Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 6, December 2024, pp. 4058~4068
ISSN: 2302-9285, DOI: 10.11591/eei.v13i6.7679

Applying genetic algorithm for optimizing return loss of proximity coupled microstrip antenna

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Article Info

Article history:

Received Oct 5, 2023
Revised Mar 17, 2024
Accepted Jun 1, 2024

Keywords:

Genetic algorithm
Input impedance
Proximity-coupled rectangular microstrip antenna
Return loss
Transmission-line method

ABSTRACT

The proximity-coupled rectangular microstrip antenna (PRMSA) is optimized using the genetic algorithm (GA) to improve key parameters such as input impedance, return loss, and voltage standing wave ratio (VSWR). Fitness functions for the GA program have been developed using the transmission-line method (TLM) to analyze the PRMSA. The stochastic search capabilities of GA address electromagnetic characteristics that are challenging for other optimization techniques. In this study, GA optimization technique has been utilized for the PRMSA; this antenna is optimized for its parameters as length of the patch, thickness, width and length of strip line in order to achieve better return loss. According to the existing results for calculating S_{11}, we arrived at the smallest and best value (-28 dB) using GA compared to previous works using other methods. Further analysis is provided on how various antenna parameters affect performance. The GA was executed for 100 generations, with the optimized results enhancing the antenna’s efficiency. The computed results closely match the experimental data, and the accuracy of these results supports the effectiveness of using GA.

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1. INTRODUCTION

Among various performance enhancement techniques, the genetic algorithm (GA), a robust optimization method, has proven to be effective across a broad spectrum of electromagnetics applications [1]–[4]. The GA has been employed to enhance the performance of microstrip patch antennas by optimizing parameters such as bandwidth, resonating frequency, directivity, gain, and size. This optimization often leads to non-conventional patch geometries. The GA has been successfully utilized to solve complex optimization problems, offering practical solutions for calculating various parameters in control units due to its high accuracy and fast convergence. GA operates based on the principles of natural selection and inheritance. Natural selection means that organisms which adapt to environmental conditions continue to survive, while those that do not adapt are eliminated. Natural inheritance involves breeding individuals chosen for their traits to produce new generations through reproduction. To tackle problems with the GA, the initial population is determined randomly. Subsequent stages are divided into two main processes: genetic operations, which include crossover and mutation, and the evolutionary process, which involves selection. In the GA, problem-solving begins with a set of points that are first encoded. Each encoded structure forms a solution set, known as a chromosome (or individual). Chromosomes consist of chains of symbols, referred to proximity coupling, a feeding mechanism where there is no direct contact between the feed line and the element, offers several advantages. This technique eliminates spurious feed radiation and achieves a high bandwidth of up to 13% by increasing the overall thickness of the microstrip patch antenna. Additionally, it allows for the use of different dielectric media for the patch and the feed line, optimizing their individual performances. By selecting appropriate substrate parameters for the two layers, this method can enhance the patch's bandwidth and minimize spurious radiation from the open end of the microstrip as genes [5]. For effective implementation, the lower layer should be kept thin. Compared to edge- and probe-fed geometries, proximity-coupled feeding naturally offers greater bandwidth [6]. In 1981, Oltman and Huebner [7] conducted research on electromagnetically coupled microstrip dipoles. Numerous studies have focused on enhancing the bandwidth of planar rectangular microstrip antennas (PRMSA) through various methods, including the addition of parasitic radiators [7]-[9], impedance matching networks [10], [11], L-probe feeding [12], [13], U-slot patches fed by U-shaped or double U-shaped stubs [14]–[16], V-slot patches fed by Y-shaped stubs [17], tooth-like-slot patches [18], and H-shaped slots in the ground plane [19]-[21].

This paper is organized into six sections. Section 2, explores the use of transmission-line (TLM) to develop a simple equivalent-circuit model of PRMSA. It introduces a simplified theory based on the broadside-coupled lines, to provide practical antennas design without relying on complex and time-consuming numerical methods. Section 3 provides an overview of the GA and the flowchart utilized. Section 4 describes three fitness functions from the literature used to optimize input impedance, return loss, and voltage standing wave ratio (VSWR). Section 5 evaluates the performance of the proximity-coupled rectangular microstrip antenna using GA optimization, comparing the results with both simulated and measured data. It also includes an analysis of how various geometrical parameters of the proposed antenna impact its performance. Finally, section 6 provides a summary of the paper.

2. TLM ANALYSIS OF PRMSA

Proximity coupling utilizes a two-layer substrate, with the microstrip line on the lower layer and the patch antenna on the upper layer, as illustrated in Figure 1. The feed line terminates in an open end beneath the patch, which is referred to as an electromagnetically coupled microstrip feed.

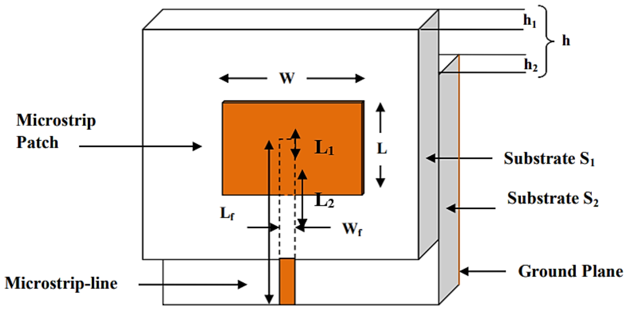

Figure 1. Geometry of PRMSA

The microstrip patch antenna can be analyzed, without taking the coupling into account, using simpler analytical methods, such as the transmission-line approach [22], [23]. However, enhancements are necessary to improve the accuracy of input impedance predictions for the antenna. Studies [24]–[26] have proposed an enhanced transmission line, to accurately determine the input impedance of the patch antenna fed by a coaxial line or a microstrip feed line. This model utilizes the equivalent-slot concept and the open-end effect, incorporating frequency expressions.

The mathematical model of the equivalent circuit is presented in Figure 2. A three-port circuit is illustrated in Figure 3 is considered. The propagation constant γ_p and the characteristic admittance Y_c, of each line section are modified by the electromagnetic coupling that occurs at port 3 [27].

The electromagnetic-coupled-line component is integrated into the enhanced TLM model. The final equivalent circuit, shown in Figure 4, includes line characteristic admittances defined as follows: $Y_{c1}=1/Z_{oo}^{P}$, $Y_{c2}=1/Z_{oo}^{f}$ and $Y_{c3}=2/(Z_{oe}^{f}-Z_{oo}^{f})$.

$$Y'_{in} = Y_{c3}\frac{Y_{in}+jY_{c3}tan\theta_2}{Y_{c3}+jY_{in}tan\theta_2} \quad (1)$$

$$[Y''_{in}]^{-1} = [Y'_{in}]^{-1} + [-jZ_{oo}^{f}\,cot\,(\theta_2)] \quad (2)$$

Y_{inf} is the final characteristic admittance may be obtained as:

$$Y_{inf} = Y_0 \frac{Y''_{in} + jY_0 tan(\beta L_x)}{Y_0 + jY''_{in} tan(\beta L_x)} \quad (3)$$

$$L_x = L_f - L_2 \quad (4)$$

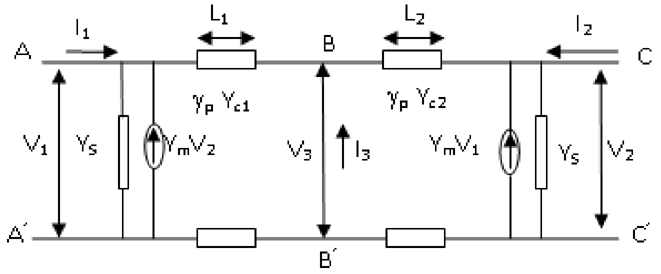

Figure 2. The equivalent circuit for the enhanced TLM model of the rectangular patch

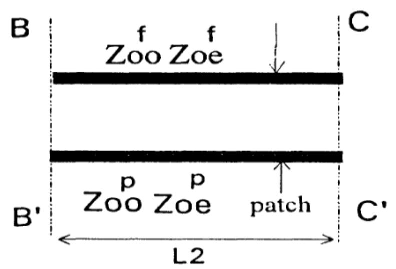

Figure 3. The broadside coupled line section

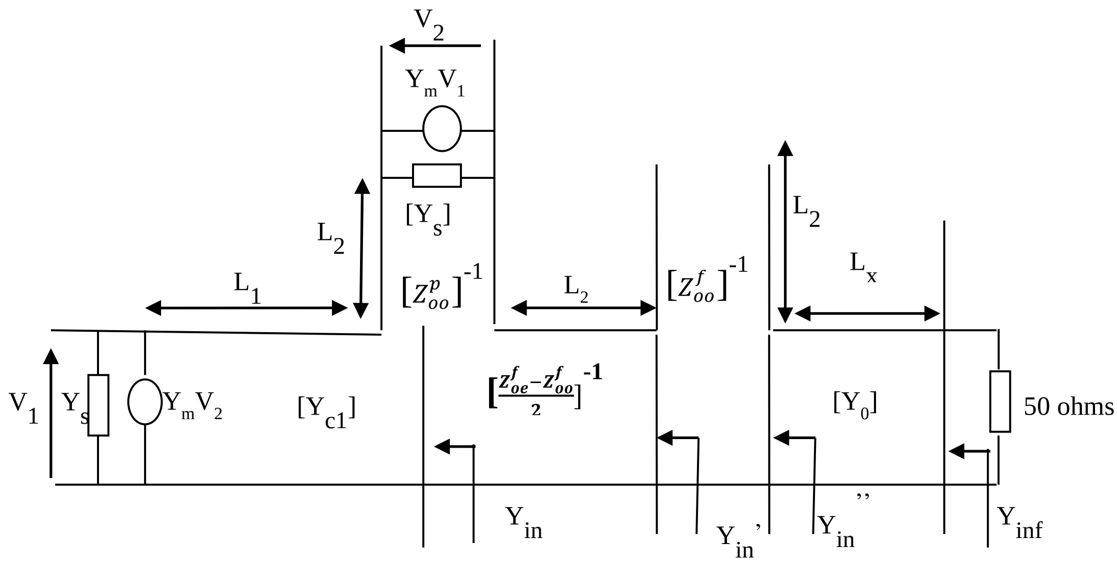

Figure 4. Final circuit of PRMSA

The odd and even mode impedances Z_{oo}, Z_{oe} may be expressed as:

$$Z_{oe} = \frac{188.3/\sqrt{\varepsilon_r}}{\frac{w/b}{1-h_1/b} + \frac{C_{fe}'}{\varepsilon}} \quad (5)$$

$$Z_{oo} = \frac{188.3/\sqrt{\varepsilon_r}}{\frac{w/b}{1-h_1/b} + \frac{w}{h_1} + \frac{C_{fo}'}{\varepsilon}} \quad (6)$$

And C_{fe}', C_{fo}' are the mode capacitances:

$$\frac{C_{fe}'}{\varepsilon} = 0.4413 + \frac{1}{\pi}\left[log\left(\frac{1}{1-h_1/b}\right) + \frac{h_1/b}{1-h_1/b} log\frac{b}{h_1}\right] \quad (7)$$

$$\frac{C_{fo}'}{\varepsilon} = \frac{b/h_1}{\pi}\left[log\left(\frac{1}{1-h_1/b}\right) + \frac{h_1/b}{1-h_1/b} log\frac{b}{h_1}\right] \quad (8)$$

3. GENETIC ALGORITHM

GA are stochastic search methods adept at handling the unique characteristics of electromagnetic problems that challenge other optimization techniques. GA provides several advantages over traditional numerical optimization methods: it can optimize both continuous and discrete parameters, does not require derivative information, handles a large number of variables, is well-suited for parallel computing, offers a range of optimal parameters instead of just a single solution, and works effectively with numerically generated data, experimental data, or analytical functions. In a computer algorithm, a chromosome is an array of genes, each assessed by a cost function to determine its value. The algorithm begins with a large set of randomly generated chromosomes. Each gene is a binary encoding of a parameter, serving as the fundamental unit of GA. The chromosomes that demonstrate the highest fitness are called parents. During the production phase, parents are chosen through a selection process to reproduce using the crossover operator. In crossover, random points are selected to exchange genetic material between parents. This process continues until a new generation is formed. Mutation plays a secondary role in basic GA operations.

Mutation introduces occasional random changes to prevent the loss of potentially useful genetic material during reproduction and crossover. This infrequent alteration of a bit in a string ensures diversity within the population. Typically, mutation rates are around one per thousand bit transfers. When a chromosome is selected for mutation, a random bit is flipped from ‘0’ to ‘1’ or vice versa. One of the main challenges of GA is the mutation operator, which can often generate poor candidate solutions, negatively impacting the entire population and overall results. However, when GA incorporates an efficient mutation strategy, both the convergence rate and population diversity improve [28].

After mutation, the fitness of the chromosomes is evaluated. Subsequently, the old generation is either completely or partially replaced. This process is repeated until the chromosomes and their associated fitness values become identical, except for those that have mutated. At this point, the GA must be stopped [29], [30]. Figure 5 shows the flowchart with proposed initial values of GA components for optimizing the parameters of a microstrip antenna.

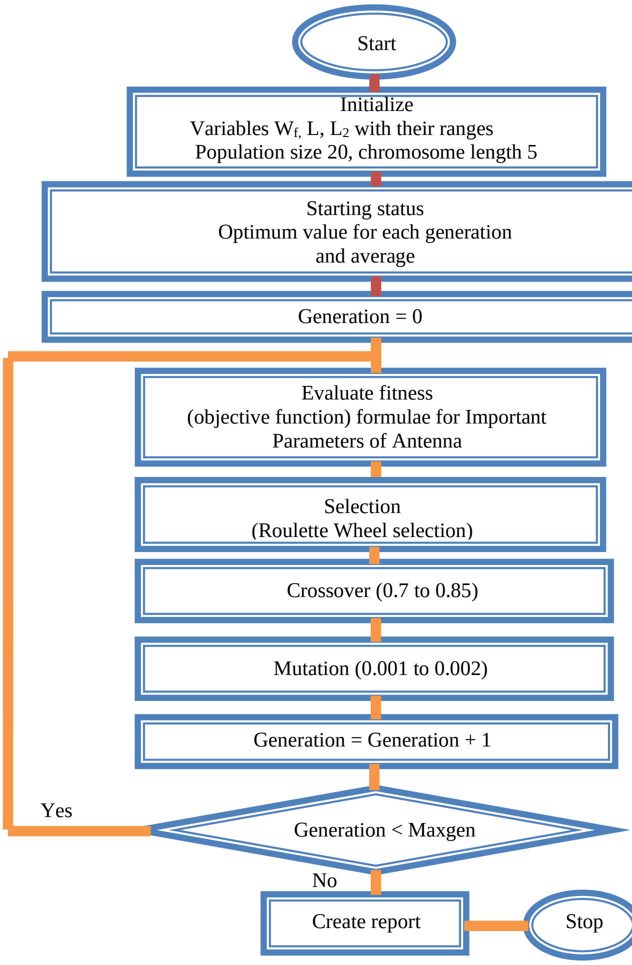

Figure 5. Flow chart of GA

4. APPLICATION OF GENETIC ALGORITHM TO THE PRMSA

All parameters, such as feed strip width (W_f), patch length (L), and patch-line overlapping (L_2), were encoded into 5-bit scaled binary coding to meet the requirements of the fitness function. For the proposed antenna, the algorithm uses the following input parameters: i) maximum of generation: 100; ii) mututation rate: 0.001-0.002; iii) crossover rate: 0.7-0.85; and iv) population size: 20.
The fitness functions are:

– Fitness function: 1—input impedance

$$Z_{in} = [Y_{inf}]^{-1} \tag{9}$$

– Fitness function: 2—return loss

$$S_{11} = \frac{Z_{in}-Z_0}{Z_{in}+Z_0} \tag{10}$$

$$|S_{11}|_{dB} = 20log\ (S_{11}) \tag{11}$$

– Fitness function: 3—VSWR

$$VSWR = \frac{1+S_{11}}{1-S_{11}} \tag{12}$$

The antenna parameters are characterized by a specific combination of input variables W_f, L, and L_2 determined using the TLM model. The GA comprises five key components: a random number generator, a fitness evaluation unit, and genetic operators for reproduction, crossover, and mutation operations.The geometry parameters of optimized PRMSA are as follows: i) frequency: 8.55 GHz; ii) patch size: L=12 mm, W=14.08 mm; iii) height of the substrate: h_1=1 mm; iv) height of the substrate: h_2=1 mm; v) patch-line overlapping: L_2=6 mm; vi) dielectric constant: ε_r=2.2; vii) length of the feedline: L_f=15.6 mm; and viii) width of the feedline: W_f=2 mm.

5. RESULTS AND DISCUSSION

This section presents and discusses the research results in detail. The discussion is divided into two sub-sections, focusing on the results obtained using the GA optimizer in MATLAB.

5.1. Performance of PRMSA using genetic algorithm optimization

Figure 6 illustrates the convergence behavior of GA, showing the fitness value versus generation. The GA toolbox is used to invoke the fitness function, and the plot displays the best and average fitness values for each generation. The best fitness value achieved is 50.32, which is also the average fitness value.

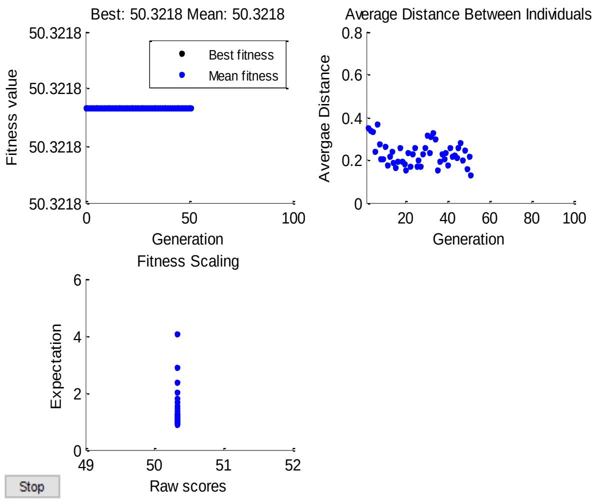

Figure 6. The best fitness, average distance, and expectation of input impedance of PRMSA

The variation of the best, mean, and expected values of the input impedance for the PRMSA reflects the GA parameters used in the analysis. It is important to note that 50 generations are typically sufficient for the algorithm to achieve convergence. In all the simulated annealing graphs shown in Figures 6 to 8 representing input impedance, return loss, and VSWR the results are observed to be accurate and meet the desired outcomes.

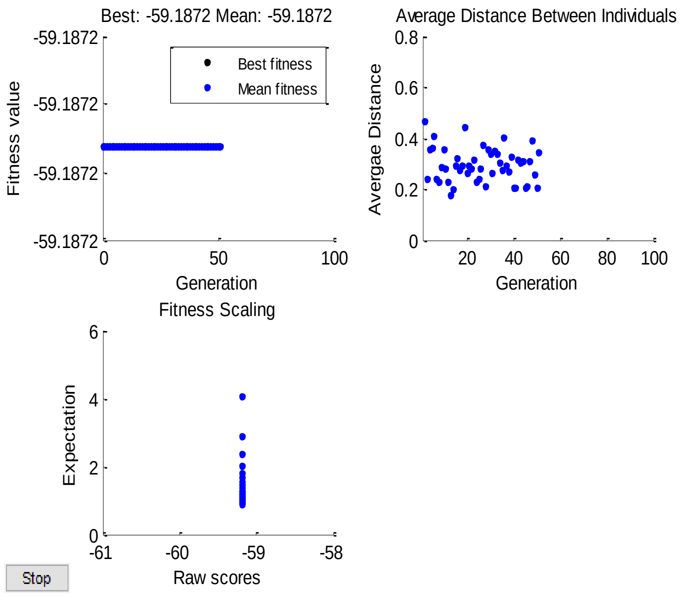

Figure 7. The best fitness, average distance, and expectation of return loss of PRMSA

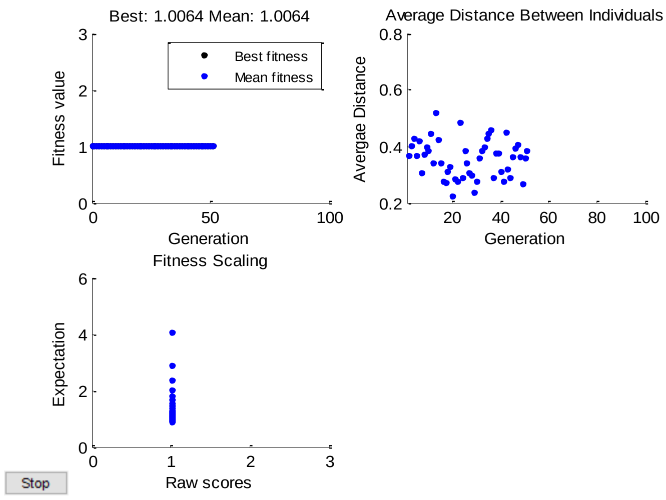

Figure 8. The best fitness, average distance, and expectation of VSWR of PRMSA

Figure 9 illustrates the genetic window where these parameters are applied. The optimal parameters obtained through the GA are as follows: patch length of 12 mm, strip line width W_f=3 mm and patch-line overlap L_2=6 mm. With these optimal antenna parameters, the return loss is -59.18 dB, the input impedance is 50.32 ohms, and the VSWR is 1.0064. The GA was implemented using MATLAB's Global Optimization Toolbox. The parameters of the PRMSA, determined via the GA program, were compared with theoretical and experimental results from other methods cited in research articles [31]. These comparisons, presented in Table 1, demonstrate good agreement.

The next subsection discusses the study conducted to evaluate how different antenna geometry parameters impact input impedance and return loss.

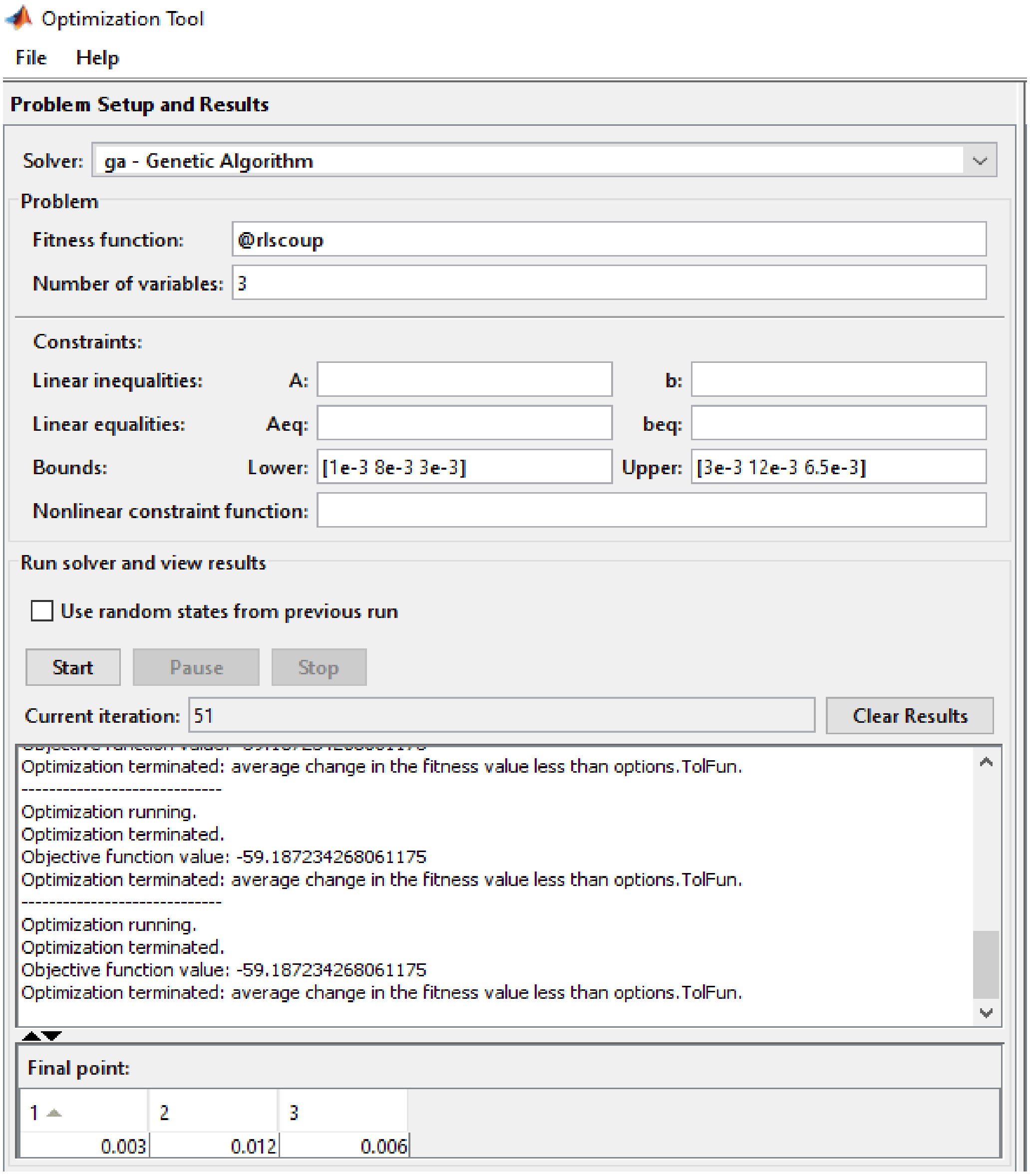

Figure 9. GA toolbox

Table 1. Comparison of parameters calculated by GA program and practical results

Parameters	Opt. values	Exp.values [31]
Return loss	-59.18 dB	-60.7dB
Input impedance	50.32 ohms	50 ohms
VSWR	1.0064	1.00

5.2. Parametric analysis of the proposed antenna

The proximity-coupled antenna PRMSA is analyzed, and the results are compared with those obtained by [32]. Figure 10 shows the variation of input impedance with frequency for different patch-line overlapping values L_2. As L_2 increases, the capacitive nature of the antenna also increases. The resonance resistance decreases as the open end of the feed strip moves towards the center of the patch. Each specific parameter is analyzed individually, with all other parameters maintained at their suboptimal values. The geometry parameters of the PRMSA considered in this analysis are as follows: i) frequency: 3.1 GHz; ii) patch size: L=29 mm, W=29 mm; iii) height of the substrate: h_1=h_2=1.6 mm; iv) dielectric constant: ε_r=4.4; v) length of the feedline: 24.41 mm; and vi) width of the feedline: 3.021 mm.

5.2.1. Effect of thickness

The impact of varying the thickness is examined first, as shown in Figure 11. It is observed that increasing the thickness from 1.2 mm to the optimal value of 1.6 mm improves the return loss (S11) at the resonant frequency. All other antenna geometry parameters are kept constant during this analysis.

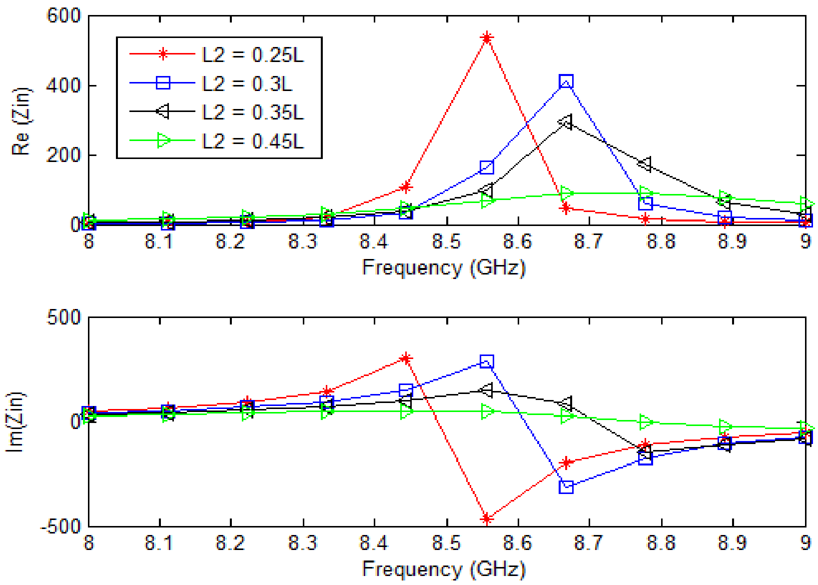

Figure 10. Variations of impedance response of a PRMSA with different patch-line overlapping L_2, L=11 mm, h_1=h_2=1.6 mm, W=9 mm, L_f=38 mm, W_f=2.2 mm, and ε_r=2.17

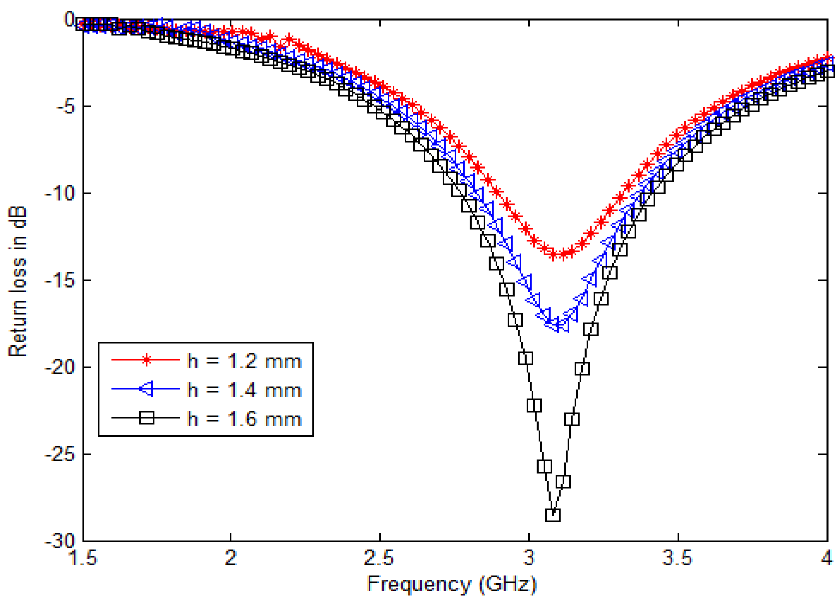

Figure 11. Return loss vs frequency of PRMSA with thickness variation

5.2.2. Effect of feed strip line width

This subsection explores the impact of varying the width of the feed strip, as depicted in Figure 12. It is observed that the reflection coefficient improves when increasing Wf from 1.02 mm to the optimal value of 3.02 mm.

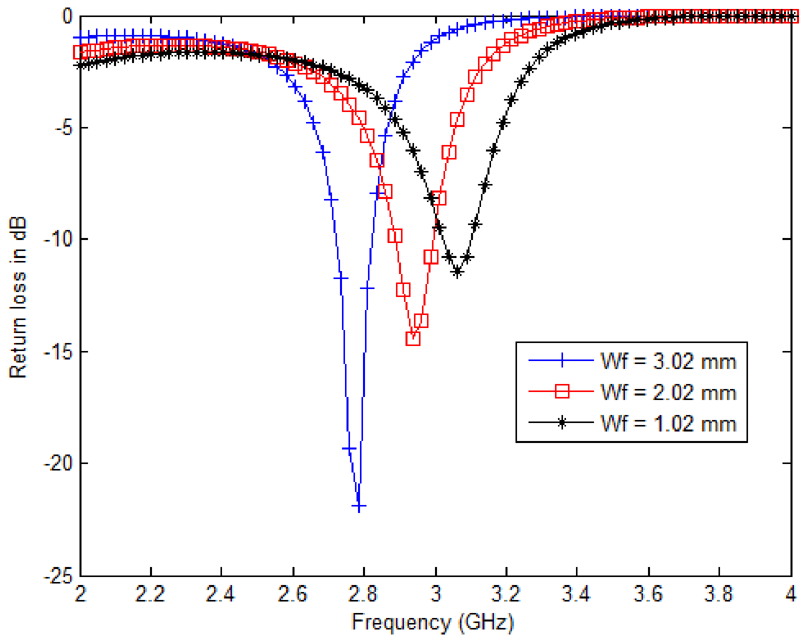

Figure 12. Return loss variation with feed strip width variation

5.2.3. Effect of feed strip line length

Figure 13 presents the impact of varying the feed-line length (Lf). It is observed that the return loss (S11) at the resonant frequency improves as Lf is increased from 19 mm to the optimal value of 21 mm. Figures 12 and 13 clearly indicate that the PRMSA performs optimally with a feed strip length of 21 mm and a width of 3.02 mm. A comparison between the unoptimized and optimized values is summarized in Table 2.

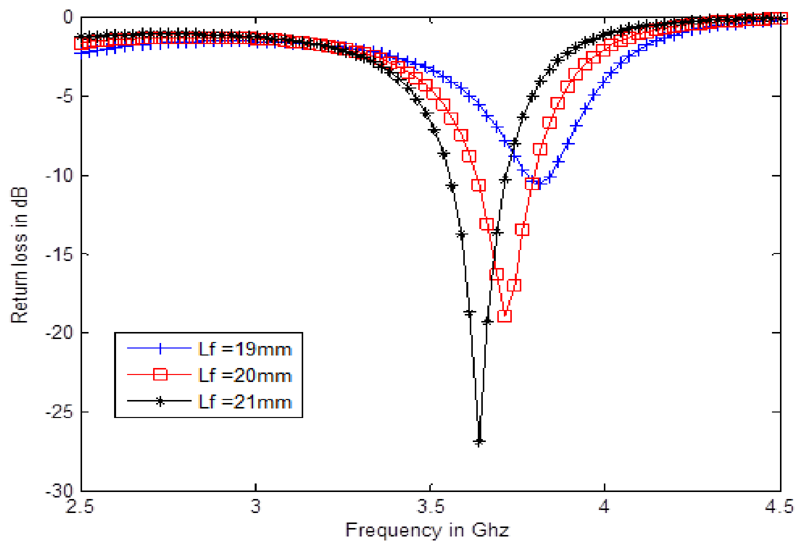

Figure 13. Return loss variation with feed strip length variation

Table 2. Comparison of S_{11} calculated by GA program and simulations results

Antenna geometry parameters (mm)	Optimized values return loss (dB)	Simulated values return loss (dB)
Thickness h=1.6	-28	-14.42 [33]
feed strip width W_f=3.02	-22	-14.5 [34]
feed strip length L_f=21	-27	-8.5 [34]

6. CONCLUSION

This passage describes the process of optimizing an antenna design, which involves defining parameters such as size, shape, and material properties, applying mathematical models to characterize the antenna and electromagnetic waves, and using numerical methods to determine the optimal solution. Despite the capabilities of modern computers, finding the optimal solution remains challenging. However, the GA stands out for its precision and speed compared to other techniques, as it optimizes the encoded parameters efficiently.

This paper presents the simulated results of a proximity-coupled rectangular microstrip antenna (PRMSA) optimized using a GA. The objective is to improve the antenna's return loss (S_{11}) at the resonant frequency. The optimized PRMSA operates at a resonant frequency of 8.55 GHz, achieving a return loss of -59.18 dB, an input impedance of 50.32 ohms, and a VSWR of 1.0064. The simulated results show excellent agreement with the measured data. Additionally, three fitness functions for the GA program have been developed using the transmission line method to analyze the microstrip antenna.

To further evaluate the performance of the PRMSA, we examined the variation in S_{11} with changes in different geometric parameters, such as substrate thickness and the width and length of the feed strip. The results indicate that S11 is -28 dB for a substrate thickness (h) of 1.6 mm, -22 dB for a feed strip width (W_f) of 3.02 mm, and -27 dB for a feed strip length (L_f) of 21 mm.

It can also be concluded that the input impedance is highly sensitive to variations in patch-line overlapping (L_2). The computed graphs of return loss show good agreement with the experimental results. Future research should focus on utilizing the GA optimization technique to enhance the performance of proximity-coupled patch arrays and other microstrip antenna structures.

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