Novel Design of A Compact Proximity Coupled Fed Antenna

Mehdi ALI[1] , Abdennacer KACHOURI[2] and Mounir SAMET[3]

**[1]University of Sfax, National School of Engineers of Sfax,
Laboratory LETI, Route Soukra Km 3.5 B.P W 1173, TUNISIA**

**[2]University of Gabes, ISSIG Higher Institute Of Industrial Systems Gabes
Gabes CP 6011 TUNISIA**

**[3]University of Sfax, National School of Engineers of Sfax,
Laboratory LETI, Route Soukra Km 3.5 B.P W 1173, TUNISIA**

Abstract

Certain applications such as RFID, on body sensors network, microwave systems usually require good matching impedance, high gain and large bandwidth for their antennas. The aperture coupled antenna is one candidate that can provide high gain large bandwidth and little packaging. Thus, it would be of interest to enhance the characteristics of a singly-fed aperture antenna used for Zigbee application.

In this paper, we are presenting a new design of aperture coupled rectangular patch antenna operating at 2.45 GHz ISM-band frequency. The objective of this design is not limited to the improvement of the impedance bandwidth but also to better the coupling involved. The cross-polarisation (X-pol), the backward radiation and the half-power beam width in two orthogonal planes are also examined.

The proposed design is based on a new aperture coupling technique in which two slots are fed by a microstrip line and coupled to a parasitic patch radiator etched on the opposite side from the slots. The matching impedance for a conventional aperture coupled microstrip antenna is obtained by the adjustment of the dimension of the slot and the feeding line. Here, the distance separating the slots is employed to control the coupling and modifying the input impedance of the antenna. Therefore, accurate matching impedance is reached with a good radiation pattern.

Keywords: *aperture coupled antenna, impedance matching, microstrip, coupling, multilayer, input impedance.*

1. Introduction

Conventional microstrip aperture antennas have at least two layers; on the higher layer is printed a conducting patch while the second is a grounded microwave substrate on which is etched the feeding line. In the other side, a slot opening is operated through which electromagnetic waves are transmitted or received.

The impedance bandwidth is a function of resonant frequency or patch size. On the other hand, the gain of microstrip patch antennas has been shown to be a strong function of the substrate permittivity and thickness. Therefore, the enhancement of gain and bandwidths for a patch antenna are always challenging tasks and especially for aperture antenna that depend on the coupling generated by the aperture in the middle placed ground plane between the patch and the feeding line[1].

Much research effort has been made to investigate modified methods for decreasing the whole area and maintaining the initial performance. Previous methods have focused on increasing the electrical field on the open end for the uniform field on the aperture [2]. Hence, the associated studies with the H-shaped slot coupled antenna, dumbbell shaped slot coupled antenna, and bow-tie shaped slot coupled antenna [3] are adopted to improve the amount of electromagnetic coupling. The impedance matching is done by acting on the aperture dimensions and the stub length that also make a shifting in the resonant frequency [4], the electrical dimension of the patch should be corrected and a difficult conciliation is hard to achieve.

This paper describes a new aperture coupled antenna with two separate slots in order to reduce the area of antenna and achieve better performance. It also exhibits excellent efficiency and soft means to attain excellent impedance matching. A comparative study is done between a basic design and the new proposed configuration.

A three-layer antenna of an ordinary FR4 substrate is designed. The matching impedance is obtained by adjusting the gap between the two apertures and a reflexion coefficient S11 about 50dB is easily achieved for a reduction of about 10% of the total surface, an enhancement of the bandwidth of 20% and the gain rises by about 3.4%.

2. Aperture coupled antenna structure

Fig.1 shows a basic antenna structure with a rectangular patch which is excited through one slot on the ground plane. Typically the lower layer is a two metallised FR4, the feeding line should be exactly etched below the aperture a shifting in the line position compared to the aperture leads to a shifting in the resonant frequency and influences the coupling[5]. We assume the following structure to avoid fabricating and assembling constraints since it is difficult to print the feeding line exactly beneath the aperture centre. The antenna will be composed of three layers made of the same material with the same thickness; a one side metallised 1,6 mm thick FR4 substrate will be used. The lower layer has on the 50Ω feeding line, the middle layer is a grounded plane with the slot aperture and finally the higher layer on which is printed the radiating patch. The aperture, the feeding line and the patch centering is obtained by operating centring holes in the three layers. The structure is assembled using epoxy glue; a compact and resistant antenna is obtained.

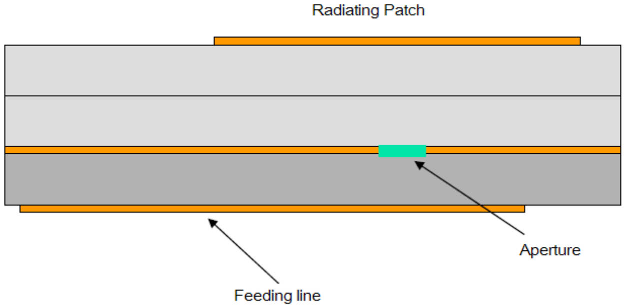


Fig.1 conventional aperture-coupled antenna

2.1 Conventional antenna testing.

An aperture coupled antenna could be replaced by the equivalent circuit shown in Fig.2. The resonant patch dimensions are determined using microstrip antenna theory equations. The slot introduces a capacitance Cs determined by considering the patch dimension, layers thickness, aperture dimension and feeding line length and width.

The aperture coupling consists of two substrates separated by a ground plane. On the bottom side of the lower substrate, there is a microstrip feed line which energy is coupled to the patch through a slot on the ground plane separating the two substrates. This arrangement allows independent optimization of the feed mechanism and the radiating element. Typically matching impedance is performed by controlling the length of the feed line and the length of the slot. The coupling through the slot can be modeled using the theory of Bethe [6],

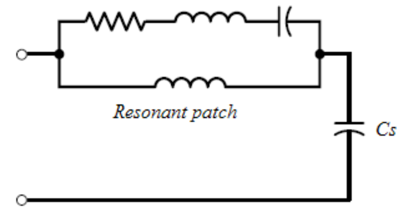


Fig. 2 The simplest equivalent circuit of an aperture coupled antenna

The 3D structure of a conventional aperture coupled antenna tested is showed on Fig.3.

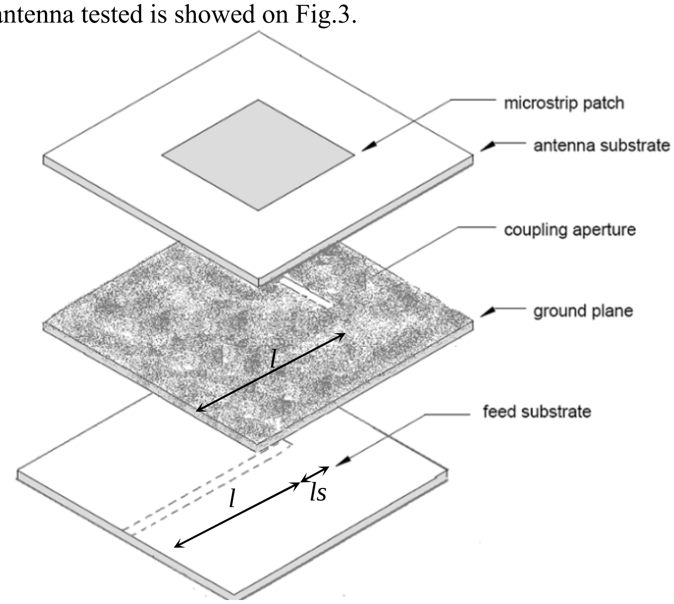
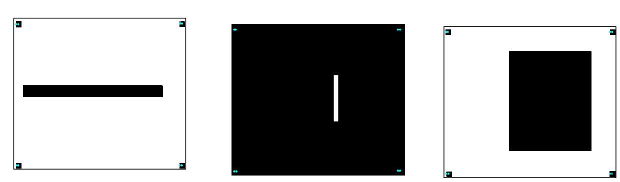


Fig.3 conventional aperture coupled antenna structure

The optimal distance *l* between the aperture and the feeding point is experimentally tested and determined as λg/2.

The mask of the conceived antenna is showed in Fig.4



(a) (b) (c)

Fig. 4 (a) lower layer, (b)Middle layer and (c) higher layer
(The substrate FR4 1,6mm one side copper metallased 30µm ϵ=4.4 ,tanδ=0.018 , total sise (50x55)mm2

The equivalent lamped element circuit is shown below.

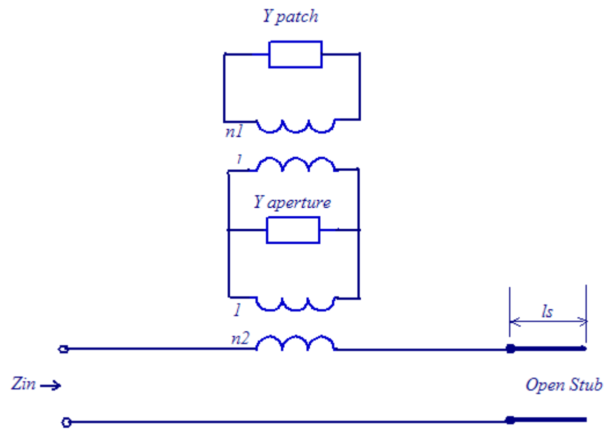


Fig.5 Lamped element equivalent circuit.

The above Figure highlights the coupling generated by the aperture. Many investigations have aimed to make the coupling better by implementing other aperture shapes.

The Slot length affects the coupling level and the back radiation level [7]. For maximum coupling, the patch and the feeding line should be centered over the slot. Hence, it is desirable to use a shape that has maximum coupling for a given size. The feed line affects the level of the radiation by carrying energy from a port to the actual antenna and so to launch guided waves only.

A simulation of the conventional antenna is done using the ADS Advanced Design System. The antenna dimension and result are summarised in Tab.1 and Tab.2.

Table 1 Conventinal Aperture Antenna dimension

Patch	W	31.5mm
	L	25.47mm
Substrate	Єr	4.4
	h	3x1.59mm
	Tanδ	0.018
metallization	t	35µm
	Metal Permeability	1
	Metal Conductance	1,83e+7
Aperture	Width (w_a)	1.35mm
	aperture large (l_a)	16.13mm
Feed line	Width (w_f)	3.41mm
	length (l_f)	25.84mm
Stub	Width (w_s)	3.41mm
	Length (l_s)	18.65mm

Table 2 Aperture conventional antenna performances

Power radiated(watts)	0.13
Effective angle(degrees)	162
Directivity(dB)	6.46
Gain(dB)	3.81
Max. Intensity(w/Steradian)	0.04
Bandwidth (GHz)	2.407-2.493

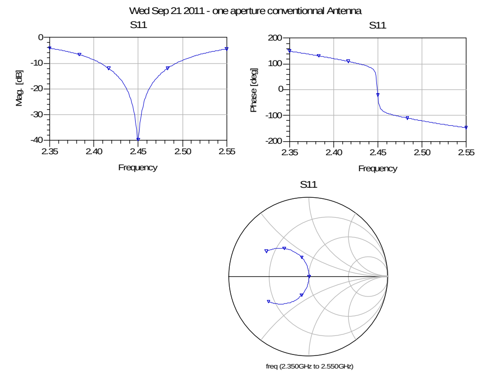


Fig.6 Simulation of the conventional aperture-coupled antenna

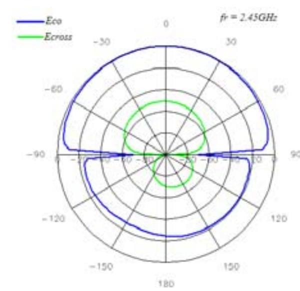


Fig. 7 Far fiel cut of The electric field Eco and Ecross of the conventional aperture coupled antenna

2.2 Enhanced gain and bandwidth aperture-coupled antenna.

The proposed enhancement of the coupling is supplied by adding another slot in the ground plane. The coupling is controlled by varying the distance between the slots. The antenna designed is illustrated in Fig.8

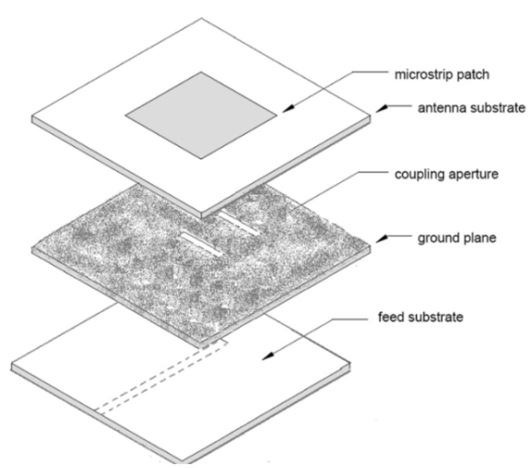


Fig. 8 3D new conceived apertures-coupling antenna.

The equivalent lamped element circuit shows that the effect of the supplimentary aperture is to increase the iductive effect. The length of the stub needed to match the impedance will be shorter than the stub used for conventional antenna and so a reduction of the anyenna dimensions will be obtaned.

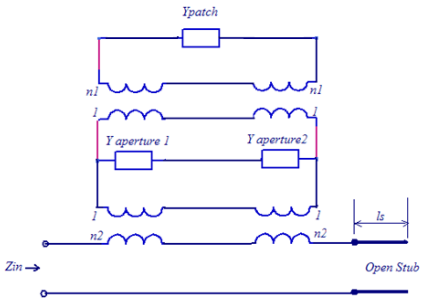


Fig. 9 Lamped element equivalent circuit two slots.

The mask of the designed antenna is shown in Fig.10.

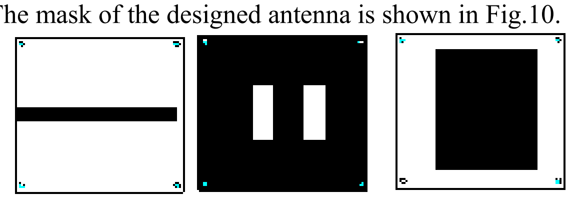


Fig. 10 Masque of the conceived antenna

The simulation results are plotted below.

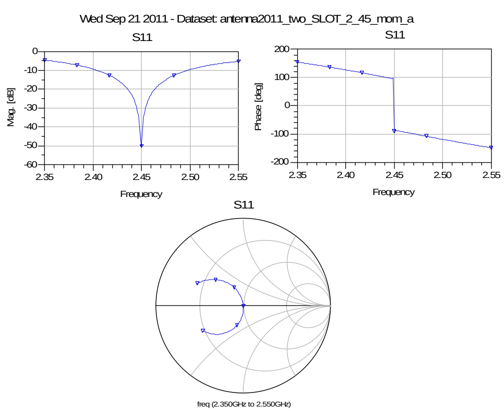


Fig. 11 Simulation results of the new conceived antenna.

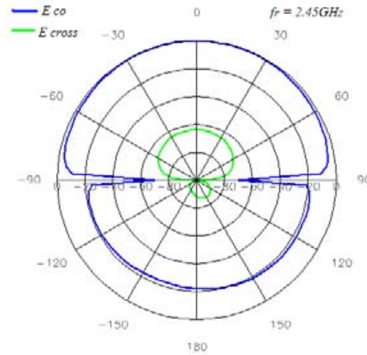


Fig. 12 Far fiel cut of The electric field Eco and Ecross

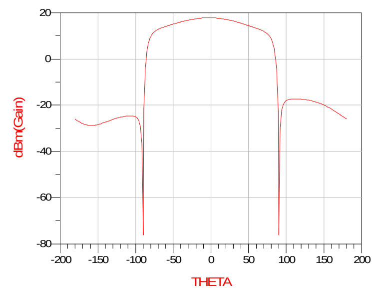


Fig. 13 The gain variation for the central frequency 2.45GHz

The antenna dimensions are placed in table 3.

Table 3 Double Apertures Antenna dimension

Patch	W	31.5mm
	L	26mm
Substrate	Єr	4.4
	h	3x1.59mm
	Tanδ	0.018
metallization	t	35µm
	Metal Permeability	1
	Metal Conductance	1,83e+7
Aperture	Width (w_{ap})	5.5mm
	aperture large (l_{ap})	13.72mm
Feed line	Width (w_f)	3.41mm
	length (l_f)	25.84mm
Stub	Width (w_s)	3.41mm
	Length (l_s)	16.7mm

The radiating results obtained from a 3D Momentum simulation are summarised in Table.4.

Table 4 Double Apertures Antenna performance

Power radiated(watts)	0.13
Effective angle(degrees)	162
Directivity(dB)	6.46
Gain(dB)	3.94
Max. Intensity(w/Steradian)	0.04
Bandwidth (GHz)	2.4 - 2.5

Both conventional antenna and our design are fabricated a photo shown that a reduction of about 20% of the total surface was obtained with a notable enhancement of the antenna radiation characteristics.

Fig. 14 On the left the conventional design on the right our design

The measurement of the reflexion coefficient of the double aperture antenna is given in Fig.15

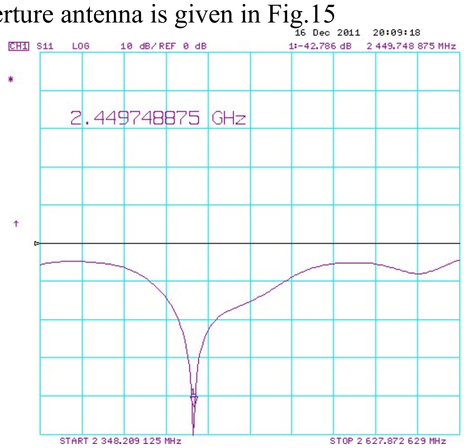


Fig. 15 S11 of the double apertures antenna

2.4 Comparative study:

We are comparing the finest tuning of the central frequency and the impedance matching of the conventional aperture coupled antenna and our design.
For both designs the inductive effect is generated by controlling the stub length as shown in the simulation done for different stub length.

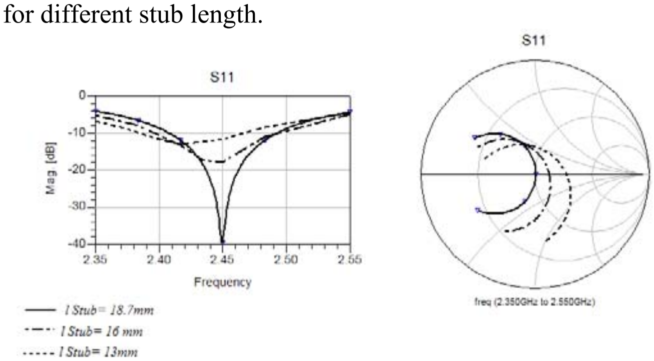


Fig. 16 effect of the stub tuning

The capacitive effect generated by controlling the aperture length for the conventional design is very sensible. The tuning of the length also affects the central resonant frequency very much as demonstrated in Fig.16 which summarizes the simulation for different aperture lengths.

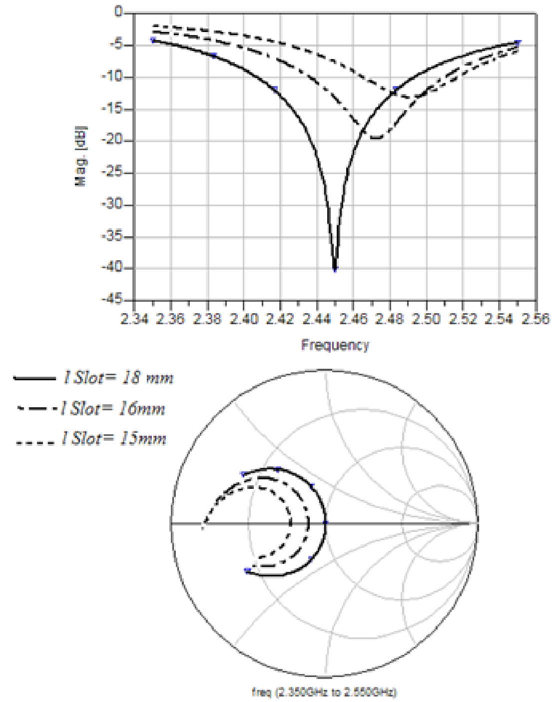


Fig. 17 Variation of the imput impedance for differents aperture length.

For a conventional antenna, as the stub increases in length, the input impedance at a fixed frequency approximately follows a constant-resistance circle in Fig., with the reactance increasing according to the reactance of the open-circuited stub. The effect of increasing the aperture size is similar to that of increasing the size of the coupling power from a waveguide to a resonant cavity. When the aperture is small, the patch is under-coupled and the resonant resistance is less than the characteristic impedance of the feed line. As the aperture size increases, the coupling and the resonant resistance increase.
A wide range of resistance and reactance values can be achieved by adjusting the aperture length and the stub length.
The Fig. 17 shows also that the resonant frequency is very sensible to the aperture length and this, on the one hand makes the antenna impedance matching and central frequency adjustment very difficult and needs many trials. On the other hand, an error due to the fabricating process leads to important impedance miss-matching.
The same work is done for the new design. The tuning of the input impedance here is controlled by adjusting the distance separating the two slots and we conclude from the result obtained in Fig.17 that the central frequency is 50% slightly shifted compared to the conventional design.

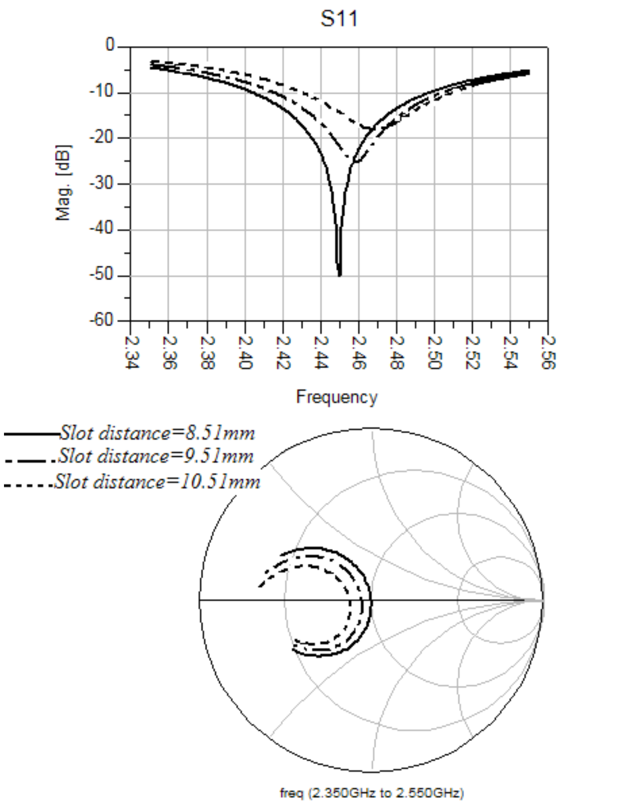


Fig.18 Variation of the input impedance and the centrale resonant frequency for different distance between the two slots.

The method proposed here is to operate two slots separated with a distance'd', the slots consent to better the coupling leading to a better Gain and the variation of the distance 'd' controls the input impedance. So, to accurately match the input impedance of the antenna to that of the feeding source, it is enough to calculate the right length of the stub and the slot and to tune the coupling between the two slots by controlling the distance between them as illustrated in Fig.18.

3. Dimension determination

In this section we will detail the theoretical study of dimension determination of the antenna elements.

3.1 The slots dimension

The slot length l_{ap} is chosen large enough so that sufficient coupling exists between the patch and the feed line but small enough so that it does not resonate within the band of operation, which usually leads to a significant radiated back lobe; a close formulation is set by [8].

$$l_{ap} = \frac{0.4\lambda_{eff}}{\sqrt{\frac{\epsilon_{eff\,(f)} + \epsilon_{eff\,(p)}}{2}}} \quad (1)$$

Were:
$\epsilon_{eff(f)}$ is the effective relative permittivity of the feed layer.
$\epsilon_{eff(p)}$ is the effective relative permittivity of the patch layer.
The slot width is usually chosen to be narrow to avoid a large back lobe component.

$$w_{ap} = 0.0164\,\lambda_{eff} \quad (2)$$

3.2 The feeding line dimension

The line characteristic impedance is taken 50Ω determined using Eq3.

$$Z_0 = \frac{87}{\sqrt{\epsilon_r + 1.4}} \ln\left(\frac{5.98h}{0.8w + t}\right) \quad (3)$$

This equation is valuable for h< 0.8w.
Where
ϵ_r = dielectric constant of the feeding layer.
h = height of the substrate.
w = width of the feeding line
t = metallisation thickness
The feeding line is divided in two distinct parts, a half wave transformer and a matching stub. The total electric length is expressed as θ_{eff} =230°
The patch is centred at (x_0 , y_0), tested to be the optimal point giving the maximum coupling taken x_0=L_{patch} and y_0=0.

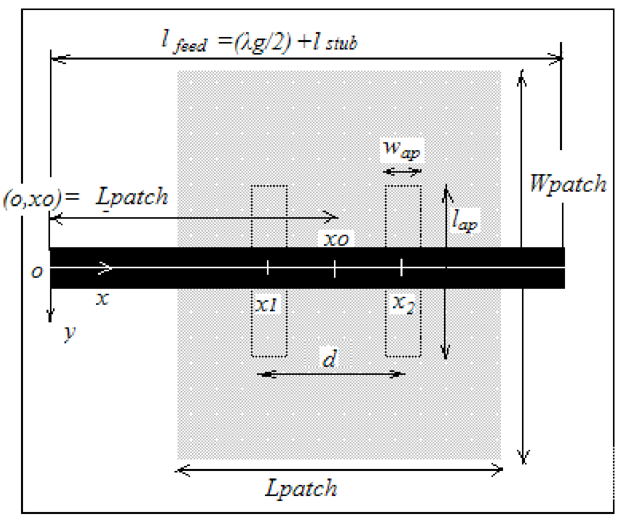


Fig. 19 position of antenna components

The stub is an open end; a tuning is necessary by controlling the stub length which can be modelled by an inductance [6] gives an accurate formula of L (nH).

$$L = 2.10^{-4}\left[\ln\left(\frac{ls}{w+t}\right) + 1{,}193 + 0{,}2235\left(\frac{w+t}{ls}\right)\right] K_g \quad (4)$$

$$K_g = 0{,}57 - 0{,}145\ln\frac{w}{h} \quad \text{for } \frac{w}{h} > 0{,}05 \quad (5)$$

For this study, we will consider the following fixed parameters:

w_{ap}=2,67mm, l_{ap}=13,7mm, ϵ_r(FR4)=4,4, tanδ(FR4)=0,018, ϵ_r(AR300)=2,2, tanδ(FR4)=0,0018, ϵ_r(Air)=1, tanδ(Air)=0, f_r=2,45GHz.

3.3 The patch dimension

The patch is a half wave resonator and is calculated using well known equations. The antenna patch dimension should be corrected. A reduction of 17% of the patch length should be applied due to the capacitive loading generated by the apertures.
The central frequency depends on many factors namely the patch dimension, the slot dimension, the slot position and the slot number.

3.4 The slots location

Conventionally, the aperture is located under the centre of the patch. This choice gives the maximum coupling but leads to less band width as demonstrated in the survey carried out here. For this design the slots are approximately located over the 50Ω impedance patch positions. The electric field collected by the two slots is superior to that collected by one slot located in the centre patch. Experiments are carried out to determine the distance separating the two slots for different aperture antennas made up of three layers. The first is made up of two layers of 1,6mm thick FR4 substrate the intermediary is an FR4 having variable thickness. The second, the higher and the lower layers are made up of 1,6mm thick FR4 substrate and the intermediary is variable thickness layer of air. The higher and the lower layers of the third antenna are made up of 1,6mm thick Arlon 300 substrate; the intermediary is variable thickness layer of air.
Finally, we will test the effect of varying the wideness W of the rectangular patch on the distance d.

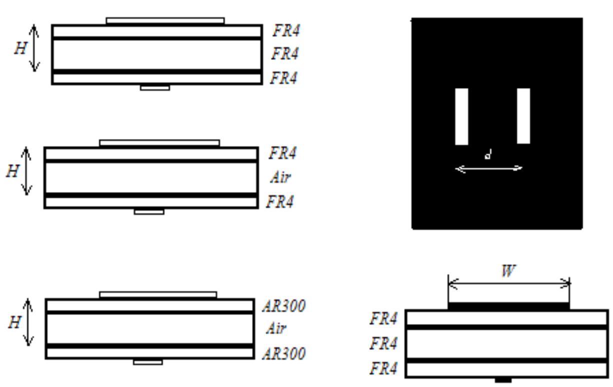


Fig. 20 Cases studied variation of H for different permittivity and variation of the wideness W.

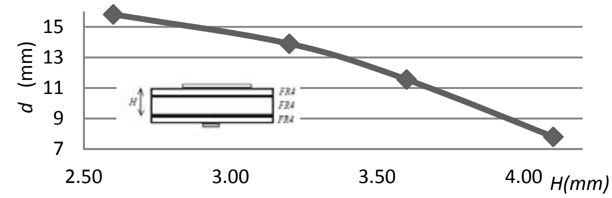


Fig.21 Aperture Antenna made up: FR4 - FR4 -FR4 (W=31,5, L=26mm)

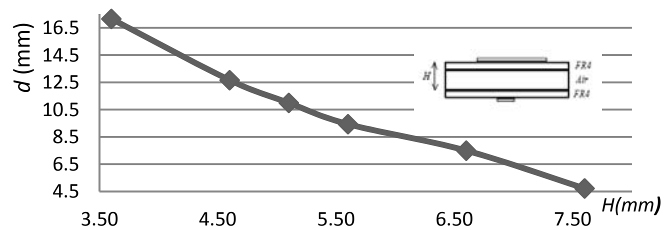


Fig. 22 A perture Antenna made up : FR4 - Air -FR4 (W=31,5, L=26mm)

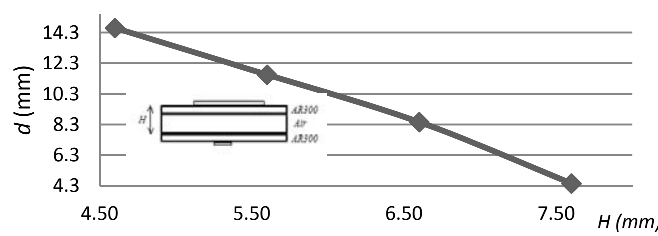


Fig.23 Aperture antenna made up : Arlon300- AIR-Arlon300 (W=31,5, L=26mm)

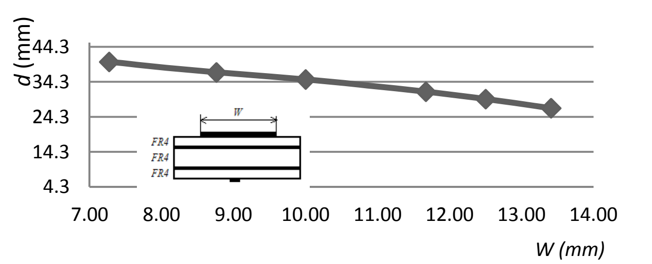


Fig.24 variation of d verses W for Aperture Antenna made up: FR4 - FR4 -FR4 (L=26mm)

From the experiments carried out, we can conclude that the distance 'd' separating the two slots depends on the coupling between the patch and the slots by varying the intermediary layer thickness, and depend on the input impedance of the patch by varying the permittivity and the patch wildness. An empirical formula giving the distance d separating the slots was determined and seems to produce accurate results for the cases studied.

$$d=\left(1-\left(0{,}295\log\left(\frac{\epsilon_{r\,(int)}+\epsilon_{r(p)}}{2}\right)+\log\frac{H}{2{,}15}+\log\frac{0{,}67W}{l_{ap}}\right)\right)L \quad (6)$$

The parameters d,$\epsilon_{eff(P)}$, $\epsilon_{eff(int)}$,L are determined in Fig.23.

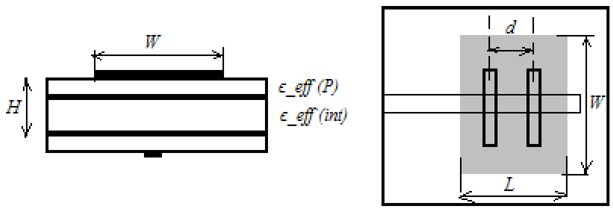


Fig. 23 Configuration of an aperture coupled antenna

Table . 5 slots distance separation for different thickness antenna made up of three layers FR4,FR4,FR4

H	2,6	3,2	3,6
d simulated	14,4	11,7	8,8
d computed	14	11,6	10

Table. 6 slots distance separation for different thickness antenna made up of three layers FR4,AIR,FR4

H	3,6	4,6	5,1	5,6	6,6	7,6
d simulated	17,8	13,7	11,0	9,4	7,5	4,7
d computed	17	13,1	11,4	10	7,4	5,1

Table. 7 slots distance separation for different thickness antenna made up of three layers Arlon300,Air,Arlon300

H	4,6	5,6	6,6	7,6
d simulated	14,6	11,5	8,4	6,9
d computed	17	13,4	10,6	8

Table. 8 slots distance separation for different wideness W antenna made up of three layers FR4-FR4-FR4

W	26,8	29,4	31,5	35,0	37,0	40,0
d simulated	13,41	12,5	11,67	10,0	8,76	7,27
d computed	13,5	12,5	11,76	10,6	9,15	8,7

From the tables we can conclude that a good agreement was found between the computed values of d and the simulated values.

4. Conclusions

The construction of a new generation of aperture coupled antennas is explained step by step with calculation details and then sensitivity analysis of the enhancement performed on the gain, bandwidth and size reduction. The most important particularity is to use two slots to control the input impedance by tuning the coupling between them. The theoretical study presented could be used by designer to conceive such antenna; the separating gap between the slots giving the best impedance matching empirical formula presented here gives good agreement between the computed values and the simulated values.

A comparative study was carried out and confirmed enhancement; a reduction of about 10% of total surface, an improvement of the band width of 20% and the gain rises to about 3.4%.

References

[1] C. Hertleer, F. De Clercq, A. Tronquo, H. Rogier, and L. Van Langenhove, " Aperture-Coupled Patch Antenna for Integration Into Wearable Textile Systems ," IEEE Antennas And Wireless Propagation Letters, Vol. 6, 2007

[2] Kwok L. Chung' and Ananda S. Mohan, "Gain and Bandwidth Enhancement of a 2.4GHz Singly-Fed Cross-Aperture Coupled Patch Antenna ," IEEE Xplore. pp. 410–413, 2002.

[3] Qinjiang Rao, Tayeb A. Denidni," A New Aperture Coupled Microstrip Slot Antenna" IEEE Transactions on Antennas And Propagation, Vol. 53, No. 9, September 2005.

[4] Balanis, C.A. Antenna Theory Analysis and Design, Second Edition. United States of America. John Wiley & Sons 2005., p734.

[5] P. Paul, J. S. Roy, S. K. Chowdhury Some experimental investigations on aperture-coupled microstrip antennas at TM_{11} mode Microwave and Optical Technology Letters 22 MAR 2007

[6] Ramesh Garg,Prakash Bhartia, Inder Bahl, Apisak Ittipiboon. Microstrip antenna design handbook 2001 ARTECH HOUSE.

[7] A.ZARREEN , S.C.SHRIVASTAVA '' An Introduction of Aperture Coupled Microstrip Slot Antenna International Journal of Engineering Science and Technology Vol.2(1), 2010, 36-39.

[8] Leung, K.W., et al., "Theory and Experiment of an Aperture-Coupled Hemispherical Dielectric Resonator Antenna," *IEEE Transactions on Antennas & Propagation*, Vol. 43, No. 1, Nov. 1995, pp. 192-198.