A SUPERDIRECTIVE ARRAY USING VERY SMALL GENETIC ANTENNAS

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ABSTRACT

For a linear periodic array, it has been shown that, as the spacing between elements decreases, the endfire directivity of the array approaches N^2, where N is the number of elements. In this paper we investigate theoretically, computationally, and experimentally the possibility of achieving this endfire superdirectivity for two-element arrays of resonant monopoles and resonant electrically small genetic-antennas.

INTRODUCTION

One of the most challenging problems in antenna design is that of the super-directive array. Nonetheless, Uzkov [1] has shown that the directivity of a linear array of N isotropic radiators can approach a maximum value in the endfire direction of N^2. This maximum directivity is approached as the element spacing of the array approaches zero and for the excitation of each isotropic element having a specified magnitude and phase (with respect to one of the elements). A directivity of N^2 represents an extraordinary "superdirectivity" compared to the maximum attainable directivity N for isotropic elements spaced half a wavelength apart, especially because the directivity of N^2 is approached as the length of the linear array approaches zero. If, in addition to the small lateral spacing, the height of the array elements could be made small, one would have a remarkably electrically small super-directive array.

These electrically small super-directive arrays are not feasible for N larger than a few elements because of the rapidly increasing accuracy with increasing N required in the values of magnitude and phase of each array element for the array to maintain a directivity close to N^2. Moreover, inexpensive low-loss resonant antennas less than about $\lambda/6$ across, where λ is the wavelength, have not been readily available. (Unless the electrically small antennas comprising the array are resonant, the input reactances of the antenna elements will be too large for the antennas to radiate a significant amount of power at feasible excitation levels. Moreover, only resonant antennas will maintain approximately the same current distributions and thus the same individual radiation patterns when they are spaced a small fraction of a wavelength apart.) During the past few years, however, Altshuler [2] has designed and built electrically small resonant "genetic antennas" as small as $\lambda/30$ across. Therefore, during the past year, we have looked into the possibility of designing two- and three-element super-directive arrays using not only resonant monopoles, but also these resonant electrically small genetic antennas as elements spaced much closer than $\lambda/2$

THEORY

Actual array elements, no matter how small, cannot be spaced closer than their physical dimensions. Thus, we had to determine to what extent the directivity of an array would be reduced from the maximum attainable value of N^2 by spacing the array elements a small but reasonable distance apart. The results of a nonlinear optimization procedure reveal that element spacing as large a $.2\lambda$ can be tolerated without more than about a 10% reduction in the maximum endfire directivity for the two- and three-element arrays, respectively.

As mentioned in the Introduction, super-directive arrays are not feasible if the necessary tolerances in magnitude and phase are too small to maintain with available microwave components. Thus, we recomputed the maximum endfire directivity versus element spacing for either a 5% magnitude error or a 5 degree phase error in the excitation coefficient of the first element. The results reveal that these substantial magnitude and phase errors do not decrease the maximum endfire directivity (N^2) more than about 10% for two- and three-element arrays if the spacing of the array elements stays larger than about $.05\lambda$ and $.15\lambda$, respectively. Moreover, these separation distances of $.05\lambda$ and $.15\lambda$ for two- and three-element arrays were shown, as explained above, to be small enough to keep the endfire directivity of the arrays close to the maximum possible values of $N^2 = 4$ and 9, respectively. Nonetheless, if the magnitude of the excitation coefficients needed to make the super-directive array radiate a significant amount of power is too large, it may be difficult to use the array antenna as a practical transmitter.

To determine the reduction in power efficiency, the total power radiated by a linear super-directive array of N elements was computed versus separation distance for a constant current excitation of the first element. This power, normalized to unity at $\lambda/2$ spacing revealed that the total power radiated by the array for a fixed current magnitude does indeed decrease with separation distance of the array elements. However, for an element spacing of $.1\lambda$ the current or voltage driving the two-element super-directive antenna array has to be increased only by about a factor of 3.3 to keep the same power that the array radiates at $\lambda/2$ spacing. For a three-element array, the total power radiated decreases faster with separation distance, but still not so much faster as to prevent a practical three-element super-directive array.

COMPUTATIONS

It has been shown that it is possible to design an electrically small self-resonant antenna using a genetic algorithm (GA) in conjunction with the Numerical Electromagnetics Code (NEC) [2]. A small antenna is often defined as having a maximum dimension that is less than the "radianlength" which is $\lambda/(2\pi)$. For this investigation we define the size of the antenna as that enclosed within a cube of height h over an infinite ground plane. Thus the total volume within which the equivalent antenna in free space is confined is $2h^3$. This definition is chosen because the computations are done with NEC, which uses Cartesian coordinates. The main problem in small antenna design is that as the size of the antenna is decreased, its reactance approaches plus or minus infinity depending on whether it behaves as an inductance (loop) or as a capacitance (monopole) off resonance. Most small antennas are inefficient and non-resonant and thus require matching networks, which are often lossy. We used a genetic algorithm (GA) in conjunction with NEC to search for resonant antenna configurations that best utilize the volume within which the antenna is confined. The objective of this optimization was to minimize the Voltage Standing Wave Ratio (VSWR) and corresponding Q of an electrically small resonant antenna. The genetic algorithm produced an antenna configuration for which the capacitive and inductive coupling between the wire segments cancel, thus achieving resonance. The far-field pattern had nearly hemispherical coverage with predominantly vertical polarization along the horizon and horizontal polarization in the zenith direction. For other angles, the wave was elliptically polarized.

Having designed an electrically small 7-wire resonant genetic antenna that would fit within a cube of .045 wavelengths on a side, we next explored its potential as an element for a two-element super-directive array. For comparison, we also analyzed an array with quarter-wave monopoles. The directivities for both types of array elements were computed as a function of spacing at a frequency of 400 MHz. For a two-element array, maximum directivity is obtained in the endfire direction when both elements are excited with equal current amplitudes and a specified phase difference. We designate the antenna further from the endfire direction as element #1 and the closer antenna as element #2. In Fig. 1 we show the behavior of several parameters for the monopole and electrically small genetic antenna array elements as a function of spacing. (The code appeared to become unstable for spacing less than about $.05\lambda$.) In Fig. 1a we plot the endfire directivity for both types of antennas. The simulated directivities for the genetic antenna and monopole for half-wavelength spacing are about 6.8 and 7.5 dB respectively. We note that these directivities slowly increase as the spacing is decreased and approach values of 9.8 and 10.5 dB The endfire directivity of the monopole array is higher than that of the genetic element array because a monopole has a higher directivity along the horizon. (The theoretical endfire directivities predicted for isotropic radiators, with the directivities of the monopole or genetic antenna added, are about .5 dB higher than the computed directivities in Fig. 1a.) In Fig. 1b we show the phase delay required for element #2 with respect to element #1 to produce superdirectivity. We note that for both the monopole and genetic antennas this phase delay is about 180 degrees for .5 wavelength spacing, decreases to about 140-150 degrees for .35 wavelength spacing and then approaches 180 degrees as the spacing is further decreased. In Figs. 1c and 1d we plot the input resistances and reactances. For the monopole, it is noted that as the spacing is decreased, the input resistance of element #1 decreases more rapidly than does that of element #2 until the spacing approaches about .05 wavelength for which the resistances of both elements are very low. Thus, in order to maintain equal current amplitudes, the voltage applied to monopole #2 must be increased as the spacing is decreased. The input resistance of the isolated genetic antenna is only a few ohms. The input resistance of element #1 decreases slowly and actually becomes negative when the spacing decreases to about .15 wavelength. This means that this antenna is actually absorbing power from antenna #2. The input reactances of both elements start to increase sharply at about that same spacing.

MEASUREMENTS

The measurements were made in a 37ft x 73ft x 38ft (11.3m x 22.3m x 11.6m) anechoic chamber. The absorbing material was marginal at a frequency of 400 MHz, but for this application it was assumed adequate. The antennas were mounted over a 4 ft x 4 ft (1.2m x 1.2m) (1.6λ x 1.6λ at 400 MHz) ground plane. A Hewlett-Packard Model 8510 Network Analyzer was used for the measurements. The ground plane had 17 holes spaced 5cm apart, through which a Type N connector with the antenna attached to its center conductor could be inserted. There was also an additional hole placed 2.5cm from the center hole, thus enabling measurements to be made at 2.5cm increments for separations from 2.5cm to 42.5cm and then with 5cm increments up to 80cm. At 400 MHz (λ=75 cm) this corresponds to separations of .033λ and .067λ up to slightly over 1 wavelength. A signal from one port of the HP 8510 was sent to a two-way power divider. One signal from the power divider went directly to a 4-port directional coupler, which was connected to element #1. The other signal went through an attenuator connected in series with a phase shifter and then to the other directional coupler and element #2. The forward (*a*) and reflected (*b*) signals for each antenna were measured with the directional couplers. In this way the amplitude and phase of the current into each antenna could be monitored and the power radiated by each antenna determined. The reference antenna, which was used to measure the directivity, was a log-periodic dipole antenna at a distance of about 10 meters from the array.

The following procedure was used to measure the endfire directivity of the 2-element monopole array as a function of element spacing. The second port of the HP8510 was used for two types of measurements. One was to measure the received signal of the monopoles at the reference antenna. The other was to measure the forward and reflected signals from the directional couplers. Ideally, for maximum endfire directivity, the currents exciting each antenna should have equal magnitudes and a phase difference which is a function of spacing. The attenuator and phase shifter were varied and set for a maximum received signal. The forward and reflected signals for each monopole were then measured and the total power radiated determined. The difference between the received power and the power radiated is the relative directivity. The directivity of the array, unlike the gain, does not take into account the ohmic losses that are incurred in transferring power to the antenna. Since the mismatch from the transmission line to the antenna becomes greater as the antennas become closer, it takes more transmitted power to produce the same input currents for closely spaced antennas.

Before the array measurements could be made, the effect of the finite ground plane on the measurements had to be investigated. The input impedance and gain of a single monopole was measured as a function of position on the ground plane. The input impedance did not vary significantly but the gain underwent a sinusoidal variation of close to 2 dB. However, this effect was not considered prohibitive since the critical measurements were made for close spacing, for which only a small region of the ground plane was utilized. Also, the measurements could be repeated for the same spacing but at different ground plane locations and averaged if necessary.

For the monopoles, the preliminary results showed that the directivity did increase slowly as the spacing was decreased; a maximum directivity of over 2 dB greater than that for one-half wavelength spacing was reached for a spacing of about .16 wavelength. We hope to have the endfire directivity measurements for the genetic antenna elements by the time of the talk.

ACKNOWLEDGEMENTS

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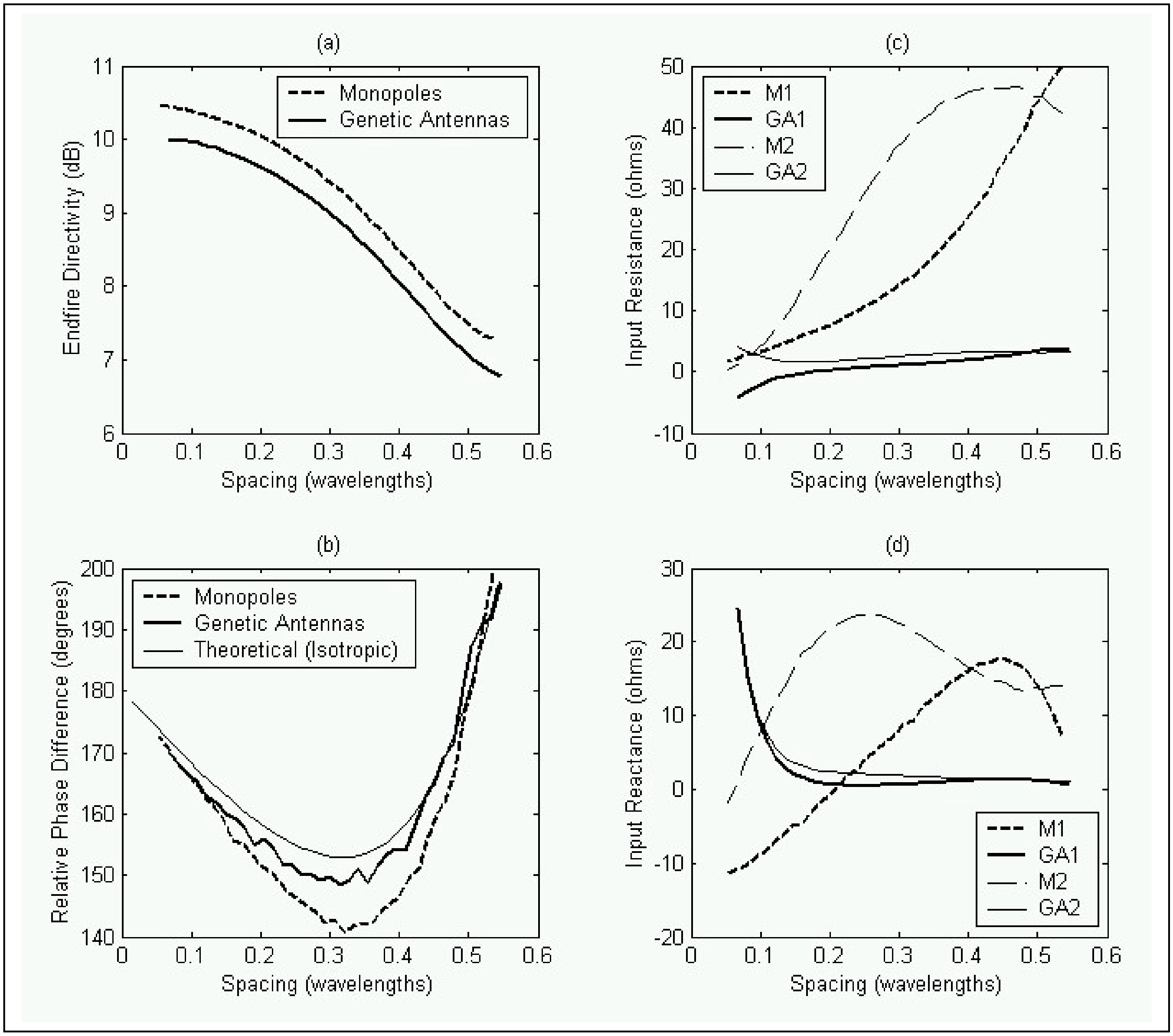

Fig. 1. Antenna array parameters as a function of spacing