Wide and multi-band antenna design using the genetic algorithm to create amorphous shapes using ellipses

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ABSTRACT

A method is demonstrated for generating compact, broadband and multi-band antennas using ellipses to create new amorphous shapes with greater bandwidth and less return loss that previously demonstrated. The genetic algorithm is used to optimize the design. Four example designs are given including amorphous patches and amorphous monopoles. FDTD is used to simulate the designs allowing the user to embed a low insertion loss design directly into a heterogenous structure or dielectric material.

I. INTRODUCTION

In the last decade, advances in computational electromagnetics and use of the genetic algorithm (GA) [1,2] have led to the development of automatic shape creation techniques that produce new antenna designs. Preliminary results by [3] introduced the technique of having the GA create the structure, rather than simply optimizing parameters in a pre-defined structure. The GA was then coupled with the method of moments (MOM) to design wide and dual-band patch antennas by removing metal cells from a standard design [4]. Choo, Ling, and others research contributions include creating an amorphous patch with broadband characteristics [5], and using the amorphous shape to simulate and build dual, tri, and quad-band patch antennas [6]. Their additional contributions include novel slot antennas, and broadband monopoles [7,8].

These methods have worked well to create wide and multi-band designs, but they have several limitations. Using a probe feed adds inductance, limiting the bandwidth [9]. These designs also have many unknowns that require large matrix inversions. In addition, the integral methods used are not well suited to simulating heterogeneous materials such as may be present in an embedded system.

This paper addresses these and other issues. By using the finite difference time domain (FDTD) method, all frequencies of interest can be analyzed, allowing broadband optimization with a single simulation. Using a microstrip feed avoids the bandwidth limitations of the probe fed patches. In addition, FDTD models heterogeneous systems without costly matrix inversions, allowing for analysis of antennas embedded in dielectric materials. In addition, a new method to create wide and multi-band antenna structures using ellipses is introduced.

II. MODEL CREATION

The genetic algorithm shown in figure (GA) is used to generate antenna designs using ellipses. First, a population of antennas are randomly generated. Then the populations chromosomes are randomly mutated and mated using a single point crossover. The GA used a double chromosome to represent the antenna design. The first chromosome contains parameters needed to generate ellipses. The second chromosome is mapped to an active area where the ellipses are located to create slots and gaps within the ellipses by removing the metal if the bit mapped to that location is '0'. In this way, the current is forced to travel around the gaps creating even more possibilities to generate multi-band designs.

The GA creates models to be simulated and passes them to QFDTD™ [10] to be analyzed. After the antenna population is analyzed, the best individuals are saved using one of the GA selection operators: Population Decimation, Tournament Selection, or Proportionate Selection. The bad antennas are discarded, and the process repeats itself until either a good solution is found, or a predetermined number of generations has passed. In this way, a good design is evolved using a natural selection process to generate more fit individuals.

A. *Ellipses*

There is very little research that uses amorphous shapes to generate antenna designs. Previous research uses a 2-D GA chromosome and filtering methods to create the amorphous shape[6,7]. The filtering adds an extra step to the process, and possibly removes small genetic changes that may be beneficial to the design. In this paper amorphous shapes are implemented using a combination of ellipses. In this way, a conventional 1-D GA chromosome is used, and filtering is not needed.

An ellipse can be defined using the formula

$$\frac{(x-a)^2}{c^2}+\frac{(y-b)^2}{d^2}\leq 1 \qquad (1)$$

where (a,b) is the center of the ellipse, and (c,d) are the major and minor radii. The chromosome parameters (a, b, c, and d) can be optimized by the genetic algorithm. By using a combination of overlapping ellipses, complex amorphous shapes can be generated as shown in Fig. 1.

B. *QFDTD™*

The individuals are analyzed using the commercial program QFDTD™ [10], which inputs and outputs all data though text files. This makes QFDTD™ ideal for linking to a GA (shown in Fig 2.) QFDTD™ uses simple FDTD update equations and the computationally efficient Mur boundary, allowing it to run fast enough to be suitable for running hundreds or thousands of simulations required for the GA optimization.

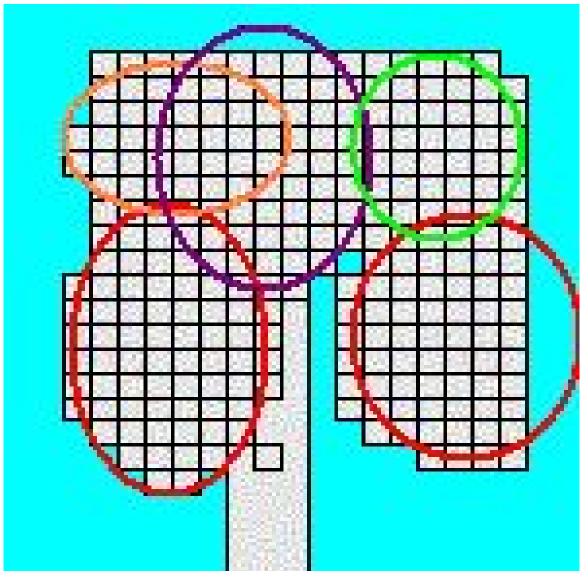


Fig 1. Amorphous antenna design created with five ellipses.

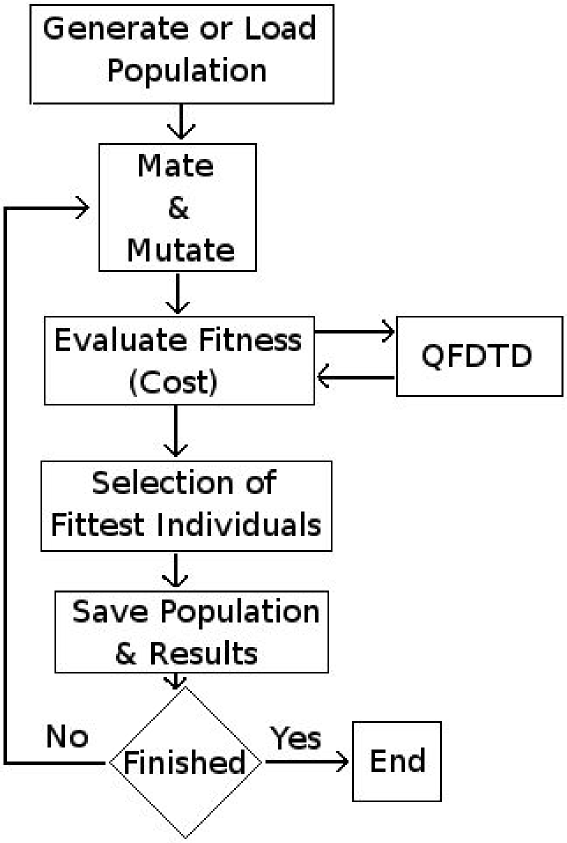


Fig. 2. Genetic Algorithm used to create designs.

III. DESIGNS GENERATED

To test the algorithm, four designs that are comparable to other GA designs found in the literature were simulated.

1. A tri-band patch antenna simulated on an FR4 substrate, optimized for low insertion loss at 1.6, 1.8, and 2.45 GHz. The patch is limited to a 32 x 32 mm^2 square over a 72 x 72 mm^2 ground plane. (similar to [6])

2. A broadband patch antenna simulated on an FR4 substrate, optimized for low insertion loss from 1.9-2.1 GHz. This patch is limited to a 40 x 40 mm^2 square over a 72 x 72 mm^2 ground plane. (similar to [7])

3. A GSM compatible dual-band monopole optimized for low insertion loss at 890-960 MHz and 1850-1990 MHz on FR4, embedded in cell phone.

4. A broadband Monopole designed for low insertion loss from 2-6 GHz on Rogers Ultra Laminate 2000.

A. *Tri-Band Patch*

Optimizing at three frequency bands is an extremely difficult task using traditional design techniques. Any change to optimize one band is likely to affect the other two. The GA excels at solving problems with many inputs and multiple optimization criteria. In [6], a tri-band patch antenna was designed to operate at 1.6 GHz (GPS/L1), 1.8 GHz (DCS), and 2.45 GHz (ISM/Bluetooth). The antenna in this paper is similarly optimized to minimize insertion loss from 1.55-1.65 GHz, 1.75-1.85 GHz, and 2.4-2.5 GHz.

The model is created using 15 ellipses with a radius range of of 4-12 FDTD cells (each cell is 0.8 mm) in an area limited to a 40x40 FDTD cell area. The substrate simulated is FR4 has a dielectric constant of 4.3 and a loss tangent of 0.016 at 10 GHz. The feed consists of a 50 ohm microstrip line. The entire model was placed within a 50x90x90 cell FDTD grid. The genetic algorithm ran with a population size of eight, and a mutation rate of 2%. It used population decimation as its selection method, and generated holes in 15% of the metal.

Fig. 3. shows that incremental improvements are made over many generations with a final solution having a cost of 2.02% insertion loss over the optimized bands. Fig. 4. shows the resulting antenna which fits in a 3.2 x 3.2 cm square. Fig. 5. shows that the 1.6 and 1.8 GHz bands merge to form a large band from 1.5 to 1.95 GHz for a total bandwidth of 26.1%. Another band is formed from 2.36 to 2.55 GHz with a bandwidth of 7.7%.

This antenna is physically smaller and gives much wider bandwidths and less insertion loss than [6]. The main difference is that [6] only optimized for 3 frequency points, and stopped optimizing after the goal of -10 dB was reached. This simulations optimized a band rather than a single point, and continued optimizing after the insertion loss was reduced to less than -10 dB. In addition, the ellipses had much freedom to move and generate an optimal design.

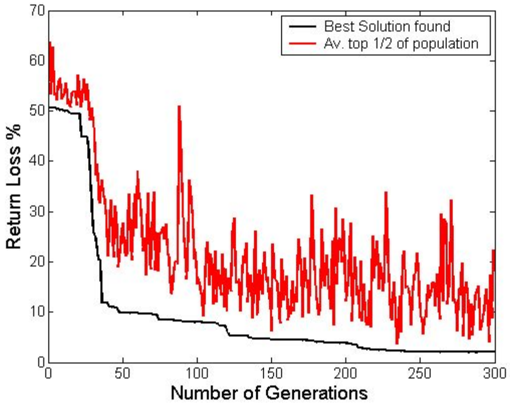
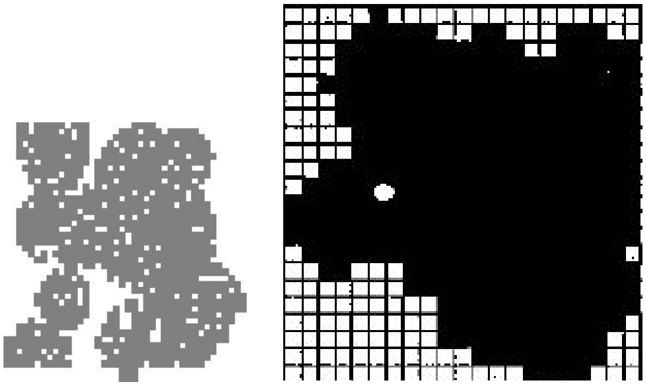


Fig. 3. Return loss of optimized antenna over 300 generations.



(a) (b)

Fig. 4. Resulting tri-band antenna. (a) ellipse antenna, (b) comparison antenna from [6] (white dot is feed point).

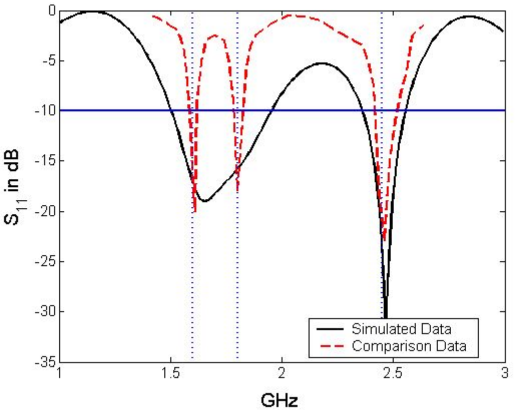


Fig. 5. Insertion loss of tri-band antenna.

B. *Broadband Patch*

A broadband antenna design was created similar to the tri-band antenna except that is optimized to reduce insertion loss between 1.6-2.4 GHz with extra emphasis on 1.9-2.1 GHz. Fig. 6 shows that good results were obtained within 5 generations of starting the simulation with small improvements up to the 30th generation. Fig. 7 shows the resulting best design. It has an area of 43 * 56 cells or 3.44 * 4.48 cm^2. Fig. 8 shows the insertion loss. It has less than -10 dB insertion loss from 1.70 to 2.28 GHz for a bandwidth of 29.1%. This compares very favorably to the 8.8% bandwidth achieved by [7] with identical size constraints.

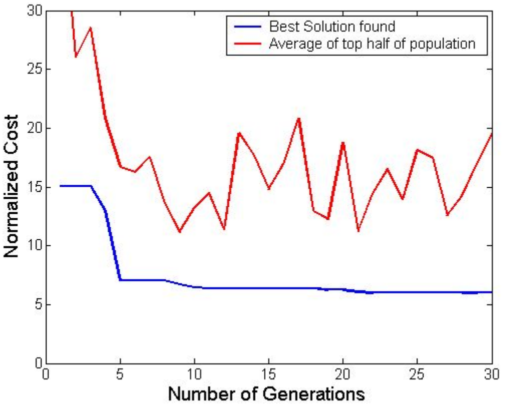
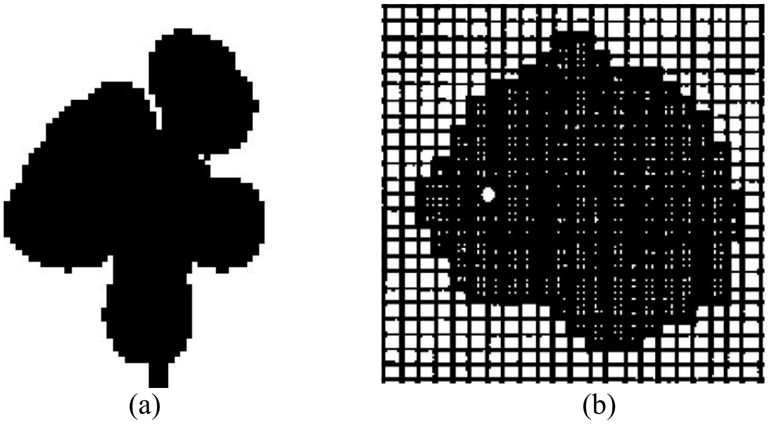


Fig. 6. Simulated cost (or fitness) of broadband patch antenna with each generation.



(a) (b)

Fig. 7. Broadband patch antenna and comparison antenna (to scale). (a) Ellipse Antenna (b) Reference Antenna (white dot is feed point) [5]

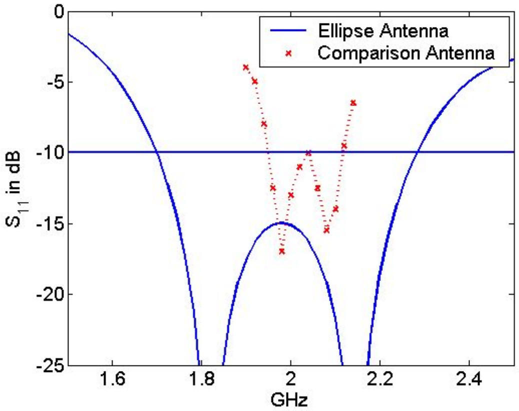


Fig. 8. Insertion loss of broadband patch antenna with comparison antenna simulation data.

C. *GSM Compatible Dual-Band Monopole*

The GSM compatible dual-band monopole antenna was originally presented in [11], and is given here for comparison. The current trend for mobile phones is to integrate the antenna into the case. This eliminates the possibility of breaking an external antenna, may reduce the specific absorption rate (SAR), and is aesthetically pleasing. Dimensions similar to a contemporary phone are used to design a dual-band GSM compatible phone with reflection loss less that -10 dB from 890-960 MHz and 1850-1990 MHz. Due to the antenna placement only the top part of a flip phone is simulated. The dimensions of the flip part of the phone are 46x85x9 mm. The antenna size is 42x38 mm with the rest of the flip acting as a ground. The model is simulated in FDTD using a 53x96x110 cell grid with cell dimensions 0.75x1x1 mm

The substrate is made of FR4 and has a dielectric constant of 4.3 and a loss tangent of 0.02 at 10 GHz[12]. The microstrip substrate is 1.5 mm (59 mils) thick. The entire phone model is 12 FDTD cells thick with the first nine cells consisting of casing (dielectric constant of 2.0 and loss tangent of 0.019 at 10 GHz), the next three consist of the FR4 substrate, and the final two consist of casing. The feed is a 50 ohm microstrip line.

For this particular design, 15 ellipses with a radius of 4-12 FDTD cells are used to create the antenna radiating element. Because the size of the antenna is constricted to a maximum width of 42 mm, additional holes were added to create slots consisting of 15% of the antenna area. These slots force the current to go around them making the antenna look electrically larger.

The GA uses a population size of eight and population decimation as its selection method. The antenna cost is the total insertion loss between 890-960 MHz and 1850-1990 MHz. The mutation rate was initially set at 10% and was eventually reduced to 1% during the optimization process.

Fig. 9 shows that after 65 generations of GA optimization a good solution is found. This solution is shown in Fig. 10. It is matched extremely well in the GSM frequency bands of 890-960 MHz and 1850-1990 MHz. Fig. 11 shows that the simulated return loss is less that -20 dB at all frequencies in the GSM bands of interest. The return loss is less than -10 dB between 810-1070 MHz and 1590 to greater than 2400 MHz for respective impedance bandwidths of 13.8% and greater than 20.3%. Fig. 12 shows an extremely flat radiation pattern, similar to that of a regular monopole at 925 MHz and a relatively flat pattern at 1915 MHz.

The antenna area not including the ground plane is 42x38 mm. The free space wavelength at 890 MHz is 769 mm. Thus the monopole size is 0.0546 x 0.0494 wavelengths in free space. The effective dielectric constant is between that of the substrate (4.2) and the casing (2.0). Creating the shape with ellipses allows the design to meander creating a compact shape as shown in Fig. 10.

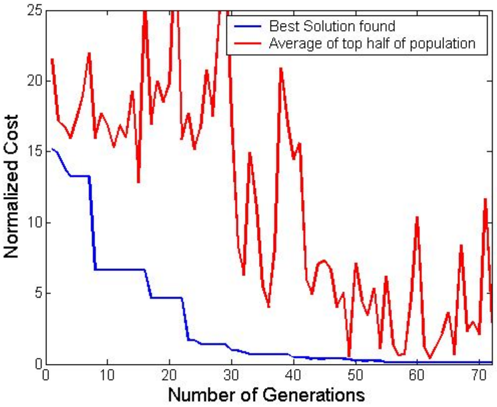


Fig. 9. Simulated cost (or fitness) of dual-band antenna with each generation.

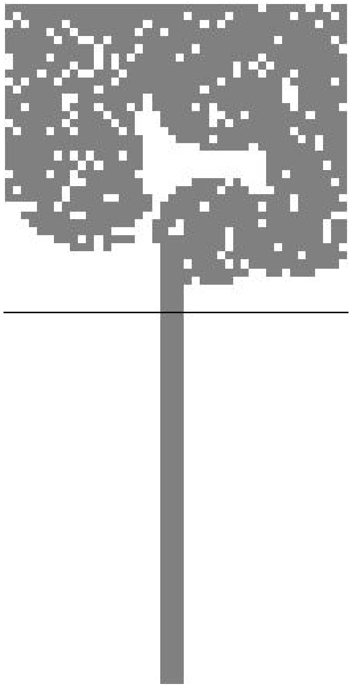


Fig. 10. Layout of integrated dual-band monopole.

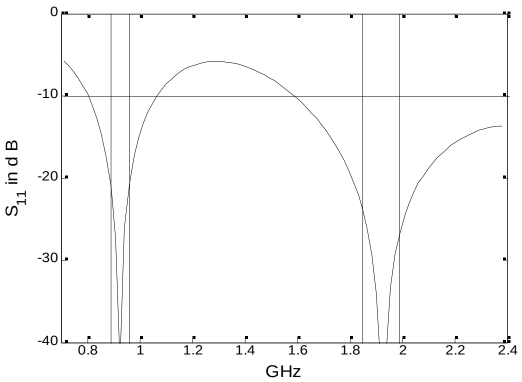
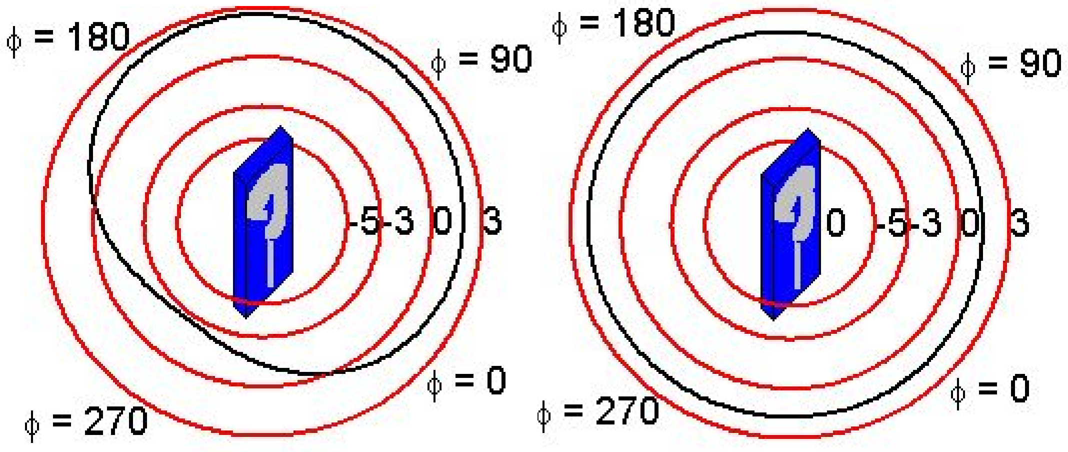


Fig. 11. Insertion loss of dual-band integrated monopole.



(a) (b)

Fig. 12. Vertical polarization directivity of GA monopole antenna at (a) 1915 MHz, (b) 925 MHz. Note that the directivity on (a) is between -3 and 3 dB and the pattern on (b) is between 1 and 2 dB.

D. *Broad-band Monopole*

For comparison a broadband monopole was simulated on Rogers Ultra Laminate 2000 substrate which has a dielectric constant of 2.6 and a loss tangent of 0.004 at 10 GHz. The microstrip substrate is 1.524 mm (60 mils) thick. The feed consists of a 50 ohm microstrip line. The FDTD grid is 50x37x48 cells, and the cell size is 0.762 * 1.423 * 1.423 mm.

The antenna shape is created with 15 ellipses with a radius of 2-4 FDTD cells limited to a 20 by 18 cell grid. The GA population size is 8 with a mutation rate of 1%. No slots or holes are added to the simulation, and the selection method is population decimation. The GA optimizes the antenna to have low insertion loss from 2-6 GHz.

Fig. 13 shows that most of the optimization took place in the first 20 generations. Fig. 14 shows the prototyped antenna. Fig. 15 shows the simulated and measured return loss. Simulated bandwidth with less than -10 dB insertion loss is from 2.15 - 6.25 GHz for a total bandwidth of 97.6%.

The monopole extends 2.56 cm (18 cells * 1.423 mm) past the ground place. This corresponds to 0.183 free space wavelengths at the lowest frequency of 2.15 GHz. This length is comparable with the dimensions found by [8] when a bandwidth of 100% is desired. Designs by [8] were in free space and didn't have a dielectric effect, but tended to have small trace widths which would reduce efficiency.

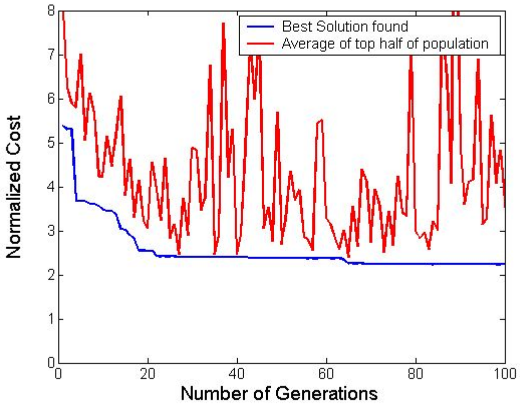


Fig. 13. Simulated cost (or fitness) of broadband monopole antenna with each generation.

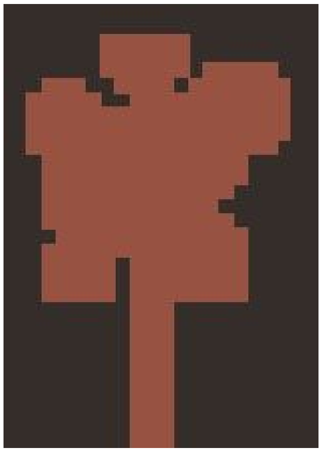


Figure 14. Photograph (to be added) of of prototyped broadband monopole.

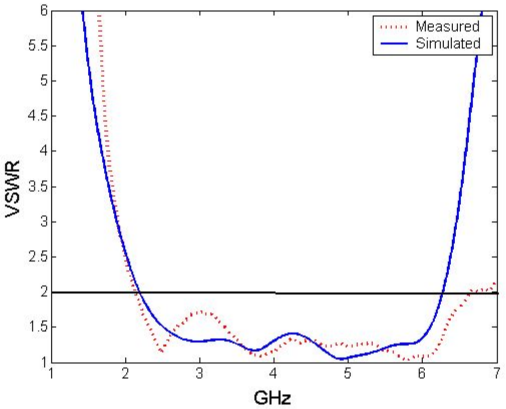


Fig 15. Measured and simulated VSWR of broadband monopole.

IV. CONCLUSION

A new method is shown for generating amorphous antenna shapes using ellipses and the GA. Four design examples are shown including a tri-band patch and monopole, and a broadband patch and monopole. The ellipse design method is simple to implement, and produces wider bandwidths and less insertion loss than previous methods. The GA generated amorphous antennas can effectively generate designs that produce less than -15 dB insertion loss across broadband and multi-band antennas. In addition because FDTD can simulate the materials around it, the GA can design an antenna that is integrated into a system. A dual-band monopole was created that had an area of only 0.0546 x 0.0494 wavelengths at the lowest frequency. The optimized antenna designs don't require a matching network, adding to the simplicity of the total solution. Measurement of the broadband monopole shows good agreement with simulated VSWR.

REFERENCES

[1] R. L. Haupt, "An Introduction to Genetic Algorithms for Electromagnetics," IEEE Antennas Propagat. Mag., vol. 37, No. 2, April 1995

[2] J. Michael Johnson and Yahya Rahmat-Samii, "Genetic Algorithms in Engineering Electromagnetics", IEEE Antennas and Propagation Magazine, vol. 39, no. 4, Aug. 1997

[3] C. Delabie, M. Villegas and O. Picon, "Creation of new resonant microstrip structures by means of genetic algorithm," Electronics Letters, vol. 33, no. 18, 28th Aug. 1997 pp. 1509-1510

[4] J. Michael Johnson and Yahya Rahmat-Samii, "Genetic Algorithms and Method of Moments (GA/MOM) for the Design of Integrated Antennas," IEEE Trans. Antennas and Propagation, vol. 47, no. 10, Oct. 1999, pp. 1606-1614

[5] H. Choo, A. Hutani, L.C. Trintinalia and H. Ling, "Shape optimisation of broadband microstrip antennas using genetic algorithm," Electronic Letters, 7th Dec. 2000, vol. 36, no 25, pp. 2057-2058

[6] H. Choo and H. Ling, "Design of Multiband Microstrip Antennas Using a Genetic Algorithm", IEEE Microwave and Wireless Components Letters, vol. 12, no. 9, Sept. 2002, pp. 345-347

[7] H. Choo and H. Ling, "Design of broadband and dual-band microstrip antennas on a high-dielectric substrate using a genetic algorithm", IEE Proc.-Microw. Antennas Propag. vol. 150, no. 3, June 2003, pp. 137-142

[8] Aaron J. Kerkhoff, Robert L. Rogers, and Hao Ling, "Design and Analysis of Planar Monopole Antennas Using a Genetic Algorithm Approach", IEEE Trans. Antennas and Prop., vol. 52, no. 10, Oct. 2004, pp. 2709-2718
[9] Aaron K. Shackelford, Kai-Fong Lee, and K. M. Kuk, "Design of Small-Size Wide-Bandwidth Microstrip-Patch Antennas", IEEE Antenna and Propagation Magazine, vol. 45, no. 1, Feb. 2003
[10] Y. Qian, and T. Itoh., "FDTD Analysis and Design of Microwave Circuits and Antennas: Software and Applications," Tokyo, Japan, Realize Inc., 1999
[11] Lance Griffiths, You Chung Chung and Cynthia Furse, "Integrated Multiband Antenna Design Using the Genetic Algorithm," IEEE International Antennas and Propagation Society Symposium and USNC/URSI National Radio Science Meeting, June 3-8, 2005, Washington DC
[12] http://www.injectorall.com/techsheetFR4.htm