Miniaturized Biocompatible Microstrip Antenna Using Genetic Algorithm

Pichitpong Soontornpipit, *Student Member, IEEE*, Cynthia M. Furse, *Senior Member, IEEE*, and You Chung Chung, *Senior Member, IEEE*

***Abstract*—Biocompatible antennas are an area of recent research that can facilitate remote communication with medical implants. This paper shows several possible designs of a "waffle-type" antenna created using genetic algorithms (GAs) that are of a size potentially suitable for cardiac pacemakers in the 402–405 MHz MICS band. In addition, methods to constrain the simulation and speed up the convergence of the GA for this type of antenna are explored. Even simple constraints such as fixing the feed and ground locations and encouraging the antenna to grow preferentially in the horizontal direction to take advantage of the longer physical dimensions of a pacemaker in that direction can appreciably improve convergence speed. One exception to this was constraining the patches to be connected together rather than distributed randomly, which caused the system to converge slower rather than faster. Also notable was that when a larger physical size was allowed, the system also converged more quickly despite a sizeable increase in the number of unknowns (subpatches) in the model. Thus, this paper provides a smaller, better matched microstrip antenna for biotelemetry and a choice of GA constraints for designing it.**

***Index Terms*—Biocompatible antenna, genetic algorithm (GA), genetic algorithm (GA) antenna, pacemaker antenna.**

I. Introduction

EMERGING medical telemetry devices have led to recent advances in the design of small, biocompatible antennas that can be implanted in the human body [1]–[4]. Inductive antennas (coils of wire around a dielectric or ferrite core) have been successfully designed for biomedical telemetry [4]–[7], although data rates are low, and size/weight and biocompatibility issues plague the coil-wound devices. For cardiac telemetry, a dipole [8] and spiral or serpentine microstrip [9], [10] have been designed for implantation in the shoulder. Also a microstrip patch antenna has been successfully used for a retinal prosthesis [11]. This paper examines a "waffle-type" microstrip antenna which works better than spiral or serpentine antennas of the same size. The antenna is designed with a genetic algorithm, and there is no apparent "sense" to how the small cells that make up the apparently random "waffle" are placed [12]–[14]. Most genetic algorithm (GA) papers have focused on how to obtain the most optimal design, by allowing all possible parameters to vary. While this may be tempting, it produces a chromosome that is so large that it is unreasonable to evaluate. Methods to constrain the GA to improve the convergence speed have focused on limiting the search size of the region. As will be shown, some constraints are more effective than others in improving convergence speed. In this paper we are focusing on obtaining a design that meets a given specification (although not necessarily the optimal design) within a given time limit by constraining the GA to reduce the number of elements in its searching area. We examine methods of limiting how the GA antenna population is constructed (how cells are attached to each other, for instance) in order to improve the overall efficiency of the method and obtain a suitable design in minimal time. The conditions that were examined are cells attached or not attached to each other, feed and ground points fixed or variable, preference for growth in one direction, overall antenna size, and stacked patch antennas. Thus, this paper provides a smaller, better matched microstrip antenna for biotelemetry and a choice of GA constraints for designing it.

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II. Method of Analysis, Evaluation and the Optimization Process

The conventional geometry of a microstrip antenna covered with insulating superstrate to prevent the body from shorting out the antenna is shown in Fig. 1. For simple simulation of this antenna (suitable for designing the antenna but not suitable for evaluating its RF power deposition compliance), it is shown imbedded in a block of 2/3 human muscle (used to represent the approximate conglomerate human tissues). In [9], it was shown that the antenna could initially be designed in a simplified block of tissue and later further optimized for the specific anatomical location. The finite-difference time-domain (FDTD) method (using XFDTD software from Remcom, Inc.) has been used extensively for the simulation of microstrip antennas and is used in the present analysis. The general features of the present algorithm are as follows: The grid size is 1 mm^3, and the absorbing perfect matched layer (PML) boundaries are 15 cells away from the antenna model. The superstrate is $36 \times 30 \times 3$ mm^3 silicon ($\epsilon r = 3.1$, $\tan\delta = 0.0025$). The substrate is $36 \times 30 \times 3$ mm^3 RT/duriod 6002 ($\epsilon r = 2.94$, $\tan\delta = 0.0012$). The antenna is imbedded centered in a $60 \times 50 \times 20$ mm^3 block of 2/3 human muscle ($\epsilon r = 32.405$ and $\sigma = 0.5208$ S/m, [15]). In order to verify the simulation results, antenna prototypes were built and were tested with an HP8510C network analyzer. Household silicon (same dielectric relative properties as medical grade silicon) was used for the superstrate. The tissue simulant material made from TX-151 powder, mixed with sugar,

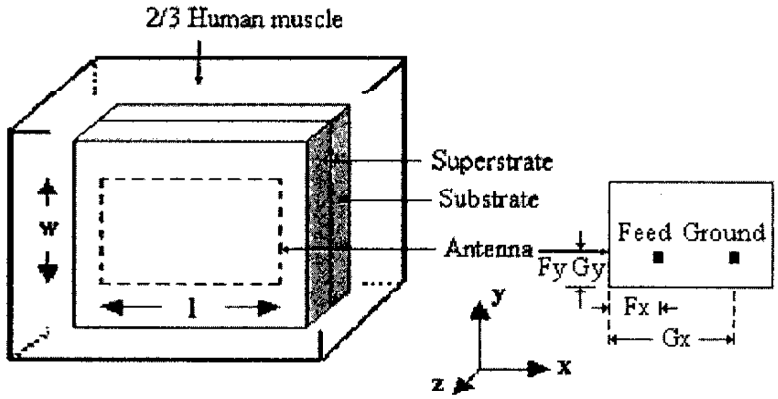


Fig. 1. Antenna model.

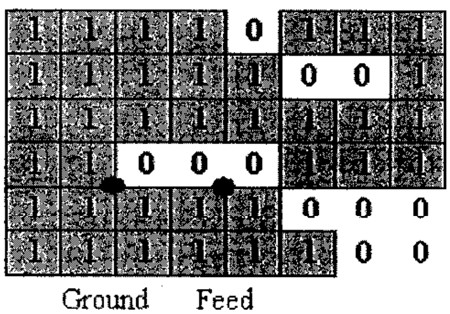


Fig. 2. Example of antenna model represented by a chromosome array of 1's and 0's.

salt, and water was used as the test material. It has a measured relative permittivity 48.9 and conductivity 0.71 S/m [16].

The main objective of this work is to design a biocompatible microstrip antenna with the lowest reflection coefficient (lower than -15 dB) in the 402–405 MHz Medical Implant Communication System (MICS) band [17]. Biocompatible materials from previous designs [9] are used. The optimization technique requires the cost function (magnitude of the reflection coefficient) to be evaluated for each test antenna, which is represented by its own chromosome.

Each chromosome is composed of genes described as a sequence of binary bits containing parameters to be optimized. Chromosomes for our examples will include the total number of subpatches and whether each subpatch is metal or nonmetal (or another material) and the location of feed and ground points. For example, if the total number of subpatches is 300, our chromosome will have 320 bits (300 bits from subpatches, five bits from feed point location in the x axis (F_X), five bits from feed point location in the y axis (F_Y), five bits from ground point location in the x axis (G_X), and five bits from ground point location in the y axis (G_Y)). A sample GA antenna is shown in Fig. 2.

The optimization process can be divided into four steps. The first step creates random initial populations that represent all chromosome parameters. The second step, which is the longest process, is the simulation of initial models. Simulating one model can take longer than 30 clock minutes (on a Pentium II machine) depending upon the size of antenna, the size of the Fourier transform and the performance of the computer. Minimizing the number of simulations is necessary to improve the usefulness of this design method. The third step is evaluating the cost function, which in this case is the magnitude of reflection coefficient in the 402–405 MHz frequency band. The antennas will be sorted from the best to the worst. The last step, which can take longer than 10 minutes for each model, is the crossover and mutation processes. By reading and sorting the cost function, the best half initial populations have been chosen as the next generation's parents, and the bottom half are discarded. After the next generation is created by crossing over and mutating the previous generation, all processes are repeated until the maximum number of generations has been reached. If, during the optimization process, the cost function is found to satisfy the requirement (-15 dB through the whole 402–405 MHz band), the process is terminated, and the corresponding model is chosen. This provides a sufficient antenna but not necessarily an optimal one.

III. Application Designs

The initial geometry analyzed is a rectangular microstrip patch (28 mm × 24 mm, unless otherwise stated) that is subsequently divided into 672 1 mm^2 subpatches. Each subpatch is assigned a control bit, either a one or a zero. A subpatch with one is metallized, and a subpatch with zero is nonmetallized. The substrate material is RT/Duriod 6002, and the superstrate is silicon. The feed point is fixed at (14 mm, 27 mm) (see Fig. 1), and the ground point is fixed at (24 mm, 17 mm). The genetic algorithm with and without limiting constraints has been used to design the patch antenna in order to compare the performance of the two designs. The patches have been simulated in five different tests: 1) attached subpatch (all subpatches must be attached to at least one other subpatch for electric continuity); 2) random subpatch (all subpatches do not need to be attached to any other subpatch); 3) varying feed and ground points with random subpatch (feed and ground locations are depended on chromosomes but are forced to contact at least one subpatch); 4) having total size corresponding to a larger cardiac pacemaker (a larger searching area with the constraint on feed and ground points); and 5) double layer stacked patch. All antennas in this paper have been simulated in a block of 2/3 human muscle with a maximum of 20 generations. The muscle is 7 mm thick outside of the pacemaker for all designs.

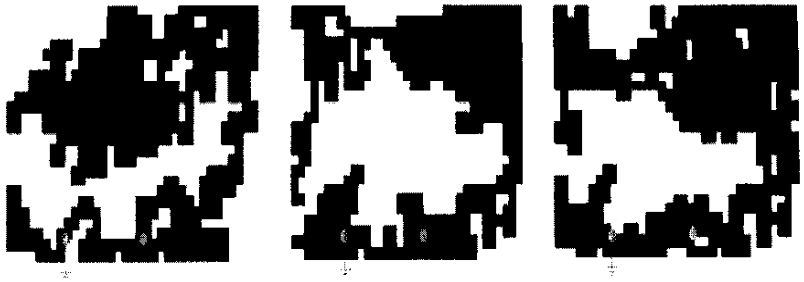


Fig. 3. Attached subpatch: the dimensions of (a) the GA antenna without constraint, (b) the GA antenna with the constraint $P(L) > P(W)$ and (c) the GA antenna with the constraint $P(W) > P(L)$.

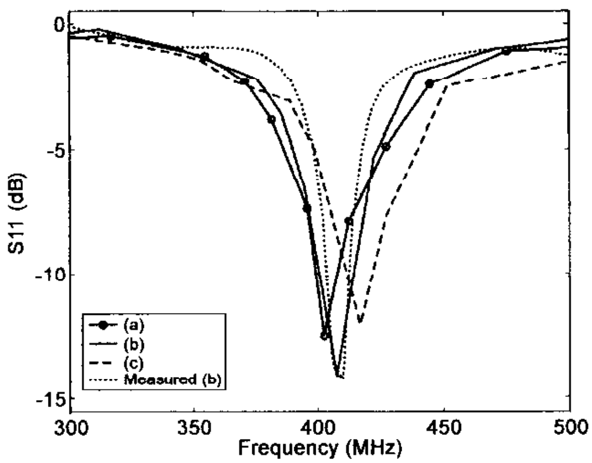


Fig. 4. Attached subpatch: comparison of $|S_{11}|$ for (a) the GA antenna without constraint, (b) the GA antenna with the constraint of $P(L) > P(W)$, and (c) the GA antenna with the constraint of $P(W) > P(L)$.

The simulations have been repeated a number of times in order to compare the results between conventional GA and the constrained GA. The parameters of the evaluation, crossover and mutation are: initial population = 48, discard rate = 0.5 and mutation rate = 12%.

IV. Results

A. Attached Subpatch

The first test assumes that a subpatch is likely to contribute less to the antenna performance if it is unattached (passive radiator) rather than attached (active radiator). Thus unattached subpatches were not allowed in this model. The GA limiting constrain in this test is that the antenna grows 10% preferentially in the horizontal direction rather than the vertical direction to take advantage of the rectangular pacemaker size. This effectively encourages the antenna to "grow" in a horizontally-connected manner, as opposed to strictly random. The GA antenna with the constraint of preferential vertical growth P(W) also has been simulated to compare with the horizontal constraint P(L). The dimensions of antennas are shown in Fig. 3 where each cell is 1 mm^2, and the total size is 28×24 mm^2. The feed point is fixed at (19 mm, 2 mm) (see Fig. 1), and the ground point is fixed at (8 mm, 2 mm). As shown in Fig. 4, the GA with the constraint of preferential horizontal growth provides better results after 20 generations than the GA with no constraints on growth and the GA with the constraint of preferential vertical growth, as expected. The stopping criterion that $|S_{11}| < -15$ dB for 402–405 MHz has not quite been reached for this case, and additional generations would be required. In order to verify the simulation results, a prototype of the horizontal constraint antenna (b) was built, and the return losses of the antenna are shown to agree extremely well with simulation in Fig. 4.

Fig. 5. Random subpatch: the dimensions of (a) the GA antenna with constraint $P(L) > P(W)$ and (b) the GA antenna without the constraint.

B. Random Subpatch

The second test is a random subpatch where the subpatch is randomly created and may be isolated from other subpatches. The constraint of preferential growth in the horizontal direction was applied, and antenna models between the GA with and without this constraint after 20 generations are shown in Fig. 5. A comparison of the $|S_{11}|$ in Fig. 6 shows that the GA with constraints gives an antenna with better results than the GA without the constraint. When comparing Fig. 4 (attached subpatches) and Fig. 6 (random subpatches), it is clear that the random subpatch antenna gives better performance than the attached subpatch. While this might seem to be counter-intuitive, it appears that the passive coupling makes the antenna act as if it is electrically longer, giving a significantly better performance over a large range. The antenna constrained to grow preferentially in the horizontal direction met the stopping criteria within 20 generations, whereas the unconstrained antenna did not. This demonstrated the effectiveness of this constraint in reducing optimization time.

C. Varying Feed and Ground Locations

The third test is to allow the feed and ground points to vary in the whole antenna region, creating a wider search area for

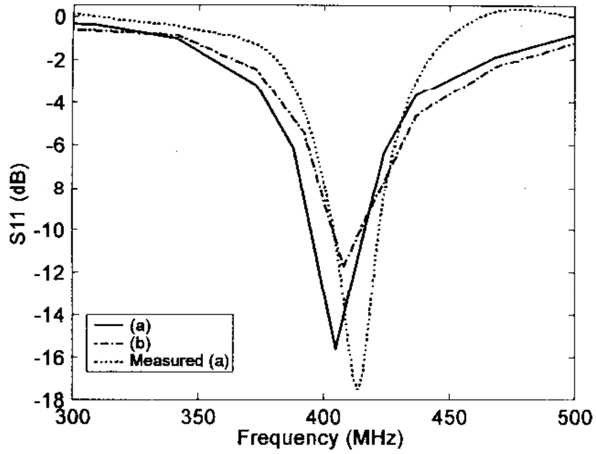


Fig. 6. Random subpatch: comparison of $|S_{11}|$ between (a) the GA antenna with constraint $P(L) > P(W)$ and (b) the GA antenna without the constraint.

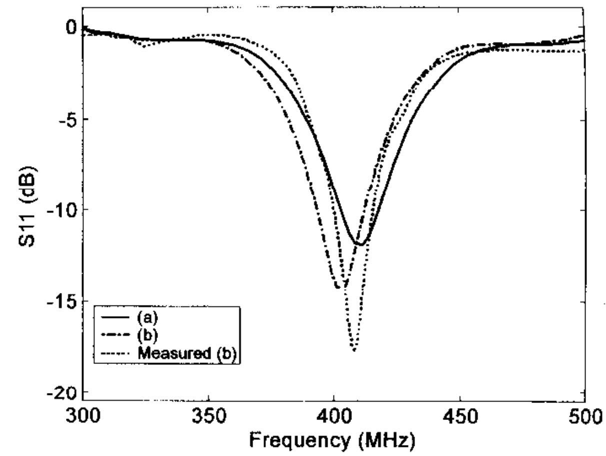
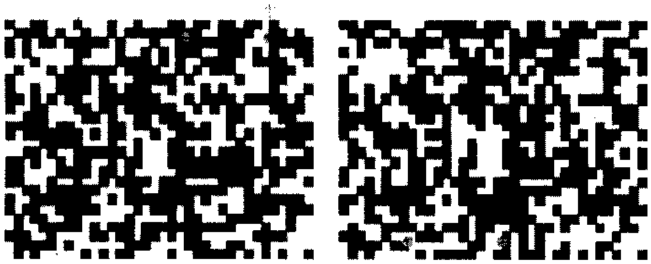
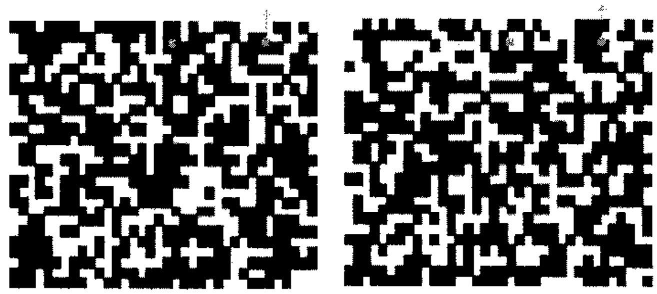


Fig. 8. Feed and ground locations: comparison of $|S_{11}|$ between (a) the GA antenna with constraint varying feed and ground and constraint $P(L) > P(W)$ and (b) the GA antenna without the constraints.



(a) (b)

Fig. 7. Feed and ground locations: the dimensions of (a) the GA antenna with constraint varying feed and ground and constraint $P(L) > P(W)$ and (b) the GA antenna without the constraints.



(a) (b)

Fig. 9. Larger antenna size: the dimensions of (a) the GA antenna with constraint $P(L) > P(W)$ and (b) the GA antenna without the constraint.

the GA, and assumably making it converge slower. The GA with constraints in this case has both the condition of a 10% horizontal preference for growth, and the locations of feed and ground pins. The feed and ground locations are dependent on (F_X), (F_Y), (G_X), and (G_Y) in the chromosomes, and are forced to connect to one of the metallized subpatches. Thus if one of them is not connected, a new chromosome will be given. The GA without constraints has no preference given to growth direction, and positions of feed and ground are fixed (same locations as antennas in Fig. 5). The antenna models and a comparison of simulation and measurement are shown in Figs. 7 and 8, respectively. As expected, the antenna with the fixed feed and ground locations converges to better performance within 20 generations than the constrained GA. The unconstrained GA converged close to the acceptable value of $|S_{11}| < -15$ dB, but the constrained GA did not. When compared to the previous test, it appears that constraining the feed and ground locations makes the GA converge more slowly to a suitable design.

D. Larger Antenna Size

The fourth test is done on a larger pacemaker body (36 mm × 26 mm). This is like the previous (third) case. For this section, the feed is fixed at (19 mm, 24 mm), and the ground is fixed at (30 mm, 24 mm). The constrained GA gives a 10% horizontal preference for growth. This case has even more search area than the previous case, since it is larger, and there are additional subpatches. One might expect this to converge more slowly than the smaller (third) case, however, the increase in allowed physical size enables the antenna to function better for lower frequencies, and therefore the performance of antennas obtained after the 20th generation is better than for the smaller antennas as shown by comparing Fig. 7 (smaller antenna) and Fig. 9 (larger antenna). The comparison of simulation and measurement is shown in Fig. 10.

E. Stacked Patch Antenna

The last test is to improve the bandwidth by stacking two patch antennas where the GA is applied to the top layer of the antenna or to both layers of antennas. Based on coupling theory, the feed and ground point will be connected only to the first antenna layer, and the electric current will couple to the second layer. In this section, feed and ground point locations are fixed at (10 mm, 23 mm) and (17 mm, 23 mm), respectively. First, a spiral antenna (a) that was designed to operate at 403.5 MHz was used for the bottom layer, and the GA was applied to the design of the second (coupled) layer antenna as shown in Fig. 11. In this test, the GA was forced to run for the full 20 generations, even though the spiral antenna already has $|S_{11}|$ less than -15 dB. When applying the GA to both layers, everything is randomly generated. The antennas are shown in Fig. 13. This is nearly

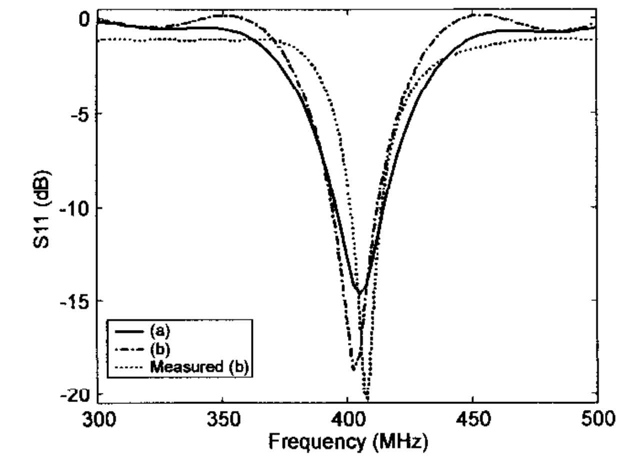


Fig. 10. Larger antenna size. Comparison of $|S_{11}|$ between (a) the GA antenna with constraint $P(L) > P(W)$ and (b) the GA antenna without the constraint.

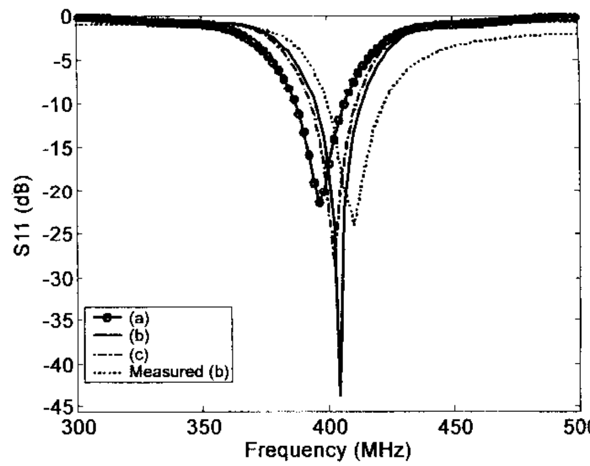


Fig. 12. Comparison of $|S_{11}|$ between (a) original (spiral) 405 MHz antenna, (b) GA with the constraint $P(L) > P(W)$, and (c) without the constraint.

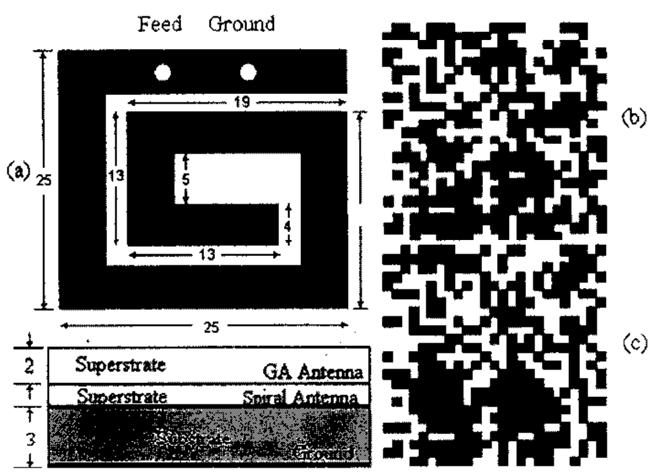


Fig. 11. Dimensions of (a) the 403.5 MHz spiral antenna (bottom layer), (b) GA antennas (top layer) with constraint $P(L) > P(W)$, (c) GA antennas (top layer) without constraint.

Fig. 13. Dimensions of (a) the GA antennas with the constraint $P(L) > P(W)$ and (b) the GA antennas without the constraint.

double the size of the chromosome in all previous tests, and is therefore expected to converge much slower. The constrained GA gives a 10% horizontal preference for growth. As shown in Figs. 12 and 14, the antennas with the constrained GA converge more quickly, and the stacked patch antenna with the GA can achieve better performance while maintaining the same overall dimensions of the antenna.

V. Conclusion

The objective of this work was to design a biocompatible antenna for the 402–405 MHz band that has $|S_{11}|$ less than -15 dB through out the whole band. This is done by simulating the antenna with FDTD and improving the design using a genetic algorithm. Several workable designs were obtained within 20 generations. It is not expected that these are optimal designs, only that they meet the designed specification within a given number of generations. A significant result that was observed is that for all cases constraining the GA in one of several ways significantly improves its convergence. Even simple constraints such as fixing the feed and ground locations and encouraging the antenna to grow preferentially in the horizontal direction to take advantage of the longer physical dimensions of a pacemaker in that direction can appreciably improve convergence speed. One exception to this was constraining the patches to be connected together rather than distributed randomly, which caused the system to converge slower rather than faster. Also notable was that when a larger physical size was allowed, the system also converged more quickly despite a sizeable increase in the number of unknowns (subpatches) in the model. These observations lead to the conclusion that reducing needless opportunities for random search will speed up convergence, and they are far surpassed by choosing constraints and models that are physically preferential. A comparison of antenna properties as a

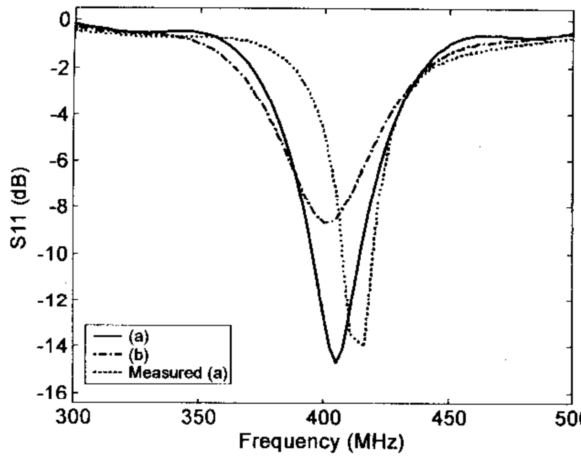


Fig. 14. Comparison of $|S_{11}|$ for the double stacked patch antenna between (a) the GA antennas with the constraint $P(L) > P(W)$ and (b) the GA antennas without constraint.

TABLE I
SIZE AND PERFORMANCES OF CONSTRAINED GA ANTENNAS COMPARED WITH SPIRAL, SERPENTINE, AND REGULAR PATCH ANTENNA

Parameters / Antenna	Size (mm^2)	S_{11} (dB)	10dB-BW (MHz)
Patch [9]	70 x 60	-18	16
Spiral [9]	27 x 17	-30	28
Serpentine [9]	27 x 17	-17	18
Attached (Fig 3)	28 x 24	-14	16
Random (Fig 5)	28 x 24	-16	18
Varying (Fig 7)	28 x 24	-14	16
Lager size (Fig 9)	38 x 24	-18	20
Stacked-spiral (Fig 10)	25 x 25	-42	19
Stacked-GA (Fig 12)	25 x 25	-15	20

function of size, S_{11} at 405 MHz and 10 dB-bandwidth between [9] and this work is shown in Table I. The best performance is obtained from a stacked antenna with a spiral antenna on the bottom and GA on the top. The spiral antenna is the next best design.

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XFDTD software from Remcom, Incorporated was used for the FDTD simulation.

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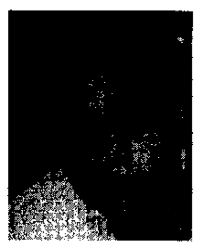

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