

# Optimal Design of CPW Slot Antennas Using Taguchi's Method

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In this study, a one-element coplanar-waveguide (CPW) slot antenna and a two-element series aperiodic CPW slot antenna array are optimized by Taguchi's method, in conjunction with a full-wave simulator to analyze the antennas, to achieve the desired goals. As a comparison, particle swarm optimization (PSO) is also used to design the two antennas. Optimization results show that the desired frequency responses of the antenna are successfully achieved by the two approaches. The optimization results from the Taguchi's method significantly outperformed the PSO method in these two slot-antenna configurations.

**Index Terms**—Coplanar waveguide (CPW), optimization techniques, particle swarm optimization (PSO), slot antennas, Taguchi method.

## I. INTRODUCTION

PARTICLE swarm optimization (PSO) [1] is an evolutionary computational algorithm and has received great attention [2]. Recently, another novel global optimization technique, Taguchi's method [3], was introduced to the electromagnetic (EM) community [4], and successfully optimized some EM applications, such as linear array synthesis [5], ultra-wideband (UWB) antenna [6], and planar filter designs [7], which demonstrated its great potential on optimization and its advantages of solving complex problem ability, good convergence, and easy coding. In this study, a one-element coplanar-waveguide (CPW) slot antenna and a two-element series aperiodic CPW slot-antenna array [8] are optimized by Taguchi's method and PSO, where a full-wave simulator IE3D, based on the method of moments, is used to analyze the antennas and is integrated with the two optimization approaches. The design objectives are that the optimized one-element antenna has a single resonant frequency at 5 GHz while the two-element antenna has a dual-resonant frequency feature at 5 GHz and 6 GHz. Moreover, by optimizing the antenna under the same optimization conditions, the performance of the two optimization approaches can be compared with each other. The two slot antennas serve as the examples of a different degree of complexity for comparison. Optimization results show that the desired frequency responses of the antenna are successfully obtained by the two approaches. The result shows that the superior optimization performance of Taguchi's method makes it a viable alternative optimization scheme for EM applications.

This paper is organized as follows. In Section II, the concept of Taguchi's method and PSO is described. Section III discusses two designs of CPW slot antennas: a single-frequency antenna and a dual-frequency antenna, and each design using Taguchi's method and PSO are also described. Section IV demonstrates optimized results of each antenna designed by the proposed Taguchi's optimization approach including the optimization performance comparison between Taguchi's method and PSO.

## II. OPTIMIZATION APPROACH, TAGUCHI'S METHOD, AND PSO

### A. Taguchi's Method

Taguchi's method was developed based on the concept of orthogonal array (OA), which can effectively reduce the number of tests required in a design process [4]. Taguchi's method provides an efficient way to determine the optimal parameters in an optimization process. The notation  $OA(N, k, s, t)$  is used to represent  $N$  rows by  $k$  columns (for  $k$  parameters) OA with  $s$  levels and  $t$  strengths. OAs have important properties, such as fractional factorial characteristics, balanced and fair characteristics, and orthogonality. The main advantage of utilizing an OA to deal with a problem is that only  $N$  experiments are needed to find a better combination of the parameter values. However,  $s^k$  experiments are needed if one uses a full factorial strategy to deal with the same problem. Obviously, the number of experiments is dramatically reduced since  $s^k$  is much larger than  $N$ .

The procedure of iterative Taguchi's method starts with the problem initialization, including definitions of solution space, fitness function, and selecting a proper OA. If  $u$  parameters are to be optimized, the selected OA should be larger than or equal to  $u$ . Typically, a three-level OA with a strength of two is adopted in order to characterize nonlinear effects of a problem. If  $k > u$ , the rest of the columns are simply ignored without affecting the orthogonality of the OA since the columns in an OA are independent of one another.

After determining the corresponding values for the  $s$  levels of each input parameter,  $N$  experiments are conducted and their fitness values are calculated as well. The corresponding signal-to-noise ratio (SNR) ( $\eta$ ) of each fitness value can be obtained by the following equation [3]:

$$\eta = -20 \log (\text{Fitness}) \text{ (dB)}. \quad (1)$$

Therefore, a smaller fitness value results in a larger  $\eta$ . The entries of the response table can be determined by the following equation [4]:

$$\bar{\eta}(m, n) = \frac{s}{N} \sum_{i, OA(i, n)=m} \eta_i \quad (2)$$

where  $m$  is the  $m$ th level and  $n$  is the  $n$ th parameter. Hence,  $\bar{\eta}(m, n)$  is an average of  $\eta$  of the  $n$ th parameter for all level- $m$ . The optimal level values of each parameter can be identified by the corresponding level of the maximum  $\bar{\eta}$ . A confirmation test

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is performed by using the optimal level value of each parameter, and its fitness value is used to check with the design goal.

If the results of current iteration do not meet the design goal, the optimal level values are used as central values for the next iteration. To reduce the optimization searching range, the level difference (LD), which is an interval of two level values, is reduced by a reduced function, RR, and

$$LD_{i+1}(n) = RR \cdot LD_1(n) \quad (3)$$

where the subscript indicates the  $i$ th iteration.  $RR = 0.85^i$  is used in this study. The larger the value of RR is, the slower the convergence rate is.

The iterative optimization process would be repeated until the design goal is obtained or the fitness value is converged.

### B. Particle Swarm Optimization (PSO)

PSO has been shown to have excellent abilities in optimizing multidimensional, discontinuous, and multiobjective problems recently [2]. In PSO, the entire swarm is composed of  $N$  particles (agents), and each particle has  $k$ -dimensional parameters needed to be optimized. The optimization process starts with problem initialization, including definitions of solution space, fitness function, and positions  $x_i$  and velocities  $v_i$  of particles randomization. When a particle discovers the best solution of the entire swarm history, the corresponding best position is stored in a vector called  $G_{\text{best}}$ . When a particle discovers a solution, which is better than the one that has been found by itself, the corresponding position is stored in a vector called  $P_{\text{best}}$ . The velocity of a particle for next iteration is defined by the following equation:

$$v_{i+1} = w v_i + c_1 R_1 (P_{\text{best},i} - x_i) + c_2 R_2 (G_{\text{best},i} - x_i) \quad (4)$$

where  $w$  is the inertial weight which varies from 0.9 at the beginning to 0.4 at the end of optimization [9].  $R_1$  and  $R_2$  are different random values with a uniformly random range between 0.0 and 1.0. The best choice for  $c_1$  and  $c_2$  is 2.0 [10].  $V_{\text{max}}$  is the maximum velocity of a particle, and is set by the half optimization range of a parameter. The new position of a particle for the next iteration is determined by the following equation:

$$x_{i+1} = x_i + v_{i+1}. \quad (5)$$

The reflection wall boundary treatment [2] is used in PSO. The sign of a velocity is changed if a position  $x_{i+1}$  exceeds the solution space.

## III. DESIGN OF SLOT ANTENNAS

The geometries of the one-element CPW slot antenna and the two-element series aperiodic slot-antenna array are shown in Figs. 1 and 2, respectively. A CPW line, which is shorted at the end of the line, is adopted in both antenna designs. The characteristic impedance of the CPW line is  $50 \Omega$ . The corresponding width ( $W_f$ ) and the corresponding gap ( $g$ ) between the ground (GND) plane and the CPW line are fixed at 4.0 mm and 1.0 mm, respectively. The width of slot elements is fixed at 1.0 mm for the two slot antennas. The distance between the shorted end and the last slot element is  $D$ , which can be adjusted for impedance matching. The distance between the input port and the first slot element is 25.89 mm. Slot elements form magnetic dipoles excited by EM energy coming from an input

port and propagating in the CPW line. The sum of  $L$  and  $l$  is approximately a half guided-wavelength at the resonant frequency 5 GHz. Hence, slot elements are one guided-wavelength dipoles. Both slot antennas are designed on substrates with a thickness of 1.27 mm, a dielectric constant of 10.2, and a dielectric loss tangent of 0.002, according to the manufacturer specifications of Rogers RO 6010LM material.

Typically, antenna designers design antennas by using a trial-and-error approach or a parametric study approach. However, it may take a long time to achieve the design goal, and the final result may not be optimal. To reduce the design period and to accurately analyze the EM model of an antenna, an external optimizer, Taguchi's method, or PSO is integrated with a simulator IE3D to design the two slot antennas. During the optimization procedure, the output files are generated by IE3D, and they are evaluated by the optimizer. If the output results do not meet the design goals, the dimensions of a slot antenna are modified and the input files of IE3D are modified as well to obtain a better impedance matching for the next iteration step. Since the main parameters affecting the impedance matching are  $L_n, l_n, G_n, d_n$  ( $n = \text{null}$  for the one-element antenna, and  $n = 1$  to 2 for the two-element antenna), and  $D$ , those parameters are chosen to be optimized to obtain good impedance matching at the resonant frequency. The main advantage of this design procedure is that it is automatically executed by the optimizer and the simulator such that the design goals could be quickly obtained.

To save the number of unknowns in an IE3D simulation, the antennas are simulated by using the magnetic current modeling method, which assumes the proposed antennas have an infinite ground plane. This modeling also reduces the simulation time a lot without decreasing the accuracy of an EM problem.

Since the time required for running a 3-D full-wave EM simulation is much larger than that of an optimizer, the time used for running an optimizer could be ignored. In this study, the number of particles and the fitness function of PSO are set to the same as those of Taguchi's method. Therefore, the optimization performance of both optimizers could be compared to each other by the number of iterations of an optimizer that are required toward the design goal.

For each antenna case, five times optimizations are conducted by PSO, and the best fitness curve is chosen to compare with that of Taguchi's method for optimization performance comparison.

### A. One-Element CPW Slot Antenna

The geometry of the one-element slot antenna is shown in Fig. 1. The dimensions of the antenna are  $L = 9.07$  mm,  $l = 3.35$  mm [8],  $G = 0.4$  mm, and  $D = 11.22$  mm. The fitness function is very important for an optimizer to evaluate the output since it is only one interconnection between the optimizer and desired goals. Moreover, the number of simulations and the number of iterations may be significantly reduced if an appropriate fitness function is chosen. In this one-element antenna optimization, the fitness function is defined as

$$\text{Fitness} = \Gamma(f = 5.0 \text{ GHz}) \quad (6)$$

where  $\Gamma$  is the reflection coefficient at the input port. A smaller fitness function represents a better design. Both algorithms are configured as minimizers. The same fitness functions shown in

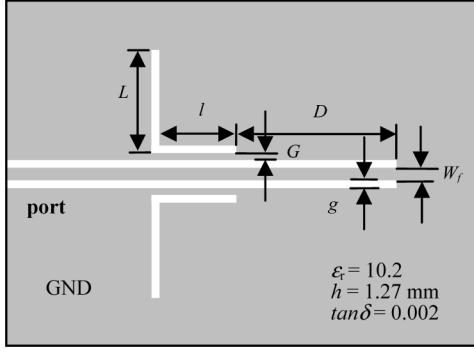


Fig. 1. Geometry of the one-element CPW slot antenna.

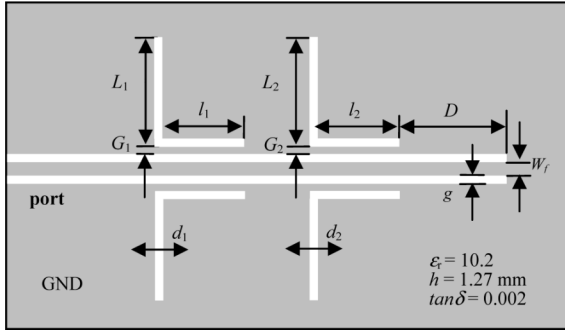


Fig. 2. Geometry of the two-element series aperiodic slot-antenna array.

(6) are used in Taguchi's method and PSO for fair comparison. During each iteration, the best fitness value is updated if a fitness value is better than the previous one. The design goal is taken as

$$|S_{11}| < -35 \text{ dB at } 5.0 \text{ GHz.} \quad (7)$$

Since there are four parameters  $L, l, G,$  and  $D$  to be optimized, an OA(9, 4, 3, 2) [11] which offers nine rows for nine simulations and four columns for four parameters is adopted in Taguchi's optimization. In PSO, nine particles (rows) and four parameters (columns) are also used for fair comparison. The solution space (unit: mm) is defined as

$$L \in (6.07, 12.07), l \in (2.35, 4.35), G \in (0.3, 0.6), \quad \text{and} \\ D \in (8.22, 18.22).$$

During optimization, the dimensions of the proposed antenna are modified to improve the impedance match at a resonant frequency of 5 GHz.

### B. Two-Element Series Aperiodic Slot-Antenna Array

The geometry of the two-element series aperiodic slot-antenna array is shown in Fig. 2. The dimensions  $L_n, l_n, G_n$  ( $n = 1$  to 2) and  $D$  of the antenna are the same as those of the one-element antenna. The initial interval between elements is 23 mm.  $d_1$  and  $d_2$  are offset values of the slot elements. If the offset value is positive, the slot element moves toward the right-hand side. The fitness function is defined as

$$\text{Fitness} = \Gamma(f = 5.0 \text{ GHz}) + \Gamma(f = 6.0 \text{ GHz}). \quad (8)$$

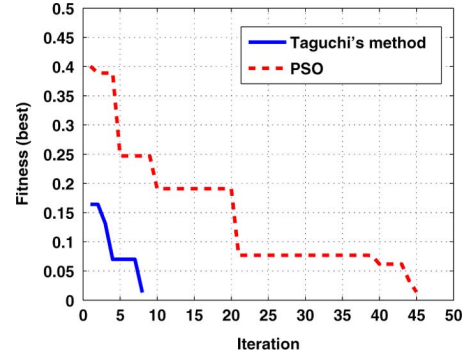


Fig. 3. Fitness curves of the two optimization approaches for the one-element CPW slot-antenna design.

TABLE I  
OPTIMIZED DIMENSIONS OF THE ONE-ELEMENT CPW SLOT ANTENNA

	(mm)			
Method	$L$	$l$	$G$	$D$
PSO	10.31	3.58	0.44	14.52
Taguchi's	10.57	3.30	0.55	14.08

The reflection coefficient  $\Gamma$  at each desired resonant frequency has equal priority in the fitness function, which can be seen as a dual-objective fitness function. The fitness function shown in (8) is used in Taguchi's method and PSO for fair comparison. The design goal is taken as

$$|S_{11}| < -35 \text{ dB at } 5.0 \text{ GHz and } 6.0 \text{ GHz.} \quad (9)$$

Since there are nine parameters  $L_n, l_n, G_n, d_n$  and  $D$ , to be optimized, an OA(27, 9, 3, 2) [11], which offers 27 rows for 27 simulations and nine columns for nine parameters, is adopted in Taguchi's optimization. In PSO, 27 particles (rows) and nine parameters (columns) are also used for fair comparison. The solution space (units in millimeters) is defined as

$$L_n \in (6.07, 12.07), l_n \in (2.35, 4.35) \\ G_n \in (0.3, 0.6), d_n \in (-4.0, 4.0)$$

and

$$D \in (8.22, 18.22).$$

During the optimization process, the dimensions of the proposed antenna are modified to improve the impedance match at resonant frequencies 5 GHz and 6 GHz.

## IV. OPTIMIZED RESULTS

In the case of the one-element slot-antenna optimization, only eight iterations are required to meet the design goal shown in (7) by using Taguchi's method as shown in the fitness curves in Fig. 3. However, 45 iterations are required by using PSO to meet the same design goal. The fitness curve of Taguchi's method decreases sharply, but the fitness curve of PSO is flat between 10 and 20 iterations and 22 to 39 iterations, which means that no optimization improvement is obtained during those iterations. The dimensions of the one-element slot antenna optimized by the two approaches are shown in Table I. The return losses of the optimized antenna by Taguchi's method and PSO are shown

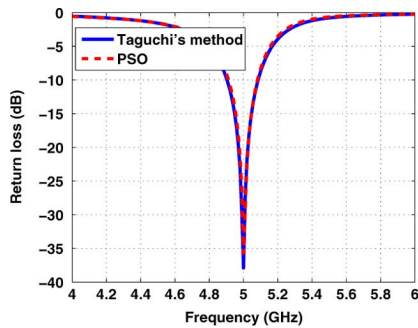


Fig. 4. Simulated return losses of the optimized one-element CPW slot antenna.

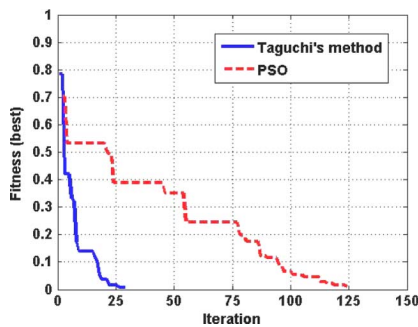


Fig. 5. Fitness curves of the two optimization approaches for the two-element aperiodic slot-antenna array design.

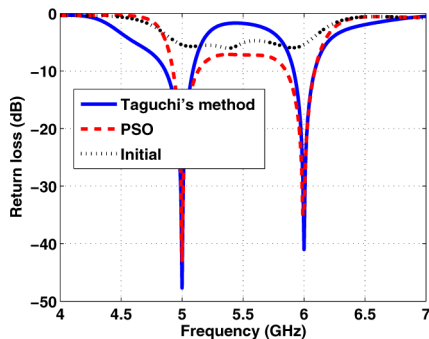


Fig. 6. Simulated return losses of the optimized two-element aperiodic slot-antenna array.

in Fig. 4. Both return losses show good impedance matching at 5 GHz.

In the case of the two-element series aperiodic slot-antenna array optimization, compared with the fitness curves shown in Fig. 5, only 29 iterations are required to meet the design goal shown in (9) by using Taguchi's method. However, 124 iterations are required by using PSO to meet the same design goal. The dimensions of the two-element antenna array optimized by the two approaches are shown in Table II. The return losses of the optimized antenna by Taguchi's method and PSO are shown in Fig. 6. Both return losses show good impedance matching at 5 GHz and 6 GHz. The frequency response of the prototype antenna is also shown in Fig. 6 for comparison. Note that the initial frequency response of the prototype antenna is quite poor before optimization.

TABLE II  
OPTIMIZED DIMENSIONS OF THE TWO-ELEMENT  
APERIODIC SLOT-ANTENNA ARRAY

	(mm)				
<b>Method</b>	$L_1$	$l_1$	$G_1$	$d_1$	$D$
<b>PSO</b>	10.52	2.40	0.39	1.28	12.31
<b>Taguchi's</b>	10.83	2.96	0.44	-1.74	15.01
	$L_2$	$l_2$	$G_2$	$d_2$	
<b>PSO</b>	8.43	3.00	0.51	0.50	
<b>Taguchi's</b>	8.11	3.34	0.30	3.76	

The number of iteration reductions for optimizing a one-element antenna and two-element antenna by Taguchi's method and PSO are around 82% and 76%, respectively, which show that Taguchi's method is quicker than PSO to achieve the same optimization goal in the two antenna cases.

## V. CONCLUSION

Taguchi's method was used in conjunction with a full-wave EM solver to design a one-element CPW slot antenna and a two-element series aperiodic slot-antenna array. Taguchi's method was compared with PSO and was found to be more efficient in the two slot-antenna examples. Taguchi's method converges at a significantly faster rate than the PSO.

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