Radiation Performance Enhancement of a Compact Fabry-Perot Cavity Antenna Using Particle Swarm Optimization

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***Abstract*—A Fabry-Perot cavity antenna (FPCA) with a compact single-layer all-dielectric superstructure is designed using particle swarm optimization (PSO). The PSO algorithm, implemented in a MATLAB code, considers Ackley function to achieve stable convergence by adjusting its internal parameters. We performed single-objective optimization using an objective function that maximizes the sum of boresight directivities at three distinct frequencies. It was found that peak directivity of 19 dBi and 3-dB directivity bandwidth of 24% can be achieved by optimizing the permittivity distribution of the superstructure with a diameter of 2.2λ_0.**

I. INTRODUCTION

Optimization techniques based on the collective behaviour of animals in nature have been increasingly used to design antennas with enhanced performance. Among many different types of the proposed algorithms, genetic algorithm and particle swarm optimization (PSO) are the most known in the electromagnetic community and have been successfully applied to a large number of antenna designs since 1990s [1], [2].

Fabry-Perot cavity antennas (FPCAs) have recently attracted significant research interest due to their advantages of low profile, simple feed mechanism and highly directive radiation patterns. One drawback of these antennas is the narrow half-power fractional bandwidth due to a high Q-factor of a resonant cavity. Hence, several attempts have been made to make FPCAs suitable for wideband operation. These techniques include the use of multiple feed sources and/or a modification to a superstructure, such as single-layered and multi-layered designs with improved transmission and reflection characteristics [3]–[7], non-uniform printing of patches [8] and inhomogeneous all-dielectric structures [9]. Very few FPCAs have been optimized using evolutionary optimization methods [10], [11]. In [10], a superstructure based on a printed double-sided frequency-selective surface was designed using a microgenetic algorithm with the goal of achieving a high-Q resonant cavity. This resulted in a peak gain of 22.15 dBi over a narrow frequency range. In [11], a real-value coding hybrid genetic algorithm was applied to design a FPCA for a base station by optimizing the dimensions of square patches and loops on its double-sided superstructure. A peak gain of 13.8 dBi and a 10% 3-dB gain bandwidth was reported.

This paper presents the results of particle swarm optimization of a FPCA with the objective of achieving higher peak directivity by employing a compact all-dielectric, single-layer superstructure, inspired by a flat gradient refractive index superstrate [9]. A custom MATLAB implementation of the well-established and simple PSO algorithm was interfaced with the CST Microwave Studio numerical solver. We compare the optimized antenna with our two previously reported designs [5], [9] with the improved radiation performance of FPCAs. Additionally, we explain how to choose the parameters of PSO in a fast manner.

II. PSO IMPLEMENTATION AND ACKLEY FUNCTION

A classical PSO with an inertia weight [12] was used in our study. The formula for updating the velocity of each particle is given by :

$$v^n_{(t)} = wv^n_{(t-1)} + c_1 rand_1 * (p^n_{(t-1)} - x^n_{(t-1)}) + \\ + c_2 rand_2 * (b_{(t-1)} - x^n_{(t-1)}), \qquad (1)$$

where n is a swarm size, t is an iteration count, $v^n_{(t-1)}$ and $x^n_{(t-1)}$ are velocity and position of n^{th} particle at $(t-1)$ iteration, $p^n_{(t-1)}$ is the best position of n^{th} particle and $b_{(t-1)}$ is the best position found by the swarm. The swarm behaviour can be controlled by adjusting swarm size n, inertia weight w, cognitive constant c_1 and social constant c_2.

The linearly decreasing inertia weight gradually eliminates the influence of the first term in the velocity update formula (1), ultimately improving the search. Similar to all stochastic optimization algorithms, PSO lacks the mathematical framework to guarantee convergence to the global optimum. Additionally, internal parameters of the algorithm (n, w, c_1, c_2) must be tuned to achieve efficient behavior of the optimizer. These aspects require several trials of the optimization process to gain some confidence that the algorithm has stable convergence and the solution found is the best one or very close to it. Finding these optimal internal values might be a time-consuming task, especially when the calculation

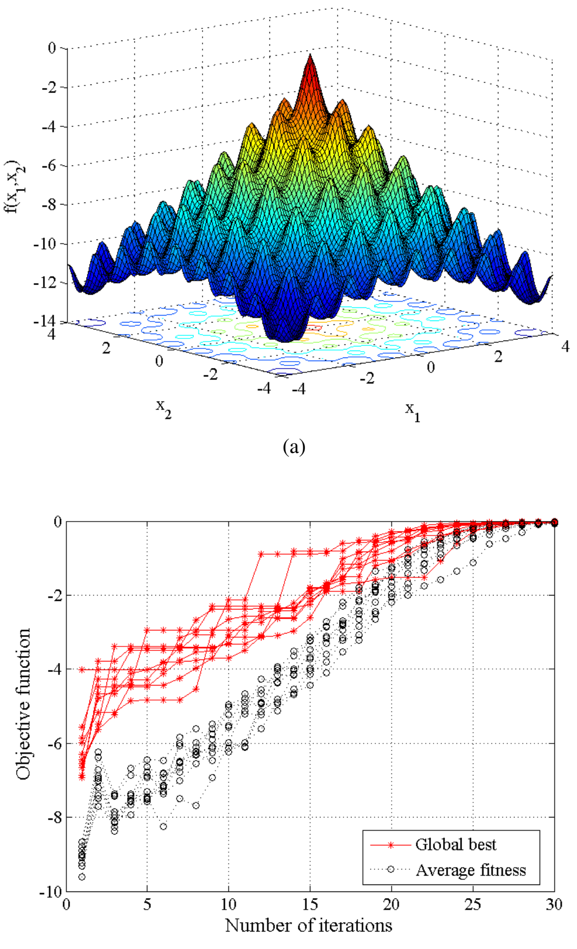

Fig. 1. (a) Ackley function (dimensionality=2). (b) PSO convergence after 30 iterations (10 trials)

of an objective function depends on an external black-box simulation. Taking into account that most antenna design optimization problems are multimodal, we first tested our optimization algorithm on an inverted Ackley function, which is a multimodal benchmark, before optimizing a FPCA. The test function has the following expression:

$$f(\vec{x}) = 20e^{-0.2\sqrt{\frac{\sum_{j=1}^{n} {x_j}^2}{n}}} + e^{\frac{\sum_{j=1}^{n} \cos(2\pi x_j)}{n}} - 20 - e, \quad (2)$$

where n is dimensionality, and $\vec{x}$ is a vector of variables in the search domain. The global solution is $f(\vec{x}) = 0$, located at $\vec{x} = x_1, \cdots, x_n = 0$. Fig. 1a shows the topology of an Ackley problem for a two-dimensional (2D) case. The general rule is to decrease the inertia weight from 0.9 to 0.4 over the course of the run [12]. Our test on the Ackley function showed that the speed of convergence could be further increased by varying the inertia w from 0.9 to 0.1. Applying the PSO with $n = 25$ and $c_1 = c_2 = 1.49$, we found the minimal number of simulations required for a quick and reliable search. Fig. 1b shows the progress of ten subsequent trials, where we intentionally did not take the mean value, for the sake of visualization. It is clear that after 30 iterations the algorithm steadily converges to the global maximum.

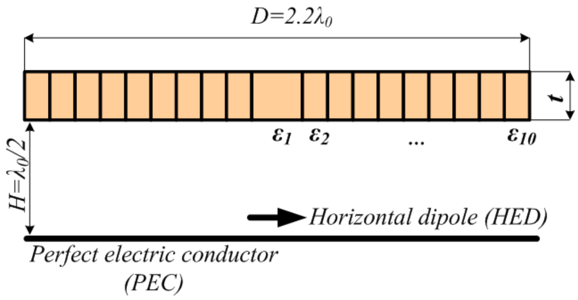

Fig. 2. Cross-section view of the optimized FPCA with D = 48 mm, H = 11 mm; λ_0 = 22 mm.

III. ANTENNA OPTIMIZATION

The antenna model to be optimized consists of a perfectly electric conducting ground plane, an all-dielectric superstructure and a horizontal electric dipole (HED) as a feed (Fig. 2). The superstructure is $2.2\lambda_0$ in diameter and consists of ten concentric dielectric rings, permittivities of which in addition to the slab thickness are the optimization parameters in this study.

The objective function is an important figure of merit, which determines the solution we aim to reach. In order to achieve higher peak directivity while keeping bandwidth reasonably wide, we defined the objective function as a sum of peak directivities at three particular frequencies:

$$O.F. = \sum_{f_i = f_1}^{f_3} Dir(f_i), \quad (3)$$

where $Dir(f_i)$ is a boresight directivity at i^{th} frequency and $f_1 = 16$ GHz, $f_2 = 16.8$ GHz, $f_3 = 17.6$ GHz. This choice of frequencies in the objective function was found to be useful in extending the bandwidth.

The boresight directivity and side lobe levels of the optimized design are shown in Fig. 3. The peak directivity and 3-dB directivity bandwidth are 19.1 dBi and 24%, respectively. It is similar to the result in [5], but the superstructure is much thinner and employs only one dielectric layer. As compared to [9], the peak directivity is improved by 1.5 dBi. The side lobe levels (SLLs) remain lower than -20 dB for the H-plane and -25 dB for the E-plane in the frequency range from 14 to 16 GHz. However, the SLL increases to -7 dB at the high edge of the operating frequency range. Although the increase in the SLLs is common for many FPCAs, it comes at the expense of reduced effective bandwidths.

IV. CONCLUSION

We proposed a method to optimize the radiation performance of a FPCA using PSO. We tested the PSO algorithm

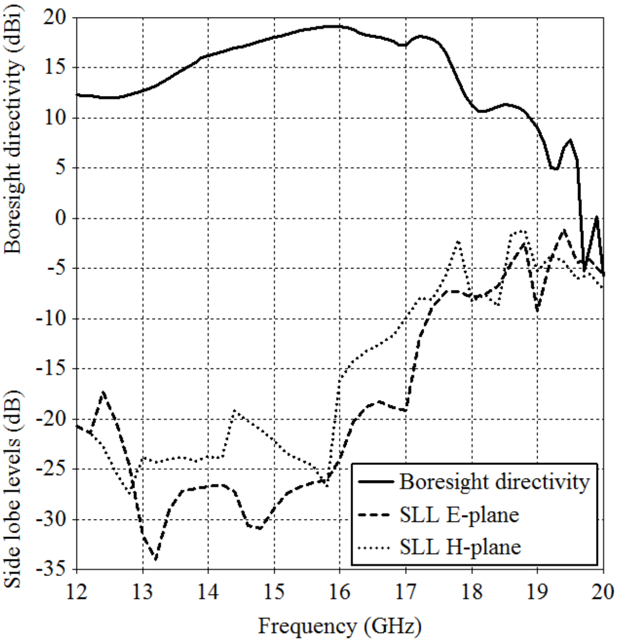

Fig. 3. Boresight directivity and side lobe levels of the optimized FPCA.

on a mathematical problem, before starting the antenna optimization. This technique can assist in finding the internal parameters much faster. The right choice of these parameters ensured stable convergence with a minimal number of simulations, which is the most time-consuming part of the antenna optimization. After choosing the optimal internal parameters of the algorithm, we optimized a FPCA maximizing the sum of peak directivities at three distinct frequencies. The optimization of a FPCA resulted in peak directivity of 19 dBi and 3-dB directivity bandwidth of 24%.

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