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Dual Sub-wavelength Fabry-Perot Cavities for Broadband Highly-Directive Antennas

Konstantinos Konstantinidis, Alexandros P. Feresidis, *Senior Member*, *IEEE* and Peter S. Hall, *Fellow*, *IEEE*

***Abstract*— A new concept for designing broadband and sub-wavelength profile Fabry-Perot type antennas is introduced. A novel multi-layer periodic array design is proposed yielding two sub-wavelength profile Fabry-Perot cavities that significantly enhance the bandwidth performance of the resulting highly-directive antenna. The design is based on two optimized double-layer periodic arrays of dissimilar dimensions, each double-layer array consisting of a capacitive Artificial Magnetic Conductor (AMC) layer and an inductive Partially Reflective Surface (PRS) layer printed on either side of a dielectric substrate. They are placed at about quarter wavelength distance from a ground plane and from each other. Thus, two air cavities are created with a total profile of less than λ/2. The proposed antenna has been simulated in CST Microwave Studio™ achieving 18.3dBi directivity with 8% bandwidth.**

***Index Terms*—Fabry-Perot cavity; Artificial magnetic conductor; Partially reflective surfaces; Leaky-wave antennas.**

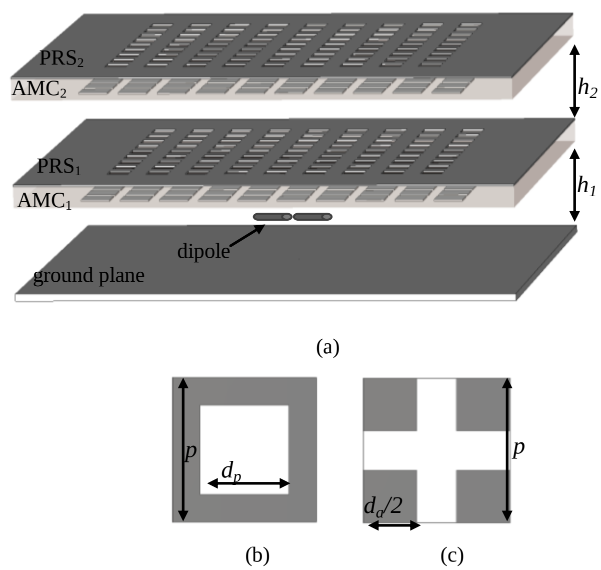

Fig. 1. (a) Scematic digramm of the proposed antenna (dimensions are not to scale), (b) top (PRS array) and (c) bottom (AMC array) view of the unit cell.

I. INTRODUCTION

Fabry-perot cavity (FPC) type leaky wave antennas have been widely investigated in recent years [1, 2], as they are good candidates for applications requiring high-gain performance and high efficiency while having low-complexity feeding networks. Typically they are formed by a Partially Reflective Surface (PRS) placed at approximately half wavelength distance over a metallic ground plane and a low-directivity primary source (e.g. dipole). In such configuration, a Fabry-Perot type resonant cavity is created that significantly increases the directivity of the primary source [1]. In order to understand the operation of this type of antennas, ray optics theory can be employed which describes the multiple reflections of the rays emerging from the primary source between the ground plane and the PRS. Maximum directivity at broadside is achieved at the cavity resonance frequency, i.e. when constructive interference occurs.

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K. Konstantinidis, A. P. Feresidis and P. S. Hall are with the School of Electronic, Electrical and Computer Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, U.K.

Artificial Magnetic Conductor (AMC) surfaces are formed from doubly periodic arrays of metallic elements printed on a grounded dielectric substrate and their key property is that they reflect electromagnetic waves with zero phase shift at a specific frequency [3]. In [4, 5] this property has been exploited for the first time to achieve a FPC antenna of sub-wavelength profile, replacing the ground plane with an AMC surface. More recently, a λ/60 profile FPC antenna has been proposed employing an AMC ground plane and a combination of an AMC and a PRS surface to further reduce the profile [6]. Nevertheless, the above profile reduction techniques suffer from a narrowband antenna performance.

In this paper, a new concept for designing broadband and sub-wavelength profile Fabry-Perot type antennas is introduced. A novel multi-layer periodic array design is proposed yielding two sub-wavelength profile Fabry-Perot cavities that significantly enhance the bandwidth performance of the resulting low profile antenna (Fig. 1a). Two double layer arrays of dissimilar dimensions are designed, each one consisting of an AMC and a PRS surface printed on either side of a dielectric substrate. They are placed at about quarter wavelength from a ground plane and from each other. Thus, two quarter-wave air cavities are created with a total profile of about λ/2. The elements on both AMC and PRS surfaces are sub-wavelength and not resonant in the frequency range of interest. A dipole, placed in the middle of the first cavity, is used as a primary source. A periodic analysis at unit cell level is initially carried out to extract and optimise the reflection characteristics of the surfaces. A finite size antenna employing the optimized multi-layer surfaces is simulated and presented in order to validate the advantages of the proposed design.

II. Design of Periodic PRS-AMC Arrays

A. Unit Cell Design

In this section, a multi-layer array structure is designed employing two pairs of composite AMC-PRS surfaces (Fig. 1a). The AMC and PRS arrays are printed on both sides of a 1.5mm thick dielectric substrate with ε_r=2.2. The AMC arrays are formed by square metallic patches with a periodicity p=5.5mm, while the PRS arrays are formed by square apertures with the same periodicity and shifted with respect to the AMC array by p/2 in x- and y-axis as shown in Fig. 1(b) and (c). Initially the first AMC-PRS array is designed, such that high reflection magnitude values and a close to zero reflection phase are obtained for normal plane wave incidence from the AMC side. The reflection phase is controlled predominately by the dimensions of the AMC while the reflection magnitude by the aperture size of the PRS.

Next, a second double-layer array is added over the first one (Fig. 2). The resonance condition for the formed cavity with thickness h_2 (Fig. 2), is written in (1) where ψ_{R1} and ϕ_{R2} are the reflection coefficient phases as shown in the figure under normal incidence. The PRS_1 array and the AMC_2 array are designed to achieve reflection phases ψ_{R1} and ϕ_{R2} respectively that satisfy (2) for a cavity thickness h_2 of about λ/4 at 13.7GHz.

Periodic boundary conditions are applied to the unit cell of the structure in CST Microwave Studio, assuming an infinite structure, and the reflection coefficients are extracted. The dimensions are shown in Fig. 2 with d_{p1}=3.4mm, d_{p2}=3.7mm, d_{a1}=d_{a2}=4mm and h_2=4.8mm. These dimensions are chosen after investigation based on the previous analysis. The phase (ψ_{R1}) and magnitude of the reflection coefficients under normal incidence at PRS_1 (first layer) are presented in Fig. 3. High magnitude values are obtained, while the reflection phase is 169^o at 13.7GHz. The complex reflection coefficient at AMC_2 is shown in Fig. 4. It can be observed that the reflection phase ϕ_{R2} is equal to -15^o at 13.7GHz. Substituting the values of ϕ_{R2} and ψ_{R1} in (2) results in a cavity thickness h_2 equal to 4.98mm, which is close to quarter wavelength.

Then, the complex reflection coefficient of the multi-layer structure for normal incidence at AMC_1, is presented in Fig. 5. The reflection phase ϕ_{R1} is zero at 13.7GHz. Moreover, a phase increase is observed around zero degrees between 13.5GHz and 13.9GHz. Based on a ray optics analysis explained in [7], for a maximum directivity within a certain frequency range, a linearly increasing with frequency phase response is required. The theoretical ideal phase derived from ray theory is also included in the graph. It is expected that at the frequencies where the two phase responses intersect, the directivity will be maximum.

Finally, the multi-layer structure is placed over a ground plane and a primary source (dipole). The first cavity thickness is set at h_1=5.5mm (Fig. 1a) which is λ/4 at 13.7GHz, where the reflection phase is equal to zero. This will produce a dual quarter-wave resonant cavity antenna with a total profile of about λ/2.

$$\phi_{R2} + \psi_{R1} - \frac{2\pi}{\lambda} 2h_2 = \pm 2N\pi, \quad N=0,1,2... \quad (1)$$

$$h_2 = (\frac{\phi_{R2}}{\psi_{R1}} - 1)\frac{\lambda}{4} + N\frac{\lambda}{2}, \quad N=0,1,2... \quad (2)$$

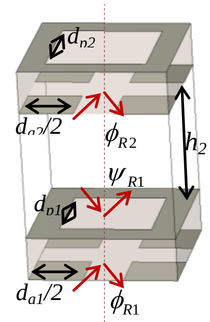

Fig. 2. Unit cell of the multi-layer structure.

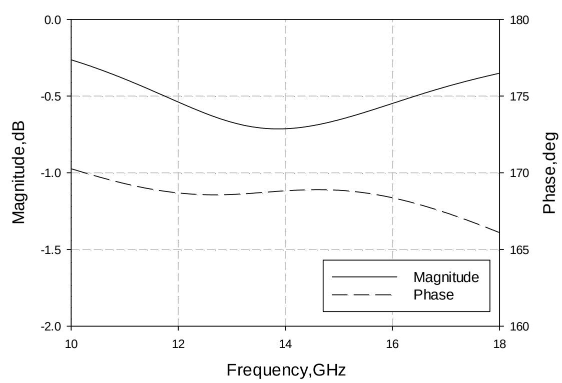

Fig. 3. Reflection magnitude and phase at PRS_1.

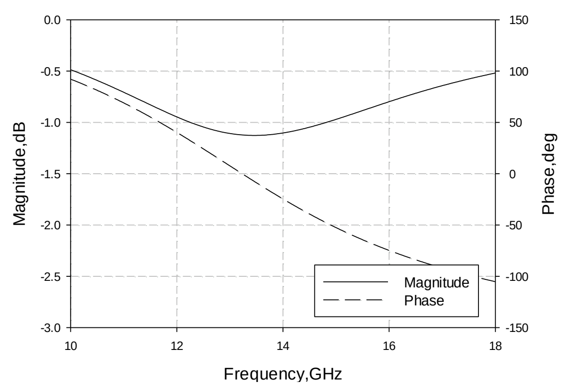

Fig. 4. Reflection magnitude and phase at AMC_2.

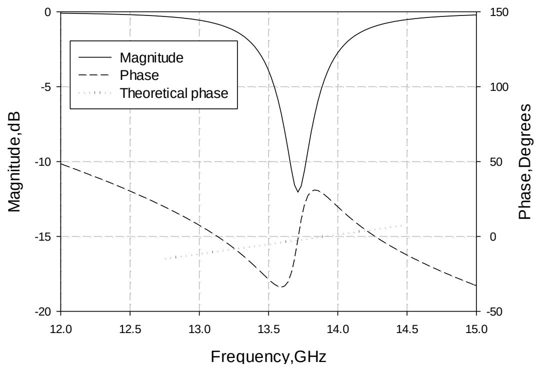

Fig. 5. Reflection magnitude and phase of the multi-layer AMC-PRS.

B. Finite Size Antenna

A finite size antenna has been implemented based on the unit cell analysis, employing two double-layer AMC-PRS structures over a ground plane (Fig. 1a). The overall lateral dimensions of the structure are 80mm x 80mm, while the cavity distances and the dimensions of the periodic elements are those mentioned in the previous subsection. The profile of the antenna is thus h_1+h_2 plus 3mm which is the total thickness of the two dielectric substrates. So in total, the antenna profile is 13.3mm, which is just over λ/2 at the central frequency 13.7GHz. An ideal dipole has been used as excitation, placed in the middle of the first cavity. The simulated directivity versus frequency is presented in Fig. 6. Two peaks occur in the directivity which correspond approximately to the two intersection points between the reflection phase of the optimised multi-layer array and the ideal phase satisfying the resonant condition. A maximum of 18.3dBi is obtained at 14.05GHz. A broadband performance is achieved with a 3-dB radiation bandwidth of 8%. The simulated H- and E-plane radiation patterns are shown in Fig. 7 for four frequencies within the operational bandwidth of the antenna. Good sidelobe level (below -10dB) is observed with the patterns deteriorating as the frequency increases which is a typical behavior in leaky wave antennas.

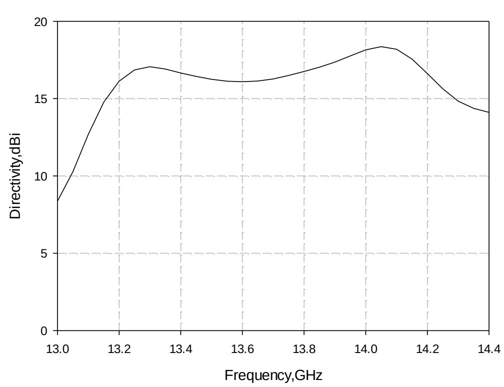

Fig. 6. Directivity vs frequency for the proposed multi-layer AMC-PRS antenna.

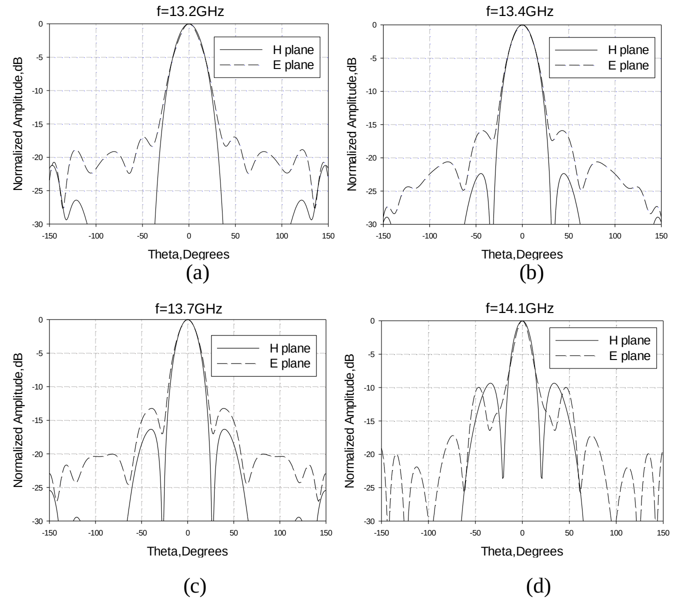

Fig. 7. Simulated H- and E-plane radiation patterns at (a) 13.2GHz, (b) 13.4GHz, (c) 13.7GHz and (d) 14.1GHz

III. Conclusion

A new technique for designing low-profile broadband FPC antennas is presented employing two optimized double-layer periodic arrays of dissimilar dimensions. Each double-layer array consists of a capacitive AMC layer and an inductive PRS layer printed on either side of a dielectric substrate. The design of the structure is optimized using ray optics analysis. Bandwidth enhancement is achieved with the proposed antenna while maintaining high directivity values.

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