A new small high-gain wideband rectangular patch antenna for X and Ku bands applications

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ABSTRACT
A new small high-gain wideband rectangular patch antenna is proposed in this paper. The antenna has a simple structure where the dimensions are about 11 mm by 7 mm by 1.58 mm leading to a good bandwidth. The antenna structure is optimized and simulated using electromagnetic commercial software, and the measured bandwidth defined by return loss \(< -10 \text{ dB}\) is 1.97 GHz from 10.94 to 12.91 GHz for simulated results and 2.75 GHz covering from 10.8 to 13.55 GHz for measured results using vector network analyser. The gain is up to 4.91 dBi with a good radiation pattern. The comparison between simulation and measurement results permits to validate the structure of the proposed antenna. The low expenses of this profile and its simple configuration allow for an easy fabrication process, with usability in many applications such as radar, satellite and wireless communication.

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1. Introduction
With the rapid development of modern Wireless Communication Technology, microstrip antenna is in researchers’ good graces because of its advantages, such as a low profile, light weight, high-gain and simple structure that ensure reliability, mobility and efficiency [1]. In addition, it is characterized by relative ease of construction, low cost, conformability to complex mounting surfaces and compatibility with printed circuit boards. In fact, this antenna provides all the advantages of printed circuit technology [2]. Thus, this type of radiating element becomes day after day popular in many wireless systems such as satellite communications, radar, medical applications, etc. [3]. However, the main disadvantage of patch antenna radiator is its narrow bandwidth. Recently, many techniques have been developed to enhance the bandwidth. The most commonly used ones are adding slots to radiating element [4–7] and partial ground plane [8,9]. In addition, the microstrip antennas are known by their disability to operate at high power levels. Therefore, the challenge in microstrip antenna design is to increase the bandwidth and gain [10]. Patch antenna arrays in the X-band have been widely reported in literature [11–15]. Several authors [16–19] have focused on technical design of microstrip patch antennas for X-band applications.

In this paper, a new high-gain wideband microstrip patch antenna operating in X and Ku bands is presented. This structure has several advantages like smallness and simplicity of the structure which leads to easy manufacturing. Fed is ensured by a microstrip line with 50 \(\Omega\). The antenna design was performed by using two electromagnetic software’s Ansoft High Frequency Structure Simulator (HFSS) and Computer Simulation Studio Microwave Studio (CST MW). The results of the two simulators were compared along with measurement results and show a good agreement.

When compared with other printed radiating elements, our antenna possesses the advantage of not only having a broad bandwidth, but also a smaller size [7,15,16].

2. Rectangular microstrip patch antenna theory
Before designing a rectangular microstrip patch antenna, there are several parameters needed to be considered which will affect the antenna bandwidth as well as the resonant frequency [20].

2.1. Patch length and width
The shape of the patch is its main parameter and naturally affects most of the antenna characteristics (Figure 1). However, the patch width has a minor effect on the resonant frequency and radiation...
pattern of the antenna. So a larger patch width increases the power radiated and thus gives decreased resonant resistance, increased bandwidth and increased radiation efficiency. The patch width should be selected to obtain good radiation efficiency if real state requirements or grating lobe are not overriding factors. It has been suggested for patch dimension that $1 < W/L < 2$ [14,21]. The patch length determines the resonant frequency, and it is critical parameter in the design; however, the patch length $L$ for $TM_{10}$ mode is given by the following equation:

$$L = \frac{C}{2f_r \sqrt{\varepsilon_r}},$$

where $f_r$ is the resonant frequency.

### 2.2. Fringing effect

To account for the fringing effect, an effective dielectric constant $\varepsilon_{eff}$ is used. The effective dielectric constant is defined as the dielectric constant of the uniform dielectric material so that:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + \frac{h}{W} + \frac{1}{h} \frac{W}{h} \gg 1\right).$$

### 2.3. Length and width

Due to fringing effect, electrically the patch dimensions will be bigger than its physical dimensions. A practical approximate formula to calculate the width and length is shown below. The following equation is used to calculate the width $W$:

$$W = \frac{C}{2f_r \sqrt{\varepsilon_r}},$$

where $f_r$ is the resonant frequency, $C$ is the free-space velocity of light ($C = 3.10^8$ m/s) and $\varepsilon_r$ is the dielectric constant of the substrate.

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**Figure 1.** Geometry of the patch antenna.

**Figure 2.** Geometry of the proposed antenna, (a) top view and (b) bottom view.
constant of substrate. To determine the length \((L)\) of the patch, the following equation is used:

\[
L = \frac{C}{2\pi \sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L. \tag{4}
\]

Normalized extension of the length \(\Delta L\) is:

\[
\Delta L = 0.412h \left( \frac{W}{h} + 0.264 \right) \left( \frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} + 0.258} \right). \tag{5}
\]

3. Antenna design

In this paper, we have validated the antenna structure depicted in Figure 2, where we have the top and the bottom views of the final structure. The proposed antenna is a rectangular patch with dimensions of 18 × 20 × 1.58 mm³ printed on an FR4-epoxy substrate, having 1.58 mm as thickness with a relative dielectric permittivity of 4.4 and 0.02 for loss tangent. This antenna is fed by a microstrip line with a characteristic impedance of 50 Ω. The ground plane of this antenna is modified and optimized to have a broadband frequency. After many series of optimization by using HFSS, we have obtained the different optimized parameters of proposed antenna listed in Table 1.

Four values of the length of the partial ground plane were tested. In Figure 3, we show the effect of changing of the length of the ground plane on impedance matching. We find that when we diminish the value of \(L_{G1}\), we get improved bandwidth and level of \(S_{11}\); the best value obtained is for \(L_{G1} = 3\) mm with increased bandwidth as illustrated in Figure 3.

As shown in Figure 4, the radiation pattern of the antenna with partial ground plane has a bidirectional radiation pattern that is not suitable for applications such as radar and X-band satellite. In order to have the radiation centred at one direction and to make the antenna supporting the X-band, we added a metallic surface to the ground plane. We have obtained the best results for a distance between ground plane and the metallic surface optimized at 1.5 mm as shown in Figure 5.

Therefore, we fixed \(d = 1.5\) mm and cut a rectangular slot in the edge of the metallic surface of the proposed antenna to observe the variations of the return loss. The simulated results are presented in Figure 6. From this figure, it is easy to notice that the bandwidth is moved in the X-band with a minimal \(S_{11}\) of about −32.99 dB with a bandwidth of 1.97 GHz from

| Table 1. Parameters values of proposed antenna. |
|-----------------------------------------------|
| Basic configuration | Parameter | Value (mm) |
|----------------------|-----------|------------|
| Substrate FR4-epoxy  | \(W_{\text{sub}}\) | 18         |
|                      | \(L_{\text{sub}}\) | 20         |
| Patch antenna        | \(W\)     | 11         |
|                      | \(L\)     | 7          |
|                      | \(W_{m}\) | 1          |
|                      | \(L_{m}\) | 12         |
|                      | \(W_{Gd1}\) | 15         |
|                      | \(L_{Gd1}\) | 11         |
|                      | \(S_1\)   | 1          |
|                      | \(S_2\)   | 0.5        |
| Ground plane         | \(W_{Grd2}\) | 15         |
|                      | \(L_{Grd2}\) | 11         |
|                      | \(L_{Grd1}\) | 3          |

Figure 3. \(S_{11}\) optimization for different values of \(L_{G1}\).

Figure 4. E-plane and H-plane radiation patterns of the proposed antenna at different frequencies (a) 11.5 GHz and (b) 12.5 GHz for proposed antenna without metallic surface Grd 2.
10.94 to 12.91 GHz that covers a part of X and Ku bands.

4. Results and discussion
The proposed antenna is simulated by using Ansoft HFSS, whose numerical analysis is based on the finite element method. Figure 7 shows the return loss of the proposed antenna. The resonance frequency at 11.6 GHz with a level of the return loss of $-32.87$ dB, the results obtained showed that the bandwidth at $-10$ dB of this antenna is in the frequency range from 10.84 to 12.78 GHz (1.94 GHz), which covers the bandwidth of the satellite and Radar applications.

To validate our use of design software HFSS, we designed and simulated the same structure as CST MW, whose numerical analysis is based on the method of the finite integration technique. Figure 8 illustrates the return loss obtained by both simulation tools. We can conclude that we have a good agreement between simulation results obtained by using CST-MW and HFSS. There is a slight difference if we consider the resonant frequency, that is, in terms of bandwidth, results are very comparable.

After comparison of the simulation results on HFSS and CST-MW, we have achieved the proposed antenna by using the LPKF machine. A photograph of a prototype antenna fed by microstrip line printed on FR4-epoxy material substrate is shown in Figure 9. The
return loss of the fabricated antenna was measured using vector network analyser VNA Master MS2028C.

Figure 10 shows the comparison between the simulated and measured return loss of the proposed antenna obtained by the experimental and the two tools for simulation. We conclude that we have a good agreement between simulations and measurements results. There exist some differences if we consider the frequencies of resonance (Table 2); however, in terms of bandwidth, the results remain very comparable. Little offset may be attributed to the fact that the substrate FR4 used for the fabrication of the antenna does not possess uniform characteristics in terms of its material properties.

Table 2. Comparison between the measured and simulated return loss.

|                | Bandwidth at −10 dB (GHz) | Resonant frequency (GHz) | Level $S_{11}$ (dB) |
|----------------|---------------------------|-------------------------|---------------------|
| HFSS           | 10.94–12.91 (1.97 GHz)    | 11.62                   | −32.99              |
| CST            | 11.06–12.96 (1.9 GHz)     | 11.6                    | −22.61              |
|                |                           | 12.5                    | −23.19              |
| Measured       | 10.8–13.55 (2.75 GHz)     | 11.4                    | −13.10              |
|                |                           | 13.17                   | −14.50              |

Figures 11 illustrates the radiation patterns, in the H-plane (x–z plane) and E-plane (y–z plane). It can be seen that the radiation patterns in x–z plane are nearly omnidirectional for the two frequencies.

Figure 12 shows the variation of the gain versus frequency. The average gain of the proposed antenna is 3.75 dB, whereas the maximum gain is 4.91 dBi which is better than that given in refs [17] and [18]. The gain is relatively good and can be improved by making an array of antennas of our prototype. The efficiency was obtained from gain and directivity and is depicted in Figure 13. An overall level of about 82%–86% can be attained in the band of 10–14 GHz.

Table 3 presents a comparison between the performance of some recently developed antennas for X-band applications and the proposed antenna. Our antenna shows wide impedance bandwidth, compact size and good gain features.
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No potential conflict of interest was reported by the authors.

Disclosure statement

No potential conflict of interest was reported by the authors.

5. Conclusion

In this paper, we proposed a miniature microstrip rectangular patch antenna for X and Ku bands applications. The antenna achieves extremely wide frequency bandwidth and good radiation characteristics in terms of radiation patterns. The measurement and simulation results are in good agreement which validate the proposed antenna with a bandwidth of 2.75 GHz and a gain is up to 4.91 dBi. According to the results obtained, using the design method presented in this paper can extremely increase the impedance bandwidth of an X and Ku bands microstrip antenna. The method can be easily revised and extended for the design of other types of wide-band patch antennas.

Disclosure statement

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