Metamaterial-based Fabry-Pérot leaky wave antennas: low profile, high directivity, frequency agility and beam steering

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Abstract. The analysis and design of subwavelength metamaterial-based Fabry-Pérot (FP) leaky wave antennas (LWAs) are presented. The antennas under investigation are formed by embedding a feeding source in a cavity composed of a Perfect Electrical Conductor (PEC) surface and a metasurface reflector. Several configurations of such antennas are presented to achieve different desired performances such as: high directivity, frequency agility and beam steering.

1. Introduction

According to the earlier work of Trentini [1], the thickness $h$ of a FP cavity antenna is given by the resonance condition:

$$h + d\sqrt{\varepsilon_r} = \left(\phi_{prS} + \phi_r\right) \frac{\lambda}{4\pi} \pm \frac{N}{2} \frac{\lambda}{2} \quad (1)$$

where $\phi_{prS}$ is the reflection phase of the PRS reflector, $\phi_r$ is the reflection phase of the reflector near the antenna, and $N$ is an integer corresponding to the order of the cavity’s electromagnetic mode. $d$ and $\varepsilon_r$ are respectively the thickness and the relative permittivity of the antenna’s dielectric board. Recent developments on FP LWAs have shown the possibility to design subwavelength resonant cavities by minimizing the total reflection phase shift $\phi_{prS} + \phi_r$ [2-5]. Indeed, Artificial Magnetic Conductor (AMC) surfaces and metasurfaces have been proposed for applications as Partially Reflective Surface (PRS) in the design of compact cavity antennas. These surfaces present a tailored reflection phase characteristic varying from $+180^\circ$ to $-180^\circ$ and crossing $0^\circ$ at the resonance frequency.

In this present work, we report the design of metamaterial-based resonant cavities for different applications. Firstly, we will show how low-profile configuration is achieved and also how directivity and gain can be considerably increased. And secondly, reconfigurability in terms of frequency and beam angle will be presented.

2. Low-profile highly directive FP LWA

FP cavity antennas are formed by placing a feeding source between two reflectors as shown in figure 1(a). In general, one of the two reflectors is PEC surface so as to prevent undesired backward radiation. The second reflector must present a high reflectivity in order to act as the so-called Partially

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Reflective Surface (PRS). This PRS is used to confine the electromagnetic waves in the cavity. Our recent works \[4, 5\] have shown that metasurfaces composed simultaneously of an inductive and capacitive grid are suitable for this purpose. The inductive grid and capacitive grid are respectively made of a periodic array of copper mesh and square patches. The grids are patterned on the two faces of a dielectric substrate as illustrated by the unit cell in figure 1(b). This metasurface presents an LC resonance where the reflection phase varies from +180° to -180° and crosses 0° at the resonance as shown by the S-parameters in figures 1(c) and 1(d). As it can be seen in equation (1), the reflection phase values of the PRS (\( \phi_{PRS} \)) are needed to calculate the thickness \( h \) of the cavity versus the frequency at which maximum boresight directivity can be obtained. Subwavelength thicknesses (\( h < \lambda/10 \)) can therefore be expected at frequencies above resonance.

![Figure 1](image1)

Figure 1. (a) Schematic of a metamaterial-based FP LWA. (b) Unit cell of the PRS. (c) Reflection and transmission magnitudes of the PRS cell. (d) Reflection and transmission phases of the PRS cell.

Figure 2(a) shows, for example, the E- and H-plane radiation patterns of a \( \lambda/30 \) thick cavity antenna with lateral dimensions 10 cm x 10 cm designed for a 9.7 GHz operation \[4, 5\]. The antenna directivity is found to be equal to 19 dBi. In order to reach higher directivity, multiple primary sources can be used to feed the cavity antenna. As it can be observed in figure 2(b), the inter-element spacing of the array plays an important role on the enhancement of the directivity. This effect is highlighted in table 1 where the performances of cavities for the different inter-element spacing are presented \[6, 7\].

![Figure 2](image2)

Figure 2. E- and H-plane radiation patterns of FP cavity antenna fed by (a) a single source, (b) multiple sources.

For \( a = 0.5\lambda \), a measured directivity of 19 dBi is obtained at 8.93 GHz. This value is very close to that of a cavity fed by a single source (see for e.g. \[4, 5\]). So, it is worth to note that conversely to classical antenna arrays, the directivity is not doubled each time that the number of sources is doubled. For \( a = \lambda \), a measured directivity of 20.9 dBi is noted at 9.07 GHz, showing clearly an enhancement of 1.9 dB with regard to the case \( a = 0.5\lambda \). It is also very important to note that the sidelobes level of the patch array is considerably reduced when embedded in the cavity. 23.21 dBi and 25.35 dBi is respectively deduced from the measured planes for \( a = 2\lambda \) and \( a = 3\lambda \). When the case \( a = 3\lambda \) is compared to \( a = 0.5\lambda \), an increase of 6.35 dB is obtained for the directivity, which is comparable to an
increase from a single patch element to a 2 x 2 patch array. The measured sidelobes level are higher (~-8dB in the H-plane) for the case $a = 3\lambda$. However, this sidelobes level is still low compared to the sidelobes level of the source alone. It is well known that an inter-element spacing of an array higher than $\lambda$ leads to high sidelobes level and also to the apparition of grating lobes. The increase in directivity is due to the fact that a larger surface of the PRS is illuminated when $a$ is bigger.

### Table 1. Performances of the cavity antennas with $h = 1.5$ mm and for different values of inter-element spacing $a$.

| $a$ (mm) | Resonance frequency (GHz) | Maximum directivity (dBi) | Secondary lobes level (dB) |
|----------|---------------------------|----------------------------|---------------------------|
| $0.5\lambda$ | 9.13 | 19 @ 8.93 GHz | -12 |
| $\lambda$ | 9.37 | 20.9 @ 9.07 GHz | -19 |
| $2\lambda$ | 9.18 | 23.21 @ 8.94 GHz | -10 |
| $3\lambda$ | 9.21 | 25.35 @ 8.96 GHz | -8 |

3. Beam steering in FP LWA

By analogy with conventional antennas where several radiating elements are placed in array with a phase shift between each element in order to have a beam pointing in an off-normal direction, the same principle can be applied to FP cavity antennas. To achieve beam steering, phase shifts can be applied between the cells of the PRS. For example, the gap spacing $g$ can be varied along the PRS [8, 9], as shown in figure 3(a). Figure 3(b) shows the beam deflection in the E-plane radiation pattern for different values of $\delta g$. To achieve electronic beam steering, varactor diodes are inserted in the cells and by applying different bias voltages along the surface, a phase variation is created [9]. Figure 3(c) shows the beam deflection in the E-plane for different values of $\delta V$.

![Figure 3.](image)

**Figure 3.** (a) Schematic view of a cavity composed of a phase variable PRS. (b) Passive beam steering. (c) Active beam steering.

4. Frequency agile FP LWA

Conversely to beam steerable cavity antennas, we do not need a locally phase-varying PRS for frequency agility applications. What we seek is the ability to change the resonance frequency of the PRS and this is possible by changing simultaneously and in the same manner the capacitance value of the varactor diodes [10-12]. An electronically controlled PRS, similar to the schematic principle of figure 3(a) is designed to operate near 2 GHz in base station antennas for mobile phone communication systems. The primary source of the cavity is a wideband microstrip patch antenna designed to cover 1.8 GHz – 2.7 GHz frequency range. A prototype having dimensions 400 x 400...
mm\(^2\) (approximately 3\(\lambda\) x 3\(\lambda\)) has been fabricated and tested. Four elementary sources constituting a 2 x 2 wideband patch array are used as primary source; the inter-element spacing being 200 mm.

Direct near field and far field performed measurements are shown in figure 4. When the capacitance of the metasurface reflector is changed by varying bias voltage of the varactor diodes, the frequency of maximum gain is tuned. As shown by the intensity maps of scanned far field, the emission frequency represented by the red spot varies from 1.9 GHz to 2.31 GHz from 0 V to 24 V, demonstrating clearly the frequency reconfigurability of the FP cavity. The radiation patterns in E- and H-planes at respectively 1.9 GHz, 2.02 GHz, 2.16 GHz and 2.31 GHz corresponding to maximum gain frequency for 0 V, 5 V, 12 V and 24 V are presented. The tuning range of maximum gain frequency results in an effective operation bandwidth close to 20%. A directivity of approximately 18 dBi is obtained experimentally.

![figure 4](image)

**Figure 4.** Far field intensity maps versus frequency and elevation angle \(\theta\) in E-plane and measured radiation patterns in E- and H-planes at maximum gain frequency for different bias voltage applied: (a)-(b) 0 V – 1.9 GHz, (c)-(d) 5 V – 2.02 GHz, (e)-(f) 12 V – 2.16 GHz, (g)-(h) 24 V – 2.31 GHz.

5. Conclusion
To summarize, we have shown different characteristics that can be obtained from a Fabry-Pérot leaky wave antenna, namely, low profile, high directivity, beam steering and frequency agility, by the judicious configuration of the metamaterial-based PRS reflector.

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