MODELING AND SIMULATION OF THE PATCH ANTENNA BY USING A BOND GRAPH APPROACH

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ABSTRACT

Further to our own studies carried out previously on the application of the bond graph approach on antennas based on localized elements, we tried in the continuation of our research to devote our studies on the antennas based on distributed elements. For that purpose, we have chooses as first departure, a patch antenna of which we want to find its scattering parameters by our own and new methodology. So we can say that in this paper, we propose a new methodology to study a patch antenna by applying the bond graph approach and the scattering formalism. This study permits us on the one hand to determine and to simulate the scattering parameters (reflexion and transmission coefficients S_{11}, S_{12}, S_{21} and S_{22}) of a patch antenna and on the other hand to modelling the incident and reflected wave propagation for all the points of this antenna by the bond graph approach.

KEYWORDS: *Patch Antenna, Scattering Matrix, Electrical Model, Microstrip Line, Scattering Parameters, Scattering Bond Graph & Simulation.*

I. INTRODUCTION

The microstrip patch antenna [4] is used in many applications in the communication systems [3] because of their ease of fabrication, low-profile, low cost and small size. In the setting of this article, we look to conceive and to use a simple and precise electrical model of square patch keeping in mind all the electric and geometric characteristics of elements radiating and of their feedings [3,4]. For that we will use our new methodology called "Scattering Bond Graph Modelling" [11,12] which combine on the same time the Scattering Formalism [11] and the Bond Graph Approach [21] witch is a graphic language unified for all the fields of the engineering and confirmed like a structured approach with the modelling and simulation of many systems. The purpose of this paper is to present and apply this new methodology to extract the scattering parameters of our studied system (patch antenna) while basing on its causal and reduced bond graph model [21].

At first, and after having to determine and simulate the scattering matrix of the studied antenna from its electrical model, we propose to use the causal bond graph model of this patch antenna [13] to find, on one hand, the integro-differentials operators [6] which is based on the causal ways and loops present in the bond graph model and, on the other hand, to extract the wave matrix [8] from these operators.

Then, we extract directly the scattering parameters [11] from the found wave matrix [8] and, at the aim to validate the found results; we make a comparison by the simulation of these scattering parameters with a simple program and the classic techniques of conception and simulation of the microwave circuits [20].

Finally, we will propose in our future work, to build a particular type of bond graph model which is able to highlight these transmission and reflection coefficients (Scattering parameters) [1].

II. Determination of the Scattering Matrix from the Patch Antenna

At this part, we will determine the reflected and the transmission coefficients (S_{11}, S_{12}, S_{21} and S_{22}) of this proposed antenna [3,19] after a small explication of this patch and by a joint use of the scattering formalism and the bond graph approach and so we will indicate the biggest application of this new methodology (Scattering bond graph).

2.1. Design of the Square Antenna

The figure 1 represents the geometry of a square micro-strip patch on a dielectric substrate with a ground plane. The antenna is mounted on a substrate material with a thickness of $H = 3.2mm$ and it has an edge of $W = 36mm$, a relative permittivity: $\varepsilon_r = 2.6$ and loss tangent: $\tan(\delta) = 0.002$. The dimension 'W' of square edge is calculated using the following equation [19].

$$W = \frac{1}{2}\frac{c}{f_r\sqrt{\varepsilon_r}} \tag{1}$$

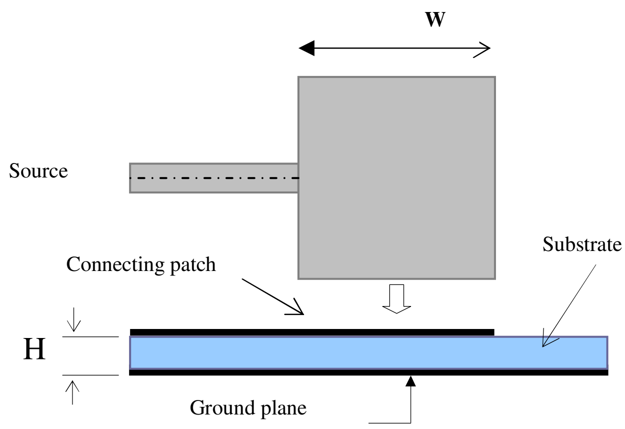

Figure1. Square patch antenna

2.2. Determination of the parameters of the antenna

At first, we are going to calculate the frequency of resonance f_r, and the total quality factor Q_T, in following we will deduct the other parameters from the following equation [7, 9].

$$C = \frac{\left(\varepsilon_{eff}\,\varepsilon_0 W^2\right)}{2H}\cos^{-2}\left(\frac{\pi x_0}{W}\right) \tag{2}$$

C: capacitance

x_0: The distance of the feed point from the edge of the patch.

W: length of the square

H: thickness of dielectric

The resonant resistance R is calculate using the following equations.

$$R = \frac{Q_T}{w_r C} \tag{3}$$

$$Q_T = \left(\frac{1}{Q_R} + \frac{1}{Q_C} + \frac{1}{Q_D}\right)^{-1} \tag{4}$$

Q_R: Radiation quality factor.

Q_C: Losses in the conductor.

Q_D: Losses in the dielectric.

$$Q_R = \frac{c_0 \sqrt{\varepsilon_{dyn}}}{4 f_r H} \tag{5}$$

$$Q_D = \frac{1}{\tan(\delta)} \tag{6}$$

$$Q_C = \frac{0.786 \sqrt{f_r Z_{a0}(W) H}}{P_a} \tag{7}$$

$$Z_a(W) = \frac{60\pi}{\sqrt{\varepsilon_r}} \left\{ \frac{W}{2H} + 0.441 + 0.082\left(\frac{\varepsilon_r - 1}{\varepsilon_r^2}\right) + \frac{(\varepsilon_r + 1)}{2\pi\varepsilon_r}\left[1.451 + \ln\left(\frac{W}{2H} + 0.94\right)\right]\right\}^{-1} \tag{8}$$

$$Z_{a0} = (W) = Z_a(W, \varepsilon_r = 1) \tag{9}$$

Z_a: Is the impedance of an air filled microstrip line.

$$P_a(W) = \frac{2\pi\left(\frac{W}{H} + \frac{\frac{W}{H\pi}}{\frac{W}{2H} + 0.94}\right)\left(1 + \frac{W}{H}\right)}{\left\{\frac{W}{H} + \frac{2}{\pi}\left[2\pi \exp\left(\frac{W}{2H} + 0.94\right)\right]\right\}^2} \tag{10}$$

$\tan(\delta)$: is the tangent of loss in the dielectric and it given by the following equation.

$$\delta = \left[\frac{H}{W}0.882 + \frac{0.164(\varepsilon_r - 1)}{\varepsilon_r^2} + \left[\frac{(\varepsilon_r + 1)\left(0.756 + \ln\left(\frac{W}{H} + 1.88\right)\right)}{\pi\varepsilon_r}\right]\right] \tag{11}$$

$$\varepsilon_{dyn} = \frac{C_{dyn}(\varepsilon)}{C_{dyn}(\varepsilon_0)} \tag{12}$$

$$C_{dyn}(\varepsilon) = \frac{\varepsilon_0 \varepsilon_r A}{H \gamma_n \gamma_m} + \frac{1}{2\gamma_n}\left(\frac{(\varepsilon_{reff}(\varepsilon_r, H, W))}{c_0 Z(\varepsilon_r = 1, H, W)} - \frac{\varepsilon_0 \varepsilon_r A}{H}\right) \tag{13}$$

$$\gamma_j = \begin{cases} 1, & j = 0 \\ 2, & j \neq 0 \end{cases} \tag{14}$$

$$Z(W, H, \varepsilon_r) = \frac{377}{H}\left[\frac{W}{H} + 1.393 + 0.667 \ln\left(\frac{W}{H} + 1.44\right)\right]^{-1} \tag{15}$$

$$f\left(\frac{W}{H}\right) = 6 + (2\pi - 6)\exp\left(-\frac{30.66}{\frac{W}{H}}\right)0.7528 \tag{16}$$

The effective dielectric constant of a microstrip line is given bellow [10]:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{H}{W}\right]^{-\frac{1}{2}} \quad (17)$$

The inductance L is given by the following equation:

$$L = \frac{1}{(w_{res})^2 C} \quad (18)$$

$$w_{res} = 2\pi f_r \quad (19)$$

2.3. Electrical model of the square patch antenna

The structure can be modelled as an RLC resonant circuit [7]. The model parameters are calculated using the formulas developed in section 1. The patch is exited by a transmission line and the dimension is determined to resonate frequency equal 2.45GHz.

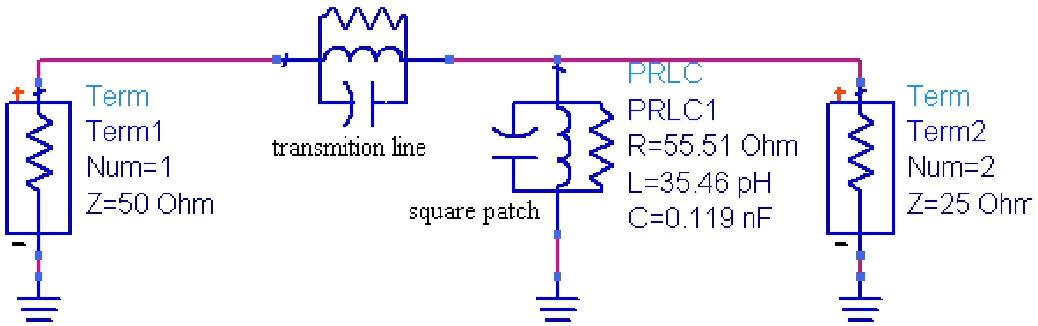

Figure2. Electrical model of the square patch antenna

2.4. Simulation results of scattering parameters

The tradition tools for simulation of the scattering parameters under HD-ADS software [13] as figure 3 refer to, visualize the coefficients of reflection.

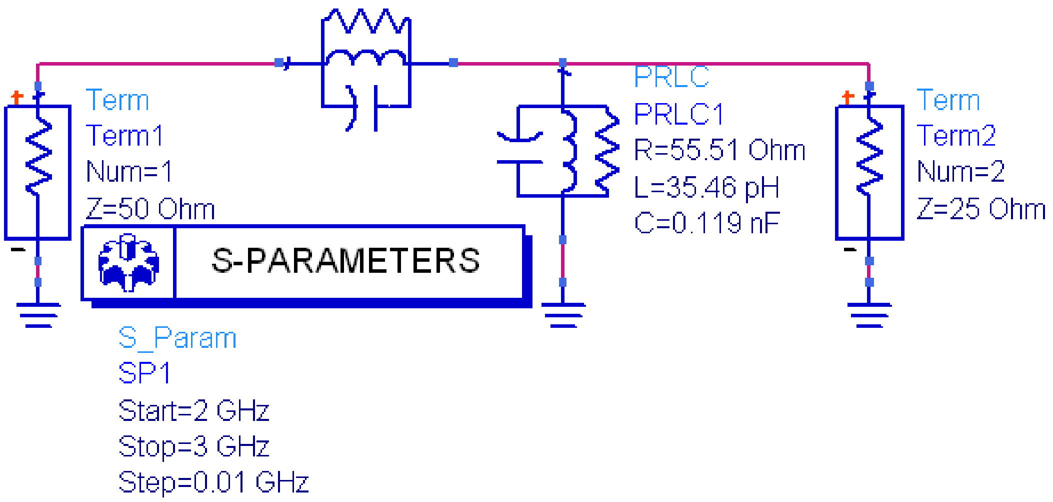

Figure3. Square patch antenna, under HP-ADS

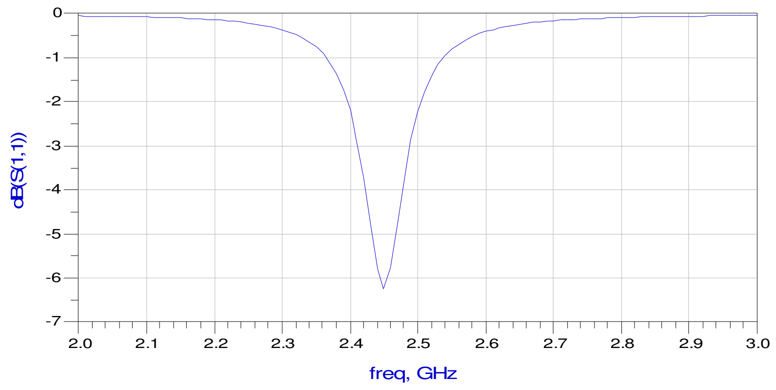

Figure4. Reflection coefficient (S_{11}) simulated of square patch antenna under HP-ADS

III. Scattering Parameters of the Square Patch Antenna Exploited from its Bond Graph Model

In this part we propose to determine the scattering parameters [12] of the patch antenna from its transformed and reduced bond graph model [13] without forgetting to pay attention to causality assignment.

3.1. Relation between bond graph model and wave scattering matrix

We can represent every physical system by a quadripole inserted between two ports P_1 and P_2 who respectively represent the source and the load of all the system [5]. This system can be represented by a generalized bond graph model transformed and reduced as figure 5 indicates it [17, 18].

Figure5. General transformed and reduced bond graph model

- ε_1 and ε_2 are respectively the reduced variable (effort) at the entry and the exit of the system.
- φ_1 and φ_2 are respectively the reduced variable (flow) at the entry and the exit of the system.

The causality assignment to the reduced bond graph model of figure 5 enables us to notice that there are four different cases of causality assignment in input-output of the process [14, 15].

3.1.1. Case 1: Flow-Effort Causality

Figure6. Reduced bond graph model with flow-effort causality

From this type of assignment causality we can deduce the following matrix.

$$\begin{bmatrix} \varepsilon_1 \\ \varphi_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varepsilon_2 \end{bmatrix} \tag{20}$$

3.1.2. Case 2: Effort-Flow Causality

Figure7. Reduced bond graph model with effort -flow causality

From this type of assignment causality we can deduce the following matrix.

$$\begin{bmatrix} \varphi_1 \\ \varepsilon_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varphi_2 \end{bmatrix} \tag{21}$$

3.1.3. Case 3: Flow-Flow Causality

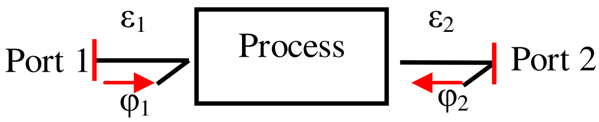

Figure8. Reduced bond graph model with flow -flow causality

From this type of assignment causality we can deduce the following matrix.

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix} \tag{22}$$

3.1.4. Case4: Effort-Effort Causality

Figure9. Reduced bond graph model with effort -effort causality

From this type of assignment causality we can deduce the following matrix.

$$\begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} \tag{23}$$

We can note that

$$H = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \tag{24}$$

H_{ij} represent the integro-differentials operators associated to the causal ways connecting the port P_j to the port P_i and obtained by the general form given below [16, 17].

$$H_{ij} = \sum_{k=1}^{n} \frac{T_k \Delta_k}{\Delta} \tag{25}$$

$$\Delta = 1 - \sum B_i + \sum B_i B_j - \sum B_i B_j B_k + \ldots + (-1)^m \sum \ldots \quad (26)$$

- Δ= the determinant of the causal bond graph
- H_{ij}= complete gain between P_j and P_i.
- P_i= input port.
- P_j= output port.
- n= total number of forward path between P_i and P_j
- T_k= gain of the k^{th} forward path between P_i and P_j
- B_i= loop gain of each causal algebraic loop in the bond graph model.
- B_iB_j= product of loop gains of any tow non-touching loops (no common causal bond).
- $B_iB_jB_k$= product of the loop gains of any three pairwise nontouching loops.
- Δ_k= the factor value of Δ for the k^{th} forward path, this value calculates himself as Δ when one only keeps the causal loops without touching the k^{th} chain of action.

We noted that:

$$a_i = \frac{\varepsilon_i + \varphi_i}{2}, \quad a_i = \frac{\varepsilon_i - \varphi_i}{2} \quad (27)$$

$$\varepsilon_i = \frac{V}{\sqrt{R_0}}, \quad \varphi_i = I\sqrt{R_0} \quad (28)$$

These are reduced voltage and current.

$$\begin{pmatrix} \varepsilon_1 \\ \varphi_1 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} a_1 \\ b_1 \end{pmatrix} \quad (29)$$

$$\begin{pmatrix} \varepsilon_2 \\ -\varphi_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} a_2 \\ b_2 \end{pmatrix} \quad (30)$$

$$\begin{pmatrix} b_1 \\ a_1 \end{pmatrix} = \begin{pmatrix} w_{11} & w_{12} \\ w_{21} & w_{22} \end{pmatrix} \begin{pmatrix} a_2 \\ b_2 \end{pmatrix} = (W) \begin{pmatrix} a_2 \\ b_2 \end{pmatrix} \quad (31)$$

By using the preceding equations; we can find for each case of causality one wave matrix.

$$W = \frac{1}{2H_{21}} \begin{bmatrix} 1 - H_{11} + H_{22} - \Delta H & -1 + H_{11} - H_{22} - \Delta H \\ -1 - H_{11} - H_{22} - \Delta H & 1 + H_{11} - H_{22} - \Delta H \end{bmatrix} \quad (32)$$

$$W = \frac{1}{2H_{21}} \begin{bmatrix} 1 - H_{11} + H_{22} - \Delta H & 1 - H_{11} - H_{22} + \Delta H \\ 1 + H_{11} + H_{22} + \Delta H & 1 + H_{11} - H_{22} - \Delta H \end{bmatrix} \quad (33)$$

$$W = \frac{1}{2H_{21}} \begin{bmatrix} 1 - H_{11} + H_{22} - \Delta H & -1 + H_{11} + H_{22} - \Delta H \\ 1 + H_{11} + H_{22} + \Delta H & 1 + H_{11} - H_{22} - \Delta H \end{bmatrix} \quad (34)$$

$$W = \frac{1}{2H_{21}} \begin{bmatrix} -1 + H_{11} - H_{22} + \Delta H & 1 - H_{11} - H_{22} + \Delta H \\ -1 - H_{11} - H_{22} - \Delta H & 1 - H_{11} + H_{22} - \Delta H \end{bmatrix} \quad (35)$$

With:

$$\Delta H = H_{11} H_{22} - H_{12} H_{21} \quad (36)$$

The following scattering matrix gives us the scattering parameters [15, 16] [17]:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} s_{11} & s_{12} \\ s_{21} & s_{22} \end{pmatrix} \begin{pmatrix} a_2 \\ a_2 \end{pmatrix} = (S) \begin{pmatrix} a_1 \\ A_2 \end{pmatrix} \tag{37}$$

The relation between equations and gives us the following equations:

$$\begin{cases} w_{11} = -s_{22}\, s_{21}^{-1} \\ w_{12} = s_{21}^{-1} \\ w_{21} = (s_{12}s_{21} - s_{11}s_{22})\, s_{21}^{-1} \\ w_{22} = s_{11}\, s_{21}^{-1} \end{cases} \tag{38}$$

The corresponding scattering matrix [16, 17] is given by:

$$S^T = \begin{pmatrix} w_{12}w_{22}^{-1} & [w_{11}w_{22} - w_{21}w_{12}]w_{22}^{-1} \\ w_{22}^{-1} & -w_{21}w_{22}^{-1} \end{pmatrix} \tag{39}$$

3.2. Application to the square patch antenna

The bond graph model of the square is giving bellow:

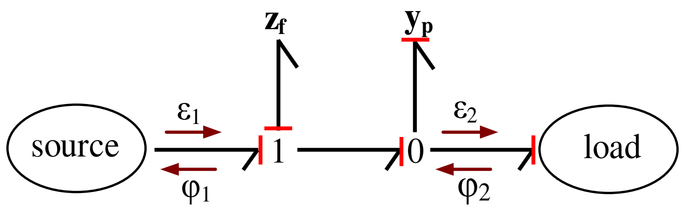

Figure10. Reduced and causal bond graph model of the square patch antenna

- z_f: The reduced equivalent impedance of the feeding line.
- y_p: The reduced equivalent admittance of the patch.

$$z_f = \tau_{C1}s + \frac{1}{\tau_{L1}s} + \frac{1}{\tau_{R1}} \tag{40}$$

$$y_p = \tau_{C2}s + \frac{1}{\tau_{L2}s} + \frac{1}{\tau_{R2}} \tag{41}$$

Where:

$$\tau_{Ci} = R_0 * C_i \tag{42}$$

$$\tau_{Li} = \frac{L_i}{R_0} \tag{43}$$

s: The Laplace operator and R_0: the scaling resistance.
The sub-model is in conformity with case (2) described previously.

$L_1 = \dfrac{-1}{z_f\, y_p}$: Loop gain of the algebraic given by sub-model.

$\Delta_1 = 1 + \dfrac{1}{z_f\, y_p}$: Determinant of causal bond graph of the model.

The following equations represent the integro-differentials [17, 18] operators of the model.

$$\begin{cases} H_{11} = \dfrac{z_f}{z_f y_p + 1} \\ H_{12} = \dfrac{1}{z_f y_p + 1} \\ H_{21} = \dfrac{1}{z_f y_p + 1} \\ H_{22} = \dfrac{-y_p}{z_f y_p + 1} \\ \Delta H = \dfrac{-z_f y_p}{z_f y_p + 1} \end{cases} \quad (44)$$

From these operators, we can determine the following scattering parameters:

$$S_{11} = \frac{-z_f + y_p + 1}{D(s)} \quad (45)$$

$$S_{12} = S_{21} = \frac{2 z_f y_p}{D(s)} \quad (46)$$

$$S_{22} = \frac{-z_f + y_p - 1}{D(s)} \quad (47)$$

$$D(s) = y_p + 2 y_p z_f + z_f + 1 \quad (48)$$

3.3. Simulation Results of the Scattering Parameters

To determine the coefficient of reflection, represented by the figure 10 we used the simple programming and simulation of the scattering parameters equations [15, 16].

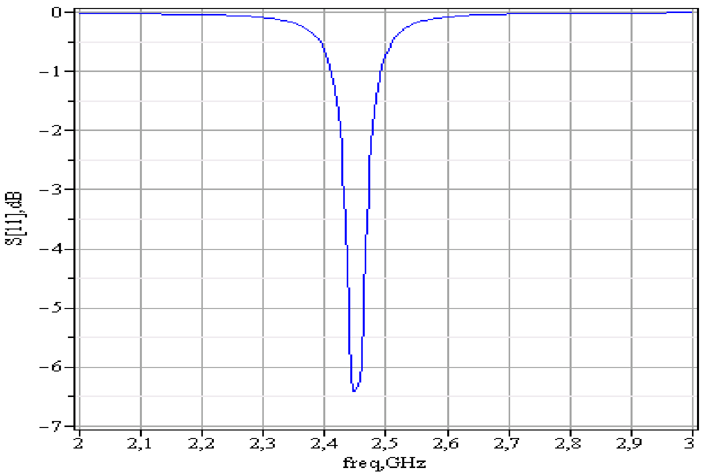

Figure10. Reflection coefficient simulated of square patch antenna using bond graph

The purpose of this simulation is to validate this new extraction method of scattering parameters from a causal bond graph model of a patch antenna we note that it is always necessary taking account of causality concept in order to get the right results as opposed to the work carried out by [13] [15] where the causality concept was ignored.

The simulation given by figure 6 is carried out in the maple software, this figure show the reflection coefficient of the patch antenna that is the same coefficient carried out in the HP-ADS software. We can see that the two results are similar. For the traditional method in microwaves and this new method using bond graph the reflection coefficient have the same resonant frequency and the same gain but with a little difference in Band width because of the difference between calculated and simulated losses. The figure 6 presents a resonant frequency equal to 2.45 GHz, a gain equal 6.4dB and a bond width about 50MHz, in the figure 4 a bond width about 78MHz [16, 17, 18].

IV. CONCLUSIONS

In this article, we showed a simple method to determinate the scattering parameters of the patch antenna. We validated the results by a simple comparison between the traditional methods used in microwaves under HP-ADS software and simulation by the methods of the reduced and causal bond graph. Now we can apply this technique to a network of antennas and to all microwaves circuits.

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