A Highly Directive Linear Array of Electrically Small Folded Helices

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***Abstract*—This work considers closely spaced linear arrays made from electrically small elements. The arrays display some characteristics of superdirective behavior at close element spacing, including increased directivity, degraded radiation efficiency, and high sensitivity to excitation tolerances. Three elements are considered, and the spherical folded helix is shown to require less sensitive excitations than short monopoles with and without top-loading. A five element folded helix array occupying a volume of 0.686λ × 0.086λ × 0.043λ is considered under two excitation cases, achieving a directivity of 13.8 dB at 21% efficiency in one and a directivity of 9.9 dB at 77% efficiency in the other.**

I. INTRODUCTION

Superdirective excitation of arrays with closely spaced elements is well characterized theoretically [1]; however, significant problems are present in its practical realization. In particular, superdirective arrays tend to suffer from low radiation efficiency and high sensitivity to excitation and mechanical tolerances [2]. However, practical arrays have been demonstrated which achieve performance near the lower bound of superdirective behavior [2]. This work considers such arrays when realized from electrically small elements and the impact of element choice on the radiation efficiency and pattern sensitivity.

II. ARRAY DESIGN

Five element linear arrays composed of electrically small elements are considered herein. Three types of elements, shown in Fig. 1, are studied: an electrically small monopole, an electrically small monopole with capacitive top loading, and an electrically small spherical folded helix. The spherical helix is similar to that introduced by Best [3], modified to have three arms and two turns per arm. Array operation is considered at 810 MHz. All three elements fit within a cylindrical area 16 mm (0.043λ) tall and 32 mm (0.086λ) in diameter. The array elements are made of copper, placed over an infinite PEC ground. The arrays are simulated in Altair FEKO, from which the resultant embedded element patterns and scattering parameters are processed.

The elements considered are intended to examine the impact of radiation resistance and quality factor in array performance. The short monopole has low radiation resistance ($R_{rad} < 1\ \Omega$) and narrow bandwidth, corresponding to a high quality factor ($Q \approx 350$). Capacitive top loading increases the radiation resistance and widens the bandwidth, resulting in lowered quality factor. The folded helix takes this process further, with high radiation resistance ($R_{rad} \approx 25\ \Omega$) and low quality factor ($Q \approx 81$, near the fundamental limit [3]).

Superdirective excitations are generated using the method of [4], which is based on a Chebyshev-type synthesis method.


(a) (b) (c)

Fig. 1. The array elements considered in this work, (a) an electrically short monopole, (b) a short monopole with capacitive top-loading, and (c) an electrically small spherical folded helix.

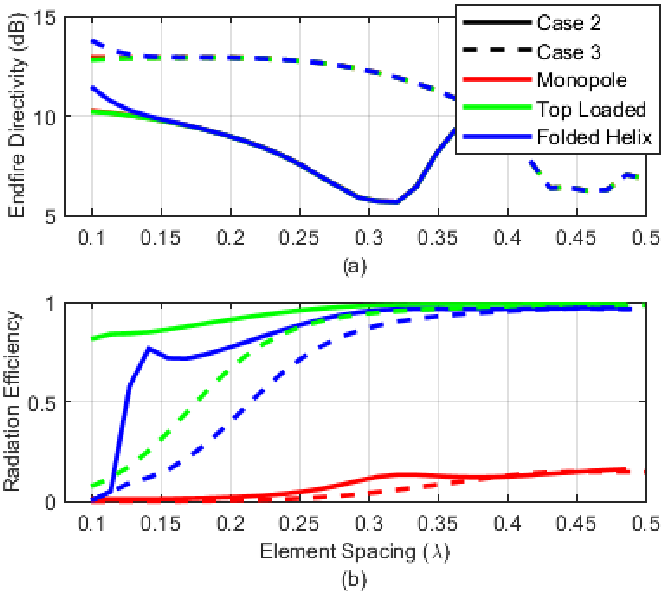

Fig. 2. Performance of each array under the two excitation cases as a function of the distance between adjacent elements, showing (a) directivity at endfire and (b) radiation efficiency.

Several methods of pattern synthesis are described, of which two are used here: "case 2", a method specifically for endfire synthesis; and "case 3", an improved endfire case where the visible region's extent is doubled by folding onto itself. This latter case is expected to lead to more sidelobes, lower beamwidth and therefore increased directivity. In this work, the array factors are synthesized with a specified sidelobe level of -20 dB. The excitation on each port of the array is compensated for mutual coupling effects in the manner of [5].

III. ARRAY PERFORMANCE

The maximum directivity of each array, which occurs in the endfire direction, is plotted in Fig. 2 (a). With close element spacing, case 2 achieves directivity exceeding 10.1 dB while case 3 achieves directivity exceeding 13.8 dB. At

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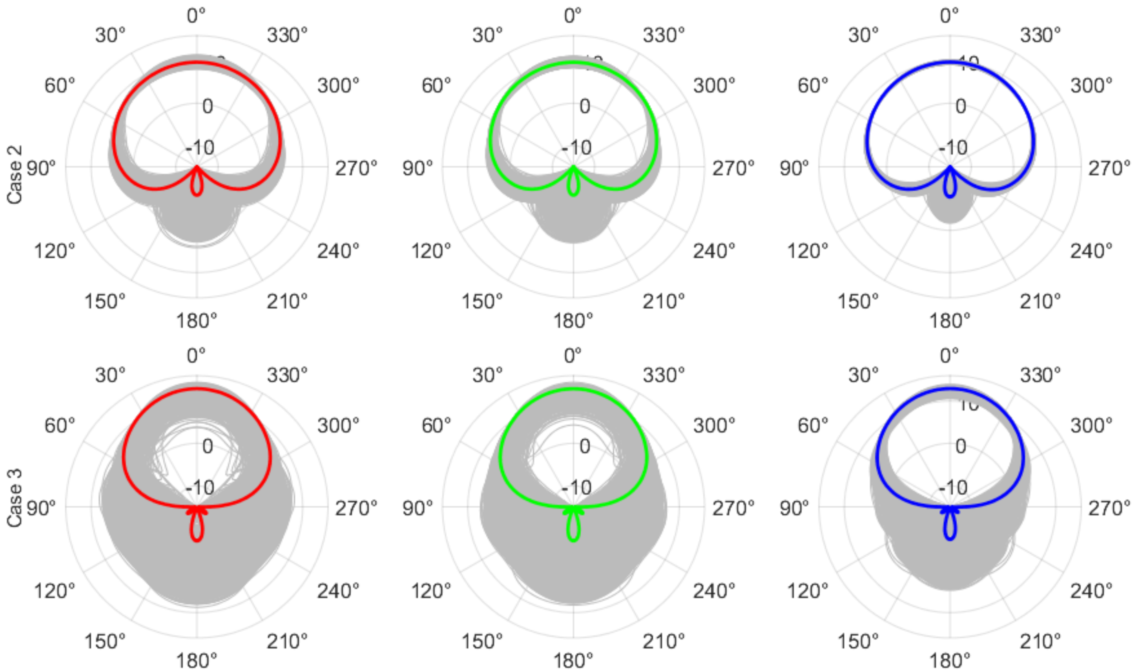

(a) (b) (c)

Fig. 3. Sensitivity analysis of the arrays to $\pm 5\%$ variation in excitation amplitude and $\pm 5^\circ$ variation in excitation phase. Thick traces are without errors; thin gray are with errors. H-plane patterns are shown at horizon ($\theta = 90^\circ$) for (a) the short monopole array, (b) the top-loaded short monopole array, and (c) the spherical folded helix array.

larger element spacings, the pattern synthesis method results in lower directivity than other methods, such as the Hansen-Woodyard synthesis. The similar directivity achieved by all three arrays is expected, since their element patterns are close to omnidirectional after compensation for mutual coupling.

The radiation efficiency of each array is shown in Fig. 2 (b). The short monopole's low radiation resistance leads to a low radiation efficiency, staying below 20% for all spacings and excitations considered. The top loaded monopole and folded helix arrays realize higher efficiency as a consequence of their higher radiation resistance. The efficiency is degraded at close spacings due to the required excitations having large phase variations between adjacent elements. This results in high currents on the elements whose radiation largely cancels in the far field, increasing losses relative to radiated power. The differences between case 2 and case 3 excitation illustrate a trade-off between the directivity of the array and the resulting efficiency, which can be adjusted depending on application.

A Monte-Carlo analysis of the radiation pattern of the arrays with 0.15λ element spacing is shown in Fig. 3. The excitation on each port is assumed to vary independently by $\pm 5\%$ in amplitude and $\pm 5^\circ$ in phase.

The case 2 excitations show relatively low sensitivity to excitation tolerance for all the arrays considered, with the endfire directivity varying by less than 2 dB. Variation in excitation contributes to increased sidelobes and backlobes, although the main lobe of the pattern remain dominant.

Conversely, the sensitivity of the case 3 excitations varies with the array type. The monopole and top-loaded monopole show high sensitivity, with the worst-case endfire directivity drooping by 9 dB for both. The spherical folded helix array shows more robustness to excitation variations, with worst case drop in endfire directivity limited to 2.7 dB and a backlobe which remains 10 dB below the mainlobe.

IV. CONCLUSION

This work considers three different electrically small monopole elements in a five-element linear array scanned for directive endfire radiation. The use of elements with higher radiation efficiency is shown to improve the array's radiation efficiency and the usage of a low-Q element is shown to reduce the realized pattern's sensitivity to excitation variations. This work suggests that the spherical folded helix is a promising candidate for the practical realization of highly directive patterns from closely spaced arrays with low profile.

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