Electrically Small Self-Resonant Wire Antennas Optimized Using a Genetic Algorithm

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***Abstract*—One of the major limitations of electrically small antennas is that as the size of the antenna is decreased its radiation resistance approaches zero and its reactance approaches plus or minus infinity. Most small antennas are inefficient, nonresonant and, thus, require matching networks. In this investigation, we use a genetic algorithm (GA) in conjunction with the numerical electromagnetics code to search for resonant wire shapes that best utilize the volume within which the antenna is confined. Antenna configurations, over a ground plane, having from two to ten wire segments, were optimized near 400 MHz and then built and tested. As the cube size deceased from a side length of 0.096λ to 0.026λ, the computed Qs increased from 15.8 to 590. The measured Qs increased from 16.0 to 134 for cubes of 0.093 to 0.037λ on edge. This process for designing small antennas using a GA produced new self-resonant antenna configurations.**

***Index Terms*—Electrically small antennas, genetic algorithms, wire antennas.**

I. Introduction

One of the most challenging problems in antenna design is that of the electrically small antenna [1]–[9]. Wheeler [1] defines a small antenna as one whose maximum dimension is less than the radianlength which is $1/2\pi$ wavelength. The associated volume is often defined as a radiancube with a radianlength equal to the side of the cube, or a radiansphere with the radianlength equal to the radius of the sphere. Chu [2] defined the electrical size of the antenna in terms of a sphere of radius a/λ, within which the antenna is enclosed. This definition is convenient for the analysis of antennas when the fields are represented by spherical wave functions. For this investigation we define the size of the antenna as that enclosed within a cube of height, h/λ over an infinite ground plane. Thus, the total volume within which the equivalent antenna in free space is confined is $2(h/\lambda)^3$. This definition is chosen because the computations are done with the Numerical Electromagnetics Code (NEC) [10], which uses Cartesian coordinates. The parameter which best characterizes the performance of a small resonant antenna is the quality factor Q, which may be defined as the ratio of the resonant frequency of the antenna to the frequency difference at which the radiated power decreases to $1/2$ that at resonance. The lower the Q, the more broadband the antenna. The main problem in small antenna design is that as the size of the antenna is decreased its radiation resistance approaches zero and its reactance approaches plus or minus infinity depending on whether it behaves off resonance as an inductance (loop) or as a capacitance (monopole). The genetic algorithm (GA) is able to produce a wire configuration that has both capacitive and inductive reactance, which cancel, thus producing resonance. Most small antennas are inefficient and nonresonant and, thus, require matching networks. Since the antenna Q is defined for a resonant antenna, the matching network for a nonresonant antenna has to be included in the calculation of Q. Wheeler [1] introduces the term radiation power factor so that the radiation efficiency of a small nonresonant antenna can be calculated. The radiation power factor is a function of the antenna radianlength, its volume and a shape factor.

In this investigation, we use a GA [11]–[13] in conjunction with NEC to search for resonant wire configurations that best utilize the volume within which the antenna is confined. The GA is an iterative optimization process that imitates the adaptation and evolution of a species of organism. The objective of this optimization is to minimize the voltage standing wave ratio (VSWR) and corresponding Q of an electrically small resonant antenna. A specified number of wire segments of unspecified lengths are connected in series and contained within a cube of specified volume. As the size of the cube, within which the antenna is enclosed, is decreased, more wire segments have to be used. We investigated configurations having from two to ten wire segments and for all cases resonant antennas were obtained. The antennas were simulated and then built and measured. Intuitively, the antenna should consist of segments that are orthogonal where possible and which do not contain parallel wires that are too close together. The resulting configurations for the two- to five-wire-segment antennas could probably have been derived using this intuitive approach. For more than five segments, we believe that the GA produced configurations that were far too complex to have been arrived at using intuition. The GA optimization was done at about 400 MHz. Operating at a lower frequency would have been preferred, since it was very difficult to build a ten-segment wire antenna that fits inside a cube less than 2 cm on a side; however, measurements at lower frequencies were not possible since a much larger ground plane and an improved anechoic chamber would have been required.

II. Approach

A. Computations

To begin the GA process, a cost function, which contains the parameters to be optimized, must first be defined. For this investigation, the only parameter to be optimized was the VSWR. Other parameters such as radiation pattern and gain were not included since they do not vary much for very small antennas. We next identify a population of possible antenna configurations.

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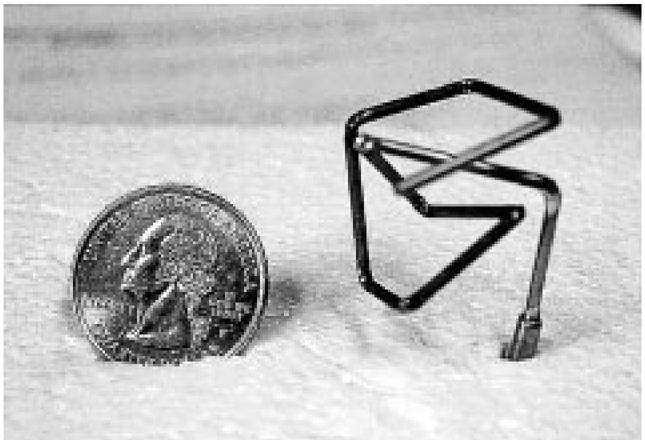

Fig. 1. A ten-segment self-resonant genetic antenna.

We chose a GA design space that consisted of a grid of thousands of points enclosed in a cube of height h/λ; these are the possible vertices of the wires that are to be connected to form the antenna. The GA randomly selects a sample population of wire configurations. Ideally, the size of this sample should be large enough so that a wide selection of possible configurations is included, yet not too large such that computation time becomes unnecessarily long. We use a sample size of 300 for our computations. The wires that make up the antenna may be connected in series or in parallel; we found that series-connected wires produced far better results. The radius of the wire was set at .8 mm, which corresponds to about a $1/16$-in-diameter wire.

For NEC computations each wire is divided into segments and each segment should typically be less than 0.1λ in length; extremely short segments, less than 0.001λ, should be avoided. The segment length should be at least an order of magnitude larger than the wire radius. Also the wire spacing should not be less than 0.001λ. A set of constraints was incorporated into the GA to assure that the above requirements were not violated. A typical simulation of less than ten wires takes less than 1 s to run on either a Pentium or a workstation; it scales as N^3, where N is the number of wires in the configuration. NEC generates an output file that contains all relevant simulation results, including the antenna input impedance, the current distribution on each wire, and the antenna gain and polarization for each angle. Each antenna configuration of the sample population is represented by a real-valued chromosome. The performance of each is evaluated, compared with the ideal performance specified in the cost function, assigned a score, and ranked. A steady-state GA with $1/3$ replacement and a 0.6% mutation rate was selected. As in the evolutionary process of "survival of the fittest," chromosomes having the best scores were mated and produced offspring while the poor performers were removed from the population. With succeeding generations the performance of the chromosomes continually improved and an optimized solution was ultimately obtained. We chose to terminate the process either after 60 generations had been reached or after ten successive generations had the same score.

The cube volumes decreased from slightly less than $.1\lambda$ on a side to less than 0.03λ on a side. The GA produced an odd-looking antenna that was optimized at a single frequency. A ten-wire genetic antenna that falls within a cube having an edge diameter of 0.038λ is shown in Fig. 1. In order to calculate the Q, it was necessary to compute the admittance at nearby frequencies. The resonance did not always occur at the design frequency but was usually not too far removed. The conductance, which is proportional to the power radiated, was calculated at the resonant frequency. The frequencies above and below resonance at which the conductance dropped to $1/2$ the value at resonance were also calculated. The Q was determined from

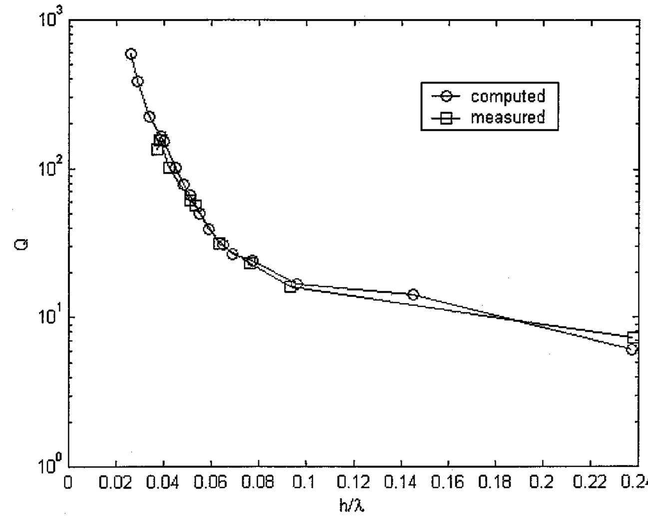

Fig. 2. Q versus electrical size of genetic antenna.

$$Q = f_0/(f_2 - f_1).$$

The radiation patterns for these antennas were also computed.

We conducted a sensitivity analysis for the genetic antenna. As expected, as the volume within which the antenna is enclosed becomes smaller the accuracy becomes more critical. When the size approaches 0.03λ, changes as small as $\pm 0.0015\lambda$ can degrade the antenna performance. After the GA produced an optimum configuration, we tried to tweak the antenna so that it would be smaller; we were not successful.

B. Measurements

The GA produced very odd antenna configurations, which were difficult to construct. The antennas were fabricated out of $1/16$-in-diameter copper tubing that was bent to the computed shape. Because of the complex configuration of the antenna, it was only possible to obtain a shape that approximated the computed design. We estimate that the antennas were built to an accuracy of ± 2 mm or about $\pm 0.0027\lambda$ at 400 MHz. The antenna was mounted over a 1.2×1.2-m ground plane (about $1.6\lambda \times 1.6\lambda$ at 400 MHz) and fed from a coaxial line terminated with a Type N connector. The admittance and VSWR were measured with a Hewlett-Packard Model 8510 Network Analyzer. As was done for the computations, those frequencies at which the antenna was resonant and at which the conductance was $1/2$ of the value of that at resonance were determined and the Q was calculated.

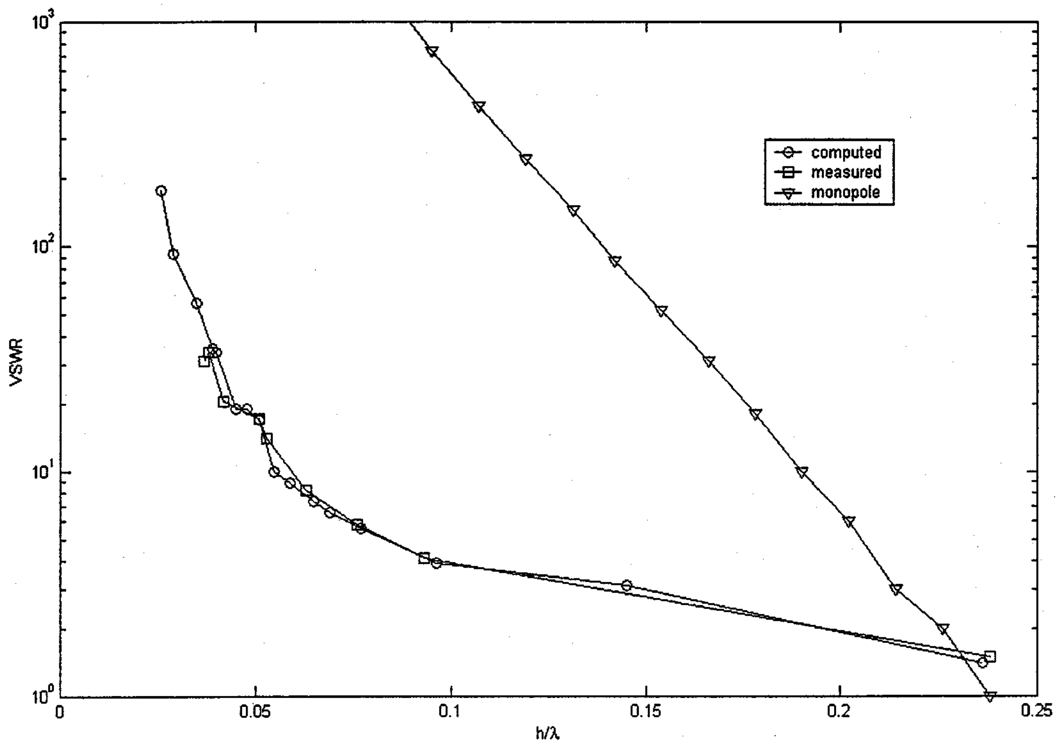

Fig. 3. VSWR versus electrical size of genetic and monopole antennas.

III. Results

A. Computations

Most of the optimized genetic antennas had a resonant frequency near 400 MHz. The electrical length of the side of the cube containing the antenna was decreased from about 0.1λ to near 0.025λ. The total length of the wire that makes up the antenna was usually between 0.25and 0.35λ. This length did not change systematically with the volume within which the antenna was enclosed. In general, there was not a significant improvement in Q if more wires were used in a volume within which a resonant antenna having fewer wires could be obtained. For example, if a resonant antenna having five wires could be contained within a cube having a side of 0.06λ, then an antenna having eight wires would have a comparable Q and VSWR for the same size cube. In Figs. 2 and 3, we plot the Q and VSWR as a function of the electrical length of the side of the cube within which the antenna is enclosed. We note that as the cube size deceases from a side length of 0.096λ to 0.026λ, the Q increases from 15.8 to 590 and the VSWR increases from 1.9 to 177. Although these are very high values of VSWR, we note that they are still about two orders of magnitude lower than those for a short monopole, as is also shown in Fig. 3. All antennas had near-hemispherical coverage. The polarization near the horizon was predominantly vertical; near zenith it was mostly horizontal and had a slightly lower magnitude than that near the horizon. For the in-between angles, the polarization was elliptical.

B. Measurements

The measured results compared very well with the computations, considering the fact that the computations were made for an antenna over an infinite ground plane; also, it was not possible to build the antennas to the exact dimensions of the computed models. For example, we were unsuccessful when we tried to construct an antenna of the simulated size of $h = .026\lambda$; the fabricated antenna performed poorly. In the future, if we are to test smaller antennas, we will either have to improve our fabrication process or operate at a lower frequency. Antennas having from two to ten segments that could be enclosed within cubes of 0.093λ to 0.037λ on edge had Qs and VSWRs ranging from 16.0 and 4.1 to 134 and 30.9, respectively. In Figs. 2 and 3, we plot the measured Q and VSWR along with the computed values as a function of the electrical length of the antennas. We were not able to show a one-to-one correspondence for each simulation and each measured result since the fabricated antennas were often self-resonant at a slightly different frequency than the simulation and had a different electrical size; thus, we plot respective sets of simulated and measured results.

IV. Summary

This process for designing small antennas using a GA produced new self-resonant antenna configurations. Using intuition, it would seem that the wires should be arranged so that they are orthogonal where possible; also, nearly parallel wires that are too close together should be avoided, thus minimizing the transmission-line currents that increase the antenna Q. Upon examining the resultant antenna designs, it seemed as though the GA converged to antenna designs that incorporate these principles. The preliminary results are very encouraging. These antennas are very inexpensive and can be easily fed from a coaxial line. Since they are self-resonant, the only matching that is required is an impedance transformer. We have made preliminary measurements on a matching network for a seven-wire genetic antenna of size $h/\lambda = .057$, VSWR of 18.5, and radiation resistance of 2.7 Ω at a frequency of 384 MHz. We designed a quarter-wave transformer using a section of microstrip and obtained a VSWR of 1.12. For some applications it may also be possible to use a lower impedance generator and feed the antenna directly. Future plans are to replace the thin wires with copper strips. Preliminary results indicate that this design will have a lower Q. Also being considered is the possibility of designing planar antennas that can be fabricated using printed circuits and dielectrics.

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