

Figure 4 Transmission of resonant cavity for PANI, PTFE, and empty cavity

sample volume should be reduced until the results fall into the linear regime.

A plot of the transmission as a function of frequency is shown in Figure 4, where three different situations are included: empty cavity, cavity with PTFE, and cavity with PANI.

The complex permittivity for PANI was then calculated from the analysis of these results using Eqs. (5) and (6). We obtained the values of 3.3 and  $0.8 \times 10^{-1}$  for real and imaginary parts of the complex permittivity, respectively. These values are consistent with that reported by other authors [20].

Finally, for water we determined  $\varepsilon' = (82 \pm 2)$  and  $\varepsilon'' = (39.2 \pm 0.6)$ . These values are in good agreement with a previous report [21].

# 4. CONCLUSIONS

In summary, we designed a cavity resonator for a TE<sub>1,0,11</sub> mode operating at 5 GHz for measurements of complex permittivity of high loss samples. The cavity was calibrated with distilled water. It was verified that the absorption characteristics remain in the linear regime for the distilled water volumes up to 27  $\mu$ l, corresponding to relative frequency shifts,  $\Delta f f_0$ , up to 0.56% and inverse quality factor shifts,  $\Delta (1/Q)$ , up to 4.2  $\times 10^{-3}$ .

The results for water and for a compressed PANI disc sample confirm the performance of our cavity.

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# IMPROVING THE RADIATION CHARACTERISTICS OF A BASE STATION ANTENNA ARRAY USING A PARTICLE SWARM OPTIMIZER

#### Z. D. Zaharis,<sup>1</sup> D. G. Kampitaki,<sup>1</sup> P. I. Lazaridis,<sup>1,2</sup> A. I. Papastergiou,<sup>1</sup> A. T. Hatzigaidas,<sup>1</sup> and P. B. Gallion<sup>2</sup>

<sup>1</sup> Department of Electronics, Alexander Technological Educational Institute of Thessaloniki, 57400 Thessaloniki, Greece

<sup>2</sup> Département Communications et Electronique, Unité de Recherche Associée au Centre National de la Recherche Scientifique, 820 Ecole Nationale Supérieure des Télécommunications, 46 rue Barrault, 75634 Paris Cedex 13, France

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**ABSTRACT:** A particle swarm optimization based technique is applied on linear antenna arrays used by broadcasting base stations. Both the geometry and the excitation of the antenna array are optimized by a suitable algorithm under the constraints of the maximum possible gain at the desired direction and the desired value of side lobe level. The matching condition of the elements of the antenna array is also required by the algorithm. The technique has been applied to antenna arrays composed of collinear wire dipoles and seems to be very promising for improving radiation patterns of base station antenna arrays in many practical applications. © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1690–1698, 2007; Published online in Wiley Inter-Science (www.interscience.wiley.com). DOI 10.1002/mop.22505

**Key words:** *antenna arrays; antenna radiation patterns; base station antennas; optimization methods; particle swarm optimization* 

# 1. INTRODUCTION

Many techniques have been suggested for the design of antenna arrays in order to produce radiation patterns that satisfy specific demands [1-5]. In many practical applications and especially when the antenna array is going to be used by broadcasting base stations, the radiation pattern is required to satisfy two basic conditions: First, the side lobe level (SLL) must be as low as possible, and second the main lobe of the pattern has to provide the maximum possible radiated power gain  $G(\theta_o)$  at the desired direction determined in the spherical coordinate system by the elevation angle  $\theta_o$ . We may refer to the above two conditions, respectively, as "condition of low SLL" and "condition of maximum gain". Usually, the condition of low SLL is considered to be satisfied when the SLL is equal to or less than a desired value SLL<sub>d</sub> (e.g., SLL<sub>d</sub> = -20 dB) depending on the specific application of the antenna array.

In addition, each element of the antenna array must satisfy the "impedance-matching condition", meaning that the input impedance  $Z_{in,m}$  of each (*m*-th) element has to be as close as possible to the characteristic impedance  $Z_o$  of the transmission line that feeds the element. One of the factors used to evaluate the impedance-matching condition is the standing wave ratio (SWR). According to transmission line theory [6, 7], the SWR at the input of the *m*-th element is derived by the expression

$$S_{\rm m} = \frac{1 + |R_{\rm m}|}{1 - |R_{\rm m}|}.$$
 (1)

 $R_{\rm m}$  is the amplitude of the complex reflection coefficient  $R_{\rm m}$ , which is calculated at the input of the *m*-th element according to the expression

$$R_{\rm m} = \frac{Z_{{\rm in},m} - Z_{\rm o}}{Z_{{\rm in},m} + Z_{\rm o}}.$$
 (2)

The optimum value of the SWR is 1 and is obtained when  $Z_{in,m} = Z_o$ , but this hardly ever happens. Thus, the impedance-matching condition is considered to be satisfied when the SWR is less than 2 (SWR < 2).

Many methods have been proposed in order to satisfy the crucial condition of low SLL. One of them is the popular method of Dolph that suggests a Chebyshev excitation amplitude distribution on the array elements [8, 9]. However, such methods become inefficient if the condition of maximum gain and the impedancematching condition are additionally taken into account for the design of the antenna array. In general, all the above conditions can be satisfied by choosing a suitable geometry of the antenna array elements. Actually, the geometry concerns the lengths of the elements and the interelement distances, while the excitation concerns the amplitude and phase of the currents applied on the elements by an appropriate feeding network.

To find the appropriate geometry and the appropriate excitation of the antenna array that satisfy the above three conditions, the present work introduces an alternative technique that uses a Particle Swarm Optimization (PSO) algorithm [10-38] developed by the authors. The objective of the algorithm is to maximize a specific mathematical expression called "fitness function" and defined according to the above three conditions. When these conditions are satisfied, the fitness function finds its global maximum value and the optimizer terminates with success. The technique has been applied to antenna arrays composed of collinear wire dipoles. In order to estimate the fitness function, the PSO algorithm needs to know the gain at the desired direction and the SLL of the radiation pattern of the antenna array as well as the SWRs at the inputs of the array elements. The values of the above parameters are derived by applying the Method of Moments [39, 40] on the wire-grid model of the antenna array. The cases studied in this work show that the technique is very effective, because it has the ability not only to improve the radiation pattern under specific requirements but also to match the elements of the antenna array to the feeding network.

# 2. PARTICLE SWARM OPTIMIZATION

PSO is an evolutionary computation method based and inspired by social behavior of swarms. So far, PSO based techniques have been applied in many areas such as function optimization, fuzzy system control and neural network training [10-38]. PSO has many similarities with other evolutionary computation methods such as genetic algorithms. However, it has no evolution operators like mutation and crossover.

In fact, PSO simulates the behavior of bird flocking or fish schooling. An illustrative example that shows this behavior is a group of birds that make random movements with random velocities searching for food in an area. Each bird has the ability to remember the location where it found the most food. Besides, all the birds have the ability to exchange information with each other and thus learn the location with the most food found so far in the search area. So, each bird adjusts its position taking into account the best position encountered by itself and the best position encountered by its neighbors. In this way, the birds are finally gathered around the position with the most food in the entire search area. The modeling of this behavior results in the PSO method.

The description of the PSO method requires the use of specific terminology. The swarm consists of S individuals which are called "particles" (like the birds in the above example). The number S of the particles is called "swarm size". The efficiency of the method seems to increase in many cases if the value of S is chosen between 10 and 50. All the particles are considered as points in a *D*-dimensional space. Thus, the position of the *i*-th particle (i = 1, ..., S) is expressed as  $X_i = [x_{il}, ..., x_{id}, ..., x_{iD}]$ . Each position coordinate  $x_{id}$  (d = 1, ..., D) varies between a lower and an upper boundary, respectively  $l_d$  and  $u_d$  ( $l_d \le x_{id} \le u_d$ ). The boundaries are usually defined by the user. The difference  $u_d - l_d$  is called "actual range" of the *d*-th dimension.

Each particle is evaluated by the fitness function mentioned above and is assigned a fitness value depending on the position of the particle, i.e.,  $F = F(X_i)$ . As the fitness function increases, the particle position gets better. The best position found up to the current (*n*-th) time step is called "pbest position" and is recorded for every particle. The pbest position of the *i*-th particle is expressed as  $P_i = [p_{il}, \ldots, p_{id}, \ldots, p_{iD}]$ .

All the particles move in the search space and update their positions. After a time interval  $\Delta t$ , the position of the *i*-th particle will change by  $\Delta X_i = V_i \Delta t$ , where  $V_i = [v_{il}, \ldots, v_{id}, \ldots, v_{iD}]$  is the velocity of the particle and  $v_{id}$  ( $d = 1, \ldots, D$ ) are the corresponding velocity coordinates. Considering a time interval of unit length, the position change becomes  $\Delta X_i = V_i$ . Thus, the position of the particle at the next time step is calculated by the expression:

$$X_i(n+1) = X_i(n) + V_i(n+1).$$
 (3)

It is obvious that the particles must update their velocity at every time step by adopting the swarm behavior mentioned above. Therefore, the velocity of each particle is updated by taking into account the best position already found by the particle (pbest position) and the best position already found by its neighbors. Two models have been used for the velocity update, the "gbest" and the "lbest" model. According to the gbest model, each individual is attracted to the best position found by any particle of the swarm. This position is the gbest position  $G = [g_1, \ldots, g_d, \ldots, g_D]$  and corresponds to the maximum fitness value  $F_{\text{max}} = F(G)$  found by the swarm up to the current time step. According to the lbest model, each *i*-th individual is attracted to the best position found by its  $K_i$  neighbors. This position is the lbest position  $L_i$ =  $[\ell_{il}, \ldots, \ell_{id}, \ldots, \ell_{iD}]$  and corresponds to the maximum fitness value  $F_{\max,i} = F(L_i)$  found by the  $K_i$  neighbors up to the current time step. The research on the performance of the two models has shown that using the gbest model the swarm tends to converge faster on optima, but it is more susceptible to convergence on local optima. Thus, the present work adopts the lbest model.

According to the gbest model, the velocity of the *i*-th particle is updated by the expression

$$V_{i}(n + 1) = wV_{i}(n) + c_{1} \operatorname{RAND}(n) [P_{i}(n) - X_{i}(n)] + c_{2} \operatorname{RAND}(n) [G(n) - X_{i}(n)], \quad (4)$$

where w is a positive parameter called "inertia weight", and  $c_1$ ,  $c_2$  are positive parameters called respectively "cognitive coefficient" and "social coefficient". The function RAND(n) generates random numbers from a uniform distribution over (0, 1). According to the lbest model, the only change is to substitute  $L_i$  for G in Eq. (4). Thus, the velocity of the *i*-th particle is updated by the expression

$$V_{i}(n + 1) = wV_{i}(n) + c_{1} \operatorname{RAND}(n) [P_{i}(n) - X_{i}(n)] + c_{2} \operatorname{RAND}(n) [L_{i}(n) - X_{i}(n)].$$
(5)

The inertia weight w represents the impact of the previous value of velocity and has fixed values between 0.0 and 1.0. The same inertia value is used for all dimensions of all particles in a given swarm. Values of inertia close to 1.0 help global exploration, while values close to 0.0 help local exploration to fine-tune the current search area. Suitable choices for the values of w provide balance between global and local exploration abilities and thus require fewer iterations to find the optimum [12]. An alternative approach is to decrease the inertia weight linearly from 0.9 to 0.4 during the optimization procedure [14]. The cognitive coefficient  $c_1$  defines how much each particle is attracted to its pbest position, while the social coefficient  $c_2$  determines how much each particle is influenced by the swarm (for gbest model) or by its neighbors (for lbest model). A good choice for both  $c_1$  and  $c_2$  is 2.0, as suggested in [16].

An alternative way of the velocity update has been recently suggested in [18]. According to the gbest model, the velocity of the *i*-th particle after a time step is calculated by

$$V_{i}(n + 1) = k\{V_{i}(n) + \varphi_{1} \operatorname{RAND}(n) [P_{i}(n) - X_{i}(n)] + \varphi_{2} \operatorname{RAND}(n) [G(n) - X_{i}(n)]\}, \quad (6)$$

while, according to the lbest model, the velocity is given by

$$V_{i}(n + 1) = k\{V_{i}(n) + \varphi_{1} \text{ RAND}(n) [P_{i}(n) - X_{i}(n)] + \varphi_{2} \text{ RAND}(n) [L_{i}(n) - X_{i}(n)]\}.$$
(7)

The parameter k, called "constriction coefficient", is defined by the expression:

$$k = \frac{2}{2 - \varphi - \sqrt{\varphi^2 - 4\varphi}},\tag{8}$$

where the parameter  $\varphi$ , sometimes called "acceleration constant", must be greater than 4 ( $\varphi > 4$ ) and is calculated by the expression:

$$\varphi = \varphi_1 + \varphi_2. \tag{9}$$

The parameters  $\varphi_1$  and  $\varphi_2$  have the same meaning as  $c_1$  and  $c_2$ , respectively. A standard choice for both  $\varphi_1$  and  $\varphi_2$  is 2.05, as recommended in [16].

An undesirable effect is that the particle's trajectory usually expands into wider cycles and eventually approaches infinity. An efficient method of solving the problem is to define a maximum allowed velocity  $V_{\max} = [v_{\max,l}, \ldots, v_{\max,d}, \ldots, v_{\max,D}]$ . Thus, for each (*i*-th) particle and each (*d*-th) dimension, if  $v_{id} > v_{\max,d}$  then  $v_{id} = v_{\max,d}$ , and also if  $v_{id} < -v_{\max,d}$  then  $v_{id} = -v_{\max,d}$ . In fact,  $V_{\text{max}}$  prevents the particle from escaping its orbit, without affecting the convergence process. The proper value of  $V_{\rm max}$ depends on the problem. It is recommended in [16] that if w = 1in Eqs. (4) and (5) it is better to set each coordinate  $v_{max,d}$  around 10–20% of the actual range  $u_d - l_d$  of the respective dimension and if w < 1 it is better to set  $v_{\max,d} = u_d - l_d$ . It must be mentioned that the use of the constriction coefficient k in Eqs. (6) and (7) was an attempt to eliminate the need for  $V_{\text{max}}$ , but most authors agree that it is still better to use  $V_{\text{max}}$  in order to keep the particles in bounds.

Nevertheless, the above parameters  $(w, k, V_{max})$  are not always able to keep the particles within the search space. To overcome this problem, three basic boundary conditions have been suggested: (i) The absorbing walls: According to this condition, when a particle hits any of the boundaries of the search space in one of the Ddimensions, the velocity component in this dimension vanishes and the particle stops at the boundary. Therefore, the boundary walls are considered to absorb the energy of the particles that try to escape the search space. The above condition is adopted by the present work. (ii) The reflecting walls: When a particle hits any of the boundaries of the search space in one of the D dimensions, the velocity component in this dimension is reversed and the particle is reflected back toward the search space. (iii) Invisible walls: According to this condition, the particles are allowed to fly over the boundaries of the search space without any restriction. The fitness function is not evaluated for the particles being outside the search space. These particles are simply assigned a very bad fitness value. Therefore, the optimization procedure saves computational time because the fitness function is calculated only for the particles inside the search space.

# 3. FORMULATION

The theory described above can be utilized to create optimizers for many problems. In the present work, this theory is used to optimize antenna arrays composed of collinear wire dipoles. The antenna arrays are considered to be used by broadcasting base stations. Thus, the radiation patterns produced by these arrays are required to satisfy the condition of low SLL and the condition of maximum gain. In addition, every array element (i.e., every wire dipole) must satisfy the impedance-matching condition. In order to optimize the antenna arrays according to the above three conditions, a PSO based algorithm has been developed by the authors. The lengths of the dipoles and the inter-element distances as well as the amplitudes and phases of the excitation currents applied on the dipoles are considered as the position coordinates  $x_{id}$  (d = 1, ..., D) of the particles. Given the values of  $x_{id}$ , a respective value  $F(X_i) = F(x_{il}, ..., x_{id}, ..., x_{iD})$  of the fitness function is extracted for the position  $X_i$  of the *i*-th particle. The goal of the algorithm is to find the gbest coordinates  $g_d$  that correspond to the maximum value  $F_{\text{max}} = F(g_1, ..., g_d, ..., g_D)$  of the fitness function. The  $g_d$  coordinates are actually the lengths of the dipoles and the inter-element distances as well as the amplitudes and phases of the excitation currents that produce the optimal antenna array design according to the above three conditions.

A swarm size of 20 particles (S = 20) is used in the algorithm. The velocity of the particles is derived by Eq. (7) according to the lbest model. Each particle is considered to be affected by three neighbors ( $K_i = 3$ , for i = 1, ..., S). The parameters  $\varphi_1$  and  $\varphi_2$  are chosen equal to 2.05, and therefore the acceleration constant  $\varphi$ resulting from Eq. (9) is equal to 4.10. The constriction coefficient results from Eq. (8), and its value (k = 0.73) as well as the values of  $\varphi_1$  and  $\varphi_2$  are used in Eq. (7). In order to prevent the swarm from explosion, the algorithm makes use of the maximum allowed velocity  $V_{\text{max}}$ . Each coordinate of  $V_{\text{max}}$  is set equal to 10% of the actual range of the respective dimension, i.e.,  $v_{\text{max},d} = 0.10(u_d - l_d)$ . Finally, the absorbing walls condition is used in the algorithm to confine the particles in the search space.

The structure of the PSO algorithm is described by the following steps:

- 1. Initialization:
- 1.1. Initialize counters *n* (to count time steps), *d* (to count dimensions), and *i* (to count particles).
- 1.2. Set the values of *S*, *D*,  $K_i$ ,  $\varphi_1$ ,  $\varphi_2$ , and *N* (maximum number of time steps).
- 1.3. Set the boundaries  $l_d$  and  $u_d$ , as well as the percentage of  $v_{\max,d}$  with respect to the actual range for every dimension  $d = 1, \ldots, D$ .
- 1.4. Initialize randomly the particle positions  $X_i$  (i = 1, ..., S) inside the search space, so that  $l_d \le x_{id} \le u_d$  (d = 1, ..., D).
- 1.5. Initialize randomly the particle velocities  $V_i$  (i = 1, ..., S), so that  $-v_{\max,d} \le v_{id} \le v_{\max,d}$  (d = 1, ..., D).
- 1.6. Evaluate the fitness function  $F(X_i)$  (i = 1, ..., S) for all the particles.
- 1.7. Set  $P_i = X_i$  and  $F(P_i) = F(X_i)$  for i = 1, ..., S (the first position of each particle is considered as pbest position).
- 1.8. Find the maximum fitness value  $F_{\text{max}}$  among the  $F(P_i)$  (i = 1, ..., S). The value  $F_{\text{max}}$  corresponds to the gbest position G, so that  $F_{\text{max}} = F(G)$ .
- 2. Optimization procedure:
- 2.1. Select randomly  $K_i$  neighbors for each *i*-th particle.
- 2.2. Find the individual that gives the maximum fitness value  $F_{\max,i}$  among the  $K_i$  neighbors of each *i*-th particle. The value  $F_{\max,i}$  corresponds to the lbest position  $L_i$  in the neighborhood of the *i*-th particle, so that  $F_{\max,i} = F(L_i)$ .
- 2.3. Update the particle velocities  $V_i$  (i = 1, ..., S) using Eq. (7).
- 2.4. Correct the velocity coordinates by taking into account the maximum allowed velocity, i.e., if  $v_{id} > v_{\max,d}$  then  $v_{id} = v_{\max,d}$ , and also if  $v_{id} < -v_{\max,d}$  then  $v_{id} = -v_{\max,d}$ .
- 2.5. Update the particle positions  $X_i$  (i = 1, ..., S) using Eq. (3).
- 2.6. Apply the absorbing walls condition in order to keep the particles within the search space, i.e., if  $x_{id} < l_d$  then  $x_{id}$

 $= l_d$  and  $v_{id} = 0$ , and also if  $x_{id} > u_d$  then  $x_{id} = u_d$  and  $v_{id} = 0$ .

- 2.7. Evaluate the fitness function  $F(X_i)$  (i = 1, ..., S) for all the particles.
- 2.8. For i = 1, ..., S, if  $F(X_i) > F(P_i)$  then  $P_i = X_i$  (the new position becomes position of the *i*-th particle).
- 2.9. For i = 1, ..., S, if  $F(P_i) > F(G)$  then  $G = P_i$  (the pbest position with the maximum fitness value in the swarm becomes gbest position).
- 2.10. Increase the counter n by 1.
- 2.11. If n < N and F(G) has been increased then repeat the procedure from step 2.2. If n < N and F(G) has not been increased then repeat the procedure from step 2.1 (i.e., the  $K_i$  neighbors must be reinitialized for each particle).
- 3. Report results and terminate, when the predefined maximum number N of time steps is reached.

The PSO algorithm was applied on the collinear antenna array of Figure 1. The array consists of M vertical-oriented wire dipoles. All the dipoles have the same length  $h_{\rm m}$  and the same radius of  $0.001\lambda$ , where  $\lambda$  is the wavelength. The excitation is applied in the middle of the length of the dipoles by an appropriate feeding network. The above described structure produces omni-directional radiation pattern on the horizontal plane and thus the antenna array can be used by broadcasting base stations located at the center of their service area. The radiation pattern on the vertical plane depends on the geometry of the array as well as on the excitation currents applied on the dipoles. The geometry of the array is determined by the lengths  $h_m$  (m = 1, ..., M) of the dipoles and the inter-element distances  $z_{m,m-1}$  ( $m = 2, \ldots, M$ ), where  $z_{m,m-1}$ denotes the distance between the *m*-th and the (m-1)-th dipole. The excitation currents are considered to have complex values. Therefore, each current is specified by its amplitude  $a_m$  and its phase  $q_m$ .

Given the values of  $h_m$ ,  $z_{m,m-1}$ ,  $a_m$ , and  $q_m$ , the antenna array is modeled as a wire grid and is analyzed by applying the Method of Moments (MoM) [39, 40]. The results derived from the MoM are the antenna array gain  $G(\theta_o)$  at the desired direction  $\theta_o$ , the SLL of the far-field radiation pattern and the input impedances  $Z_{in,m}$  (m = 1, ..., M) of the dipoles. In order to estimate the fitness function, the PSO algorithm needs the values of  $G(\theta_o)$  and SLL in deciBel (dB), extracted respectively by the expressions

$$G^{\rm dB}(\theta_o) = 10 \log[G(\theta_o)], \tag{10}$$

$$\dot{S}LL^{dB} = 10 \log(SLL), \tag{11}$$

as well as the values  $S_m$  (m = 1, ..., M) of the SWRs at the respective feeding points of the dipoles. From the values of  $Z_{in,m}$  derived by the MoM it is easy to calculate the SWRs by using Eqs. (1) and (2), where  $Z_0$  is considered equal to 50 Ohm.

The optimal antenna array must satisfy the three above-mentioned conditions concerning maximum gain, low SLL and impedance matching. Therefore, the fitness function must be formed as a weighted sum of three respective terms, as given by the following equation:

$$F = W_1 F_1 + W_2 F_2 + W_3 F_3. \tag{12}$$

The first term  $F_1$  corresponds to the condition of maximum gain and is simply described by the antenna array gain  $G^{dB}(\theta_o)$  in dB at the desired direction  $\theta_o$ , as given below:



Figure 1 Collinear wire-dipole antenna array

$$F_1 = G^{\rm dB}(\theta_o). \tag{13}$$

It is obvious that  $F_1$  always has positive values, which have to be as high as possible in order to satisfy the condition of maximum gain. The second term  $F_2$  corresponds to the condition of low SLL and is described by the expression

$$F_2 = A - \mathrm{SLL}_\mathrm{d}^\mathrm{dB},\tag{14}$$

where

TABLE 1 Structure Characteristics of an Optimized Collinear Antenna Array, Composed of 10 Wire Dipoles and Excited by Uniform Current Distribution, With Main Lobe Direction at  $\theta_{o} = 90^{\circ}$ 

т	$h_m\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.482		1.000	0.0	1.38
2	0.482	0.946	1.000	0.0	1.35
3	0.482	0.795	1.000	0.0	1.62
4	0.482	0.633	1.000	0.0	2.00
5	0.482	0.581	1.000	0.0	1.97
6	0.482	0.605	1.000	0.0	1.97
7	0.482	0.581	1.000	0.0	1.98
8	0.482	0.640	1.000	0.0	1.62
9	0.482	0.778	1.000	0.0	1.37
10	0.482	0.958	1.000	0.0	1.39
$G^{\rm dB}(\theta_{\rm o}) = 11.50$		$SLL^{dB} = -$	-20.27	$S_{\rm av} = 1$	.67

$$A = \begin{cases} \text{SLL}^{dB}, & \text{if SLL}^{dB} > \text{SLL}^{dB}_{d} \\ \text{SLL}^{dB}_{d}, & \text{if SLL}^{dB} \le \text{SLL}^{dB}_{d}, \end{cases}$$
(15)

and SLL<sub>d</sub><sup>dB</sup> is the desired value of SLL in dB. The meaning of Eq. (15) is that only values of SLL<sup>dB</sup> greater than SLL<sub>d</sub><sup>dB</sup> have influence on the value of  $F_2$ . Values of SLL<sup>dB</sup> equal to or less than SLL<sub>d</sub><sup>dB</sup> may not affect the value of  $F_2$ , because they satisfy the condition of low SLL. In general,  $F_2$  has positive values and vanishes only when the condition of low SLL is satisfied. The third term  $F_3$ corresponds to the impedance-matching condition and is described by the following formula:

$$F_{3} = \sum_{m=1}^{M} (S_{m} - 1) + \sum_{m=1}^{M} B_{m},$$
(16)

where

$$B_m = \begin{cases} 0, & \text{if } S_m \le 2\\ 10^6, & \text{if } S_m > 2 \end{cases}$$
(17)

As shown in Eq. (16),  $F_3$  consists of two summation terms. The first one is a convergence term that aims at making the SWRs approach their optimum value, which is equal to 1. The second summation term is a penalty term that makes the SWRs avoid values greater than 2. This is achieved by adding a large penalty value to  $F_3$ , e.g.  $10^6$ , for every value  $S_m$  greater than 2, as shown in Eq. (17). In fact, the second summation term is more effective than the first one in satisfying the impedance-matching condition.

TABLE 2 Structure Characteristics of an Optimized Collinear Antenna Array, Composed of 10 Wire Dipoles and Excited by Uniform Current Distribution, With Main Lobe Direction at  $\theta_0 = 100^{\circ}$ 

••• •••					
m	$h_m\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.479		1.000	0.0	1.43
2	0.479	0.847	1.000	34.6	1.47
3	0.479	0.706	1.000	95.1	1.52
4	0.479	0.645	1.000	128.9	1.82
5	0.479	0.562	1.000	167.1	2.00
6	0.479	0.557	1.000	-154.0	2.00
7	0.479	0.553	1.000	-124.7	2.01
8	0.479	0.575	1.000	-73.2	1.72
9	0.479	0.772	1.000	-49.6	1.55
10	0.479	0.753	1.000	35.4	1.25
$G^{\rm dB}(\theta_{\rm o}) = 11.07$		$SLL^{dB} = -$	-19.22	$S_{\rm av} = 1$	1.68



**Figure 2** Radiation patterns of two optimized collinear antenna arrays, composed of 10 wire dipoles and excited by uniform current distribution, with main lobe direction respectively at (a)  $\theta_o = 90^\circ$  and (b)  $\theta_o = 100^\circ$ 

The first summation term plays only an auxiliary role, because the SWRs are not always going to converge to their optimum value. In general,  $F_3$  has positive values and vanishes only when all the  $S_m$  (m = 1, ..., M) are equal to 1. The coefficients  $W_1$ ,  $W_2$ , and  $W_3$  are weight factors and they declare the importance of the corresponding terms that compose the fitness function. Provided that  $W_1 > 0$ ,  $W_2 < 0$ , and  $W_3 < 0$ , the fitness function increases as the three above-mentioned conditions tend to be satisfied. Finally, when the fitness function finds its global maximum value, all the requirements are satisfied and the PSO algorithm terminates with success.

#### 4. RESULTS

Several examples are presented in order not only to raise the robustness of the proposed technique but also to derive some optimized structures that can be used in practical applications. In each example, the antenna array is optimized for two different main lobe directions, respectively at  $\theta_o = 90^\circ$  (broadside case) and  $\theta_o = 100^\circ$ . The results extracted from the optimization procedure are summarized in a table, while the radiation pattern on the vertical plane is shown in a corresponding diagram. In particular, each table shows the lengths of the dipoles, the inter-element distances, the amplitude and the phase of the excitation currents, and finally the SWRs at the feeding points of the dipoles. It must

TABLE 3Structure Characteristics of an Optimized CollinearAntenna Array, Composed of 10 Wire Dipoles, With DesiredSLL Equal to -20 dB and Main Lobe Direction at  $\theta_o = 90^\circ$ 

m	$h_m\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.481		1.000	0.0	1.18
2	0.481	0.981	1.660	0.0	1.15
3	0.481	0.981	3.181	0.0	1.24
4	0.481	0.933	3.989	0.0	1.24
5	0.481	0.944	4.035	0.0	1.22
6	0.481	0.955	4.084	0.0	1.22
7	0.481	0.939	3.947	0.0	1.24
8	0.481	0.940	3.020	0.0	1.23
9	0.481	0.978	1.654	0.0	1.16
10	0.481	0.981	0.994	0.0	1.19
$G^{\rm dB}(\theta_{\rm o}) = 11.96$	SLL <sup>dB</sup>	= -20.00	$S_{\rm av}$	= 1.21	

TABLE 4 Structure Characteristics of an Optimized Collinear Antenna Array, Composed of 10 Wire Dipoles, With Desired SLL Equal to -20 dB and Main Lobe Direction at  $\theta_0 = 100^{\circ}$ 

т	$h_m\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.482		1.000	0.0	1.47
2	0.482	0.809	1.036	19.8	1.28
3	0.482	0.852	0.684	-6.5	1.00
4	0.482	0.577	1.029	171.0	1.37
5	0.482	0.833	1.870	-132.3	1.39
6	0.482	0.807	2.365	-112.0	1.47
7	0.482	0.803	2.183	-56.7	1.35
8	0.482	0.818	1.908	-12.7	1.35
9	0.482	0.802	1.246	49.0	1.18
10	0.482	0.871	0.513	89.1	1.01
$G^{\rm dB}(\theta_{\rm o}) = 10.31$		$SLL^{dB} = -$	-20.00	$S_{\rm av} = 1$	.29

be noted that the 1st dipole, located at the position z = 0, is considered as reference dipole. Thus, the excitation amplitude and the excitation phase of the rest dipoles are presented in the tables, respectively, with reference to the excitation amplitude and the excitation phase of the first dipole  $(a_1 = 1, q_1 = 0)$ . It is obvious that in the broadside case, the excitation phases are not subject to optimization because the dipoles of broadside arrays are always in phase and thus  $q_m = 0$  ( $m = 1, \ldots, M$ ). Also, each table shows the values of  $G^{dB}(\theta_0)$  and SLL<sup>dB</sup> of the optimized antenna array as well as the average value  $S_{av}$  of the SWRs of the array elements. Finally, the radiation patterns are normalized with reference to the value of  $G^{dB}(\theta_0)$ .

The first example is an effort to optimize a collinear antenna array composed of 10 wire dipoles and excited by uniform current distribution, meaning that the excitation currents applied on the dipoles have the same amplitude. The practical advantage of this type of excitation is that the feeding network is very simple and easily implemented in practice. On the contrary, the feeding networks needed for nonuniform excitation distributions are usually complex and quite inefficient. Nevertheless, an important question is how much low SLL can be achieved by using uniform current distribution, provided that the optimized antenna array must satisfy the condition of maximum gain and the impedance-matching condition as well. Thus, the desired value of SLL is set equal to -40



**Figure 3** Radiation patterns of two optimized collinear antenna arrays, composed of 10 wire dipoles, with desired SLL equal to -20 dB and main lobe direction respectively at (a)  $\theta_0 = 90^\circ$  and (b)  $\theta_0 = 100^\circ$ 

TABLE 5Structure Characteristics of an Optimized CollinearAntenna Array, Composed of 10 Wire Dipoles, With DesiredSLL Equal to -40 dB and Main Lobe Direction at  $\theta_0 = 90^\circ$ 

m	$h_{m}\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.484		1.000	0.0	1.34
2	0.484	0.908	2.440	0.0	1.37
3	0.484	0.861	4.303	0.0	1.37
4	0.484	0.851	6.025	0.0	1.38
5	0.484	0.846	6.915	0.0	1.38
6	0.484	0.848	6.590	0.0	1.38
7	0.484	0.851	5.425	0.0	1.38
8	0.484	0.852	3.788	0.0	1.38
9	0.484	0.858	2.109	0.0	1.38
10	0.484	0.877	0.930	0.0	1.39
$G^{\rm dB}(\theta_{\rm o}) = 11.21$		$SLL^{dB} = -$	-40.00	$S_{\rm av} = 1$	.37

dB and the optimization procedure is applied on the antenna array, considering that  $a_m = 1$  (m = 1, ..., M). Two cases are studied concerning the two main lobe directions,  $\theta_o = 90^\circ$  and  $\theta_o = 100^\circ$ , mentioned above. The results of the two cases are given, respectively, in Tables 1 and 2, while the corresponding radiation patterns are presented in Figure 2. It is obvious that the uniform excitation cannot help the antenna array to achieve very low SLL. The best value of SLL achieved by uniform excitation distribution is necessary if the desired SLL has to be less than -20 dB.

The next example is an effort to optimize the same 10 wiredipole array, considering nonuniform current distribution. It is interesting to make a comparison between uniform and nonuniform excitation regarding the impedance-matching condition and to see if better values of SWR are achieved by using nonuniform excitation. In order to have a fair comparison, the SLL that is going to be achieved in the case of nonuniform excitation must not exceed the respective value of SLL obtained from uniform excitation. Thus, the desired SLL is set equal to -20 dB and the antenna array is optimized for two different main lobe directions,  $\theta_{\rm o} = 90^{\circ}$  and  $\theta_{\rm o} = 100^{\circ}$ , considering nonuniform current distribution. The results of the two cases are given, respectively, in Tables 3 and 4, while the corresponding radiation patterns are presented in Figure 3. It is obvious that the nonuniform excitation can really help in achieving better values of SWR. A predictable implication observed in the nonbroadside case ( $\theta_0 = 100^\circ$ ) is that the radiation pattern is not as directional as in the broadside case. However, it will be shown below that this implication can be avoided by increasing the number of the array elements.

TABLE 6Structure Characteristics of an Optimized CollinearAntenna Array, Composed of 10 Wire Dipoles, with DesiredSLL Equal to -40 dB and Main Lobe Direction at  $\theta_o = 100^\circ$ 

т	$h_m\left(\lambda ight)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.484		1.000	0.0	1.70
2	0.484	0.772	2.627	31.8	1.61
3	0.484	0.761	4.624	66.5	1.57
4	0.484	0.758	6.492	105.1	1.56
5	0.484	0.741	7.964	144.1	1.53
6	0.484	0.739	7.737	177.1	1.48
7	0.484	0.742	3.928	-148.4	1.42
8	0.484	0.708	2.447	-22.5	1.30
9	0.484	0.746	3.732	11.1	1.43
10	0.484	0.760	1.880	22.2	1.52
$G^{\rm dB}(\theta$	$P_{\rm o}) = 9.93$	$SLL^{dB} = -$	-40.00	$S_{\rm av} = 1$	.51



**Figure 4** Radiation patterns of two optimized collinear antenna arrays, composed of 10 wire dipoles, with desired SLL equal to -40 dB and main lobe direction respectively at (a)  $\theta_{o} = 90^{\circ}$  and (b)  $\theta_{o} = 100^{\circ}$ 

The proposed technique can also be applied in order to derive structures with very low SLL. Therefore, the desired SLL is set equal to -40 dB and the 10 wire-dipole array is optimized for  $\theta_0 = 90^\circ$  and  $\theta_0 = 100^\circ$ , considering nonuniform current distribution. The results are given, respectively, in Tables 5 and 6, while the corresponding radiation patterns are shown in Figure 4. Actually, this example reveals the robustness of the proposed technique. The technique has the ability not only to achieve very low SLL but also to obtain very good values of SWR for all the array elements. Nevertheless, a degradation of the antenna array gain is caused in the nonbroadside case. This implication has also been reported in the previous example and is usually observed in nonbroadside cases. As mentioned above, an increase in the number of the array elements helps to avoid this implication.

TABLE 7Structure Characteristics of an Optimized CollinearAntenna Array, Composed of 20 Wire Dipoles, With DesiredSLL Equal to -20 dB and Main Lobe Direction at  $\theta_o = 100^\circ$ 

т	$h_{m}\left(\lambda ight)$	$z_{\mathrm{m},m-1}\left(\lambda\right)$	$a_m$	$q_m$ (deg)	$S_m$
1	0.482		1.000	0.0	1.14
2	0.482	0.545	1.460	-171.5	1.29
3	0.482	0.628	1.270	163.6	1.84
4	0.482	0.862	1.020	-122.8	1.40
5	0.482	0.858	1.572	-78.4	1.48
6	0.482	0.803	2.191	-27.1	1.41
7	0.482	0.824	2.192	27.2	1.36
8	0.482	0.813	2.288	72.1	1.43
9	0.482	0.771	2.267	137.9	1.33
10	0.482	0.738	1.778	-177.6	1.86
11	0.482	0.564	2.854	-158.6	1.79
12	0.482	0.779	2.417	-103.8	1.48
13	0.482	0.786	2.592	-40.3	1.32
14	0.482	0.834	2.408	-7.0	1.44
15	0.482	0.777	2.458	60.1	1.28
16	0.482	0.893	1.658	103.9	1.30
17	0.482	0.798	2.102	146.7	1.40
18	0.482	0.807	1.870	-142.3	1.31
19	0.482	0.826	1.984	-91.6	1.34
20	0.482	0.794	1.501	-39.2	1.21
$G^{\rm dB}(\theta_{\rm o}) = 14.13$		$SLL^{dB} = -$	-20.02	$S_{\rm av} = 1$	.42

TABLE 8 Structure Characteristics of an Optimized Collinear Antenna Array, Composed of 20 Wire Dipoles, With Desired SLL Equal to -40 dB and Main Lobe Direction at  $\theta_0 = 100^{\circ}$ 

т	$h_m\left(\lambda\right)$	$z_{m,m-1}(\lambda)$	$a_m$	$q_m (\mathrm{deg})$	$S_m$
1	0.484		1.000	0.0	1.66
2	0.484	0.793	1.979	48.6	1.50
3	0.484	0.810	3.071	94.7	1.57
4	0.484	0.748	4.293	145.8	1.50
5	0.484	0.775	5.342	-164.9	1.48
6	0.484	0.771	5.961	-115.6	1.46
7	0.484	0.772	6.303	-65.1	1.45
8	0.484	0.771	6.168	-13.3	1.44
9	0.484	0.764	5.839	38.4	1.42
10	0.484	0.775	5.132	90.6	1.42
11	0.484	0.751	4.452	140.2	1.45
12	0.484	0.722	3.406	-174.9	1.59
13	0.484	0.637	2.876	-135.4	1.83
14	0.484	0.659	2.890	-98.3	1.69
15	0.484	0.717	2.921	-55.0	1.50
16	0.484	0.776	2.779	-7.7	1.45
17	0.484	0.763	2.409	45.3	1.40
18	0.484	0.769	1.928	98.1	1.39
19	0.484	0.742	1.182	158.3	1.32
20	0.484	0.831	0.679	-150.0	1.20
$G^{\rm dB}(\theta_{\rm o}) = 13.80$		$SLL^{dB} = -$	-40.00	$S_{\rm av} = 1$	.49

cases of the last two examples are studied again, but this time the antenna array is assumed to be composed of 20 wire dipoles. Specifically, the main lobe direction is set at  $\theta_o = 100^\circ$  and the 20 wire-dipole array is optimized for two cases of SLL, i.e.  $SLL_d^{dB} = -20$  and  $SLL_d^{dB} = -40$ , considering nonuniform current distribution. The results are given, respectively, in Tables 7 and 8, while the corresponding radiation patterns are shown in Figure 5. Both cases exhibit very directional patterns and very good values of SWR.

# 5. CONCLUSIONS

The cases studied in the present work show that the proposed technique is capable of improving either broadside or nonbroadside radiation patterns under the constraints of the maximum



**Figure 5** Radiation patterns of two optimized collinear antenna arrays, composed of 20 wire dipoles, with main lobe direction at  $\theta_o = 100^\circ$  and desired SLL respectively equal to (a) -20 dB and (b) -40 dB

possible gain and the desired value of SLL. In addition, the technique results in very good values of SWR for all the array elements. The ability to find structures where all the elements are matched to the feeding network makes the technique very useful in practice. It was also shown that the proposed technique is highly promising even in cases where very low SLL is required.

The antenna arrays derived from the above study are suitable for broadcasting applications. But this is not the only usage of the PSO based technique. The technique is capable of optimizing many types of antennas and therefore is suitable for many applications in communications area.

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# MULTIMODE FIBER RING-DOWN PRESSURE SENSOR

# Huiye Qiu,<sup>1</sup> Yishen Qiu,<sup>1</sup> Zhihao Chen,<sup>2</sup> Baoyu Fu,<sup>1</sup> Xiyao Chen,<sup>3</sup> and Gaoming Li<sup>1</sup>

 Key Laboratory of Optoelectronic Science and Technology for Medicine, Fujian Normal University, Fuzhou, China
 Institute for Infocomm Research, 21 Heng Mui Keng Terrace, Singapore 119613

<sup>3</sup> Department of Physics and Electronics Communications, Fujian Mingjian College, Fuzhou, China

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**ABSTRACT:** A fiber-loop ring-down spectroscopy based on multimode fiber is proposed for pressure measurement. It has been found that the

multimode fiber-loop ring-down pressure sensor has higher sensitivity and larger dynamic range up to  $6.2 \times 10^7$  Pa compared to the single mode counterpart. Good stability and repeatability of the sensor are also demonstrated. © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1698–1700, 2007; Published online in Wiley Inter-Science (www.interscience.wiley.com). DOI 10.1002/mop.22553

Key words: optical fiber sensor; spectroscopy; pressure

## 1. INTRODUCTION

Fiber-loop ring-down spectroscopy (FLRDS) has received considerable attention for various applications in recent years [1-9]. This new technique uses optical fiber loop as the ring-down cavity where high reflectivity elements are not required. The optical device is based on the measurement of the decay of light in a fiber loop cavity. The exponential decay is a function of the cavity losses, cavity length. The sensing mechanism is based on the changes in the cavity losses that are related to changes of physical, chemical, and biological parameters. The multimode fibers were used to form cavities in references [1-3, 9]. They carried out research on the effects of losses of fiber and connector, bending, displacements on the ring-down characterization [2]. No further applications for pressure measurement were reported. On the other hand, some research groups used single mode fibers to form the cavities for the measurements of strain, temperature, pressure, and gas [5-8]. Wang and Scherrer [7, 8] first developed a fiber ringdown pressure sensor with good performances in terms of stability, repeatability, and dynamic range. In the pressure sensor they used a DFB laser at 1650 nm, single mode fiber and couplers. The dynamic range for pressure measurement was  $6.8 \times 10^6$  to  $18 \times$ 10<sup>6</sup> Pa as the fiber jacket remained in the sensor head. In this article, however, we study a new ring-down pressure sensor based on multimode fiber. A VCSEL source at 850 nm is used. It has been found that the multimode fiber based pressure sensor has higher sensitivity and larger dynamic range than the single mode counterpart presented in [8].

# 2. EXPERIMENT AND RESULT

The principle for pressure measurement by using fiber-loop ringdown spectroscopy (FLRDS) is simple. When the external pressure is applied to a section of fiber cavity, an additional cavity loss is induced. So, the change in the ring-down time is observed. The linear relation between the pressure applied and the ring-down time is given by [8]

$$\left(\frac{1}{\tau} - \frac{1}{\tau_0}\right) = \frac{c\beta lS}{L}P,\tag{1}$$

where  $\tau$ ,  $\tau_0$  are the ring-down time for pressure applied and non pressure, respectively, *c* is the speed of light in the fiber,  $\beta$  is the pressure-induced loss coefficient, *l* is length of the fiber contacted with the pressure, *S* is the contacted area, *L* is the total fiber-loop length, and *P* is pressure. Equation (1) indicates that the pressure can be obtained by measuring the ring-down time,  $\tau$  and  $\tau_0$ . It should be noted that the measurement is independent from power fluctuations of the light source.

The schematic representation of the device is shown in Figure 1. The output light from a pulsed VCSEL laser diode is launched into the multimode fiber loop cavity via the fiber coupler 1. A small amount of light is coupled out from the cavity through the second coupler and then detected by an APD detector. A typical ring-down trace is obtained as shown in Figure 2. The pulsed 850 nm VCSEL module has a pulse width of 10 ns and repetition rate