A compact asymmetrically slotted antipodal Vivaldi antenna for MIMO imaging systems

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Abstract
In this paper, we propose a Compact Asymmetrically Slotted Antipodal Vivaldi Antenna (CAS-A VA) design for MIMO imaging systems. The structure has the ability to extend the antenna bandwidth in low-end frequencies achieving a fractional bandwidth of 123.32 % (4.743–20) GHz. Good results are obtained in term of return loss, radiation pattern and gain. A time-domain study has been also performed to characterize the antenna behavior in case of an UWB pulse is used. To further validate our design, an application for MIMO imaging system is also proposed and evaluated. The antenna is used as the MIMO array element, thus forming a compact array and enabling to construct an optimal topology which improve significantly the microwave imaging quality by generating high-resolution images. The results demonstrate that the proposed antenna is a good candidate for microwave MIMO imaging applications.

Keywords Ultra-wide band · Antipodal Vivaldi antenna · Microwave imaging · Time domain analysis

1 Introduction
Recently, active microwave imaging has become of a great interest in both academic and industrial communities. It is widely used in several applications for detecting and locating objects [1–3]. For better images, high resolution is required in these imaging systems which can be theoretically enhanced by a large aperture and a wide fractional bandwidth [4]. For that reason, many studies had substantiated that MIMO arrays combined with ultra-wideband (UWB) technology - with a fractional bandwidth of more than 20 % - is the perfect option not only for high resolution but also for the ability of its signals to penetrate in different optically opaque materials. For such systems, designing a suitable antenna is a crucial step. In general, the antennas should have a wide fractional bandwidth, small size, simple, and low cost of fabrication [2]. Beside these requirements, gain and radiation pattern stability, low signals distortion have to be achieved. Hence Vivaldi antennas have always been the most suitable thanks to their wide fractional bandwidth, small size, simplicity, and cost-free [5]. Besides that, gain and radiation pattern stability, low signals distortion are also achieved. The conventional Vivaldi tapered slot antenna (TSA) was firstly introduced by Gibson in 1979 [6]. However, the TSA presents some limitations in term of bandwidth and feeding complexity. Few years later, Gazit has proposed a new family of the Vivaldi antennas (Antipodal Vivaldi Antenna: A VA) [7]. The A VA is proposed to solve both the bandwidth limitation and the feeding problem in coplanar ones by eliminating the complexity of the balun. Obviously, in the Antipodal Vivaldi Antenna, one of the material layers is printed on top and the other one is printed on the bottom of the dielectric substrate material. This antenna can be fed easily by micro-strip line, soldering the connector to the two sides of the PCB material. In the literature, many kinds of Vivaldi antennas have been investigated for different aims [8–12]. However, even if the A VA antennas can achieve high frequency end of the operating band, the low-end frequency is still limited. Thus, Moosazadeh et al [13] have proposed an elliptically-tapered antipodal Vivaldi antenna where the low-frequency is extended to 1.65 GHz using comb-shape slits. In [14], a Koch fractal slots are used in the design of the A VA to improve the antenna frequency band for medical microwave imaging applications. Another antipodal Vivaldi antenna is proposed in [15] using a triangular slits and bending the inner edges of the top and bottom radiators to extend the lower cut-off frequency (which is extended to 2 GHz) and enhance the antenna gain. Although,
dimension of these antennas are relatively large (≥ 100 mm) which limits their use in MIMO array systems for microwave imaging applications. In many studies, the designs rely on the symmetry of the two faces of the AVA antenna. In our work, we propose a small antipodal Vivaldi antenna where the concept involves introducing slots asymmetrically in both sides of the antenna expecting to further enhance its performances. The compact asymmetrically slotted AVA (CAS-AVA) based on a conventional antenna design can extend the lower operating frequency from 8 GHz to 4.74 GHz. The rest of this paper is organized as follows: section 2 presents the proposed Vivaldi antenna geometry and design procedure. The results and discussion of the frequency domain analysis and parametric studies are given in section 3. In section 4, we present the time domain analysis followed by exploring the experimental results in section 5. The MIMO imaging system constructed using the designed antenna is presented in section 6 as well as the imaging results. Finally, the paper is concluded in section 7.

2 The proposed compact asymmetric slotted antipodal Vivaldi antenna (CAS-AVA)

We consider a conventional Basic AVA (see Fig. 1) with dimensions of 24x33 mm² printed on a FR4 substrate with a dielectric permittivity of εᵣ = 4.3, and thickness h = 1.5 mm. The metallization of both faces is of a thickness t = 0.035 mm. A 50-Ohm micro-strip line will feed the antenna. The tapers of the Vivaldi antenna are defined accordingly to an exponential profile given by the equations below:

\[ y = c_1 \exp^{(R_x)} + c_2 \]  
\[ c_1 = \frac{y_2 - y_1}{\exp^{R_x} - \exp^{R_x_1}} \]  
\[ c_2 = \frac{y_1 \exp^{R_x_2} - y_2 \exp^{R_x_1}}{\exp^{R_x_2} - \exp^{R_x_1}} \]

Where \( R \) presents the opening rate of the exponential taper and \( c_1, c_2 \) are constants defined by Eqs. 2 and 3, \((x_1, y_1) \) and \((x_2, y_2) \) are the starting and ending points of the taper curve respectively. Numerical simulations are done the electromagnetic simulator CST MWS software (Computer Simulation Technology- Microwaves Studio) [16]

It is worth to note that the B-AVA impedance matching cannot achieve a frequency lower than 7.98 GHz (Fig. 2). For that reason, we have exploited the advantage of inserting slots in the interest of widening the antenna bandwidth. Firstly, three slots are introduced symmetrically in both top and bottom faces of the antenna. The slots lengths are approximated in a first time with respect to the lower frequency using

\[ L_s = \frac{c}{2f_{low}\sqrt{\epsilon_{eff}} + 1} \] [17]

Afterward, a series of parametric studies are carried out in order to fix slots dimensions for a best impedance matching. These modifications brought a change in the antenna impedance matching where we notice a broadening in the low frequency; however they brought also a mismatch in the band [7–11] GHz as presented in Fig. 2.

Conducted by this drawback, we have modified the conventional concept shape of the AVA to an asymmetric form. We present in Fig. 3 the final design of the proposed Compact Asymmetrically Slotted AVA (CAS-AVA), where we kept the three slots in the antenna top while introducing a single rectangular slot in the antenna bottom also approximated by the previous equation.
3 Results and discussions

In this section, we will discuss the antennas results in frequency domain, the discussion concern return loss behavior, current distribution, radiation pattern, gain and efficiency.

3.1 Return loss

To fix the slots dimensions, several parametric studies are conducted on the parameters $W_1$, $Ls_1$, $W_2$ and $Ls_2$ of the top and bottom slots. For the top slots we present in Fig. 4 and Fig. 5 the effects of the width $W_1$ and larger $Ls_1$ on the return loss parameter. The introduction of these slots has considerably enhance the impedance matching in low frequencies except in a slight frequency range from 7.43 to 8.07 GHz. The chosen values are $W_1 = 9 \text{ mm}$ and $Ls_1 = 5 \text{ mm}$.

For the bottom slot, we present in Fig. 6, the effect of the slot width ($W_2$) on the antenna impedance matching. It is clearly shown that better results are obtained for $W_2 = 3 \text{ mm}$. Regarding the slot larger, the Fig. 7 presents its influence on the return loss parameter. The antenna matching is improved for the value $Ls_2 = 9 \text{ mm}$.

The impedance matching of the proposed CAS-A VA compared with the B-VA and the symmetric A VA is depicted in Fig. 8. The CAS-A VA lower frequency can be extended to the limit of 4.74 GHz. No upper limit has been found before 20 GHz with a fractional bandwidth of more than 123%. Final parameters are listed in Table 1.
Table 1 Optimized dimensions of the CAS-AVA

| Variable | Dimension (mm) |
|----------|----------------|
| W        | 24             |
| L        | 33             |
| $W_f$    | 2              |
| $W_1$    | 9              |
| $W_2$    | 3              |
| $L_{s1}$ | 5              |
| $L_{s2}$ | 9              |
| $r$      | 10             |

Fig. 9 Current distributions on the proposed antenna at different frequencies

3.2 Current distribution

In Fig. 9 the current distributions of the CAS-AVA at several frequencies 4.9 GHz, 7 GHz and 10 GHz are illustrated. It is clearly noticed that the current density is higher around the lower slot region in low frequencies and take a high level around upper slots in high frequencies. So that, additional path for surface current is created with the slots introduction. That leads to create new resonances as confirmed in Fig. 8 compared to the B-AVA.

Fig. 8 Basic AVA, Basic AVA without bottom slot and CAS-AVA return losses

3.3 Radiation pattern

Both E and H plane radiation patterns of the proposed antenna are plotted in Fig. 10 at several frequencies notably 5GHz, 11GHz and 16 GHz. As we can see, the antenna presents a directional radiation patterns at all mentioned frequencies. Worth noticing that, the CAS-AVA is more directive in E plane than H plane.

3.4 Gain and efficiency

The realized gain vs frequencies of the CAS-AVA; is shown in Fig. 11. In the operational frequency band, the gain values vary in the range [1−5.43] dB where the maximum gain is picked at 15 GHz with a value of 5.43 dB. For our application, this gain is considered satisfactory given the proximity of the antenna and objects to explore.

The radiation efficiency is a primordial parameter as it measures the radiated power with respect to the power injected to the antenna. In Fig. 12 is illustrated the radiation efficiency of both the conventional basic AVA and the proposed CAS-AVA. We notice a slight degradation in efficiency levels but it remains above 70% in the entire operating frequency band as illustrated.
4 Time domain analysis

In microwave imaging applications, evaluating the time domain behaviour and studying the dispersion is a crucial step for UWB antennas [18]. It can be estimated with the measurement of signal distortion through transfer function, group delay parameter [19] and system fidelity factor SFF [20]. For that, time domain analysis of the proposed antenna is carried out by considering a system of two identical CAS-A VA antennas (See Fig. 13). The two CAS-A VA are separated by distance noted $d=10$ cm. This is needed to have the antennas in the far-field region of each other. The antennas are placed in two different orientations, face orientation (see Fig. 13a) and side orientation (see Fig. 13b). One of the two antennas is assumed to be the transmitter and the other one acts as a receiver. The transmitter CAS-A VA generate the Gaussian’s 5th derivative pulse shown in Fig. 14, since it’s spectrum meets the FCC\(^1\) mask. For our application we have used the numerical model of Gaussian derivative given by the relation below [21]:

$$y(t) = A \left( \frac{-t^5}{\sqrt{2\pi}\sigma^{11}} + \frac{10t^3}{\sqrt{2\pi}\sigma^9} - \frac{15t}{\sqrt{2\pi}\sigma^7} \right) \exp\left(\frac{-t^2}{2\sigma^2}\right)$$  \hspace{1cm} (5)

Where $A$ is a constant chosen to meet the limitations set by the FCC. To cover the right frequency band, the value of $\sigma$ was set at 50.788 ps.

To achieve a transmission process without significant distortion, the transfer function ($S_{21}$) magnitude and phase should be respectively flat and linear. We have drawn in Fig. 15 both magnitude and phase of $S_{21}$. we observe that the $S_{21}$ phase is fairly linear and the $S_{21}$ magnitude is quite flat around $-30$ dB in the operating frequency band ensuring a best transmission with less distortion.

As well, a flat group delay parameter is also required, and mathematically it can be evaluated through the transfer’s

\(^1\) Federal Communications Commission.
Fig. 15 Transfer’s function magnitude and phase for face orientation and side orientation

Fig. 16 Group delay versus frequencies

function phase by 6.

\[ \text{Groupe delay} = -\frac{d\phi}{df} \]  \hspace{1cm} (6)

Where \( \phi \) is the \( S_{21} \) phase. A constant group delay results to in linear \( S_{21} \) phase. It can be seen from the Fig. 16, which presents the simulated group delay that it is around 0.6 ns and flat in the entire operating frequency band with variation of less than 1 ns.

The system fidelity factor is an important parameter for quantifying distortion; it judges the resemblance between the transmitted and received signals. A value less than 50% of the SFF will deliver a high distortion. It can be calculated using 7 [22].

\[
SFF = \max \left( \frac{\int_{-\infty}^{\infty} S_t(t) \cdot S_r(t - \tau) dt}{\sqrt{\int_{-\infty}^{\infty} |S_t(t)|^2 \cdot \int_{-\infty}^{\infty} |S_r(t)|^2 dt}} \right)
\]  \hspace{1cm} (7)

\( S_t(t) \) and \( S_r(t) \) are the transmitted and received signals respectively. The normalized transmitted and received time signals are illustrated in Fig. 17. The SFF results for the two different orientations are summarized in Table 2. We notice that SFF achieves more than 89%, in other words, the proposed antenna will not seriously distort the transmitted signal.

5 Experimental results

In order to verify the impedance matching of design, the proposed antenna has been fabricated (Fig. 18), fed by a 50 \( \Omega \) SMA connector and tested with ANRITSU MS2037C VNA. It is clearly shown from the Fig. 19 the agreement between the simulated results and the ones reached by the measurement. At high frequencies (\( \geq 10 \text{ GHz} \)), the degradation is possibly caused by the substrate dielectric materials on signal loss of the microstrip line.

Table 3 summarizes characteristics in terms of dimensions and bandwidth of others designed antennas in recent related
work. As seen, reported antennas can achieve a wide bandwidth at the expense of large dimensions while our design can fulfill a satisfactory tradeoff between size and large bandwidth.

6 MIMO imaging system with the proposed CAS-AVA

In the interest of demonstrating the designed antenna validity for microwave imaging, we designed a MIMO array using CAS-AVA with a 2D topology as shown in Fig. 20.

Designed under CST MWS software which allows 3D simulations, the model of this simulation includes the antenna array as well as a metallic non-regular target as presented in Fig. 21. The largest dimension of the target being 100 mm and it is placed at a distance d = 5 cm from the array.

Identical antennas are used in Tx and Rx arrays with a fractional bandwidth greater than 123%, as well the same UWB impulse is used for all transmitters (Fifth Gaussian derivative). The scattered signals are received in terms of transfer functions in frequency domain over all the frequency band. Then, they are transferred into time domain by the inverse Fourier Transform. The gathered data from all Tx/Rx pairs are processed using Back Projection (BP) imaging algorithm [1] to reconstruct a three dimensional image of the target.

As we can observe from the 3D reconstructed image in Fig. 22, our system (using the CAS-AVA) can clearly detect the presence of metallic target with its geometric shape.

7 Conclusion

In this paper, a novel compact low profile Antipodal Vivaldi Antenna (AVA) for MIMO imaging system is proposed. A basic AVA has been modified to obtain a larger bandwidth by introducing slots in both sides of the antenna. The simulation results show a good performance in terms of return loss parameter, gain, wide bandwidth and radiation pattern. The proposed antenna is well suited for UWB applications.

We have designed a MIMO array imaging system based on the proposed antenna, in order to confirm its performance. The results show that the proposed antenna CAS-AVA is suitable for our application where it can be easily integrated in the MIMO imaging system enhancing as well the image resolu-
tion. As future work, one can target more complex simulation scenarios in terms of topologies for buried object detection applications.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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