Ultra WideBand Matching of the Rectangular Microstrip Patch Antennas (RMPA) Using Microstrip Non Uniform Transmission Lines (MNUTL)

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Abstract
Simulation and modeling configurations of Rectangular Microstrip Patch Antennas (RMPA) are dealt with in this paper. Microstrip Non Uniform Transmission Lines (MNUTL) are used to feed the RMPA leading to ultra-wideband impedance matching. Microstrip linear and sinus tapered characteristic impedance lines and Microstrip uniform lines are both taken to feed the same antenna patch and finally to compare their performances. The analysis is based upon the Finite Difference Time Domain method FDTD combined with the Absorbing Boundary Conditions Perfectly Matched Layers (ABC PML). An RMPA whose resonance frequency is 7.5 GHz is analyzed over a frequency band from 5GHz to 16GHz by calculating the return loss and the input impedance from the time-domain simulated data.

Keywords: Microstrip Antennas, MNUTL, FDTD-PML technique, Ultra Wideband impedance matching.

1. Introduction
Microstrip Antennas are widely used thanks to their several advantages that make them suitable for many applications, such as: Telecommunications, Telemetry, Military, and Medicine [1, 10]. The main purpose is to make them compact on a large band of frequencies and to improve the bandwidth. Many techniques can be used, such as: mechanism of parasitic coupling, gap-coupled, directly coupled, etc. As mentioned above, MNUTLs will be investigated in order to achieve this goal [7].

Several numerical methods are available to analyze electromagnetic problems. The FDTD, a full wave method, has been used to solve electromagnetic problems since 1966 [3,6]. As presented first by Berenger [4], the PML technique is suitable to model the unbounded conditions. Hence, the FDTD-PML algorithm can be used to analyze structures under unbounded conditions, including antennas of any shapes, Radar, Bio-electromagnetic problems, etc.

In this paper, the FDTD-PML technique is adopted to analyze several RMPAs. The use of the Fast Fourier Transform FFT is required to treat time-domain simulated data and finally to set the system frequency dependence.

2. FDTD Method
As well known, the FDTD method is adopted to solve Maxwell curl equations by means of discretization of time and space. Easy to implement, the algorithm is that the six vector electromagnetic components located in each cell (Fig. 1) must be updated at each time step [13]. However, as the number of the cells increases, the number of time steps increases also. These equations are:

\[
\text{rot } \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t} - \sigma_m \vec{H} \tag{1}
\]

\[
\text{rot } \vec{H} = \varepsilon \frac{\partial \vec{E}}{\partial t} + \sigma_e \vec{E} \tag{2}
\]

where \(\sigma_e\) and \(\sigma_m\) are electromagnetic losses and \(\varepsilon\) and \(\mu\) are permitivity and permeability of a dielectric medium. Maxwell equations can be developed according to cartesian coordinates, as follow:

\[
\frac{\partial}{\partial y} E_z - \frac{\partial}{\partial z} E_y = -\mu \frac{\partial}{\partial t} H_x - \sigma_m H_x \tag{3}
\]

\[
\frac{\partial}{\partial z} E_x - \frac{\partial}{\partial x} E_z = -\mu \frac{\partial}{\partial t} H_y - \sigma_m H_y \tag{4}
\]

\[
\frac{\partial}{\partial x} E_y - \frac{\partial}{\partial y} E_x = -\mu \frac{\partial}{\partial t} H_z - \sigma_m H_z \tag{5}
\]

\[
\frac{\partial}{\partial y} H_z - \frac{\partial}{\partial z} H_y = \varepsilon \frac{\partial}{\partial t} E_x + \sigma_e E_x \tag{6}
\]
\[
\frac{\partial}{\partial z} H_x - \frac{\partial}{\partial x} H_z = \varepsilon \frac{\partial}{\partial t} E_y + \sigma_e E_y \quad (7)
\]
\[
\frac{\partial}{\partial x} H_y - \frac{\partial}{\partial y} H_x = \varepsilon \frac{\partial}{\partial t} E_z + \sigma_e E_z \quad (8)
\]

The system or the volume under test is seen as a fine number of cells and it must be backed with a PEC (Perfect Electric Conductor) or a PMC (Perfect Magnetic Conductor). The stability and the precision of the FDTD algorithm are given by Courant-Friedrichs-Levy (CFL) stability condition:

\[
\Delta t \leq \frac{1}{V \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \quad (9)
\]

where \(\Delta x\), \(\Delta y\) and \(\Delta z\) are the mesh grid and \(V\) the wave velocity in the dielectric substrate.

### 3. PML Technique

The system under study is extended in an infinite medium and any machine cannot simulate such a system. So, the solution is to surround the system of interest by ABC. The ABC PML is adopted from others because it is easy to implement and the outgoing waves are attenuated properly.

In the PML technique, the system is divided into three areas: The main area which contains the device under test, the PML area to mitigate the outgoing waves and the PEC or PMC area to back the system (Fig. 2). Regardless to the system dimensions, in the PML area, each component field is split into two sub-components [4].

The variation of the conductivities which is the main parameter of the PML is a function of PML thickness and geometry profile (polynomial and geometric profiles).

\[
\sigma_x = \left( \frac{\text{pos}_x}{\text{dpml}} \right)^m \sigma_{\text{max}} \quad (10)
\]

\[
R_0 = \exp \left[ -\frac{1}{m+1} \frac{\text{dpml}\sigma_{\text{max}}}{\varepsilon c} \right] \quad (11)
\]

where the parameters \(m\), \(\text{dpml}\), \(\text{pos}_x\), \(\varepsilon\) and \(\sigma_{\text{max}}\) represent the polynomial degree, PML area thickness, current layer thickness, the wave velocity in the vacuum medium, the electromagnetic permittivity and electric conductivity maximum, respectively.

The technique adopted in order to generate the incident wave and to determine the total consists in defining two planes (Source and reference Planes) separated by a minimum distance \(d\) (Fig. 7) in line length direction. As given in recent articles [17], the Source Plane is always in the main area between the ground and the conductor strip.

### 4. Microstrip Non Uniform Transmission Line (MNUTL)

As mentioned above, the main purpose is to feed the RMPA leading to the ultra-wideband impedance matching. To reach this goal, one can use cascaded microstrip uniform lines (Fig. 3) or the MNUTL (Fig.4). By using first technique, many drawbacks rise, such as: bulky system, coupling phenomenon, mismatching between two Microstrip lines, etc. However, the use of the MNUTL appears as the main solutions to overcome some of the drawbacks.
where \( L_i \) and \( w_i \) (\( i=1,2,\ldots,n \)) are the length and width of the current line.

The MNUTL’ properties depend on the tapered function. In the MNUTL [8], the characteristic impedance depends on the tapered functions: sinus, Gaussian, Blackman, Kaiser, Welch, Hanning, Hamming, Cones, Bartlett, etc [15]. Each microstrip tapered line is seen as infinity of uniform line sections cascaded (Fig. 4) and it is easy to calculate the scattering parameters of each section.

Among many methods, the Finite Difference, the Taylor’ Series Expansion and the Fourier’s Series Expansions are most used to analyze these structures.

In this paper, the FDTD method should be used and the microstrip sinus and linear tapered lines will be analyzed and the results will be compared to those of the uniform line. However, the analysis of the MNUTL by the FDTD-PML technique requires a very small space grid. For example, in the microstrip sinus taper configuration, the bandwidth depends on the induce-modulation and the magnitude value.

5. Configuration of the Rectangular Microstrip Patch Antenna (RMPA)

5.1. RMSA Dimensions

An RMPA consists of a radiating patch on one side of a dielectric substrate and the ground plane on other side. As explained in [14], feeding techniques, such as: coaxial probe, microstrip line, electromagnetic coupling, aperture coupling and coplanar waveguide can be used. In this paper, only the MNUTL and MUTL are used to feed the same patch.

Knowing the resonant frequency \( f_r \), the relative permittivity \( \varepsilon_r \) of the substrate and the substrate thickness \( h \), we obtain the dimensions of the antenna [18].

\[
W = \frac{c}{2f_r \sqrt{\varepsilon_r \frac{\varepsilon_r + 1}{2}}} \quad (12)
\]

\[
L_{\text{eff}} = \frac{c}{2f_r \sqrt{\varepsilon_{\text{eff}}}} \quad (13)
\]
\[ \Delta L = 0.412h \left( \frac{\varepsilon_{\text{eff}} + 0.3}{\varepsilon_{\text{eff}} - 0.258} \right) \left( \frac{w}{h} + 0.264 \right) \]

\[ L = L_{\text{eff}} - 2\Delta L \]

As shown in the figures 4 and 5, the feeding microstrip line is located at the non radiation edge where the input impedance is 50 Ω. In this situation, the impedance matching between the line and the antenna is verified. The reflection coefficient is low at the resonant frequency.

5.2. Parameters of the antenna

The time-domain simulated data must be handled by means of FFT to have parameters such as: the input impedance of the antenna, the return loss and the directivity of the antenna. Our purpose is to determine the frequency dependence of the reflection coefficient from voltages, currents or electromagnetic field to the reference plane. All calculations rely on the electrical components of the plane wave.

A. Return loss

The microstrip antenna is seen as a simple device with a single port and it can be characterized by its reflection coefficient, which is the ratio between the reflected and the incident waves. The frequency domain expression is obtained only from the FFT of time-domain simulated data:

\[ S_{11}(t) = \frac{E_{z\text{tot}} - E_{z\text{inc}}}{E_{z\text{inc}}} \]

Fig. 7 RMPA Fedded by microstrip uniform line

Instead of microstrip line, we connect a MNUTL between the reference plane and edge. The idea is to modify some of their parameters (such as: MNUTL’s length, width’s amplitude) in order to achieve the Ultra Wideband Matching.

Fig. 8 RMPA feded by Microstrip sinus tapered line

Fig. 9 RMPA fedded by Microstrip linear tapered line

As shown in the figures 4 and 5, the feeding microstrip line is located at the non radiation edge where the input impedance is 50 Ω. In this situation, the impedance matching between the line and the antenna is verified. The reflection coefficient is low at the resonant frequency.
Where \( E_{\text{ztot}} \) and \( E_{\text{zinc}} \) represent the total and incident electric fields, respectively.

### B. Input impedance

The input impedance is defined as the input impedance of the line down to the input of the antenna given by the famous equation impedance transformer (Eq. 18).

\[
Z_{\text{ina}} = Z_{\text{car}} \frac{1+S_{11} \exp(2j\beta La)}{1-S_{11} \exp(2j\beta La)} \tag{18}
\]

where \( \beta \), \( L_a \) and \( Z_{\text{car}} \) represent the wave number, the length of the line (from the reference plane to the antenna) and the characteristic impedance of the Microstrip line (50 Ohms).

The wave number \( \beta \), as a function of the frequency, is given by:

\[
\beta(f) = \frac{2\pi f \sqrt{\varepsilon_{\text{eff}}(f)}}{C} \quad \text{(rad/m)} \tag{19}
\]

where \( \varepsilon_{\text{eff}}(f) \) and \( C \) represent the actual relative permittivity and the propagation speed in a vacuum respectively.

### 6. Results and Discussions

The antenna (Fig. 4) has a resonant frequency at 7.5 GHz. The incident and total waves are calculated at the reference plane whereas the reflected wave is obtained from the difference between total and incident waves. The excitation plane is located at the area of 3 cells PML and the reference plane is defined to a minimum of 10 cells from the source plane. Other parameters are summarized in the tables below (Table 1 and 2).

#### Table 1: space and time steps

<table>
<thead>
<tr>
<th>( \Delta x )</th>
<th>( \Delta y )</th>
<th>( \Delta z )</th>
<th>( \Delta t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4 mm</td>
<td>0.4 mm</td>
<td>0.265 mm</td>
<td>0.44167 ps</td>
</tr>
</tbody>
</table>

#### Table 2: cells and time steps number and the parameters \( R \) and \( m \)

<table>
<thead>
<tr>
<th>Time steps</th>
<th>( N_x )</th>
<th>( N_y )</th>
<th>( N_z )</th>
<th>( R )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>52</td>
<td>86</td>
<td>14</td>
<td>( 10^{-4} )</td>
<td>3</td>
</tr>
</tbody>
</table>

From 5 GHz to 16 GHz (Fig. 11), we notice more than 4 resonances but some are very matched with narrow bandwidth. As mentioned, the main purpose is both to match the input impedance and to enlarge the bandwidth of the system by means of Non Uniform Transmission Lines.
From fig.12, the imaginary value of the input impedance is around zero and the real part in maximum at 7.59GHz frequency resonant.

By using the linear tapered line instead of microstrip uniform transmission line (MUTL), the antenna is adapted ranging 5GHz to 16GHz with a good level. For the linear tapered line, the bandwidth and the matching level depend on the ration R (Eq. 20) between the MNUTL’s length and MUTL’s length.

\[ R = \frac{L_{MNUTL}}{L_{MUTL}} \]  

Fig. 13 Return loss vs. frequency of the RMPA feeded by the microstrip linear tapered line

So, as the R decreases, the results tend to those of the microstrip uniform line.

By comparing the results (fig. 14, 13 and 11), the MNUTL show good results compared to the MUTL. First, the MNUTL offer level of impedance matching less than 16 dB for the Microstrip linear and sinus tapered lines. Secondly, they provide an ultra-wideband bandwidth unlike the microstrip line for which there is a low bandwidth around each resonance frequency.

7. Conclusion

Despite the CFL condition stability, the FDTD-PML technique remains a good tool for analyzing the microstrip patch antennas. Through the results, we can say that the Microstrip non uniform transmission lines are essential in the design of transformers impedances leading to the ultra-wideband matching of the Microstrip rectangular patch antennas. The matching level was found good comparatively to the microstrip uniform line. In this paper, we have dealt with two types: linear and sinus tapered lines. Those structures should be employed to design other microwaves devices, such as: filters, couplers, connectors, etc.

References


Gaspard SINGENDAKUMANNA received Bachelor and Master degrees in science and Technology and in telecommunications and microwave devices from Faculty of Science and Technology - Cadi Ayyad University in Marrakech and National School of Applied Sciences in Fès - University Sidi Mohamed Ben Abdellah, Morocco in 2009 and 2011, respectively. He is currently pursuing his Ph.D. degree in science and engineering techniques at the Faculty of Science and Technology in Fès - University Sidi Mohamed Ben Abdellah. His research interests include numerical method, Electromagnetic Compatibility, Microwave antennas, embedded and RFID systems, RF and microwave applications.

Nabih EL OUAZZANI received the Ph.D degree in microwave circuits, especially microwave filters, from the university of Limoges - France at the IRCOM Institute (Institute of research in microwave and optical communications) in 1995. Since 1995 he has been a professor at the faculty of science and techniques – Fès, Morocco (FST –Fès). He has been carrying out many activities with respect to research and education. The disciplines that are relevant to his expertise are high frequency technology and telecommunication technology. He is also involved in the research area of electromagnetic compatibility (EMC) in VLSI and MMIC circuits. The methods of simulation and analysis are based upon modelling and applying numerical codes such as FDTD and MNA. He has authored and co-authored numerous publications in the field of recursive microwave filters, planar circuit interconnections, skin effect and arbitrary non uniform transmission lines. He co-organized many international conferences related the ICT and telecommunication subjects in Morocco and participated in scientific committees. He is now at the head of the team of EMC research within the LSSC laboratory (Laboratory of signals, systems and components) at the FST-Fès (Morocco).