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Design of Wideband Resonant Cavity Antenna using Particle Swarm Optimization

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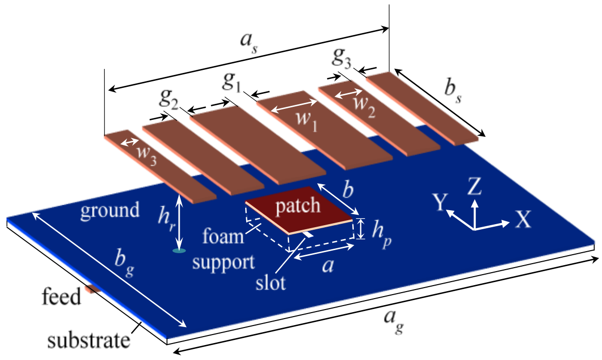
Abstract*: A wideband optimization technique of a Resonant Cavity Antenna (RCA) is demonstrated using a very simple and efficient Particle Swarm Optimization (PSO) approach. The proposed optimization method appears to be attractive as it is driven conveniently by a commercial EM-simulator. This may be treated as a 70-dimensional as well as a wideband optimization problem to optimize ten antenna parameters. The proposed technique offers maximum about 17.6 dBi broadside gain using the optimally designed antenna. The peak-gain is maintained above 11 dBi over the 50% antenna bandwidth.

***Keywords* : antenna optimization, particle swarm optimization, Fabry-Perot cavity antenna, resonant cavity antenna.**

I. INTRODUCTION

Resonant cavity antenna (RCA) is popular for its high gain features [1]–[9]. This may be a possible substitution of a bulky array or reflector antennas. The principle of Fabry-Perot laser of fiber-optics [10] is extended to antennas for microwave and millimetre-wave applications. In an optical communication system, a directive source is essential to improve the coupling efficiency between the laser and the fiber core [10]. The Fabry-Perot mechanism is applied to realize such a highly directive laser. A similar working principle has also been used to realize a high-gain RCA which is popularly known as Fabry-Perot cavity antenna. Like optical lasers, the directive pattern of an RCA may be explained using the ray-tracing mechanism [1]–[7]. In RCAs, a superstrate layer is symmetrically placed above the ground plane at $\lambda/2$ height, λ being the guided wavelength. The high directive pattern is due to the formation of a uniform wave-front. A radiating aperture [1], microstrip patch [2], or dielectric resonator antenna [3] are common examples of primary radiating element for cavity excitation. The superstrate layers are usually engineered with metal, dielectric or their composite materials to realize a partially reflecting surface (PRS) [1]–[7]. These PRS configurations were made semi-transparent to leak electromagnetic energy through the superstrate surface. The leaky-wave analysis was also used to explain its high gain features. PRS configurations are usually made of dielectric [1], [2] photonic or electromagnetic bandgap material [4], metamaterial [6], frequency selective surface [6], and metal-grid structures [3].



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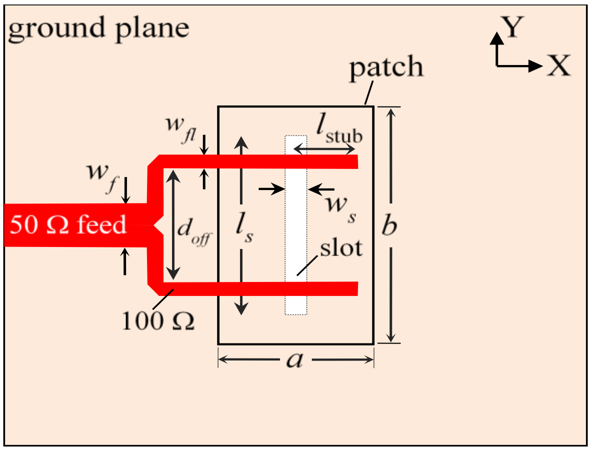

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Fig. 1. Proposed antenna geometry seen from the (a) side and (b) top. Rectangular microstrip patch: $a = 9$, $b = 16$, height = h_p; ε_{rf} (foam)=1.07; metal-grid superstrate: size ~ ($a_s \times b_s$), height = h_r, thickness = 20 mil; strip-widths→ w_1, w_2, w_3, slit-widths→ g_1, g_2, g_3; Feed: $w_f = 1.6$, $w_{f1} = 0.5$, slot length→l_s, $w_s = 1$, $d_{off} = 4.5$, stub-length= l_{stub}, 20 mil substrate→ε_{rs} ~2.2; Ground-plane: a_g=b_g=90; (all parameters are in mm).

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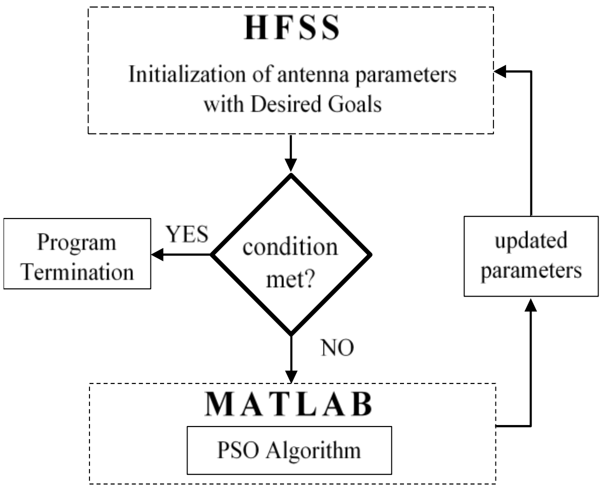


Fig. 2. Flowchart describing the simulation driven optimization process using PSO algorithm.

Their high-gain properties were studied using the reflection

TABLE I: Specifications For Wideband Optimization

Target Parameters	Optimum Goal Specifications	Frequency Range (GHz)		
		Start value	End value	Step value
S_{11}	$S_{11} \leq -30$ dB	9	15	1
Broadside Gain (at θ=0 & ϕ=0)	Broad Side Gain ≥20 dBi	9	15	1

properties of the superstrate [7].

It was a long-standing notion to have a PRS superstrate for an RCA design [1]–[7]. A new concept was proposed for the first time in [11] where a metal-sheet superstrate as a fully reflecting surface (FRS) were used. The high directivity features of these antennas ware explained using the aperture field theory [12]. The far-field pattern was obtained from the aperture-field Fourier transform [13]–[15]. This was demonstrated as a combination of triangular pulses. The height, width, and position of these pulses were controlled to determine the antenna far-field pattern. A metal grid superstrate [16] also reveals a similar aperture field distribution. Handling too many parameters is a very difficult task to realize the optimum characteristics, especially for wideband antenna design. The conventional optimization approach cannot be used to design the antenna, especially for maintaining the high-gain over its wide bandwidth. The problem could be solved using an optimizer which could handle a multi-objective/ multi-dimensional problem. Particle Swarm Optimization (PSO) could be the most efficient approach to handle such electromagnetic design problems [17], [18].

In this paper, a wideband optimization method has been proposed to design an RCA using metal-grid superstrate. The PSO has been used to tackle such a multi-dimensional problem [17], [18]. The metal-grid and other antenna parameters are controlled to attain minimum reflection coefficient and high gain over the bandwidth. The PSO script has been written to establish a link between the commercial EM-solver and the MATLAB. ANSYS HFSS has been used for the execution of the search operation driven by PSO. This will continue until the antenna performance reaches its optimum level. This appears to be an efficient and accurate technique with minimum execution time. Optimized parameters are presented based on the simulation studies (HFSS) and MATLAB. The proposed approach excellently works not only to realize very wide bandwidth but also to achieve high gain over the band. About 17.6 dBi maximum broadside gain has been achieved with 11 dBi peak-gain maintained over the 50% impedance bandwidth using the optimally designed antenna.

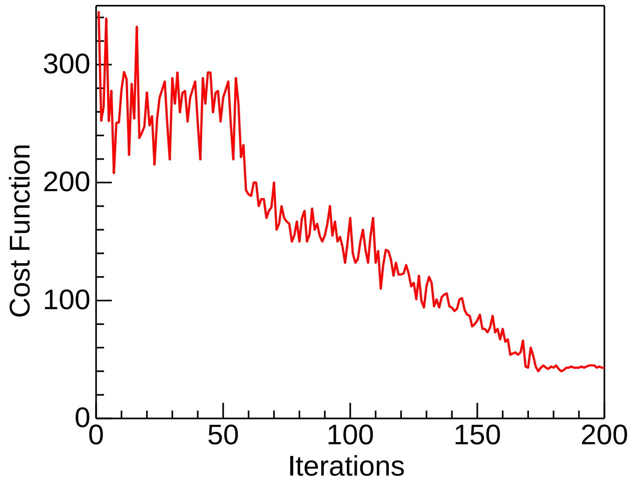


Fig. 3. Variation of cost function with the progress of simulation process.

II. PROPOSED ANTENNA GEOMETRY

The primary objective of this design approach is to realize an optimized RCA offering high gain over its wide operating bandwidth. The intention is to use the PSO algorithm integrated with HFSS through the MATLAB platform. To initiate the optimization process, an RCA configuration has been conceived. Fig. 1 shows the configuration of the proposed antenna. A rectangular microstrip patch is used as the primary radiating element with a dual-offset aperture feed configuration [19]. This has been used to realize a primary radiator with wideband broadside-pattern. A metal-grid superstrate has been symmetrically placed above the primary radiator. Foam spacers have been used to provide mechanical support to the superstrate.

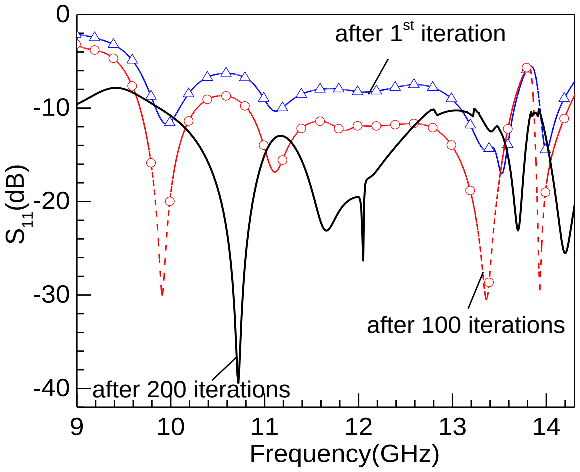
III. OPTIMIZATION FOR IMPROVED DESIGN OF ANTENNA

The flow chart of the proposed method is shown in Fig. 2. Inbuild optimization tool of HFSS has been employed through the MATLAB platform. A communication link has been maintained between HFSS and MATLAB through a virtual channel written in a scripting language. The MATLAB code for the search operation has been prepared following the PSO algorithm. After each iteration, HFSS will return the cost-function to the MATLAB program. This returns a cost function value based on the antenna parameters and the optimization goals.

TABLE II: PARAMETERS SELECTED FOR OPTIMIZATION

Target Parameters*	l_s	l_{stub}	b_s	h	w_1	w_2	w_3	g_1	g_2	g_3
Initial value	10	1	45	15	10	5	7	2	5	2
Optimum values after 200 iterations	12	3.8	50	18	13.7	7	5	3.52	3	3

*All dimensions are in mm.



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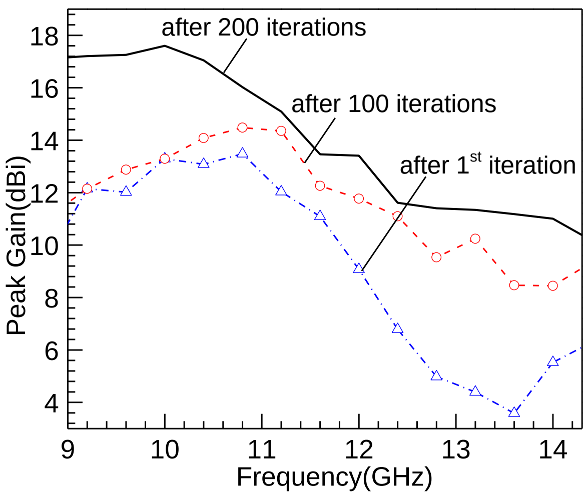

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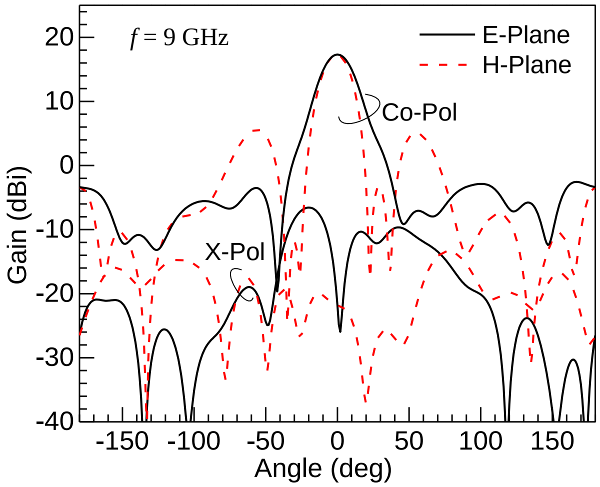
Fig. 4. S_{11} and peak-gain over the antenna bandwidth compared at different iterative stages: (a) S_{11} and (b) peak-gain. Parameters: All other parameters as in Fig. 1 and Table II.

The simulation process has been initiated with ten crucial antenna parameters (l_s, l_{stub}, b_s, h, w_1, w_2, w_3, g_1, g_2, g_3). They have been selected with a goal to achieve the return-loss ≤ –30 dB and broadside-gain ≥ 20 dBi. This would be a ten-dimensional problem if the optimization performed at a single frequency point. But, in the present approach, a wideband optimization has been carried out from 9 GHz to 15 GHz with 1 GHz frequency steps. Therefore, this may be treated as a 70-dimensional (10×7) wideband optimization problem. Goal specifications are described in Table-I. Maximum 200 iterations have been allowed for attaining minimum cost function value. It takes about 28 hours of simulation time to reach very close to the desired goal. Overall simulation progress for attaining minimum cost function is shown in Fig. 3. A list of optimized parameters is shown in Table-II.



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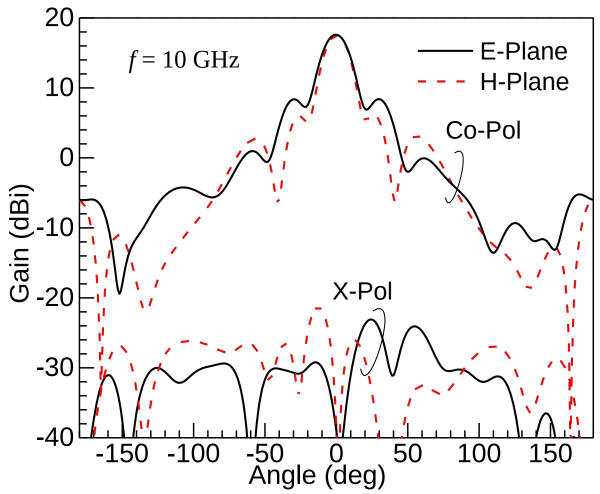

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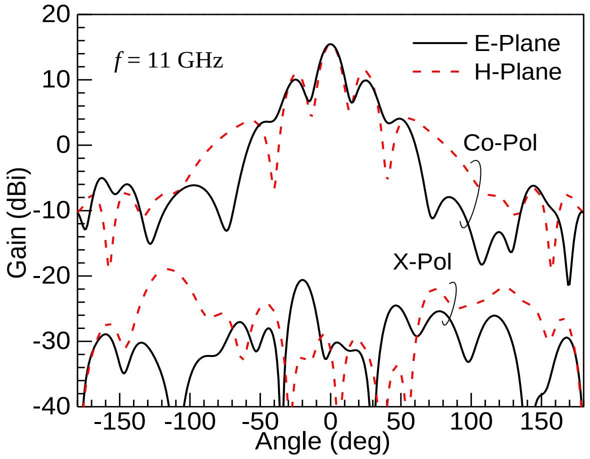
Fig. 5. E-plane and H-plane patterns: (a) at 9 GHz and (b) at 10 GHz. Parameters as in Fig. 1 and Table II.

IV. RESULTS AND DISCUSSION

The S_{11} and gain performances at different iterative stages are compared in Fig. 4. Impedance matching and gain characteristics are not acceptable after the first iteration. Gradual improvement in impedance-matching has been observed over the operating frequency band. Broadside gain also improves significantly, especially near the higher frequencies. The optimized antenna gain is varying between 11 dBi to 17.6 dBi over its 50% impedance bandwidth.

Optimized principal-plane radiation patterns are obtained at 9 GHz, 10 GHz, 11 GHz, 12 GHz, 13 GHz, and 14 GHz. They are presented in Figs. 5(a), 5(b), 6(a), 6(b), 7(a), and 7(b) respectively. The polarization-purity and back radiation properties are acceptable over the matching bandwidth. However, the sidelobe level performance degrades with the increase in frequency.



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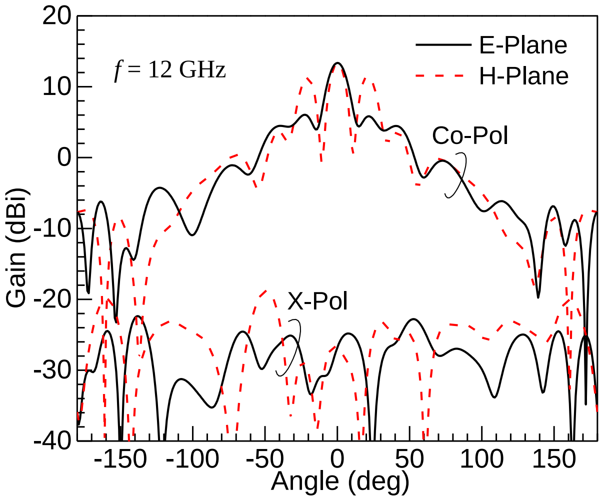

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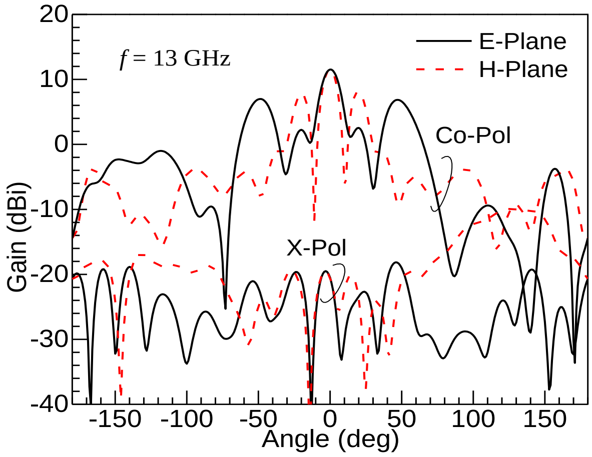
Fig. 6. E-plane and H-plane patterns: (a) at 11 GHz and (b) at 12 GHz. Parameters as in Fig. 1 and Table II.



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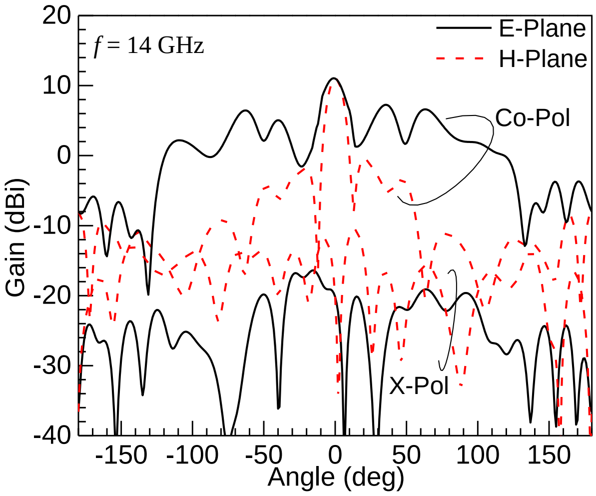

(b)

Fig. 7. E-plane and H-plane patterns: (a) at 13 GHz and (b) at 14 GHz. Parameters as in Fig. 1 and Table II.

V. CONCLUSION

The proposed approach appeared to be very simple and efficient to optimize many antenna parameters over the wide operating bandwidth. The PSO algorithm has been successfully implemented to optimize and design a high-gain as well as wideband resonant cavity antenna. A more complex optimization problem with a complex antenna design may be solved using this proposed approach. Maintaining high gain over the wide operating bandwidth is the key feature of this proposed antenna. As much as 17.6 dBi peak-gain has been successfully realized with 50% antenna bandwidth. Very large simulation time is the major lacuna of this approach with limited computer resources.

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