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DESIGN AND OPTIMIZATION OF A LOGO-TYPE ANTENNA FOR MULTIBAND APPLICATIONS

W.-C. Weng* and C.-L. Hung

Department of Electrical Engineering, National Chi Nan University, Puli 54561, Taiwan, R.O.C.

Abstract—This study respectively uses two optimizers, iterative Taguchi's method and particle swarm optimization, combined with the method of moments to optimize a logotype planar antenna for multiband applications. The proposed antenna consists of four metal letters, NCNU, which is the abbreviation of the authors' university name. This antenna can be used for university logo or advertisement applications. The antenna also serves as an example to compare the optimization performance of these two optimizers. Optimization results show that Taguchi's method achieves much better optimization performance than particle swarm optimization. This study also investigates the electromagnetic characteristics of the proposed antenna by parametric study using simulation. The presented optimization methods could be applied to designing similar logotype antennas.

1. INTRODUCTION

Planar antennas offer the advantages of small size, light weight, and low cost. An antenna's performances such as, VSWR, gain, radiation pattern, compactness, are concerned by a designer. It would be great if a logo could be included in the antenna geometry with good antenna features. Few works related to logo-type antennas have been proposed. In [1], a single E-shaped radiating element was embedded into the company logo. Two logo patch antennas shown in [2] were designed by an experimental effort. This study designs a planar multiband planar antenna with a unique shape using several metal strips to form the NCNU shape, which is the abbreviation of the authors' university. In the proposed antenna, the entire logo of the

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* Corresponding author: Wei-Chung Weng (wcweng@ncnu.edu.tw).

four letters (NCNU) behaving as an antenna can be considered as novel. Figure 1 illustrates the geometry of the proposed antenna. In the proposed design, a 50 ohms microstrip feeds the antenna [3]. Since the radiating elements of the antenna consist of many strips, exciting different modes makes the antenna suitable for multiband purposes [4]. In our previous work [5], the antenna, which has a slot cut on a patch, was designed using a trial-and-error approach based on the designer's electromagnetic experience. Many strips in the antenna geometry must be adjusted to achieve a good impedance matching in the working bands. However, it is usually a tough task to compromise all bands and achieve good impedance matching using the trial-and-error approach because some strips are key components for two or more bands.

After conducting many trial simulations, the resulting antenna may not have the best design even if it meets designed specifications. In addition, designing this logo-type antenna is challenging because of the following reasons. Firstly, the size ($W3$ and $L3$) and strip width (W) of the four letters need to be all identical. Secondly, the ground plane is one of radiating elements. The use of the ground plane as radiator has been useful to design multiband handset antennas [6–9]. In the proposed antenna, the width, $W1$, of the ground plane cannot be adjusted arbitrarily. The four letters and ground plane should be symmetric to the 50 ohms microstrip. Thirdly, to keep the NCNU shape, no any other strips or slots are allowed to add to the four letters or to the ground plane. The above constraints greatly limit the designer's flexibility, especially using a trial-and-error approach, to design the proposed antenna. This study uses two optimization techniques, iterative Taguchi's method [10] and particle swarm optimization (PSO) [11], combined with the method of moments (MoM) [12] to design and optimize the logo-type antenna. The two optimizers can be viewed as global optimizers; thus, the optimized results could be considered the optimum. The advantage of the proposed approach is that it finds the optimal solution automatically without any manual adjustments during the optimization process. This process greatly reduces the time required to solve an electromagnetic problem. Optimization results show that the iterative Taguchi's method achieves much better optimization performance than PSO in this study. Comparing the optimized antennas with the previous planar multi-band antenna [5], we find that the $|S_{11}|$ curves are all satisfactory with the design specification. For the antenna gain performance, the gains of the proposed antenna optimized by iterative Taguchi's and PSO outperform the previous work [5]. For the antenna size comparison, the antenna size of the previous work is almost the same as that of the Taguchi-optimized antenna. Although the proposed antenna can be applied for the authors' university only, the antenna serves as an example to design a logo-type antenna using the proposed approach.

This paper is organized as follows. Section 2 presents a brief description of the iterative Taguchi and PSO optimization processes. Section 3 discusses the optimization and measurement results of the proposed antenna. Section 4 performs a parametric study and discusses its results. Finally, Section 5 provides a brief conclusion of this study.

2. ANTENNA DESIGN BY OPTIMIZATION APPROACHES

2.1. The Antenna Design

The proposed antenna structure shown in Figure 1 consists of three parts. The ground plane, with a size of $W1$ by $L1$, was printed on the bottom side of an FR4 substrate with the relative permittivity of 4.4, the loss tangent of 0.02, and the thickness (h) of 1.6 mm. A 50 ohms microstrip with a width ($W2$) of 3.0 mm and NCNU-shaped strips with a uniform width (W) of 2.0 mm were printed on the upper side of the substrate. Each letter had the same size, $W3$ by $L3$. The gaps between the four letters were $L4$ and $W4$ to enable electromagnetic energy coupling. The $W4$ was fixed at 0.5 mm. A small strip, $W5$, connected the lower N letter and U letter, creates a current path. The $L2$ is the gap between two N-shaped letters and the ground plane. The $L2$ can be used to control the antenna impedance match. The initial

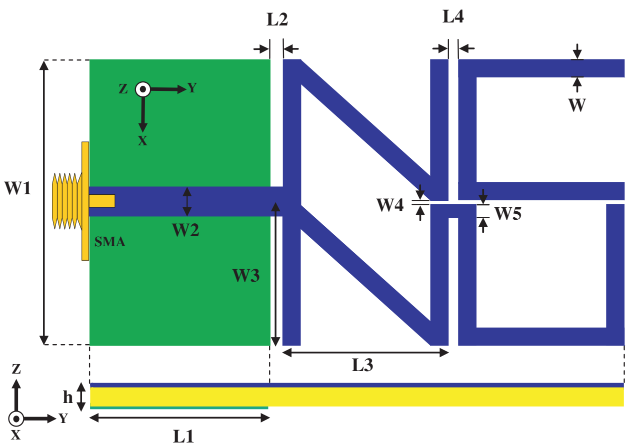

Figure 1. The geometry the proposed antenna.

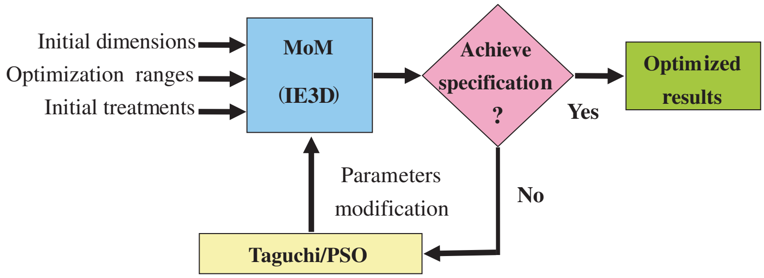

Figure 2. The flow chart of the optimization design approach.

dimensions are used to create the prototype of the proposed antenna. Table 1 lists the initial dimensions of the proposed antenna.

We use iterative Taguchi's method and PSO respectively in conjunction with the method of moments (MoM) to design the proposed antenna. Figure 2 shows the flow chart of the design process. In the optimization process, the codes of the two optimizers modify the dimensions of parameters if the design goal is not achieved. Then, the IE3D uses the modified dimensions of parameters for the next simulation. The engine of IE3D is ie3d.exe. The ie3d.exe along with the geometry file (*.geo) and simulation file (*.sim) should be indicated in the optimization code. Once the dimensions of parameters have been modified in the simulation file, the ie3d.exe is launched for the results of simulation. A detailed description of modifying a parameter value appears in [10]. The detailed description of handling the optimization cod and IE3D can be found in [12]. Thanks to the power of the two optimizers, this study does not apply design treatments [5] such as the asymmetric ground and the gap in the lower N-shape. These two optimizers can optimize many parameters simultaneously. This antenna optimization process optimizes seven parameters, $L1$, $L2$, $L3$, $L4$, $W1$, $W3$, and $W5$, to achieve the design goal. Table 1 lists the initial dimensions and optimization ranges of these parameters. If the designer wants the antenna to be compact, the designer may limit the optimization ranges of parameters. The antenna specifications are as follows

$$\begin{gathered}|S_{11}(f)| < -10\,\text{dB} \quad \text{for} \quad 2.4\,\text{GHz} < f < 2.5\,\text{GHz}, \\ 3.3\,\text{GHz} < f < 3.7\,\text{GHz}, \quad \text{and} \quad 5.0\,\text{GHz} < f < 6.0\,\text{GHz}.\end{gathered} \tag{1}$$

The fitness value represents the difference area between $|S_{11}|$ and $-10\,\text{dB}$ in the frequencies shown in (1). In other words,

$$\text{fitness} = \sum (|S_{11}| + 10)\Delta f, \quad \text{if } |S_{11}| > -10\,\text{dB}, \tag{2}$$

Table 1. The initial dimensions, optimization ranges, and optimized dimensions obtained by Taguchi's and PSO of the logo-type antenna case shown in Figure 1. (Unit: mm).

Parameters	Initial Dimensions	Optimization Ranges	Optimized Dimensions by Taguchi	Optimized Dimensions by PSO
L1	18.0	14.0–24.0	20.37	21.17
L2	1.0	0.5–1.8	1.80	1.80
L3	15.0	13.0–21.0	19.29	19.67
L4	1.0	0.5–2.0	0.50	0.86
W1	30.5	18.5–42.5	20.00	18.50
W3	13.0	12.0–18.0	13.23	12.93
W5	1.0	0.5–1.8	0.50	0.50

where Δf is the interval of frequency. The MoM simulation in this study sets Δf at 0.01 GHz. The smaller the fitness value is, the better the performance of the $|S_{11}|$. A personal computer with an Intel Quad Q8200 2.33 GHz CPU and 4 GB RAM performed both optimization approaches combined with the MoM simulation.

The proposed antenna serves as a test example for comparing the optimization performance of the two optimizers. Using the same initial condition, design goal, and number of particles, this study compares the optimization performance of the two optimizers. Since full wave electromagnetic simulations require more time than conducting the optimizer itself, the optimization performance of the optimizer can be compared by the number of iterations required toward to the design goal.

2.2. Antenna Design Using Iterative Taguchi's Method

The conventional Taguchi's method finds the optimal solution only via one iteration to be applied in many areas. However, the solution found by the conventional Taguchi's method (no iteration) is far from the optimal solution. In 2007, Weng et al. introduced an iterative Taguchi's method [13] to the electromagnetic community. The iterative Taguchi's method is a novel optimizer rarely used to solve electromagnetic problems. Since 2007, only a few studies have addressed the problems such as antenna synthesis [13, 14], ultra-wideband antenna [15], planar filter [16], and slot antenna [17].

The optimization procedure in Taguchi's method is as follows.

Step 1: Determine an appropriate orthogonal array (OA),

Table 2. The three-level orthogonal array, OA(18, 7, 3, 2), is adopted in the iterative Taguchi's optimization.

	Parameters						
Experiments	L1	L2	L3	L4	W1	W3	W5
1	0	0	0	0	0	0	0
2	1	1	1	1	1	1	0
3	2	2	2	2	2	2	0
4	0	0	1	2	1	2	0
5	1	1	2	0	2	0	0
6	2	2	0	1	0	1	0
7	0	1	0	2	2	1	1
8	1	2	1	0	0	2	1
9	2	0	2	1	1	0	1
10	0	2	2	0	1	1	1
11	1	0	0	1	2	2	1
12	2	1	1	2	0	0	1
13	0	1	2	1	0	2	2
14	1	2	0	2	1	0	2
15	2	0	1	0	2	1	2
16	0	2	1	1	2	0	2
17	1	0	2	2	0	1	2
18	2	1	0	0	1	2	2

optimization range, fitness function, and optimization goal in advance. This study optimizes seven parameters, and adopts the OA(18, 7, 3, 2) [18] for optimization. The OA in Table 2 offers 18 experiments in one iteration.

Step 2: Conduct experiments to calculate the fitness value and signal-to-noise (S/N) ratio, η. The following formula determines the value of η [19]:

$$\eta = -20 \log(\text{fitness}). \tag{3}$$

A small fitness value produces a large η. Note that the η is a parameter of Taguchi's method and is not the signal to noise (S/N) ratio defined and used in communication engineering. The global best, $G_{\text{best},i}$ is the optimal level value of an experiment in the i-th iteration and is updated if the current fitness value is better than that of the $G_{\text{best},i}$

Step 3: Build the response table using the following equation for each parameter n and each level m [10, 13]:

$$\bar{\eta}(m,n) = \frac{s}{N} \sum_{i,OA(i,n)=m} \eta_i, \tag{4}$$

where $\bar{\eta}(m, n)$ is the average η in the response table of the m-th row and the n-th column. N is the number of experiments 18 in this case, and s is the OA's level set to 3.

Step 4: Identify the optimal level value by finding the largest $\bar{\eta}$ in each column in the response table. Then, conduct the confirmation experiment and compare its fitness with that of the $G_{\text{best},i}$.

Step 5: Reduce the optimization range. In the iterative Taguchi's method, the level difference of the $(i+1)$-th iteration can be obtained by

$$LD_{i+1} = LD_i RR, \tag{5}$$

where RR is the reduced rate, set to 0.8. The level difference is reduced iteration by iteration. The $G_{\text{best},i}$ of each parameter serves as the central value (value of level 1). The values of level 0 and level 2 for next iteration can then be obtained by the central value minus and plus the level difference LD_{i+1}, respectively. If a level value exceeds the boundary of the optimization range, the level value is set to the boundary value. The iterative Taguchi's method uses the level difference, which is reduced iteration by iteration, to search the global optimum.

Step 6: Note that when the number of iteration reaches a certain value, the level difference of a parameter becomes small and does not affect the entire output response. The designer may use the following equation to determine the termination criteria of Taguchi's method:

$$\frac{LD_i}{LD_1} \leq 0.01, \tag{6}$$

where the subscript i denotes the i-th iteration. If the level differences of all parameters satisfy the above termination criteria, the optimization process ends.

Step 7: Repeat *Step 2* to *Step 6* until the $G_{\text{best},i}$ of an experiment achieves the design goal or converges to the fitness value.

For the sake of brevity, this section excludes other detailed concepts of iterative Taguchi's method, which can be found in [10, 13].

2.3. Antenna Design by Particle Swarm Optimization

Particle swarm optimization (PSO) has recently become a popular optimization technique in electromagnetic applications [20–27]. PSO is a global optimization technique, and has demonstrated its ability to optimize complex, multidimensional, and discontinuous problems. This study adopts the classical version of PSO, and describes the PSO optimization procedure as follows.

Step 1: Determine the number of particles, optimization range, fitness function, and optimization goal in advance. Then, initialize the positions and velocities of particles with random values. This study uses 18 particles to find the optimal solution.

Step 2: Conduct experiments, calculate fitness value, and update the global best, $G_{\text{best},i}$ and the personal best, $P_{\text{best},i}$ of a particle in the i-th iteration if the current fitness value is better than $G_{\text{best},i}$ and $P_{\text{best},i}$.

Step 3: Update the particles velocity using the following equation:

$$v_{i+1} = wv_i + cr_1(P_{\text{best},i} - x_i) + cr_2(G_{\text{best},i} - x_i), \tag{7}$$

where w is the inertia weight, which varies from 0.9 to 0.4 over the course of the iteration. In this study, c is set to 2.0, while r_1 and r_2 are uniform random values ranging from 0.0 to 1.0.

Step 4: Update the particles position using the following equation:

$$x_{i+1} = x_i + v_{i+1}. \tag{8}$$

If x_{i+1} exceeds the optimization range boundary, set x_{i+1} to the value of the boundary and change the sign of v_{i+1}.

Step 5: Repeat *Step 2* to *Step 4* until the $G_{\text{best},i}$ of a particle achieves the design goal, reaches or converges to the fitness value.

For the sake of brevity, this section excludes other detailed concepts of PSO optimization, which can be found in [20].

3. RESULTS AND DISCUSSIONS

The Taguchi's process terminates after 44 iterations because it is satisfactory (6). The best fitness value at the 44th iteration was 1.02 which reveals minor portions of the $|S_{11}|$ curves do not meet the antenna specifications in (1). Figure 3 shows that the PSO optimization process reached the same fitness value of 1.02, but required 150 iterations. This demonstrates that Taguchi's method achieved much better optimization performance than PSO in this case. The fitness curve of the Taguchi's method drops rapidly in the first few iterations, and continues to decrease as the number of iteration increases. However, the PSO fitness curve drops in the first fifty iterations, and then slowly decreases for the 50th-150th iterations.

Figure 4 shows the $|S_{11}|$ curves of the antenna optimized by Taguchi's method and PSO along with that of the initial antenna. Before the optimization process, the $|S_{11}|$ of the initial antenna was

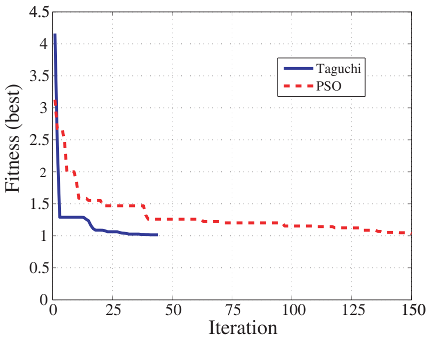

Figure 3. The convergence curves of the best fitness in the iterative Taguchi's method and PSO.

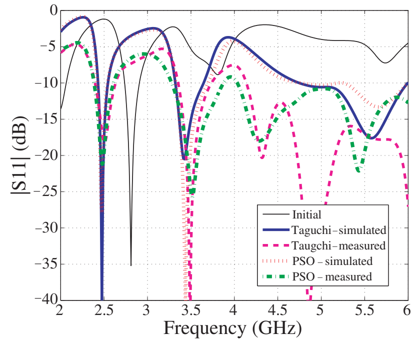

Figure 4. The $|S_{11}|$ curves of the proposed antenna optimized by iterative Taguchi's method and PSO along with that of the initial antenna.

quite poor. The simulated $|S_{11}|$ curves of Taguchi's method and PSO agree with each other except for a slight difference between 5.0 GHz and 6.0 GHz. This result demonstrates that the two optimizers approximately meet the same design goal shown in (1) although Table 1 shows that some dimensions optimized by the two optimizers are different. Three resonant modes at about 2.45 GHz, 3.5 GHz, and 5.6 GHz were successfully excited. The simulated $|S_{11}|$ of Taguchi's method shows that the first band of the proposed antenna has a bandwidth of 120 MHz (2430 MHz–2550 MHz) for IEEE 802.11b/g applications. The second band has a bandwidth of 330 MHz (3320 MHz–3650 MHz) for WiMAX applications [28]. The third band has a bandwidth of 1250 MHz (4750 MHz–6000 MHz) for IEEE 802.11a applications. Observing the four $|S_{11}|$ curves (excluding the initial curve) shown in Figure 4, the resonances are all at 2.45 GHz with a good agreement among them. The impedance bandwidths of the measured $|S_{11}|$ (below -10 dB) at resonant frequencies are wider than those of the simulated ones.

This study adopted the optimized dimensions shown in Table 1 to fabricate the proposed antenna. Figure 5 shows a picture of the Taguchi-optimized antenna fabricated on an FR4 substrate. The antenna size is 3310.3 mm^2 (71.25 mm by 46.46 mm) with 10.0 mm substrate buffers which are the length between the antenna's metal edge and substrate edge. The PSO-optimized antenna was also fabricated with the same 10.0 mm substrate buffer length. The antenna size is 3355.6 mm^2 (73.17 mm by 45.86 mm). The antenna size of

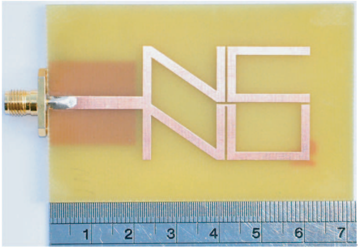

Figure 5. A picture of the proposed antenna optimized by the iterative Taguchi's method. The antenna was fabricated on an FR4 substrate measuring 71.25 mm by 46.46 mm with a relative permittivity of 4.4, loss tangent of 0.02, and thickness of 1.6 mm.

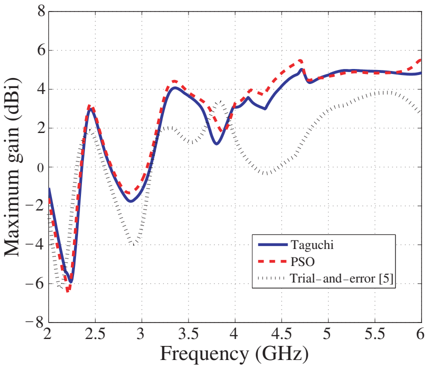

Figure 6. The simulated maximum gain of the proposed antenna optimized by the iterative Taguchi's method and PSO along with the gain of the antenna designed by a trial-and-error approach [5].

the previous work [5] with the same 10.0 mm substrate buffers is 3307.8 mm^2 (65.5 mm by 50.5 mm), which is almost the same as that of the Taguchi-optimized antenna.

Figure 6 shows the simulated maximum gains of the proposed antennas optimized by Taguchi's method and PSO along with the gain of the antenna designed by a trial-and-error approach [5]. The maximum gains of Taguchi's and PSO's are close to each other. Also, the gains are larger than trial-and-error approach about 1 dBi, 2 dBi, and 1 dBi at 2.45 GHz, 3.5 GHz, and 5.6 GHz, respectively.

Figure 7 shows the simulated surface current distributions on the printed metal portions of the substrate at 2.45 GHz, 3.5 GHz, and 5.6 GHz. This figure shows that the lengths, which have strong currents

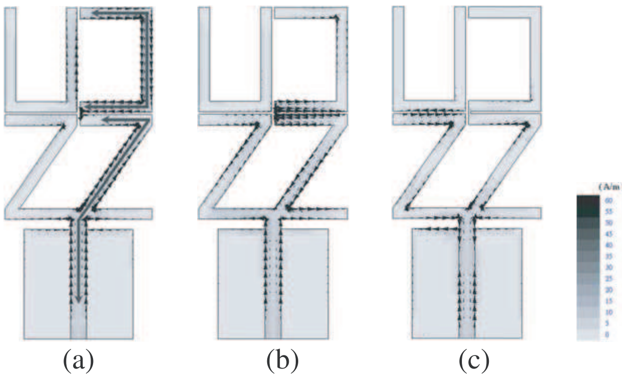

Figure 7. Simulated surface current distributions of the proposed antenna optimized by Taguchi's method at (a) $f = 2.45\,\text{GHz}$, (b) $f = 3.5\,\text{GHz}$, and (c) $f = 5.6\,\text{GHz}$.

flowing on the strips, are about half-wave guided length. For example, the currents in Figure 7(a) mainly flow on the U-shaped strip and the lower N-shaped and portion of the 50 ohms microstrip. The lengths of the currents indicated by the two arrow lines are about 47 mm. This is approximately half-wave guided length at the resonant frequency 2.45 GHz. Similar conditions appear at other resonant frequencies. Therefore, the antenna is mainly excited at half-wave length modes. The resonant frequency of the antenna at 3.5 GHz mainly depends on the strip connecting the N-shaped and the U-shaped as Figure 7(b) shows. The ground plane ($z = 0\,\text{mm}$) of the proposed antenna is also a part of the radiation elements since some currents flow on the plane, as Figure 7(c) shows. The dimension of the ground plane can be adjusted to achieve better impedance matching.

Figure 8 shows the measured radiation patterns of the proposed antenna optimized by Taguchi's method. The radiation patterns of the x-z plane cut are omnidirectional. In addition, the radiation patterns of the y-z plane cut resemble the shape of donuts. Therefore, the proposed antenna is essentially a dipole-type antenna.

4. PARAMETRIC STUDY

To understand the effects of geometric parameters on the frequency responses of the proposed antenna, this study conducts parametric analysis using a MoM-based electromagnetic simulator [12]. The dimensions optimized by Taguchi's method were adopted as the central value, and the dimension of each parameter value was adjusted while

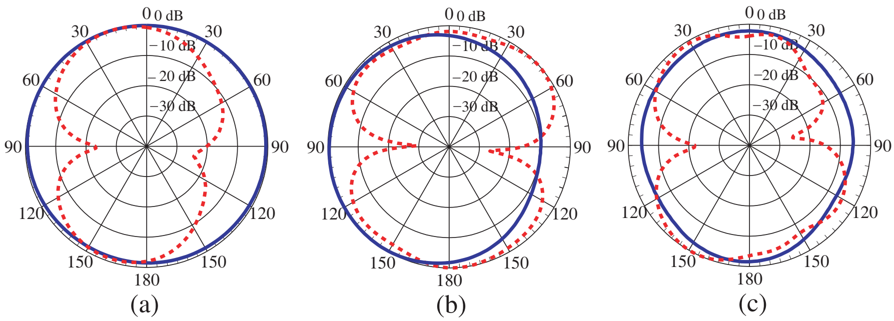

Figure 8. Normalized measured radiation patterns of the proposed antenna optimized by Taguchi's method. Solid lines are the x-z plane cut and dotted lines are the y-z plane cut. (a) $f = 2.45\,\text{GHz}$, (b) $f = 3.5\,\text{GHz}$, and (c) $f = 5.6\,\text{GHz}$.

the dimensions of other parameters remained fixed to observe the contribution of the parameter. This study investigates the dimensions of parameters $L3$, $W1$, $W5$, and $L2$.

Figure 9 shows the effects of varying the width of letters, $L3$. The $L3$ affects the $|S_{11}|$ in the bands of interest. The resonant frequencies at approximately 2.45 GHz and 3.5 GHz decrease as $L3$ increases. The value of $L3$ affects the $|S_{11}|$ more at 2.45 GHz than at 3.5 GHz. The current distributions shown in Figure 7(a) confirm this situation, showing that more currents flow on the metal strips denoted by $L3$. Therefore, the value of $L3$ is a significant parameter affecting the impedance matching.

Figure 10 reveals the effects of varying the value of the ground plane width, $W1$. The value of $W1$ has a significant effect on the $|S_{11}|$ at higher frequencies between 4.0 GHz and 6.0 GHz. However, $W1$ does not have a significant effect the $|S_{11}|$ at frequencies below 4.0 GHz.

The value of the strip width, $W5$, connects the N-shaped and U-shaped letters, significantly affects the resonant frequency at 3.5 GHz. The current distributions shown in Figure 7(b) confirm this situation. The higher the $W5$ is, the higher the resonant frequency is. However, the $W5$ does not affect the $|S_{11}|$ at other frequency responses as Figure 11 shows.

The $L2$, which is the gap between the letters and the ground plane, does not affect the $|S_{11}|$ at the resonant frequency 2.45 GHz. However, the $L2$ affects the $|S_{11}|$ at the resonant frequency 3.5 GHz and the higher frequencies between 4.5 GHz and 6.0 GHz, as Figure 12 shows.

This parametric analysis in this study also considers $L1$, $L4$, and $W3$. However, the figures of results were excluded for brevity, and the following paragraph summarizes the results.

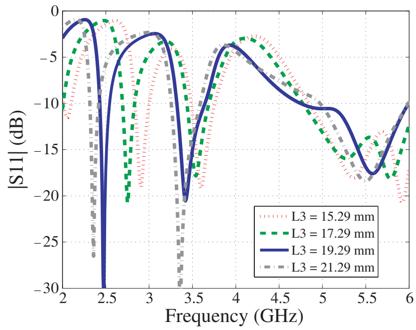

Figure 9. Effects of varying the width of letters, $L3$.

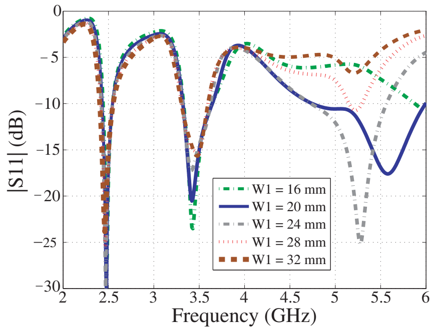

Figure 10. Effects of varying the ground plane width, $W1$.

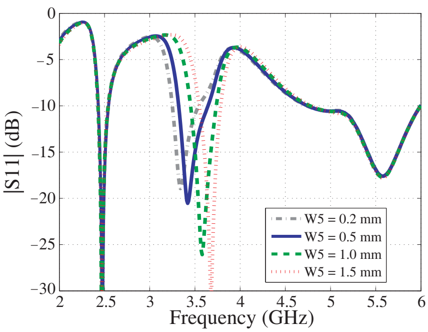

Figure 11. Effects of varying the strip width, $W5$

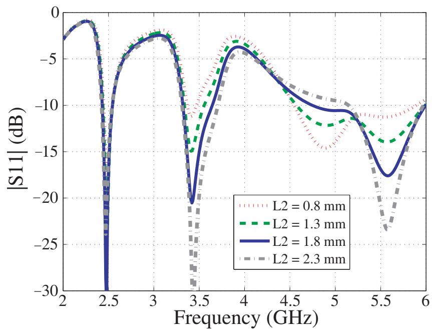

Figure 12. Effects of varying the $L2$, the gap between the letters and the ground plane.

The $W3$ affected the $|S_{11}|$ in the bands of interest, showing results similar to those of $L3$. The values of $L3$ and $W3$ are the most sensitive parameters affecting the $|S_{11}|$. Therefore, the letter sizes, $L3$ and $W3$, must be carefully determined in the design of this proposed antenna. The $L4$ does not affect the $|S_{11}|$ in the observed frequency of 2.0 GHz to 6.0 GHz. Consequently, the value of the $L4$ does not need to be optimized, and can be fixed at a value. The $L1$ affects the $|S_{11}|$ higher frequencies between 4.0 GHz and 6.0 GHz, and has a similar effect as that of $W1$. As a result, the ground plane size, $L1$ and $W1$, affects the $|S_{11}|$ in the higher frequencies.

5. CONCLUSION

This paper presents a novel planar dipole antenna with university initials, NCNU, for multiband applications. Two optimizers, including iterative Taguchi's method and particle swarm optimization, were respectively combined with the method of moments to design the proposed antenna. Both optimization approaches successfully obtained the desired goal in the bands of interest. The antenna design process is automated and better results can be obtained efficiently by using these optimization approaches. This study also compares the performance of the two optimizers under the same optimization conditions. Optimization results indicate that iterative Taguchi's method achieved much better optimization performance than PSO. Numerical simulations and experimental measurements show that the proposed antenna achieves good performances. The current distributions excited at resonant frequencies reveals that the proposed antenna operates at half-wave guided length modes. The parametric study of the proposed antenna shows that the values of $L3$ and $W3$ are the most sensitive parameters affecting the $|S_{11}|$. The presented optimization techniques in this study could be applied not only to design logo-type antennas but also to solve a variety of electromagnetic problems.

ACKNOWLEDGMENT

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