Optimization of Printed Yagi Antenna Using Invasive Weed Optimization (IWO)

S. H. Sedighy, A. R. Mallahzadeh, M. Soleimani, and J. Rashed-Mohassel

***Abstract*—In this letter, the Invasive Weed Optimization (IWO) method is applied to design and optimize a printed Yagi antenna. The optimization goals are set to reach an antenna with a VSWR less than 1.5 and a high-gain radiation pattern. The fitness function is calculated by FEKO, which uses the method of moments for evaluating the structures. By implementing this simple closed-loop algorithm, the best available structure has been achieved compared to the results of the previous studies. Finally, a C-band optimized version of the antenna is fabricated and tested. The experimental data are in good agreement with the simulation results, which verifies the performance of the IWO method.**

***Index Terms*—Director, driver, Invasive Weed Optimization (IWO), printed Yagi antenna.**

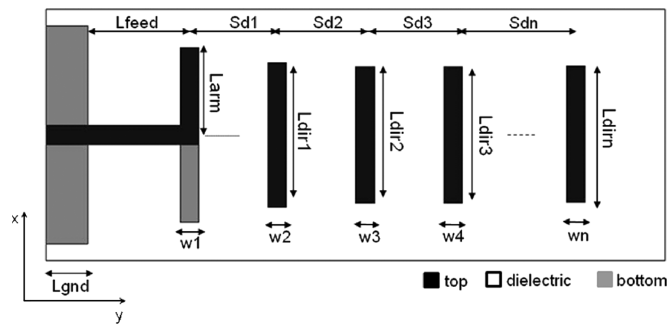

Fig. 1. Bi-PYA configuration with optimization parameters.

I. Introduction

The MICROSTRIP-FED quasi-Yagi antenna, which was originated from the Yagi–Uda antenna, was introduced first by Huang in 1991 [1]. Its structure consists of a half-wavelength dipole and an approximately quarter-wavelength rectangular director for increasing the gain and improving the front-to-back ratio [1]. Its low profile, small size, light weight, and low cost, along with ease of fabrication and installation, make it suitable for utilization in the hybrid and monolithic integrated circuits [2]. Also, a novel dipole quasi-Yagi antenna was presented and optimized in [3]–[5] in order to increase the antenna bandwidth. In this antenna, the driver and the directors are placed on the top of the substrate, while the truncated ground reflector is placed on the bottom. The driver dipole is fed through a broadband microstrip-to-coplanar-strips transition. This feeding configuration is complicated and requires long transmission lines. The narrowband delay line used in the antenna structure restricts the bandwidth and creates an unbalanced condition for the antenna operation. To solve this problem, Zheng proposed a biplanar printed Yagi antenna (Bi-PYA) with a simplified feeding network, which is shown in Fig. 1 [6]. This antenna consists of a microstrip line and one director arm on the top of the substrate and a truncated ground reflector with another driver arm at the bottom of the substrate. This design was optimized by Navarro to achieve a gain greater than 7 dBi and 10% bandwidth at 2.45 GHz [2].

In this letter, Invasive Weed Optimization (IWO) method is used to design and optimize a Bi-PYA. This algorithm, which is inspired from colonizing weeds, was first proposed by Mehrabian and Lucas in 2006 [7] and was investigated in several other articles such as [8]–[12]. The electromagnetic analysis of Bi-PYA is conducted by means of the commercially available FEKO, which is based on the method of moments (MoM). IWO suggests some structures in any iteration that are evaluated by FEKO and ranked according to their fitness. Then, the trial structures with lower fitness are eliminated, yielding the best available structures. This process continues until all requirements are satisfied and the optimized structure is obtained. By implementing this scenario, the best available structure can be simply reached by a closed-loop algorithm, whereas in the tuning method, many groups of values must be blindly evaluated for the parameters. Also, in comparison to other studies like [2], better results are obtained in this approach within the same structure.

II. IWO Procedure

IWO is a numerical stochastic search algorithm that mimics natural behavior of weed colonizing in the opportunity spaces for optimizing the function. This algorithm is simple. However, it has been shown to be effective in converging to an optimal solution by employing basic properties—e.g., seeding, growth, and competition—in a weed colony. To simulate the colonizing behavior of weeds, some basic properties of the process are as follows [7].

1) Finite number of seeds are spread out over the search area.
2) Every seed grows to a flowering plant and produces seeds depending on its fitness.

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S. H. Sedighy and M. Soleimani are with the Department of Electrical Engineering, Iran University of Science and Technology (IUST), Tehran, Iran (e-mail: sedighy@iust.ac.ir; soleimani@iust.ac.ir).

A. R. Mallahzadeh is with the Department of Electrical Engineering, Shahed University, Tehran, Iran (e-mail: mallahzadeh@shahed.ac.ir).

J. Rashed-Mohassel is with the Department of Electrical and Computer Engineering, University of Tehran, Tehran, Iran (e-mail: jrashed@ut.ac.ir).

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TABLE I
IWO PARAMETER VALUES FOR BI-PYA OPTIMIZATION

Symbol	Quantity	Value
N	Number of initial population	40
$Itermax$	Maximum numbers of iterations	110
D	Problem dimension	6
$Pmax$	Maximum number of plant population	40
$Smax$	Maximum number of Seeds	5
$Smin$	Minimum number of Seeds	1
N	Nonlinear modulation index	3
$\sigma_{initial}$	Initial value of standard deviation	3
σ_{final}	final value of standard deviation	0.01
$Lgnd$	Truncated ground width	$0.09\lambda_g < Lgnd < 0.39\lambda_g$
$Lfeed$	Microstrip feed line length	$0.24\lambda_g < Lfeed < 0.54\lambda_g$
$Larm$	driver arm length	$0.15\lambda_g < Larm < 0.45\lambda_g$
Sd	Spacing between directors	$0.25\lambda_g < Sd < 0.55\lambda_g$
$Ldir$	directors lengths	$0.44\lambda_g < Ldir1 < 0.74\lambda_g$

3) The produced seeds are being randomly dispersed over the search area and grow to new plants.
4) This process continues until the maximum number of plants is reached. Then, only the plants with high fitness can survive and produce seeds, and others are eliminated. The process continues until the maximum number of iterations is reached and, hopefully, the plant with the best fitness is the closest one to the optimal solution. This process is addressed in more detail as follows.

Population Initialing: A population of initial solutions is spread out over the n-dimensional problem space with random positions.

Reproduction: A certain population of plants is allowed to produce seeds depending on its own and the colonies' lowest and highest fitness: The number of seeds each plant produces increases linearly from the minimum possible seed production level to its maximum level.

Spatial Dispersal: Randomness and adaptation in the algorithm is provided in this part. The generated seeds are randomly distributed over the n-dimensional search space by normally distributed random numbers with a mean value equal to zero, but with differing variances. This ensures that the seeds are randomly distributed and are accumulated near the parent plant. However, standard deviation (SD) σ of the random function reduces from a previously defined initial value, σ_{initial}, to a final value, σ_{final}, in every step (generation). In simulations, a nonlinear variation shows a satisfactory performance, which is given as

$$\sigma_{\text{iter}} = \frac{(\text{iter}_{\max} - \text{iter})^n}{\text{iter}_{\max}^n}(\sigma_{\text{initial}} - \sigma_{\text{final}}) + \sigma_{\text{final}} \quad (1)$$

where $\text{iter}_{\max}$ is the maximum number of iterations, σ_{iter} is the SD at the present step, and n is the nonlinear modulation index.

The experimental studies suggest that the results from IWO are as good as (in some cases, even better than) the results from other methods. The performance of IWO is comparable to other evolutionary algorithms, and its results are satisfactory for all test functions [7].

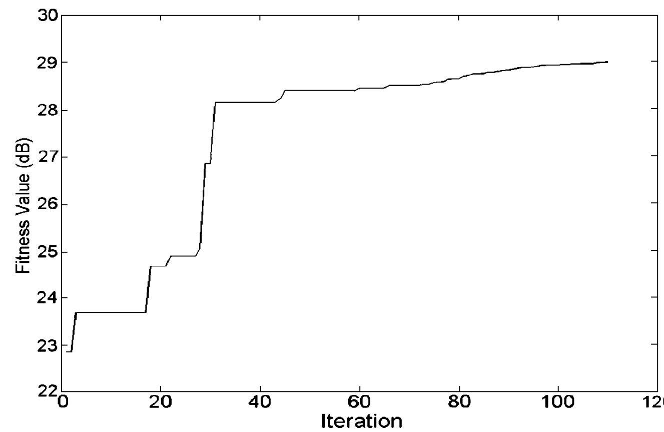

Fig. 2. Fitness of structure versus iteration.

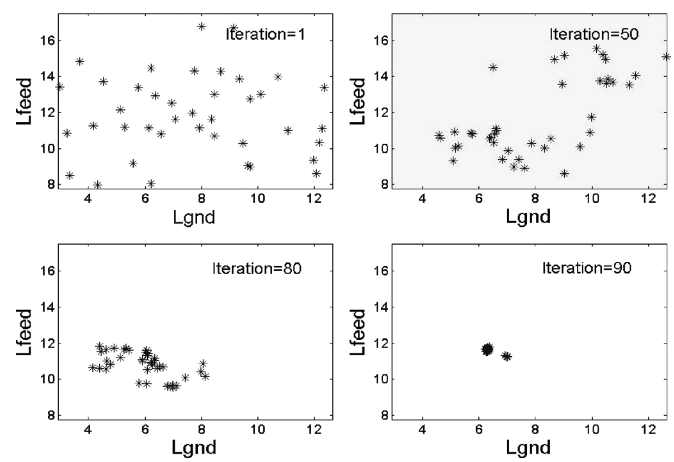

Fig. 3. Distribution of the seeds in the search area for 1, 50, 80, and 90 iterations.

III. ANTENNA DESIGN

The antenna configuration is drawn in Fig. 1. To match the input impedance, the width of the driver should be designed to reach 50 Ω input impedance. By increasing the number of the directors, the beamwidth of the radiation pattern increases. However, S_{11} is not affected. The antenna bandwidth is affected by the separation distance between directors and the drivers.

To reach the desired antenna performance, several variables can be optimized. In this letter, the truncated ground width ($Lgnd$), driver arm length ($Larm$), microstrip feed line length ($Lfeed$), widths (wi), and lengths of directors ($Ldiri$) and their separations (Sdi) are selected as the optimization variables. After selecting optimization variables, trial antenna structures (initial seeds) are randomly selected in the search area (plant area). Each trial structure (weeds) produces new trial structures (reproduction seeds) depending on its fitness (fitness of cultivated plant), $S_{\max}$ (maximum number of seeds) and $S_{\min}$ (minimum number of seeds). These newly produced structures are distributed by a normal distribution in the neighborhood of the parents and the standard deviation calculated by (1). The reproduced structures (seeds) and parent structures (parent weeds) are analyzed by FEKO and ranked according to their fitness. For reaching the maximum number of plants in the colony ($P_{\max}$), weeds with lower fitness are eliminated.

TABLE II
OPTIMIZATION VALUES

variable mm	Lgnd	Lfeed	Larm	Sd	Ldir1	Ldir2	Gain	BW
IWO	6.50	11.8	10.04	11.38	17.94	16.90	11.6	11%

TABLE III
OPTIMIZATION RESULT FOR BI-PYA WITH DIFFERENT DIRECTORS

Number of Directors	Max Gain dB	H Plane		E Plane		S11 dB	BW
		SLL dB	HP deg	SLL dB	HP deg		
1	8.34	-16.3	95.6	-24.8	68.2	-22.7	8%
3	10.39	-9.19	61.2	-20.9	51.6	-18.4	9.5%
5	11.42	-9.6	65.6	-19.4	46	-21.4	11%
7	13.1	-10.5	35	-14.3	32	-23.5	8%
9	13.7	-10.5	34.9	-15	36	-24.3	12%

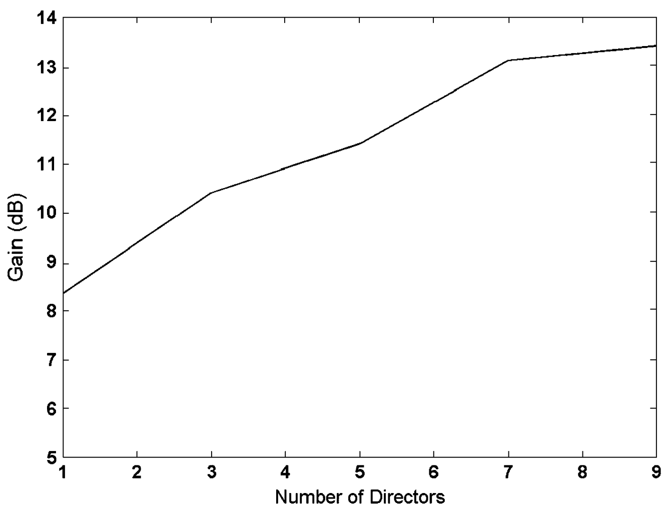

Fig. 4. Bi-PYA gain versus the number of directors.

This approach continues until all requirements are satisfied and the optimized structure is determined.

The central value of the search area for optimization variables is determined according to the tuning optimized results obtained in [2], which are based on the wavelength scale. Then, several wide ranges are defined around each central value in order to reach the best possible structure.

Fitness of each structure is calculated by

$$f = \begin{cases} (-w_1 S_{11} + w_2 \text{Gain}) & S_{11} > S_t dB \\ (-w_1 S_t + \text{Gain}) & S_{11} < S_t dB \end{cases} \quad (2)$$

where f is the fitness of each trial structure and S_t is the acceptable threshold of S_{11}. The parameters w_1 and w_2 are properly selected weighting coefficients.

To be more specific, structures with $S_{11} < S_t dB$ compete with each other just according to their gains. Therefore, IWO algorithm converges with the structures with $S_{11} < S_t dB$ and with maximum available gains. The w_1/w_2 ratio determines the importance of input impedance matching against the gain. If other parameters, such as BW, are added to the fitness function,

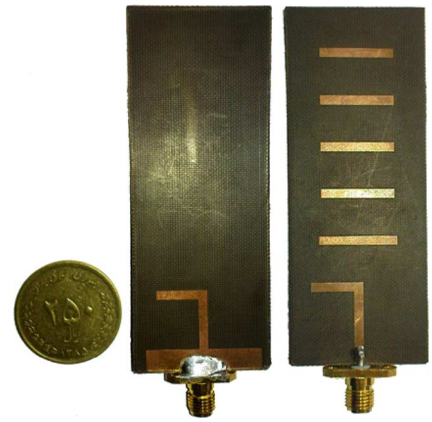

Fig. 5. Picture of the fabricated antenna.

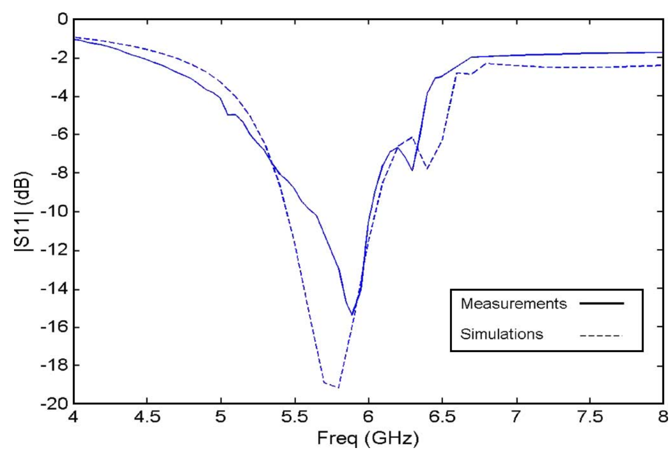

Fig. 6. Simulation and measurement results.

the convergence time of the algorithm will be increased exponentially, and the algorithm will converge more slowly.

A structure is optimized with five directors and 18 variables ($w1$–$w5$, $Ldir1$–$Ldir5$, $Sd1$–$Sd5$, $Lgnd$, $Lfeed$, and $Larm$). Also $w_1 = w_2 = 1$ and $S_t = -15$ dB are selected in the fitness function. The results of the performed optimizations for these 18 variables show that the best available structure based on the fitness function can be achieved only by optimizing six variables ($Lgnd$, $Lfeed$, $Larm$, Sd, $Ldir1$, and $Ldir2$), and increasing the number of variables does not result in a significantly better structure.

TLX-8 substrate with $\mathrm{h} = 0.76$ mm and $\varepsilon_r = 2.55$ is selected for optimizing and realizing the antenna structure. The parameters of the algorithm and the related search area are specified in Table I. The fitness of structure versus iterations are demonstrated in Fig. 2. Also, seed distributions in the search area are shown for four iterations in Fig. 3. The seeds are colonized around the optimized point in the last iterations.

The optimization results of the Bi-PYA at $f = 5.8$ GHz with five directors is demonstrated in Table II. This optimization is done to reach the best available gain with $S_{11} < -15$ at the design frequency based on the optimized parameter values tabulated in Table I. The results of the IWO algorithm are better than the results achieved in [2]. The obtained gains in this reference for one, three, and five elements are 4, 5, and 7.5 dBi,

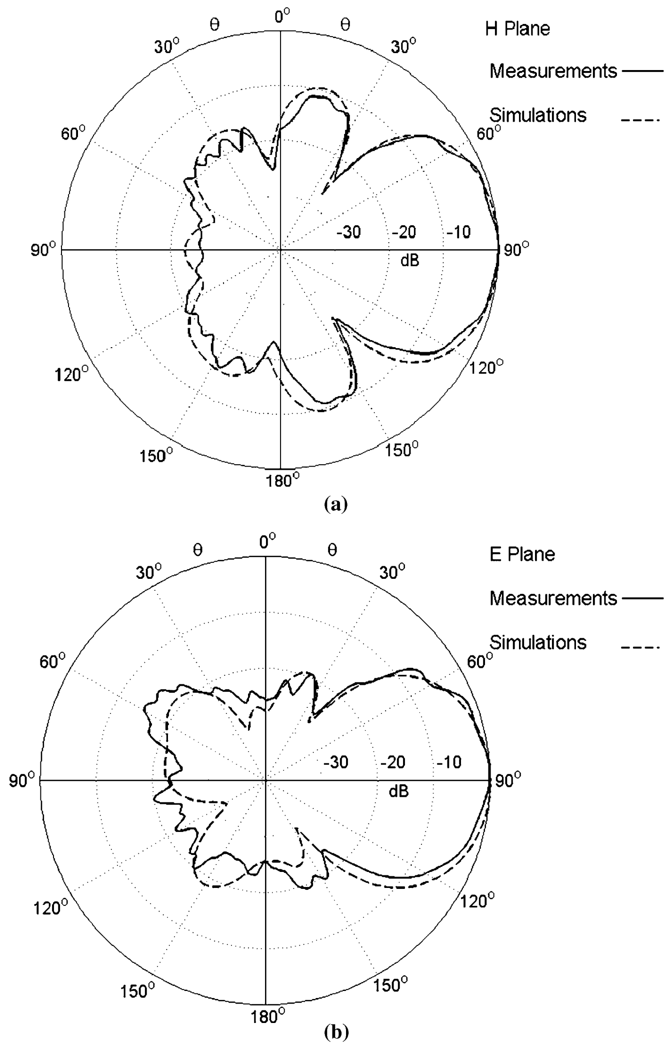

Fig. 7. Simulation and measurement results for (a) H-plane ($\phi = 90°$) and (b) E-plane ($\theta = 90°$) radiation pattern at $f = 5.8$ GHz.

respectively, whereas the present study in this letter obtained 8.34, 10.39, and 11.42 dBi for the same prototypes. This comparison verifies the performance of the IWO method.

To increase the gain of the proposed antenna, the antenna is optimized by being evaluated with different directors. Based on the performed optimization results, six optimization variables ($Lgnd, Lfeed, Larm, Sd, Ldir1$, and $Ldir2$) are selected in any case. The results of these optimizations are shown in Table III, which indicate that the director's increase raised the antenna gain, but the convergence time increased dramatically.

As shown in Fig. 4, the antenna gain does not change in a linear form by changing the number of the directors. Similar to the wire Yagi antenna, adding to the number of directors resulted in a little gain improvement. In fact, there is a "point of diminishing returns" [13] in the Yagi antenna structure.

IV. Results

Fig. 5 shows the manufactured antenna printed on the TLX-8 substrate. The optimized dimensions using IWO are tabulated in Table II. Figs. 6 and 7 show the comparison of the simulation and measurement results. A good agreement is observed between the full-wave simulation and measured results for the optimized structure, which verifies the performance of the IWO method.

V. Conclusion

The invasive weed optimization of a Bi-PYA is surveyed in this letter. The antenna is analyzed by FEKO and optimized by IWO to achieve the best gain with VSWR < 1.5. By implementing this scenario, the best available structure simply reached through a closed-loop algorithm and better results, compared to the results of the previous studies, are obtained within the same structure. The optimization results show that similar to wire Yagi antennas, there is a "point of diminishing returns" in the gain of the Yagi antenna. Finally, an optimized Bi-PYA with five directors is fabricated on the TLX-8 substrate. Bandwidths higher than 10% and a gain greater than 11 dB are obtained from this structure.

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