Extending the Bandwidth of a Superdirective First-Order Probe for Spherical Near-Field Antenna Measurements

Oleksiy S. Kim
Electromagnetic Systems, Department of Electrical Engineering
Technical University of Denmark (DTU)
Kgs. Lyngby, Denmark
E-mail: osk@elektro.dtu.dk

***Abstract*—A superdirective array of electrically small dipole radiators can effectively be used as a compact and lightweight first-order probe (a directive antenna radiating predominantly spherical modes with the azimuthal index $|\mu| = 1$) in spherical near-field antenna measurements at low frequencies. This contribution shows that a very narrow frequency bandwidth peculiar to superdirective antennas can be extended to practical values by the proper design of the array elements as well as by relaxing the maximum directivity condition, while keeping $|\mu| = 1$ modes dominating in the radiation spectrum of the antenna. The resulting probe has the relative bandwidth of 3% and directivity above 9 dBi; its height is 0.5λ over a 1λ circular ground plane.**

I. INTRODUCTION

In spherical near-field (SNF) antenna measurements, the far-field pattern of an antenna under test (AUT) is obtained by the near-to-far-field transformation applied to the data measured on a sphere of finite radius enclosing the AUT, usually in the near-field. In this process, the influence of the probe radiation pattern is accounted by introducing a probe correction, which is the most efficiently done for first-order probes [1], that is, antennas radiating only spherical modes with the azimuthal index $|\mu| = 1$. Open-ended cylindrical waveguides and conical horns excited by the fundamental TE_{11} cylindrical mode are $|\mu| = 1$ antennas, and thus, most frequently used as probes in SNF measurements. However, these kind of antennas become impractical at frequencies below 1 GHz due to their weight and bulkiness.

A lightweight and compact alternative to the classical probes is a superdirective linear array of electrically small resonant magnetic dipole radiators proposed in [2], see Fig. 1. Electrically small size of the array elements (capacitively loaded loops) ensures that they radiate essentially a dipole mode (TE_{10} spherical mode — the lowest order $|\mu| = 1$ mode). Just two of these elements (one active and one passive) combined in a superdirective array (total height 0.27λ) on a circular ground plane (1λ in diameter) yield the directivity of 9.2 dBi, which is sufficient for a SNF probe. The main disadvantage of the superdirective probe presented in [2] is its very narrow frequency bandwidth, which is only 0.2% at -10 dB level.

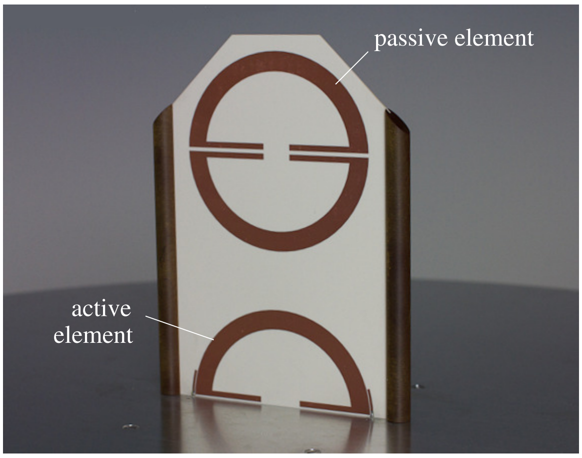

Fig. 1. Superdirective P-band first-order probe for SNF measurements [2].

The concept of the superdirective probe has been further advanced to extend its frequency bandwidth to practical values. In this process, the goal was to maximize the bandwidth, while keeping the directivity above 9 dBi. The results of these efforts are reported here.

II. DIRECTIVITY AND Q OF A SUPERDIRECTIVE ARRAY

The maximum endfire directivity of an array of N elementary magnetic dipoles arranged equidistantly along a line normal to an infinite ground plane can be found as [2]

$$D_0 = 2 \sum_{n=0}^{N-1} a_n \cos(nkd), \tag{1}$$

where k is the propagation constant of free space and d is the distance between the dipoles. Here, it is assumed that the fist dipole with index $n = 0$ is located on the ground plane. As shown in [2], the excitation coefficients a_n ensuring the maximum endfire directivity D_0 are found by solving the following system of linear equations

$$\sum_{n=0}^{N-1} a_n h_{mn} = \cos(mkd), \quad m = 0, 1, ...N-1, \tag{2}$$

where

$$h_{mn} = \frac{1}{2}\sum_{\pm}\left\{\frac{\sin[(m \pm n)kd]}{(m \pm n)kd}\left(1 - \frac{1}{[(m \pm n)kd]^2}\right) + \frac{\cos[(m \pm n)kd]}{[(m \pm n)kd]^2}\right\}, \quad \text{for } m \neq n \tag{3a}$$

$$h_{mn} = \frac{1}{3} + \frac{\sin(2nkd)}{4nkd}\left(1 - \frac{1}{(2nkd)^2}\right) + \frac{\cos(2nkd)}{2(2nkd)^2}, \quad \text{for } m = n \neq 0 \tag{3b}$$

and $h_{mn} = 2/3$ for $m = n = 0$. The maximum endfire directivity as a function of the inter-element distance d for two magnetic dipoles ($N = 2$) is plotted in Fig. 2. It is observed that as $d \to 0$, the directivity approaches the maximum value of 11.5 dBi. This is superdirectivity, which comes for a price of high sensitivity to various errors (for example, in the element positioning) and a narrow frequency bandwidth. The later can be quantified using the Q-factor, which is inversely proportional to the bandwidth.

The Q of a superdirective array is proportional to the Q of individual array elements and a so-called “geometrical Q” [3], which read as

$$Q_g = \frac{\sum\limits_{n=0}^{N-1} a_n a_n^*}{\sum\limits_{n=0}^{N-1}\sum\limits_{m=0}^{N-1} a_n h_{mn} a_m^*}. \tag{4}$$

The Q_g corresponding to the maximum endfire directivity is also plotted in Fig. 2. It is seen that not only the maximum directivity grows as the distance between the array elements decreases, so does the Q_g as well, and in a very fast rate; the bandwidth shrinks correspondingly.

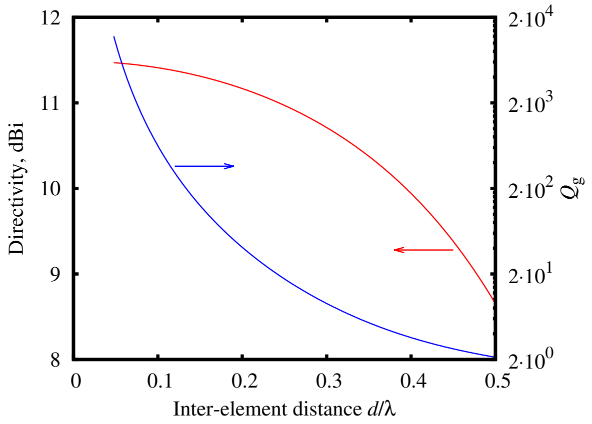

Fig. 2. Maximum endfire directivity D_0 and geometrical Q of a 2-element superdirective array over a ground plane versus the inter-element distance d.

Fortunately, we do not need the highest possible directivity; as noted above, anything above 9 dBi is sufficient. This means that we can improve the bandwidth of our 2-element superdirective array by using a larger inter-element distance. Another mean to improve the bandwidth is to extend the bandwidth of individual array elements.

III. ARRAY ELEMENT WITH EXTENDED BANDWIDTH

The frequency bandwidth of an electrically small radiator is inversely proportional to its radiation Q, which in turn is inversely proportional to the cube of the antenna electrical size (Chu lower bound [4]). This implies that the bandwidth of the superdirective array can be increased by enlarging its elements. However, the size cannot be arbitrary large, because this gives rise to higher-order azimuthal modes $|\mu| \neq 1$ [2], which should be suppressed.

Alternatively, the bandwidth can be improved by efficiently utilizing the volume around an element, that is, instead of a single-loop element as in Fig. 1 utilize a multiple-loop element, such as the one shown in Fig. 3. With the diameter just 1.3 times larger than that of the element in Fig. 1, this three-loop element yields more than 4 times larger bandwidth. Adding more loops could slightly further improve the bandwidth [5], but at the cost of the rising manufacturing complexity.

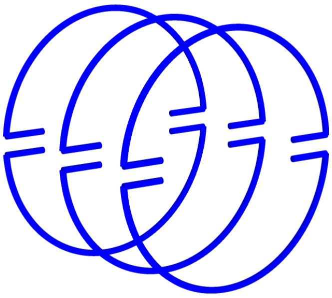

Fig. 3. Resonant magnetic dipole element composed of three capacitively loaded loops for extended bandwidth.

IV. SUPERDIRECTIVE ARRAY WITH EXTENDED BANDWIDTH

The distance between centres of the elements in the array in Fig. 1 is 0.19λ. Doubling this distance to 0.38λ will reduce the Qg by ten times, according to Fig. 2. Such a superdirective array composed of the improved three-loop elements should then provide much larger bandwidth than that of the array in Fig. 1, while still being compact and lightweight. Numerical simulations indeed show 15-fold increase in the bandwidth (see Fig. 4). The simulated directivity of the improved superdirective probe varies from 9.5 dBi to 10.6 dBi in the frequency band 428-443 MHz, while its mode spectra is that of a good first-order probe.

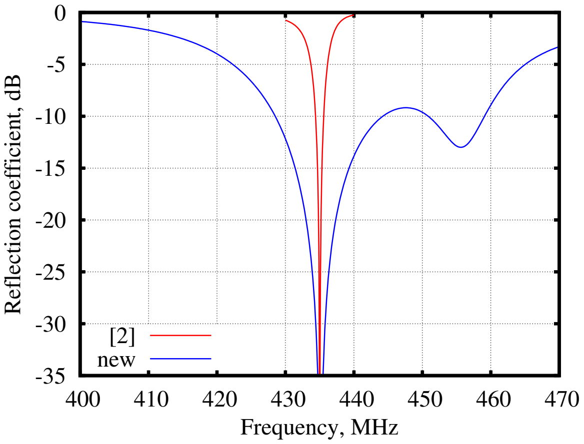

Fig. 4. Simulated reflection coefficient for the 2-element superdirective array from [2] and the new superdirective array composed of three-loop elements.

V. CONCLUSIONS

The frequency bandwidth of a superdirective array proposed in [2] as a compact and lightweight first-order probe for spherical near-field antenna measurements is extended from 0.2 to 3% by redesigning the array elements as well by reducing the "geometrical" Q of the array. The improved probe utilizes the same circular ground plane of 1λ in diameter, its height is 0.5λ above the ground plane. The probe yields the directivity above 9 dBi over its 15 MHz operating frequency band (at -10 dB level) with the central frequency of 435 MHz.

ACKNOWLEDGMENT

This work is supported by the European Space Agency under the ESA Contract No. 4000111981/15/NL/MH.

REFERENCES

[1] J. E. Hansen, *Spherical Near-Field Antenna Measurements*. London, U.K.: Peter Peregrinus, 1988.

[2] O. S. Kim, S. Pivnenko, and O. Breinbjerg, "Superdirective magnetic dipole array as a first-order probe for spherical near-field antenna measurements," *IEEE Trans. Antennas Propagat.*, vol. 60, no. 10, 2012.

[3] M. Uzsoky and L. Solymar, "Theory of super-directive linear arrays," *Acta Phys. Hungarica*, vol. 6, no. 2, pp. 185–205, 1956.

[4] L. J. Chu, "Physical limitations of omni-directional antennas," *J. Appl. Phys.*, vol. 19, no. 12, pp. 1163–1175, 1948.

[5] O. S. Kim, "Low-Q electrically small spherical magnetic dipole antennas," *IEEE Trans. Antennas Propagat.*, vol. 58, no. 7, pp. 2210–2217, July 2010.