# Development of Rotating Antenna Array for UWB Imaging Application

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***Abstract*-The detection of concealed metallic weapons in bags/suitcase by using UWB (ultra widbeband) imaging is a cheap alternative to the security in the airport, subway or public area, compared to X-ray machines. In this paper, we have proposed and studied a novel UWB imaging system, including a rotating UWB antenna array, RF components and the 2D implementation of the delay-and-sum (DAS) imaging algorithm.**

***Keywords—UWB imaging; Antenna array; Time-domain; Delay-and-Sum***

## I. INTRODUCTION

Imaging is one of the most popular applications of UWB (ultra wideband) technology, for the reasons of low cost and no health hazards. The detection of concealed metallic weapons in bags/suitcases is vital to the security in the airport, subway or public area. To reduce the cost associated with the deployment X-ray machines, UWB imaging technology is proposed to be a cheap alternative. Suitcase imaging is based on the UWB Radar technology to detect and locate the object through the opaque obstacle. This imaging technology works on the contrast of the permittivity of the target and the surrounding material. Due to the strong contrast between metal targets and other objects in the suitcase, it is easier to attain the imaging of metal targets.

In order to achieve better resolution and imaging result, most of the existing UWB imaging systems have a large profile because of the large antenna array structure. For example, the UWB 3D imager presented in [1] is able to image the concealed objects in the suitcase and people over a distance. It uses four antenna array units, operating as two independent bi-static Radars, which are co-polar vertical and co-polar horizontal polarization respectively. Each antenna array unit contains 25 elements, total in 49 cm length. Although this system can be applied in multiple applications, it is not in compact size. The UWB through-wall imaging system in [2] uses 16 Vivaldi antenna array elements for its antenna structure, each of which also consists of 16 single antennas. It is not so complicated in the array structure, but the coupling between so many antennas needs to be considered while designing.

This paper will present a novel UWB imaging system with a spiral rotating antenna array. The rotating antenna array make the imaging system compact and low cost. The paper is structured as follows. The structure and the performance of the rotating antenna array will be described in details in the second section. The two-dimensional reconstructed imaging method based on delay-and-sum (DAS) algorithm will be presented in the third section. Then the simulated results will be discussed in the fourth section. Finally, the conclusion will be given.

## II. ANTENNA ARRAY

### *A. Corrugated Balanced Antipodal Vivaldi Antenna*

In order to make the UWB imaging system compact and better in imaging performance, the antenna element should be small and high/stable gain over the operating bandwidth. Considering these requirements, the Vivaldi antenna is a good choice for UWB imaging. Among most types of Vivaldi antennas, the balanced antipodal antenna is chosen as the candidate for our UWB imaging system.

A novel corrugated balanced antipodal Vivaldi antenna has been designed for our purpose. This antenna has three metallic layers and two supporting substrates. The structure of the three layers is shown in Fig. 1. Like the sandwich structure, the radiated antenna layer is in the middle of the two supporting FR4 substrates, while the top and bottom metallic layer, which can be treated as the ground layer, are attached on the outermost side of these two substrates. The top and bottom ground layer is in the same shape, as shown in Fig. 1 (a), while the centre radiated one is in the mirrored shape with them, as shown in Fig. 1 (b). The radiated flare is shaped of inner and outer exponential edge, and cut with linear slot lines.

TABLE I. THE DIMENSIONS OF THE CORRUGATED BAVA

| Parameter | W | L | wm | $L_1$ | $L_2$ | $d_s$ | $d$ |
|---|---|---|---|---|---|---|---|
| Value (mm) | 35 | 75 | 1.5 | 10 | 32 | 0.7 | 0.9 |

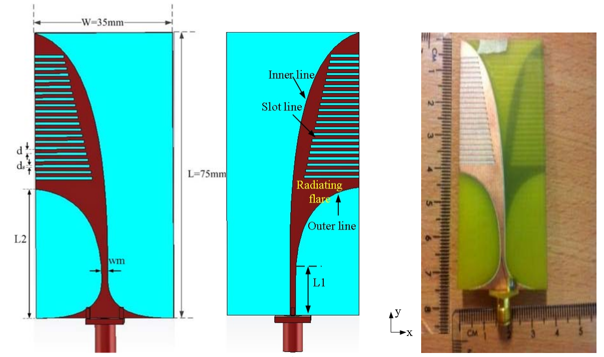


Fig. 1. Physical structure of the corrugated BAVA; (a) Top and Bottom layer view; (b) Middle layer view; (c) The fabricated antenna.

These slot lines are all in the same length ds along y-axis, keeping the same distance d between them. They are reduced in width along x-axis linearly from lower side to upside of the radiating flare. The dimensions of the parameters for this antenna are listed in Table I.

This antenna has an impedance bandwidth from 2.8 GHz up to 12 GHz in simulation and from 3 GHz to 12 GHz in measurement, as shown in Fig. 2. The red line is the measured result while the blue line is the simulated one. The deep attenuation around 5.5 GHz in simulation has been shifted to 4 GHz in measurement, mainly because of the gap between the two substrates at the side of the feeding SMA connector. The fabricated antenna only uses the SMA to connect the two substrates so that there will be a little gap of air between them.

The corrugated structure of this antenna can alter the phase of the currents flowing along the outer edges of the antenna substrate, and change the direction of the electric field at the edge of the substrate. It is evident from the current flow on the surface of the radiating layer at different frequency, shown in Fig. 3 (a). At 3 GHz, the current flow is forced to travel along the edge of the flare. At higher frequency, as shown in Fig. 3 (b), the current is not affected too much due to the slot lines. Thus, it can improve the gain of the antenna in lower frequency, as shown in Fig. 4.

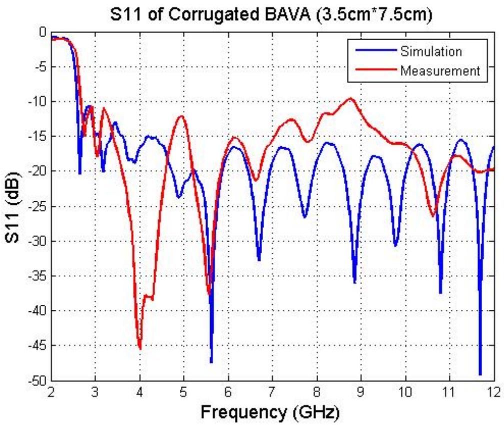


Fig. 2. The simulated and measured $S_{11}$ of corrugated BAVA.

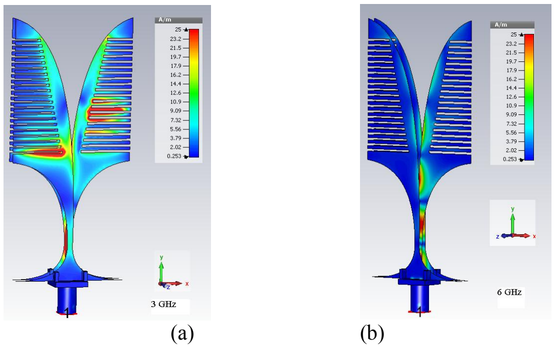


Fig. 3. Current flow on the surface of BAVA at different frequency; (a) 3 GHz; (b) 6 GHz.

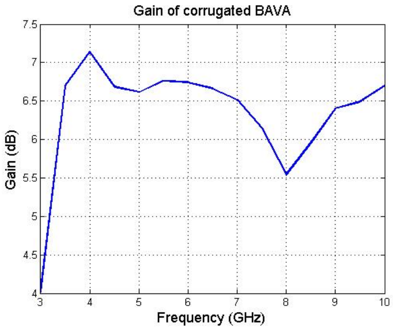


Fig. 4. Simulated gain of the corrugated BAVA.

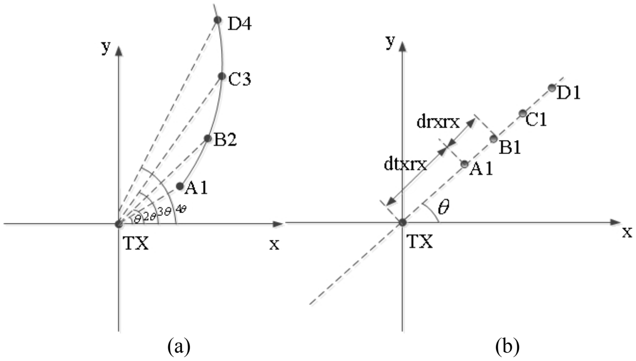


Fig. 5. The structure of the rotating receiving antenna array; (a) Rotating antenna array; (b) Equal arm of the receiving antenna array.

## *B. Rotating antenna array structure*

When used in the UWB imaging system, the rotating receiving antenna array is composed of four elements, placed on a spiral arm, as shown in Fig. 5 (a). The four elements receiving antennas are assumed as A1, B2, C3 and D4. The angle between the neighboring receiving antennas is assumed as $\theta$. After rotating one circle around the centre transmitting antenna, the four receiving antennas are equal to be the one in a straight arm, which are A1, B1, C1 and D1 shown in Fig. 5 (b). In such an arrangement, the distance $d_{rxrx}$ between the neighboring receiving antennas will not be limited by the antenna's width. Also, the mutual coupling between the elements can be reduced.

Although this rotating antenna array is composed of four elements, after rotating a circle, it is equal to have *N* elements of antennas in space. Here *N* is followed equation (1). It is obvious that the rotating antenna array structure make it possible to have large numbers of antennas equivalently in space by using fewer antenna elements in reality.

$$N=n\times 360^{0}/\theta \tag{1}$$

Where *n* is the number of elements in the receiving antenna array.

### C. *UWB imaging system*

This UWB imaging system used for scanning the concealed target inside the suitcase consists of RF front end, antennas and signal processing parts. The antennas consist of one fixed horn antenna to be the transmitting antenna and one rotating spiral receiving antenna array. An electromagnetic wave transmitting through RF is radiated by transmitting antenna, penetrates through the suitcase, and is reflected by the concealed target. Then it is received back via receiving antenna array. After the signal is received by the receiving antenna, it will travel through RF front end to the signal processing part. Finally through signal processing, the images will be reconstructed on a PC. The whole architecture of the imaging system is shown in Fig. 6.

The receiving antenna array rotates in space with the interval angle of θ. At each position, the receiving antenna elements work one by one controlled by the switch. When the receiving antenna array is rotated over 360 degree, it is equal to have a 2D antenna array with N elements. It is seen that the antenna elements/switches are reduced so that the whole system is cheap and more compact. Another important thing is that reducing the antenna elements, the coupling between antenna elements will be much less, resulting a good SNR.

Therefore, this system has the ability to have better imaging quality when the receiving antenna array is rotating to obtain more measured data.

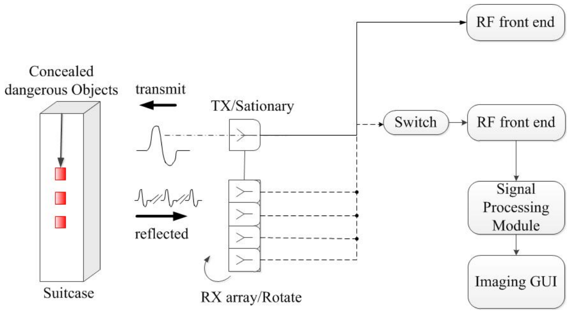


Fig. 6. The UWB imaging system in architecture.

## III. TWO-DIMENSIONAL IMAGING METHOD

The imaging scheme is based on DAS algorithm. The fundamental of the method is shown in Fig. 7 (a). Assuming the transmitting antenna is placed at $x_t=(x_t,y_t)$, the reflected signal from the target T is received by m-th receiving antenna located at $x_{rm}=(x_{rm},y_{rm})$. The target is located at $x_j=(x_j,y_j)$. The signal received by the *m-th* receiving antenna is given by [3] in equation (2).

$$b_m(t)=\omega_m a(t-\tau_m) \tag{2}$$

Here, $a(t)$ is the transmitted signal. $\omega_m$ is the weighting factor of the *m-th* receiving antenna. It is represented the pulse attenuation and determined by antenna influence, system loss and so on. $\tau_m$ is the delay time when the signal travels from the transmitting antenna to the target and then back to the *m-th* receiving antenna, which is given by

$$\tau_m=[d(x_i,x_j)+d(x_j,x_{rm})]/c \tag{3}$$

Here *c* is the speed of the light in free space (m/s) and $d(x,y)$ is the direct distance between two position *x* and *y*. This process is repeated until the *m-th* receiving antenna. The M outputs are processed as follows. The region of space is divided into a finite number of pixels in small square unit. The signal corresponding to the image of the *i-th* pixel, located at $(x_i,x_j)$ is obtained by applying time delays to the outputs of the M receiving antenna, and adding them, which is shown in Fig. 7 (b) and given by

$$f_i(t)=\sum_{m=1}^{M} b_m(t+\tau_m) \tag{4}$$

The imaging value for the *i-th* pixel is obtained by passing through the signal $f_i(t)$. In this case, the pixels in the region will have different values so that the target can be reconstructed.

The 2D reconstructed image is based on combination of each rotation plane of the antenna array. In each plane, the method is based on the delay-and-sum (DAS) imaging method described above. Here, *X* axis is assumed as the direction along the width of the target while *Y* axis is along the height of the target and *Z* axis is along the down range distance.

In *XY* plane, when receiving antenna array A0, B0, C0 and D0 are at the angle of $0^0$, the reconstructed image highlighted in red can be achieved for "image1" in Fig. 8. When rotating the helix receiving antenna array to different angles, the coordinate X-axis and Y-axis will be considered to rotate the same angle with the receiving antenna array so that the reconstructed image will be rotated in terms of the varied coordinate, which is similar to the area "image m", "image n" and "image q" in Fig. 8. After rotating a circle, the area highlighted in red will be merged into the final reconstructed result.

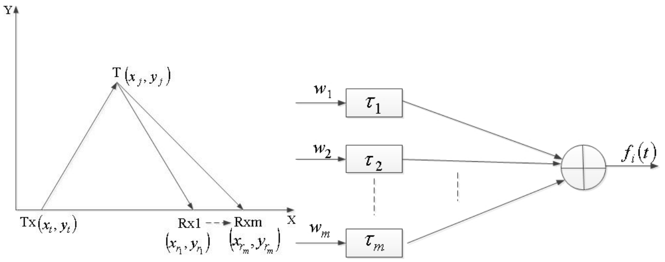


Fig. 7. Delay-and-Sum reconstructed method; (a) Detecting process; (b) Tme-domain beam former.

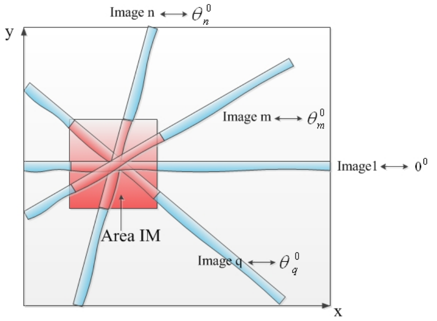


Fig. 8. The 3D reconstructed imaging method.

## IV. SIMULATION RESULT

### A. *The simulation model*

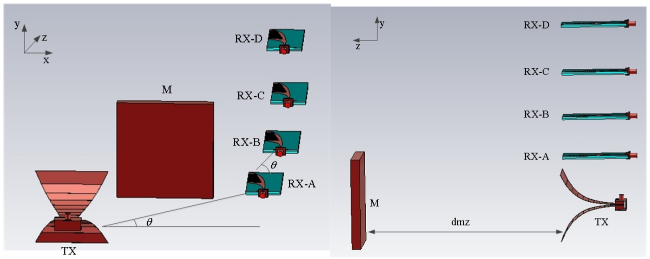
The simulated model of this UWB imaging system is shown in Fig. 10, including horn antenna (transmitting antenna), four elements rotating antenna array (receiving antenna) and one metallic target (10 cm × 10 cm). The transmitting antenna and receiving antenna are in the same vertical plane (*XY* plane). The metallic target is placed a distance of dmz at Z direction in front of the antenna array.

In this model, the distance $d_{txrx}$ between TX and RX-A is assumed as 20 cm. The equivalent distance $d_{rxrx}$ between the neighboring receiving antennas is 2.8 cm, while the angle of $\theta$ is $10^0$. The metallic target is placed at down range distance dmz of 50 cm in front of the system. The truncated sine signal is excited to TX, following the equation (5) as below.

$$f_{TruncatedS\ ine}(t)=\begin{cases}\sin 2\pi f_c t & kT\le t\le kT+\tau\\ 0 & kT+\tau\le t\le (k+1)T\end{cases}\tag{5}$$

Where $k$ is the periodic times; $T$ is the signal repetition period 10 us; $\tau$ is the signal duration 1 ns; $f_c$ is the centre frequency 4.5 GHz.

At first, the angle between the receiving antenna A1 and TX is $10^0$, thus the angle between receiving antenna B2, C3, D4 and TX are $10^0$, $20^0$ and $30^0$ respectively. Rotate the spiral receiving antenna array three times so that 16 different positions of RX have been obtained. Among them, the equivalent straight arm of receiving antenna array is A4, B4, C4 and D4, which are at the same angle of $30^0$ from TX. Repeating the rotation for one circle, there will be 36 groups of equivalent straight antenna array arm covering the whole scanning space.



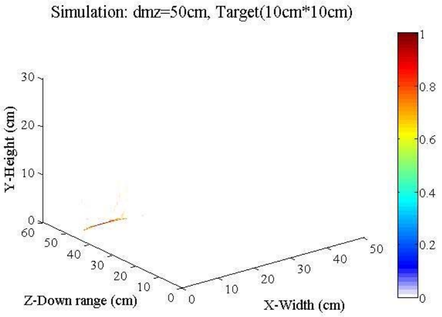
(a) (b)

Fig. 9. The simlatied model of the imaging system; (a) Front view; (b) Side view.

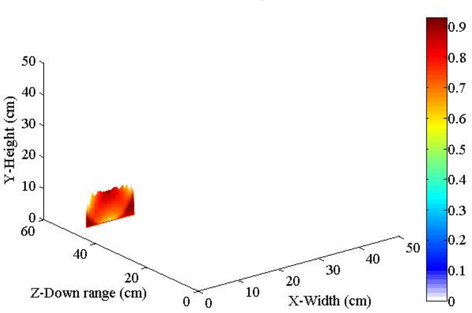
### B. *The reconstructed image*

Based on the reconstructed algorithm described in the third section, the image can be reconstructed via different positions of the receiving antenna. If the receiving antenna array is stable, which means only one group of the received data has been obtained, the UWB imaging system scans only one plane of the target. Therefore, the achievable image result of the target is only to be 1D, as shown in Fig. 10 (a).

If the receiving antenna is rotating, the two-dimensional image can be obtained, just like the one shown in Fig. 10 (b). The part highlight in red is the proposed metallic target in the simulation model. It is located at about 50 cm of down range distance. The size of the target is similar to 10 cm × 10 cm.



(a) No rotation



(b) With rotation of the antenna array

Fig. 10. The reconstructed images for the simlation model.

## V. CONCLUSION

A spiral rotating antenna array based on corrugated BAVA has been designed for a novel UWB imaging system. The two-dimensional imaging method based on the delay-and-sum algorithm has been proposed and implemented. The 2D imaging result has been achieved in simulation by rotating the receiving antenna array.

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