GEOLOCATION AND NAVIGATION IN SPACE AND TIME

Potentialities of reduced BFN antennas for spatial Ku-band applications

Potentialités des antennes à formateur de faisceaux réduit pour applications spatiales en bande Ku

Phased array, mutual couplings, parasitic elements
Antenne réseau, couplages mutuels, éléments parasites

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Abstract/Résumé

To reduce the complexity of radiating arrays, we propose an architecture based on periodic lattice, parasitic elements and multi-excitations. The aim is to reduce the complexity of the beam forming network (BFN) while maintaining enough beam shaping controls. In this work, we detail the principle of this architecture with a simple example based of microstrip antennas within a 10x10 square grid whose only 30% of the elements are fed. Then, we explore the potentiality of reduced BFN antennas for spatial Ku-band applications by considering an architecture with an improved bandwidth, and a triangular grid of 57 elements with only 7 elements fed.

Pour réduire la complexité des antennes réseau, nous proposons une architecture utilisant une distribution périodique d'éléments rayonnants et d'éléments parasites, afin de créer un système multi-excitations. L'objectif est de diminuer la complexité du réseau formateur de faisceau tout en maintenant un nombre de contrôles suffisant pour la reconfiguration de l'antenne. Au cours de ce travail, nous détaillons en premier lieu les potentialités du concept avec un exemple d'une antenne réseau à maille carré de 10x10 éléments, dont seulement 30% des éléments sont excités. Puis nous testerons l'applicabilité de cette architecture pour une application spatiale en bande Ku, utilisant une antenne à 57 éléments disposés suivant une maille triangulaire, et dont seuls 7 accès sont excités.

1. Introduction

Phased array antennas have attracted a lot of research interest due to their capability to provide simultaneously a high gain and beam scanning. However, this technology is still expensive, complex and restricted to military and spatial applications. Indeed, phased array antennas need complex Beam Forming Networks (BFN) which are difficult to design, bulky and expensive [1]. Moreover, couplings between elements can affect the management of the antenna active SWR. That is why having a low-priced and efficient technology is an important challenge, particularly for high gain antennas. Many technologies were put forward to overcome these limitations [2] : thinned array [3], where some radiating elements are off or connected to dummy loads, sparse array [4] with removed elements, or also clustered array based on sub-arrays [5]. Nevertheless, designing irregular arrays is complicated because classical approximations based on periodicity are inapplicable. To overcome these latches, we propose an alternative concept to simplify BFN of antennas by using parasitic elements on a regular grid. The idea is based on the hybridization of concepts coming from antennas with parasitic elements and from lacunar elements antenna arrays, in order to maximize the effective area of the antenna, while minimizing the number of elements connected to the BFN. This architecture offers an interesting tradeoff between performances, cost and complexity [6].

In this paper, we appraise the potentialities of reduced BFN antennas in a specific frequency band. At first, the general architecture of reduced BFN antennas and its working principle will be presented. Next, a basic example to show some potentialities of the concept validity will be given. Finally, the results obtained with a reduced BFN antenna in Ku band will be shown.

2. Presentation of the reduced BFN antenna concept
Présentation des antennes à formateur de faisceaux réduit

Reduced BFN antennas are based on regular arrays where all the radiating elements are the same. The originality of this concept is based on the parasitic elements which are loaded on reactive impedances, passive or tunable, and which contribute to the radiation pattern objectives, fixed or reconfigurable. The loads associated with these parasitic elements are synthesized so that they simultaneously contribute to both the optimization of the radiation pattern objective and to an active VSWR constraint. A basic schematic is done Figure 1. This architecture preserves the periodicity in order to simplify the computation of the EM problem.

It can be seen as an application and an extension of the work proposed initially by Harrington approach [7]. Contrary to most applications of Harrington's researches, as electronically steerable parasitic array radiator (ESPAR), our approach is not limited in terms of radiating elements and the antenna can include one or more excited elements to optimize the aperture efficiency of the antenna. One of the main objective in the design is to ensure strong couplings between elements and to spread their contributions on the antenna panel. The loads connected to parasitic elements act as a degree of freedom to tune their reflection coefficient, in order to satisfy simultaneously a radiation objective and a matching constraint. Compared to a classical array, the architecture has a good potentiality to manage the active VSWR of the ports connected to the BFN thanks to the parasitic elements and their loads that help to manage couplings contributions.

A reduced BFN antenna is designed in three steps :

- Design of the unit element and the array geometry,
- Determination of the S-matrix and extraction of radiation patterns Φi for each element thanks to an EM simulation software like CST MWS,
- Synthesis process with Matlab to determine the value of each complex load (ideally reactive) and the weightings of ports connected to the BFN.

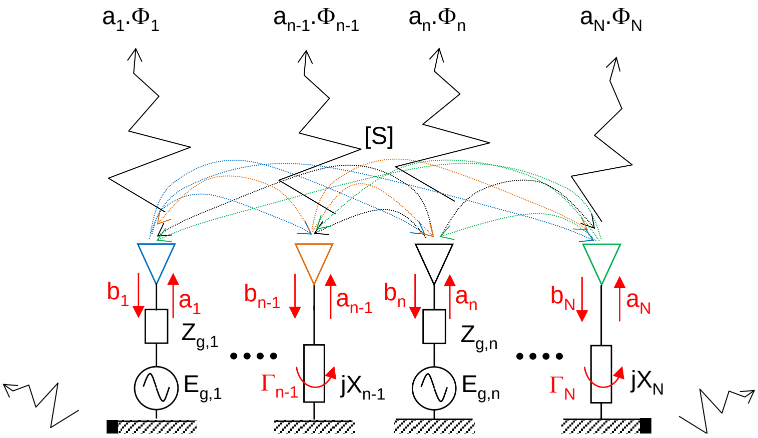

Figure 1 : principle of reduced BFN antennas, with the interaction with S matrix, reactive loads and radiating elements

3. Typical performances on a basic example of reduced BFN antenna

Performances typiques sur une antenne à formateur de faisceau réduit

3.1. Presentation of the antenna

Présentation de l'antenne

This example is based on a panel of classical square microstrip patches designed to operate at 11.8 GHz. The patches are excited by coaxial connectors as shown in Figure 2-a. These elements are arranged in a periodic square lattice of 10x10 elements. In order to show the potentialities of the reduced BFN antennas, we excite only 30 elements among 100. The excited elements are randomly chosen on the grid as shown Figure 2-b. This choice is arbitrary and may lead to some difficulties to realize the BFN. It is only chosen to demonstrate that it is possible to compute the loads that are able to satisfy the objective and constraints of the specifications, whatever the location of active ports. In these cases, it consists in maximizing the directivity in a specified direction and to satisfy a constraint on the frequency range ($|S_{ii}|_{active} \leq -10$ dB between 11.5 and 12 GHz)

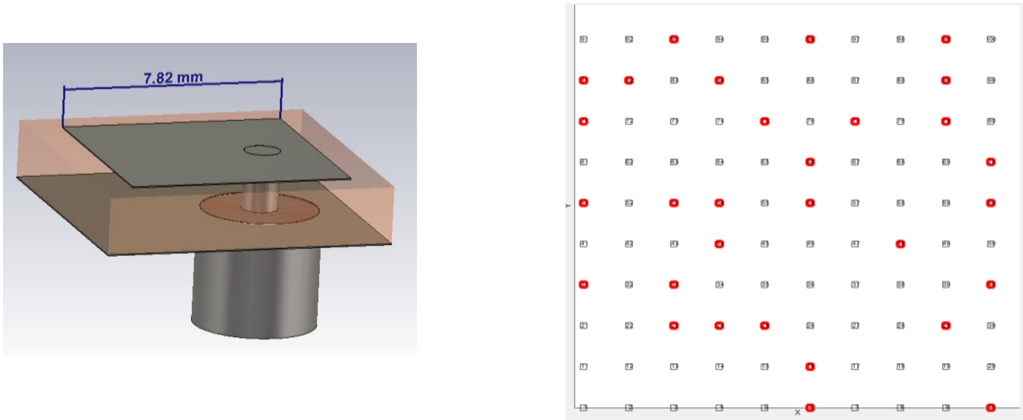

Figure 2 : a) element of the antenna array b) rectangular grid with excited elements (red) and parasitic ones

3.2. Results of the synthesis
Résultats des synthèses

To show the potentiality of the antenna, two directions are chosen : axial radiation {θ = 0° ; φ = 0°} and a beam steering {θ =30° ; φ = 0°}. Figure 3-b and figure 5-b show a cartography of the coupled waves. Red squares corresponds to elements connected to the BFN. The color of parasitic elements is then linked to couplings. The more the elements tends to red, the more the couplings are stimulated, resulting in an improved contribution to the overall efficiency. We can notice a significant contribution of parasitic in the two configurations tested. For elements connected to the BFN, the color is related to the coupled waves. Therefore, a green or blue level relates to an active matching better than -10 dB.

Figure 4 and figure 6 show the active matching of the fed elements.

Notice that in these results, loads are considered as reactive ones, without any losses. In a practical case, the gain will be affected by the technology chosen for the loads. As example, reflection-type phase shifter can be used with varactors diodes. For better performances, MEMS can be a good solution.

3.2.1. Objective pattern 1 : {θ = 0° ; φ = 0°}

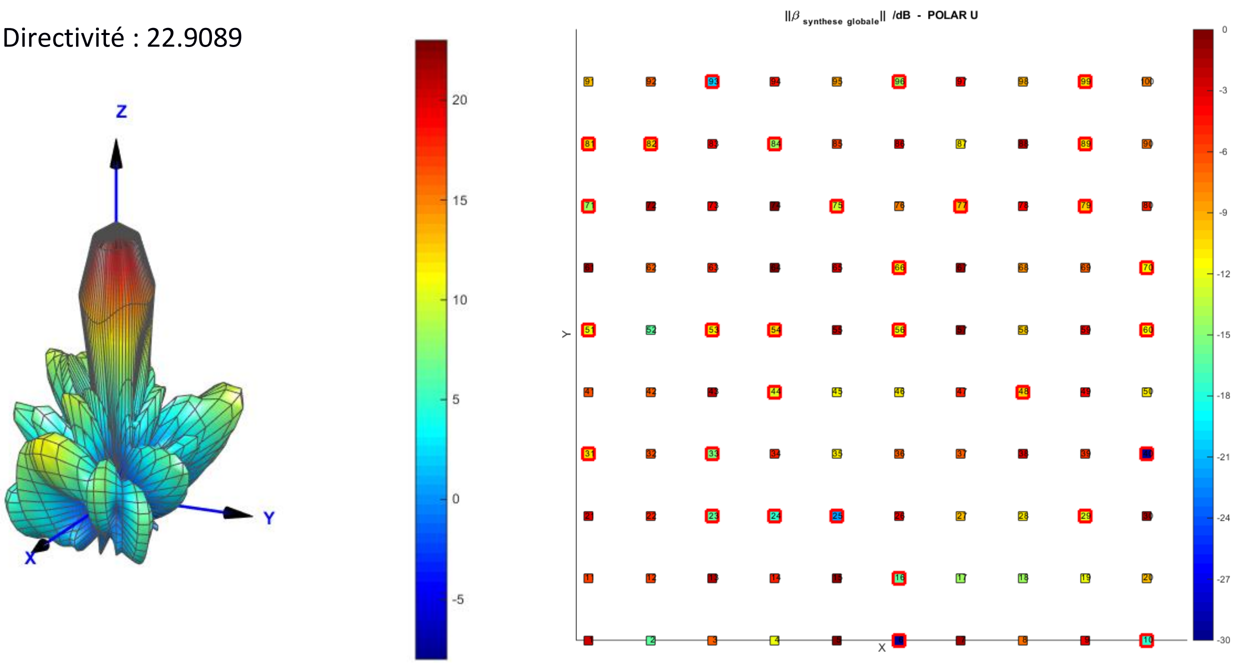

Figure 3: a) radiation pattern obtained with optimization 1 b) excitation weighting (modulus). Red squares correspond to elements connected to the BFN.

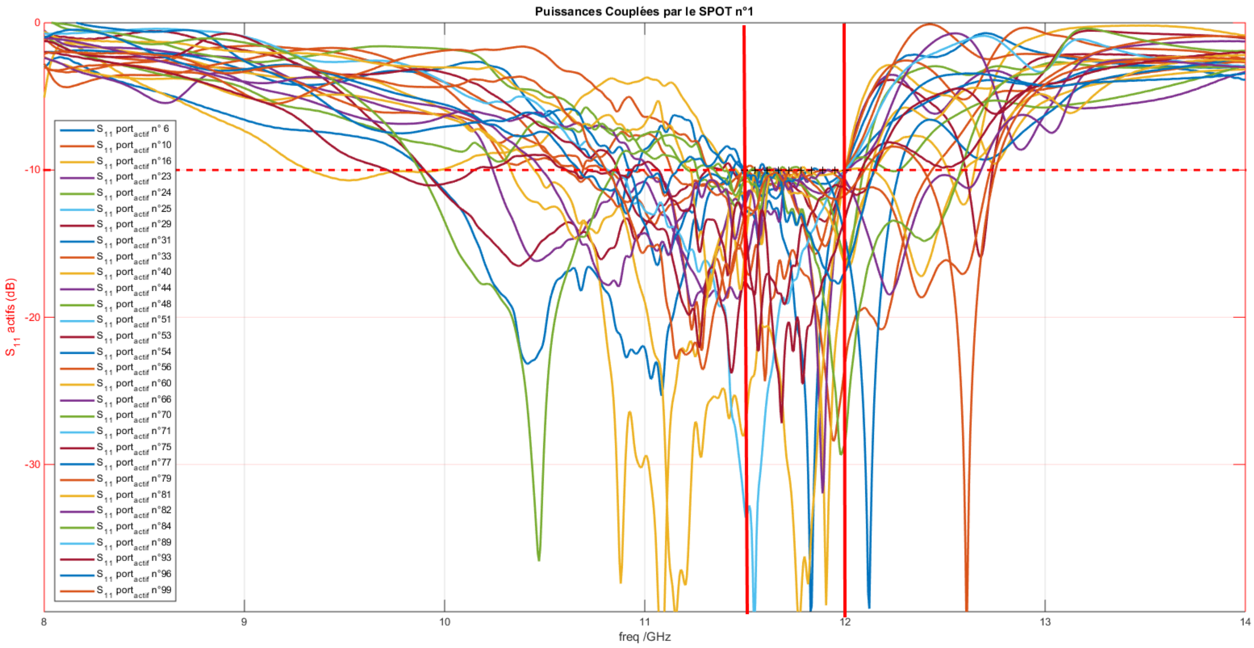

Figure 4: active Sii for objective 1, the optimization bandwidth is delimited by the two red lines, with an constraint set to -10 dB

3.2.2. Objective pattern 2 : {θ = 30° ; φ = 0°}

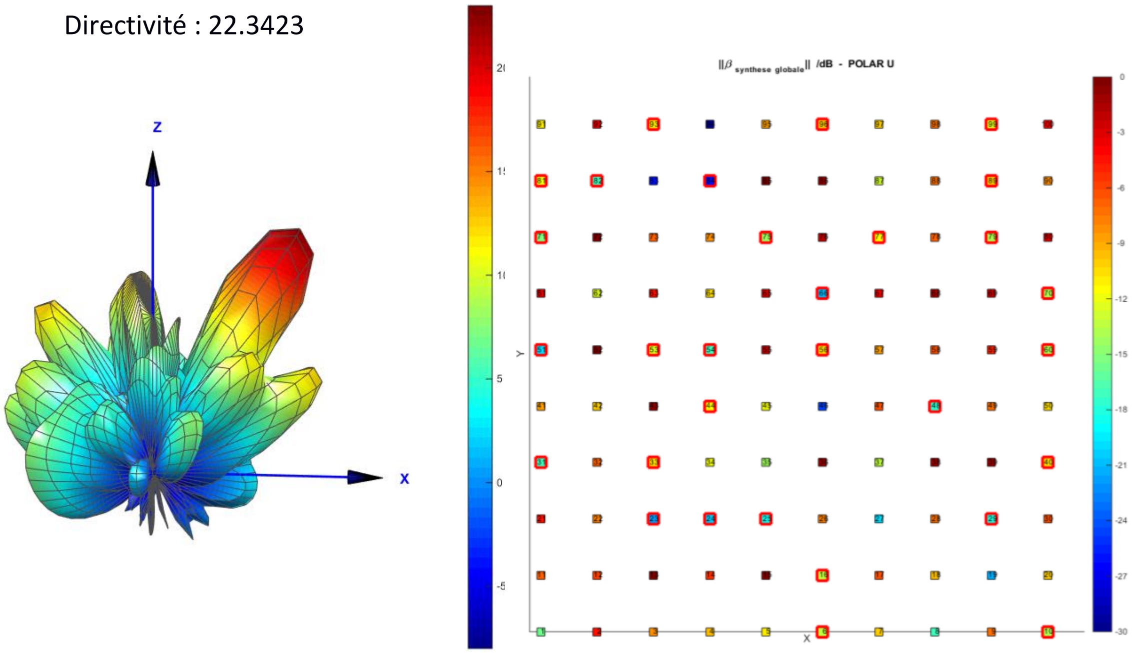

Figure 5: a) radiation pattern obtained with optimization 2 b) excitation weighting (modulus)

For each case, Figure 4 and 6 show that the active matching on the bandwidth is satisfactory (i. e. the reflection coefficients are smaller than -10dB between 11,5 and 12GHz). Directivity of a reduced BFN antenna whose only 30% of the elements are excited is quite similar to the directivity of a classical array, as mentioned in the Table. In this case, this reference directivity is calculated from the one of an equiamplitude and equiphasis aperture area. But we have to put into perspective this point as we considered the reactive loads as ideal in these simulations. In Figure 3-b and 5-b it clearly appears that parasitic elements are strongly coupled and contribute to the final radiation pattern. We can conclude that, with appropriate loads, it is possible to stimulate the effective aperture of the panel even if only 30% of the elements are excited.

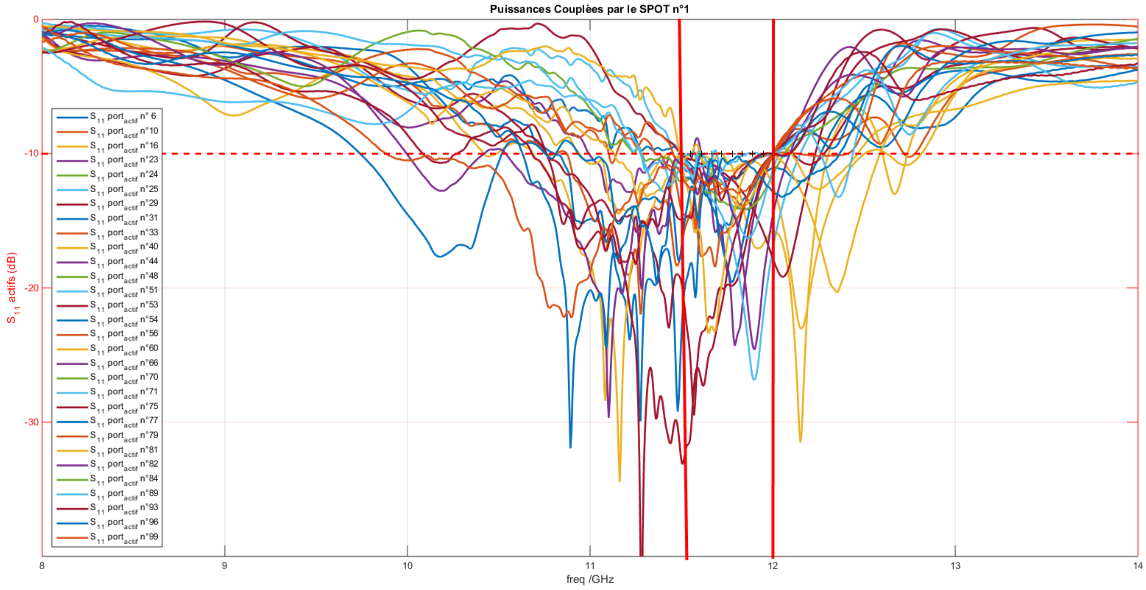

Figure 6: active Sii for objective 2, the optimization bandwidth is delimited by the two red lines

Objective pattern	Directivity max for an ideal array of the same surface	Directivity obtained
1	23.0 dBi	22.9dBi
2	22.4 dBi	22.3dBi

4. Application to a bi-band antenna
Application à une antenne bi-bande

4.1. Design of the antenna
Présentation de l'antenne

The goal of this part is to show the potentiality reduced BFN antennas for spatial applications in Ku-band, where it is necessary to realize a transmit and receive link (Rx : 11.7-12.2 GHz ; Tx : 14-14.5 GHz). An element is designed to work on this band. As Figure 7-a shows, the element is composed of a square patch and a stacked bow-tie to improve the matching bandwidth. An aperture excites the element through a microstrip line. Figure 7-b shows the element reflection coefficient that is below -10 dB on the whole bandwidth.

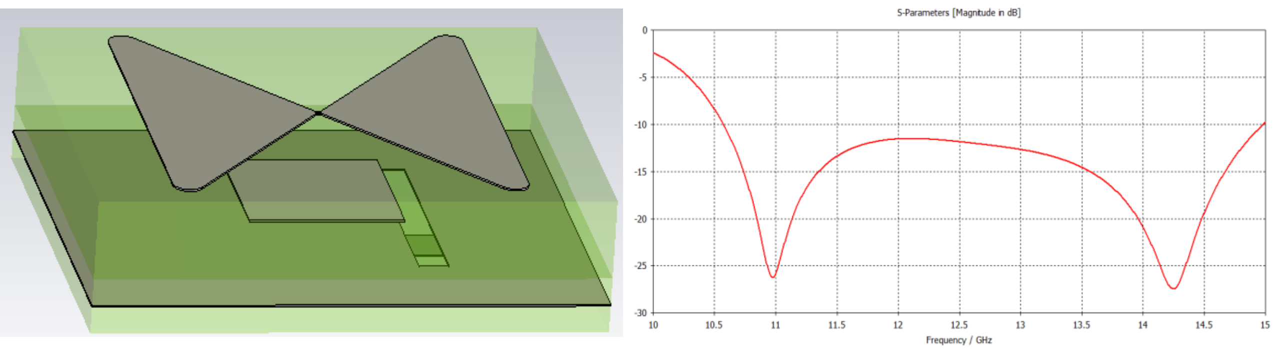

Figure 7: a) antenna element for a Ku-band application b) S11 of the element

We choose a triangular grid in order to optimize couplings between elements. Indeed, tests on bow-tie elements show better couplings between elements diagonally placed. Moreover a stabilization of couplings is observed on the full bandwidth thanks to the triangular grid. The grid is displayed in Figure 8.

Contrary to the previous example, a more conventional distribution of the excited elements has been chosen to take into account design features of the BFN. So seven elements are excited for the hexagonal distribution and the center element.

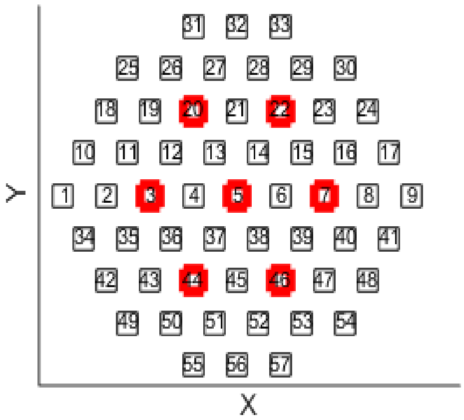

Figure 8: antenna array grid and excited elements (in red)

4.2. Results
Résultats

We have synthesized two configurations to realize a beam steered in the direction {θ = 30° ; φ = 0°}. The first one correspond to the low part of Ku-band (11.7-12.2 GHz) and the second one to the high part (14-14.5 GHz).

4.2.1. Objective 1 : {f = 12GHz ; θ = 30° ; φ = 0°}

This first synthesis is realized on the lower band of the Ku-band. We obtain a directivity of 18.7dBi (Figure 9-a) and all the active $|S_{ii}|$ satisfy the -10dB constraint (Figure 9-b).

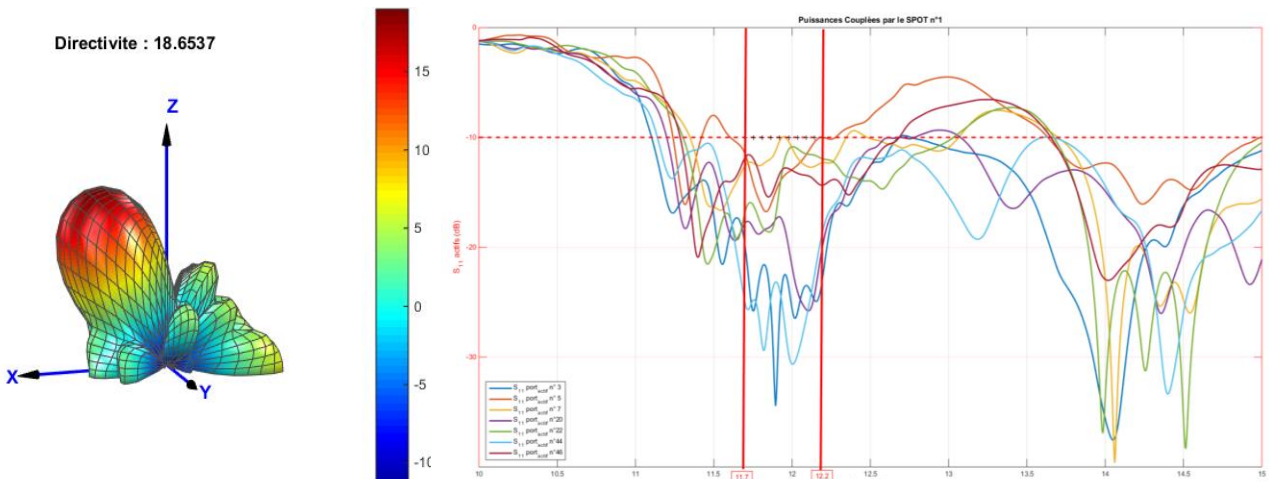

Figure 9: a) Radiation pattern at 12GHz b) Active Sii

4.2.2. Objective 2 : {f = 14GHz ; θ = 30° ; φ = 0°}

The synthesis of the reduced BFN antenna on the higher part of the Ku-band shows a directivity slightly lower than the one obtained at 12GHz, even if it reaches 18 dBi (Figure 10-a). The active matching is correct on the full bandwidth between 14-14.5 GHz (Figure 10-b) i.e. the reflection coefficient is lower than -10dB.

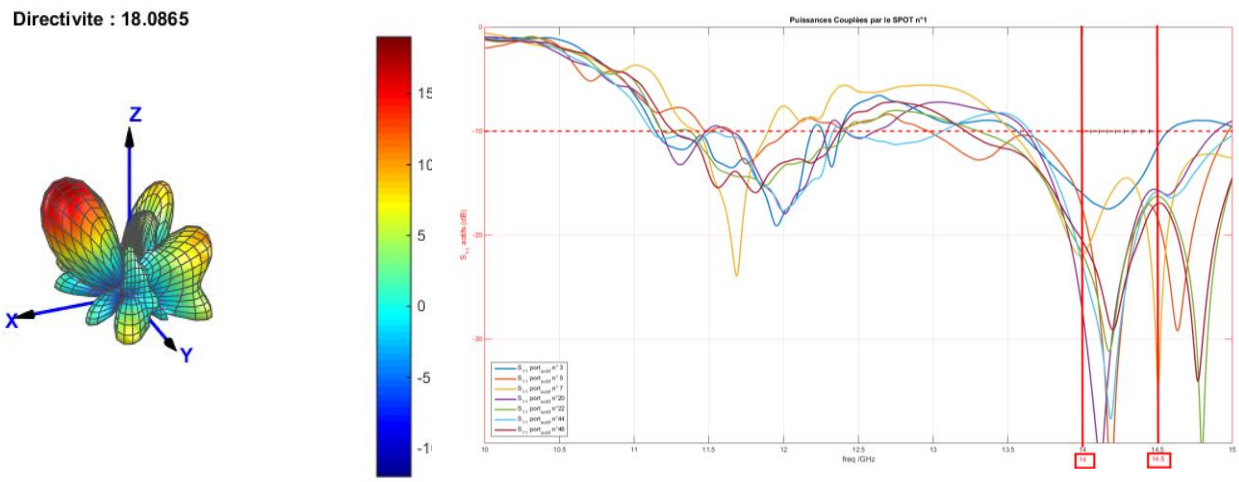

Figure 10: a) Radiation pattern at 14GHz b) Active Sii

A comparison with the directivity of an ideal aperture is performed in the Table below. A difference lower than 3 dB is observed, confirming the potentialities of this solution.

Objective pattern	Directivity max for a classical array of the same surface	Directivity obtained
1	21.3 dB	18.7dB
2	21.3 dB	18.1dB

We note a correct beam steering and good active reflection coefficients on each bandwidth. A slight degradation of directivity appears which is explained by the small number of excited elements (12%). The difference of directivity between the lower and the higher band is caused by higher couplings at lower frequencies. Nevertheless, these performances are really interesting considering the number of excited elements which permits a great simplification of the BFN.

5. Conclusion

An interesting concept of reduced BFN antenna is presented in this paper. We demonstrate the interest of the combination of excited elements and parasitic ones. We proved that it is possible to manage both active matching and radiation patterns with this concept. We showed the capabilities of this concept for Tx/Rx Ku-band applications. For such applications, we estimated the performance numerically on a triangular grid array of 57 elements. Great possibilities are offered by reduced BFN antennas to adapt phased array antennas to mass market by simplifying their design and reducing their cost.

6. Acknowledgment
Remerciements

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7. References
Références

[1] J. S. Herd and M. D. Conway, “The Evolution to Modern Phased Array Architectures,” *Proc. IEEE*, vol. 104, no. 3, pp. 519–529, Mar. 2016.

[2] P. Rocca, G. Oliveri, R. J. Mailloux, and A. Massa, “Unconventional Phased Array Architectures and Design Methodologies—A Review,” *Proc. IEEE*, vol. 104, no. 3, pp. 544–560, Mar. 2016.

[3] A. Ishimaru and Y.-S. Chen, “Thinning and broadbanding antenna arrays by unequal spacings,” *IEEE Trans. Antennas Propag.*, vol. 13, no. 1, pp. 34–42, Jan. 1965.
[4] C. Coman, I. Lager, and L. Ligthart, “Design considerations in sparse array antennas,” 2006, pp. 72–75.
[5] R. Haupt, “Reducing grating lobes due to subarray amplitude tapering,” *IEEE Trans. Antennas Propag.*, vol. 33, no. 8, pp. 846–850, Aug. 1985.
[6] A. Oueslati, C. Menudier, M. Thevenot, and T. Monediere, “Potentialities of hybrid arrays with parasitic elements,” 2014, pp. 1829–1830.
[7] R. Harrington, “Reactively controlled directive arrays,” *IEEE Trans. Antennas Propag.*, vol. 26, no. 3, pp. 390–395, May 1978.