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Small Array Design Using Parasitic Superdirective Antennas

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***Abstract*—In this paper, a printed parasitic (loaded) end-fire three-element superdirective antenna array for $866MHz$ frequency band is proposed. The array dimensions are $110 \times 107.5mm^2(0.32\lambda \times 0.31\lambda)$ and it achieves a total directivity of $9.2dBi$. Then two of this antenna are integrated in a 3D array with total dimensions of $200 \times 110 \times 107.5mm^3(0.58\lambda \times 0.32\lambda \times 0.31\lambda)$ achieving a total directivity of $11.6dBi$.**

***Keywords*—ESA, compact, end-fire, broadside, superdirectivity, parasitic element**

I. Introduction

Electrically Small Antennas (ESAs) are interesting for emerging multi-band wireless technologies. However, these antennas, that are characterized by their narrow bandwidths, low efficiencies and quasi-omnidirectional radiation patterns, cannot be used alone in pointing applications where high directivities as well as compactness are required. In such cases, superdirective ESAs, where the array elements are very closely placed together, may be an attractive solution.

There has been a considerable research on the design of superdirective antenna arrays [1]-[8]. Early works were mainly based on wire-type unit-elements [1]-[3]. Recently, multiple planar parasitic superdirective ESAs were presented [5]-[7]. In this paper, we present a parasitic superdirective three-element array. Then, we show the possibility to use this antenna as a unit-element to design a compact 3D array.[1]

The rest of the paper is organized as follows: The simulation results are given in section II. The 3D array inter-element distance effect is studied in section III. The experimental results are presented in section IV. Finally, conclusions are drawn in section V.

II. Simulations and Results

The initial unit-element used in this work is a miniaturized printed half-loop antenna [6]. It is printed on a 0.8mm-thick Rogers RO4003 substrate and its dimensions are $24 \times 20mm^2$.

A. Superdirective Unit-Element

The method described in [7] is used to design a three-element array for a $866MHz$ with an inter-element distance of 0.1λ. The array is integrated in a Printed Circuit Board (PCB) via an analysis similar to the one presented in [8]. Fig. 1(a) shows the antenna geometry and dimensions in millimeters. The fully-driven array calculated excitation coefficients and the required optimal loads for transforming this array to a parasitic (loaded) one are given in Table I. The fully-driven array achieves a maximum simulated (ANSYS HFSS [9]) total directivity of $9.5dBi$. However, as it can noticed, some negative resistances are required to transform this array to a parasitic one. Neglecting theses resistances, total directivities of $7.3dBi$, $9.2dBi$ or $7.2dBi$ can be achieved in case of exciting the first-, second- or third- element. The highest directivity in the case of exciting the second element is due to two reasons. First, in this case, only one negative resistance is neglected. Second, the excitation coefficient of this element is the highest, and hence, the array directivity is more sensitive to the changes in this element's excitation. Fig. 1(b) shows the parasitic antenna (exciting the second element and loading the first and third one with $68\Omega//4.5pF$, $0.6pF$) simulated end-fire directivity ($D_{(\theta=90^o,\phi=90^o)}$) and input reflection coefficient magnitude in dB. The figure shows that the end-fire directivity is maximum at the design frequency. The antenna has an impedance bandwidth ($S_{11} < -6db$) of $2.8MHz$ and a directivity bandwidth ($D_{max} - 1dB$) of $2.6MHz$. Fig. 1(c) shows the antenna 3D total directivity radiation pattern at the resonance frequency ($866MHz$). The figure shows a directive pattern with a maximum directivity of $9.2dBi$ in the end-fire direction. This directivity is $2.44dBi$ greater than Harrington's normal directivity limit [10]. Fig. 3 shows the antenna 2D total directivity radiation patterns in horizontal (XoY) and vertical (YoZ) planes at the resonance frequency. The Half Power Beam-Width (HPBW) in horizontal and vertical planes are respectively $60°$ and $72°$. The Front to Back Ratio (FBR) is about $16.9dB$. Due to the mutual coupling, the antenna presents a relatively small radiation efficiency (11.2%). Finally, this antenna is significantly smaller than a Yagi-Uda antenna covering the same frequency band and with the same directivity which dimensions are about $500 \times 152mm^2$ [11]. However, the miniaturization comes with some decrement in the antenna efficiency.

TABLE I. Fully-driven array calculated current excitation coefficients and required loads for transforming the array to a parasitic one

Element no.	Magnitude [A]	Phase [degree]	Optimal Load [Ω]
1	1	0	17.9-j30
2	1.4	-146	-53-j45.3
3	0.2	69	-3526.9-j3305.5

[1]This work was done with the funding of the French National Research Agency as part of the project "SOCRATE" and the support of the "Images et Reseaux" cluster of Brittany region, France.

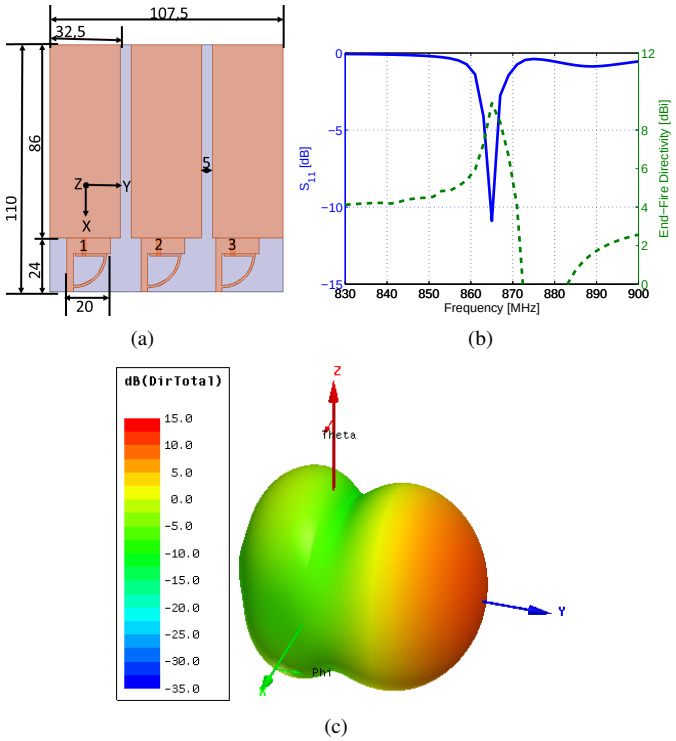


Fig. 1. Superdirective unit-element geometry and simulated parameters. (a) Geometry and dimensions, (b) input reflection coefficient magnitude in dB and end-fire total directivity, and (c) 3D total directivity radiation pattern at the resonance frequency (866MHz).

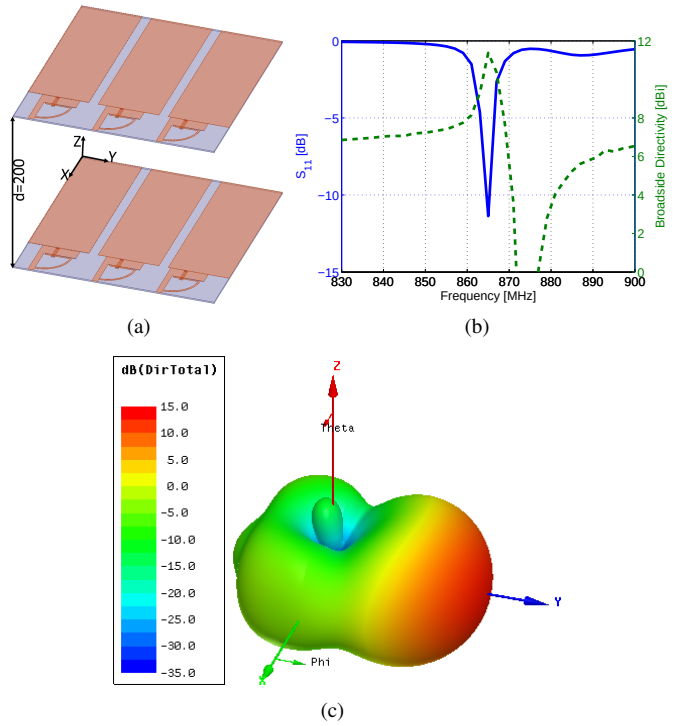


Fig. 2. Broadside array geometry and simulated parameters. (a) Geometry and dimensions, (b) input reflection coefficient magnitude in dB and end-fire total directivity, and (c) 3D total directivity radiation pattern at the resonance frequency (866MHz).

B. Compact Array Design

Two elements of the planar array are stacked along Z-axis with an inter-element distance of $200mm(0.6\lambda)$ as shown in Fig. 2(a). The two driven-elements are excited with equal power. Fig. 2(b) shows the antenna input reflection coefficient magnitude and directivity. The figure shows that the antenna's total directivity is also maximal around the resonance frequency of $866MHz$. The antenna has an impedance bandwidth of $2.8MHz$ and a directivity bandwidth of $3MHz$. Fig. 2(c) shows the antenna 3D total directivity radiation pattern. The figure shows a directive pattern with a maximum directivity of $11.6dBi$ in the direction $(D_{(\theta=90^o,\phi=90^o)})$. Fig. 3 shows the antenna 2D total directivity radiation patterns. The HPBW in horizontal and vertical planes are respectively $56°$ and $42°$, the FBR is $17.2dB$, and the Side Lobe Level (SLL) is $-11.4dBi$. Finally, the antenna presents a radiation efficiency of 9.7%. Comparing with the initial end-fire array, it can be noticed that the total directivity is increased by $2.4dB$. The horizontal HPBW is almost the same, while the vertical one is divided by 1.7. As for antenna FBR and efficiency, they are approximately the same as the initial end-fire's ones. This antenna is significantly smaller than equivalent (presents the same directivity) commercial antennas which dimensions are about $698.5 \times 215.9 \times 88.9mm^3$ [12].

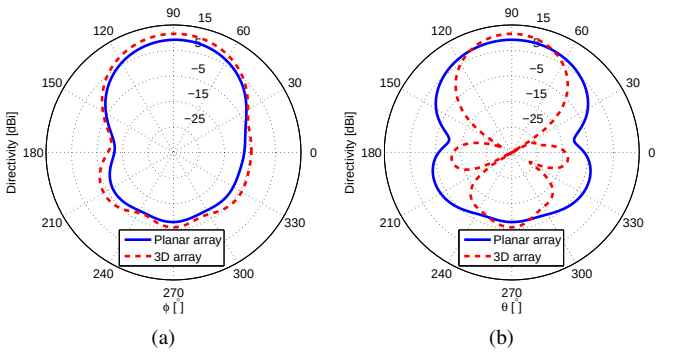
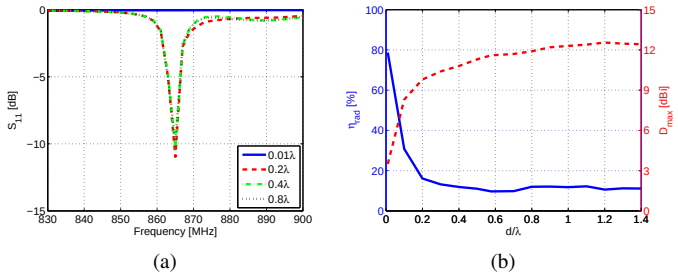


Fig. 3. Two arrays' simulated 2D total directivity radiation patterns at the resonance frequency (866MHz). (a) Horizontal plane and (b) vertical plane.

III. Distance Effect

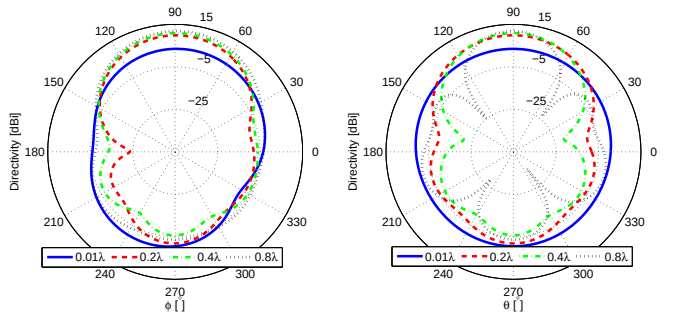
To study the effect of the distance between the two parasitic arrays (d) (refer to Fig. 2(a)), we change this distance from 0.01λ to 1.4λ while monitoring the antenna reflection coefficient, total directivity and radiation efficiency. Fig. 4(a) shows the array simulated input reflection coefficient magnitude as a function of the distance. The figure shows that for $d = 0.01\lambda$ the array does not have any resonances in the observed band. This is due to the high mutual coupling. As the distance increases the mutual coupling decreases and the array resonance frequency converges to the one of the unit-elements. Fig. 4(b) shows the array simulated maximum total directivity and radiation efficiency as a function of the distance. The figure shows that for very small distances, the antenna's efficiency is maximal and as the distance increases

the efficiency decreases. This is mainly due to the the lost of superdirectivity for very small distances. Fig. 5 shows the array simulated 2D total directivity radiation patterns at the design frequency as a function of the distance. The figure shows that for very small distances, the array directive pattern is lost and the array has a quasi-omnidirectional radiation pattern. This is also due to the high coupling effect that makes the applied loads unsuitable for having directive unit-elements. As the distance increases, the achieved directivity also increases till 1.2λ when it starts decreasing again.



(a) (b)

Fig. 4. Broadside array simulated parameters as a function of the distance (d). (a) Input reflection coefficient magnitude in dB, and (b) maximum total directivity and radiation efficiency.

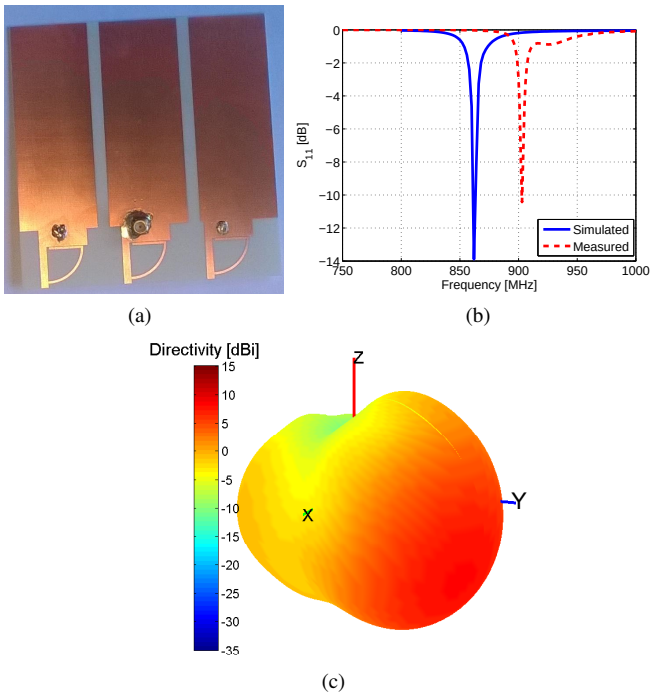


(a) (b)

Fig. 5. Broadside array simulated 2D total directivity radiation patterns at the resonance frequency (866MHz) as a function of the distance (d). (a) Horizontal plane and (b) vertical plane.

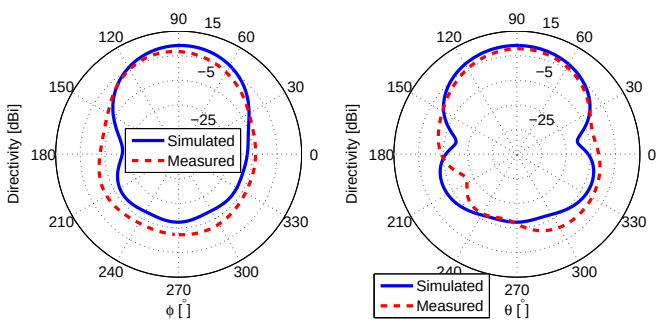
IV. Experimental Results

A prototype of the planar array was fabricated and measured for results validation. Fig. 6(a) shows a photograph of the prototype. Fig. 6(b) shows the antenna measured input reflection coefficient magnitude in dB. The measured resonance is $903MHz$ (4.7% shifted compared to the simulated one). This shift is mainly due to the coaxial cable effect and the dispersion of SMD components. Due to the antenna low efficiency, it is not easy to measure its far-field radiation pattern in the presence of a coaxial cable. Hence an optical probe from enprobe [13] was used and the measurements were performed in SATIMO stargate (SG 32) near-field measurement system. Fig. 6(c) shows the measured 3D total directivity radiation pattern at the resonance frequency $(903MHz)$. This pattern is in a good agreement with the simulated one. The measured directivity is $8.1dBi$. Fig. 7 shows measured 2D total directivity radiation pattens in horizontal and vertical planes. The HPBW in horizontal and vertical planes are respectively 67.5^o and 73° and the FBR is $8.5dB$. The small difference may be attributed to the measuring system and environment as well as the dispersion of SMD components.



(a) (b) (c)

Fig. 6. Planar array experimental results. (a) Fabricated prototype, (b) input reflection coefficient magnitude in dB and (c) 3D total directivity radiation pattern at the resonance frequency (903MHz).



(a) (b)

Fig. 7. Planar array measured 2D total directivity radiation patterns at the resonance frequency (903MHz). (a) Horizontal plane and (b) vertical plane.

V. Conclusion

In this paper, a parasitic end-fire three-element superdirective antenna array for $866MHz$ frequency band was proposed. The array dimensions were $(0.32\lambda \times 0.31\lambda)$ and it presented a total directivity of $9.2dBi$ and radiation efficiency of 11.2%. The proposed array was, in turn, integrated in 3D array of total dimensions of $(0.58\lambda \times 0.32\lambda \times 0.31\lambda)$ achieving a total directivity of $11.6dBi$ and radiation efficiency of 9.7%. This array is significantly smaller than classical arrays achieving the same directivity.

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