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Network Characteristic Modes Optimisation for Wideband and Superdirective Small Antennas

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Abstract

The recent development in communication systems requires more compact antennas to be integrated on a limited space in order to operate on the desired radio standards. Nevertheless, as the antenna size decreases with respect to the wavelength, it becomes limited by bandwidth, efficiency and directivity. Recently, several researches have focused on a new class of compact antennas with high directivity. Such antennas are called superdirective anetnnas. However, despite the high directivity achieved, the antennas suffer from very narrow bandwidth and low efficiency. This paper presents an approach to enhance the bandwidth of superdirective arrays based on characteristic modes analysis. By optimizing the modes in the unit element of the array, it is possible to obtain a wideband superdirective array.

1. Introduction

The Theory of Characteristic Modes (TCM) [1] have been extensively used as a tool to analyze and design antennas for various applications [2-4]. Due to the physical insights provided by TCM a desired antenna performance can be achieved by suppressing or exciting specific modes [5].

Following the same principal as TCM the Network Characteristic Modes (NCM) is used to analyze the modes of an N port network, or more precisely a multiport antenna system [6-12]. The authors in [7], presented a methodology to design wideband reactively loaded electrically small antenna based on NCM. For a given antenna geometry, specific ports are defined inside the antenna. By choosing the proper loading topology using NCM analysis, optimized load values are calculated in order to match the compact antenna in a wide bandwidth. These optimized loads, serve in manipulating the radiating modes inside the antenna, in order to achieve a desired bandwidth.

On the other hand, in order to overcome the low directivity of small antennas, compact arrays of closely spaced Electrically Small Antennas (ESAs) are designed [13]-[14]. If each element of this array is excited with the proper current magnitude and phase, an extraordinary "superdirectivity" can be achieved. However, such arrays suffer from a very narrow bandwith and efficiency.

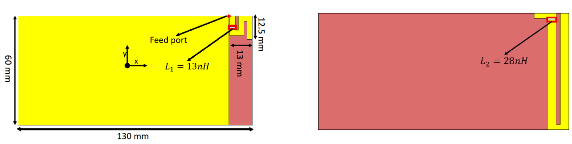
In this paper, we present a modal approach to enhance the banwidth of superdirective array in terms of matching and directivity. The approach is based on designing an array based on wideband reactively ESA as unit element. This unit element can ensure a wideband behavior of the array. Finally, the optimal current phase and magnitude is calculated by optimizing the excitation coefficient of the network characteristic fields.

2. Wideband Superdirective Array

As stated in the introduction, a wideband ESA is considered as a unit element to design the array :

2.1 Unit Element

The unit element of the array is presented in Fig. 1. The antenna is formed of an S-shaped monopole antenna integrated on a PCB. In order to compensate the large capacitance of the monopole, an inductive parasitic meander line is placed in the near field of the antenna. The meander line is connected through a via to the ground plane (Fig. 1b). Using the bandwidth optimization methodology presented in [9], the antenna is inductively loaded at two positions with $L_1 = 13nH$, and $L_2 = 28nH$. With this loading, the admittance of the characteristic modes [10] are optimized in order to have the wide band behavior $[0.84\ GHz - 1.05\ GHz]$ which represents 20% with respect to the central frequency (Fig. 2a) in addition to an efficiency higher that 80% in this bandwidth (Fig. 4b) . The antenna is mounted on a Rogers RT5880 substrate. The overall antenna dimensions are $(130mmx60mm)$ corresponding to $(0.38\lambda x0.17\lambda)$ for a reference frequency of $0.88GHz$ while the radiating part dimensions are confined to $(0.037\lambda x0.17\lambda)$.



(a) (b)

Figure 1 Unit element. (a) Top view, (b) bottom view.

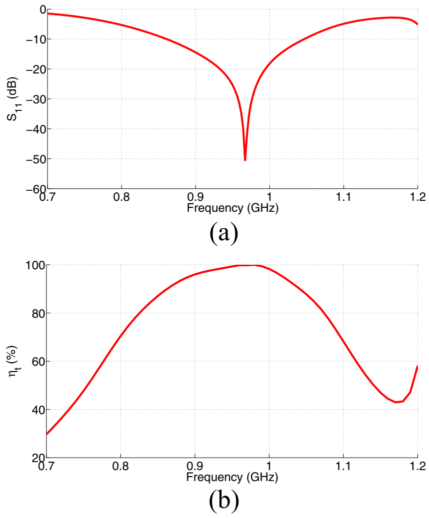


Figure 2 Characteristics of the unit element. (a) Input reflection coefficient, (b) total efficiency.

2.1 Two-Element Endfire Array

After designing the internally loaded wideband unit element, a two-element endfire array is considered. The geometry of the array is given in Figure 3. The inter-element separation is 65 mm. Ports 1 and 2 are driven while the internal ports are loaded by the previously optimized inductances, where $L_1 = L_3 = 13nH$ and $L_2 = L_4 = 28nH$. Since the unit element is matched over a wideband, the two element array is also matched in a wideband. Figure 4 shows the input reflection coefficient of the array at the input ports. Both ports are matched in a wideband $[0.84 - 1.04\ GHz]$ (21.2%) for port 1 and $[0.84 - 1.14\ GHz]$ (30.3%) for port 2. Nevertheless, in order to achieve a high directivity, the port should be excited by the proper current magnitude and phase. Following the modal approach presented in [11], the excitation coefficients of the characteristic fields are optimized in order to achieve the maximal directivity. By exciting the first element with a current of $0.7e^{j230^\circ}$ relative to the second element, the array achieves a maximal directivity of 7.1 dBi at 910 MHz.

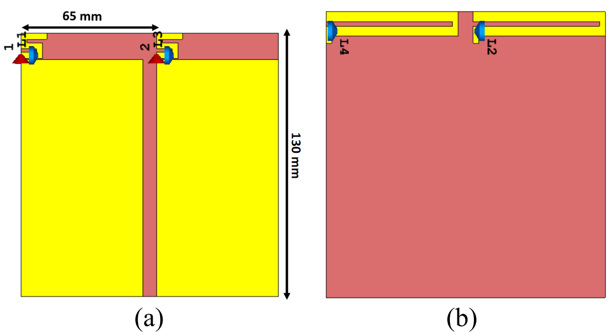


Figure 3 Two-element array geometry. (a) Top view, (b) bottom view

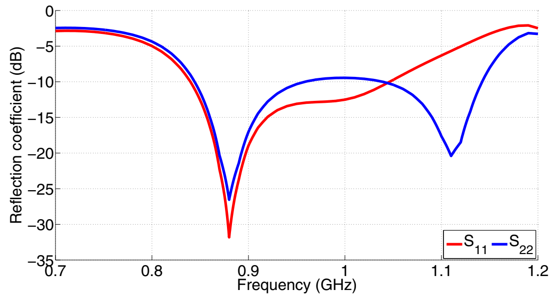


Figure 4 Input reflection coefficient of the two-element array

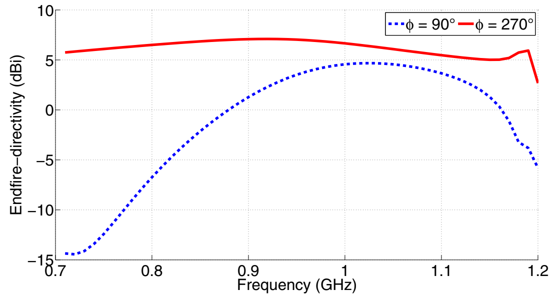


Figure 5 Endfire directivity of the two-element array fed with the optimized excitations

Moreover, with this excitation, the array exhibits a relatively constant directivity over a wide bandwidth. The $1 - dB$ directivity bandwidth is $[0.74 - 1.06\ \text{GHz}]$(35 %) (Figure 5).

Hence, using an approach based on the NCM, a wideband superdirective two-element array was designed.

2.2. Three-Element Array

To study the possibility of achieving a wideband directivity for more complex cases. A Third element is added to the array, while maintaining the same inter-element separation (65 mm). The reflection coefficient of the array at the input ports is shown in Figure 6. The wideband matching is still maintained at the array ports. However, the matching level of the second port is increased due to the high mutual coupling between the closely spaced elements. Using the same approach the optimal excitation is calculated. Port 1 and port 3 are respectively excited by $I_1 = 0.59e^{j186^\circ}$ and $I_3 = 0.68e^{j169^\circ}$. With this excitation, the array exhibits a maximal directivity of 9.8 dBi at 890 MHz. Moreover, the 1 dB directivity bandwidth is $[0.8 - 0.99\ GHz]$ (22 %) . Therefore, a wideband superdirective behaviour can also be achieved for a three element array.

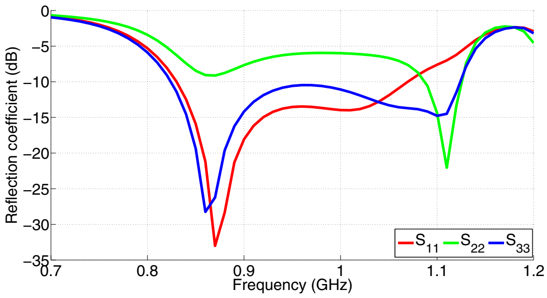


Figure 6 Input reflection coefficient of the three-element array

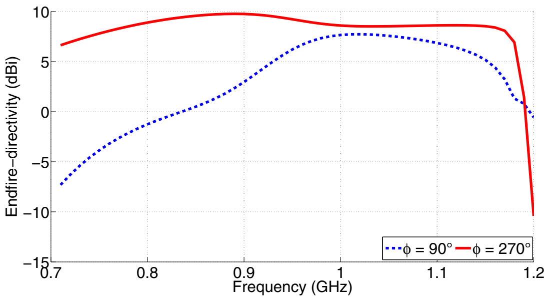


Figure 7 Endfire directivity of the three element array fed with the optimized excitations

3. Conclusion

In this paper, a modal approach was presented to design a wideband supredirective array. By using the NCM optimization, a wideband electrically small antenna is designed. The antenna is internally loaded with inductances at two positions. These inductances serve in manipulating the radiating modes inside the antenna in order to match it in a wide bandwidth. A two and three-element endifre arrays are then formed based on this antenna as a unit element. It was shown that in both cases it was possible to achieve a wideband directivity if the array ports are properly excited. However, there is still a compromise between the complexity and the performance of the unit element and the array. A higher number of internal ports and much complex loading topology can provide a better control on the current and hence a wider bandwidth. On the other hand, adding more elements in the array will result in a higher directivity, while decreasing bandwidth and efficiency values. In addition, due to the high coupling levels as the number of the elements in the array increases, the array becomes much more sensitive to the changes in the excitation coefficient, therefore any slight numerical error might lead to a significant decrease in the directivity level.

6. Acknowledgements

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