# Compact Filtering-Diamond Antenna Designed For 5G Applications at the n77-Band

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# Compact Filtering-Diamond Antenna Designed For 5G Applications at the n77-Band

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**Abstract** A new compact microstip filtering Diamond Antenna (DA) is presented in this article for possible applications in the Fifth-Generation (5G) at the n77-band (3.3 GHz- 4.2 GHz), such as, Fixed Satellite Service (FSS) which is a radiocommunication system between fixed earth stations utilizing one or more satellites. The structure is implemented on an FR4 Epoxy substrate wich has a dielectric constant $\epsilon_r = 4.4$, a loss tangent $\tan(\delta) = 0.025$ and a thickness h equal to 1.6 mm. The substrate has a small size of $39.7 \times 30 \times 1.6\ mm^3$ which make it suitable to be integrated in various intelligent systems.
A good results are obtained with this design, starting with the reflection coefficient $S_{11}$ which is equal to -22.31 dB at the first resonant frequency 3.57 GHz and -34.41 dB at the second resonant frequency 4.10 GHz. Several other results will be presented and discussed later in this article. The software used for the simulation is High-Frequency Structure Simulator (ANSYS HFSS) which employs the finite element approach.
A prototype of the filtenna (filtering Antenna) was fabricated and measured using the Vectorial Network Analyzer 3656D (VNA).

**Keywords** Compact, Hairpin-Filter, Diamond Antenna, Filtenna, 5G, n77-band

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- **Availability of data and material** This work has no associated data.
- **Code availability** Not Applicable.
- **Conflicts of intere/Competing interests** The authors declare no conflicts of interests.

## Data Availability Statement

All data generated or analysed during this study are included in this published article. There is no separeted data.

## Acronyms and Terms

**DA:** Diamond Antenna
**5G:** Fifth-Generation
**FSS:** Fixed Satellite Service
**HFSS:** High-Frequency Structure Simulator
**WLAN:** Wireless Local Area Network
**GPS:** Global Positioning System
**3rd Generation Partnership Project:** 3GPP
**DGS:** Defected Ground Structure
**NEMA:** National Electrical Manufacturers Association
**VSWR:** Voltage Stdanding Wave Ratio
**SIHR:** Stepped Impedance Hairpin Resonator
**VNA:** Vectorial Network Analyzer

## 1 Introduction

In the previous few decades, the field of wireless communication has seen unprecedented expansion, this expansion due to the appearance of many wireless goods and services, such as Wireless Local Area Network (WLAN), Bluetooth, mobile phones and Global Positioning System (GPS) [1]. These services appeared thanks to the evolution of the different generations of cellular telephony, beginning with the first generation (1G) showed up in 1980 and passing through the 2G-3G-4G to the current generation 5G and the 6th generation expected for 2030 [2].
As we all know the 5G band is composed of three bands, the sub 1GHZ, the sub 6GHZ and the millimeter band, these bands are also divided into n small bands numbered according to the 3rd Generation Partnership Project (3GPP) in the summary of Release 15 work items [3].

Multi-function integrated modules are becoming more popular in wireless communication systems as a result of their small circuit size and good performance [4]. The most significant functions of the communication system are radiating and filtering, why we are interested in filter and antenna ? because the latter radiates and the first removes all unnecessary frequencies, therefore, combining these functions into a single module will eliminate the additional circuit and improve the circuit's overall performance [5]. In this sense, several integrated filters have been proposed [6–8], among these filters, hairpin filter is widely used for its simplicity, for example, in [9] a microstrip six-order hairpin band pass filter operating at the X-band frequency was designed by using open stub and Defected Ground Structure (DGS), the substrate used is the Rogers RT5880, which has a loss tangent of 0.0009. In [10] Two third-order hairpin filter designs have been developed for possible applications in the 5G (3.7 GHz- 4.2 GHz) and (5.975 GHz- 7.125 GHz) low frequency bands. The achieved results for these two filters with regard to the reflection coefficient are higher than -35 dB.
Also for miniature antennas, several examples have been discussed [11–13], among this antennas what is called Diamond Antenna (DA) [14, 15]. In order to benefit from the two functionalities radiating and filtering while keeping a small size these two components which are the filter and the antenna are combined in one module it is called the filtenna or filtering antenna [16–18]. In [19] a filtenna was fabricated by using two hairpin filters consisting of three U-shaped resonators with a length equal to the half-wavelength guided in the substrate. The RO4350B dielectric substrate was employed, which has a dielctric constant of 3.48. In [20] a novel printed monopole antenna with Stepped Impedance Hairpin Resonator (SIHR) loading was implemented on a Rogers RO4003C substrate. The filtenna operates at 2.53 GHz and the achieved gain is around 2.63 dB.
In this article a new filtenna design is proposed consisting of a hairpin filter made of three folded U-shaped resonators connected with a Diamond Antenna (DA) in order to eliminate all unwanted frequencies and keep only the n77 band frequencies which are between (3.3 GHz and 4.2 GHz). The structure is designed and fabricated on a small FR4 Epoxy substrate. The obtained results are encouraging in terms of impedance matching, radiation pattern and gain.

## 2 Microstrip Filtenna Configuration

Figure 1 shows the structure of the proposed filtenna, it consists of a monopole microstrip Diamond Antenna (DA) connected with a hairpin filter. The bottom side contains a partial ground plane.

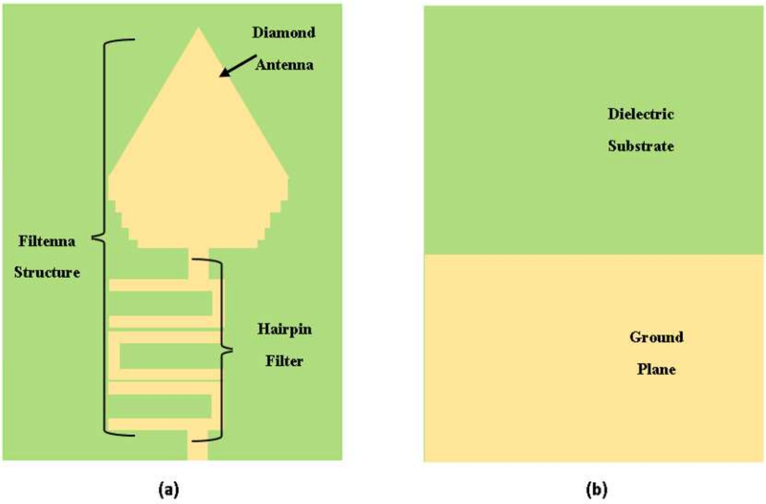


Fig. 1: Filtenna structure layout: (a) Top view (b) Bottom view

Both components are connected and matched to the same 50 Ω impedance. The hairpin filter consists of three folded U-shaped resonators coupled together, the spaces between the resonators are taken as equidistant.
The filtenna was established on an FR4 Epoxy substrate which is a standard defined by the National Electrical Manufacturers Association (NEMA) for a glass fiber reinforced epoxy resin composite [21].
With their suitable cost, FR4s are the standard option for short-run PCB manufacturing or electronic prototyping.
FR4 has the advantage of a good strength-to-weight ratio. It does not absorb water, retains high mechanical stresses and good insulation capacity in dry or wet environments [22].

## 3 Evolution of The Proposed Filtenna Design

### 3.1 Diamond Antenna

A Diamond Antenna with a pointed summit and shifted transmission line has been designed as shown in figure 2. The used conductor in this design is copper which has a thickness of 0.035 mm, it is also used for the bottom side as a partial ground plane.
The dimensions of the structure are presented in table 1.

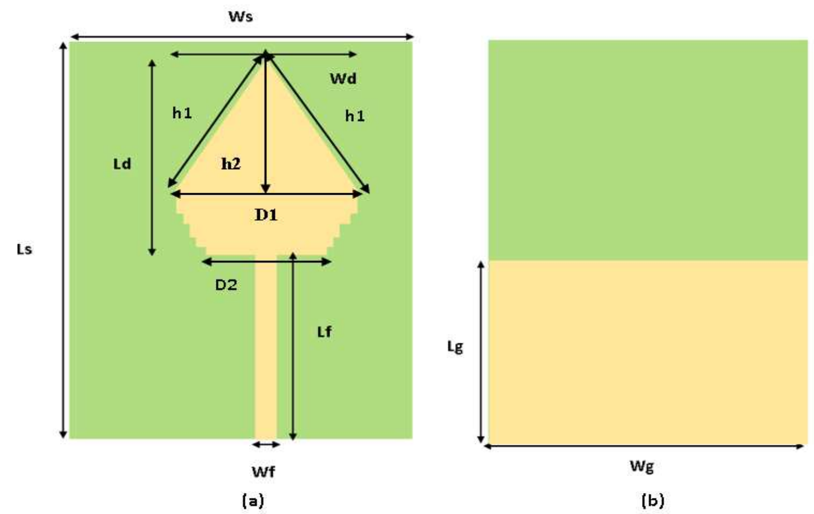


Fig. 2: Structure of the Diamond Antenna: (a) Top view (b) Bottom view

Table 1: Dimensions of the Diamond Antenna parameters

| Parameters | $L_S$ | $W_S$ | $L_d$ | $W_d$ | $L_f$ | $W_f$ |
|---|---|---|---|---|---|---|
| Dimensions (mm) | 39.7 | 30 | 18.3 | 16 | 19.5 | 1.5 |
| Parameters | $h_1$ | $h_2$ | $D_1$ | $D_2$ | $L_g$ | $W_g$ |
| Dimensions (mm) | 15.36 | 12.8 | 16 | 12 | 17.3 | 30 |

### 3.2 Hairpin Filter

The hairpin filter is a part of the linear planar resonators and who says resonator says a section of line whose length is a fraction of the guided wavelength $\lambda_g$. Generally the resonators's length of the hairpin filter are approximately equal to the half-wavelength guided in the substrate $\lambda_g/2$.
In this paper we have proposed a hairpin filter composed of three U-shaped resonators that have the same dimensions (length and width), these dimensions are calculated using the following theoretical equations:
For the width of the resonator we have:

$$\frac{W_r}{h} = \frac{2}{\pi}\left((B-1) - ln(2B-1) - \frac{\epsilon_r - 1}{2\epsilon_r}\left[ln(B-1) + 0.39 - \frac{0.61}{\epsilon_r}\right]\right) \quad (1)$$

With:

$$B = \frac{60\pi^2}{Z_c\sqrt{\epsilon_r}} \quad (2)$$

In our case the characteristic impedance is $Z_c = 50\ \Omega$ and the relative permittivity is $\epsilon_r = 4.4$.
Therefore, B= 5.64 and $\frac{W_r}{h} \approx 1.04$.

We obtaine the resonator's width $W_r \approx 1.65$ mm.
The length of the resonator is obtained by the following equations:

$$L_r = \frac{\pi}{K_0\sqrt{\epsilon_{reff}}}(meter) \tag{3}$$

With:

$$K_0 = \frac{2\pi f_c}{c}(meter^{-1}) \tag{4}$$

The chosen center frequency is $f_c = 3.8$ GHz

$$W = \frac{c}{2f_c\sqrt{\frac{\epsilon_r+1}{2}}} \tag{5}$$

The effective relative dielectric constant given by the microstrip synthesis as:

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{\frac{-1}{2}} \tag{6}$$

We obtaine the resonator's length: $L_r = \approx 19.85mm$

We can conclude that,

$$L_r = \frac{\lambda_g}{2} \approx 19.85mm$$

Noting that, $\frac{\lambda_g}{2}$ is the half-wavelength guided in the substrate which can be given as:

$$\frac{\lambda_g}{2} = \frac{c}{2f_c\sqrt{\epsilon_{reff}}} \tag{7}$$

The hairpin filter structure is shown in figure 3. The ground plane under the filter is complete. The dimensions of the whole structure are presented in table 2.

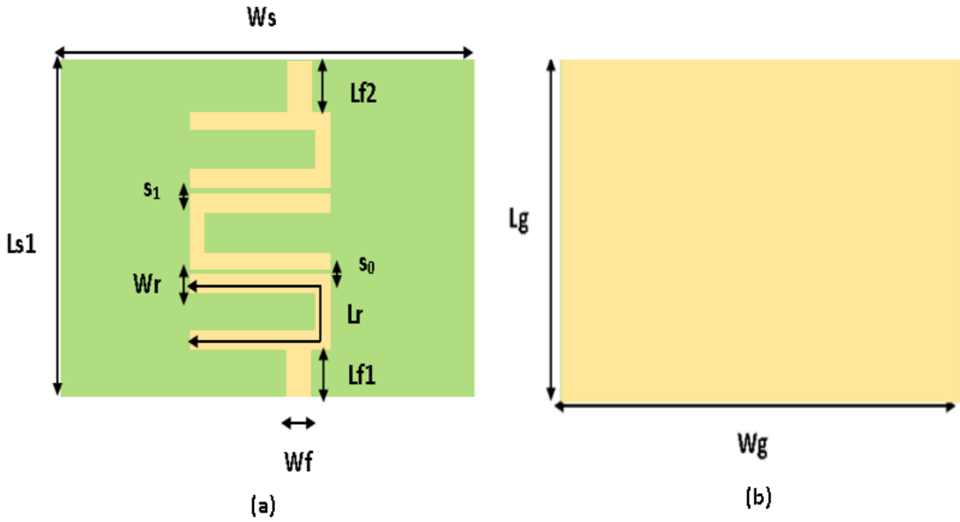


Fig. 3: Structure of the proposed filter: (a) Top view (b) Bottom view

Table 2: The optimal dimensions of the hairpin filter parameters

| | | | | | | |
|---|---|---|---|---|---|---|
| Parameters | $L_{S1}$ | $W_S$ | $L_{f1}$ | $L_{f2}$ | $L_r$ | $W_r$ |
| Dimensions (mm) | 17.3 | 30 | 3 | 3 | 23.85 | 1.65 |
| Parameters | $S_0$ | $S_1$ | $W_f$ | $L_g$ | $W_g$ | |
| Dimensions (mm) | 0.2 | 0.2 | 1.5 | 17.3 | 30 | |

### 3.3 Proposed Filtenna

Figure 4 shows the proposed filtering antenna design. The transmission line in the Diamond Antenna configuration (figure 2) is replaced by the hairpin filter configuration of figure 3.
The dimensions of the structure are assembled in table 3.

Table 3: Dimensions of the proposed filtenna parameters

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Parameters | $L_S$ | $W_S$ | $L_d$ | $W_d$ | $D_1$ | $D_2$ | $L_{f1}$ | $L_{f2}$ |
| Dimensions (mm) | 39.7 | 30 | 18.3 | 16 | 16 | 12 | 3 | 3 |
| Parameters | $h_1$ | $h_2$ | $L_r$ | $W_r$ | $S_0/S_1$ | $W_f$ | $L_g$ | $W_g$ |
| Dimensions (mm) | 15.36 | 12.8 | 23.85 | 1.65 | 0.2 | 1.5 | 17.3 | 30 |

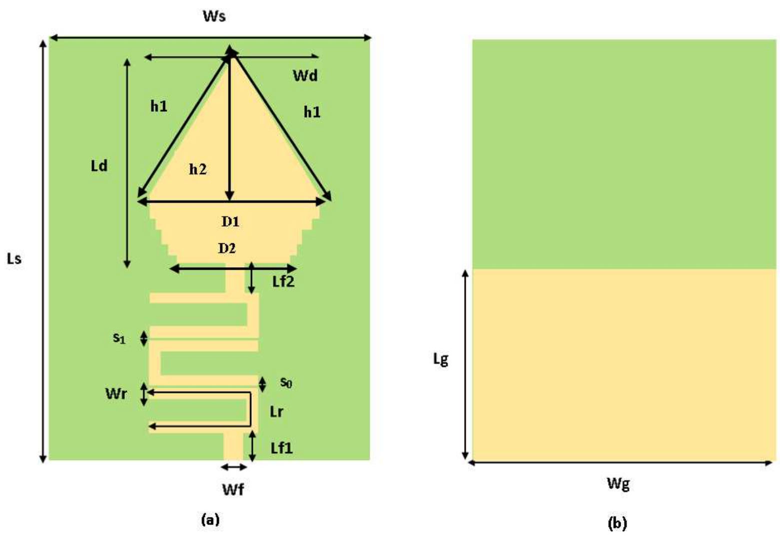


Fig. 4: The proposed filtenna structure: (a) Top view (b) Bottom view

## 4 Simulation Results and Discussions

### 4.1 Reflection Coefficient of the Diamond Antenna

The reflection coefficient versus frequency of the Diamond Antenna is represented in the figure 5.
According to the following figure we remark that, the antenna has two bands, the first one is from 3.02 GHz to 5.75 GHz, and the second one is from 10.77 GHz to 11.99 GHz. We are interested in the first band because it includes the n77-band. The problem is that there are frequencies in the bandwidth that are ineffective for 5G applications and can cause interference. Hence, the idea of integrating hairpin filter with Diamond Antenna to eliminate all the undesirable frequencies and keep only those of 5G spectrum in particular frequencies of the n77-band (3.3 GHz- 4.2GHz).

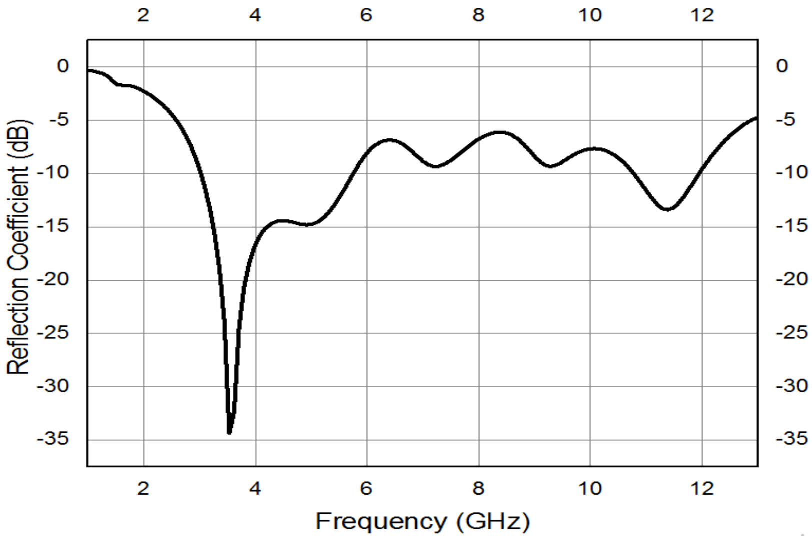


Fig. 5: Reflection coefficient of the Diamond Antenna

### 4.2 Parametric Study for the Hairpin Filter

A parametric study was made and presented in figure 6 and 7 for the length of the resonators and the Y position of the two input lines, respectively, in order to optimize the center frequency value and the bandwidth.

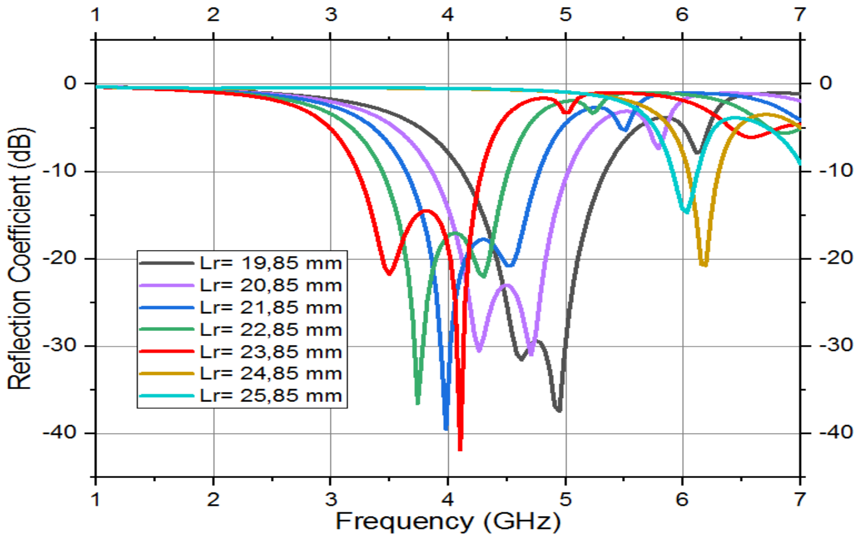


Fig. 6: Reflection coefficient vs.frequency for different values of Lr

We remark in figure 6 that, the length of the resonators that we theoretically demonstrated ($L_r = 19.85$ mm), gave a bandwidth that was a little shifted from the desired one, therefore, we tried to modify the resonators length using a parametric study.
We observed that, as the length of the resonator increases, the bandwidth moves to the left, towards the desired band n77 (3.3-4.2 GHz). We also remark that, the perfect adaptation is achieved for the value $Lr = 23.85$ mm, if we exceed this length we risk losing the adaptation and also the chosen bandwidth.
The position of the two input lines of the hairpin filter also had a significant impact on the value of the reflection coefficient.

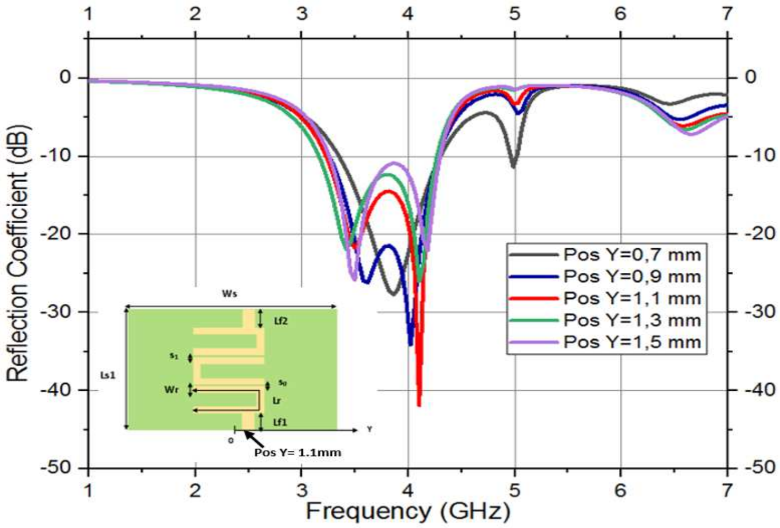


Fig. 7: Reflection coefficient versus frequency for different positions of the two inputs

We observed in the previous figure that, for the position Pos Y=1.1mm, there is a minimum of reflected waves, which is very suitable in the antenna field. We also remark that, if we get close to Pos Y=0 mm, we have the beginning of appearance of a second unwanted band on the right which can disturb our system.
The reflection and transmission coefficient of the hairpin filter are shown in figure 8. For the minimum of reflection we have the maximum of transmission.

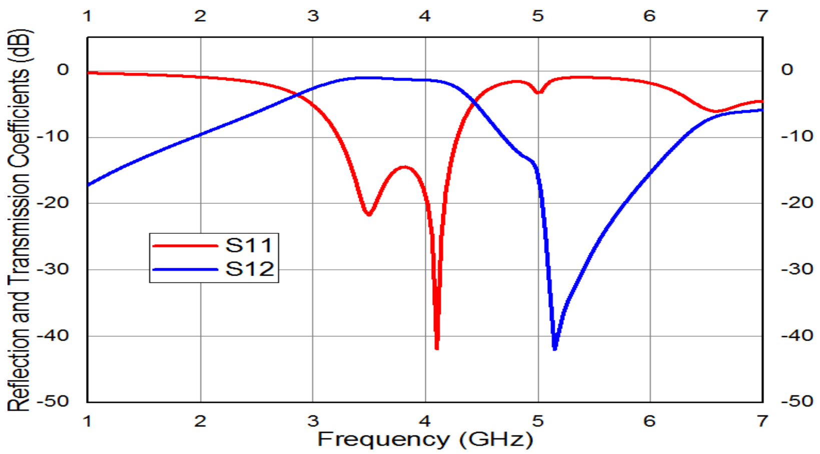


Fig. 8: Reflection and transmission coefficient of the proposed filtenna

## 4.3 Simulated Results for the Proposed Filtenna

### *4.3.1 Reflection Coefficient*

Figure 9 shows the reflefction coefficient of the proposed filtenna versus frequency.

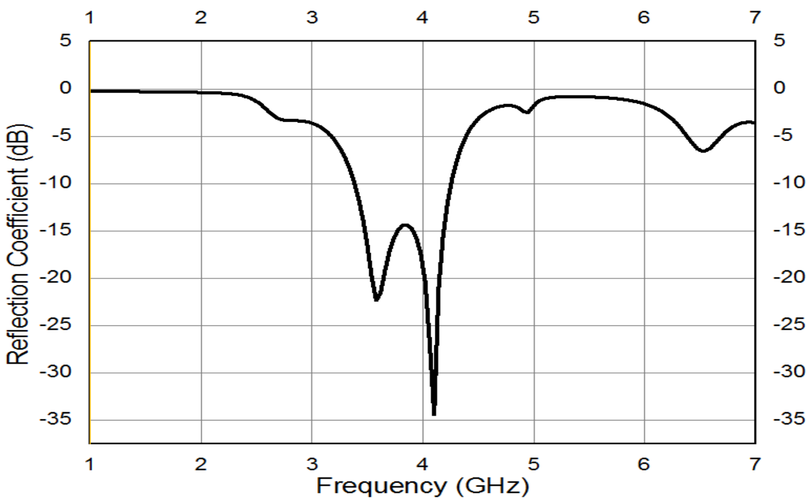


Fig. 9: Reflection coefficient of the proposed filtenna

We remark from the previous figure the effect of the hairpin filter on Diamond Antenna. The unwanted frequencies obtained by the Diamond Antenna have

been eliminated by the filter.
The proposed filtenna has a bandwidth of 750 MHz (from 3.45 GHz to 4.21 GHz) which is in the n77 band (3.3GHz- 4.2GHz), it has two resonant frequencies 3.57 GHz and 4.10 GHz where, the $S_{11}$ is equal to -22.31 dB and -34.41 dB, respectively.

*4.3.2 VSWR*

The simulated Voltage Stdanding Wave Ratio (VSWR) is shown in figure 10

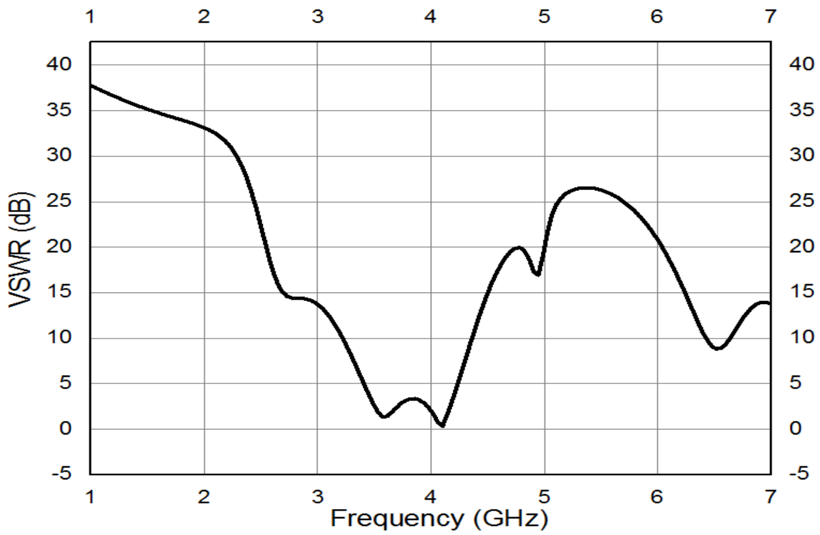


Fig. 10: VSWR versus frequency

We remark that, at the second resonant frequency 4.10 GHz the regime is very close to that of progressive waves ($VSWR = 0.33$), in another way, the adaptation is excellent. For the first resonance frequency 3.57 GHz, the VSWR is around 1.32.
Both results are very good since they are less than 2, this means that 10% of the incident power is reflected and 90% of the incident power is transmitted.

*4.3.3 Input Impedance*

Figure 11 shows the input impedance of the proposed filtenna which is composed of a real part represented in blue and an imaginary part in orange.
knowing that, a good impedance matching corresponds to an input impedance whose real part tends to the value of the characteristic impedance 50 Ω and the imaginary part tends to zero at the resonant frequency.

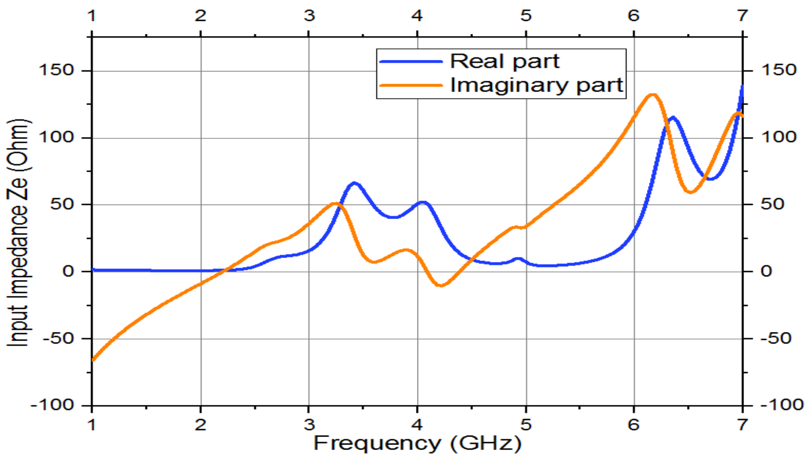


Fig. 11: Input Impedance versus verquency

At the second resonant frequency 4.10 GHz, we can observe that, the input impedance is optimal $Z_e = 50.01 - j1.90$. For the second resonant frequency 3.57 GHz, the input impedance at is given as $Z_e = 51.29 + j7.62$ which is compatible with the previous results.

### *4.3.4 Gain*

Figure 12 depicts the simulated 3D radiation pattern at both resonance frequencies 3.57 GHz and 4.10 GHz. For these frequencies, the observed gain is equal to 5 dB.

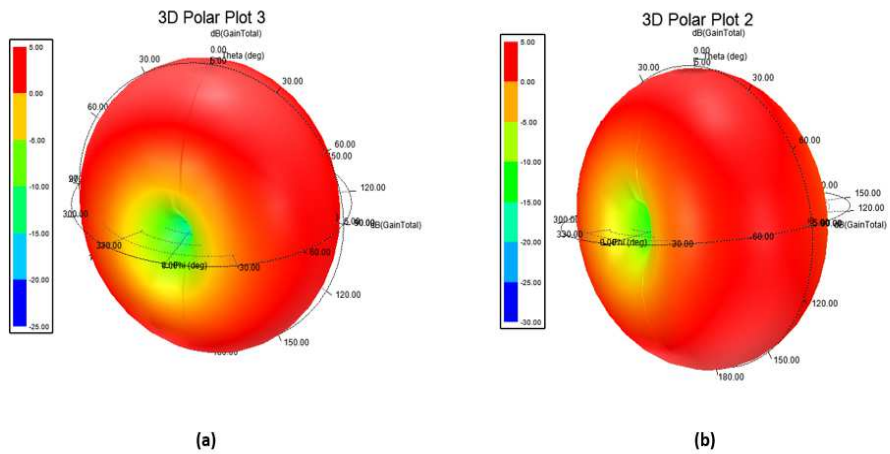


Fig. 12: 3D radiation pattern at: (a) 3.57GHz and (b) 4.10GHz

### 4.3.5 Radiation Pattern

The simulated 2D radiation patterns in the E-plane and H-plane for the two resonant frequencies 3.57 GHz and 4.10 GHz are presented in figure 13. We remark that the two obtained diagrams are nearly identical, bi-directional in the E-plane and omni-directional in the H-plane.

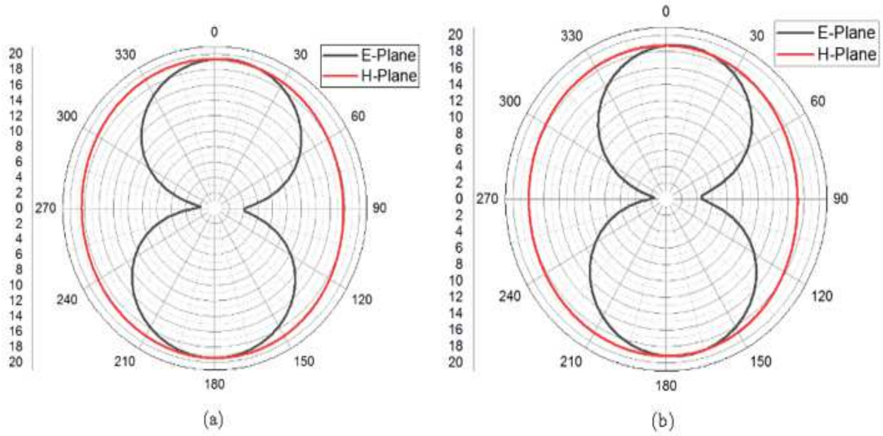


Fig. 13: 2D radiation pattern at: (a) 3.57 GHz and (b) 4.10 GHz

### 4.3.6 Parametric Study for the Ground Plane of the Filtenna

A parametric study was made and represented in figure 14. This study consists in observing the effect of the ground plane by changing the length and the width.

We have chosen the length and the width of the ground plane $L_g = 17.3$ mm and $W_g = 17.3$ mm compared to the other lengths and widths because, they provide perfect adaptation as well as a minimum of reflected waves in the margin of (6GHz-7GHz).

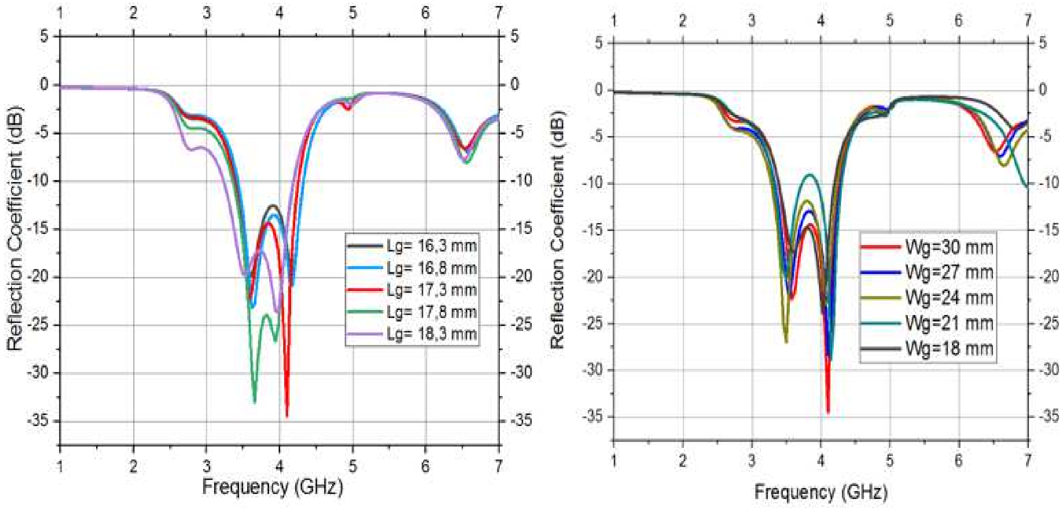


Fig. 14: Reflection coefficient versus frequency for different values of $L_g$ and $W_g$

## 5 Measured Results for the Proposed Filtenna

Figures 15 and 16 show the photograph of the proposed filtenna prototype and its measured results, respectively.


(a) (b)

Fig. 15: Prototype of the proposed filtenna: (a) Top view (b) Bottom view

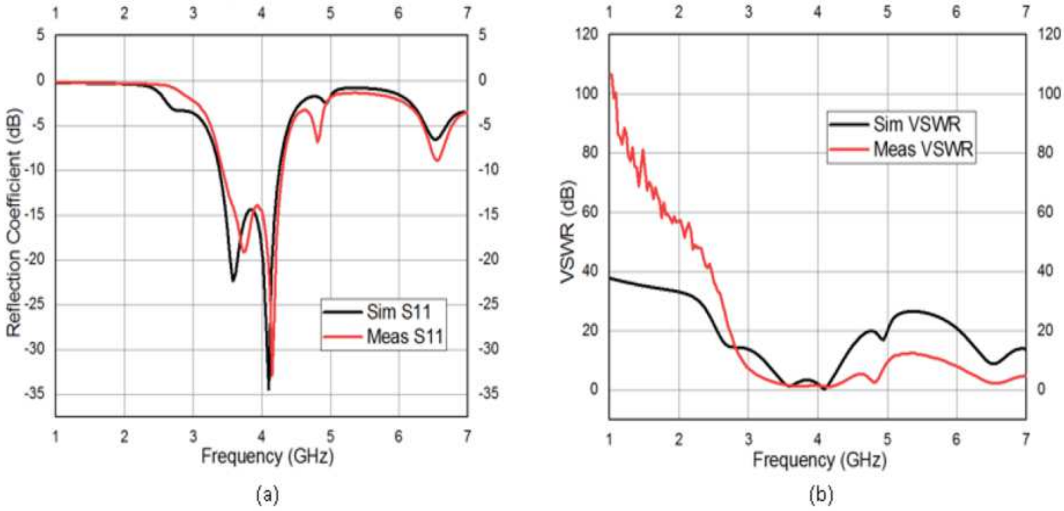


Fig. 16: Measured and simulated results: (a) Reflection Coefficient and (b) VSWR

We observe that, the measurement curve follows approximately that obtained by simulation for both the reflection coefficient and the Voltage Standing Wave Ratio (VSWR).
There is a small shift for the reflection coefficient value of the first resonant frequency 3.57 GHz and a noisy VSWR in the 1GHz-2.5GHZ band, these problems are due to the soldering on the feed line and the ground plane also there is the phenomenon of disturbance that intervenes because of the waves that pass in the radiation field of the antenna.
In the following table, we compared the performance of our filtenna to the performance of other recently released filtennas.

Table 4: Comparison study

| References | Reson.Freq (GHz) | Ref.Coeff (dB) | Gain (dB) | Size ($mm^2$) |
|---|---|---|---|---|
| [23] | 3.5/7.5 | -11.12/-32.1 | 9.8/6.2 | $156 \times 90$ |
| [24] | 3.42/14.55 | -16.3/-35.8 | 5.6/5.8 | $40 \times 38$ |
| [25] | 20/29 | -21.3/-42.4 | 5.62/7.41 | $21.9 \times 9.8$ |
| Proposed Filtenna | 3.57/4.10 | -22.31/-34.41 | 5/5 | $39.7 \times 30$ |

Comparing our work to other published works we could say that, the performance of our filtenna is good in terms of reflection coefficient and dimensions which makes it suitable to be integrated into various electronic devices for possible 5G applications such as Fixed-Satellite Service (FSS).

## 6 Conclusion

A new filtenna has been designed in this article, the simulations performed have proven very good results in terms of reflection coefficient, radiation pattern and gain, not to forget compactness and small dimensions of the filtenna which play a very important role in the development of low cost technologies. This filtenna is therefore suitable to be integrated in different new systems for possible applications in 5G band especially for those operating in the n77 band (3.3GHz-4.2GHz).

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