ANALYSIS OF THE DISCREPANCIES FABRICATING ERROR OF MICROSTRIP ANTENNA

ALI Mehdi [1], KACHOURI Abdennacer [2] & SAMET Mounir [1]
[1]Laboratory LETI, National School of Engineers of Sfax, Route Soukra Km 3.5 B.P W 1173, TUNISIA
[2]ISSIG Higher Institute of Industrial Systems Gabes, CP 6011, TUNISIA
Email: [1]Mahdi-ali@hotmail.fr, [2]Abdennaceur.kachouri@enis.rnu.tn, [1]Mounir.samet@enis.rnu.tn

ABSTRACT

Microstrip patches can be very efficient candidates for inexpensive antennas when narrow bandwidth and medium gain are required.

However, divergence in substrate parameters and manufacturing tolerances mean that a wider frequency bandwidth and a better control of radiation characteristics are necessary in the mass production of printed antennas.

The theory developed here is quite adequate to solve antenna problems involving dielectrics. The discrepancy between designed and measured resonant frequency could be overcome.

In this paper an available method to enhance the antenna bandwidth is presented to solve the shifting of the resonance frequency. The proposed trick here is to shift the feeding point and so the traditional antenna is converted to a dual frequency operating for two clause frequencies. On the other hand a trimming of the external fingers of the loading device is operated to adjust the capacitance needed to obtain an accurate impedance matching.

Key words: *Accuracy, Bandwidth, Dual Frequency, Low Cost, Interdigital-Capacitor, Manufacturing Tolerances, Substrate.*

1. INTRODUCTION

Antennas made on inexpensive substrate are especially interesting for low cost tag and sensors. On the other hand an increasing need for accuracy and high-performance is required.

The deviations in the effective electrical dimensions of the patch antenna from the designed values are source of discrepancies between the designed and obtained resonant frequencies [1]. The deviations may include the variation in the value of the relative permittivity of the substrate material (ϵ_r) and the loss tangent given by the manufacturer.

Various studies using tunable microstrip antenna have been reported. [2] Suggests including two tuning stubs attached to the antenna. Introducing posts between the patch and the ground plane was used by [3].

By using presently available techniques, one can easily achieve an impedance bandwidth enhancement. Broadband antenna could be obtained ether by using specific feeding methods such as aperture coupled feed and capacitive coupled feed or using compact designs with shorting pin, chip-resistor loading [4], stacked shorted patches [5] and chip-capacitor loading [6]. However, due to the introduced ohmic loss of the loading, the antenna gain is decreased.

The proposed antenna is a wideband microstrip-patch antenna introduced for possible wireless local-area network (WLAN) applications in the 2.4-2.5 GHz frequency range. Two modes are exited simultaneously the fundamental and a closer mode resonant frequency. The antenna is fed by a coupling mechanism connected between the radiating element and the load. A microstrip interdigital capacitor is used for matching the impedance for both frequencies. The dualband band operating antenna is obtained by switching the feeding point, this method was introduced by [7] for the purpose of enlarging the band width.

Trimming of the external fingers of the loading device may be necessary to adjust the capacitance needed to obtain an accurate impedance matching.

2. MICROSTRIP ANTENNA PARAMETERS

Microstrip patch antenna is built up in two parallel metal layers and a dielectric material in between them. The size of this patch depends on the wavelength and thus the microstrip patch antenna is classified as a resonant antenna. As with all resonant antennas, the bandwidth is narrow [8] and depend principally on the substrate on which the antenna is printed.

Substrate like FR4 is used for wide cheap applications, designer should take in the count the parameters fluctuation, and manufacturing errors with the purpose of optimizing results and cost. The relative permittivity is the measurement of the degree to which an electromagnetic wave is slowed down as it travels through the insulating material. In fact using low permittivity substrate allows increasing the gain and the band width but in detriment of the rise of the antenna size.

3. THEORETICAL STUDY

Determining the parameters having an incidence on the final result is important. A typical antenna is illustrated in (fig. 1).

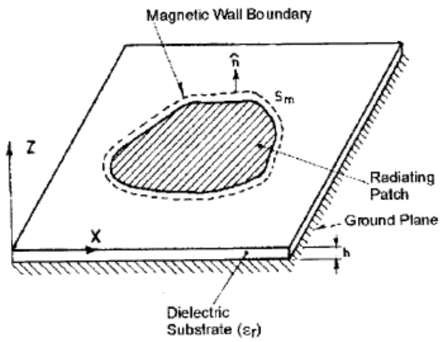

Fig. 1. Geometry *of a microstrip antenna*

Considering assumption cavity model we can write the inhomogeneous wave equation as:

$$\nabla_t^2 E_z + k^2 E_z = j\omega\mu_0 \hat{z}.\bar{J} \qquad \text{Ex.(1).}$$

Where $k^2 = \omega^2\mu_0\epsilon_0\epsilon_r$ Ex.(2).

$\bar{J}$ is the excitation electric current density.

$\hat{z}$ is the unit vector normal to the plane of the patch.

∇_t is the transverse del operator respecting of the z axis.

The electric field can be written as

$$E_z(x,y) = \sum_m \sum_n A_{mn}\, \Psi_{mn}(x,y) \qquad \text{Ex.(3).}$$

Where A_{mn} are the amplitudes coefficients corresponding to the electric field mode vector or eigenfunctions Ψ_{mn}. Substituting eq1 for E_z and multiply both side with Ψ_{mn}^* and integrate over the area of the patch the amplitude coefficient becomes:

$$A_{mn} = \frac{j\omega\,\mu_0}{k^2 - k_{mn}^2}\frac{\iint J_z \Psi_{mn}^* ds}{\iint \Psi_{mn}\,\Psi_{mn}^*\, ds} \qquad \text{Ex.(4).}$$

$$k_{mn}^2 = \frac{m\pi}{L^2} + \left(\frac{n\pi}{W}\right)^2 \qquad \text{Ex.(5).}$$

where $m, n = 1,2,3 \ldots$, L, W patch dimensions, and k will be expressed further.

Therefore,

$$E_z = j\omega\mu_0 \sum_m \sum_n \frac{1}{k^2 - k_{mn}^2}\frac{\iint J_z \Psi_{mn}^*\, ds}{\iint \Psi_{mn}\,\Psi_{mn}^*\, ds} \qquad \text{Ex.(6).}$$

The magnetic field can be written as:

$$\vec{H} = \frac{1}{j\omega\,\mu_0}\hat{z} * \nabla E_z \qquad \text{Ex.(7).}$$

The input impedance of the antenna is defined as:

$$Z_{in} = \frac{V_{in}}{I_{in}} \qquad \text{Ex.(8).}$$

Where V_{in} is the RF voltage at the feed point calculated as:

$$V_{in} = -E_z h \quad E_z\,(at\ the\ feed\ point) \qquad \text{Ex.(9).}$$

The feed current is expressed as follow:

$$I_{in} = \iint J_z\, ds \qquad \text{Ex.(10).}$$

We can define several losses such as P_d dielectric loss, P_c conductor loss, and P_r radiation loss which could be taken into account by defining an effective loss tangent as:

$$\delta_{eff} = \frac{1}{Q} \qquad \text{Ex.(11).}$$

Q is called the quality factor of the loss cavity and defined as follow:

$$Q = \frac{\omega_r W_T}{P_d + P_c + P_r} \qquad \text{Ex.(12).}$$

Where W_T is the total energu stored in the patch at the resonance ω_r given by (Ex. 12).

$$W_T = \frac{\epsilon_0\,\epsilon_r}{2}\iiint |E_z|^2 dV \qquad \text{Ex.(13).}$$

So δ_{eff} could be expressed as:

$$\delta_{eff} = \frac{P_d + P_c + P_r}{\omega_r W_T} \qquad \text{Ex.(14).}$$

The different losses are expressed by the following:

$$P_d = \omega\,.\,tan\delta\,.\,W_T \qquad \text{Ex.(15).}$$

$$P_c = \frac{\omega . W_T}{h\sqrt{\pi f \mu_0 \sigma}} \qquad \text{Ex.(16).}$$

If we define the skin depth for the conductor as:

$$\Delta = \sqrt{\pi f \mu_0 \sigma} \qquad \text{Ex.(17).}$$

We can obtain:

$$P_c = \frac{\Delta}{h} \qquad \text{Ex.(18).}$$

$$\delta_{eff} = tan\delta + \frac{\Delta}{h} + \frac{P_r}{\omega_r W_T} \qquad \text{Ex.(19).}$$

With the losses described in terms of δ_{eff} the expression of k^2 is modified as:

$$k^2 = k_0^2 \epsilon_r \left(1 - j\delta_{eff}\right) \qquad \text{Ex.(20).}$$

To yield the final expression for E_z.

$$E_z = j\omega\mu_0 \sum_m \sum_n \frac{1}{k_0^2 \epsilon_r (1 - j\,\delta_{eff}) - k_{mn}^2} * \frac{\iint J_z \Psi_{mn}^* \, ds}{\iint \Psi_{mn} \Psi_{mn}^* \, ds} \qquad \text{Ex.(21).}$$

The latter brief review of the cavity model available in [9] shows the dependence of the electric field set, the input impedance with the permittivity and the loss constant of the substrate. Errors on defining the value of the characteristic of the substrate exactly will have a determinant result on success of the implementation of the antenna.

3.1. Tolerance analysis.

A first order change in the resonant frequency can be obtained by using tolerance analysis [9] resulting in:

$$|\Delta f_r| = \left[\left(\frac{\partial f_r}{\partial L}\Delta L'\right)^2 + \left(\frac{\partial f_r}{\partial \varepsilon_{eff}}\Delta\varepsilon_{eff}\right)^2\right]^{\frac{1}{2}} \qquad \text{Ex.(22).}$$

Where $L' = L + 2\Delta L$ Ex.(22 -A).

$$\Delta L = 0.412\, h \left[\frac{(\epsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.813\right)}\right] \qquad \text{Ex.(22 -B).}$$

$$\epsilon_{eff} = \left[\frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{h}{W}}}\right]\right] \qquad \text{Ex.(22 -C).}$$

$\Delta\varepsilon_{eff}$ is the change in the effective relative permittivity due to inaccuracy in the fabrication of the patch and tolerances in substrate parameters it is given by

$$\Delta\varepsilon_{eff} = \left[\left(\frac{\partial\varepsilon_{eff}}{\partial W}\Delta W\right)^2 + \left(\frac{\partial\varepsilon_{eff}}{\partial h}\Delta h\right)^2 + \left(\frac{\partial\varepsilon_{eff}}{\partial\varepsilon_r}\Delta\varepsilon_r\right)^2 + \left(\frac{\partial\varepsilon_{eff}}{\partial t}\Delta t\right)^2\right]^{\frac{1}{2}} \qquad \text{Ex.(23).}$$

Where *t* is the metallization thickness, ΔW, Δh , Δt, $\Delta L'$ are the tolerances in patch parameter.

$\left(\frac{\partial\varepsilon_{eff}}{\partial W}\Delta W\right)$ *and* $\left(\frac{\partial\varepsilon_{eff}}{\partial t}\Delta t\right)$ could be neglected so:

$$\frac{|\Delta f_r|}{f_r} = \left[\left(\frac{\Delta L'}{L}\right)^2 + \left(\frac{0,5}{\varepsilon_{eff}}\right)^2 \left(\left(\frac{\partial\varepsilon_{eff}}{\partial h}\Delta h\right)^2 + \left(\frac{\partial\varepsilon_{eff}}{\partial\varepsilon_r}\Delta\varepsilon_r\right)^2\right)\right]^{\frac{1}{2}} \qquad \text{Ex.(24).}$$

It is easy to conclude that sources of error witch influence the final design are the evaluation of the permittivity constant, the loss tangent values and manufacturing tolerances *L* as a result of inaccuracies which depend on the chemical process used in the photo-etching.

4. STUDY OF THE DEFECT INVOLVED BY AN ERROR MADE ON PERMITTIVITY AND THE LOSS TANGENT.

Antennas have been mostly fabricated on cheap substrates such as FR4 which typically exhibit dielectric constants no greater than 5 and a loss tangent 0.02.

4.1. Effect of error on the permittivity value

A microstrip antenna is simulated for different value of the dielectric constant as errors manufacturing. The computed result based on manufacturer substrate given values is illustrated in Table 1.

Table 1. Effect of a manufacturing error on ϵ_r

Permittivity (ϵ_r)	Resonance frequency	Reflection coefficient
4.50	2.40	-40dB
4.32	2.45	-45dB
4.20	2.48	-45dB
4.10	2.51	-40dB
4.00	2.55	-40dB

The latter study establishes that an error made on the permittivity of the substrate will cause a deviation of the resonant frequency.

4.2. Effect of error on the tangent loss

The antenna is simulated for different values of loss tangent as an error fabricator indication, results are mentioned in table2.

Table 2. Effect of an error on tanδ

Loss tangent (*Tan δ*)	Resonance frequency	Reflection coefficient
0.02	2.45	-32dB
0.018	2.45	-45dB
0.015	2.45	-26dB

The tolerance of the loss tangent is supposed to be about 5% of nominal value. This error leads to a miss matching in the impedance.

5. SOLVING DESIGN PROBLEMS

The problems listed could be resumed in a switching of the resonant frequency and mismatching impedance. Using a wider bandwidth antenna seems to be a solution for the first problem.

The bandwidth of an antenna is the range of frequencies over which it is effective, usually centered around the resonant frequency. The bandwidth of an antenna may be increased by several techniques, Small antennas are usually preferred for convenience, but there is a fundamental limit relating bandwidth, size and efficiency.

Generally it is important to find a way to enhance the bandwidth especially when it's not possible to use thick substrate and when reducing antenna dimension is needed. The band width is given by Eq.26.

$$BW = \frac{16}{3\sqrt{2}}\frac{p}{e_r}\frac{1}{\epsilon_r}\frac{h}{\lambda_0}\frac{W}{L}q \qquad \text{Ex.(25).}$$

where *p and q* are approximated by the relation

$$p = 1 - \frac{0.16605}{20}(k_0W)^2 + \frac{0.02283}{560}(k_0W)^4 - 0.0091(k_0L)^2 \qquad \text{Ex.(26).}$$

$$q = 1 - \frac{1}{\epsilon_r} + \frac{2}{5\epsilon_r^2} \qquad \text{Ex.(27).}$$

W,L are the calculated antenna dimensions for the resonant frequency.

ϵ_r *and h* are the permettivity and the substrate thickness.

e_r is the antenna radiation effeciency.

It's clear that the impedance band width depends on the substrate characteristic and the antenna dimensions.

5.1. Solving deviation operating frequency

One of the weaknesses of the microstrip antenna printed on a thin substrate is the narrow band width so an error on evaluation permittivity of the substrate may switch the operating frequency.

By widening the band width the switched resonance frequency still in the range covered by the antenna.

The solution proposed in this paper is to shift the load from the center of the radiating edge so that we could excite two close modes and make the antenna operate as a bi-band antenna; the fundamental mode and a closer mode.

Indeed by moving the location of the feeding point along the non radiating edge it is possible to make the patch resonating to a second frequency f_{r2} given by the empirical equation given[10] Eq.29.

$$f_{r2} = f_r log_{10}\left(\frac{19+\frac{W}{L}}{2}\right)\left(\frac{1-\epsilon_{eff}}{14.33f_r}\right)\left(1-\frac{\frac{W}{2}-|y|}{6{,}32W}\right)\left(\frac{\sqrt{d}+0{,}157}{d^{0.32}}\right) \qquad \text{Ex.(28).}$$

Were f_r is the fundamental TM_{10} mode given by (Eq. 29).

$$f_r = \frac{c}{2L\sqrt{\epsilon_r}} \qquad \text{Ex.(29).}$$

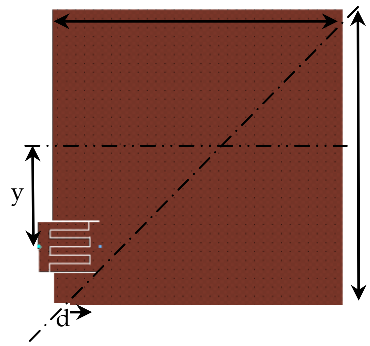

Figure 2. Switched feeding point antenna

Table 3 resumes different values of simulated antenna resonant frequencies for different loading point |y|.

Table 3. Variation of f_{r2} when the feeding point is switched away from the center

feed point location (y)	Resonance frequency	Resonance frequency
5,5mm	2,468 GHz	2.419 GHz
8,6mm	2,467 GHz	2,412 GHz
9mm	2,467 GHz	2,38 GHz

The antenna is simulated using Advanced Design System software 2005.The antenna parameter are (L=W= 27mm, y = 5.6mm, d = 4.5mm, s = 0.1mm, w =0,7mm, ϵr = 4.32 and Tanδ =0,018).
The simulation is carried with 8 GHz Mesh the antenna (27.6 x 28.3) mm^2 is divided in 1600 cells to obtain an accurate result. The simulation lasts 50 mn the parameters are extracted using a 3 D simulation.

5.1.1. Return loss S11 evaluation

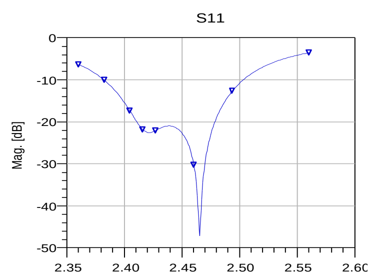

Figure 3. The return loss of the switched fed point antenna

5.1.2. Matching impedance

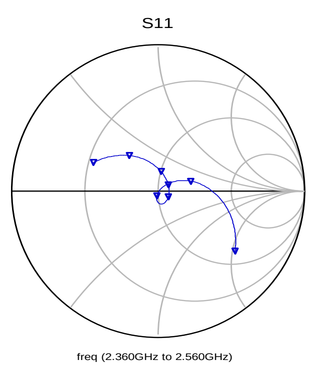

Figure 4. Smith chart impedance matching

5.1.3. Effective angle

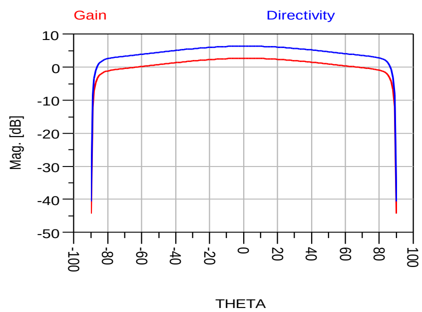

Figure 5. Antenna Efficiency

5.1.4. Gain variation

The gain is measured for different value of the frequency.

Table 4. Gain Variation.

Resonant frequency	2,40	2,42	2,46	2,5
Gain (dB)	2,05	2,09	2,32	2,67

An approximate constant gain is obtained; it is worth noticing that the gain is better around the second resonance frequency fundamental mode.

5.2. Solving impedance mismatching

This antenna will be fed by using capacitive loading .The impedance is accurately matched by adjusting the interdigital capacitor finger's length (fig.6) dimensions.

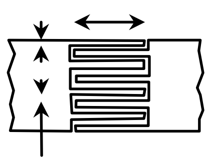

Figure. 6 A microstrip interdigital capacitor

The antenna could be modeled by the lamped element formed by two blocks; the resonant RLC circuit modeling the patch, the second is the capacitive loading ensured by the interdigital capacitor as shown on (Fig. 7).

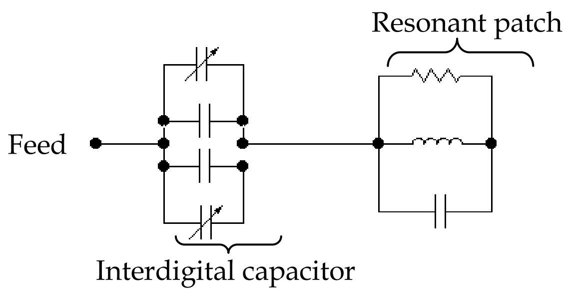

Figure 7. Proximity loaded antenna equivalent circuit

A very simple closed-form expression suggested by [11] for estimation of capacitance in pF of the interdigital capacitor may be given by

$$C = 3.93710^{-5} l\,(\epsilon_r + 1)[0.11(n-3) + 0.252] \qquad \text{Ex.(30).}$$

Where n is the number of fingers, l the fingers length and ϵ_r is the relative dielectric constant of the substrate.
The capacitance is tuned by calculating the number and the length of the fingers.

Due to etching errors and error on the value of the loss tangent, a mismatch is noted as shown on (fig. 9).

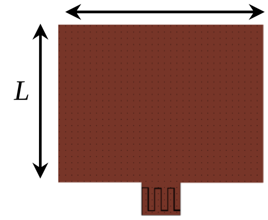

Figure 8. Antenna L=27mm,W=35mm, tanδ=0.018, ϵ_r=4.32, l=3.81mm, s=0.1mm, w=1mm

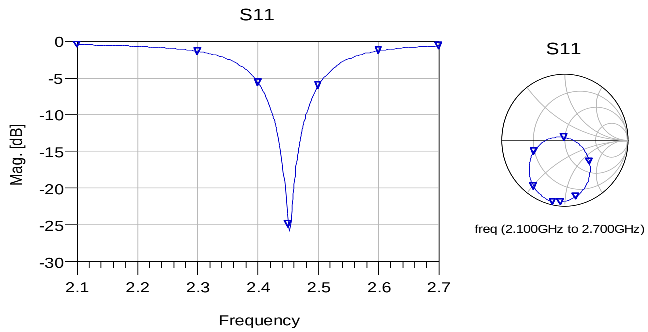

Figure. 9 Results of simulating Antenna

The proposal here is to tune the capacitance of the feeding device. To attain accurate matched impedance a trimming of the external fingers may be necessary to adjust the capacitance as shown on (fig. 10).

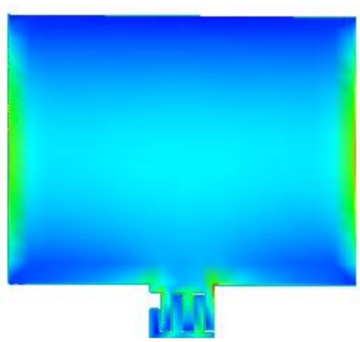

Figure 10. Antenna tuned capacitance

The obtained result is better; the measured results are proved by the return loss and the Smith chart.

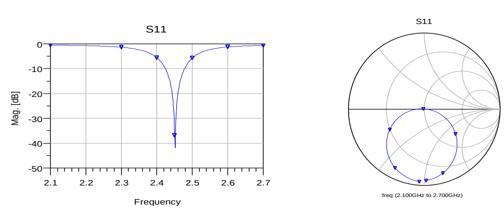

Figure 11. The Return loss S11 verses frequency and Smith chart impedance matching at 50Ω

6. CONCLUSION

In order to optimize the performance of the microstrip low cost antenna, a method was exposed to overcome manufacturing errors involved by the evaluation of the substrate characteristics and industrial fabrication process. A proximity single fed planar antenna fed in a located point; convert the traditional antenna to a dual frequency antenna for two operating clause frequencies leading to 100% bandwidth enhancement. Then experimental trimming of the fingers length may be necessary in the final design stages to obtain an accurate impedance matching.

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