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A Compact Loaded DETSA Antenna With Enhanced Directivity Using Characteristic Modes Optimization

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Abstract— This paper presents the design of an Ultra Wideband (UWB) antenna mainly dedicated for Ground Penetrating Radar (GPR) application in the frequency band between 150 MHz up to 550 MHz. With its compact electrical size, the initial double exponentially tapered antenna (DE TSA) exhibited a low directivity and Front-to-Back ratio in the lower band. With the guidance of the Characteristic Modes Analysis (CMA), it was possible to identify the best loading position as well as the optimized load values to enhance these antennas properties. The optimized loaded DETSA demonstrated a significant directivity enhancement and a Front-to-Back ratio that exceeds 4dB in the band.

Keywords—UWB, DETSA, Characteristic modes analysis, Network Characteristic loads, embedded loading, GPR.

I. INTRODUCTION

In the light of the massive advancement of Ultra Wideband (UWB) systems, the demand on the antenna properties in terms of size, weight, profile and radiation performance is becoming more and more exigent [1]. In general, the constraints imposed on reducing the physical size of the antenna imply a significant degradation in the performance of the antenna and hence a poor UWB system performance. It is therefore necessary to find new design approaches that provide the best compromise between the antenna size and the desired system performance.

In the past decade, Characteristic Modes (CMs) became a very popular approach in antenna designs [3,4]. The deep physical insights provided by the Characteristic Modes Analysis (CMA) offers guidelines towards enhancing the performance of the antenna under study. Another interesting form of CMs is the Network Characteristic Modes (NCMs) [5] which deals with the antenna as a multiport network. This aspect have found interesting application in boosting the performance of small antennas in terms of directivity and bandwidth. By combining the NCM with an optimization algorithm, the authors in [6-7] introduced a design methodology to find the optimized loads that can achieve a desired antenna performance.

An exhaustive number of UWB antennas could be found in literature [8-10]. The Double Exponentially Tapered Slot Antenna (DESTA) represents an interesting candidate for UWB applications due to its compact size and ultra large bandwidth [9-10]. However, despite its large bandwidth, DETSA designs generally suffer from low directivity in the lower part of their operating band. This characteristic might be an inconvenience in certain UWB applications where the

high directivity and Front-to-Back Ratio (FBR) of the antenna are essential to maintain an efficient system performance. This is the case for GPR systems whose resolution is dependent on the radiation properties of the antenna [10].

This paper presents the design of a DETSA antenna with enhanced directivity and FBR in its bandwidth of operation. The design approach is based on the methodology proposed in [6]. An initial DESTA geometry, which exhibits a poor directivity in the low band is proposed. Using the CMA, internal port positions are defined for eventual loading inside the antenna structure. The multiport impedance matrix of the antenna is then used to compute the NCMs of the multiport antenna and their associated characteristic fields. Finally, the NCM is combined with an optimization algorithm in order to find the weighting coefficients of the characteristic fields that would boost the directivity of the antenna in the desired band. Based on these weighting coefficient, the embedded antenna loads are computed. The loaded antenna exhibits significant enhancement compared to the unloaded case. A prototype is fabricated and experimental characterizations of radio electrical properties confirm the antenna performance improvements.

II. ANTENNA DESIGN

The initial DETSA geometry (Antenna I) is shown in *Figure 1* (a). The antenna occupies an area of 552 x 413 mm² and is excited at port 1. The tapered curves C1 and C2 are expressed in (1) while their associated parameters are given in *Table 1*.

$$\begin{cases} C1(x) = s * \exp(r_1 * x), & 0 < x < TL_1 \\ C2(x) = w_0 + s * \exp(r_2 * x), & 0 < x < TL_2 \end{cases} \quad (1)$$

Table 1 parameters of the tapered contours C1 and C2

s	r_1	r_2	TL_1	TL_2	w_0
2.7	0.0078	0.0109	600	390	60

Antenna I (Design I) exhibits an unstable radiation in the bandwidth of interest [Figure 2]. Below 300 MHz, the radiated power of Antenna I is distributed almost equally between the front and the backwards hemisphere. This is reflected by the FBR which is close to 0 dB in the frequency band below 300 MHz [Figure 6 (b),blue curve]. Moreover, in

this frequency band, the antenna suffers from a poor directivity in the forward direction ($\phi = 0^\circ, \theta = 90^\circ$) [Figure 6 (a)]. This radiation behavior is unsuitable for certain UWB applications where it is essential to maintain a directive pattern throughout the operating bandwidth in the direction of a specific target.

Enhancing the radiation properties of the proposed antenna could be possible by applying some geometrical optimizations. However, such approach is time consuming especially with the presence of various design parameters that could make it more complex to optimize the geometry.

The radiation pattern of Antenna I could be simply modified by introducing loads at specified positions inside the antenna geometry. These loads will serve in manipulating the surface current distribution of the antenna in order to boost the radiation in the forward hemisphere. The proposed approach is inspired by the methodology presented in [6]. Using the radiation patterns of the characteristic fields, the modal weighting coefficient a_n were optimized in order to maximize the directivity in a desired direction. The value of the parasitic loads was then calculated in order to generate the optimized current.

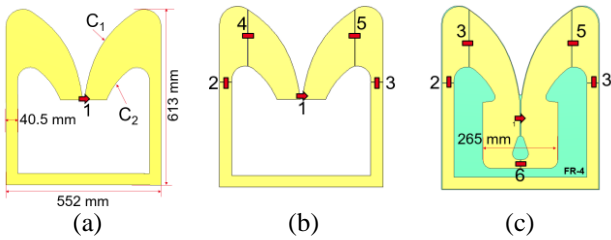


Figure 1 Antenna geometry. (a) Antenna I, (a) Antenna I with embedded ports, (c) Antenna II with embedded ports

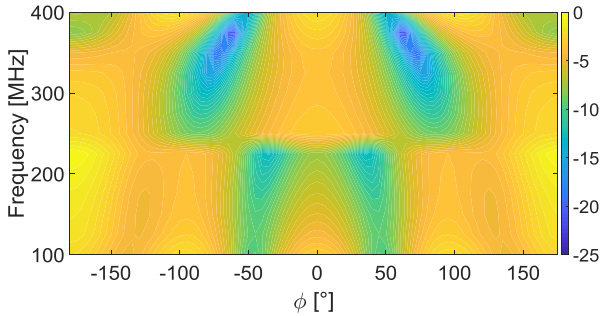


Figure 2 Normalized radiation pattern of Antenna I versus frequency

A. CMA of the Initial Antenna

Before applying the design methodology in [6], loading positions have to be identified on the antenna structure. This step is critical in order to ensure an efficient contribution of the optimized loads in the modification of the radiation pattern of the antenna

Based on the characteristic modes analysis, four loading positions have been selected as illustrated in Figure 1 (b). Two loads are placed in the upper part of the closed loop strip, while the other two ports are placed in the front part of the tapered geometry. These positions were chosen after analyzing the characteristic modes that are supported by the

antenna structure. Figure 3 shows the Modal Significance (6) of the modes in the bandwidth of interest. modes 1 and 2 are resonant at 150 MHz, while mode 4 becomes significant around 250 MHz. The surface current distribution of modes 1, 2, 4, 5, 6 is shown in Figure 4. modes 1, 5, and 6 exhibit current nulls at the pre-defined excitation position (port 1 as shown in Figure 1). Hence, these modes will not be coupled with the excitation to radiate energy and therefore will not be considered in the analysis. On the other hand, at 250 MHz, mode 4 exhibits a maximal current in the top part of the close loop strip. This high current distribution is at the origin of the low forward directivity of Antenna 1 [Figure 6 (a)]. Hence, the first two loading ports (2 and 3) are chosen at this position. It should be noted that mode 4 exhibits equally a high current distribution in the backward strip. However, for the sake of simplicity no loads have been defined at this position. On the other hand, mode 2 (at 150 MHz) exhibits high surface current distribution at the excitation point. Since Mode 2 contributes in the radiation of the antenna in the lower part of the band, the other two ports (3 and 5) are placed in the front tapered geometry. These ports would contribute in enhancing the radiation properties of the Antenna 1 in the lower part of the band as well as in the high frequencies.

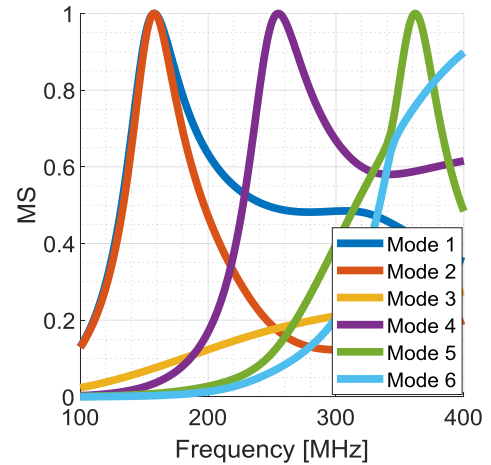


Figure 3 Modal Significance of the initial Antenna

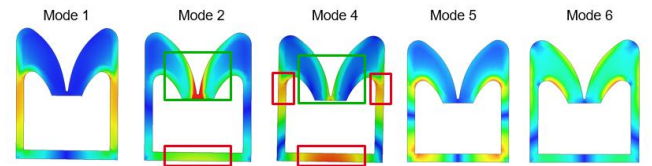


Figure 4 Surface current distribution of the characteristic modes

B. Loaded Antenna

After specifying the desired loading position thanks to CMA, the impedance matrix of the 5-ports antenna [Figure 1 (b)] is calculated using the full wave simulator.

The radiation patterns of the network characteristic fields in the azimuth plane versus frequency are given in Figure 5. It

should be noted that with the actual 5-ports configuration, there exists 5 characteristic fields. However, the characteristic currents \bar{I}'_4 and \bar{I}'_5 present a null at the excitation position, which implies a null radiation in the desired direction. Hence the radiated fields E'_4 and E'_5 are not taken into account in the optimization.

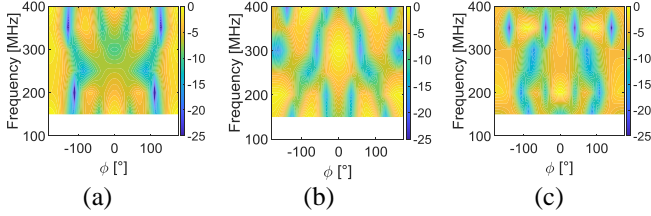


Figure 5 Normalized radiation patterns of the network characteristic fields. (a) E'_1 , (b) E'_2 , (c) E'_3 .

Following the optimization procedure in [6], the modal weighting coefficients are calculated at discrete frequency points in the bandwidth 150MHz-400 MHz. The loading values at the internal ports are then deduced from the optimized modal weighting coefficients. Table 2 shows the chosen load values at port 2 ($R1=52 \Omega$, and $L1=561 \text{ nH}$) and port 3 ($R2=7 \Omega$, $L2=7.8 \text{ nH}$). a sub-optimal solution is proposed where the optimal loads at 150 MHz are placed at ports 2 and 3 in order to suppress the currents in the closed loop at low frequencies [Table 2]. With this configuration (Design II), the antenna exhibits an enhanced performance compared to the initial design [Figure 6], with up to 6dBi enhancement in the directivity in addition to a 3dB increase in the FBR.

In order to improve the radiation performance of the antenna and to bring the design closer to a practical realization, some geometry modifications (Antenna II) are applied. The excitation of Antenna II is backed by a tapered circular form and mounted on a 1.6 mm FR4 substrate ($\epsilon_r = 4.3$, $\tan\delta = 0.02$) [Figure 1(c)]. The overall dimensions of the modified antenna are identical to the initial one. Five internal loading positions are identified using the guidelines of the CM analysis. Following the same approach above, the internal ports are loaded by the following optimized load given in Table 2.

Table 2 selected load values

Antenna	Port 2& Port 3	Port 4 and Port 4	Port 6
I	R=52 Ω L=561 nH	R=6.7 Ω L=7.8 nH	N/A
II	L=390 nH	R=7 Ω L=1.6 nH	R=300 Ω

With this configuration (Design III), the antenna exhibits an enhanced directivity over the whole band ($D_{Max} = 6 \text{ dBi}$ at

300 MHz), associated with an enhanced FBR ($FBR_{Max} = 8.7 \text{ dBi}$) as shown in Figure 6.

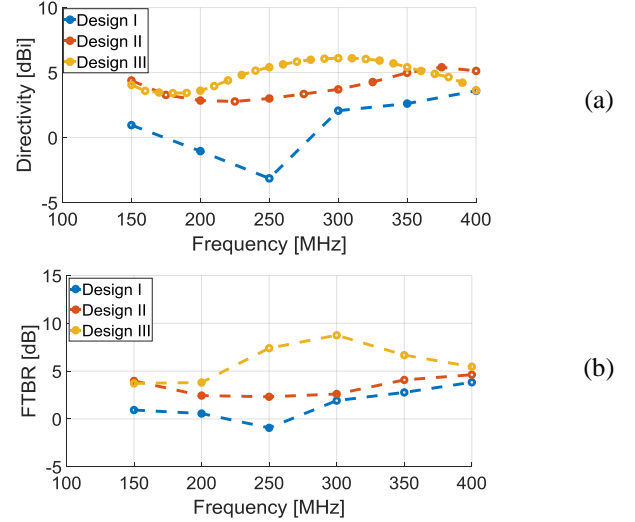


Figure 6 Performance of the different designs. (a) Directivity($\phi = 0^\circ, \theta = 90^\circ$), (b) front-to-back ratio.

III. MEASUREMENTS

The loaded Antenna II was fabricated and measured. Figure 7 shows the impedance and radiation measurement setups of the optimized design. The loaded antenna exhibits an UWB impedance behavior showing a good agreement with the simulation Figure 8 (a). The antenna impedance is matched to 50 Ohms ($|S_{11}| - 10 \text{ dB}$) from 160 MHz up to 560 MHz. On the other hand, the IEEE gain in the forward direction ($\phi_0 = 0^\circ, \theta_0 = 0^\circ$) exhibits degraded values in the bandwidth [200-300 MHz]. This is due to the resistive load at port 6 which degrades the radiation efficiency of the antenna. However, the antenna maintains a directive pattern starting from 150 MHz (Figure 9). The 2D gain pattern plotted in the azimuth plane as a function of frequency shows a stable beam shaping in the direction of interest. Therefore, by combining the NCM with the DE algorithm, it was possible to optimize the radiation performance of the DETSA antenna in an UWB.

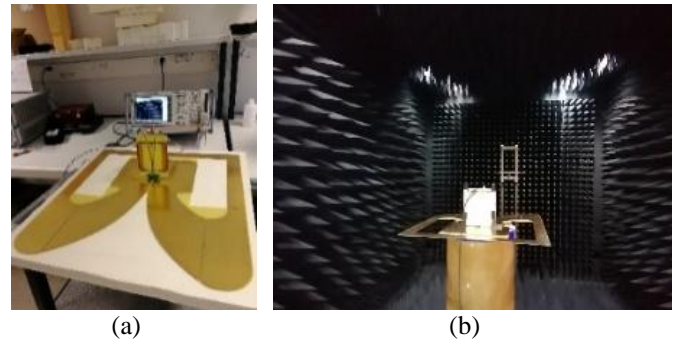


Figure 7 Fabricated Prototype and measured setup in VUHF large size anechoic chamber

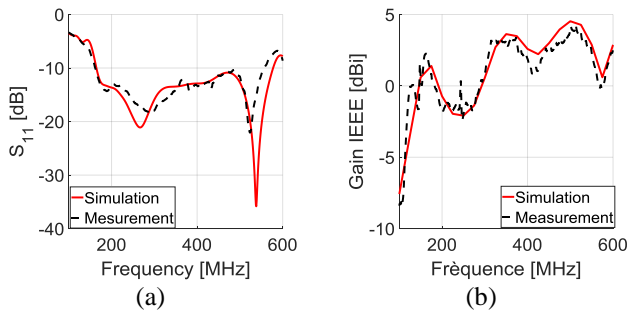


Figure 8 Input reflection coefficient of the measured prototype versus simulation results.

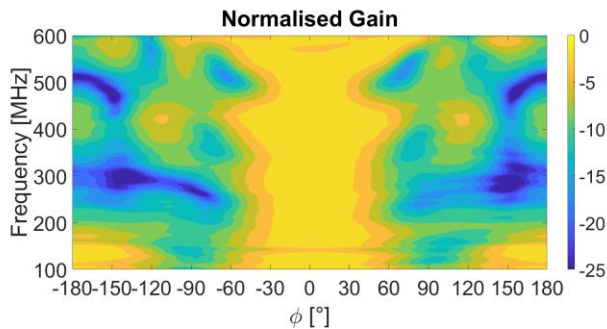


Figure 9 Normalized gain in the azimuth plane as a function of frequency.

IV. CONCLUSION

This paper presents a systematic approach to design an UWB antenna for high resolution GPR application. Starting with an initial DETSA antenna having a poor directivity and FBR, it was possible to improve the antenna radiation performance using embedded optimized loads. The load positions and values was determined using the characteristic modes analysis. Compared to the initial design, the loaded antenna exhibits a significant enhancement in directivity (up to 7 dB increase at 250 MHz) and FBR (8 dB increase at 250 MHz). The fabricated loaded antenna exhibits a good agreement with the simulation with an UWB impedance matching in addition to a directive pattern over the whole bandwidth of operation.

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