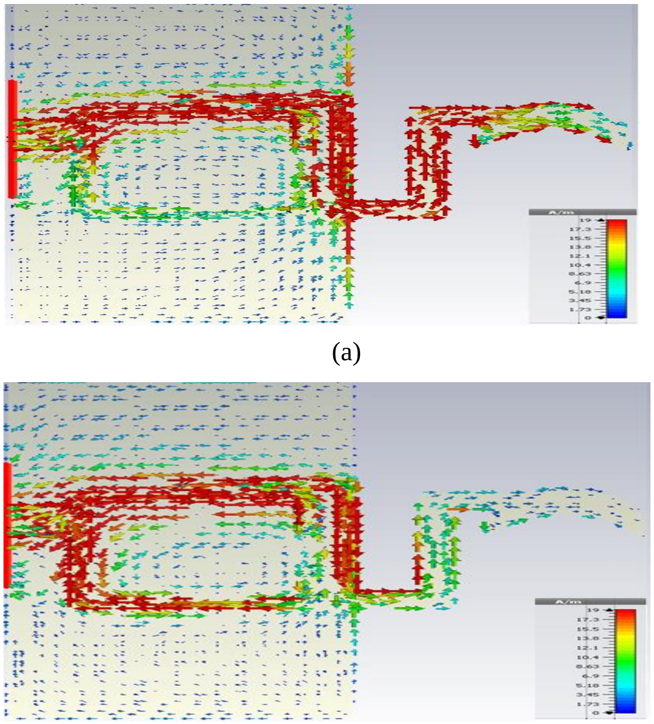


Fig. 5. Simulation reflection coefficient of the proposed filtenna with and without filter.



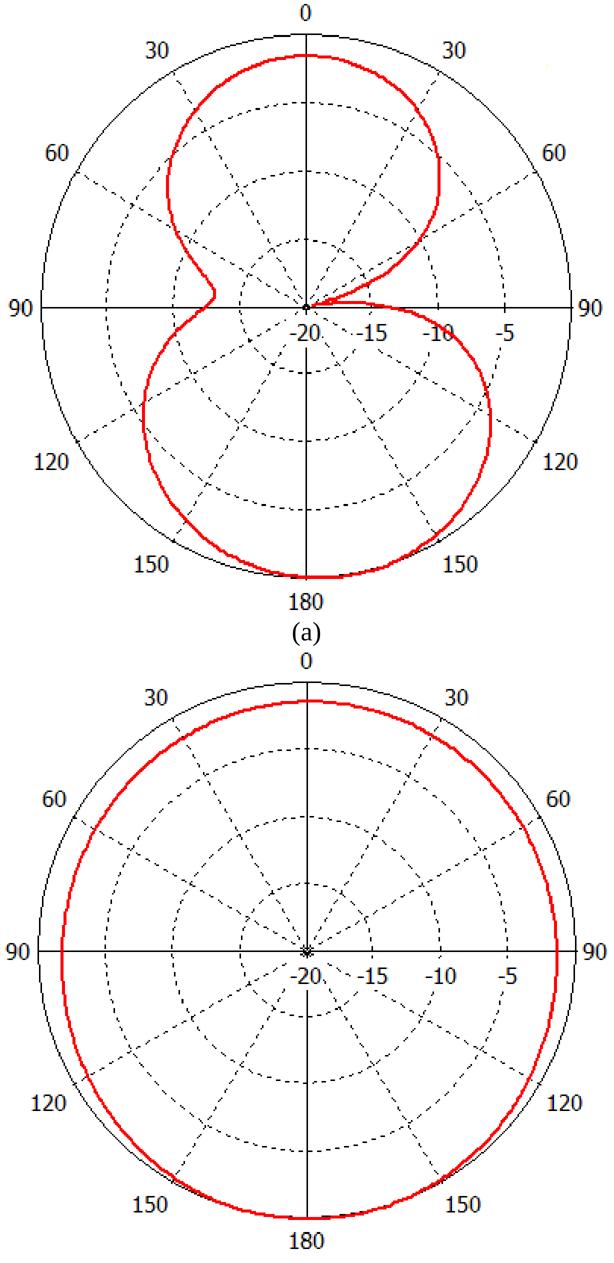
(a)

(b)

Fig. 6. Simulation current distribution (a) at 3.7GHz and (b) at 3.86 GHz.

The simulated 2D-polar power patterns of the filtenna at 3.7GHz are illustrated in Figs. 7. (a) and (b), respectively. It is clear that the filtenna provides good radiation characteristics with a bidirectional power pattern shape in the E-plane, a stable omnidirectional radiation patterns in H-plane, and gain value of 2.923 dBi.

Table Π presented a comparison between proposed filtenna and some other filtennas in terms of dielectric constant ε_r and the overall size $L * W$.



(a)

(b)

Fig. 7. Simulated normalized power pattern of the proposed moon shaped filtenna at 3.7GHz (a) E- plane (b) H- plane.

V. CONCLUSION

A compact filtenna with sharp rejection capability of the non-desired radiation outside the 5G mid-band has successfully been designed. A printed circuit antenna is combined electromagnetically with a half CLL filter to form the proposed design. In spite of its small size ($24.2 \times 27 \times 0.8\ mm^3$), the filtenna matching and radiation characteristics are so suitable for radiating the 5G mid-band EM energy and suppressing the others that cause interference with them. The filtenna reflection coefficient has reduced values at the pass band (3.6-3.8 GHz) that reaches to less than -17dB. The omnidirectional radiation pattern of the proposed design and its compact size make the filtenna to be a superior selection for portable 5G mid-band gadgets.

TABLE II
The Comparison of Dielectric Constant and Size of the Proposed Filtenna and Pervious Filtennas.

Design	Dielectric constant ε_r	size
The proposed Filtenna	2.2	24.2*27
The Application of Reconfigurable Filtenna in Mobile Satellite Terminals [17].	3.48	34.24*26.58
A Compact, Frequency-Reconfigurable Filtenna with Sharply Defined Wideband and Continuously Tunable Narrowband States [18].	3.48	50*30
A Compact, Vertically Integrated Duplex Filtenna With Common Feeding and Radiating SIW Cavities [19].	2.2	45*60
Experimentally Validated, Planar, Wideband, Electrically Small, Monopole Filtennas Based on Capacitively Loaded Loop Resonator [21].	3.48	29*27

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