Gain Enhancement in a Fabry-Perot Cavity Antenna using Phase Correcting Miniaturised FSS

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Abstract—This paper investigates a method to enhance the radiation pattern of a Fabry – Perot cavity antenna (FPCA) through the use of frequency selective surfaces (FSS) to improve aperture phase distribution. Four FSS sheets were used as walls of a fully enclosed FPCA operating at 2 GHz. Electromagnetic rays at the edge of the FPCA incur a phase change when reflected off the FSS walls making the complete aperture phase distribution more uniform thereby increasing directivity. Simulations demonstrated that the phase correcting FSS walls significantly enhance the directive radiation properties of the FPCA. This includes a 2.1 dBi increase in peak directivity, and a 14.3 % reduction in 3 dB beamwidth (from 42° to 36°).

Keywords—aperture phase, directivity enhancement, Fabry-Perot cavity antenna (FPCA), frequency selective surface (FSS), patch antenna, phase correcting

I. INTRODUCTION

Phase distribution across the aperture of a Fabry – Perot cavity antenna (FPCA) is not uniform. There is a difference in phase that increases as reflections inside the cavity move further out from the radiating antenna in the centre. This phase nonuniformity occurs across the aperture inside the cavity and also in the electromagnetic (EM) waves that are propagated outside the antenna. If this aperture phase distribution is made more uniform, peak directivity will be increased.

Various methods have been studied to improve the phase distribution of conventional antennas. These methods include improvements to the conventional dielectric plano-hyperbolic lens antennas (DPHLA) through the use of phase shifting surfaces (PSS) [1] and other methods that utilise PSS and frequency selective surfaces (FSS) [2] – [5]. Other methods to improve phase distribution include phase correcting lenses such as the Fresnel zone plate lens antenna [6], [7].

Like light rays in an optical lens, EM rays from the single point source in a lens antenna can be focussed, thereby increasing directivity. While the EM rays in the FPCA initially emanate from a single source, such as a patch antenna, the infinite number of EM rays reflecting inside its cavity make it difficult to improve phase uniformity in the same way as the lens antenna. Therefore, other methods of phase correction must be used to improve phase distribution across the FPCA.

This paper presents a patch antenna excited FPCA with its cavity enclosed by convoluted element FSS walls. The FSS has been designed so that phase change caused by reflections off the FSS walls bring the phase at the FPCA aperture's edge

closer to the phase in the centre. This paper is organised as follows. Section II describes the conventional FPCA and its aperture phase distribution. Section III describes the FSS and its phase changing characteristics. Finally, Section IV discusses the design of the modified FPCA that uses FSS walls that are designed to bring greater uniformity to the FPCA's aperture phase distribution. Improvements to the FPCA's aperture phase distribution and its radiation pattern will also be presented in section IV.

II. CONVENTIONAL FPCA AND APERTURE PHASE DISTRIBUTION

The conventional FPCA consists of a partially reflecting surface (PRS) superstrate situated above and parallel to, a fully reflecting ground plane. A single radiator, such as a patch antenna, sits above the ground plane separated by a thin substrate. When the radiator is excited multiple EM rays will reflect inside the cavity between the PRS and the ground plane while some rays will propagate through the PRS in the longitudinal direction of propagation. The distance between the PRS and the ground plane is set at $\lambda_0/2$ such that rays projecting through the PRS are in phase. This has the effect of increasing the directivity and therefore the gain of waves propagated in the longitudinal direction [8]. However, waves also propagate inside the cavity, transverse to the desired direction of propagation and they cause a phase change that increases as they move out from the centre radiator. This phase change causes nonuniformity of phase across the FPCA's aperture and consequently in the longitudinally propagated wave.

III. THE FSS AND ITS PHASE ALTERING PROPERTIES

CST Microwave Studio (www.3ds.com) simulations showed that when a frequency swept plane wave was used to illuminate a 2 GHz stop band convoluted element FSS [9], as expected the phase of the reflection coefficient varied from less than 180° to more than 180° as the frequency passed over the resonant frequency. The FSS was then scaled incrementally smaller and larger than its original size in CST to observe changes to its resonant frequency and the phase of its reflection coefficient at 2 GHz. As expected, smaller and larger unit cells produced higher and lower resonant frequencies of the stop band FSS respectively. For example, decreasing the FSS element dimensions such as peak length and peak-to-peak distance shown in Fig. 1(a) and Table 1 has the effect of increasing track size and narrowing the gap

between them. This has the effect of increasing inductance and capacitance, thereby lowering the resonant frequency of the FSS. It was also found that the phase of the reflection coefficient at 2 GHz for larger and smaller unit cells could be moved above and below 180° . This useful property of this FSS is used to change the phase of reflected EM rays inside the cavity of an FPCA operating at a slightly higher frequency than the stop band of the FSS. After extensive scaling and simulating of the original unit cell in it was found that a unit cell that is 1.05 times the size of the original unit cell caused the required positive phase change ($+30^\circ$) at 2 GHz while still maintaining high reflectivity at that frequency. This FSS unit cell is shown in Fig. 1(a), has a stop band centred 1.98 GHz and is used to make FSS sheets like that shown in Fig. 1(b). The FSS sheets behave as reflective walls that enclose the cavity of an FPCA operating at 2 GHz. The unit cell is printed on a 0.1 mm high PET substrate and its dimensions are shown in Table I. The convoluted elements of this FSS mean its unit cells are much smaller than a conventional 1.98 GHz patch element FSS and has greater angular stability [10]. Thirteen unit cells of the convoluted element FSS fit along the 245 mm (1.63λ) long FPCA walls. In contrast, the sides of a patch in a conventional square patch element FSS need to have a length in the order of $\lambda_0/2$, so only three of those unit cells would fit along an FPCA of the same length. As a lot more of these convoluted elements FSS unit cells can fit along the FPCA's walls, there is greater angular stability and the FSS walls approximate closer to a continuous surface.

Fig. 1. (a) The 1.98 GHz stop band FSS unit cell showing dimensions was used to make (b) FSS sheets used for the walls of the FPCA.

TABLE I. FSS UNIT CELL ELEMENT DIMENSIONS

Parameters	Description	Dimensions
L_1	Element length	12.6 mm
L_2	Outer peak to outer peak	18.9 mm
L_3	Outer peak to inner peak	12.6 mm
L_4	Peak length	3.15 mm
d_1	Peak thickness	1.18 mm
d_2	Trace width	0.79 mm
d_3	Peak to peak	2.1 mm
θ	Peak angle	21°

IV. PROPOSED FPCA WITH FSS WALLS

A conventional FPCA shown in Fig. 2(a) is enclosed by four FSS walls made up of 13 unit cells long by 6 unit cells high as shown in Fig. 2(b). The radiator for the FPCA is a 2

GHz probe fed patch antenna that is 55.6 mm wide and 44.1 mm long. The patch is on a 3.8 mm thick Rogers RO4725 substrate with a ground plane backing. A 19.05 mm thick piece of substrate only FR4 ($6 \times$ sheets of 3.175 mm) was used for the PRS. It has a 2 GHz reflection coefficient of 0.71 which is within the recommended range of between 0.7 and 0.9 for an effective PRS [8] in an FPCA. When this PRS is fabricated, it will need to be glued and pressed during curing to remove any air gaps between layers that would alter the frequency response of the PRS. After running a parameter sweep of the FPCA's cavity in CST it was found that maximum directivity was achieved with a cavity height of 90 mm. As the height of the six unit cells is 91.2 mm this was the logical number to use for the height of the FSS walls. The FSS walls are 13 unit cells long (245 mm or 1.63λ).

Fig. 2. (a) A conventional FPCA and (b) the proposed FPCA with enclosed FSS phase correcting walls with cutout to show the patch antenna of the FPCA inside.

A. Phase Correction

First the conventional FPCA with no sides operating at 2 GHz and shown in Fig. 2(a) was modelled and simulated in CST. To measure the phase across the conventional FPCA's aperture, thirteen E field probes were placed 18 mm apart, parallel to the X axis, along the middle of, and at one quarter wavelength above the PRS. As can be seen in Fig. 3, the normalised phase distribution is from 0° to -62° from the centre of the aperture to the edge respectively.

Fig. 3. Phase distribution across the FPCA's aperture when it has no sides, copper sides and FSS sides.

When the FSS walls made up of the unit cells shown in Fig. 1(a) were used to enclose the FPCA's cavity as shown in Fig. 2(b), a much flatter normalised phase distribution from 0° to -32° was observed across the aperture and is shown in Fig. 3. The FPCA was also enclosed with only copper walls so that a comparison could be made between the FSS walls and perfectly reflecting walls. When the copper walls were in place a normalised phase distribution from 0° to -49° was observed across the aperture and is also shown in Fig. 3.

B. Radiation Pattern

The conventional FPCA with no walls produced a maximum directivity of 12.01 dBi with a 3 dB beamwidth of 42° . The FPCA enclosed with copper walls produced a slightly higher maximum directivity of 12.15 dBi and a 3 dB beamwidth of 46° . The FPCA enclosed with the phase correcting FSS walls produced a maximum directivity of 14.12 dBi, a 3 dB beamwidth of 36° and a maximum realised gain of 13.5 dBi. Real materials were used for the design and simulation of this FPCA in CST, so these simulated results include expected losses. The maximum directivity of the FPCA with phase correcting FSS walls is 2.11 dBi greater than that of the conventional FPCA and 1.97 dBi greater than that of the FPCA with copper walls. The 3 dB beamwidth of the FPCA with FSS walls is 14.3% less than that of the conventional FPCA and 21.7% less than that of the FPCA with copper walls. The E plane directivity patterns of all configurations of the FPCA are shown in Fig. 4. It is planned to fabricate this FPCA, take radiation pattern measurements, and compare them to these simulated results.

Fig. 4. E Plane directivity patterns of the FPCA with no sides, copper sides and FSS sides.

The S_{11} frequency response of the FPCA without walls, copper walls and the 1.98 GHz stop band convoluted element FSS walls are shown in Fig. 5. The 3 dB directivity bandwidth of the FPCA with no walls is 70 MHz, from 1.97 to 2.04 GHz, which is 3.5% of the centre frequency. The 3 dB directivity bandwidth of the FPCA with copper walls is also 70 MHz, from 1.97 to 2.04 GHz, which is 3.5% of the centre frequency. The 3 dB directivity bandwidth of the FPCA with the 1.98 GHz stop band convoluted element FSS walls is 60 MHz, from 1.97 to 2.03 GHz, which is 3% of the centre frequency. The percentage bandwidth of the FPCA with FSS walls has been reduced by 0.5% due to the narrow frequency response of the FSS unit cell.

Fig. 5. The reflection coefficient of the FPCA with no walls, copper walls and phase correcting FSS walls.

V. CONCLUSION

A novel FPCA that uses convoluted element FSS walls to improve aperture phase distribution has been presented in this paper. The 2 GHz reflection coefficient phase properties of a stop band FSS centred at 1.98 GHz were utilised to induce phase change across the aperture of an FPCA operating at 2 GHz. This phase change brought about greater phase uniformity across the FPCA's aperture, thereby increasing peak directivity. This high gain, compact antenna would be effective for applications such as fixed wireless broadband for wireless internet service providers (WISP), or similar applications.

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