

# Design of a Microstrip Filtering Antenna for 4G and 5G Wireless Networks

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<https://doi.org/10.26636/jtit.2023.171423>

**Abstract** — The filtering antenna provides both radiation and filtering features and is an important component for the RF front-end of wireless devices. The main function of a filtering antenna is to reject out-of-band signals, thus reducing the interference from adjacent channels. The aim of the present work is to design a 2.6 GHz microstrip filtering antenna for 4G and 5G global mobile services. The filtering antenna is designed using a hairpin bandpass filter integrated with an elliptical microstrip aerial. Good impedance matching is obtained by using appropriate dimensions of the hairpin bandpass filter. The 10 dB return loss bandwidth of the filtering antenna is approx. 5.7%, with the maximum gain for the elliptical filtering antenna of approx. 2.2 dB. Good agreements between the measured and simulated results are obtained for the proposed filtering antenna and the bandwidth covers almost the entire 2.6 GHz band.

**Keywords** — *elliptical microstrip patch antenna, filtering antenna, hairpin bandpass filter.*

## 1. Introduction and Related Work

The International Telecommunications Union (ITU) has recommended the 2.6 GHz band (2.5 GHz to 2.69 GHz) for providing global broadband mobile services over 4G and 5G networks. This part of the frequency spectrum will be important for future mobile broadband applications [1]. There are several frequency channels below and above this band which are already in use in other mobile services. Therefore, to avoid interferences from adjacent frequency bands, it is necessary to develop an antenna system which will be able to filter out the out-of-band signals. For mobile devices, a planar microstrip antenna is the most suitable solution, as in its simplest form it is a metallic radiating patch etched on a dielectric PCB substrate backed by a ground plane.

Using a microstrip antenna, multiple frequency support, polarization diversity and reconfigurability can be achieved very easily [2]. A filtering antenna or simply a “filtenna” radiates and receives passband signals and filters out the adjacent out-of-band signals [3]. There are several approaches to in-band filtering for the RF front-end, each characterized by its own advantages and disadvantages. In [4], a short-ended coupled line relying on ceramic technology is researched for designing a filter to be used at the base station to ensure high power handling capability. A dual microstrip line low pass (LPF) filter is proposed in [5], offering the characteristics of

a wide stop band and a sharp roll-off rate. To suppress the higher order harmonics, a non-uniform filtering method is used in [6] for designing an active antenna for a wireless local area network (WLAN). In [7], a programmable filter with adaptive fold characteristics is used to improve the jamming suppression quality over a wide frequency band of the RF front-end.

For practical applications, the design of a filtering antenna is application-specific. The flatter gain response within the passband of a filtenna of a fan-shaped radiator with a defected ground structure (DGS) using a Butterworth bandpass filter is analyzed in [8]. In [9], a high gain filtering antenna is described, using a driven patch and a stacked patch with shorting pins and an U-slot, embedded on the patch. A wideband, compact and reconfigurable filtering patch antenna is designed in [10], where the feed network consists of three J-shaped probes, a Wilkinson power divider, and phase shifters. A low-profile polarization diversity filtering antenna design is presented in [11], where the antenna is fed by a custom-designed coupling probe. A duplex filtenna, using substrate integrated waveguide (SIW) and two vias, is described in [12] to enhance the selectivity of the passband with impedance bandwidth of 4.2% at 9 GHz. The design of a dual circularly polarized cavity backed filtenna using SIW technology is presented in [13], where the operating bandwidth of 12% is achieved at 10 GHz. In [14], a vertically integrated full duplex filtering antenna with a SIW cavity is designed, offering the measured gain of 4.36 dBi and impedance bandwidth of 3.2% at 4 GHz. The design of the filtenna presented in [15] relies on a circular radiator with coplanar feed, shorting stubs and a 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 [16], a slot-loaded rectangular patch with shorting pins, coupled lines and DGS are used to achieve good impedance matching and high gain.

From a literature survey, it is found that the main drawbacks of the available filtering antennas are related to their high design complexity. Many of those systems are not coplanar and compact. In many papers, at out-of-band frequencies, the return loss exceeds the acceptable minimum value and such aerials are not able to minimize the undesired radiation caused by notching frequencies. The designs of filtering antennas are

also application-specific and the described solutions are of the general purpose variety.

In this paper, the design of a microstrip filtering antenna incorporating a hairpin filter with elliptical microstrip antennas is presented for the 2.6 GHz band and the bandwidth of 190 MHz. The design is of a very simple, compact, and coplanar type with a bandpass filter. The proposed antenna is fabricated on FR4 type substrate with the dielectric constant  $\epsilon_r$  of 4.4, loss tangent ( $\tan \delta$ ) of 0.0025 and height  $h$  of 0.8 mm. The design is simulated by CST software and is measured by an MS2037C vector network analyzer to validate the simulated results. An anechoic chamber is used to measure the radiation patterns. The dimensions of the elliptical filtering antenna are  $40 \times 40$  mm, i.e.  $0.35\lambda_0 \times 0.35\lambda_0$  at 2.6 GHz.

The design of the hairpin bandpass filter is described in Section 2. The design and measurements of the elliptical filtering antenna are presented in Section 3. The conclusions and the future research work are described in Section 4.

## 2. Design of Microstrip Hairpin Filter

Due to their compact size and simple design, microstrip hairpin filters are among the most popular bandpass filters [17]–[19]. These filters are made of an U-shaped structure that is created by folding half-wavelength resonators of parallel-coupled filters. Coupling between the lines of the resonators can be reduced by folding the lines [20], [21]. Figure 1 shows a component of a hairpin bandpass resonator circuit. It occupies less space in the integrated form and the length of the filter is shorter.

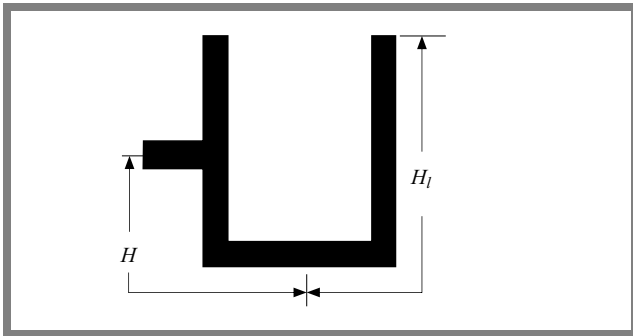


Fig. 1. Hairpin filter.

In hairpin filter structures, tapped inputs are mostly used. When compared to the coupled-line input, tapped line input takes less space in the integrated form. The design of a hairpin filter requires an equal ripple low pass prototype. Figure 2 shows the equivalent circuit of an  $n$ -th-order hairpin bandpass filter.

Each resonator is modeled as an inductor-capacitor pair. Two resonators are coupled at  $m_{j,i+1}$ .  $Q_1$  and  $Q_n$  are the input/output quality factors, respectively. Dimensions and spacing of the hairpin filter can be estimated using the quality factor and the coupling coefficient [20], [21].

$$Q_1 = \frac{g_0 g_1}{\text{FBW}}, \quad (1)$$

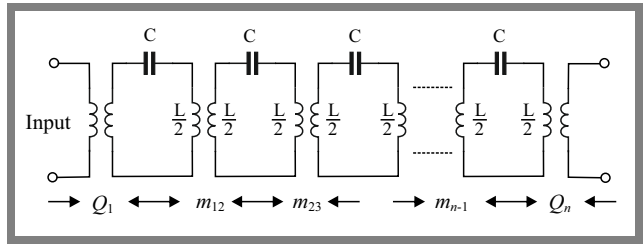


Fig. 2. Equivalent circuit of an  $n$ -th order hairpin bandpass filter.

$$Q_n = \frac{g_n g_{n+1}}{\text{FBW}}, \quad (2)$$

$$m_{i,i+1} = \frac{\text{FBW}}{\sqrt{g_i g_{i+1}}} \text{ for } i = 1 \text{ to } n-1, \quad (3)$$

where  $g_0, g_1, g_2, \dots, g_{n+1}$  are the normalized low pass components and FBW is the fractional bandwidth. If the self-coupling of the hairpin filter is not considered, then the tapped position  $H$  can be determined from Fig. 1 as:

$$H = \frac{2H_l}{\pi} \sin^{-1} \left( \sqrt{\frac{\pi Z_L}{2QZ_0}} \right). \quad (4)$$

In this equation,  $Z_L$  is the load impedance,  $Z_0$  is the characteristic impedance of the hairpin filter, and  $H_l$  ( $\lambda_g/4$ ) represents the arm length of the hairpin filter and  $\lambda_g$  is the guided wavelength.

For the design of the third order hairpin line filter, it is considered that the fractional bandwidth (FBW) is  $20\% = 0.2$  of mid-band frequency  $f_0$  of 2.61 GHz and passband ripples of 0.5 dB. Parameters of the low pass prototype and the cut-off frequency are computed using Tab. 1 [21]. For a normalized low pass cut-off frequency of  $\Omega_c = 1$ , the designed low pass prototype elements have  $g_0 = g_4 = 1$ ,  $g_1 = 1.4029$ ,  $g_2 = 0.7071$ , and  $g_3 = 1.9841$ . Eqs. (1)–(4) can be used to derive the bandpass design parameters after the low pass parameters have been determined.

Tab. 1. Summary of the prototype filter's parameters.

Number of resonators	Normalized low pass components					
	$N$	$g_1$	$g_2$	$g_3$	$g_4$	$g_5$
1	1	0.6986	1.0000			
2	2	1.4029	0.7071	1.9841		
3	3	1.5963	1.0967	1.5963	1.0000	
4	4	1.6703	1.1926	2.3661	0.8419	1.9841

The line width of the hairpin resonators is 1.5 mm, resulting in  $Z_r = 59 \Omega$  and the separation between the two arms of 0.6 mm. At mid-band frequency  $f_0 = 2.61$  GHz, the hairpin resonator's quarter-guided wavelength  $H_l$  is 15.25 mm. From Eqs. (1) and (3), the calculated values 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 the tapped line input and output. The characteristic impedance of the tapped line is  $Z_0 = 50 \Omega$ . As a result, the width of the tapped line is 1.23 mm. Equation (4) is used to calculate the tapping

location  $H$ , which is 10.5 mm, as shown in Fig. 1. Figure 3 depicts a simulated and fabricated prototype of the microstrip hairpin filter design.

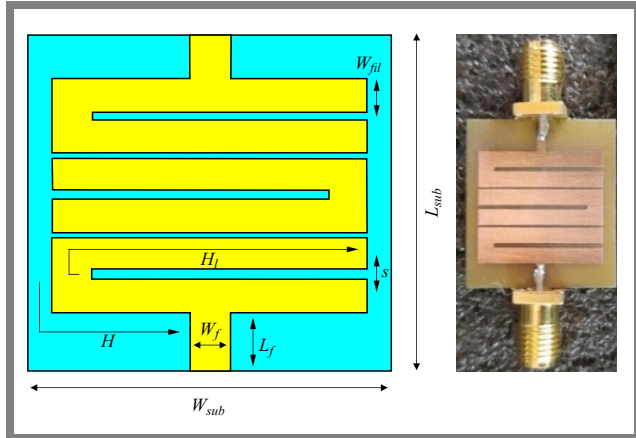


Fig. 3. The design and fabricated prototype of the hairpin filter.

The dimensions of the hairpin filter marked in Fig. 3 are:  $L_{sub} = 22$  mm,  $W_{sub} = 20$  mm,  $H = 10.5$  mm,  $H_l = 15.25$  mm,  $W_{fil} = 2.2$  mm,  $W_f = 1.23$  mm,  $L_f = 4$  mm and  $S = 0.2$  mm.

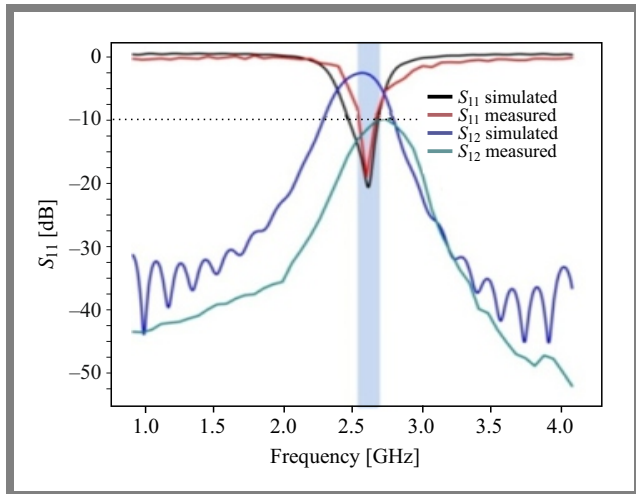


Fig. 4. Simulated and measured results for hairpin filter.

The simulated and actual  $S_{11}$  and  $S_{12}$  values of the designed hairpin filter are shown in Fig. 4. The simulated and measured results plots show a high degree of similarity. The  $S_{12}$  plots indicate that a lower insertion loss is offered by the hairpin bandpass filter designed. The bandwidth is 220 MHz (2.46 GHz–2.68 GHz) for the simulated filter, whereas the measured bandwidth is 150 MHz (2.53 GHz–2.68 GHz).

### 3. Design of Microstrip Filtering Antenna

The resonance frequency of an elliptical patch is given by [22], [23]:

$$f_r = \frac{k_{nm}C}{q\pi r e \sqrt{\epsilon_{reff}}} \tag{5}$$

Here  $c$  is the free-space velocity of light,  $k_{nm}$  is the  $m$ -th root of  $n$ -th order Bessel function and  $\epsilon_{eff}$  is the effective permittivity of the substrate which is given, for an elliptical patch, by:

$$\epsilon_{reff} = \epsilon_r - \frac{0.35\epsilon_r}{2} \left[ \frac{h}{a} + \frac{h}{b} + \frac{h^2}{ab} \right], \tag{6}$$

where  $b$  is the semi-major axis and  $a$  is the semi-minor axis of the elliptical patch. Dimensions of the elliptical patch are tuned to 18 mm × 8 mm. The substrate is backed by a partial ground plane of 23.3 × 40 mm. The overall dimensions of the filtenna are 40 × 40 mm. The hairpin filter is used with a microstrip feed line to provide a filtering antenna. The simulated and fabricated elliptical patch filtering antennas are depicted in Fig. 5. The dimensions of the elliptical filtering antenna are:  $L_{sub} = 40$  mm,  $W_{sub} = 40$  mm,  $b = 18$  mm,  $a = 8$  mm and  $L_g = 23.1$  mm.

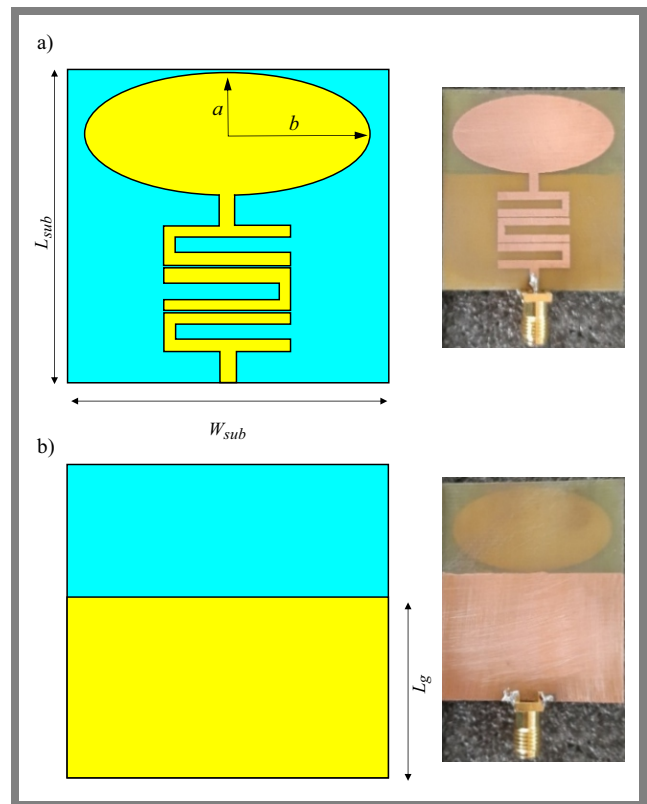


Fig. 5. Front and back of the elliptical filtering antenna prototype.

The simulated return loss plot of the elliptical patch filtering antenna with a varying major axis is shown in Fig. 6. The radius of the minor axis is fixed at 8 mm and the radius of the major axis varies from 8 to 18 mm. The aspect ratio  $e$ , i.e. the ratio between the semi-major axis and the semi-minor axis of the elliptical patch varies from 1 to 2. The major-axis dimension of 18 mm offers the lowest return loss at the operating frequency.

The simulated return loss plot of the elliptical patch filtering antenna with a varying minor axis radius is shown in Fig. 7. The radius of the major axis is fixed at 18 mm and the radius of the minor axis changes from 2 to 6 mm. The aspect ratio

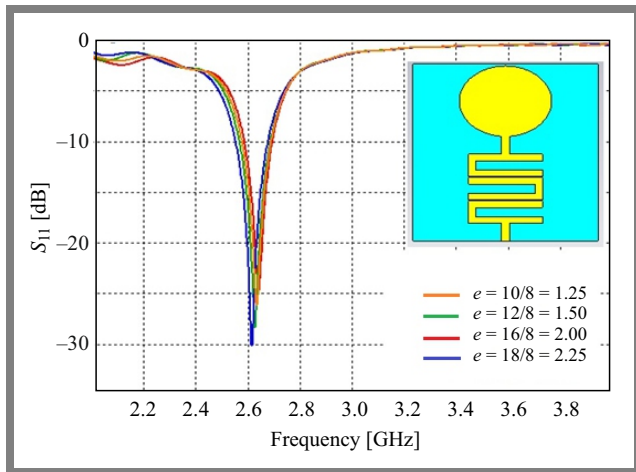


Fig. 6.  $S_{11}$  for the elliptical patch filtering antenna, for different aspect ratios.

$e$  varies from 3 to 9. The minor axis radius of 6 mm is the optimal value, as it offers a low return loss at the operating frequency.

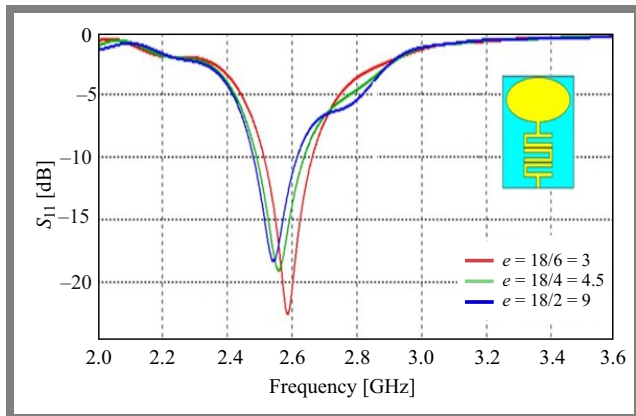


Fig. 7.  $S_{11}$  vs. frequency for the elliptical patch filtering antenna with different aspect ratios.

A batch of simulations with different lengths is performed to obtain the length of the partial ground plane of 23.1 mm to achieve better characteristics. The return loss of  $-47.27$  dB is achieved for the ground plane length of  $L_g = 23.1$  mm.

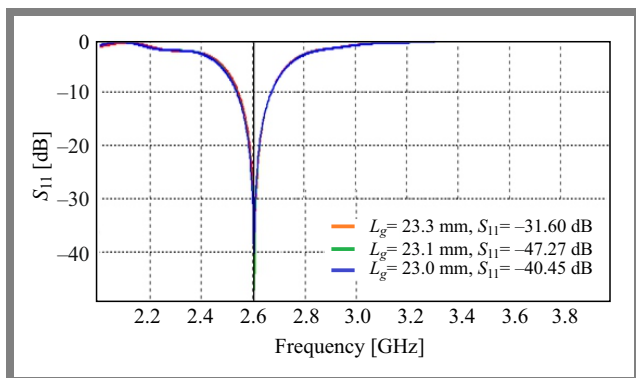


Fig. 8. Return loss vs. frequency characteristics for varying dimensions of the ground plane of the elliptical filtering antenna.

The return loss plot for the optimization of the ground plane is shown in Fig. 8.

With the aspect ratio of  $e = 18/8 = 2.25$ , the proposed design offers an operating frequency of 2.61 GHz for the ground plane length of 23.1 mm. The proposed antenna has been simulated and fabricated using these values. The return loss plots of both scenarios are shown in Fig. 9. The simulated results coincide with the actual measurements. At 2.61 GHz, the return loss of  $-28$  dB and  $-26.4$  dB are achieved. The 10 dB return loss bandwidths of 220 MHz and 150 MHz are achieved in simulations and actual measurements, respectively.

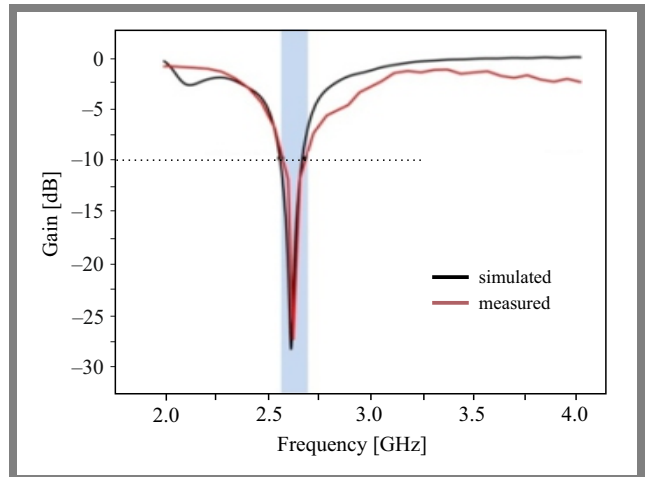


Fig. 9. Simulated and measured results for a microstrip elliptical filtering antenna with the aspect ratio of 2.25.

Figure 10 shows the radiation patterns on two main planes at 2.61 GHz for the elliptical filtering antenna. The measured and simulated results are highly similar.

Figure 11 shows a comparison between the measured and simulated gain of the filter. The maximum simulated gain is 2.2 dB at 2.61 GHz, while the measured gain is 2.1 dB.

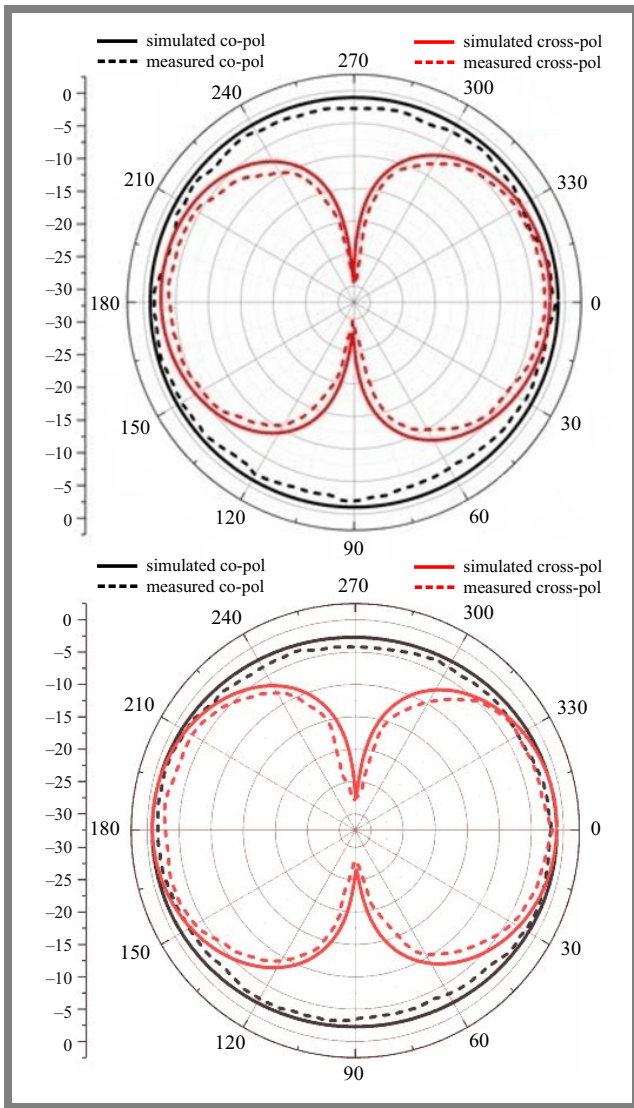
The summary of simulated and measured results, with different values of such as return loss, bandwidth, and gain for the hairpin filter and the filtering antenna, is presented in Tab. 2.

Tab. 2. Performance comparison of the proposed filtering antenna.

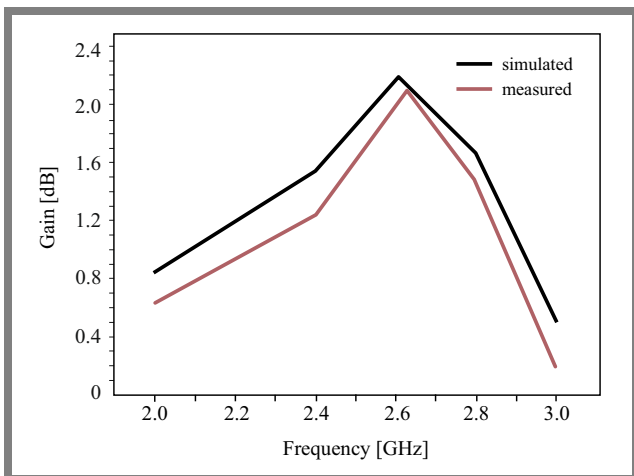
Type	Center frequency	$S_{11}$	10 dB return loss bandwidth	Gain
Hairpin filter	2.608 GHz (s)	$-27.94$ dB (s)	220 MHz (s)	—
	2.60 GHz (m)	19.9dB (m)	150 MHz (m)	
Elliptical filtering antenna	2.61 GHz (s)	$-33.95$ dB (s)	125 MHz (s)	2.2 dB (s)
	2.61 GHz (m)	$-26.4$ dB (m)	110 MHz (m)	2.1 dB (m)

(s) – simulated, (m) – measured





**Fig. 10.** Simulated and measured radiation patterns of the proposed antenna for: a) E-plane and b) H-plane.



**Fig. 11.** Simulated and measured gain of the proposed antenna.

The simulated and measured results for the elliptical microstrip filtering antenna are compared with results presented in other papers [13], [24]–[26] in Tab. 3.

**Tab. 3.** Performance comparison of the proposed filtering antenna.

Reference	Type of design	Band [GHz]	10 dB return loss bandwidth [MHz]	Gain [dB]
[13]	Two-pole Butterworth filter with fan-shaped patch and DGS	2.4	460	2.3
[24]	Coupled-line planar resonator with a second order Chebyshev filter and coplanar waveguide	2.45	343	1.2
[25]	Square-ring patch coupled with capacitor-loaded planar line filter	2.4	72	2.5
[26]	Multilayered filtenna on grooved ground plane	2.6	70	2.2
Proposed	Elliptical filtering antenna with coplanar hairpin filter	2.6	125 (s) 110 (m)	22 (s) 2.1 (m)

(s) – simulated, (m) – measured

The aerial designs presented in papers [13], [26] are difficult to manufacture and in some cases the systems are not coplanar. Elliptical filtering antennas, as proposed in this paper, are easy to design and provide moderate gain with sufficient bandwidth for applications in 2.6 GHz global mobile services.

### 4. Conclusion

The proposed filtering antenna is compact due to use of a coplanar filter greatly which also reduces its design complexity. Good coincidence between the simulated and measured results is achieved. The antenna has moderate gain, nearly omnidirectional radiation patterns and covers almost all bandwidths of the 2.6 GHz band used for rendering global mobile services over 4G and 5G networks. At the out-of-band frequencies, the achieved return losses are very low, which minimizes the undesired radiation caused by notching frequencies. Small differences between the measured and simulated results are caused by imperfections in the design of the filtenna prototype. This research work will be extended in the future to design multiple frequency microstrip bandpass filtering antennas for ultra-wideband (UWB) applications.

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