Abstract—A method for designing sub-wavelength-profile and broadband high-gain planar antennas is presented. A novel multi-layer periodic array design is proposed for sub-wavelength Fabry-Perot cavity type antennas with enhanced bandwidth performance. Three double-sided periodic arrays are designed and optimised, each double-sided array consisting of a capacitive Artificial Impedance Surface (AIS) and an inductive Partially Reflective Surface (PRS) printed on either side of a dielectric substrate. They are placed at about sixth of a wavelength from a ground plane and from each other. Thus, three air cavities are created with a total profile of \( \lambda/2 \). The proposed antenna has been simulated using CST Microwave Studio\textsuperscript{TM} and measured achieving 16.9\,dBi directivity with 10.7\% 3dB bandwidth. The gain-bandwidth product of the measured prototype outperforms any previous Fabry-Perot antenna design with this profile.

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

I. INTRODUCTION

Metamaterial based structures have been extensively employed in recent years to achieve antenna directivity enhancement [1-3]. A typical implementation of planar highly directive antennas that has attracted significant interest in the past is based on periodic superstrates to create Fabry-perot cavity (FPC) type leaky wave antennas [4, 5]. These designs provide high efficiency and eliminate the need for a complex feeding network. The superstrate, typically formed by a doubly periodic array of elements, is placed at approximately half wavelength distance over a metallic ground plane and a low-directivity primary source (e.g. dipole). The periodic array acts as a Partially Reflective Surface (PRS), which suggests that a leaky-wave approach can be adopted to interpret the operation of the formed antenna [6-8]. Moreover, a ray optics theory has been successfully employed to describe the operation of this type of antennas and estimate the directivity performance [9, 10]. According to this theory, maximum directivity is achieved when constructive interference occurs between the direct rays emerging from the primary source and the reflected rays which undergo multiple reflections between the ground plane and the PRS [9, 10].

Due to the resonance related operation of FPC antennas, they suffer from narrow bandwidth. Recently, a technique for bandwidth improvement was introduced [11] using the coupling between two surfaces to obtain a positive phase gradient that satisfies the resonance condition of the antenna cavity for a certain frequency range. This technique was further investigated in more recent works employing different

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configurations [12-16]. However, this technique implies an increase to the total antenna profile, since the coupled surfaces have a large separation of half wavelength between them and also from the ground plane, resulting to a total profile of over a wavelength.

The profile reduction of FPC type antennas has also been studied extensively by replacing the ground plane with an Artificial Magnetic Conductor (AMC). AMCs are formed by a periodic arrangement of metallic patches on a grounded dielectric substrate and were first introduced by Sievenpiper et al. [17]. Their key property is that they reflect electromagnetic waves with zero phase shift at a specific frequency. This property has been exploited to obtain λ/4 profile highly directive antennas [18-22]. A further profile reduction has been proposed demonstrating operation of sub-wavelength cavity modes (~λ/16) [23] and an ultrathin directive antenna (~λ/60) [24], both employing an AMC ground plane and a combination of an AMC and a PRS superstrate. However, all the above designs were characterized by narrow bandwidth. Recently, a first report of a method to achieve bandwidth enhancement of sub-wavelength profile FPC was presented in [25].

In this paper, we present a novel multilayer sub-wavelength profile FPC antenna with a significantly increased bandwidth performance (Fig. 1a). Three double-sided arrays are employed each one consisting of an Artificial Impedance Surface (AIS) and a PRS surface with sub-wavelength unit cell dimensions printed on either sides of a dielectric substrate. They are placed at a distance of about λ/6 from a ground plane and from each other. Thus, three air cavities are created with a total profile of ~λ/2. The elements on both AIS and PRS surfaces are sub-wavelength and non-resonant in the frequency range of interest (Fig. 1b). Two optimised microstrip-fed slots are used as a low directivity source to excite the sub-wavelength cavities (Fig. 1c). A periodic analysis is initially carried out to extract the reflection characteristics of the surfaces and estimate the antenna performance. Three finite size antennas are presented using a single-layer, a double-layer and a three-layer AIS-PRS respectively.

This paper is organized as follows. The design of a single-layer AIS-PRS for a λ/6 profile antenna is described in Section II (A), including periodic analysis. Then, a double-layer structure is presented in Section II (B) employing two pairs of AIS-PRS surfaces. Subsequently, a three-layer structure designed formed by three composite AIS-PRS surfaces at a distance of λ/6 from each other, is analyzed in Section II (C). In Section III the design and comparison of three finite size antennas based on the periodic analysis in the previous sections is carried out as well as a comparison between the proposed three-layer AIS-PRS antenna and a conventional single-layer Fabry-Perot antenna of λ/2 profile in terms of directivity and bandwidth. Fabrication and measurements of the proposed three-layer antenna are presented in Section IV and finally conclusions are given in Section V.

II. UNIT CELL DESIGN OF AIS-PRS

A. Single-layer AIS-PRS

Initially a single layer AIS-PRS structure is designed. The AIS and PRS arrays are printed on both sides of a 1.55mm thick dielectric substrate with εr=2.2. The AIS array is formed by square metallic patches with a periodicity p=5.5mm, while the PRS array is formed by square apertures with the same periodicity, shifted with respect to the AIS array by p/2 in x and y-axis. The unit cell dimensions are shown in Fig. 1(b) for the bottom (AIS) side and for the top (PRS) side, with d0=3mm and d1=4.4mm. In order to create a λ/6 cavity, the reflection phase of the structure φr has to satisfy (1) for h=λ/6 (π is the phase introduced by the total reflection at the ground), i.e. to be -60° at the desired operating frequency, with high reflection magnitude values to achieve a high directivity antenna. The phase is controlled predominantly by the dimensions of the AIS while the magnitude by the aperture size of the PRS. Therefore the dimensions of the unit cell have been carefully selected to obtain the required reflection phase at 14GHz. Periodic boundary conditions are applied in the simulation software, assuming an infinite structure to extract the reflection coefficients. The simulated reflection characteristics are presented in Fig. 2. It can be observed that high values of magnitude are obtained due to the highly reflective PRS and a reflection phase of ~60° is obtained at 14GHz.

$$\phi_r = -\frac{2\pi}{\lambda} - 2h = \pm 2N\pi, \; N=0,1,2... \; (1)$$

![Fig. 2. Reflection magnitude and phase of single layer AIS-PRS.](image)

B. Double-layer AIS-PRS

Next, the concept of the sub-wavelength profile antenna is extended for multilayer structures. In this section, a double layer structure is designed employing two composite surfaces of AIS-PRS. Initially the first layer is designed following the procedure that was followed for the design of the single AIS-PRS layer. The dimensions are chosen such that high reflection magnitude values and a reflection phase of ~60° are obtained. Next, a second layer is added at λ/6 distance from the first one. The resonance condition (2) for the second cavity is derived from (1) after replacing the reflection phase π from the ground plane with ψ1, which is the reflection phase at the
first layer from the PRS side. In this case, the reflection phase at the second layer from the AIS side is $\phi_{R2}$ (Fig. 3). Since $\psi_{R1}$ is replacing the full reflection from the ground plane, the PRS of the first layer should be designed to achieve a phase of around $\pi$ (180$^\circ$). Substituting $h_2$ with $\lambda/6$ in (3), which arises rearranging equation (2), the value of $\phi_{R2}$ can be calculated. For $N=1$ and $\psi_{R1}=172^\circ$, it can be extracted that $\phi_{R2}$ should be $-68^\circ$ at the operational frequency for the equation to be satisfied.

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

$$h_2 = (\psi_{R2} - \frac{\psi_{R1}}{\psi_{R1}} \frac{\lambda}{4} + N\frac{\lambda}{2}, \quad N=0,1,2... \quad(3)$$

Periodic boundary conditions are then applied to the unit cell of the multilayer structure and the reflection coefficients are extracted. The dimensions are shown in Fig. 3 with $d_{a1}=3mm$, $d_{a2}=3.6mm$, $d_{a3}=d_{a4}=4.4mm$ and $h_1=3.6mm$. Furthermore the thickness of the first cavity is $h_1=4mm$. These dimensions are chosen after investigation, in order to obtain the desired values for the reflection phases $\phi_{R1}$, $\phi_{R2}$ and $\psi_{R1}$. The phase and magnitude for reflection at the PRS$_1$ (first layer) are presented in Fig. 4. High magnitude values are obtained, while the reflection phase $\psi_{R1}$ is stable at 172$^\circ$ around the resonant frequency. For the second layer, the complex reflection coefficient at the side of AIS$_2$ is shown in Fig. 5. It can be observed that the reflection phase $\phi_{R2}$ is -70$^\circ$ around 14GHz. Inserting the values of $\psi_{R1}$ and $\phi_{R2}$ for $f=14GHz$ at (3) the cavity distance is $h_2=3.53mm$ which is in good agreement with the actual value that has been used. Finally, the complex reflection coefficient for incidence at AIS$_2$, including the complete double layer unit cell in the simulation, is presented in Fig. 6. It should be noted at this point that the selection of the aperture size of the PRSs has been such that a phase increase would be achieved in the frequency range of operation. This derives from (1), which shows that for a maximum directivity within a certain frequency range, a linearly-increasing-with-frequency phase response is required. Indeed, from Fig. 6 it can be observed that a phase increase occurs for $\phi_{R1}$, between 13.6GHz and 13.8GHz. The theoretical phase derived from (1) for $h_1=4mm$ is also included in the graph. It is expected that at the frequencies where the two phase responses intersect, the directivity will be maximum. Moreover, the reflection phase $\phi_{R1}$ is -50$^\circ$ at 13.7GHz, resulting in a cavity thickness of $h_1=3.95mm$ from the ray optics analysis, which again is close to the actual value that has been used for the design.
C. Three-layer AIS-PRS

In this subsection a three-layer AIS-PRS structure is presented. It must be emphasized that all three AIS-PRS layers in this design are different from the double-layer structure presented in the previous section II (B). Based on the conclusion extracted from the analysis in the previous subsection, the concept is further extended here to the design of three composite AIS-PRS layers of sub-wavelength profile. The unit cell of the structure is shown in Fig. 7. The first two layers are designed to satisfy (2) and (3) as described in the previous sections. For the third layer the dimensions are chosen such that the reflection phase $\phi_{R3}$ will result in a cavity of $h_3 = \lambda/6$ at the central frequency. The new optimised dimensions are $d_{p1}=3.5\text{mm}$, $d_{p2}=3.1\text{mm}$, $d_{p3}=4.3\text{mm}$, $d_{a1}=d_{a2}=d_{a3}=4.4\text{mm}$, $h_2=3.9\text{mm}$ and $h_1=2.64\text{mm}$ (Fig. 7). Also, the first cavity thickness $h_1$ is set at 3.65mm (Fig. 1a).

Periodic boundary conditions are applied to the unit cell of the structure and the reflection characteristics are calculated. For incidence at PRS$_1$, the magnitude and phase of the reflection coefficients are presented in Fig. 8. For incidence at the AIS$_2$ (second layer) the reflection magnitude and phase are presented in Fig. 9. It can be seen from Fig. 8 and Fig. 9 that the reflection phases $\psi_{R1}$ and $\phi_{R2}$ at 13.7GHz, are 171° and -53° respectively. These values correspond to a cavity thickness $h_2=4.1\text{mm}$ which is close to the optimised one. In Fig. 10 and Fig. 11, the reflection coefficients for incidence at PRS$_2$ and AIS$_3$ are depicted respectively. In this case, the reflection phases $\psi_{R2}$ at 13.7GHz is 188°, while $\phi_{R3}=-90°$ at the same frequency. Substituting this values in the resonance condition for the third cavity, gives $h_3=2.5\text{mm}$. Finally, the reflection coefficients of the complete structure, for incidence at the first layer (AIS$_1$) are shown in Fig. 12. It can be observed that a double reflection phase increase with frequency is obtained for $\phi_{R1}$ from 13.1GHz to 14.2GHz. The theoretical ideal phase for $h_1=3.65\text{mm}$ is again included in the graph. The obtained phase follows closely the ideal phase indicating that a more broadband antenna performance for this optimised three layer structure is expected. Moreover, the reflection phase $\phi_{R1}$ is -65° at 13.7GHz, giving a cavity thickness of $h_1=3.5\text{mm}$ which determines the distance from the ground plane (Fig. 1a).

![Fig. 7. Unit cell of the three layer structure.](image)
It is evident that an improved response, corresponding to the resonant modes of the two coupled cavities. It can be observed that three peaks occur in the directivity curve at 13.8GHz with a 3dB radiation bandwidth of 10.7%. A fluctuation of less than 2dB is observed over the operational bandwidth. The antenna dimensions could be further optimised to achieve a more flat directivity response. Comparing the aforementioned antenna designs presented in the figure, it is evident that the three AIS-PRS layer antenna achieves a more broadband performance. It can also be observed that three peaks occur in the directivity curve in the latter case, corresponding to the three resonant modes. A more detailed comparison between the three designs in terms of maximum directivity and 3dB bandwidth is presented in Table I.

<table>
<thead>
<tr>
<th>Antenna Design</th>
<th>Directivity max (dBi)</th>
<th>Bandwidth 3dB</th>
</tr>
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<tbody>
<tr>
<td>Single-Layer AIS-PRS</td>
<td>17</td>
<td>4.1%</td>
</tr>
<tr>
<td>Double-Layer AIS-PRS</td>
<td>17.2</td>
<td>7%</td>
</tr>
<tr>
<td>Three-Layer AIS-PRS</td>
<td>16.9</td>
<td>10.7%</td>
</tr>
</tbody>
</table>

Finally, based on the periodic analysis of the three AIS-PRS layer structure, a three-layer finite size antenna has been implemented as shown in Fig. 1(a). The antenna has the same overall lateral size like the previous two cases. The dimensions of the elements and the cavity distances are those mentioned in Section II (C). The total profile of the antenna in this case is \( h_1+h_2+h_3 \) which is approximately \( \lambda/2 \). The double-slot feeding structure is used again, to ensure a matching covering the antenna’s operation frequency range (see Section IV). The simulated directivity response of the antenna is presented again in Fig. 13. A maximum of 16.9dBi is achieved at 13.8GHz with a 3dB radiation bandwidth of 10.7%. A fluctuation of less than 2dB is observed over the operational bandwidth. The antenna dimensions could be further optimised to achieve a more flat directivity response. Comparing the aforementioned antenna designs presented in the figure, it is evident that the three AIS-PRS layer antenna achieves a more broadband performance. It can also be observed that three peaks occur in the directivity curve in the latter case, corresponding to the three resonant modes. A more detailed comparison between the three designs in terms of maximum directivity and 3dB bandwidth is presented in Table I.
B. Comparison with a Conventional \(\lambda/2\) Profile Fabry-Perot PRS Antenna

In this subsection, a comparison of the proposed three AIS-PRS layer antenna with a conventional \(\lambda/2\) profile Fabry-Perot antenna is carried out. The antenna under study consists of one layer aperture PRS placed at half wavelength distance in front of a ground plane. It is fed using the same feeding technique comprising the microstrip line fed slots. The investigated structure has been designed to operate in the same frequency band and achieve the same maximum directivity as the proposed antenna so that a fair comparison can be performed. In Fig. 14, the directivity versus frequency for the two evaluated designs is shown. The conventional Fabry-Perot antenna achieves a maximum directivity of 16.8\,dB at 13.7GHz with a 3dB bandwidth of 5.6%. It can be extracted from the figure that the proposed three AIS-PRS layer antenna outperforms the single layer antenna in terms of bandwidth while keeping the same total profile (\(\lambda/2\)). Moreover, the directivity response of the proposed structure shows a faster roll-off. From Table II, it can be seen that the 2dB radiation bandwidth is more than doubled in the case of the proposed antenna compared with the single layer PRS antenna. Finally, the radiation patterns at the two edges of the operational bandwidth of the single layer antenna are shown in Fig. 15 for both antennas. As can be seen from the figure, a significantly improved sidelobe level is obtained with the proposed antenna, especially for the E-plane patterns. More specifically, the sidelobe level for the E-plane at 13.3GHz is -8dB and -13dB for the conventional antenna and the proposed antenna respectively. At 14.1GHz where higher order modes tend to deteriorate the radiation patterns of such type leaky wave antennas, the obtained improvement is more evident, with sidelobe levels of -3dB and -12dB for the single layer antenna and the three AIS-PRS layer antenna respectively.

![Fig. 14. Directivity vs frequency comparison between the proposed three layer AIS-PRS antenna and the single layer Fabry-Perot antenna.](image)

**TABLE II.** ANTENNA PERFORMANCE COMPARISON BETWEEN THE SINGLE LAYER FABRY-PEROT ANTENNA AND THE PROPOSED THREE LAYER AIS-PRS ANTENNA

<table>
<thead>
<tr>
<th>Antenna Profile</th>
<th>Directivity max (dB)</th>
<th>Bandwidth (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Layer (\lambda/2)</td>
<td>16.8</td>
<td>4.5</td>
</tr>
</tbody>
</table>
Fig. 16. (a) Photograph of the fabricated three layer AIS-PRS, (b) Both sides of AIS-PRS and (c) Both sides of the feeding structure.

Fig. 17. Simulated and measured S11 of the proposed antenna.

Fig. 18. Simulated and measured realized gain of the final antenna.

Fig. 19. Simulated and measured radiation patterns for the (a) H-plane and (b) E-plane in five frequencies over the operational bandwidth of the antenna.

V. CONCLUSIONS

A technique for designing sub-wavelength profile antennas achieving broadband highly directive performance has been demonstrated through simulated and experimental results. Three sub-wavelength antennas have been investigated based on optimised composite double-layer arrays. A dual-resonant feeding mechanism was employed to cover the broad bandwidth of the antenna. The design of the antenna structures has been optimised using a combination of ray optics analysis and periodic full-wave simulations. Finally, a prototype of the three AIS-PRS layer antenna was fabricated and tested achieving 16.3dBi gain and 10.9% 3dB bandwidth with $S_{11}$...
below -10dB. The antenna has a profile of \( \lambda/2 \) and outperforms other reported antennas with the same profile.

**REFERENCES**


