STUDY OF PHOTONIC CRYSTAL BASED DIRECTIVE ANTENNAS

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INTRODUCTION

We describe a theoretical and numerical study for the design of directive antennas. These antennas, useful for microwave telecommunications, should be much more compact than classical solutions. Another benefit is the possibility to use a single feeding device. We investigate and compare two solutions.

The first one is based on a Perot-Fabry like planar resonant cavity. A ground plane acts as one of the walls of the cavity, whereas the opposite wall (or mirror) is made with a metallic photonic crystal. The parameters of this periodic mesh are optimized in order to obtain a suitable directivity for the emitted field. This structure is excited by a source located in the cavity.

The second solution uses the specific properties of a metallic photonic crystal at the band edge. The resulting structure is made of a ground plane covered by a photonic crystal with a source embedded inside.

For the study of these structures, specific numerical codes have been developed. The two-dimensional case is used for the preliminary studies. We show that, for thin wires, many properties can be derived from the two-dimensional model. Three-dimensional codes based on Harrington's wire approximation allow us to get a more realistic model. In order to reduce the computational burden of the 3D codes, two methods are suggested. In the first one, we take advantage of the periodicity (in the two directions parallel to the ground plane) to reduce the unknowns to one period only, using a fast bi-periodic Green's function. In the second one, we take advantage of the partial block-Toeplitz structure of the impedance matrix.

All along the paper, we assume that the wires are infinitely conducting. This assumption is justified, since our objective is related to an experimental realization in the Ku band (14 GHz).

1. TWO-DIMENSIONAL PEROT-FABRY LIKE RESONANT CAVITY

In this section, we design a Perot-Fabry like resonant cavity whose mirrors are made of metallic grids. The structure under investigation is in fact made with a ground-plane, the emitting device (patch, monopole,…) and covered by a mirror. In our case, experimental constraints led us to consider mirrors made of two metallic grids. In the numerical modeling, the ground plane is taken into account by the image theory.

From the reciprocity principle, the angular range for the emission is directly linked with the angular selectivity of the structure illuminated by a plane wave under the incidence θ. The well known properties of the Perot-Fabry also state that the angular and frequency bandwidths are closely linked together, and depend on the reflectivity R of the mirrors. Let us for instance suppose that we require a 1% bandwidth. We know that:

$$\frac{\Delta\lambda}{\lambda} = \frac{4}{\varphi\sqrt{m}} \qquad (1)$$

where φ is the phase shift when the wave goes back and forth inside the cavity, and $m = 4R/(1\text{-}R)^2$. For the first mode fitting the image theory, the value of φ is equal to 4π. Consequently, R must be equal to about 0.94. This aim is fulfilled using the filtering properties of periodic metallic wires, and a numerical optimization leads to the following parameters: the period of the grid, as well as the spacing between the two grids, is equal to 0.58 cm, the radius of the wires is 0.0259 cm, and the distance between the ground plane and the first grid is 0.9335 cm.

Fig.1 shows the transmission of the symmetric structure (with 2 identical mirrors, i.e. 4 grids) illuminated by a plane wave with a wavelength λ, whose electric field is parallel to the wires. The frequency half-power bandwidth is indeed close to 1%, and the angular bandwidth is $2\times6.1°$. Note that in this case, the structure is a grating, thus infinite along the periodicity direction.

Let us know consider a finite structure excited by a source placed inside the cavity. The source that we use is a set of wire antennas parallel to the direction of invariance (i.e. perpendicular to the plane of the Fig.2). These sources represent a 2D equivalent of the currents flowing on the surface of a patch. Due to the image theory, we also use antisymmetric sources. Fig.2 shows that these sources excite the resonant mode of the cavity. The radiation pattern (Fig.3) presents a narrow lobe: the half-power beamwidth is 2×4.4°, which is even narrower than the transmission curve of Fig.1. Note that in all the paper, the radiation patterns are in arbitrary unit. Note also that throughout the paper, the computations for the 2D models with finite number of wires are done using a rigorous modal method based on scattering matrices, the fields being expressed as Fourier Bessel series [1].

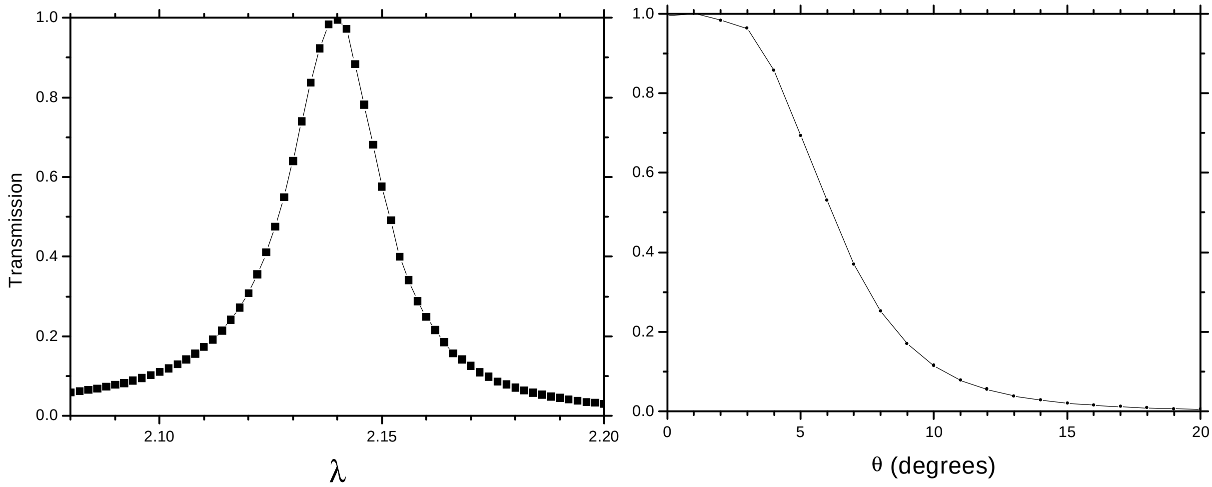

Fig.1. Transmission of the Perot-Fabry structure, for θ = 0 (left) and for λ = 2.14 cm (right).

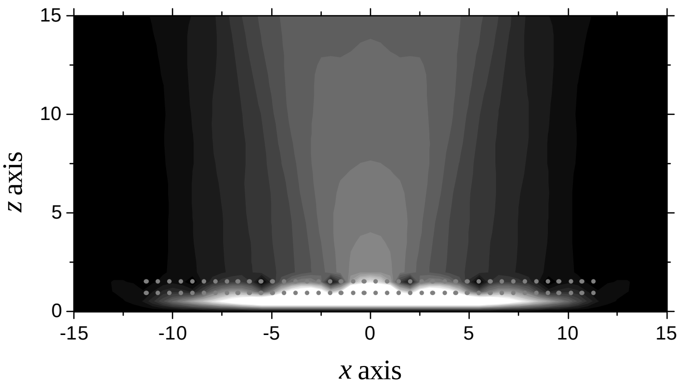

Fig.2. Map of the field modulus radiated by the Perot-Fabry cavity. The gray points show the location of the grid wires which act as a mirror. The ground plane is the plane z = 0. The wire antenna sources are regularly placed at z = 0.184 cm and between $x = -0.43\,\mathrm{cm}$ and $x = 0.43\,\mathrm{cm}$. The wavelength is λ = 2.14 cm. The same definition of the axes will be used all along the paper. All dimensions are in cm.

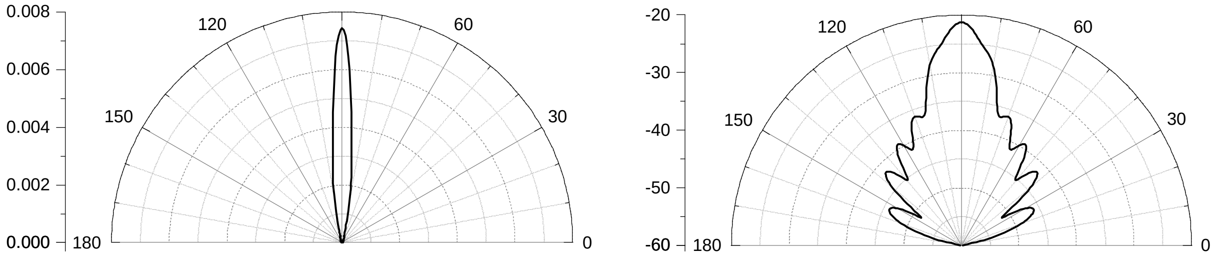

Fig.3. Radiation pattern at infinity for the device of Fig.2. Linear scale (left) and dB scale (right).

It is interesting to study the behavior of this antenna when the wavelength moves around the resonant wavelength. For this purpose, we found useful to represent the 2D directivity. This quantity D characterizes the intensity radiated in the direction θ :

$$D(\theta) = \frac{U(\theta)}{\frac{1}{2\pi}\int_0^{2\pi} U(\theta)\,\mathrm{d}\theta} = \frac{U(\theta)}{\frac{P_{scat}}{2\pi}} \qquad (2)$$

where $U(\theta)$ is the radiation intensity. Fig.4 gives the value of $D(90°)$ in the direction of the maximum of emission. It shows that the directivity keeps interesting values even if the wavelength is slightly shifted.

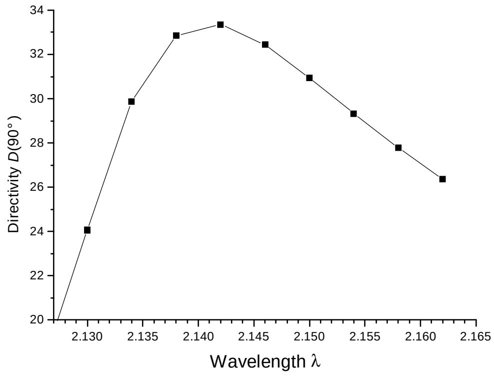

Fig.4. Variation of the directivity $D(90°)$ versus λ.

2. TWO-DIMENSIONAL METALLIC PHOTONIC CRYSTAL

In this section, we show a possible way to design directive emitting antennas using the filtering properties of photonic crystals. Metallic photonic crystals present two kinds of bandgaps: a large low-frequency gap, and smaller gaps for higher frequencies. In this study, we make use of the large low-frequency gap. Let us first study the transmission of a grating made of five grids of wires parallel to the y-axis. We denote by d_x the period along the x-axis (the period of the grating) and by d_z the vertical spacing between two grids. The idea of expanding a photonic crystal along a particular direction in the design of directive emitters has been already suggested in [2]. Fig.5 shows that the edge of the gap moves with the incidence. Therefore, a convenient choice of the parameters can lead to a structure which transmits in normal incidence and stops the higher incidence waves. This short and heuristic explanation can be put in a rigorous form using the dispersion curves of the Bloch modes inside the photonic crystal, and the interested reader will find all the details in a recent paper [3], but in a different context (not in relation with antennas).

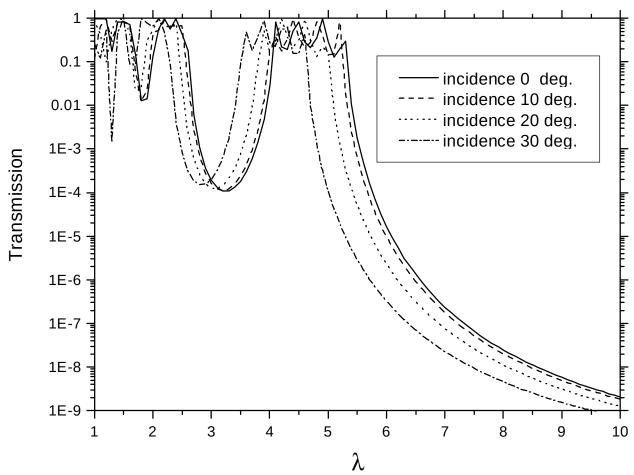

Fig.5. Transmission of a plane wave through a stack of 5 grids with $d_x = 1$ and $d_y = 2$. The radius of the wires is r = 0.05. All dimensions can be scaled by multiplication by an arbitrary factor.

Let us now turn to a model directly linked with the experimental study that we want to realize. In the 3D experimental structure, we found convenient to realize the grids by etching of a thin copper plate. Consequently, the cross section of the wires will not be a circle, but a rectangle. After optimization of the parameters in order to match realization constraints and get interesting properties around 14GHz, it appears that convenient parameters are the following: the cross section of the metallic wires is 0.014 cm thick (along the z-axis) and 0.085 cm large (along the x-axis), $d_x = 0.58\ \text{cm}$, $d_z = 0.68\ \text{cm}$. Fig.6 shows the total field for a crystal made with 40×8 of these wires above a ground plane located at $z = 0$. The sources are the same as in Fig.2, but their vertical location is here $z = 2.7$ cm, i.e. in the center of the crystal. The radiation pattern exhibits a narrow lobe (Fig.7). In order to compare this antenna to the one depicted in section 1, we draw in Fig.8 the 2D directivity. The present device provides a higher directivity, but the curve is sharper than the one of Fig.4.

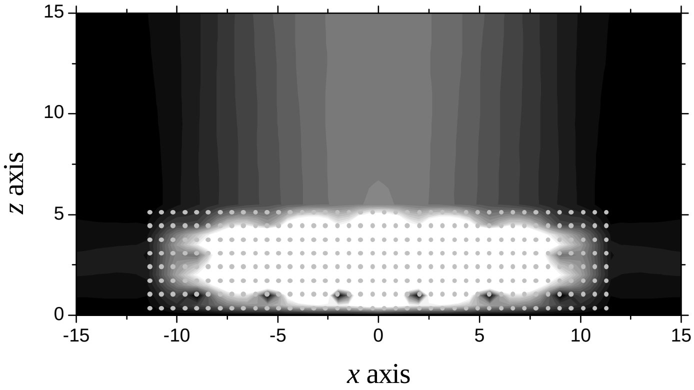

Fig.6. Map of the field modulus radiated by the photonic crystal based antenna. The wavelength is $\lambda = 2.14$ cm. All dimensions are in cm.

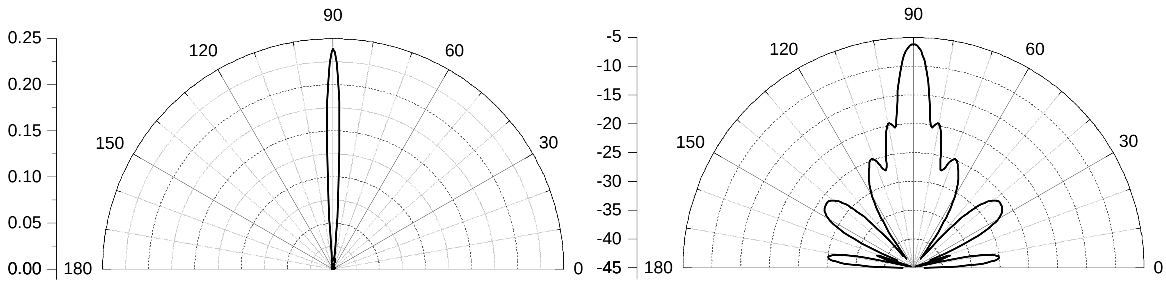

Fig.7. Radiation pattern at infinity for the device of Fig.6. Linear scale (left) and dB scale (right).

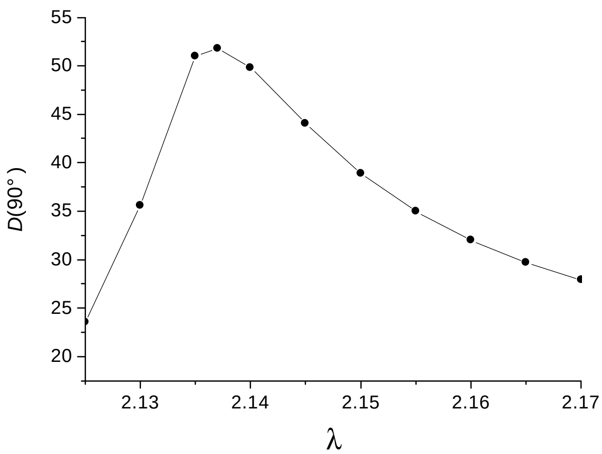

Fig.8. Variation of the directivity $D(90°)$ versus λ.

3. THREE-DIMENSIONAL MODELING

The previous 2D preliminary studies provided us a good understanding of the behavior of both solutions. But the modeling of the actual 3D problem (a patch source at the vicinity of a ground plane, covered by a finite array of metallic wires) is a harder task. We use an integral method based on the Harrington's thin wire approximation [4]. Unfortunately, a realistic modeling leads to a linear problem with several hundreds of thousands of unknowns. In order to circumvent this numerical problem, we assume that the grids are periodic (infinite extent along the *x* and *y* axes parallel to the ground plane). Thus we can take advantage of the periodicity of this structure, which is nothing else but a grating: if the incident field is pseudo-periodic (a plane wave for instance), the unknowns are reduced to one period only. We consider that the incident field on the grating is the field radiated by the patch in the absence of the grating. This field is transformed in a plane-wave packet using a FFT. The drawback is that the number of grating problems to solve is equal to the number of plane waves in the plane-wave packet. To speed up the computations, we have developed a numerical technique for the efficient computation of the bi-periodic Green's function [5]. Using these techniques, we are able to run our code on a personal workstation.

Let us return to the Perot-Fabry cavity, but now in the 3D case. The grids become a bi-periodic array of crossed wires instead of an array of parallel wires (2D case). We keep the same parameters as in section 1. Fig.9 clarifies our notations. Fig.10 gives the radiation patterns at infinity for the patch without the grating. Obviously, we get a broad pattern. The dissymmetry in the plane $x = 0$ is due to the position of the feeding point. When the patch is covered with the two arrays of crossed wires, we observe (Figs. 11 and 12) that the emission is concentrated in a narrow lobe. It is worth noticing that the arrays of wires do not affect the polarization of the emitted field, which stays linearly polarized in the lobe.

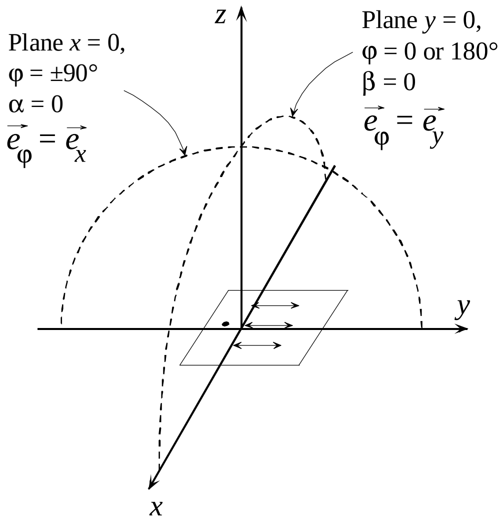

Fig.9. Notations. Sketch of the patch, showing the feeding point, and the principal direction of the surface currents (arrows). θ and φ are the usual angles of spherical coordinates. The patch is 0.86×0.86 cm large, the feeding point is 0.16 cm from the edge, and the distance from the ground plane is 0.184 cm.

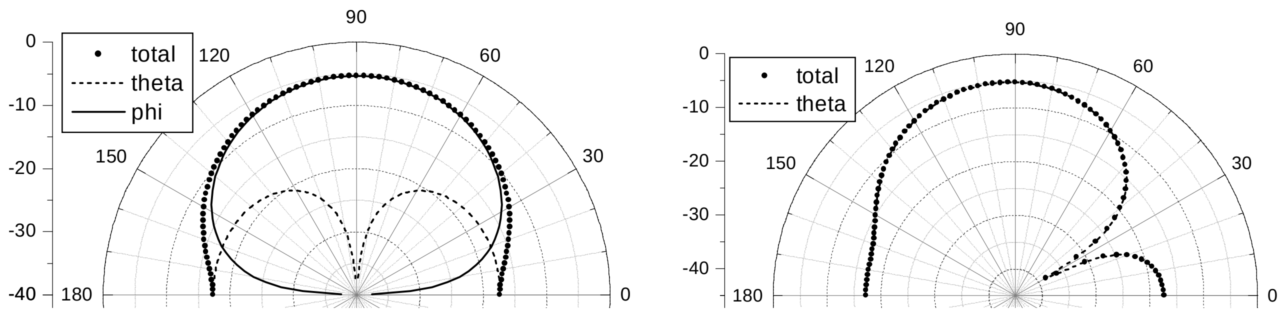

Fig.10. Radiation patterns (dB scale) of the patch without the grating. In the planes $y = 0$ (left) and $x = 0$ (right). On the right figure, the φ component is not visible since it is much less than -45dB.

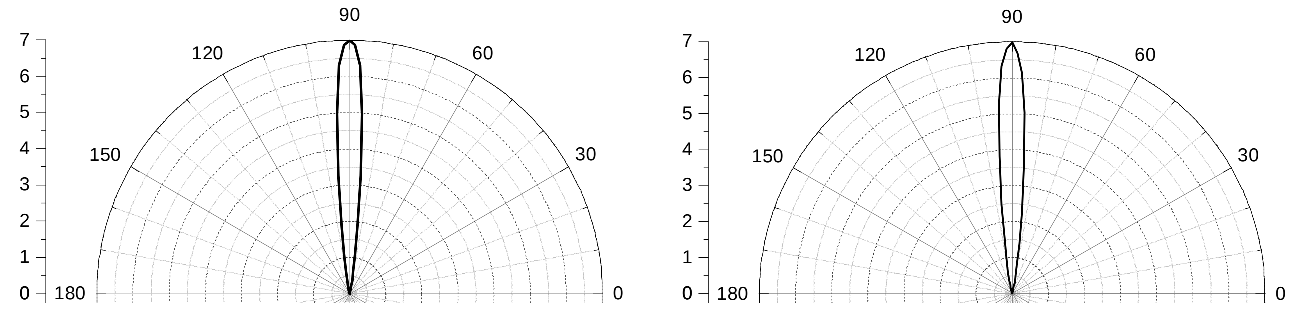

Fig.11. Radiation patterns (linear scale) of the patch covered by the grating. In the planes y = 0 (left) and x = 0 (right). The half-power beamwidth is 2×5.1° (left) and 2×5.5° (right).

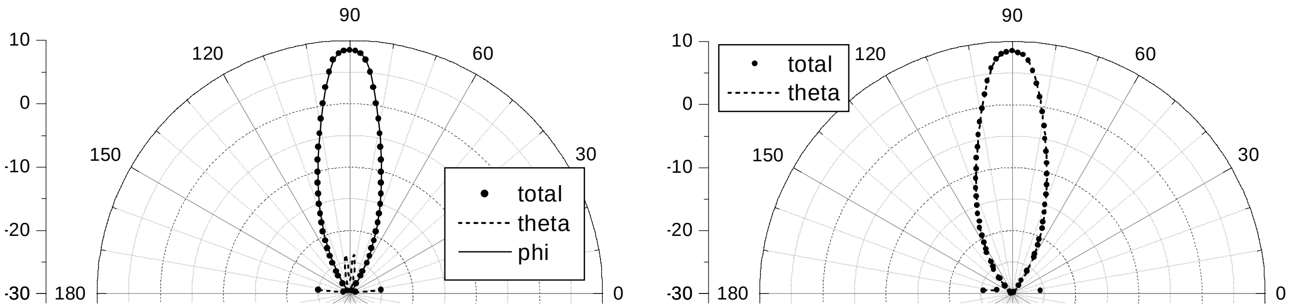

Fig.12. Same as Fig.11, but dB scale.

PERSPECTIVES

We are presently developing another way to circumvent the numerical problems linked with the large number of unknowns in the 3D structure. The idea is to take advantage of the partial block-Toeplitz structure of the impedance matrix involved in the Harrington's formalism, combined with the use of an iterative solver. Compared with the FFT decomposition described in section 3, this technique will allow us first to take into account the interaction between the source and the arrays of wires, and second to modelize a finite structure.

An experimental study is also in progress, and we expect that we will be able to present soon some measurements showing the relevance of our approach.

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