An Electrical Model to U-Slot Patch Antenna with Circular Polarization

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***Abstract*—The microstrip antenna is one of the best antenna structures, due to its low cost and compact design. In this paper, a coaxial feed circularly polarized square patch antenna is designed using the U-slot. The proposed antenna is suited for the RFID readers in the SHF band. This structure of antenna of FR-4 substrate (dielectric constant = 3.5), is capable to cover the range of frequency of 2.4 to 2.5GHz. The size of patch is 25*25 mm^2. An equivalent electrical model of this antenna was proposed and simulated by the ADS software. The simulated gain is 4.189 dBi and S_{11} bandwidth is about 100 MHz. Analysis and modeling of the proposed antenna was carried out using the CST and HFSS simulator based on the finite element method. The simulation results obtained are presented and discussed.**

***Keywords*—RFID; circularly polarization; U-slot antenna; RFID reader antenna; Electrical model**

I. Introduction

Previously, the circular polarization was created by feeding the antenna to different locations and with a 90 ° phase shift. At that time, the feeding was made directly (without slot) using a coaxial cable or micro-strip line. With the feeding in one place, circular polarization is induced either by making the antenna slightly rectangular (instead of square). Either by cutting two of its corners or by making a diagonal opening in its metallization. These three topologies have been studied by Sharma et al. [1].

The choice in this work stopped on the antenna with truncated corners. In addition to maintaining symmetry at the diagonal, this configuration is easier to conceive since it has a degree of freedom of less than the opening in the metallization. The latter can vary in length and width while the truncation is symmetrical. According to Sharma [1], the antenna with truncated corners provides the lowest axial ratio. But has a slightly smaller bandwidth (axial ratio) than the other topologies [2]-[4].

Many techniques have already been applied to the design of broadband antennas. For example, an insulated slot in a patch, the addition of different slot shapes at the radiating element, such as the L-shaped slot, a T-shaped slot, an H-shaped slot and the fractals slot have also been reported for large bands [5]-[9]. Among these techniques, a U-shaped slot will be used on the patch of the coaxially fed square patch antenna.

These types of antennas also have broad applications in long range and wireless identification or communication systems, such as RFID which is one of the new identification techniques and where the size of the system depends essentially on the size of the antenna [10]. In order to analyze this structure, a new electrical model is developed and compared to a physical patch.

Many calculation methods are adopted to resolve the maxwell equations and then analyse the performance of the antennas. Among these, three of them are broadly used in simulation software:

1) The method of moments (MoM) is used among others in ADS software.

2) The method of finite integral (FIT) is used in the software CST Microwave Studio [11], [12].

3) The Finite Element Method (FEM) is used in the software HFSS [11].

In this work, the method of moments will be adopted to analyze the performance of the electrical model and the results will be compared with those obtained by the Finite Integral and the Finite Element Method.

II. The Approaches to Get the Electrical Model of the Square Patch Antenna

The patch antenna can be modeled simply by a parallel or serial RLC circuit. To calculate its characteristics, the study based on the RLC circuit is the most used. In the next step, the parameters of the RLC circuit in the equivalent electrical model of the patch antenna will be calculated. The parameters of the proposed model are determined using the same solution of Nasimuddin and A. K. Verma [17].

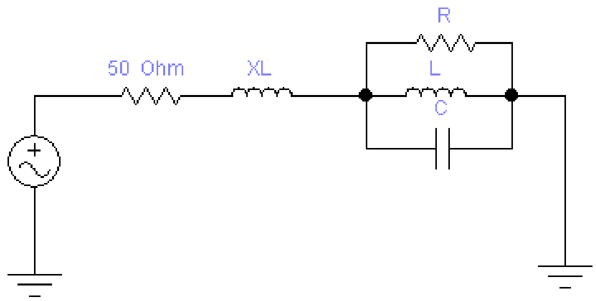


Fig. 1. Electrical model of square patch

The input impedance of a square patch excited by a coaxial cable is given in [18] by equation (1):

$$Z_{in} = R + jX$$

$$Z_{in} = \frac{R}{1+Q_T^2\left(\frac{f}{f_r}-\frac{f_r}{f}\right)^2} + j\left(X_L - \frac{RQ_T\left(\frac{f}{f_r}-\frac{f_r}{f}\right)}{1+Q_T^2\left(\frac{f}{f_r}-\frac{f_r}{f}\right)^2}\right) \quad (1)$$

The resonant resistance R of our parallel circuit RLC is given in [18] by equation (2):

$$R = \frac{Q_T h}{\pi f_r \varepsilon_{dyn} \varepsilon_0 A}\cos^2\left(\frac{\pi X_0}{a}\right) \quad (2)$$

f_r: resonant frequency.

X_0: the distance of the feed point from the edge of the patch.

h: thickness of dielectric.

A : air of the square patch

a : length of the edge

The total Quality factor Q_T is calculating in [18] by equation (3):

$$Q_T = \frac{1}{\frac{1}{Q_R}+\frac{1}{Q_C}+\frac{1}{Q_D}} \quad (3)$$

Q_R is the radiation quality factor, Q_D is the losses in the dielectric and Q_C is losses in conductor.

$$Q_R = \frac{C_0\sqrt{\varepsilon_{dyn}}}{4 f_r h} \quad (4)$$

$$Q_C = \frac{0.786\sqrt{f_r Z_a} a h}{P_a} \quad (5)$$

$$Q_D = \frac{1}{T_g \delta} \quad (6)$$

The impedance of a microstrip line filled with air "Za" is given by equation (7):

$$Z_a(a) = \frac{60\pi}{\sqrt{\varepsilon_r}}\left(\frac{a}{2h} + 0.441 + 0.082\left(\frac{\varepsilon_r - 1}{\varepsilon_r^2}\right) + \frac{\varepsilon_r+1}{2\pi\varepsilon_r}\left(1.451 + L_n\left(\frac{a}{2h}+0.94\right)\right)\right) \quad (7)$$

$$Z_{a0}(a) = Z_a(a, \varepsilon_r = 1)$$

$$P_a = \frac{2\pi\left(\frac{a}{h} + \frac{\frac{a}{\pi h}}{\frac{a}{2h}+0.94}\right)\left(1+\frac{a}{h}\right)}{\left(\frac{a}{h}+\frac{2}{\pi}L_n\left(2\pi\exp\left(\frac{a}{2h}+0.94\right)\right)\right)^2};\ \frac{a}{h}\geq 2 \quad (8)$$

The dynamic permittivity ε_{dyn} is calculated by (9):

$$\varepsilon_{dyn} = \frac{C_{dyn}(\varepsilon)}{C_{dyn}(\varepsilon_0)} \quad (9)$$

$$C_{dyn}(\varepsilon) = \frac{\varepsilon_0\varepsilon_r A}{h y_n y_m} + \frac{1}{2y_n}\left(\frac{\varepsilon_{reff}(a,h,\varepsilon_r)}{C_0 Z(a,h,\varepsilon_r=1)} - \frac{\varepsilon_0\varepsilon_r A}{h}\right)$$

$$y_j = \begin{cases}1, & j=0\\ 2, & j\neq 0\end{cases} \quad (10)$$

$$Z(a,h,\varepsilon_r=1) = \frac{377}{2\pi}L_n\left(\frac{f\frac{a}{h}}{\frac{a}{h}} + \sqrt{1+\left(\frac{a}{2}\right)^2}\right) \quad (11)$$

$$f\left(\frac{a}{h}\right) = 6 + (2\pi - 6)\exp\left(-\left(\frac{30.666}{\frac{a}{h}}\right)^{0.758}\right) \quad (12)$$

The formula of C_{dyn} is used to determine the capacity C and to determine the inductance L we use the following equations:

$$w_{res} = 2\pi f_r \quad (13)$$

$$w_{res} = \frac{1}{\sqrt{LC}} \Rightarrow L = \frac{1}{w_{res}^2 C} \quad (14)$$

Equation (15) allows us to calculate the inductive reactance of coax, taking d0 the diameter of the probe:

$$X_L = \frac{377 f h}{C_0}L_n\left(\frac{C_0}{\pi f d_0\sqrt{\varepsilon_0}}\right) \quad (15)$$

III. Antenna Structure and Design

The geometry of the proposed antenna is shown in figure 1. The square patch antenna was truncated to create a circular polarization (CP). The proposed antenna is printed on a FR-4 substrate of relative permittivity ε_r = 3.5 and thickness h= 3.2 mm and fed by a coaxial cable. Many studies have practiced this mode of feeding [13]-[15]. The substrate is stacked with two layers of FR-4 to allow for greater bandwidth, higher gain and efficiency radiation. In order to increase the impedance and the bandwidth of S11, the truncated square patch antenna has been loaded by a U-slot which introduces a capacitance making it possible to eliminate the inductance due to the vertical feed probe.

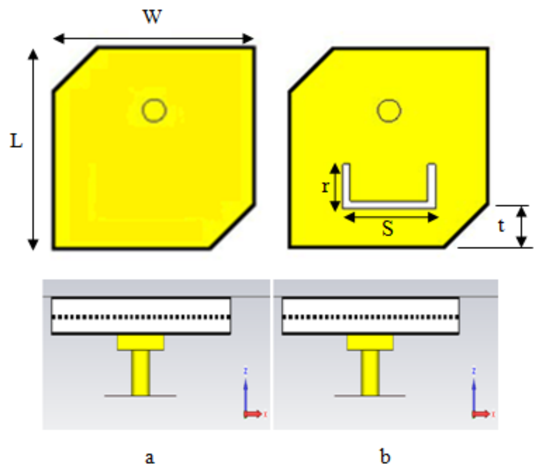


Fig. 2. Design for U-slot Patch Antenna (a): without the slot, (b): with the slot

TABLE. I. Optimized Parameters of the Proposed RFID U-Slot Patch Antenna

Parameters	t	r	s	W	L	ε_r	h
Value(mm)	5	6	12	25	25	3.5	3.2

The truncations made on the square antenna make this element the most difficult to conceive. When taken individually, it can be modeled by a disturbed cavity. The latter will induce a resonant mode perpendicular to that existing without the truncations. To obtain a circular polarization, these modes must have the same amplitude and be out of phase by 90°. The study of a truncated cavity was carried out by Haneishi et al., [16] who set up an equivalent circuit In the case of an antenna fed by a coaxial cable, the resonance frequency of the orthogonal modes (f_{rl} and f_{r2}) is calculated as a function of the surface of the non-truncated antenna (T) and the total truncated surface (Δt) The relation between all these parameters is given by [16]

$$\left|\frac{\Delta_t}{T}\right| Q_0 = \left|\frac{\Delta_t}{T}\right| \frac{f_0}{\Delta_f} = \left|\frac{\Delta_t}{T}\right| \frac{f_0}{f_{r1} - f_{r2}} = \frac{1}{2} \tag{16}$$

Q_o is the quality factor of the cavity and f_0 is the resonance frequency of the undisturbed antenna.

IV. Results and Discussion

Characteristics of the proposed patch antenna were simulated in this section using the CST software. The simulated curves of return loss as a function of the frequency by varying the section "t" of the proposed antenna are shown in figure3. It is noted that the proposed antenna with t = 5 mm gives the best return loss to the antenna desired frequency. Therefore, we fixed t = 5mm and cut a U-shaped slot in the radiating element of the proposed antenna to observe the variations of the return loss. The simulated results are presented in figure4. From this figure it is easy to notice that the desired frequency at 2.45GHz of the proposed antenna is obtained by the slotted structure.

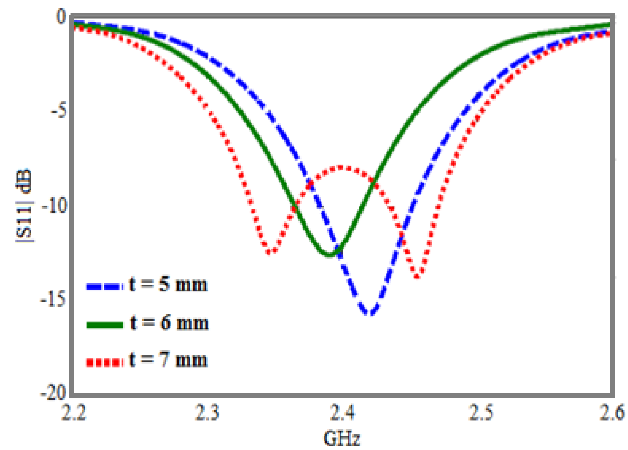


Fig. 3. Simulated return loss of square patch antenna with varieties value of (t)

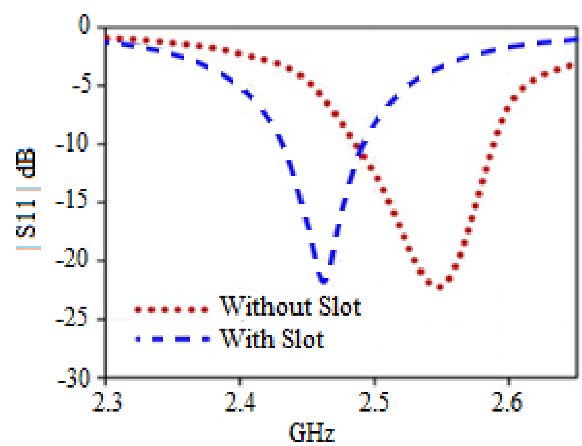


Fig. 4. Simulated return loss for the proposed antenna with and without the slot (with CST)

Figure 5 shows the response of the reflection coefficient of the proposed antenna obtained from the simulation CST and HFSS with respect to the calculated response of the equivalent circuit model.

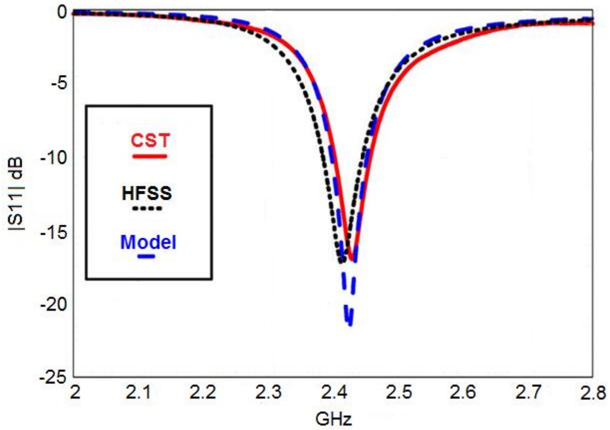


Fig. 5. Simulated return loss for the proposed antenna

Figure 5 shows the reflection coefficient S11 of the proposed antenna obtained from CST and HFSS relative to that obtained from the equivalent circuit using ADS. In Table II the detailed characteristics of these responses are listed. It can be noted from Table II that the requirement of the SHF band 2.45 GHz is satisfied. The results simulated by CST and HFSS agree with that obtained from ADS with some slight differences. This difference is due to the fact that the structure simulator in the CST and HFSS software accounts for all the coupling effects in the simulated antenna physical structure whereas in the equivalent circuit model only the individual elements are taken into account without taking into account the coupling between them.

TABLE. II. COMPARISON OF THE BAND CHARACTERISTICS OBTAINED FROM THE THREE MODELING METHODS

	S11 (dB)	Start freq (GHz)	End freq (GHz)	Center freq (GHz)	BW (GHz)
CST	-18	2.40	2.47	2.45	0.07
HFSS	-18	2.38	2.44	2.41	0.06
ADS	-22	2.39	2.46	2.43	0.07

Figure 6 shows the axial ratio as a function of the frequency. We chose the criterion RA < 3 dB to measure the bandwidth. Note that the bandwidth is also very low. In effect, its value is only 0.30%. This low value comes from the use of truncated corners. Sharma [1] showed that this type of antenna could not provide a large bandwidth at the axial ratio.

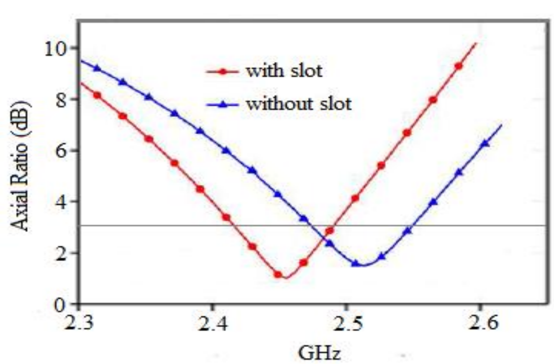


Fig. 6. Simulated axial ratio for the proposed antenna

Figure 7 shows the 3D radiation pattern of the proposed antenna for the resonant frequency 2.45GHz. We note that for this frequency, we have a directional diagram, the efficiency of the radiation which equals 96.7% and the total efficiency is 93.3%. The gain obtained is 4.29 dB. The HPBW value is 92.0 Deg.

The linear and nonlinear gain of theta / phi 0^{o} in polar form are represented respectively by figure 8.

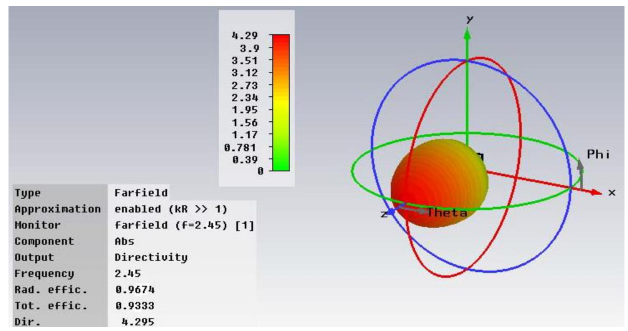


Fig. 7. 3D Farfield for U-slot antenna

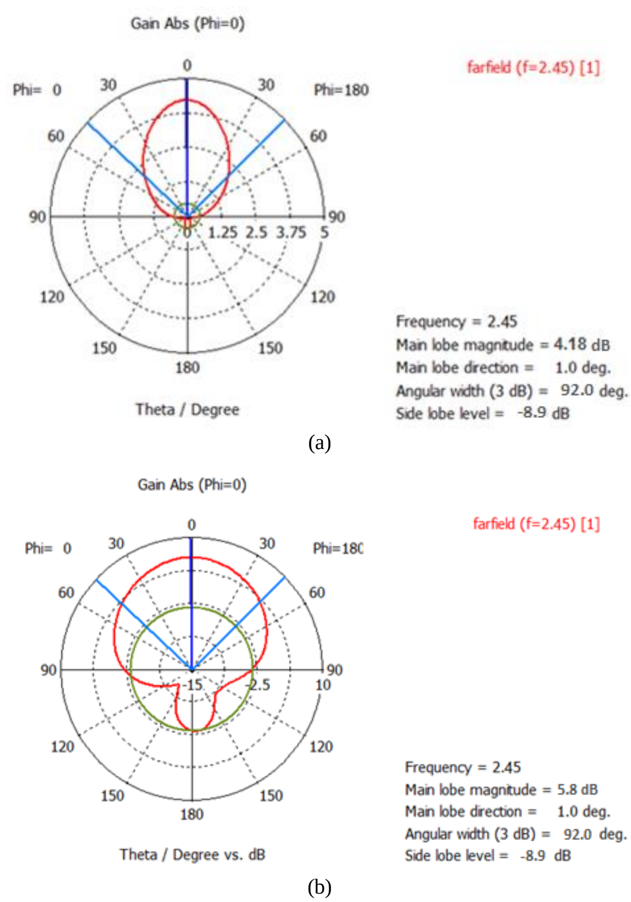
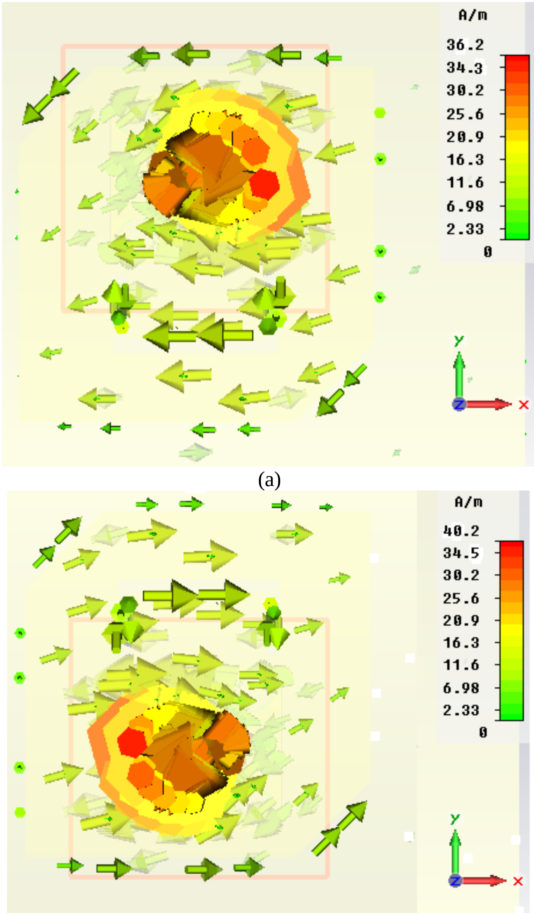


Fig. 8. The polar pattern: (a) Linear and (b) Non-linear

Figure 9 shows the propagation of current from the coaxial feed in the patch. Indeed, by truncating the patch antenna, it generates a circular polarization (CP). Note that when the upper right part and the lower left part of the resulting truncated refers to the right circular polarization, RHCP. The antenna can work with truncated LHCP at another diagonal axis.



(a)

(b)

Fig. 9. Surface current at U-slot Patch Antenna, (a): LHCP and (b): RHCP

V. Conclusions

Evaluation and study of antennas is based on their properties and characteristics. The latter vary from one application to another. According to the requirements defined by the application, the antenna design method can be chosen. Thus, each method has its advantages in well-defined cases. For our application, we chose the method of electrical modeling for the analysis of square patch antenna structures referred to RFID readers.

The proposed antenna is circularly polarized using the truncation method. Indeed, the LHCP and RHCP polarization depend on the corners of the diagonal axis which are truncated. This truncated square patch antenna with U-shaped slot has been designed to achieve high bandwidth, high radiation efficiency and resonant frequency equal to 2.35 GHz.

The modeling method that we have applied in this work has several advantages. In fact, it allows to simulate structures in a simple, fast and efficient way. In addition, once the model is built, we can track changes in antenna parameters based on changes in antenna geometry, position and nature of excitation. So we can integrate these antenna structures easily into RFID systems.

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