Wheel-of-Time Array Devoted to Near-Field Imaging Applications

K. Alkhalifeh(1), R. Sarkis(2), C. Craeye(1)
(1)Université catholique de Louvain, (2) AGC company
ICTEAM Institute, Place du Levant, 2, 1348 Louvain-la-Neuve
{khaldoun.alkhalifeh, christophe.craeye}@uclouvain.be, remi.sarkis@eu.agc.com

Abstract— **The design and fabrication of an ultra-wideband (UWB) imaging radar system for near-field applications is presented. First, the geometric parameters related to the elliptical curve of Vivaldi antenna, i.e. major and minor radii and center, are introduced as additional design parameters. Second, the complete circular UWB radar imaging system is fabricated. Finally, time-domain responses of a target under test are processed. An initial near-field image of the target under test in the area of radiation exposure is depicted, and the target is localized.**

I. INTRODUCTION

Recent years have seen a growing interest in exploiting ultra-wideband (UWB) technology for imaging applications. The wide bandwidth provides the range resolution, while the array interferometry provides the azimuthal discrimination. UWB systems are used in medical applications to obtain internal images of various objects [1]. Large bandwidth is very important for this type of applications, where high frequencies provide high resolutions and low frequencies penetrate considerably deeper into the object.

Vivaldi antennas printed on a substrate have been used in several imaging systems [2]. Recent studies focused on metal antennas to reduce loss in the dielectric material [3]. In the current work, 10 connected metal elements were arranged in a circular array to form the UWB imaging system, which we called the "Wheel-of-Time" (name proposed by Eloy de Lera Acedo from University of Cambridge) [8]. New design solutions for Vivaldi antennas were applied to improve the antenna efficiency over the bandwidth of interest. The new method is based on the formulation of the design curves, which are main elements of the antenna construction.

One approach to imaging a target is radar-based. A short-time pulse is sent toward the target under test (TUT) using one or more antennas. In the presence of a target, reflections can be measured and inform us about the composition of the object. Recently, time-domain systems have been successfully used for breast cancer detection [4].

The remainder of this paper is organized as follows. Section II presents the design of a traditional 3D Vivaldi antenna. Then, the new design solution is applied on the antenna and the improved 3D Vivaldi antenna is discussed. In Section III, the "Wheel-of-Time" array is presented. The experimental setup in the presence of a reference target (RT) is illustrated. In Section IV, time-domain responses are processed in the free space, reference target and TUT by performing an Inverse Fourier Transform. An imaging algorithm is implemented to give an initial localization of targets. The image map has been located successfully the target. Section V concludes the paper.

II. DESIGN OF THE ISOLATED 3D VIVALDI ANTENNA

A. *Traditional 3D Vivaldi antenna*

Notch-antenna feeds are usually comprised of a stripline-to-slotline or microstrip transitions [5]. This complex feeding adds significant losses, and affects at the sensitivity of the receiving arrays.

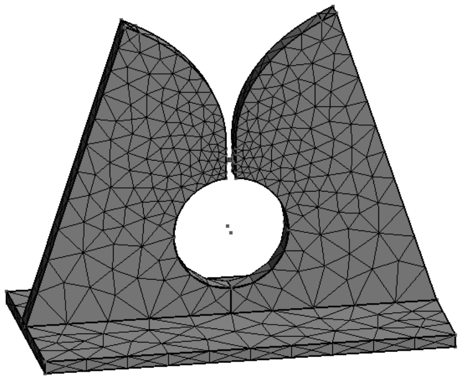

Figure 1: Mesh view of the 3D Vivaldi antenna.

One of the best solutions to overcome this problem consists of considering the feed as one of the built-in 3D metal antenna component like 3D Vivaldi circular array [6]. The shape of the traditional Vivaldi slot has been modified to fit the design of the circular antennas array as shown in Fig.1. The type of taper profile is elliptical.

An electromagnetic simulation software (MOM3D) developed at UCL and based on the Method of Moments is used to simulate the different structures.

The width of the ground plane is chosen to 10 cm, and the thickness to 5 mm for the optimized behavior.

The effect of adding the ground plane mainly appears at lower frequencies (Fig. 2), through a reduction of the real part of the antenna impedance. The simulation result exhibits a bandwidth from 1.6 GHz to 4.6 GHz with respect to a -10 dB matching criterion, except for the slightly inconvenient peak between 2 and 3 GHz. Thus, to optimize the antenna for the entire required frequency band of 1.6 GHz to 4.6 GHz more parameters should be played with.

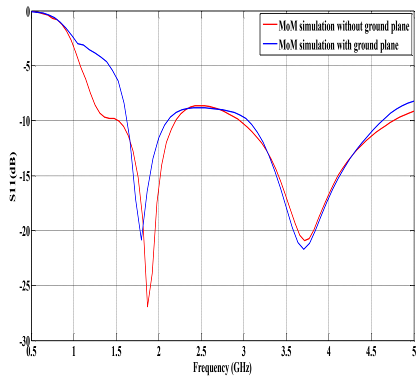

Figure 2: Effect of adding the ground plane on the reflection coefficient.

B. *The improved 3D Vivaldi antenna*

In tapered slot antennas, the general frequency of radiation depends on the width of aperture. The taper profile of a Vivaldi antenna provides all possible aperture widths from the higher frequencies (minimum distance) to lower frequencies (maximum distance). As a result, the shape of the taper profile is crucial for wideband antenna performance.

By keeping the start and end points of the elliptical arc at pre-determined positions, one can obtain a set of center positions and corresponding major and minor radii for optimization, as illustrated in Fig. 3.

The elliptic profile is parameterized as:

$$\frac{(x-x_c)^2}{b^2}+\frac{(y-y_c)^2}{a^2}=1$$

Where $C(x_c,y_c)$ is the ellipse center.

Let us consider the known points $S(x_1,y_1)$ as the start point of the arc, and $E(x_2,y_2)$ as the end point.

$$(x_1-x_c)^2.a'^2+(y_1-y_c)^2.b'^2=a'^2.b'^2 \quad (1)$$

$$(x_2-x_c)^2.a'^2+(y_2-y_c)^2.b'^2=a'^2.b'^2 \quad (2)$$

By subtracting (1) from (2), we get

$$\frac{a'}{b'}=X=\sqrt{\frac{(y_2-y_c)^2-(y_1-y_c)^2}{(x_1-x_c)^2-(x_2-x_c)^2}}$$

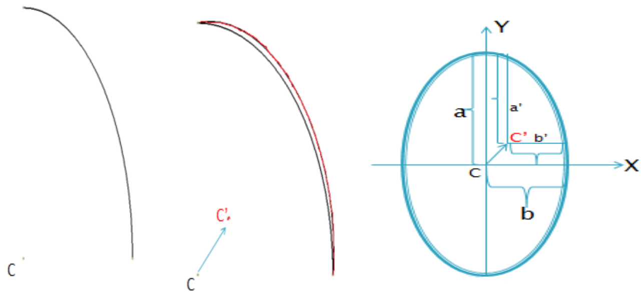

Figure 3: If one wants to move the ellipse center from $C(x_c,y_c)$ to $C'(x_c',y_c')$ while keeping the start and end points of the elliptical arc at specific positions, it is necessary to recalculate the major and minor radii, a' and b' respectively.

Then,

$$b'=\frac{\sqrt{(x_1-x_c)^2.X^2+(y_1-y_c)^2}}{X}$$

$$a'=\sqrt{[(x_1-x_c)^2.X^2+(y_1-y_c)^2]}$$

The last two parameters could be easily calculated from the start and end points of the elliptical arc, and the position of the new ellipse center.

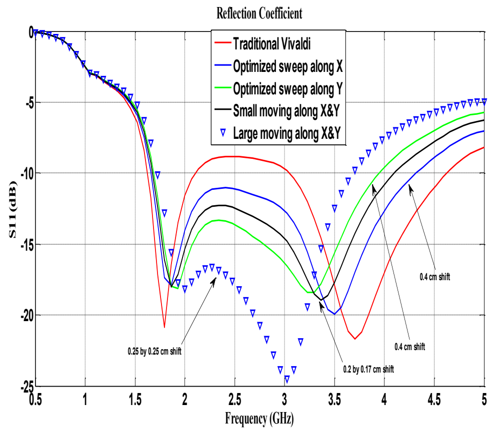

Figure 4: Reflection coefficients obtained by changing the ellipse center along X and Y axes.

This technique has been applied to the 3D single Vivaldi antenna. The simulation results confirm the importance of optimizing the elliptical curve in the Vivaldi antenna, as seen in Fig. 4.

The ellipse center has been shifted for many positions along only X, only Y and X&Y axes. 0.4 cm center shift is used along the X axis only (shown in blue line, Fig.4). The same value is used along the Y axis only (shown in green, Fig.4). In the same way, giving small steps along X and Y together (0.2 cm, 0.17 cm) slightly affect the reflection coefficient (shown in black, Fig.4), which large shifts (0.25 cm, 0.25 cm) contribute significantly to changing the reflection coefficient over the band of interest (shown in blue triangles, Fig. 4). Lowering the low frequency radiation cut-off without increasing the antenna size is one of challenges for the design of Vivaldi antennas. From simulation results, obtained for varying positions of the ellipse, promising solutions are achieved. One more validation (Fig. 5) is made with the CST Microwave Studio software, for the case of the center of the ellipse shifting along X and Y, in small steps (black curve shown in Fig. 4).

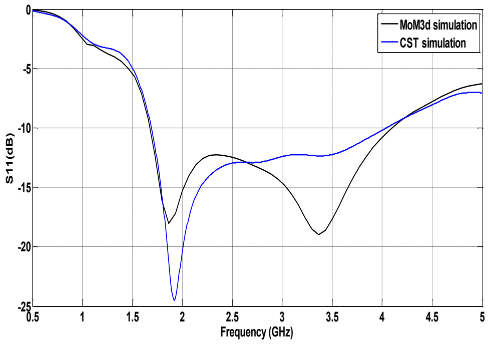

Figure 5: Comparison between the reflection coefficient obtained from simulations with MoM3D and CST for the case "center shift along X&Y, in small steps".

III. WHEEL OF TIME ARRAY

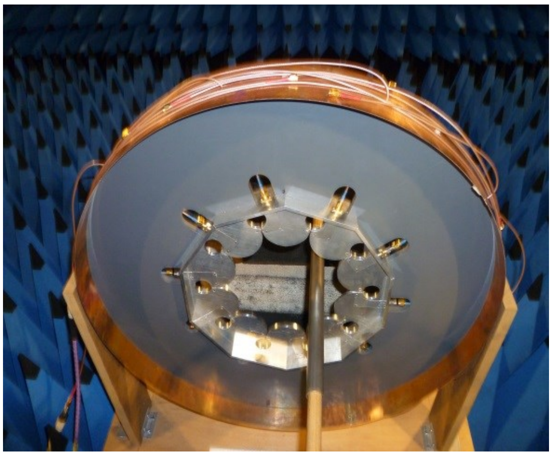

Figure 6: UWB radar imaging system prototype, illustration of the experimental setup.

The configuration of the proposed UWB microwave imaging system [7] is illustrated in Fig. 6. The system is built around a 10-element circular array antenna. We named it the "Wheel-of-Time" [8]. A reference target (hollow metallic tube with a diameter of 2.25 cm and a thickness 0.3 cm) is located at the position of (-3.5 cm, -3 cm).

IV. PRELIMINARY IMAGING

An imaging algorithm, inspired from positioning procedures [9] is implemented for imaging a target. The "wheel-of-Time" had just been fabricated, so the measurements have been taken without fine array calibration. The method uses the time-difference of arrival at each receiver with respect to a reference target [10]. The imaging algorithm relies on correlations Cr,i between signals received at a given antenna and those predicted from a reference target with the same transmitting antenna.

Time domain responses are shown in Fig. 7 for two cases: the free space and the reference target when antenna 1 is transmitting and antenna 2 is receiving (next to each other).

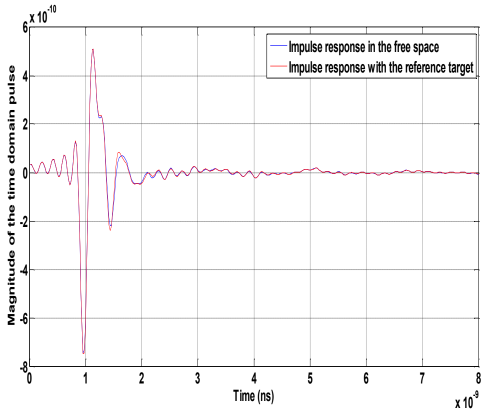

Figure 7: Impulse responses obtained from measurements in the anechoic chamber and VNA.

The obtained impulse duration is 0.4 nanosecond. This duration indicates that the antennas present very little dispersion and are favorable to accurate localization and positioning.

The same metallic tube is used as a target under test at a different position (shown in a dark circle, Fig. 9).

It is to be noted that multiple reflections between the target and the array is not accounted for by this algorithm. Fig. 8.b shows how difficult it is to distinguish the TUT response among signals scattered from other antennas.

For every pixel on the image map, this time difference is calculated a priori and is tabulated.

$$\Delta t(x; y) = \frac{(TRR - TTR)}{c}$$

where Δt(x; y) is the time difference for the round trip TRR (transmitter-reference-receiver) and TTR (transmitter-target-receiver) for the pixel at (x; y) as indicated in the image map Fig. 9 and c is the speed of light. The size of the observation field is 12 by 12 cm.

The initial image is obtained after production of every pixel corresponding to all possible positions of the target in the area of radiation exposure.

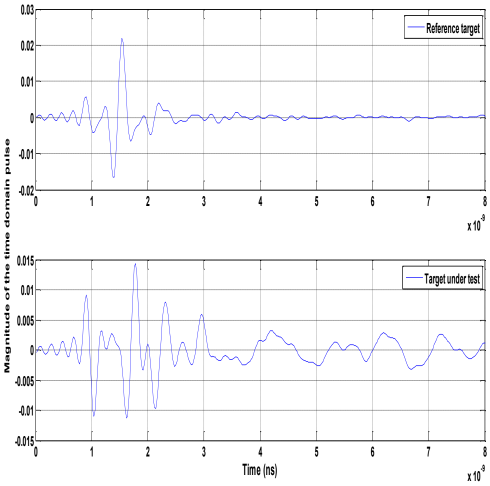

Figure 8: The difference in time between time domain responses: a) free space and the RT b) free space and TUT.

The correlation function Cr,i is the correlation between the response Vt;i(t) at receiving antenna i and the reference response Vt;r(t+Δt) at the same receiving antenna, where Δt corresponds to the time difference in the arrival for the round trip TRR and TTR. The shown ripples are due to non-zeros ripples generated by correlations between the reference antenna and estimated targets. The image map shows a good recognition of the target dimensions and position.

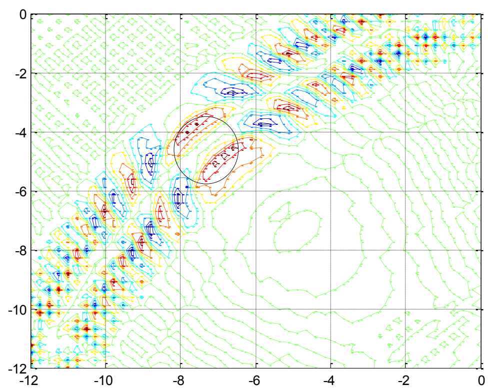

Figure 9: Image map obtained from measured responses.

V. CONCLUSION

An additional degree of freedom in the Vivaldi antenna design is added by modifying the major and minor radii of the ellipse curve, as well as the position of the center with respect to the feeding point. A UWB imaging prototype consisting of 10 elements has been realized. Time-domain responses have been processed in order to provide an initial image and locate small targets. The image map indicates that the algorithm successfully finds the target under test for smooth surfaces. A precise calibration procedure and a more advanced imaging algorithm will be developed to allow the study of more complex targets.

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