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# Review of Highly-Directive Flat-Plate Antenna Technology with Metasurfaces and Metamaterials

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***Abstract* — A review of the development of enhanced directivity applied to high gain antennas is shown here, illustrating the various design possibilities. Fabry-Perot cavities (FPC) covered by partially reflective surfaces (PRS) made by high density dielectric layers or frequency selective surfaces is the standard way to obtain such antennas. Ground planes may be substituted by artificial magnetic surfaces to reduce the overall thickness. metamaterials with low permittivity have been used to generate highly directive beams as well. In all cases high directivity is produced by the excitation of low attenuating leaky waves in the antenna transverse direction.**

***Index Terms* — EBG materials, Fabry-Perot Cavities, high gain antennas, periodic structures.**

## I. Introduction and Historical Overview

High directivity with flat antennas are attractive because of ease of fabrication, they have a low profile, and they are mainly built with a planar technology. Furthermore they can be lighter than reflector antennas and easier to install. They have found applications in various domains such as satellite communications and wireless broadcasting.

Various configurations have been designed in the past years that produce high directivity at broadside. Here we provide first an historical overview of such configurations, then we show the fundamental principles of operation, fabrication and testing. Then we explore the new ideas that came out in the past years with the use of metamaterials and metasurfaces to extend the previous designs.

The first flat antenna that was designed to produce a high directivity at broadside excited by a single source was in 1956 [1]. It consisted by a partially reflective surface (PRS) located approximately a quarter wavelength from a ground plane. The structure forms a Fabry-Perot Cavity (FPC) and successive bounces of the trapped rays escape with a coherent summation along a certain direction thus producing a directive beam, that could also be at broadside. Successively, other fundamental studies were done in 1985 [2] and in 1988 [3] where the reflective surface was substituted by a dense, quarter wavelength, dielectric, still over a half wavelength cavity. Importantly, in the 1988 paper, the idea that the excitation of a leaky wave contributes to the high directivity was established for the first time. In 1993 [4] instead of a single dielectric layer, it was proposed that higher directivity could be achieved when several layers are used to form the top cover of the cavity. In 2001, the concept introduced by Von Trentini was generalized to other geometries and actual designs were made [5]. Along the same ideas, the PRS layer proposed initially by Von Trentini was generalized to more exotic periodic structures (metasurfaces) [5]. They were able to control the resonant frequency and thus the operating bandwidth which was commensurate with modern communication systems.

Besides PRS surfaces made of Frequency Selective Surfaces (FSS) over a cavity, studies on Electromagnetic Band Gap (EBG) structures led to the idea that a resonant defects in an EBG material could be used to produce high directivity outside the crystal [6]-[11]. In practice, in these studies the reflective superstrate was replaced by a single or multiple layers of EBG material, still over a resonating cavity.

The antennas described above could be excited by a single source located inside the cavity such as a coaxial probe, a microstrip patch, a slot in the ground plane or by a waveguide horn. Some examples will be shown during the presentation related to fabrication of prototypes, showing the performances of such antennas in terms of bandwidth, aperture efficiency etc.

The above concepts have been used to design a FPC that hosts a dual polarized array with sparse elements [13]. The unusual large distance between array elements allows the design of the beam forming network on the same plane of the array, also for dual polarization.

With the recent advent of artificial magnetic conductors, realized by periodic surfaces properly designed to offer a high impedance with a reflection coefficient with approximate zero phase delay, the metallic ground plane has been replaced [14-15] with artificial periodic magnetic conductor [16] to further decrease the thickness of this highly directive antenna. The design, principle of operation and performances will be shown during the presentation.

It will be shown that high gain antennas have been obtained also following another route. Instead of a FPC covered by a PRS, made by a metasurface or by a dense dielectric layer, in the past few years it has been shown that sources located in grounded slab made of plasma produce a high directivity, also at broadside. This has been discovered when the unwanted plasma cover in satellite antennas was studied in

[17]. Successively, a pioneering study of Gupta [18] and [19] has shown that a metamaterial slab made of parallel wires excited by a single source could produce a high directivity. As shown also by other authors, a material made of wires behaves electromagnetically like a plasma, with a plasma cutoff frequency that depends on the radius of the wires and on their period. The same idea was used in [20] that studied and realized a metamaterial made of wire grids that produces high directivity. A detailed explanation of the phenomena was done in [21], that have provided also design criteria for directivity and bandwidth. In that paper it is shown that a high directive beam in this class of antennas is also produced by an excited leaky wave with small attenuation constant and large phase velocity. In [22] The leaky wave model of [21] was compared with a ray-optics description. A larger class of metamaterials for directivity enhancement is analyzed in [23] where low and high permittivity and permeability and the concept of low and high impedance materials are analyzed to produce enhanced directivity. We briefly compare this class of antennas with those previously described with the PRS, as it has been done in [24] where the figure of merit equal to the product between the directivity and the bandwidth has been introduced.

Also other EBG structures [24-27] not based on Fabry-Perot Cavities that produce high directivity will be shown in this presentation but the main goal is to provide a unique point of view that unifies all the numerous previous studies conducted in the past, even from apparently distinct routes.

For the basic properties and parameterization of enhanced radiation achieved with a PRS cover of a FPC, together with designs of proper artificial surfaces we address the reader to [26]-[30].

## II. General Idea for the Design

Leaky wave antennas made by a FPC covered by a PRS may generate a directive beam at broadside or at a direction off broadside depending on the initial design [3],[4],[26]-[30]. For broadside radiation the height of the cavity [Fig.1(a)] is close to half wavelength since the PRS surface (either made by a FSS or by and EBG made of dielectric layers) has low impedance seen from inside. Various designs have been proposed for the PRS since [1]. Useful simple approximate formulas that express the gain and pattern bandwidth as a function of the PRS subscettance are reported in [26]-[29]. As shown in Fig. 1(b) the ground plane can be substituted by an artificial magnetic conductor and the resonant condition is achieved with a smaller thickness. A design example is shown in Fig. 2 where a flat antenna with an AMC of transverse dimensions of 15cm x 15cm exhibits a gain of 19 dB at 14 GHz [14]. The measured antenna bandwidth defined from the -3 dB gain level and 10 dB return loss is about 2%.

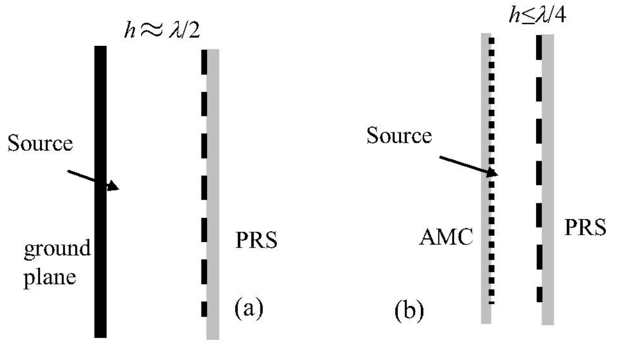


Fig. 1. General design of FPC antennas made by a ground plane and a PRS (a). In (b) the ground plane has been substituted by an artificial magnetic conductor (AMC) permitting a thickness reduction [14],[15].

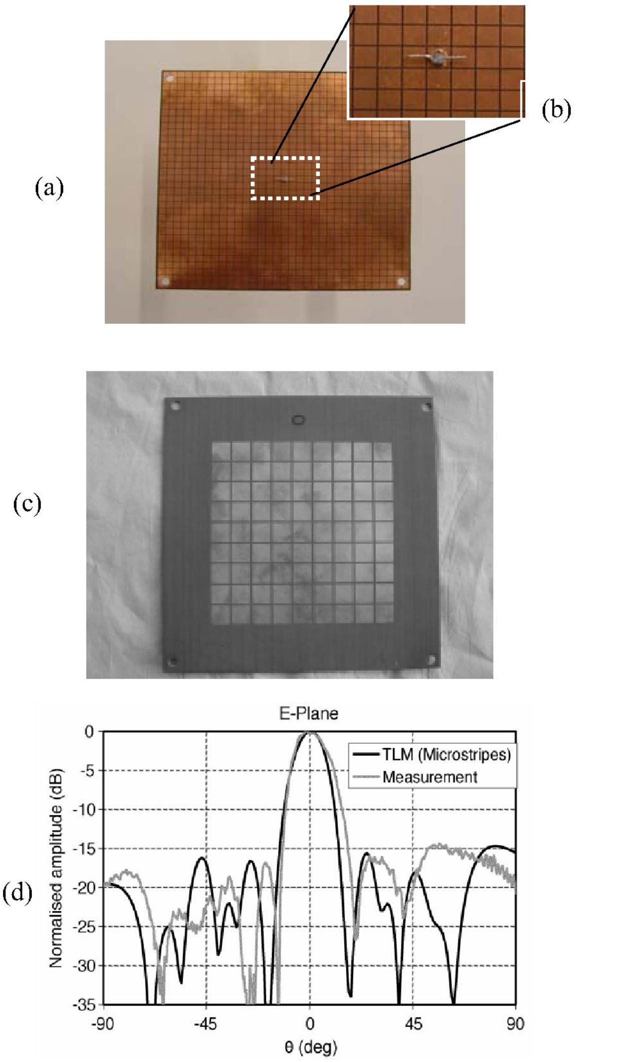


Fig. 2. Photographs of metamaterial AMC ground plane (a) (15cm x15cm), with a dipole antenna feed (b), and the PRS superstrate (c) made of metallic patches [14]. (d) Measured E-plane radiation pattern compared with simulations: 3-D time domain Transmission Line Modeling (TLM) tool (Microstripes) simulations [14].

Another application example of such FPC antennas is shown in Fig. 3 where a dual polarized antenna is made by two interleaved 2x2 arrays under a 2-layers EBG structure [13]. The EBG structure forms the PRS cover of the FPC as in [4]. A gain of 19 dB is achieved in each polarization with an impedance bandwidth of 5.7%. The advantage of having the enhanced gain due to the 2-layers of high permittivity dielectric is that the space of the patch antennas is larger than usual. As for the case of Fig. 3 the array element distances are $1.6\lambda_0$ where $\lambda_0$ is the free space wavelength. In [13] it has been shown that there are optimal distances. Larger element distances are useful for having complicated feeding networks, even on the same plane of the patches, and to reduce the number of array elements.

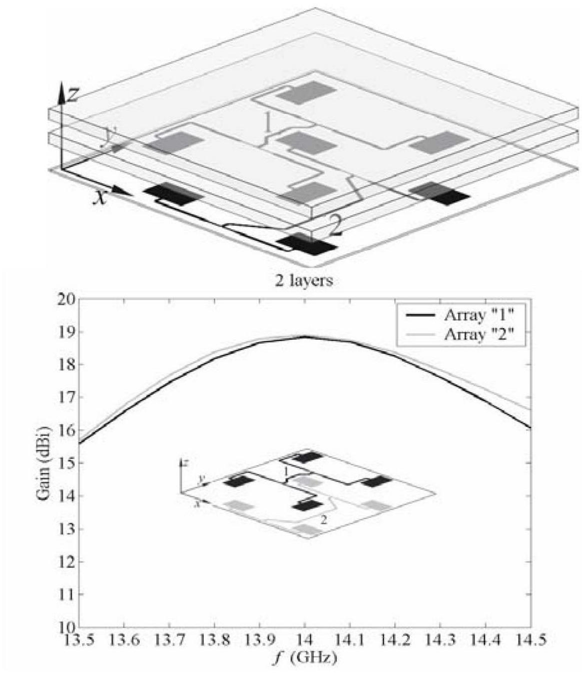


Fig. 3. Dual polarized antenna made of two 2x2 interleaved arrays. The gain for each polarization is 19 dB [13]. All patches and feeding networks are printed on the same layer.

As a last example we show that high directivity can by achieved also by a slab made by a wire medium [18]-[21]. In this case the FPC cavity is not made by air covered by a low impedance PRS but instead by a low effective permittivity material (the wire medium) with a resonant thickness. The operating wavelength should be just above the plasma frequency [31] of the wire medium [21]. The wire medium is spatially dispersive [31] but this phenomena actually helps to obtain a circularly symmetric directive beam at broadside.

In Fig. 4 we show the H-plane of a radiation pattern of an ideal dipole in the middle of the wire medium [21] compared with that of the same dipole in the homogenized version of the wire medium. The simulated results for the wire medium have been obtained with a method of moments (MoM).

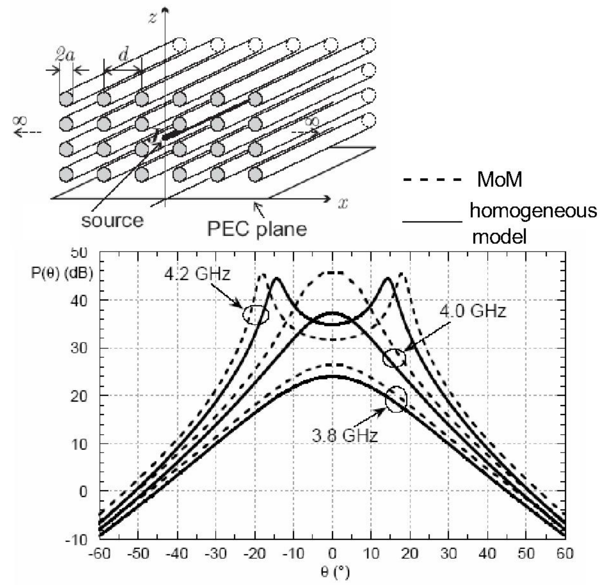


Fig. 4. Radiation pattern (H-plane, arbitrary units) produced by a dipole inside a wire medium slab over a ground plane [21].

## VII. CONCLUSION

A detailed overview of the technology and design possibilities for flat planar antennas that exhibit enhanced directivity has been shown here, together with three illustrative examples. The advantage is that high directivity is achieved with one or a few radiating elements with the main disadvantage of a reduced bandwidth. In all cases discussed in the introduction and in the illustrative examples the high directivity is generated by a slowly attenuating leaky wave that produces a large equivalent field aperture.


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