Design of Wideband Resonant Cavity Antenna using Particle Swarm Optimization

Koushik Dutta, Anirban Chatterjee, Satyajit Chakrabarti, Sunandan Bhunia

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 λ/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]. Their high-gain properties were studied using the reflection properties of the superstrate [7].

Fig. 1. Proposed antenna geometry seen from the (a) side and (b) top. Rectangular microstrip patch: $a = 9, b = 16$, height $= h_r$; $\varepsilon_r$ (foam)=1.07; metal-grid superstrate: size $\sim (a \times b)$, height $= h_s$, thickness $= 20$ mil; strip-widths $\rightarrow w_1, w_2, w_3$, slit-widths $\rightarrow g_1, g_2, g_3$; Feed: $w_f = 1.6$, $w_{st} = 0.5$, slot length $\rightarrow l_s$, $w_s = 1$, $d_{st} = 4.5$, stub-length $\rightarrow l_{st}$, 20 mil substrate $\rightarrow \varepsilon_s \sim 2.2$; 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.

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.

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

<table>
<thead>
<tr>
<th>Target Parameters</th>
<th>( l_s )</th>
<th>( l_{stub} )</th>
<th>( b_s )</th>
<th>( h )</th>
<th>( w_1 )</th>
<th>( w_2 )</th>
<th>( w_3 )</th>
<th>( g_1 )</th>
<th>( g_2 )</th>
<th>( g_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value</td>
<td>10</td>
<td>1</td>
<td>45</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Optimum values after 200 iterations</td>
<td>12</td>
<td>3.8</td>
<td>50</td>
<td>18</td>
<td>13.7</td>
<td>7</td>
<td>5</td>
<td>3.52</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

*All dimensions are in mm.

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 \(\leq -30\) dB and broadside-gain \(\geq 20\) 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 \((10 \times 7)\) 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.

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.

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.

Overall simulation progress for attaining minimum cost function is shown in Fig. 3. A list of optimized parameters is shown in 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.
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.

REFERENCES


AUTHORS PROFILE

Dr Koushik Dutta is an Assistant Professor in the Department of Electronics and Communication Engineering, Netaji Subhash Engineering College, Kolkata. After finishing his B.Sc Physics Honours, he had received his B.Tech., M.Tech., and PhD degrees from Institute of Radio Physics & Electronics under the University of Calcutta. He has researched in developing high-gain resonant cavity antenna with a new concept and theory. He has published over 24 papers in top peer-reviewed Journals and Conferences. Dr Dutta is a Senior Member of IEEE and life member of the Institute of Engineers (India). Presently he is the Student Activity Chair of IEEE Kolkata Section. He received the National Scholarship from MHRD, India in 1999 and IEEE outstanding volunteer Award in 2017. His current research interests include dielectric resonator antenna, microstrip-patch antenna, circularly polarized antenna, Fabry-Perot antenna, and polarization modulation.

Anirban Chatterjee received the B. Tech and M. Tech from Netaji Subhash Engineering College in 2007 and 2012, respectively. He has two years’ experience in the telecom industry with sound knowledge in BSS and infra equipment. He was with Dipnam Project Pvt. Ltd. and ZTE Telecom India Pvt. Ltd since 2007. He joined Meghdad Saha Institute of Technology, Kolkata in 2013 as an assistant professor. Presently, he is pursuing his PhD degree at Netaji Subhash Engineering College under Maulana Abul Kalam Azad University of Technology, West Bengal, India. He has published and presented three IEEE conference papers. His research interests include smart antennas, high gain antennas, dielectric resonator antennas, electromagnetic metamaterials and their antenna applications.

Satyajit Chakrabarti received the BTech, MTech, and PhD degree in Radio Physics and Electronics from the University of Calcutta in 1996, 1998, and 2018 respectively. From 1998 to 1999, he was with Semiconductor Complex Limited, Govt. of India. Since 1999, as a scientist, he is serving the Society of Applied Microwave Electronics Engineering and Research, a premier R&D organization of the Govt. of India. He is a guest lecturer in the Institute of Radio Physics and Electronics, University of Calcutta. He has 21 years of experience in the field of antennas and has over 50 published papers in peer-reviewed journals and international conferences. He has developed different types of antennas at various frequency bands from 1-110 GHz and is involved in a number of design and development projects for the Govt. of India. He is an SM of IEEE and a Fellow of the Antenna Test and Measurement Society of India.

Sunandan Bhunia has obtained his B.Tech and M.Tech from Institute of Radiophysics and Electronics, Calcutta University in 2002 and 2004 respectively. He has obtained PhD degree in engineering from Jadavpur University in 2009. He was awarded gold medal from Vidyasagar University for 1st class 1st in Physics (H) in 1999. He is currently working as Associate professor in the department of Electronics and Communication Engineering, Central Institute of Technology, BTAD, Assam. He has published about 40 research articles in reputed international & national journal and conferences. His area of research interest includes, Microstrip Antenna, Microstrip Filter, and Frequency Selective Surfaces, VLSI etc.