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Analyse et conception d'antennes très large bande en utilisant la théorie des modes caractéristiques

Analysis and design of miniaturized extremely wide band antenna using characteristic mode theory

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Mots clés: antenne très large bande, antenne miniature, théorie des modes caractéristiques, antenne pour sondage spectral.

Abstract
A planar extremely-wide-band antenna is designed and simulated. The proposed antenna is a printed elliptical slotted monopole antenna with a triangular ground plane, fed by semi-ring triple feed followed by a tapered CPW line. The frequencies covered for a VSWR ≤ 2 extends from 0.65 GHz to 12 GHz with stable radiation patterns to guarantee minimal pulse distortion. This configuration has been achieved by analyzing the currents on the antenna by means the characteristic mode theory. Both numerical and experimental results are presented. This miniaturized antenna (largest dimensions of the order of 0.14 λ) is a good candidate for wide band spectrum sensing in the context of cognitive radio applications.

Introduction
With the diversity of wireless systems, flexibility for operating between different standards is required. Cognitive radio (CR) consist the future system that can propose this flexibility. The federal communications commission (FCC) has defined a cognitive radio as a radio that can change its transmitter parameters based on an interaction with the environment in which it operates. At the hardware level, the implication for future antenna design is the varying degree of reconfiguration and band tuning will be required. CR can have different possible architectures but all of them require a spectrum-sensing unit. In this paper we will focus on the design of a spectrum-sensing antenna used by such systems. The most important challenges for sensing antennas are their dimensions and radiation pattern stability at all the operating frequencies of the communication systems present in the environment [1], [2].

In this paper, a novel design of extremely wideband printed elliptical monopole fed by tapered CPW line is proposed and investigated based on a triple-feed at the bottom of the line [3]. Once a good antenna matching is achieved, obtaining a stable radiation pattern on the whole frequency band can prove to be a challenge.

We propose to analyze the current modes on the radiator using the theory of characteristic modes (TCM). Indeed, TCM, developed by Garbacz in 1971 [4] and later refined by Harrington and Mautz [5] has been proposed to analyze radiating modes of any conductive structure and has been used successfully for the design of diverse wire and planar antennas [6]. Here, TCM is used to provide physical insight into the radiating phenomena, thus allowing performance enhancement at particular frequencies where the radiation pattern is distorted. This novel antenna design proposes three significant performance enhancements, namely, miniaturization of total dimensions, the shifting of the lowest operating frequency towards low frequencies and a stable radiation pattern over the frequency band (0.65 GHz – 12 GHz) to ensure that the antenna is a good candidate for CR spectrum sensing applications.

1. Design challenges and optimisation techniques
The antenna proposed was inspired by designs for UWB systems. These include various printed antenna with different shapes and enhanced bandwidths. The shapes of the printed antennas can be rectangular [7], triangular-ring [8], circular [9], annular-ring [10], and elliptical [3], [11], [12] . The monopole antenna chosen is an elliptical one since through the variation of its elliptical ratio, a higher degree of freedom is obtained for impedance matching. Since the sensing

antenna needs to operate in a large band frequency, both wide bandwidth impedance matching and stable radiation pattern are required. Furthermore the antenna should propose good performances at low frequencies while having an small electrical size. Miniaturization for frequencies below 2 GHz can prove to be a challenge. The bandwidth of such antennas is proportional to the metallic volume contained in a fictitious sphere with a diameter of the largest antenna dimensions. The theory of characteristic modes will be used with the aim of forcing the total surface current to flow over the whole surface of the radiator.

2. Theory of characteristic modes (TCM)

Characteristic modes J_n can be defined as a set of orthogonal real surface currents associated to any conducting object, which depend of object shape and size, and are independent of any excitation source. By definition, the modes are related to the power that can be radiated by the conducting body [5]. Associated to the characteristic currents, a set of characteristic fields E_n can be computed. Therefore, the field radiated by the antenna can be expressed as a superposition of these characteristic fields or modal fields. To each characteristic mode is associated an eigenvalue, λ_n. This parameter provides useful insight: its magnitude provides information on the radiation of the associated modes. One can deduce that the reactive power of a mode is proportional to the magnitude of its eigenvalue. In other words, the smaller the magnitude of the eigenvalue, the more the mode radiates when excited. Furthermore the sign of the eigenvalue determines whether the mode contributes to storing magnetic energy ($\lambda_n > 0$) or electric energy ($\lambda_n < 0$). Finally, the last parameter called the modal significance (MS) is studied to determine how much the mode contributes to the total radiation with a coefficient normalized to the fundamental mode (first mode), as a function of frequency.

3. Antenna Analysis

Figure 1 shows the configuration of the proposed antenna with the design parameters given in Table 1. In order to take into account additional constraints (bandwidth, radiation pattern stability), the design methodology consists in two parts. The first part is related to the excitation, matching system and ground plane, while the second one deals with the radiator using TCM. The main idea is that since the total current is a contribution of a set of orthogonal current modes with a defined bandwidth, thus exciting many modes means adding the bandwidth of each one to the total bandwidth, hence increasing it.

3.1. Analysis of an isolated elliptical disc

First, characteristic modes study of an elliptical disc (radiator) are required. Figure 2 shows the eigenvalues of the first six current modes J_{1-6}. The choice of taking just the first six modes is relative to a threshold applied to the eigenvalues in dB (modes with $| \lambda_n | < 30$ dB are not retained). The sign of the eigenvalues informs us about the nature of the reactive impedance on the monopole: except for the third mode, all the others have a negative sign for the eigenvalue before tending to zero. This indicates that the intrinsic impedance of the disc is capacitive. The extra information that this theory can provide us is with the MS. Figure 3 show the MS of the disc modes where we observe that till 10 GHz just the two first modes have an MS close to 1 which mean that these are the main radiating modes. In next section we will present how these curves will varies by modifying the structure and adding the excitation system in order to excite all these modes.

3.2. Feeding system and ground plane

Authors in [9] and [10], explains how parametric study allow the determination of the optimum value for an elliptical disc excitation. The variation of the radiator size changes its input impedance; this impedance results from the contribution of different current modes intrinsic impedance. Since we have chosen a =15 mm and b =13 mm to reduce total dimension, using TCM to determine the nature of the disc input impedance can be helpful besides the parametric study. The access of the CPW line (w_b =1.7 mm with the gap W =3 mm) was chosen to have a 50 Ω at the input and is tapered according to an exponential model in order to increase the bandwidth of the excitation. The impedance matching varies slightly with the slope of the exponential curve. The inductive nature of a tapered line was used to compensate the capacitive nature of the elliptical disc. The choice of a triangular ground plane limits coupling with the radiator. At the end of the CPW line a triple-feed has used to excite the radiator in 3 equidistant points to increase the number of excited mode i.e. to decrease the cut-off frequency of higher modes. This effect can be seen by comparing the MS of the elliptical disc alone and with the trident excitation in Figures 3, 4 and 5. For example the MS value of the 2^{th} mode at 6 GHz on the disc alone can be achieved at 3 GHz with the trident excitation, idem to the 1^{th} mode.

One of the most critical parts in the design is at the excitation point level between the feeding line and the radiator. The distance 'g' between the tapered feeding line and the monopole has an important role because through this part the wavelength changes from the guided wavelength of a Q-TEM mode to that of a free space wave. The radii of the ring and its width also influence the impedance matching constraints. Optimization of these parameters needs to be done in parallel because they are directly related. The optimal value of g is 3 mm and of the ring width d_{21} is 0.35 mm.

3.3. Radiator design using TCM

The main miniaturization task was for the radiator, because all the other design parameters are function of a and b. As mentioned before, decreasing the monopole dimensions (radiator) impact the cut-off frequencies of higher modes. Then the additional spot is to well known how we can arrange these modes to radiate as it's predicted for a monopole. The radiation pattern for the antenna is unstable and has a dip for θ = 0° at 7.78 Ghz (Figure 6). This dip is caused by the radiation of the 6th mode, which contributes to the global radiation. From the modal significance (MS) of the first 6 modes shown in Figure 5, one can see that the 6th mode has an acceptable coefficient so that its effect on the total radiation is not negligible. From Figures 2 and 5, we see that higher modes contribute more to the radiation at higher frequencies ($| \lambda_n = 0 |$ or MS is close to 1), where in the lower band the first two modes are responsible for the radiation. Radiation patterns in lower frequency band [0.5-2] GHz are stable despite that mainly the first two modes are radiating. This may have a secondary effect on the total efficiency, which will be studied in further work. As described in the previous section, manipulating modes (first 6 modes) on the radiator allow to determine how we can modify the shape to ensure that the mode radiates better. This is the case with the first, 5th and 6th modes at 7.78 Ghz where one can observe (Figures 7, 8 and 9) that J_1 and J_5 does not radiate properly and J_6 is radiating in an orthogonal direction to the desired pattern which causes the dip in the total radiation pattern since the MS of the this modes (J_6) is high at this frequency. This problem was solved by inserting a $\lambda/2$ slot in V shape in order to change the mode current path without changing other modes current (Figures 10 and 11) neither the power matching (Figure 12).

4. Numerical and experimental results

Figure 13 shows the simulated and measured S_{11}-Parameters of the fabricated antenna with the slot described in the pervious section. The return loss value is less than -10 dB in the range of frequencies extending from 0.67 to 12 Ghz. In Figures 7, 8 and 9 the effect of the slot on the radiation patterns due to the current densities J_1, J_5, and J_6 can be observed. The other modes pattern are not affected by to the current density analysis done previously .The total power pattern is very stable in the whole frequency range as shown in Figure 14. If the performances of the antenna described in this paper are compared to a reference antenna proposed by Liu et al [3], one can note that the smallest operating frequency is 670 MHz for our antenna compared to 1.07 GHz for the reference antenna. Moreover, the total dimensions of the our proposed antenna is 68×33 mm^2 while the reference antenna has total dimensions of 124×110 mm^2, the comparison shows that the proposed antenna is smaller five times than the reference one.

5. Conclusion

In this paper, the design, simulation and measurement of an EWB antenna are presented. A miniaturized design was proposed with an antenna five times smaller than previously published one. The theory of characteristic modes was used to analyze and optimize the excitation and radiation behavior. Very good performances are obtained for S_{11}-Parameters of this miniaturized antenna with a very good agreement between simulations and measurement. The antenna radiation pattern is very stable in the frequency band.

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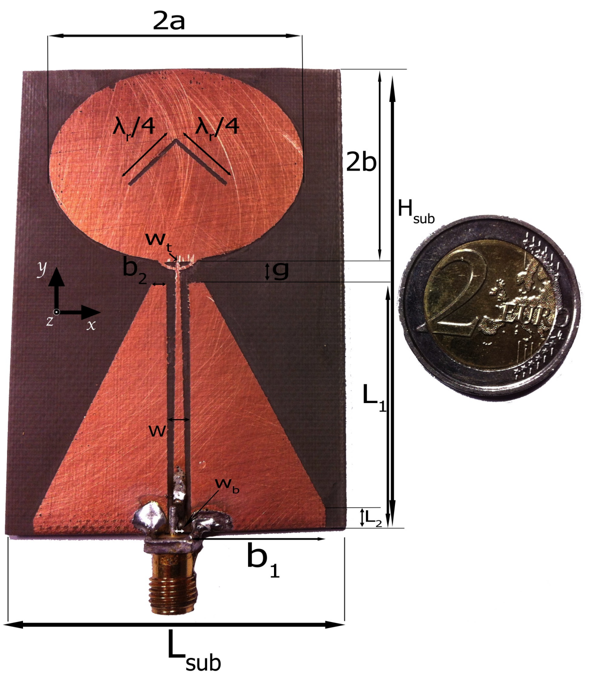


Figure 1: Proposed antenna printed on an 1.55 mm thick Arlon substrate (εr=10.2, tan(δ)=0.0023)

H_{sub}	L_{sub}	a	B	L_1	L_2
68	33	15	13	35	3.5
b_1	b_2	W	w_b	w_t	G
15	2	3.15	1.7	0.35	3.28

Table 1 Dimensions of the proposed antenna [mm]

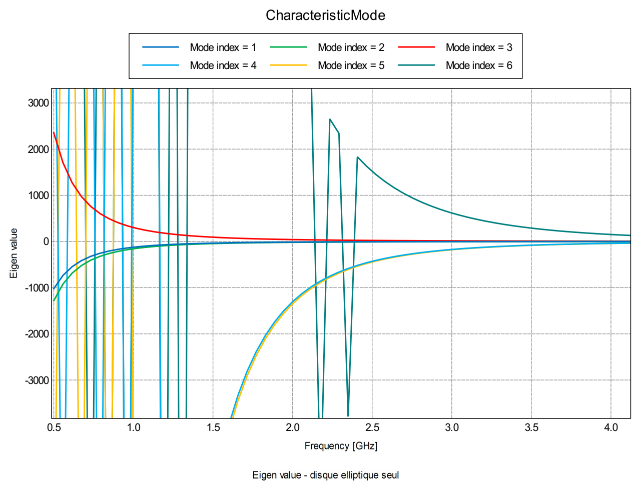


Figure 2: Eigen values of an elliptical disc 15×13 mm

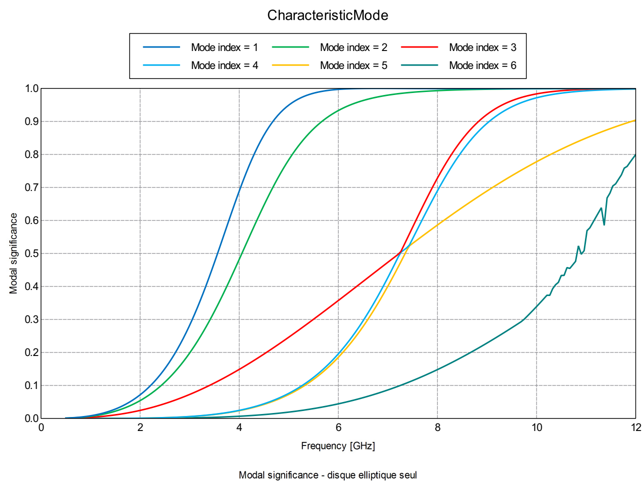
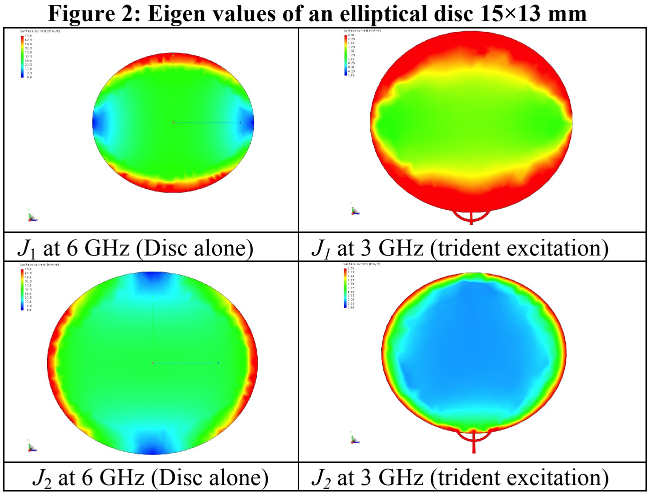


Figure 3: Modal significance of an elliptical disc 15×13 mm.



J_1 at 6 GHz (Disc alone) | J_1 at 3 GHz (trident excitation)

J_2 at 6 GHz (Disc alone) | J_2 at 3 GHz (trident excitation)

Figure 4: Impact of trident excitation on the first two modes.

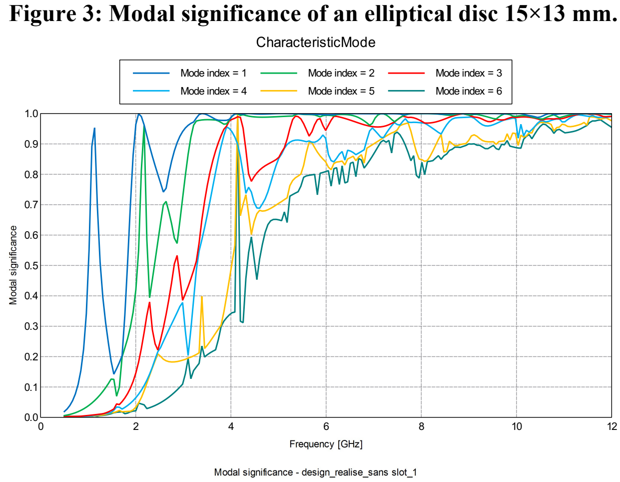


Figure 5: Modal significance of the antenna without slot.

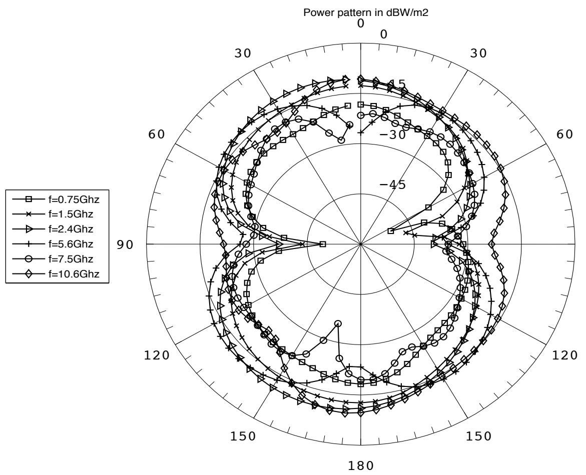


Figure 6: Power pattern of the antenna without slot over the entire band

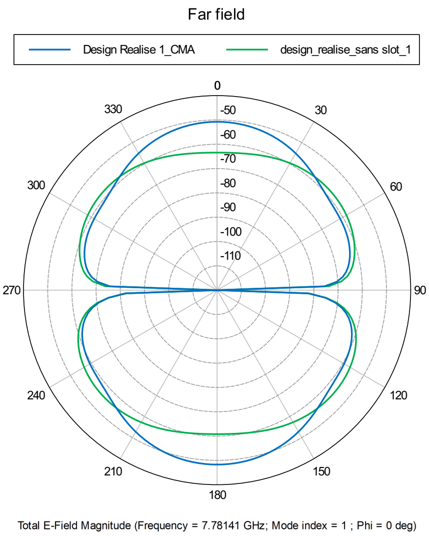


Figure 7: Slot effect on the 1th mode radiation pattern at 7.78 Ghz

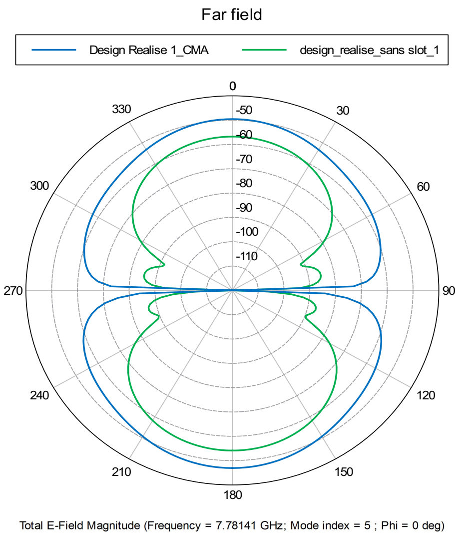


Figure 8: Slot effect on the 5th radiation mode pattern at 7.78 Ghz

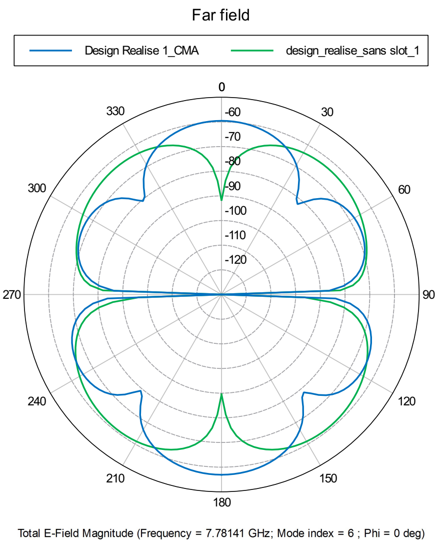
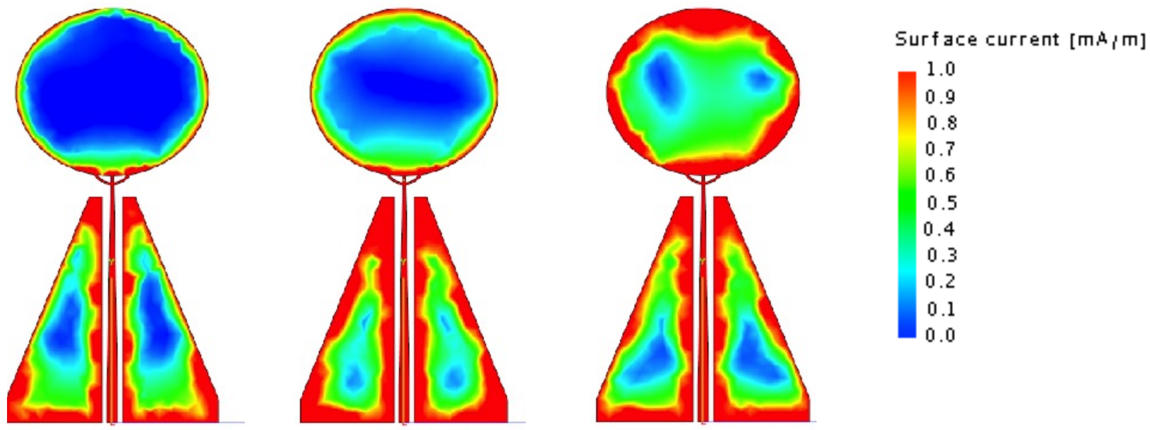


Figure 9: Slot effect on the 6th radiation mode pattern at 7.78 Ghz



J_1 J_5 J_6

Figure 10: Current density of the antenna without slot at 7.78 GHz for the 1st, 5th and 6th mode (Scale [0-1] mA/m)

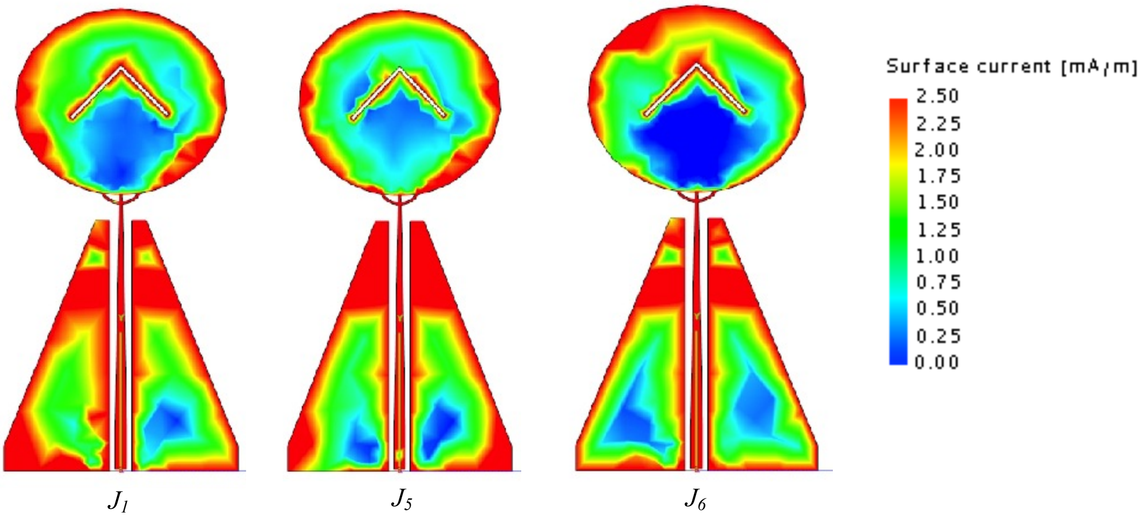


Figure 11: Current density of the antenna with slot at 7.78 GHz for the 1st, 5th and 6th mode (Scale [0-2.5] mA/m)

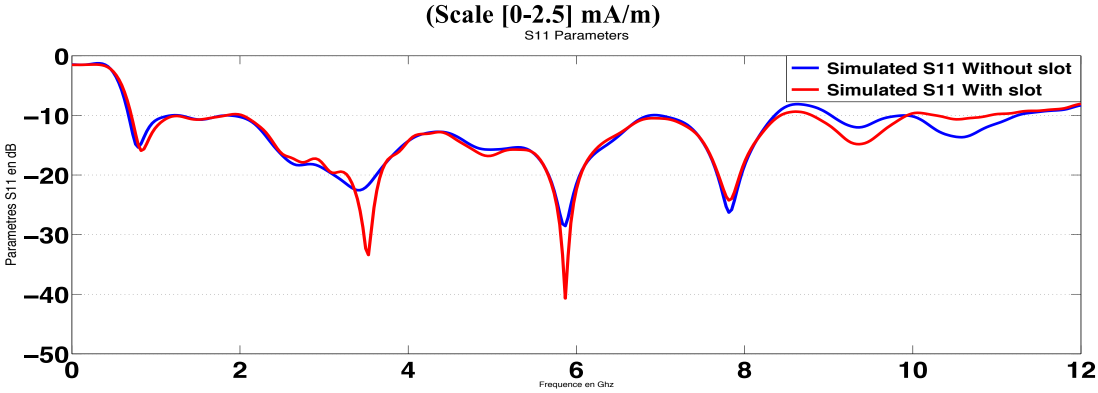


Figure 12: Simulated S11-Parameters showing the slot effect.

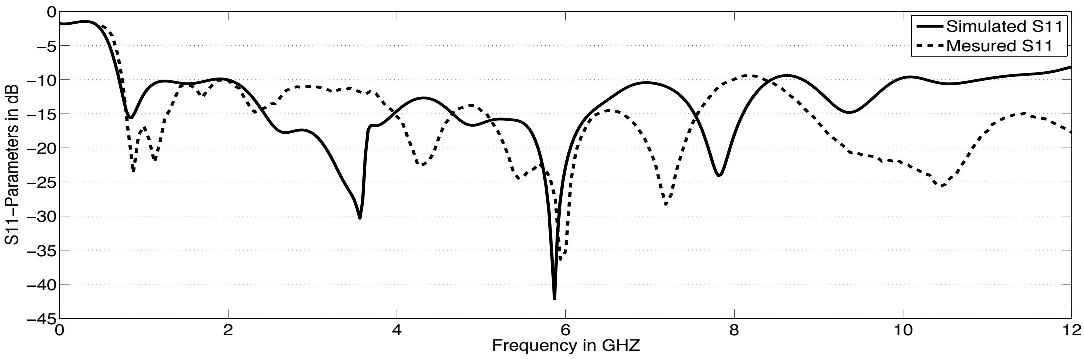


Figure 13: Comparison between simulated and measured S11

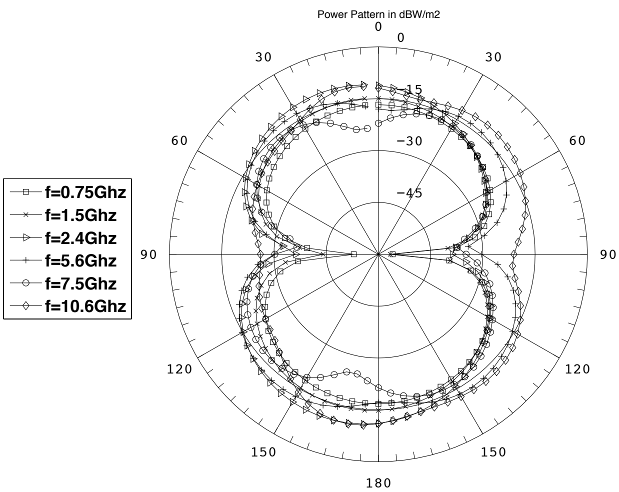


Figure 14: Power pattern of the antenna with slot over the entire band