Comparative Study and Analysis of High Permittivity and Low Permittivity Continuous Phase Correcting Structures for EBG Resonator Antennas

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***Abstract*—This paper presents low-profile continuous phase correcting structures (PCS) for conventional electromagnetic bandgap resonator antennas (ERAs). This PCS has been implemented using a relative high-permittivity-dielectric material and is compared with a low-permittivity Rexolite PCS reported previously. The use of high permittivity materials is not advisable for the PCS design as it increases reflections from the input surface of the PCS; a PCS is supposed to be highly transmitting structure. However, it was found that if a high-permittivity-dielectric PCS is placed above ERA with a proper spacing then high reflections can be used to an advantage. Overall peak directivity of an ERA with TMM4 PCS is 1 dB more than that of the Rexolite PCS along with 44% reduced height profile.**

I. Introduction

Electromagnetic band gap resonator antennas (ERAs) have low profile, simple configurations and possess highly directive radiation characteristics [1], [2]. ERAs, also known as Fabry-Perot resonator antennas or resonant cavity antennas, comprised of a cavity created between a fully reflecting surface and a partially reflecting structure (PRS) [3]. The PRS can be a 1D, 2D or 3D periodic structure that leaks directive electromagnetic energy in the boresight direction of the ERA [4], [5], [6]. Recently, an insightful investigation into aperture phase distribution of ERAs has opened an area of research focused on enhancing radiation performance of ERAs by improving their aperture phase distributions [7], [8]. It has been found that the aperture phase distribution of conventional ERAs is highly non-uniform, which adversely affects their directive radiation properties. All-dielectric discretized and continuous phase correcting structures (PCSs) have been designed to improve the phase distribution and hence the directivity of such ERAs [7], [8]. Both types of designs have been implemented using a low-permittivity-dielectric material, which was chosen to minimize reflections from PCS. However the height of the resulting structures were large due to large guided wavelength in the low-permittivity-dielectric material. This paper focuses on reducing the height of the continuous PCS demonstrated using Rexolite 1422 dielectric material ($\varepsilon_r = 2.53$) in [8]; the PCS will be referred to as Rexolite PCS hereafter.

The large height is a potential bottleneck and reduce the application horizon of ERAs by excluding applications with space limitations. This paper investigates the height profile issue with an intent to reduce the profile while maintaining same level of performance. A relatively high-permittivity-dielectric material (Rogers TMM4, $\varepsilon_r = 4.5$) is used to design a continuous PCS (referred to as TMM4 PCS hereafter) and its performance is compared with that of the Rexolite PCS. Considerably reduced profile was achieved for TMM4 PCS due to small guided wavelength in TMM4 dielectric.

The rest of the paper is organized such that section II explains the phase correcting structures in general. Section III is about designing a continuous PCS, and Section IV discusses the improvements in the radiation performance of an ERA with the PCS.

II. Phase Correcting Structures and a Typical ERA

One of the oldest application of phase correction is a lens that has been used to focus a beam of light emanating from a less-directive optical source. In technical terms a lens transforms a spherical wavefront passing through it into a planar wavefront. Thick large glass-lens were developed for the purpose, which were efficient but bulky and heavy. Their weight and profiles were later reduced and more compact lenses were developed such as Fresnel lenses. Inspired from the use of lens in optics, its potentials were explored in the field of electromagnetics to design high gain antennas. Lenses were designed to focus the beam of electromagnetic radiation from low gain antennas. There are number of lens designs reported in literature for traditional radiating structures such as horn antennas [9], [10], [11], [12], [13]. The design principle of a lens is based on ray-optics, where a radiating source is approximated as a point source.

The theory has been successfully adopted and demonstrated for antennas with radiating apertures that are small enough to be approximated as a point source. On the other hand, radiating structures such as ERAs do not have a single radiating point as rays leaks across their physical aperture. A cross section of a typical ERA is shown in Fig. 1. It consists of a feed antenna backed by a fully reflecting metallic ground plane. A PRS is placed at a half wavelength spacing from the ground plane, which creates a cavity with the ground plane. The cavity resonates due to constructive addition of successive reflections from the ground plane.

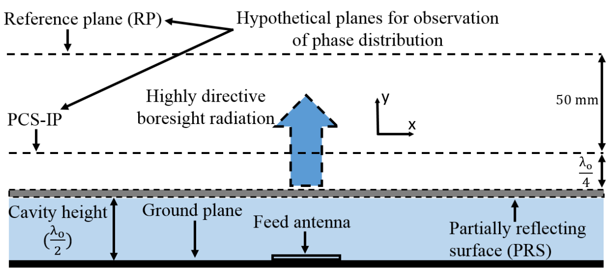


Fig. 1. A cross section view of a conventional ERA used as a base antenna for the proposed phase correcting structure (PCS).

At resonance, rays emerge from multiple points across the aperture creating wavefronts with a non-uniform phase distribution. A comprehensive technique to correct this phase non-uniformity using a PCS has been presented recently; it uses actual phase distribution on the aperture and curve fitting to design a continuous PCSs for ERAs [7].

III. Low-Profile Continuous PCS Design

A continuous PCS was designed with TMM4 for the conventional circularly polarized (CP) ERA shown in Fig. 1. The CP-ERA uses two orthogonal linearly polarized (LP) ideal dipoles as a feed antennas, which were placed near to ground plane. A 3.17 mm thick un-printed slab of Rogers TMM4 is used as the PRS while the cavity height was tuned to 13.2 mm. Two hypothetical planes, parallel to PRS, are considered to observe the input and output phase distribution of the PCS. Using the terminologies introduced in [8], the input plane is referred to as PCS input plane (PCS-IP) and the output plane is referred to as reference plane (RP). The PCS-IP is 8 mm above the PRS and RP is at a spacing of 25 mm from PCS-IP. Cross section of PCS-IP and RP can be seen in Fig. 1.

Phase distribution along the H-plane in PCS-IP is determined by placing virtual e-field probes along the H-plane. Normalized plot of this phase distribution is shown in Fig. 2, which shows that the phase distribution is symmetric around the center of aperture. An analytical expression, referred to as $\theta(r)$ hereafter, with N sinusoidal terms is used to fit the input phase distribution. This $\theta(r)$ has to be transformed to a constant output phase (referred to as $\phi(r)$ hereafter) by providing a phase delay (referred to as $\Delta\phi(r)$).

The expression for the height profile required to transform $\theta(r)$ into $\phi(r)$ is given in [8], which is:

$$h(r) = d - \frac{\lambda_0}{2\pi(\sqrt{\varepsilon_r}-1)}\left(\sum_{n=1}^{N} a_n\left(\sin(c_n) - \sin(b_n r + c_n)\right)\right) \qquad (1)$$

where ε_r is the relative permittivity of the TMM4 dielectric material used for the PCS, λ_o is the free space wavelength at the design frequency of 11 GHz, $d = 25\ mm$ is the upper limit for the thickness of the PCS, a_n, b_n and c_n are coefficients generated for the best fit of analytical expression in the input phase and are given in Table I. N=8 are the number of sinusoidal terms used in curve fitting, while $0 \leq r \leq 81\ mm$ is the radial distance from the center of aperture. The height profile of TMM4 PCS is calculated at the operating frequency and for given input phase distribution and is compared with Rexolite PCS in Fig. 3. The use of high permittivity dielectric material has drastically reduced the height profile of the PCS. The 3D model of the TMM4 PCS used to evaluate performance in simulation is shown in Fig. 4.

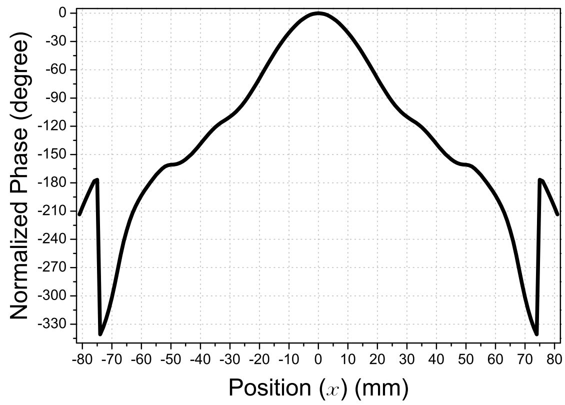


Fig. 2. Normalized phase distribution (θ) of E_y along the H-plane in the PCS-IP.

TABLE I. Coefficients of the Global Analytical Expression Used to Approximate Antenna Phase Non-Uniformity on the Aperture.

n	a_n	b_n	c_n
1	291.3	0.0357	2.902
2	136.8	0.053	-0.5402
3	24.33	0.1539	0.296
4	24.97	0.2259	1.634
5	168.2	0.5242	-4.953
6	553.6	0.5373	-2.182
7	17.89	0.2642	3.897
8	390.1	0.5425	0.815

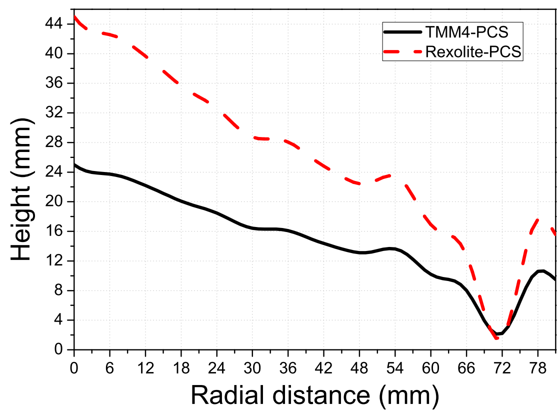


Fig. 3. Height profile of the two PCS, maximum height of TMM4 PCS is almost half of Rexolite PCS.

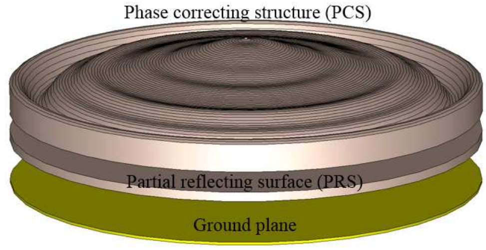


Fig. 4. ERA with the 3D model of TMM4 PCS used for simulation.

IV. Simulated Results

The ERA with the TMM4 PCS was simulated in CST Microwave Studio (CST MWS). The radiation pattern of ERA with the PCS was in general more directive in boresight direction across the operating bandwidth but the the peak directivity was slightly shifted to the higher frequency. To nullify this offset in directivity, the cavity height was retuned to 14.2 mm. To appreciate the improvements in radiation performance, the far-field directivity patterns of the ERA with and without PCS are compared in Fig. 6. The increase in peak directivity at the operating frequency is about 10 dB, this enhancement is slightly better than that achieved with the Rexolite PCS reported in [8]. The ERA has an excellent axial ratio within 3dB beamwidth of the ERA, as shown in Fig. 5. Axial ratio is less than 3dB within a beamwidth of $\sim 26^o$ in the broadside direction, which indicates acceptable CP performance of the ERA with TMM4 PCS.

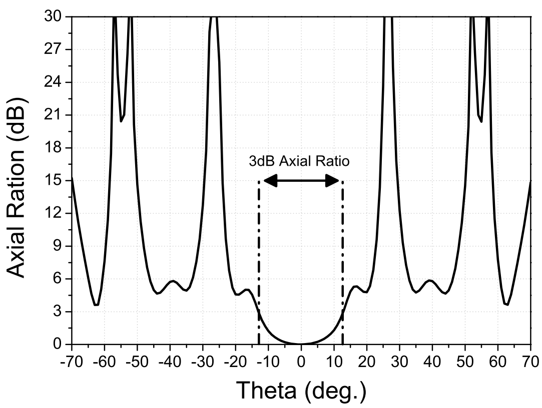


Fig. 5. Axial ratio of the ERA with TMM4 PCS.

The peak directivity with TMM4 PCS is higher than that obtained with Rexolite PCS. Although both have similar transmission phase response their transmission and reflection magnitude responses are different. To investigate this further, reflection coefficients are computed along the radial distance for both the PCSs and are plotted in Fig. 7. TMM4 PCS has reasonably strong reflections in the center of aperture, i.e. $|r| \leq 40$. Use of Multiple reflecting surface separated by quarter wave spacing as a 1D periodic structure have been used to increase the directivity of ERAs[14], [2]. The separation between TMM4 PCS and PRS is close to $\lambda_o/4$. Although same separation exist with Rexolite PCS but since the reflections from the Rexolite PCS were small therefore the overall directivity improvements were only due to phase correction. Reflections from a surface improves amplitude distribution on the aperture, which can be observed clearly from the electric field magnitude plots of the two cases shown in Fig. 8.

The e-field coming out of the PCS is significantly more uniform than without PCS. This phase uniformity of E_y is clearly evident in Fig. 9, which shows field propagation both with without PCS. Another critical figure-of-merit of a resonant cavity antenna is its 3dB directivity bandwidth. Unlike traditional highly directive ERAs (directivity$\geq$20 dBi), which have extremely narrow 3dB directivity bandwidth,

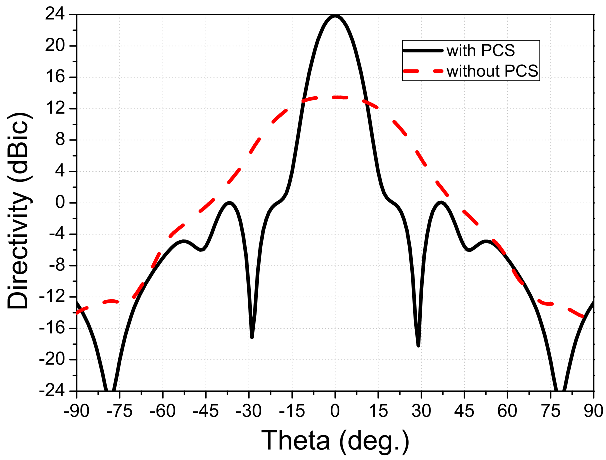


Fig. 6. Directivity pattern of the ERA with and without TMM4 PCS.

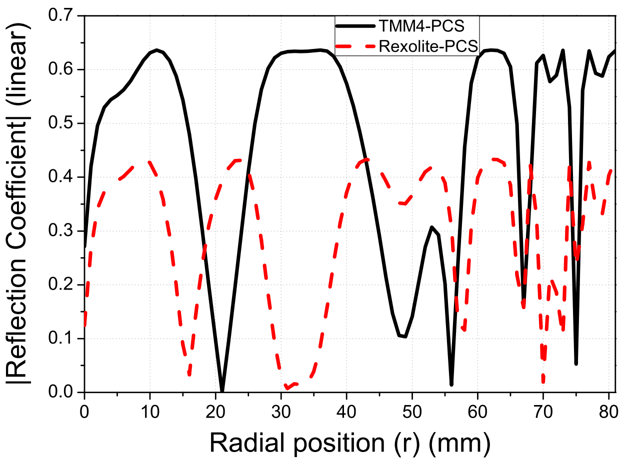
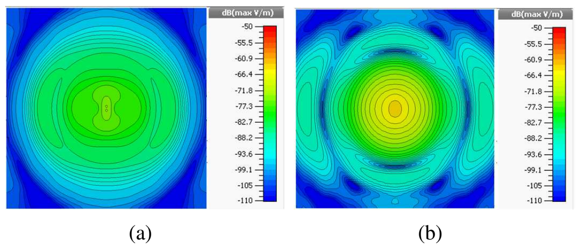


Fig. 7. Magnitude of reflection coefficient at the input of PCSs. TMM4 PCS has strong reflections in most of the aperture than Rexolite PCS



(a) (b)

Fig. 8. Electric field magnitude on the physical aperture of the ERA (a) with TMM4 PCS (b) with Rexolite PCS.

the 3dB directivity bandwidth of the ERAs with the PCS is very encouraging and appreciable. The directivity variation with frequency is shown in Fig. 10, where 3dB directivity bandwidth is almost 800 MHz (from 10.6 GHz to 11.4 GHz), which is 7.8% of the centre frequency. Investigation of directivity bandwidth was not primary goal of this work, hence will not be discussed further. Nevertheless it is an interesting point for investigations in future.

The performance improvements of the ERA with TMM4 PCS are comparable with those obtained with Rexolite PCS. At the

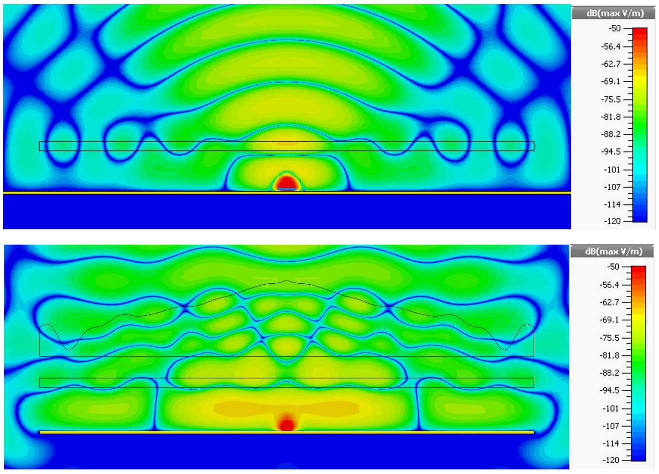


Fig. 9. Electric field propagation along the direction of propagation with and without TMM4 PCS.

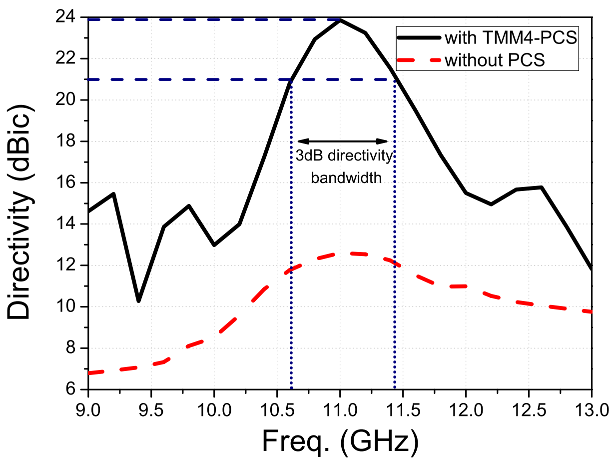


Fig. 10. Peak directivity of the ERA with and without TMM4 PCS.

same time TMM4 PCS is attractive and preferable because of its small height that is almost half of the Rexolite PCS. The key parameters of the two designs are compared in Table II.

Conclusion

A low profile continuous phase correcting structure (PCS) design using Rogers TMM4 has been presented for conventional electromagnetic band gap resonator antennas. The performance and physical dimensions of TMM4 PCS are compared with an earlier proposed design of Rexolite PCS, reported in [8]. Rexolite material has a low permittivity and was used to minimize reflections from the input surface of the PCS. The use of higher permittivity material (TMM4) increases reflections but if placed with proper separation from the PRS the strong reflections can be used to improve amplitude distribution and hence directivity. The thickness of the TMM4 PCS is 44% less than that of the Rexolite PCS yet it provides similar improvements in ERA directivity.

TABLE II. Performance and profile comparison of TMM4 PCS and Rexolite PCS.

Parameter	Rexolite PCS	TMM4 PCS
Maximum height (mm)	45	25
Peak directivity (dBic)	23	23.9
3dB directivity bandwidth (%)	11	7.8

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