A compact Vivaldi-shaped array using antipodal Vivaldi antennas for beamforming application

Julien Harel[#1], Mohamed Himdi[#], Olivier Lafond[#], Olivier Clauzier[*], Olivier Vivares[*]

[#]CNRS, IETR (Institut d'Électronique et des Technologies du numéRique)—UMR 6164, Univ Rennes, Rennes, France

[*]AVANTIX SAS, Aix-En-Provence, France

[1]julien.harel@univ-rennes.fr

***Abstract* — A compact ultra-wideband Vivaldi antenna with a Chebyshev tapering profile to enhance the impedance bandwidth is proposed for beamforming applications. This antenna shows a good VSWR<2.1 between 1.13 and 30 GHz. An array is created and the cross-polarization is cancelled with a mirrored disposition of both antennas. The beam tilt is then controlled by an array arrangement of the radiators along a Vivaldi shape.**

***Keywords* — array, beam shaping, miniaturization, ultra-wideband (UWB), Vivaldi antenna.**

I. Introduction

Ultra-wideband (UWB) antennas are widely used in civilian and military fields of communications and radar, such as UWB communication system, beamforming, 5G, ground penetrating radar and biomedical diagnosis. Among UWB antennas, we can notably cite the coplanar Vivaldi antenna, conceptualized by Gibson in 1979 [1]. This antenna is linearly polarized, has a planar structure and has many advantages, notably its wide impedance bandwidth with constant gain, the possibility of having a directive radiation pattern, its low cost and ease of production. However, the microstrip line to slot coupling feed transition used in the coplanar Vivaldi design results to a limited impedance bandwidth in high frequency. To overcome this, Gazit [2] proposed the antipodal Vivaldi antenna (AVA) to extend the impedance bandwidth thanks to a wideband transition from microstrip line to tapered slot flare. However, the two flares on different layers introduce a higher cross-polarization level compared to the coplanar Vivaldi. Using Vivaldi antennas for beamforming applications requires a tilting arrangement of those because of the end-fire radiating nature of Vivaldi antennas, but reduce inevitably the compactness of such systems. In order to improve the compactness, a dual Vivaldi antenna array arrangement is created along a Vivaldi shape, allowing an improved tilting effect of the radiation pattern than for an oblique like shape.

II. Antenna design and array conception

A. Antenna design

The proposed topology of the single antenna, inspired by [3], is showed on Fig. 1 and is designed as follow : The antenna is fed by an UWB microstrip balun with an elliptical shape. In order to have a smooth transition between the feed line and the exponential tapered slot, a straight slot line from (x=-W_f ; y=0) to (x=0 ; y=y_1) is created, where W_f is the width of the microstrip feed line. After this, an exponential tapered curve is defined by eq. 1 :

$$x = C_1 e^{Ry} + C_2 \tag{1}$$

while

$$C_1 = \frac{x_2 - x_1}{e^{Ry_2} - e^{Ry_1}} \tag{2}$$

$$C_2 = \frac{x_1 e^{Ry_2} - x_2 e^{Ry_1}}{e^{Ry_2} - e^{Ry_1}} \tag{3}$$

where R is the rate of the exponential transition, $P_1(x_1,y_1)$ and $P_2(x_2,y_2)$ are the coordinate positions of the start and end points of the exponentially tapered slot, as shown by the red dots in Fig. 1.

Following [3], a Chebyshev tapering profile is defined by eq. (4) to widen the bandwidth with a better impedance matching at low frequencies. The length of this curve is normalized with the variable L_c, then rotated by an angle $\theta = -27.65°$.

$$x = N(\frac{y}{L_c})^4 - N(\frac{y}{L_c})^2 \tag{4}$$

With N the opening rate of the Chebyshev function, and $0 \leq y \leq L_c$.

$$L_c = \sqrt{(\frac{W}{2} - W_f)^2 + y_2^2} \tag{5}$$

The antenna is printed via a silver coating on a PET substrate of relative permittivity 3, loss tangent of 0.002 and thickness 0.128mm. The optimal parameters of geometrical dimensions of the Chebyshev AVA given by parametric studies to improve the impedance bandwidth are listed in Table 1. The optimal parameters for R is 0.16 and N is 70. The reflection coefficient of this antenna, depicted on Fig. 2, shows a good $VSWR < 2.1$ starting from 1.13 GHz and up to 30 GHz.

Table 1. Geometrical dimensions of the proposed antenna

Parameters	Value (mm)
W_f	1.11
L	95
W	100
x_1	0
y_1	50
x_2	41.445
y_2	84
R_x	48.4
R_y	15

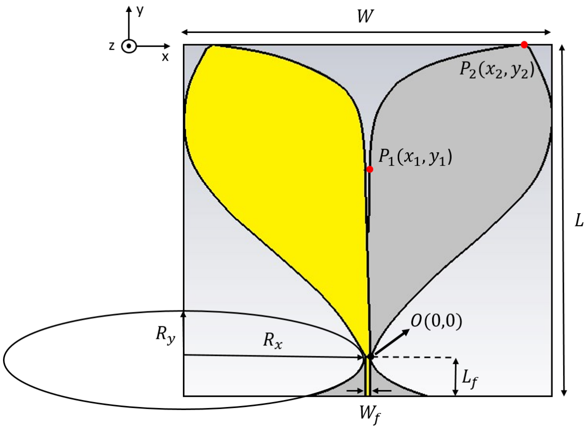


Fig. 1. Geometry of the Chebyshev AVA

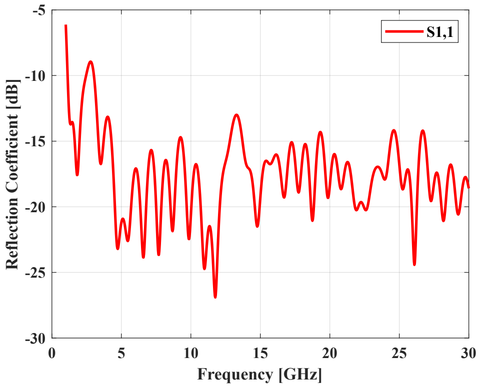


Fig. 2. Simulated reflection coefficient

B. Array conception

In order to improve the directivity of the antenna, an array in the H-plane is created by adding a second Vivaldi antenna at a distance $d = \frac{\lambda}{2}$ at 1 GHz (i.e. $d = 150mm$), (Fig. 3a). The second antenna is a mirrored version of the first antenna, allowing the orthogonal components of the E-field (corresponding to the cross polarization) to cancel each other at broadside [4], (Fig. 3b).

However, the array factor of the combined radiation pattern leads to high grating lobes in the upper frequency band. In order to reduce the grating lobe level in high frequencies, it is possible to arrange the elements with an oblique angle α [5], determined by eq. 6. An oblique array with a maximum distance $d = 150mm$, corresponding to an $\alpha = 52,1°$ angle, is depicted in Fig. 3c,

$$\alpha = sin^{-1}\frac{h/2}{L} \tag{6}$$

This effect can be obtained via the exponential tapered slot of the Vivaldi antenna : theoretically, EM waves at low frequency radiates through the end of the aperture, whereas EM waves at high frequencies will radiate mostly at the start of the slot (Fig. 4b). Adding an oblique angle thus create different distances for the array between low and high frequencies. Increasing this angle linearly increase the distance between the two antennas,

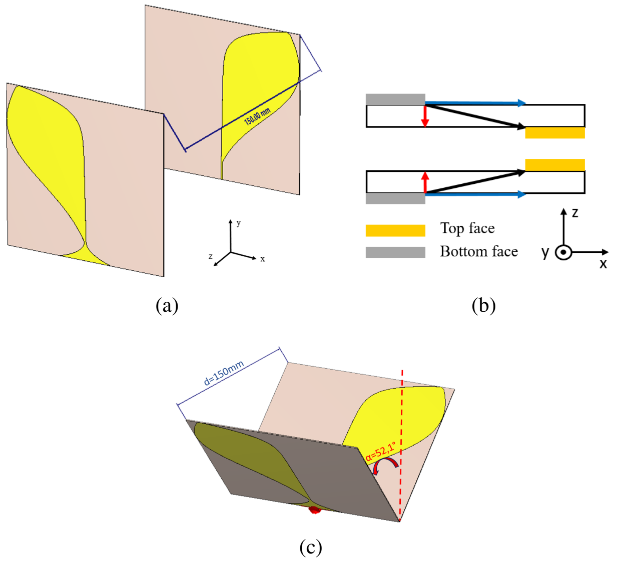


Fig. 3. (a) H-plane planar array with mirrored AVA at h=150mm; (b) E-field direction of the mirrored AVA array; (c) H-plane oblique array with mirrored AVA at d=150mm

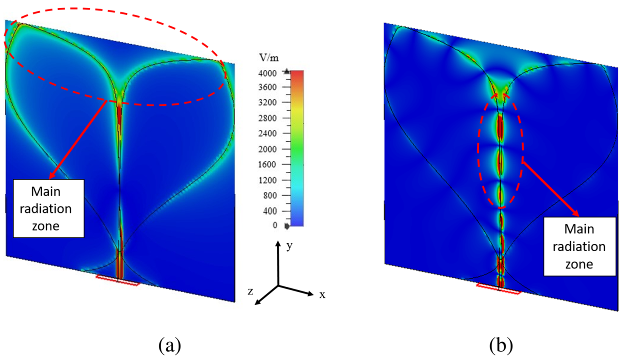


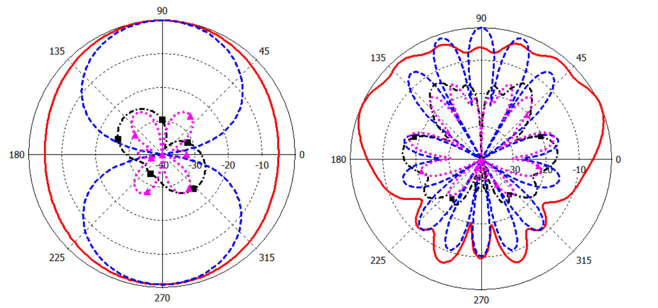
Fig. 4. E-field distribution of the AVA at frequencies of (a) 1 GHz; (b) 10 GHz

which will in theory increase the directivity at low and high frequency [5].

However, the oblique arrangement of the array will also produce a tilt of the radiation pattern in the H-plane, tilt of the same value as the angle α. At high values of angle, this tilt will decrease the directivity of the array because radiation patterns of both antennas are not pointing towards the same direction, hence reducing the array factor. Since the radiation pattern in H-plane is quasi-omnidirectional due to the dipole-type nature of Vivaldi antenna at low frequency, their will always be an array factor as in Fig. 5a at 1 GHz, but the effect of reducing the directivity will be effective when the radiation pattern of the single antenna becomes directive and tilted at high frequency (e.g. 6 GHz, Fig. 5b).

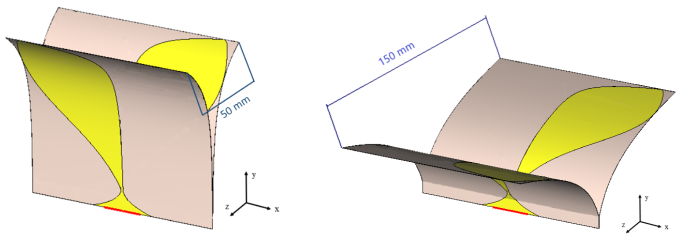
C. Array in Vivaldi shape

In order to increase the beam tilt and optimize the effect of the array spacing along the antenna on the radiation pattern, we curved both antenna surfaces according to a Vivaldi curvature eq. (1). Different Vivaldi curves are created to realize different distances d : 50mm (Fig. 6a); 100mm and 150mm (Fig. 6b).



(a) (b)

Fig. 5. Normalized simulated H-plane Co-polar (blue dots), Cross-polar (black square) of the AVA planar array d=150mm & Co-polar (red line), Cross-polar (magenta triangle) of the oblique array d=150mm at (a) 1 GHz; (b) 6 GHz



(a) (b)

Fig. 6. H-plane Vivaldi array at (a) d=50mm; (b) d=150mm

Those distances are chosen to maximize the array factor at low frequency for high values of d ($d = 150mm$ corresponding to $\frac{\lambda}{2}$ at 1 GHz) or for higher frequencies ($d = 50mm$ corresponding to $\frac{\lambda}{2}$ at 3 GHz). All Vivaldi curves have the same opening rate $R = 0.06$.

The excitation of this array is proceeded as follow : As we want to minimize the distance between antennas to optimize the array factor in the high frequency radiation zone, we chose to feed our array via a stripline excitation line. To ensure a good simulation, this excitation is planar on 3mm, and then the antennas are bended. To do so, the dielectric substrate needs to be thin to be bended, which is why we work with a PET substrate of thickness 0.128mm. The act of folding have no effect on the Reflection Coefficient parameter since the AVA is a travelling wave type antenna.

III. Simulated results and discussion

The directivity of the oblique array at $d = 150mm$ is compared to the vivaldi array at various distances in Fig. 7. Among the three cases of the vivaldi array, the case $d = 150mm$ has the higher directivity between 1 to 2 GHz, followed by $d = 100mm$ and finally $d = 50mm$. However, we can note that the $d = 50mm$ case has the highest directivity of the three after 3 GHz and on the entire bandwidth. In fact, although the space between antennas for $d = 100mm$ & $d = 150mm$ are larger than for the $d = 50mm$ case, so theoretically there should be a better directivity for both cases, a tilt phenomenon is appearing at high values of d. Due to the quasi-omnidirectionnal radiation pattern of the vivaldi antenna, this tilt is not present in the low frequency band, but appears at 4 GHz for $d = 100mm$ and 3 GHz for $d = 150mm$

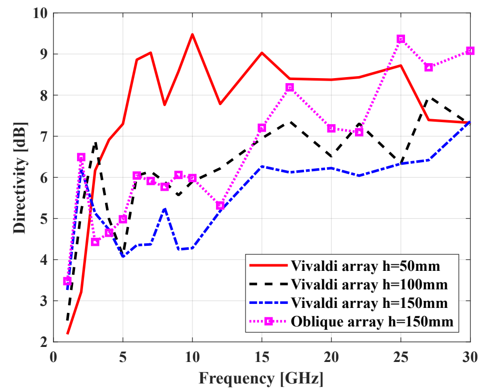


Fig. 7. Directivity comparison of the Vivaldi array at different distances and the oblique array at h=150mm

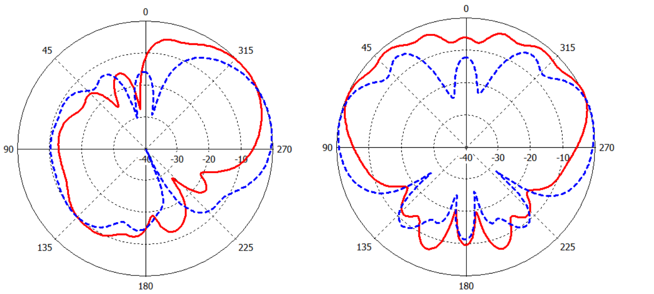
with a mean value of $53,6°$ for $d = 100mm$ and $74°$ for $d = 150mm$.

By doing a comparison between the vivaldi array and the oblique array, we can see an enhancement of the tilt angle with the vivaldi array case. This can be seen in the $d = 150mm$ case at 6 GHz in Fig. 8a where both antennas are excited alone. The oblique configuration has a tilt angle of $53°$ whereas the vivaldi configuration has a tilt angle of $74°$, therefore an increase of the beam tilt angle of $21°$ with the same compactness. Table 2 shows a comparison of tilt angles between the vivaldi and the oblique array arrangement with antennas excited alone, depending on the maximum distance between radiators. We can see that the Vivaldi array case always has a higher tilting effect, which is also increasing quicker due to the exponential shape. By combining the radiation patterns in the array case in Fig. 8b, we can then obtain two symmetrical patterns towards both sides in the vivaldi array case, whereas the oblique case have a wider radiation pattern.

The tilting effect can be observed in the H-plane radiation pattern of the three vivaldi array cases over frequency, starting at 1 and 2 GHz where we can clearly see the array factor enhancing the directivity of the array in Fig. 9b. At 3 GHz, Fig. 9c, the tilting effect starts taking place for the $d = 150mm$ case where we can see a formation of two symmetrical patterns towards both sides, whereas $d = 50mm$ and $d = 100mm$ are still directive. At 6 GHz, radiation patterns of $d = 50mm$ and $d = 100mm$ are wider than previous frequencies, due to the tilting effect which is not high enough to induce two symmetrical patterns like the $d = 150mm$ case.

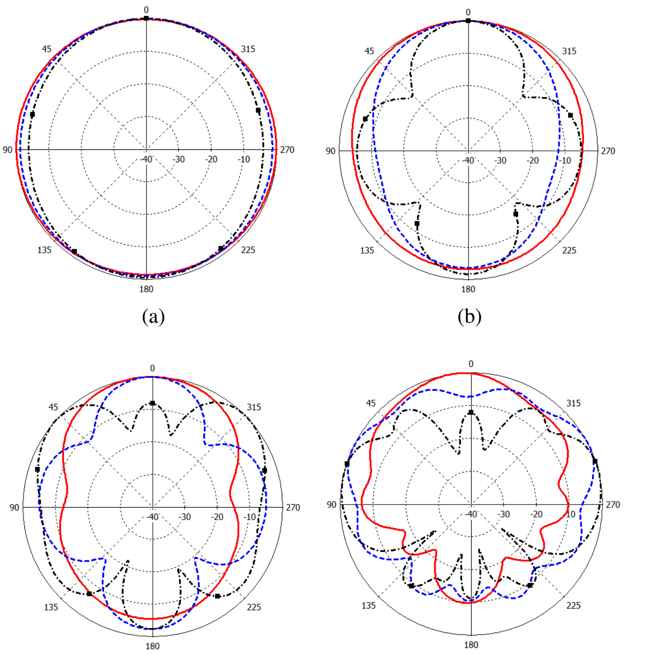
Table 2. Comparison of tilt angle for the oblique and vivaldi array arrangement at various distances

Distance (mm)	Array type	Tilt angle (°)
50	Oblique	15,2
	Vivaldi	30,4
100	Oblique	31,7
	Vivaldi	53,6
150	Oblique	52,1
	Vivaldi	74



(a) (b)

Fig. 8. Normalized H-plane radiation pattern for the oblique (red line) and vivaldi (blue dots) arrays at h=150mm, 6 GHz (a) antennas alone; (b) array



(a) (b)

(c) (d)

Fig. 9. Normalized simulated H-plane radiation patterns of the AVA for d=50mm (red line), d=100mm (blue dots), d=150mm (black square) at (a) 1 GHz; (b) 2 GHz; (c) 3 GHz; (d) 6 GHz

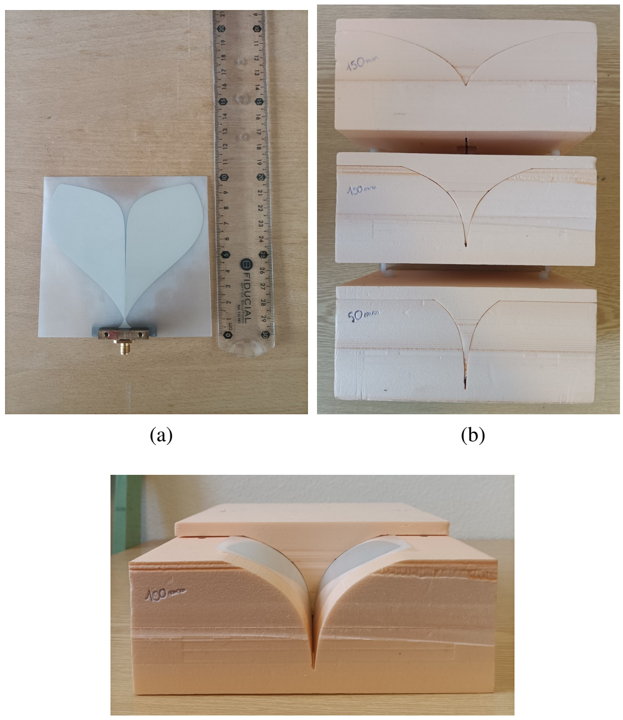
IV. Measurement Setup

In order to verify the effectiveness of the proposed array, two Vivaldi antennas have been fabricated and assembled with a stripline excitation in Fig. 10a. As to shape the array along a Vivaldi curvature, Styren foams were cut using heated wire technique along Vivaldi shapes with various distances ($d = 50mm$; $d = 100mm$; $d = 150mm$), (Fig. 10b). An example of the array bent along the $d = 100mm$ case is represented in Fig. 10c.

Reflection coefficient and radiation pattern measurements are in the process of being carried out.

V. Conclusion

In this article, a Vivaldi antenna with a Chebyshev tapering profile was proposed for beamforming applications. The Chebyshev profile allows an enhancement of the impedance bandwidth with compact dimensions of 95mm x 100mm. A beam tilt is formed with an array arrangement of two antennas along a Vivaldi curvature, and can be controlled by varying it's shape. A comparison is performed in simulation and showed that the Vivaldi shape array has a better compactness for the same tilt angle than an oblique arrangement array.



(a) (b)

(c)

Fig. 10. a) Fabricated Vivaldi array; b) Foams with Vivaldi shapes; c) Array bent along the d=100mm Vivaldi curvature

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