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Design of a miniaturized patch antenna for 2.45/5.8 GHz applications

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ABSTRACT

A miniaturized antenna for 2.45 and 5.8 GHz applications is presented in this paper. The designed antenna is based on two metamaterial unit cells which resonate at 2.45 and 5.8 GHz. They are etched on the ground plane of the conventional patch antenna that resonates at 3.38 GHz. The substrate and metal chosen in this design are respectively, Epoxy FR-4 (with permittivity 4.4, loss tangent of 0.025, and thickness of 1.6 mm) and copper annulled. The simulation of the antenna was done with a CST solver. The proposed miniaturized antenna has two main bands: the inferior band 2.45 GHz and the superior band 5.8 GHz. On the inferior band, the gain and bandwidth are 1.39 dB and 76.4 MHz, and on the superior band, they are 2.05 dB and 160 MHz.

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1. INTRODUCTION

Connecting small devices to radio frequency identification (RFID) applications 2.45 and 5.8 GHz requires a miniature antenna that fits the body of the device. As it is known in the antenna field design, the resonance frequency and its performances are inversely proportional to the antenna size. Hence, the antenna designer should use the convenient technique of miniaturization, such as material loading, reshaping antenna geometry (use of fractal structures, adding truncation, and slots), shorting and folding, modification of the ground plane, and the use of metamaterial [1], with the appropriate manner to conceive a miniaturized antenna without impact negatively the antenna performances.

As it was compared between the known miniaturization techniques in the review [2], the use of metamaterial is the best miniaturization technique which allows a high rate of miniaturization, but this technique has not a standard design procedure. In this context, we aim to contribute with a methodology to design a miniaturized dual band antenna for RFID application by using only the metamaterial to create the lower band 2.45 GHz and the superior band 5.8 GHz.

Before giving a review of what was done in the literature to design a miniaturized antenna by using metamaterial and the creation of multiband antennas by using other techniques, we present here a brief definition of metamaterials, their historic evolution, and their applications. Metamaterial is an artificially designed material that presents electromagnetic properties that do not exist in nature like: negative permittivity and permeability. Metamaterials are classified as epsilon negative (ENG), ‘mu’ negative (MNG), and double negative (DNG) metamaterial depending on the sign of the permittivity ‘epsilon’ and the permeability ‘mu’, if epsilon <0 and mu >0, the material is ENG metamaterial, if epsilon >0 and mu <0, it is an MNG metamaterial and if epsilon <0 and mu <0, the material is a DNG metamaterial. It was studied theoretically by Veselago [3]. The first fabrication of this material was realized by studies [4], [5], it is a DNG metamaterial, that consists of MNG and ENG metamaterials which were demonstrated by studies [6], [7]. Due to their particular properties’ metamaterials were applied in many fields of research to study their physical impact, they were used in sensors, cloaking devices, absorbers, and antenna design [8]. In this last research area, metamaterials were applied to improve gain and efficiency, enhance directivity, increase bandwidth, create multiband antennas, and miniaturize antennas [9]–[13].

In the following, some works were extracted from literature to highlight what authors did and what they found in those two subjects of antenna design: antenna miniaturization using metamaterial and dual bands antenna conception [14]–[21]. For the antenna miniaturization topic in [14], the author designed two double negative permittivity’s and permeability (DNG) metamaterial unit cells beside a half-loop antenna, and therefore he shifted back the initial resonance frequency from 1.05 to 0.866 GHz. In study [15], the author designed a miniaturized rectangular patch antenna, he etched on the ground plane of a conventional patch antenna, two complementary split ring resonator (CSRR) unit cells symmetrical to the microstrip feed line, this way of design led him to achieve 45.7% as rate of reduction. In study [16], the author designed a printed dipole antenna that operates initially at 2.8 GHz but after inserting 8 negative permeability (MNG) split-ring resonator (SRR) unit cells in the vicinity of the dipole antenna, the author shifted back the resonance frequency to 2.45 GHz and achieved a size reduction of about 13%. For multi-band antenna design: In study [17], the author proposed four bands antenna, he started with the design of 2.5 GHz patch antenna, after that he modified the radiating element (the patch); by this modification of the patch, he obtained two other frequencies 4.5 and 5.8 GHz and finally he etched two ENG metamaterial (CSRR) unit cells on the ground plane of the antenna, therefore, he crated the fourth band 3.5 GHz which is the resonance frequency of the ENG unit cell. In study [18], the author etched a t-shaped slot in the radiating element of the conventional patch antenna to obtain the resonance frequency of 5.8 GHz, then he etched on the ground plane of the antenna two ENG metamaterial unit cells and so he obtained the second resonance frequency of 2.45 GHz.

In our proposed design methodology, we have used only metamaterial to respond to both the subject’s antenna miniaturization and frequency band creation. We have started with the design of a 3.4 GHz conventional patch antenna, and then we have etched on its ground plane two metamaterial unit cells: an MNG unit cell at 2.45 GHz and an ENG unit cell at 5.8 GHz. The following sections of this paper present in detail the steps that flowed in the design of our proposed antenna and the interpretation of the found results.

2. ANTENNA DESIGN METHODOLOGY

In this section, we present the steps of our design: first, we have designed a conventional patch antenna that has a resonance frequency bigger than the target lower resonance frequency of our proposed antenna which is 2.45 GHz, for example: 3.38 GHz. Second, we have designed two metamaterial unit cells that resonate at 2.45 and 5.8 GHz. Third, we inserted in the ground plane of the 3.38 GHz conventional patch antenna the two-unit cells at a particular position, to make them excited and resonate at 2.45 and 5.8 GHz. By this manner of design, we have designed a new antenna that resonates at 2.45 and 5.8 GHz with the size of 3.38 GHz conventional patch antenna.

2.1. Step 1: design of the conventional patch antenna

2.1.1. Calculating the length and width of the patch

Based on the (1)-(6) of the transmission line model (TLM), explained in [19], we have calculated the length (L) and width (W) of the conventional patch antenna as shown in Figure 1. Equation (1) led us to calculate the W of the patch. If we assume that the resonance frequency is fr=3.38 GHz, εr=4.4 (‘εr’ is the relative permittivity of the substrate), h=1.6 mm (‘h’ is the thickness of the substrate), c=3×108 m/s (‘c’ is the speed of light), the W of the patch is W=WP=26.99 mm. By substituting ‘fr’, ‘εr’, ’c’, and ‘W’ by their values in (2)-(6) the L of the patch is L=LP=20.71 mm.

$$f_r = \frac{c}{2W\sqrt{\frac{\varepsilon r+1}{2}}} \tag{1}$$

$$\varepsilon reff = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2} \times \left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

$$Leff = \frac{\lambda}{2\sqrt{\varepsilon reff}} \quad (3)$$

$$\lambda = \frac{c}{fr} \quad (4)$$

$$\frac{\Delta L}{h} = 0.412 \times \frac{(\varepsilon reff+0.3)\times(\frac{W}{h}+0.264)}{(\varepsilon reff-0.258)\times(\frac{W}{h}+0.8)} \quad (5)$$

$$Leff = L + 2 \times \Delta L \quad (6)$$

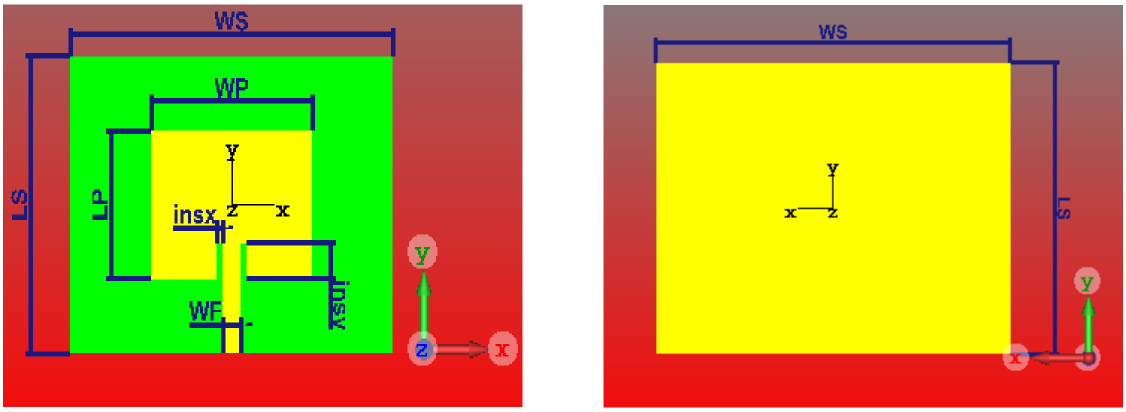
2.1.2. Calculating the width of the feed line

To feed our antenna we have chosen a microstrip feed line with an inset among different feeding techniques such as microstrip line with and without inset, coaxial probe, proximity coupling, and coplanar waveguide (CPW), these feeding modes are explained and compared in [20]. Microstrip feed line with inset is simple to design and permits to obtain high gain. To calculate 'W' of the microstrip line which corresponds to the characteristic impedance 'Z_0'of 50 Ω, we have used (7) extracted from [21].

For Z0=50 Ω, h=1.6 mm ('h' is the thickness of the substrate) and εr=4.4 ('εr' is the relative permittivity of the substrate), the width of the feed line 'WF' is W=WF=3.083 mm.

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r}\left(\frac{W}{h}+1.393+0.667\,ln\left(\frac{W}{h}+1.44\right)\right)} \quad (7)$$

Now with the CST solver, we design and simulate the 3.38 GHz conventional patch antenna as shown in Figure 1, Figure 1(a) shows the top view, and Figure 1(b) shows the back view. The Epoxy FR-4 with εr=4.4, thang loss equal to 0.025, and a thickness of 1.6 mm was chosen as a substrate of the antenna, and copper annulled was chosen as a metal of the conducting elements of the antenna. The other parameters of the antenna are WP=26.99 mm, LP=20.71 mm, WS=2*WP, LS=2*LP, WF=3.083 mm, isny=5 mm, and insx=1 mm.



(a) (b)

Figure 1. Conventional microstrip patch antenna for (a) top view and (b) back view

Figure 2 illustrates the simulated reflection coefficient, S11, of the conventional patch antenna, the blue curve presents the S11 of the conventional patch antenna whose width and length were approximated by TLM. As we can see (the blue curve), the resonance frequency of the antenna is 3.33 GHz, which is different from 3.38 GHz, the one assumed in TLM to calculate the dimensions of the conventional patch. CST simulator is based on the full-wave method, the finite integration technique (FIT), which is more accurate than the TLM method [22]. Hence, we optimized with CST the width 'WP' and length 'LP' of the patch until we obtained the resonance frequency 3.38 GHz (red curve). The new dimensions of the conventional patch which correspond to 3.38 GHz are WP=26.082 and LP=20.431.

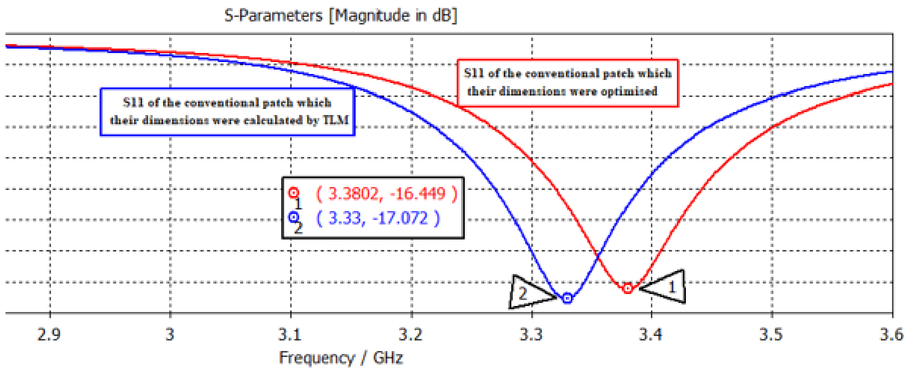


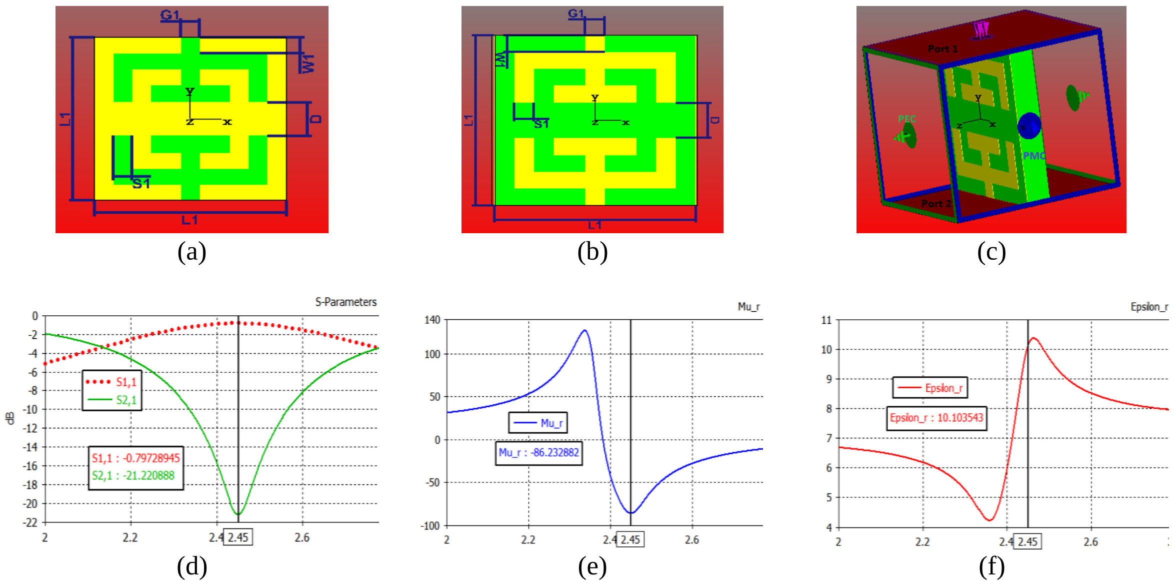
Figure 2. S11 of the conventional antenna with TLM (blue curve) and with full wave method (red curve)

2.2. Step 2: design and study of the metamaterial unit cells

2.2.1. The 2.45 GHz unit cell

The 2.45 GHz unit cell is shown in Figure 3. The unit cell used in this work consists of two concentric copper annulled square rings, with two splits in the sides, parallel to the ‘X’ axis of each ring and rectangle copper annulled wire parallel to the four splits, all structures of the unit cell are printed on Epoxy FR-4 with permittivity=4.4 and h=1.6 mm as shown in Figure 3(a). Its complementary, Figure 3(b) shows the obtained by substituting the void in the front part of the structure with copper annulled and the copper with the void. At the same resonance frequency, the complementary unit cell is the negative image of the unit cell (Babinet and duality principles) [23].

To verify the sign of the permeability and permittivity at 2.45 GHz, the desired resonance frequency of the metamaterial structure, this last was placed between two waveguide ports (1,2) located at the negative and positive part of the Y axis. In the Z and X axes, perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundaries are applied respectively as shown in Figure 3(c). The simulation was done by the CST Microwave Studio electromagnetic simulator. Figure 3(d) illustrates the reflection coefficient (S11) and transmission coefficient (S21) of the metamaterial structure, Figure 3(d) shows that this metamaterial unit cell resonates at 2.45 GHz when the values of its parameters are L1=8 mm, W1=0.5mm, S1=0.5mm, G1=1mm, and the D=4 mm. Those S-parameters (S11) and (S21) are used to extract the effective permittivity (Figure 3(e)) and permeability (Figure 3(f)) of the unit cell. As shown in Figures 3(e) and (f), this unit cell has a positive permittivity at 2.45 GHz and a permeability negative at 2.45 GHz. So, it is an MNG at 2.45 GHz.



(a) (b) (c)

(d) (e) (f)

Figure 3. Design of the 2.45 GHz unit cell of (a) the metamaterial unit cell, (b) its complementary, (c) boundary condition, (d) S-parameters, (e) the permittivity, and (f) the permeability

2.2.2. The 5.8 GHz unit cell

The 5.8 GHz unit cell is shown in Figure 4. The second unit cell used in this work consists of two squares SRR as shown in Figure 4(a). Figure 4(b) is its complementary (CSRR). Figure 4(c) shows the boundary condition. By following the same steps as section 2.2.1., we conclude that this unit cell resonates at 5.8 GHz as shown in Figure 4(d) when G2=W2=S2=0.4 mm and L2=0.4.25 mm. As shown in the permittivity (Figure 4(e)) and the permeability (Figure 4(f)), this unit cell is an epsilon ENG, its permittivity is negative at 5.8 GHz and its permeability is positive at 5.8 GHz.

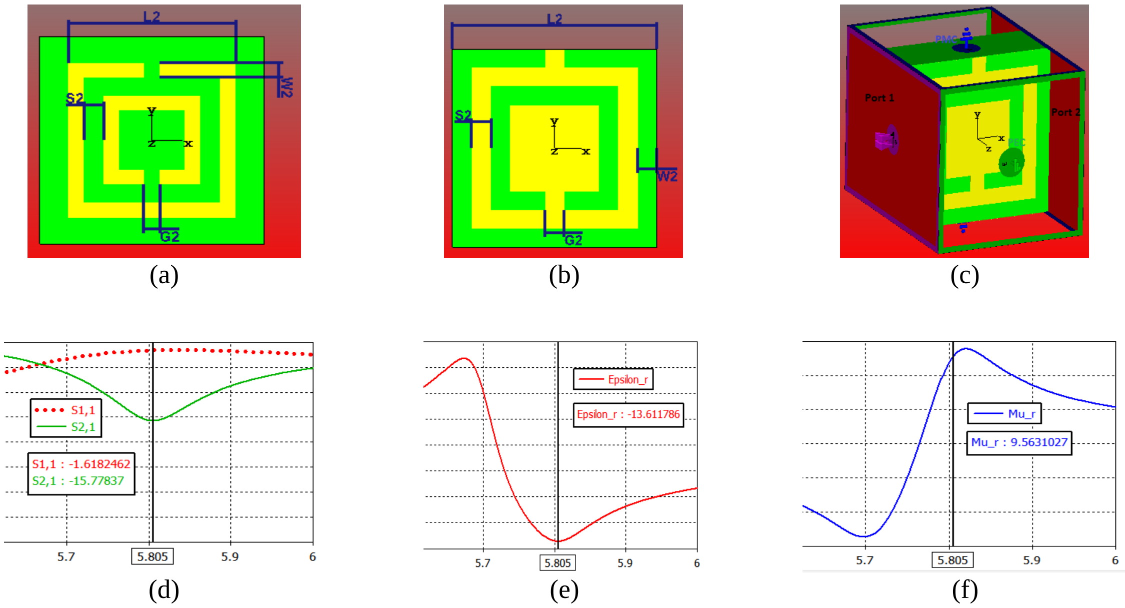


Figure 4. The 5.8 GHz unit cell of (a) the metamaterial unit cell, (b) its complementary, (c) boundary condition, (d) S-parameters, (e) the permittivity, and (f) the permeability

2.3. Step 3: design of the metamaterial dual band antenna

As shown in Figure 5, in the ground plane of the conventional patch antenna previously studied which resonates at 3.38 GHz, we etch the two metamaterial unit cells already studied in section 2.2., the center P1 of the MNG unit cell 2.45 GHz was placed at a distance X1 from the center of the ground plane of the patch while the center P2 of the ENG unit cell 5.8 GHz was placed at a distance X2. Figure 5(a) shows the back view of the MTM patch antenna and Figure 5(b) shows the dimensions of the MTM unit cells.

In order to define the right values of X1 and X2 for which the two unit cells were excited and made the new MTM antenna resonate at 2.45 and 5.8 GHz, a parametric study about X1 and X2 was done until we found the desired frequencies as shown in Figure 6. From Figure 6, we noticed that at X1=9.5 mm and X2=0.75 mm, the new MTM antenna resonates at the two researched frequencies 2.45 and 5.8GHz.

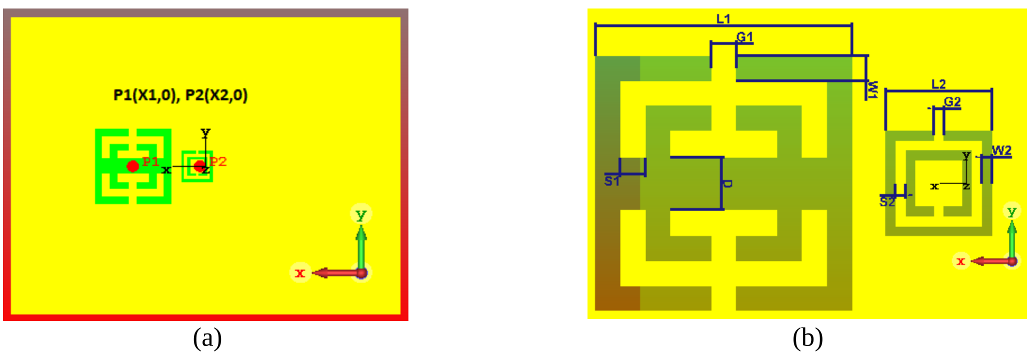


Figure 5. The ground plane of the conventional patch antenna of (a) the back view of the MTM patch antenna and (b) the dimensions of the MTM unit cells

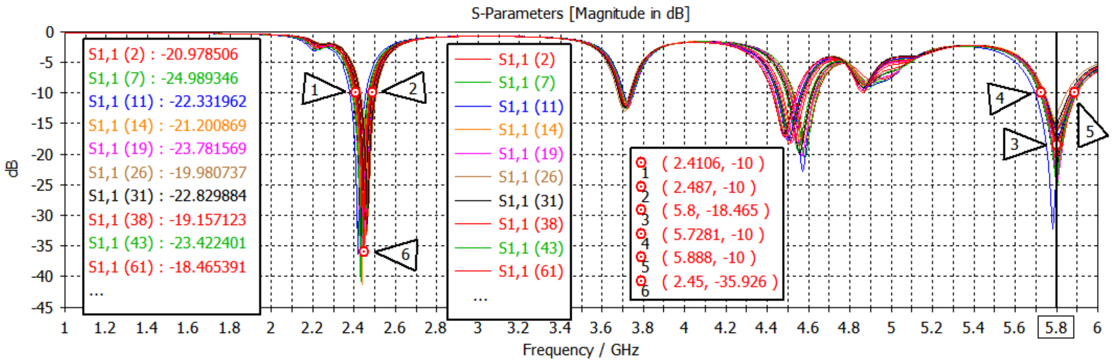


Figure 6. Reflection coefficients parametric study about X1 and X2 of the newly designed antenna

Figure 7 gives the general steps to follow to design a miniaturized or dual bands inspired metamaterial antenna. First, we design a conventional patch antenna that resonates at a frequency superior to the lower target frequency. Second, we design the metamaterial unit cells that resonate at the desired frequencies and have negative permittivity and/or permeability. Third, we each studied metamaterial unit cells on the ground plane of the conventional patch and did a parametric study about their position in the ground plane until the newly inspired metamaterial antenna resonated at the resonance frequencies of the metamaterial unit cells.

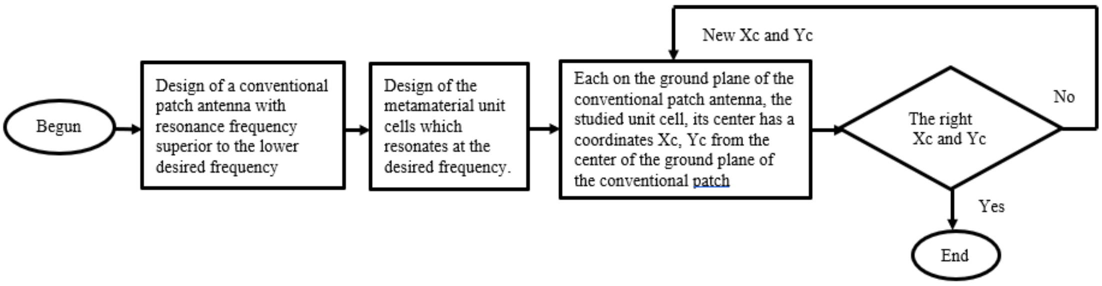


Figure 7. The general diagram design antenna with metamaterial

3. SIMULATION RESULTS AND DISCUSSION

Figure 8 shows a comparison between the reflection coefficient curves, S11, of the 3.38 GHz conventional patch antenna with and without the two metamaterial unit cells. From Figure 8, we notice that after etching the two metamaterial unit cells on the ground plane of the conventional patch antenna, two main resonance frequencies appeared, the inferior resonance frequency of 2.45 GHz and the superior resonance frequency of 5.8 GHz both are the resonance frequencies of the unit cells previously studied. This result leads us to deduce that we have designed a miniaturized dual-band antenna that resonates at 2.45 and 5.8 GHz with the real size of a conventional patch antenna which initially operates at 3.38 GHz. Because of the inverse proportionality between the resonance frequency and the size of the antenna, it is obvious that the size of a 3.38 GHz conventional patch is inferior to the size of a 2.45 GHz conventional patch antenna. So, if you brought a conventional patch, which initially resonates at 3.38 GHz, and resonates at 2.45 GHz, that means you've done a miniaturization.

To define the rate of reduction achieved by this way of design, we use again TLM to calculate the dimensions of the 2.45 GHz conventional patch antenna (we follow the same steps in section 2.1). Table 1 presents the dimensions of both 2.45 GHz antennas; The standard patch approximated by TLM and the proposed antenna. From Table 1, our proposed antenna is 50% smaller than the 2.45 GHz conventional patch antenna.

Table 1. The dimensions of the 2.45 GHz conventional patch antenna and the proposed antenna

Antenna	Volume (LS×WS×h) in mm^3
Conventional patch at 2.45 GHz (approximated by TLM)	57.62×74.46×1.6
The proposed antenna at 2.45 GHz	40.862×52.164×1.6

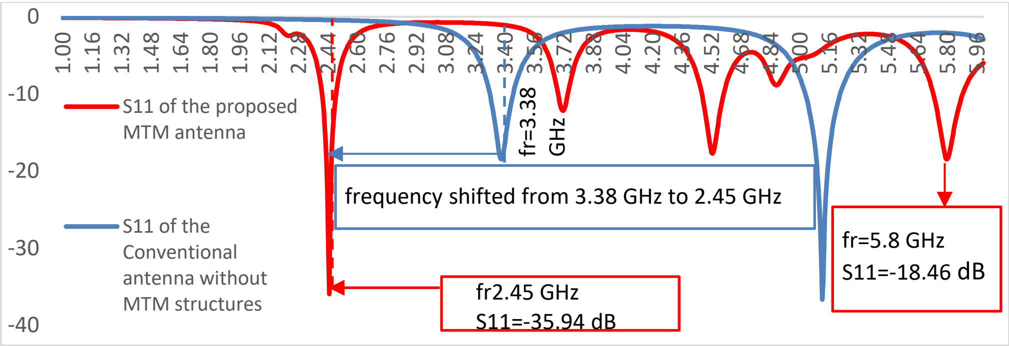


Figure 8. The reflection coefficient (S11) of the MTM antenna and the conventional antenna

Figure 9 illustrates the reflection coefficient curve of the proposed antenna. In the inferior band, the bandwidth is 76.4 MHz, it is from 2.4106 to 2.487 GHz and the S11 is -35.946 dB at 2.45 GHz. In the superior band, the bandwidth is 160 MHz, it is from 5.728 to 5.888 GHz and the reflection coefficient for its central resonance frequency of 5.8 GHz is -18.465 dB. Thus, this proposed antenna will be potentially used for RFID.

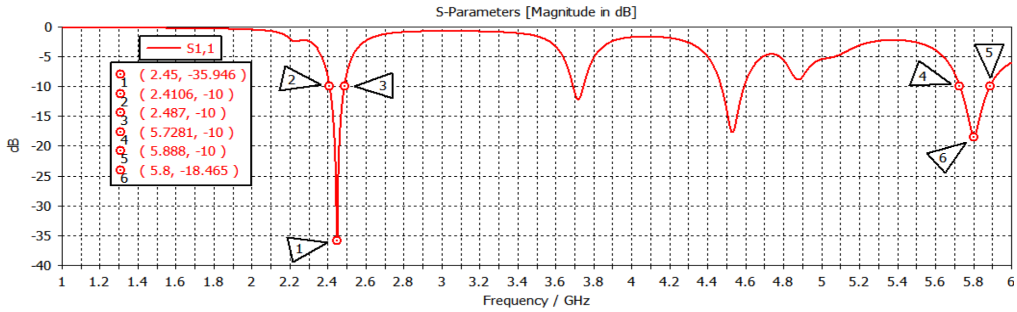


Figure 9. Reflection coefficient of the designed MTM antenna

Figure 10 represents the gain evolution over frequency. For the inferior band, the gain varies from 0.96 to 1.33 dB, it is at a maximum of 1.39 dB at its central resonance frequency of 2.45 GHz. For the superior band, the gain varies from 1.21 to 2.14 dB and it is at 2.1 dB at its central resonance frequency of 5.8 GHz.

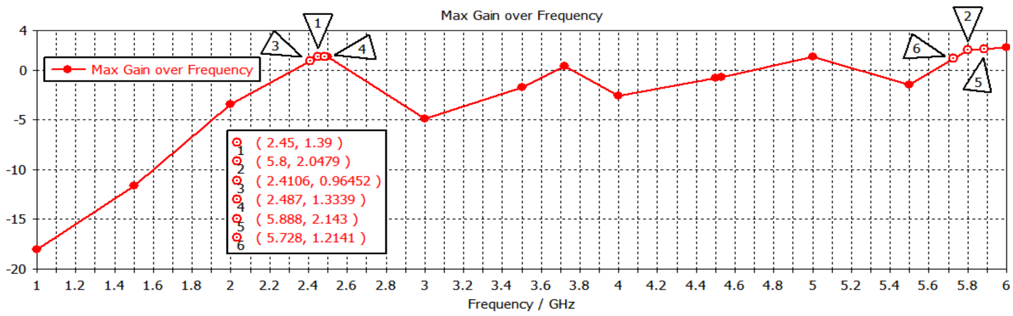


Figure 10. Gain evolution over frequency

Table 2 presents a comparison between our work and others reported in literature which operate at the same bands 2.45 and 5.8 GHz. All the compared works used the low-cost substrate Epoxy FR-4 with a thickness of 1.6 mm except the work [24] whose substrate is RT duroid 5880 with a thickness of 1.5875 mm. As shown in Table 2, our work presents the best-reduced size antenna, The nearest antenna size proposed in the work [24], is 13.39% bigger than our work even if it used an expensive substrate than Epoxy FR-4. In the bands 2.45 and 5.8 GHz our antenna has bandwidths of 76.4 and 160 MHz, reflection coefficients of -35.95 and -18.47dB, which means that the antenna has a good impedance matching in both central frequencies, a gain of 1.39 and 2.1 dB which are 3.54 and 4.25 dBi. All those feature made from our antenna a good candidate for RFID small devices.

Table 2. Comparison of our proposed antenna with other published work

Reference	Antenna Size (mm^3)	Reduction/Ref (%)	Substrate	Freq (GHz)	BW(MHz)	Gain (dBi)	S11(dB)
This work	3410.4	NA	FR4	2.45 and 5.8	76.4 and 160	3.54 and 4.25	-35.95 and -18.47
[25]	3937.5	13.39	RT/duroid-5880	2.45 and 5.8	36 and 341	6.93 and 5.07	-31 and -23.7
[26]	4320	21	FR4	2.45 and 5.8	120 and 160	3.09 and 0.64	≤ -23 and ≤ -28
[24]	4500	24.21	-	2.45/5.2	100 and 370	2.8 and 5	≤ -20 and ≤ -42
[27]	11520	70.4	FR4	2.45 and 5.8	85 and 285	5.39 and 7.34	≤ -25 and ≤ -15

4. CONCLUSION

In this paper, we have presented a design procedure to follow to conceive dual-band miniaturized antenna by using the metamaterial technique which is not a standard one. So, we believe that this design methodology will be adopted by researchers in the domain of antenna miniaturization and offer the readers a base start to understand the benefits of metamaterial in antenna design. By applying this methodology in this work, we have designed a reduced antenna that operates at two main bands; the lower band 2.45 GHz and the superior band 5.8 GHz, we have demonstrated that those two frequencies were created by an ENG and MNG metamaterial unit cells after etching them on the ground plane of a conventional patch antenna. The achieved reduction rate is 50% in comparison with the 2.45 GHz conventional patch antenna. The proposed antenna has a bandwidth of 76.4 MHz and a gain of 1.39 dB at the central resonance frequency of 2.45 GHz bandwidth of 160 MHz and a gain of 2.05 dB at the central frequency of 5.8 GHz. Those features made from this antenna a candidate for 2.45/5.8 GHz applications such as RFID.

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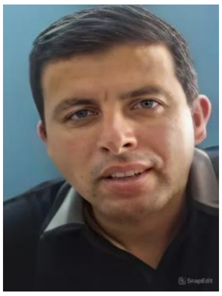

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