Design of a Dielectric Phase-Correcting Structure for an EBG Resonator Antenna Using Particle Swarm Optimization

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***Abstract*—This paper presents a novel method to design an all-dielectric phase correcting structure (PCS) to improve phase uniformity on the aperture of a classical electromagnetic band gap resonator antenna (ERA). This PCS has fixed permittivity, but varying thickness in a plane perpendicular to the dominant radiated E-field component. A particle swarm optimization (PSO) algorithm and a commercial time-domain solver are combined to optimize the PCS thickness. The proposed PCS not only significantly reduces the phase non-uniformity, but also improves the broadside directivity of the ERA by 4.6 dBi.**

I. INTRODUCTION

Recently, electromagnetic band gap resonator antennas (ERAs), also known as Fabry-Perot resonator antennas, have attracted significant attention from the electromagnetic community. Simple feeding mechanism, highly directive radiation pattern and ease of fabrication are considered as the main advantages of this type of antenna. Conventional ERAs consist of a resonant cavity created between a ground and a partially reflecting superstructure (PRS), which is located at $\lambda_o/2$ distance above the ground plane, where λ_o is the free-space wavelength at the resonance frequency [1]-[2]. The cavity is often excited by a small feed antenna.

Our recent investigations on many ERAs revealed that their phase distributions are quite non-uniform on their aperture and deteriorate when the permittivity of the PRS is low [3]. Non-uniform phase distribution originates from travelling wave effects in the cavity and it degrades directivity and overall performance of ERAs. To address this problem and to achieve better radiation characteristics, a phase correcting structure (PCS) is proposed.

Methods based on optical ray theory have been utilized in several other antennas such as different types of lens antennas to do phase correction [4]-[5]. However, such an approach is not applicable to ERAs. To be more precise, in lens antenna the source of radiation is approximated by a point source placed in the focal point of the lens, whereas there are multiple reflections back and forth in the cavity between PRS and the ground plane. As a result, such a point source assumption is not applicable for ERAs and the whole aperture should be considered as the source of wavefront. Thus, phase transformation should be done by a PCS for all rays emitted from the PRS.

In this paper, a novel method to enhance radiation performance of ERAs by improving the phase distribution is proposed. In our approach, a particle swarm optimization (PSO) algorithm is employed to provide the required phase transformation by designing a phase correcting structure (PCS) with varying thickness. Section II describes the configuration of the ERA under consideration and the method to record the input and output phase values. Section III explains how the PSO algorithm is implemented and Section IV presents results obtained by the time-domain solver of CST Microwave Studio.

II. ERA DESIGN

Fig. 1 shows the configuration of the ERA designed to operate at 13.5 GHz. An unprinted dielectric slab with a permittivity of 3.55 and loss tangent of 0.0027 (Rogers RO4003) is placed at a height of 11 mm, corresponding to $\lambda_o/2$, from the ground plane. The feed antenna is a waveguide-fed slot in the ground plane with dimensions of 12×7.5 mm. The physical area and the thickness of the PRS slab are $6\lambda_0 \times 6\lambda_0$ and $\lambda_g/4$, respectively, where λ_g is the guided wavelength at the design frequency. The ground plane size is $8\lambda_0 \times 8\lambda_0$. To record phase distribution on the aperture, a hypothetical plane is considered at $\lambda_o/4$ above the PRS, this is referred to input phase plane. Another hypothetical plane is considered at a distance of $2\lambda_o$from the PRS. This is called the output phase plane. Here we expect a nearly uniform phase distribution after placing PCS between the two planes. The phase of E_Y component of the electric field is recorded at discrete points on the two reference planes. To do that, the plane apertures are divided into 24 equal columns (parallel to y-axis) with a width of $\lambda_o/4$ as depicted in Fig. 1. The phase values at the center of each column are recorded.

To obtain a uniform phase distribution on the output phase plane, we define an arbitrary constant value for the output phase (ϕ_{output}) and calculate the required phase shift for each recorded input phase values (ϕ_{input}) on the input phase plane. So, the required phase shift is given by

$$\triangle\phi = \phi_{output} - \phi_{input} \tag{1}$$

Here we set the output phase to 360°. Thus, for each column a specific amount of phase shift ($\triangle\phi$) should be provided by the PCS. Consequently, the problem is translated into an easier and more straightforward task which is finding an appropriate

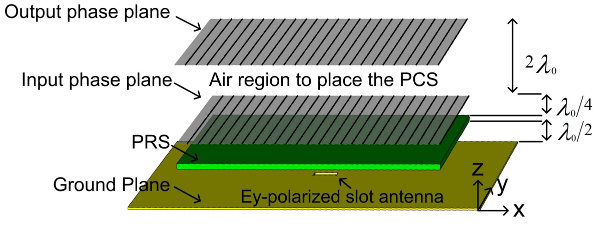

Fig. 1. Configuration of the exemplary ERA along with the input and output phase planes.

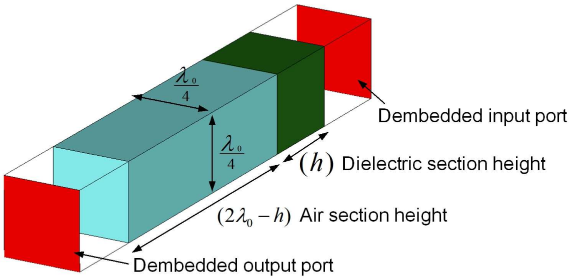

Fig. 2. Unit cell optimization model

height of dielectric material for each column to provide the calculated $\triangle\phi$ by (1). This task is done by the Particle Swarm Optimization (PSO), which is discussed in the next section.

III. DESIGN AND OPTIMIZATION OF PCS

To achieve the required phase shift in each column a PSO algorithm is implemented in Matlab and interfaced with the time-domain simulator in CST microwave studio (CST MWS). PSO like ant colony optimization [6]-[7] and genetic algorithm [8] is a member of evolutionary algorithm family. It was introduced in 1995 [9] and was inspired by imitating the behavior of a swarm of bees, a school of fish or a flock of birds during their food-exploring activities. PSO was then introduced to the electromagnetic society and several modifications have been done on different electromagnetic devices by this evolutionary algorithm [10]-[13]. More details about PSO and how it works with CST MWS are explained in [13]. Due to the symmetrical phase distribution on the ERAs aperture, only 12 distinct phase transformers are needed to compensate phase differences on the H-plane (parallel to the x-axis in Fig. 1). Therefore, a unit cell is designed with input and output ports which correspond to the input and output phase planes. The space between the two ports is filled with Taconic HT-1.5 dielectric material with $\varepsilon_r = 2.35$ and of course air, as depicted in Fig. 2. It means that the effect of air on phase correction in each unit cell has also been considered. The PSO algorithm was run 12 times to find the best dielectric height (h) in each unit cell to reach the required phase shift in each column. Hence, this becomes a one-dimensional single-objective optimization problem.

In the proposed algorithm, particle population is set to 4 and reflecting boundary condition is applied. The solution spaces for h is limited to $[0.1, 43]$ mm. In order to avoid excessive evaluations, a stop condition with the accuracy of 2 degree is considered in the algorithm. Optimization results from the particle swarm are summarized in Table I. The minimum number of iterations is 2, while the maximum iteration number is 12, which is occurred for Column 3. Finally, the PCS with the required height for each Column is placed at input phase plane's position. A full configuration of the ERA with the PCS is shown in Fig. 3.

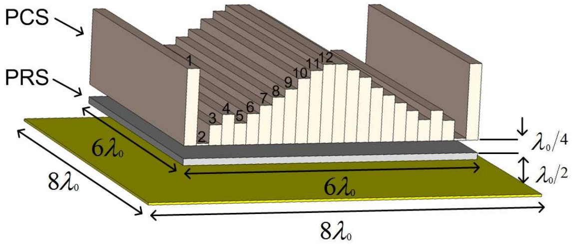

Fig. 3. Designed ERA with the proposed PCS.

TABLE I. PSO RESULTS;$\phi_{output} = 360°$

Column number	ϕ_{input} (Deg.)	$\triangle\phi$ (Deg.)	Dielectric height (mm) (mm)	Iteration number
1	249.9	65.1	33.2	3
2	17.2	342.8	0.9	6
3	88.0	272.0	9	12
4	119.6	240.4	13.1	3
5	91.7	268.3	9.3	3
6	122.9	237.1	13.3	2
7	153.8	206.2	16.6	8
8	179.7	180.3	20.2	2
9	214.5	145.5	23.6	2
10	251.4	108.6	28.1	11
11	282.4	77.6	31.2	3
12	300.3	59.7	33.8	7

IV. RESULTS

The ERA, shown in Fig. 3, was simulated in CST MWS to verify the proposed approach. The phase of E_Y electric field component in the H-plane at the output phase plane is plotted in Fig. 4. It can be seen from this figure that phase uniformity is significantly improved by the PCS. By considering $45°$ phase deviation from the center of the aperture as the uniform phase region, it can be seen that the width of uniform phase region extended from 42 mm to 83 mm, corresponding to 31% and 63% of the total aperture width, respectively. This gives an enhancement of phase uniformity by about 200% and also improves the antenna directivity, as shown in Fig. 5. The peak directivity increased from 11.3 to 15.9, an improvement of 4.6 dBi, while the side lobe level is 14.8 dBi. The input reflection coefficient is shown in Fig. 6. It is clear that the input matching remains better than 12 dB at the design frequency of the antenna (13.5 GHz), despite around 4 dB reduction when the PCS was placed on the ERA.

V. CONCLUSION

A novel method to simultaneously improve the radiation performance and phase uniformity of an electromagnetic bandgap resonator antenna (ERA) by employing the particle swarm optimization is presented in this paper. An all-dielectric phase correcting structure (PCS) was designed and optimized using PSO for a conventional ERA. Results verify that the width of the uniform phase region has been doubled with

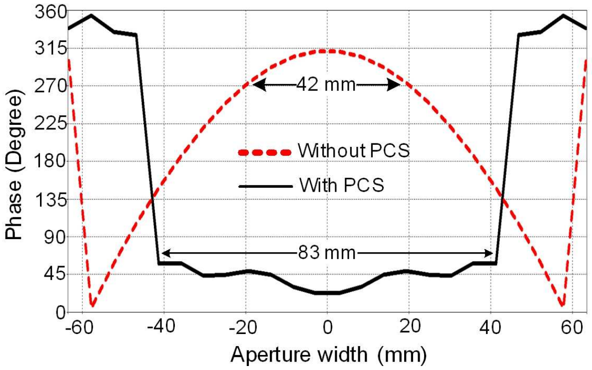

Fig. 4. Phase distribution of the E_Y component on the output phase plane at 13.5 GHz.

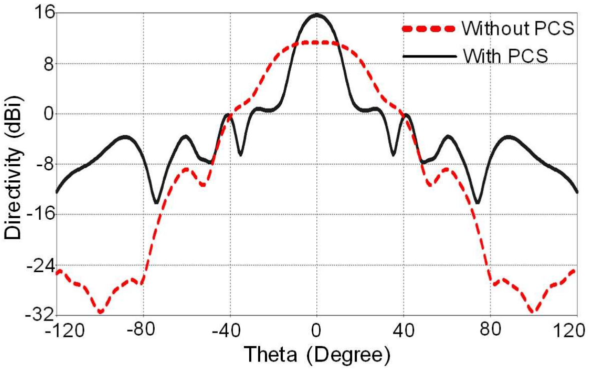

Fig. 5. H-plane farfield directivity of the ERA at 13.5 GHz.

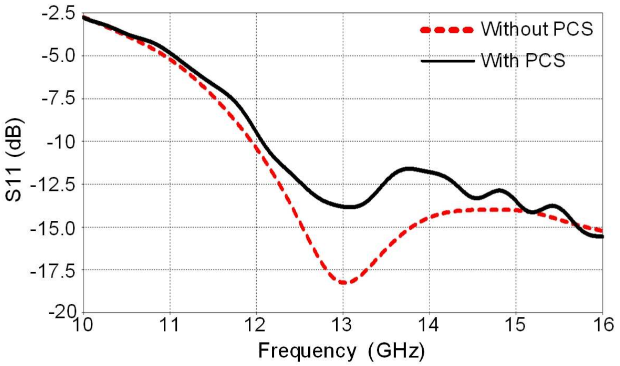

Fig. 6. Input reflection coeficient of the ERA.

the proposed PCS, resulting in 4.6 dBi increase in the peak directivity.

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