Institut FRESNEL MARSEILLE

STUDY OF PHOTONIC CRYSTAL BASED DIRECTIVE ANTENNAS

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Aim: design of directive, compact (~ flat), metallic, broadband antennas, using a single feeding device (patch, monopole), in microwave domain

Two solutions are presented:

- Perot-Fabry like resonant cavity
- photonic crystal antenna

Method of investigation:

- 2D modeling for preliminary study
- 3D modeling
- experiment

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.

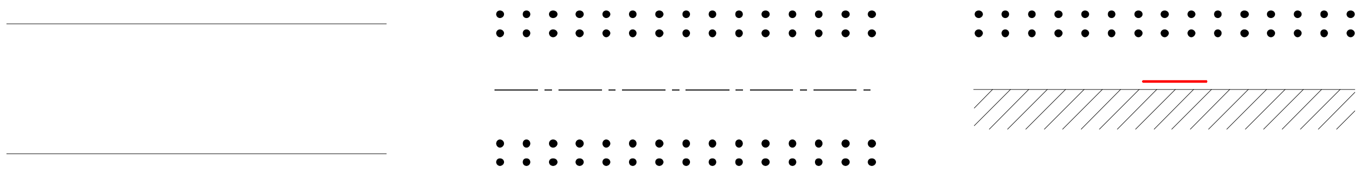
For the study of these structures, specific numerical codes have been developed. The two-dimensional case is used for the preliminary studies. We show that, for thin wires, many properties can be derived from the two-dimensional model. Three-dimensional codes based on Harrington's wire approximation 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.

PEROT-FABRY LIKE RESONANT CAVITY

2D STUDY

We use a rigorous modal method based on scattering matrices, the fields being expressed as Fourier Bessel series [1].

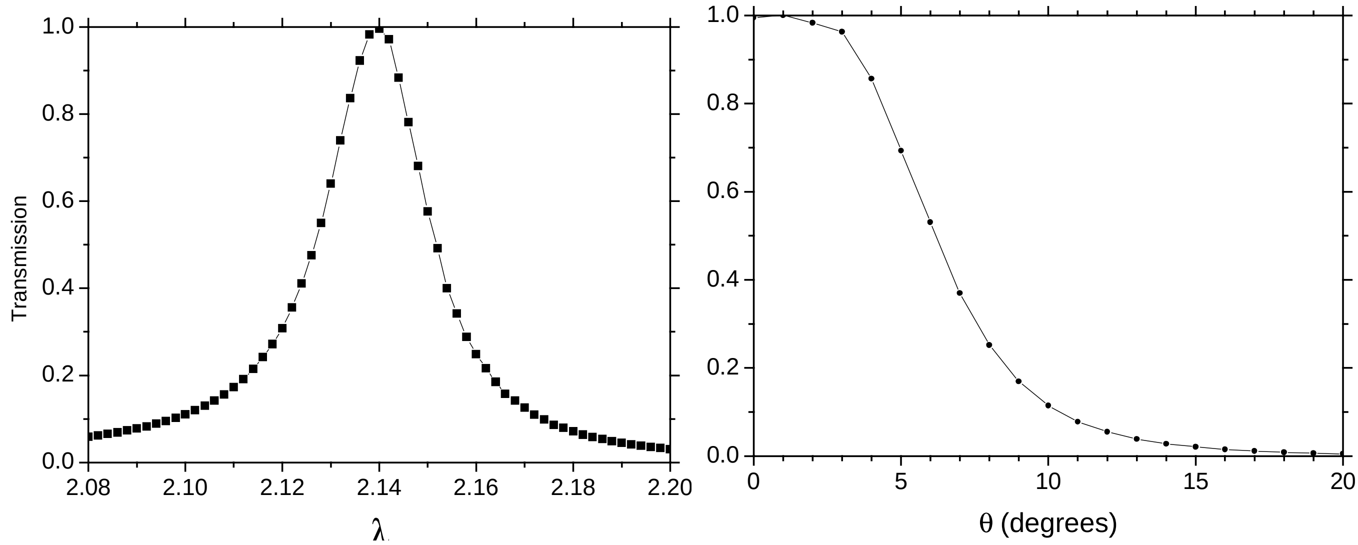
Perot-Fabry cavity whose mirrors are made of metallic grids.



Properties of the Perot-Fabry → the angular and frequency bandwidths are closely linked together, and depend on the reflectivity R of the mirrors.
1% bandwidth → $R \approx 0.94$

Numerical optimization → 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.

[1] D. Felbacq, G. Tayeb, and D. Maystre *Scattering by a random set of parallel cylinders*. J. Opt. Soc. Am. A, Vol.**11**, No.9, p.2526-2538, 1994

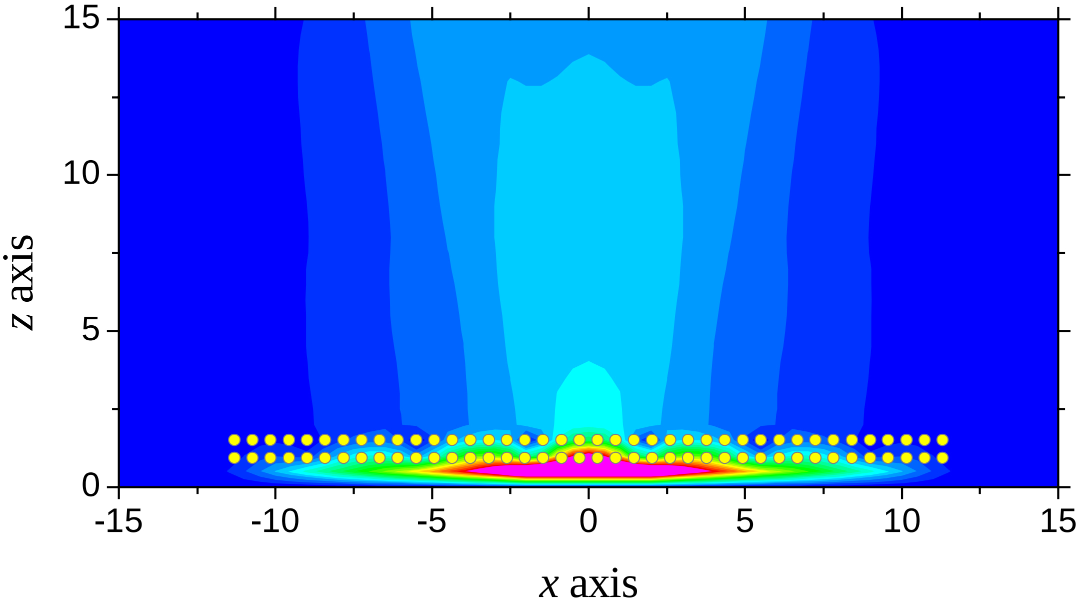


Transmission of the structure made with 4 infinite grids, illuminated by a plane wave, for $\theta = 0$ (left) and for $\lambda = 2.14$ cm (right).

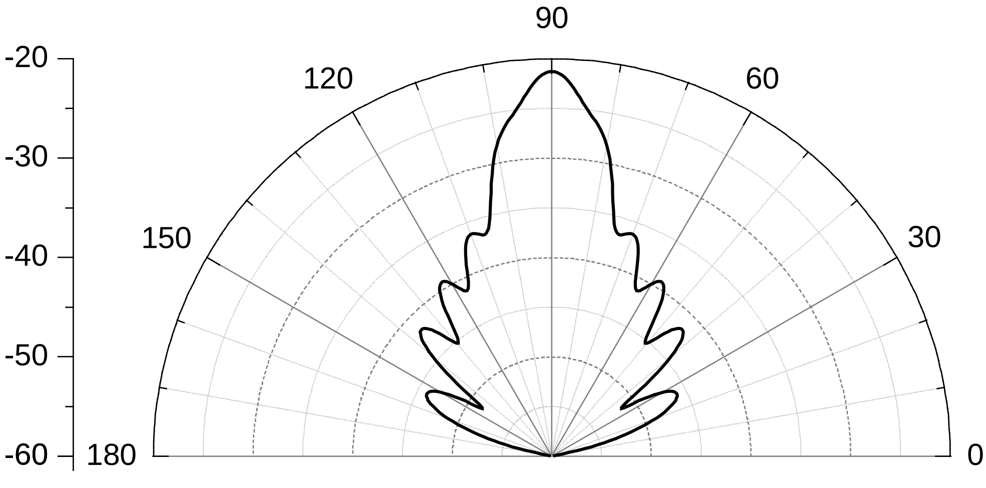
The frequency half-power bandwidth is close to 1%, and the angular bandwidth is $2\times6.1°$.

Finite structure excited by a source placed inside the cavity.

The source that we use is a set of wire antennas modeling the currents flowing on the surface of a patch.
These sources excite the resonant mode of the cavity.



Map of the field modulus. λ = 2.14 cm.

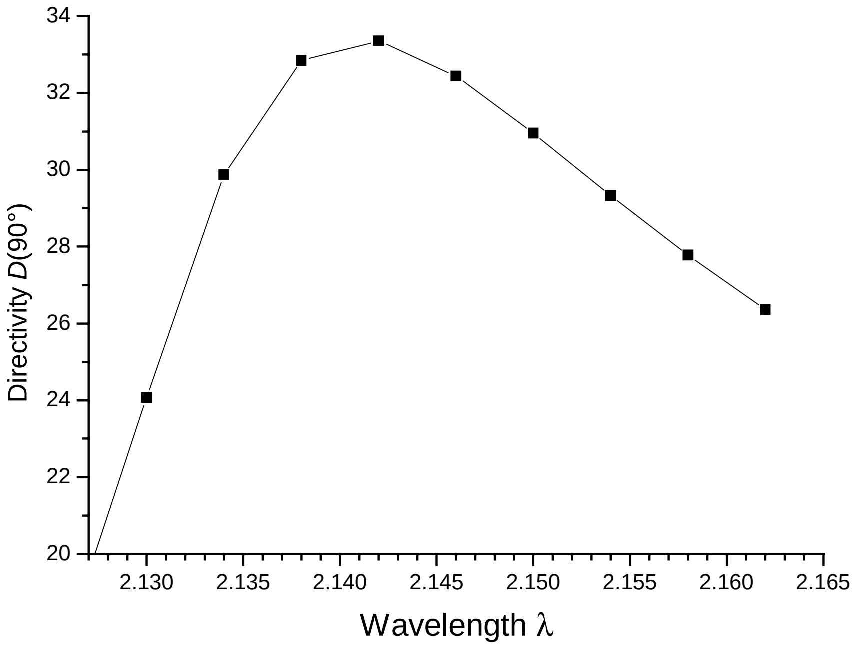


Radiation pattern in dB scale.
The half-power beamwidth is 2×4.4°

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 :

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

where $U(\theta)$ is the radiation intensity.



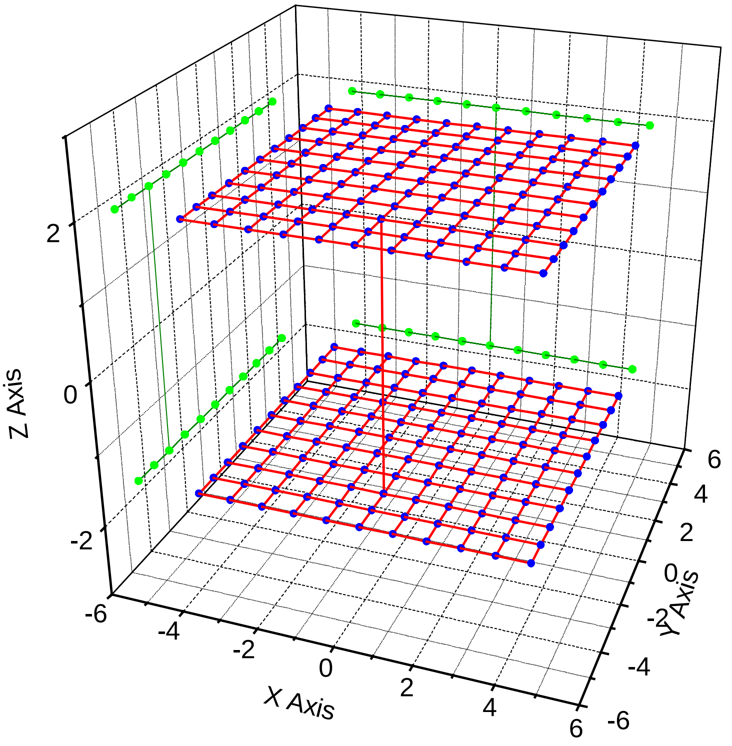
Variation of the directivity *D*(90°) versus λ.

The directivity keeps interesting values even if the wavelength is slightly shifted.

THREE-DIMENSIONAL MODELING

PATCH ALONE

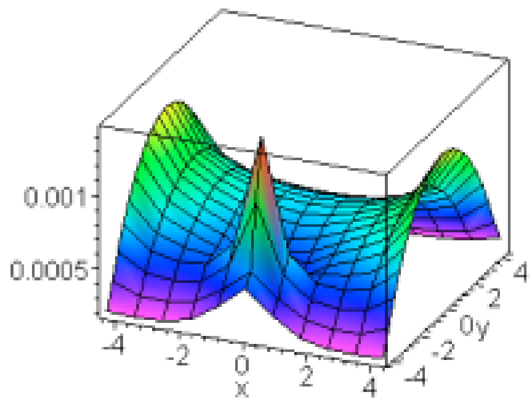
We use a method derived from Harrington's approximation for thin and infinitely conducting wires[2]



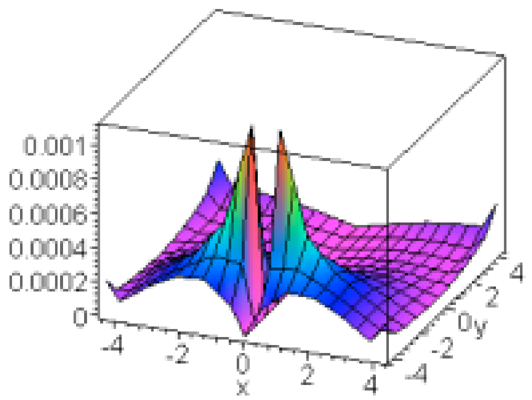
The patch is modeled by a set of wires.
The ground plane is taken into account using the image theory.

For λ = 21.43mm:

Iy current



Ix current



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[2] G. Guida, D. Maystre, G. Tayeb, P. Vincent. Electromagnetic modelling of three-dimensional metallic photonic crystals. J. Electromagnetic Waves and Applications, Vol.**12**, p.1153-1179, 1998

PATCH + GRIDS (bi-periodic array of crossed wires)

The general solving of the 3D problem (patch + finite grids) is huge (linear problem with several hundreds of thousands of unknowns).

In order to circumvent this problem:

1. Assume that the grids are periodic (infinite extent along the *x* and *y* axes parallel to the ground plane). The grids become a periodic grating. Thus we can use the periodicity if the excitation is pseudo-periodic (for instance a plane wave).

2. Compute the field diffracted by the patch on the ground plane (without the grids), then expand it in a plane wave packet using FFT.

3. Consider this field as the incident field on the grids, and solve several grating problems (each of them being related to a Fourier component of the field radiated by the patch).
   Constraints:
   - no coupling between the source and the grating,
   - no edge effects due to the actual finite extent of the grids.

Need of a bi-periodic Green's function. A fast numerical algorithm has been developed to this end[3].

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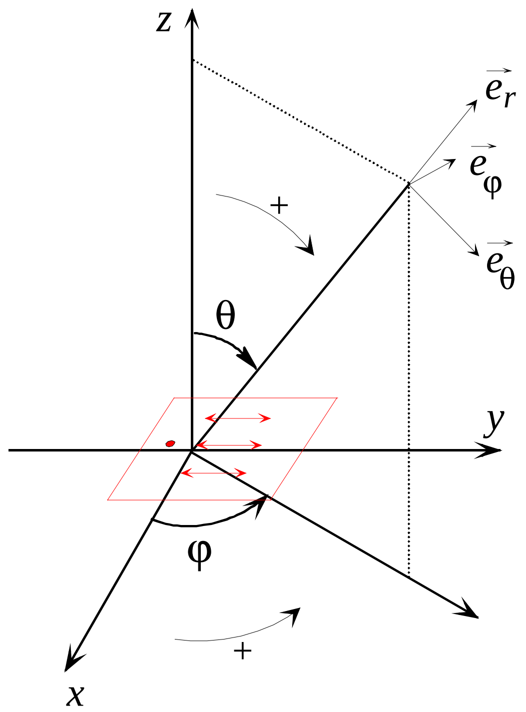
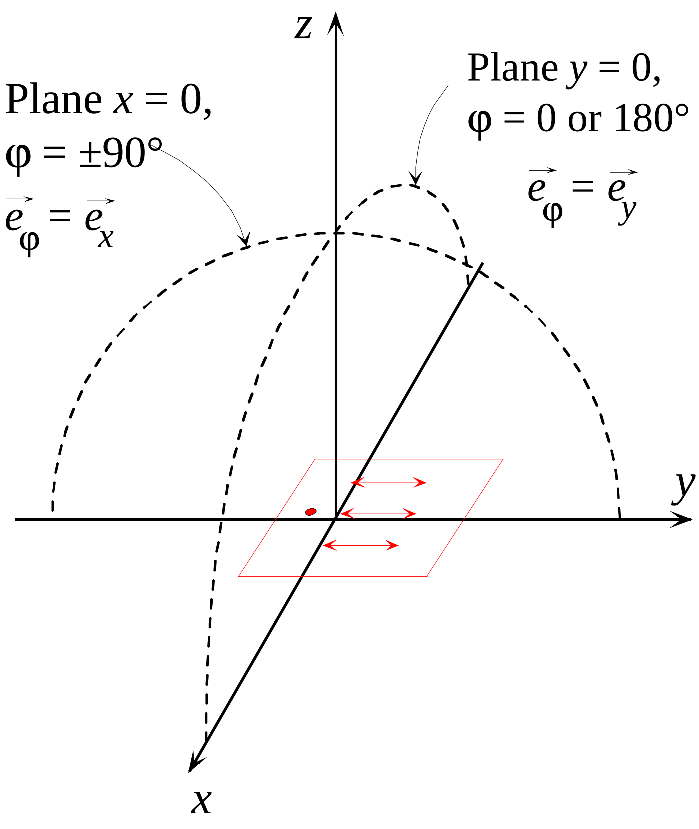
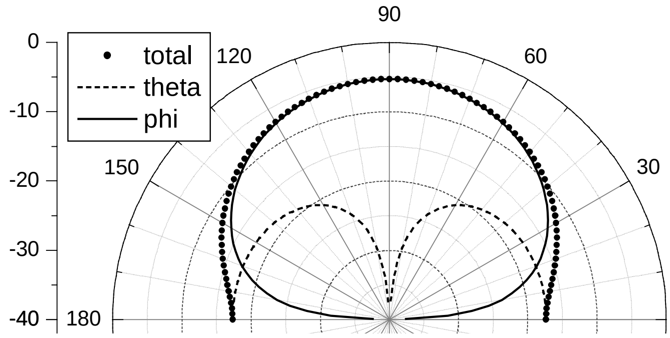
[3] N. Guérin, S. Enoch and G. Tayeb, *Combined method for the Computation of the Doubly Periodic Green's Function*, Journal of Electromagnetic Waves and Applications, vol.15, pp.205-221, 2001.

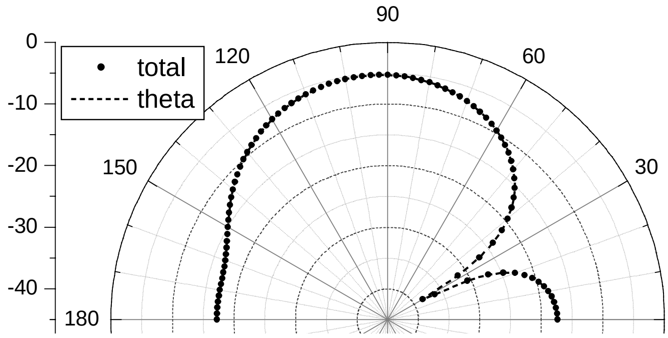




Sketch of the patch, showing the feeding point, and the principal direction of the surface currents (arrows).
θ and φ are the usual angles of spherical coordinates.
The patch is 0.86×0.86 cm large, the feeding point is 0.16 cm from the edge, and the distance from the ground plane is 0.184 cm.

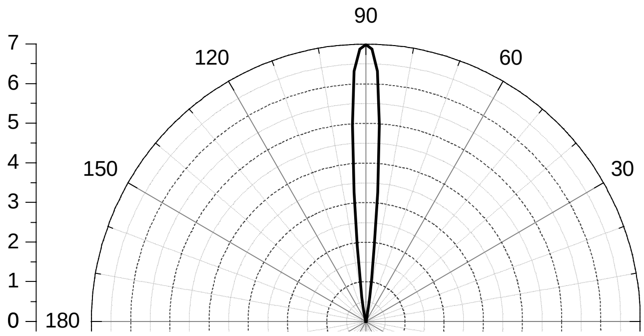


Plane y = 0

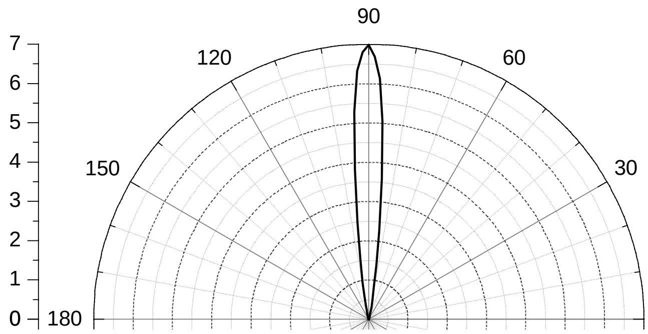


Plane x = 0

Radiation patterns (dB scale) of the patch without the grating. On the right figure, the φ component is not visible since it is much less than -45dB.

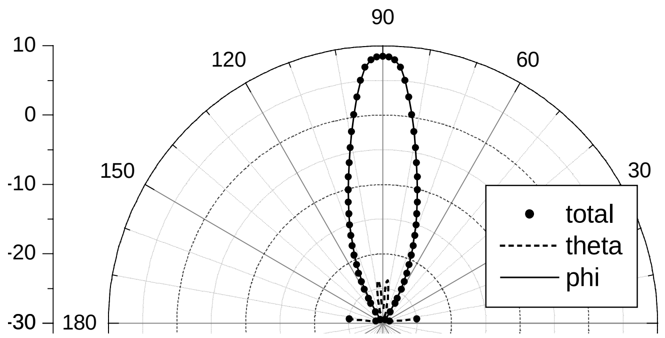


Plane y = 0

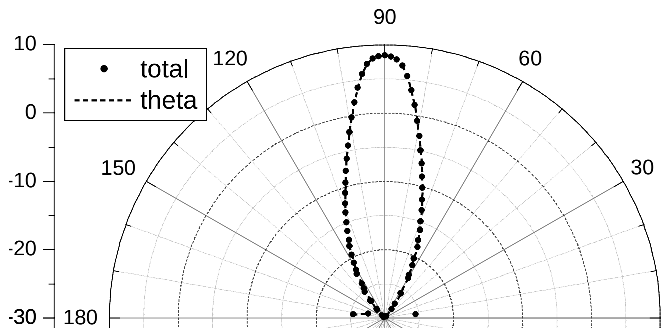


Plane x = 0

Radiation patterns (linear scale) of the patch covered by the grating. The half-power beamwidth is 2×5.1° (left) and 2×5.5° (right).



Plane y = 0



Plane x = 0

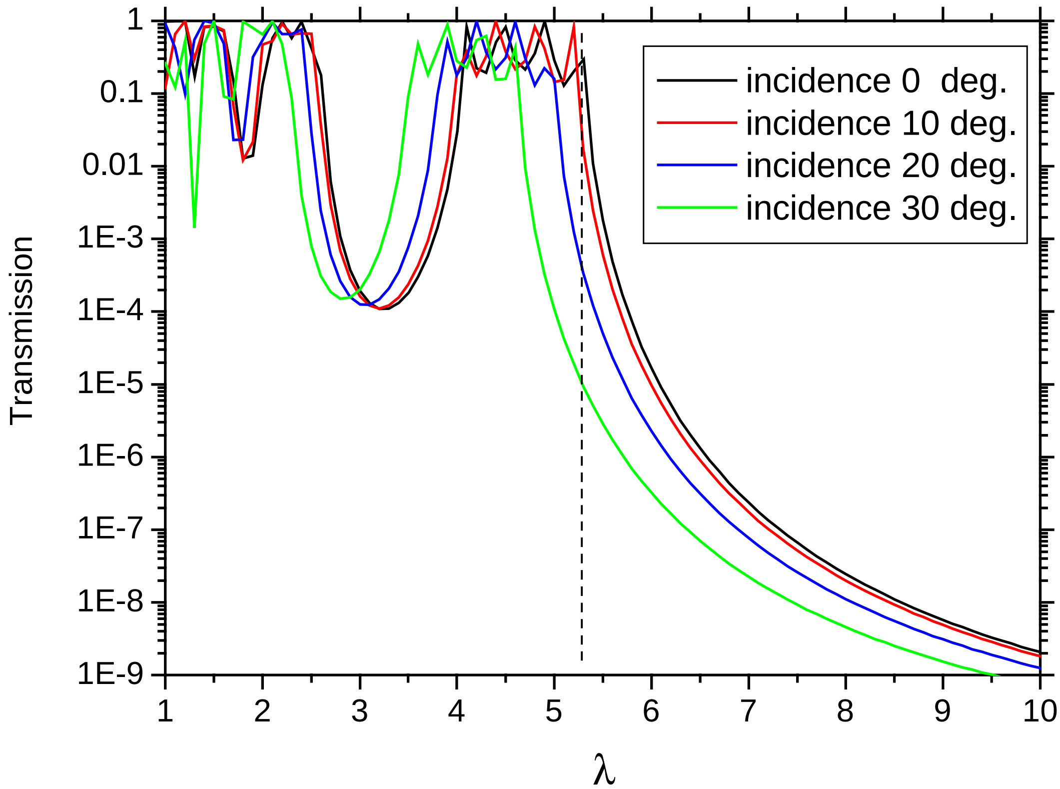
Same, but dB scale.

The emission is concentrated in a narrow lobe. The arrays of wires do not affect the polarization of the emitted field, which stays linearly polarized in the lobe.

METALLIC PHOTONIC CRYSTAL BASED ANTENNA

Design of directive antennas using the filtering properties of photonic crystals near the band edge.

2D STUDY



Transmission of a plane wave through a stack of 5 metallic grids.

The edge of the gap moves with the incidence.
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 [4].

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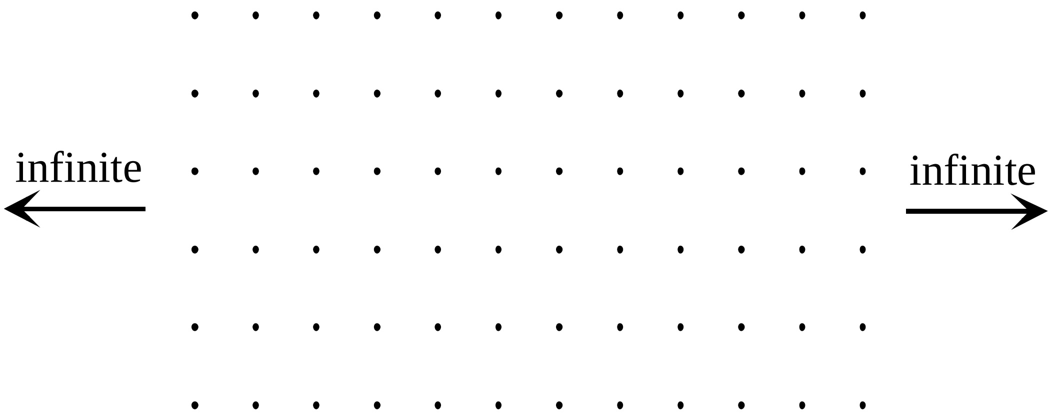
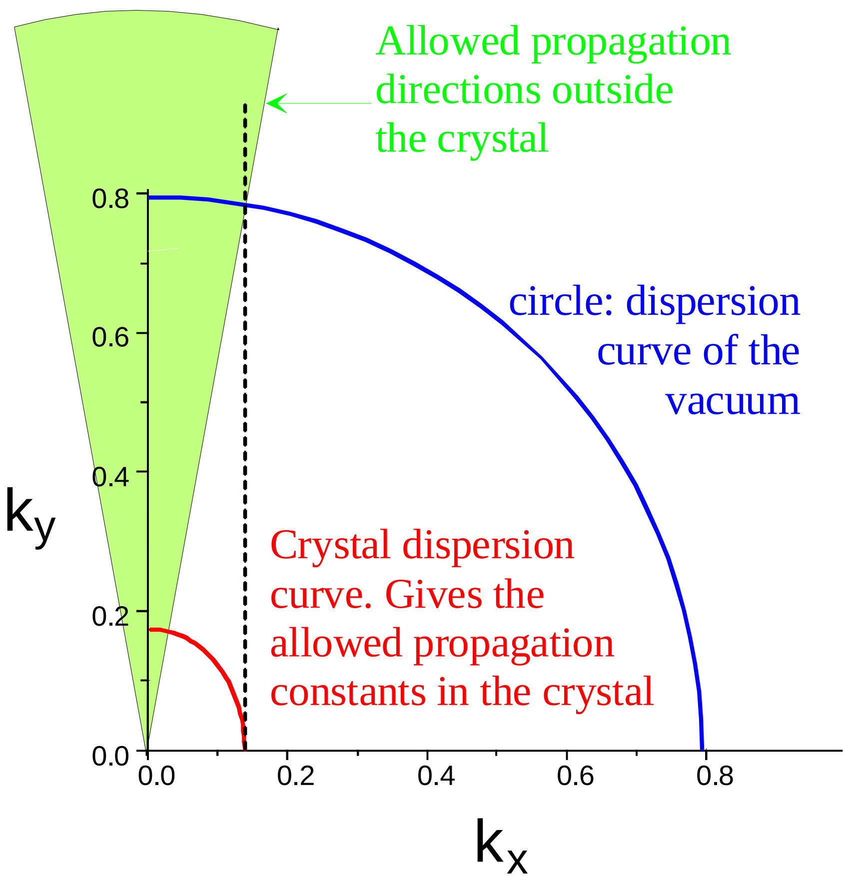
[4] B. Gralak, S. Enoch and G. Tayeb, *Anomalous refractive properties of photonic crystals*, J. Opt. Soc. Am. A **17**, pp.1012-1020, 2000.

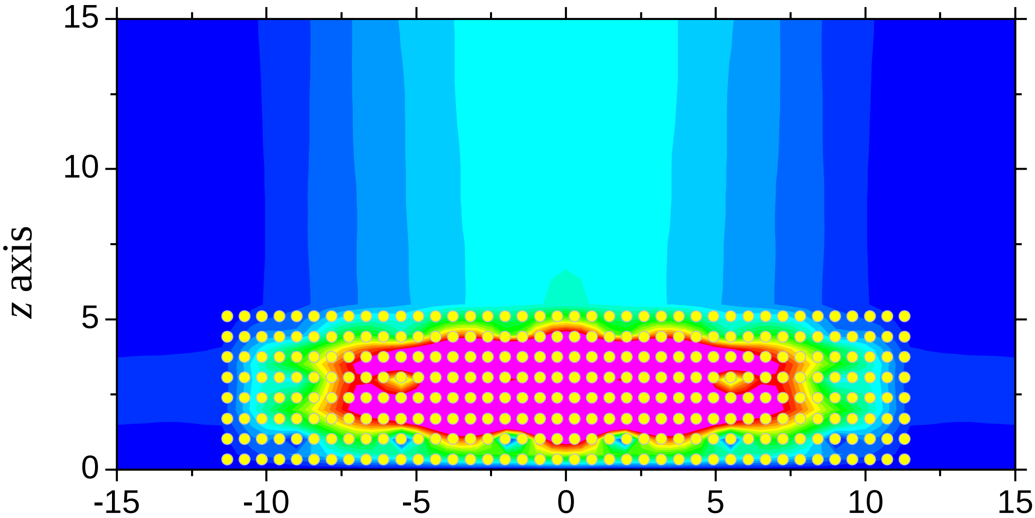
Interpretation of the directivity of the emitted field using Bloch modes



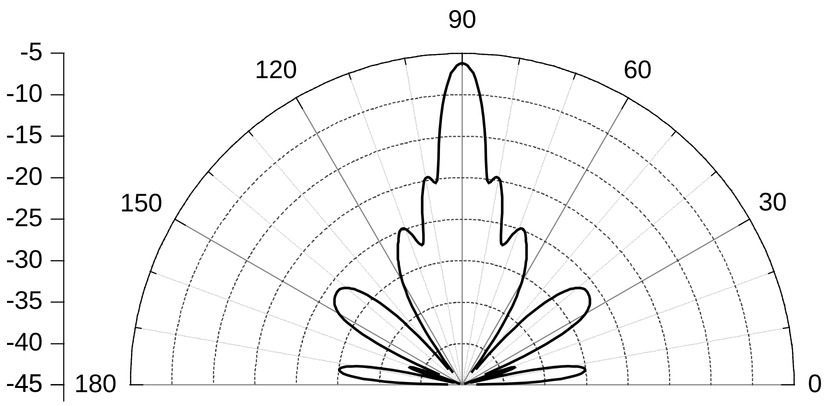
In the infinite structure the field can be represented as a sum of Bloch modes: $\psi_{\vec{k}}(\vec{r}) = e^{i\,\vec{k}\cdot\vec{r}}\; u_{\vec{k}}(\vec{r})$

For a fixed wavelength λ, the dispersion relation is a curve in the (k_x, k_y) plane:

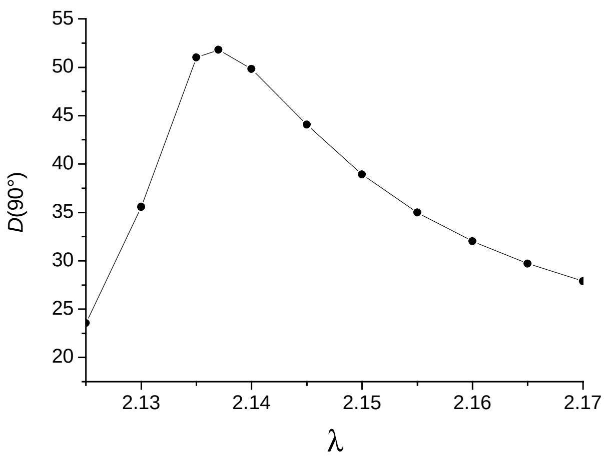




Field modulus radiated by the photonic crystal based antenna. 40×8 wires with rectangular cross section, above a ground plane. Excitation by a patch-like source in the middle of the structure. λ = 2.14 cm.



Radiation pattern, dB scale. The half-power beamwidth is 2×3.4°.



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

The present device provides a slightly higher directivity than the Perot-Fabry cavity, but a slightly lower frequency bandwidth.

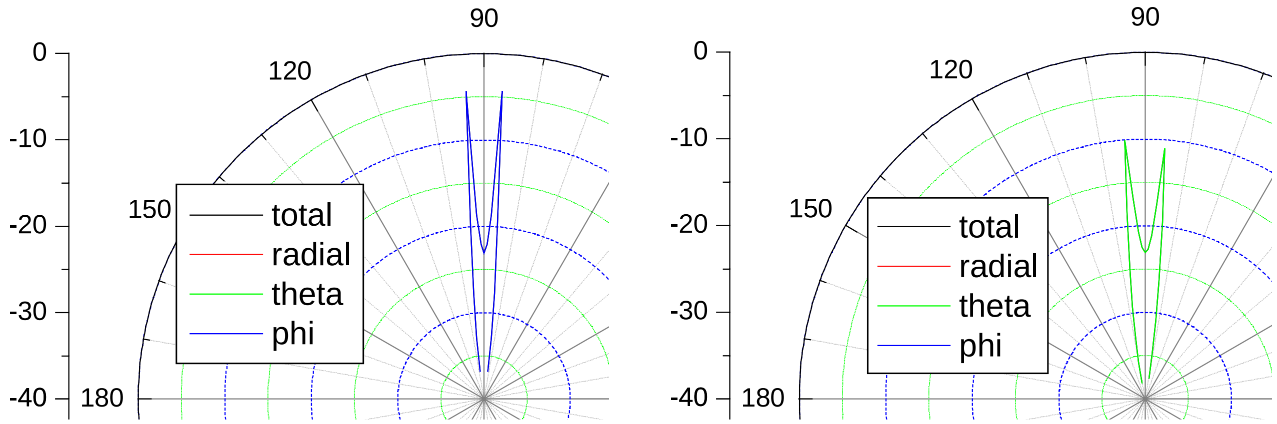
From the 2D study:

Many attempts with different sources, varying their position and the wavelength
→ it seems difficult to excite a directive emitting mode of this device with a source located near the ground plane

THREE-DIMENSIONAL MODELING

The source is located in the middle of the PBG structure.

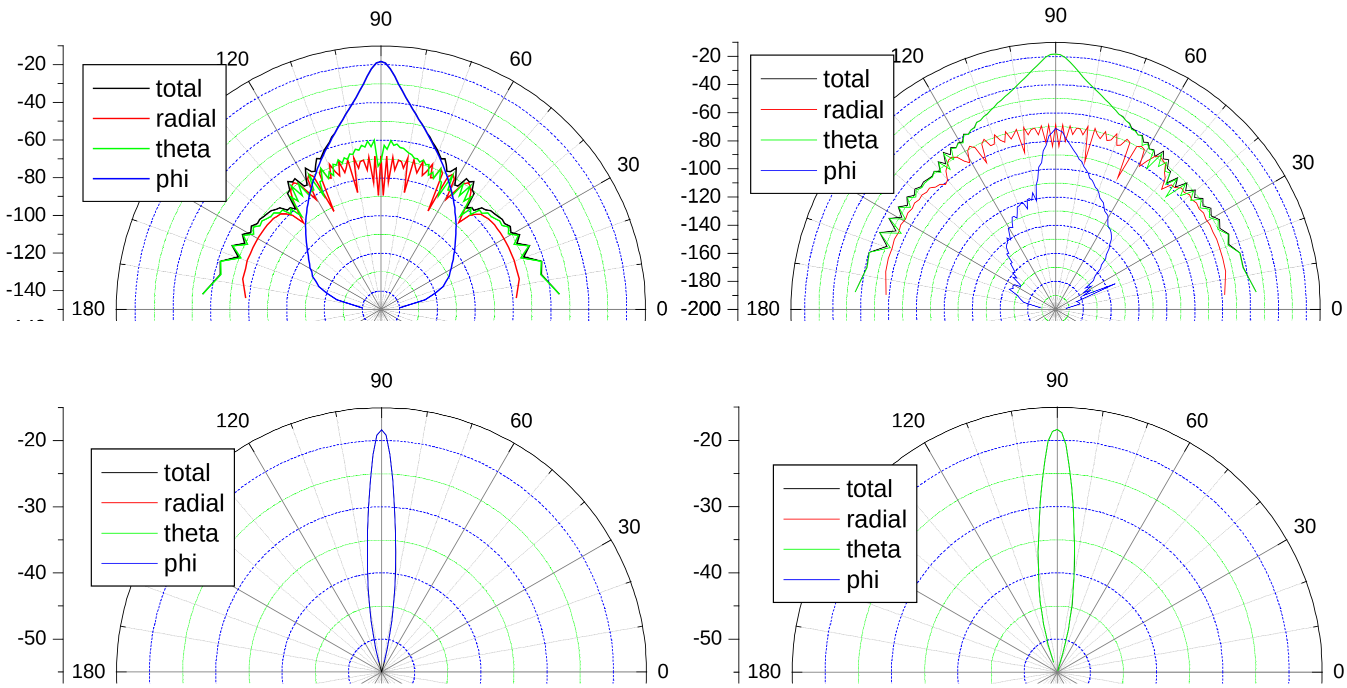
First attempt starting from the values directly determined by a 2D study: λ = 21.1mm , radius of the wires 0.275mm.



Plane φ = 0°   Plane φ = 90°

Radiated field (dB)

Greater radius of the wires: λ = 21.1mm , radius of the wires 0.277mm



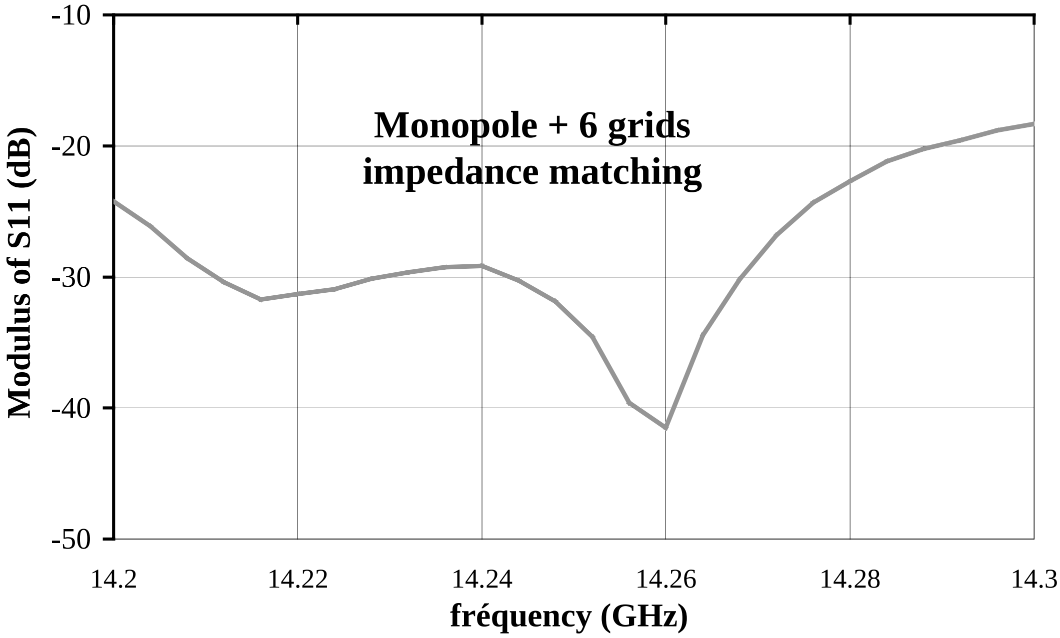
Plane φ = 0°   Plane φ = 90°

Beamwidth: 2×2.0°   2×2.6°

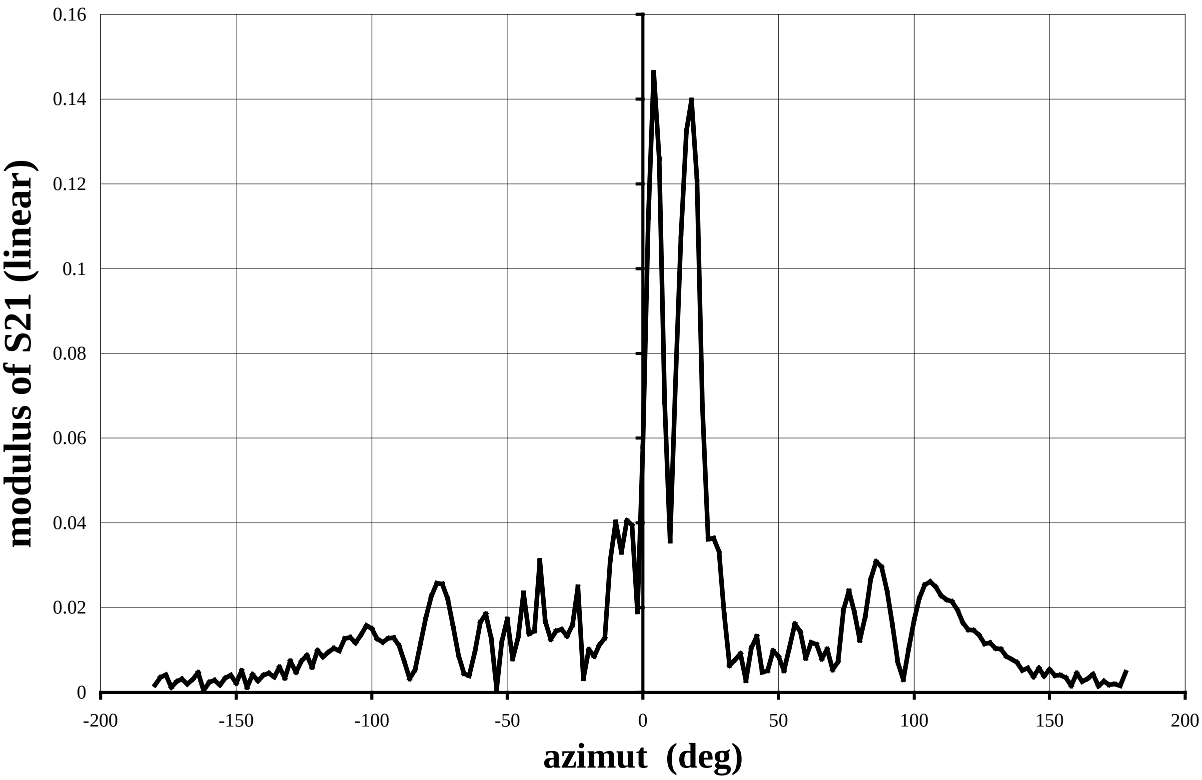
EXPERIMENTAL STUDY

It is just beginning…

Antenna with 6 grids etched from copper sheets



Radiation pattern : monopole + 6 grids, 14.26 GHz



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 here, this technique will allow us

- to take into account the interaction between the source and the arrays of wires
- to model a finite structure.

The experimental study is in progress.

REFERENCES

[1] D. Felbacq, G. Tayeb, and D. Maystre, "Scattering by a random set of parallel cylinders," *J. Opt. Soc. Am. A*, vol.11, pp.2526-2538, 1994.

[2] G. Tayeb, D. Maystre, "Rigorous theoretical study of finite size two-dimensional photonic crystals doped by microcavities," *J. Opt. Soc. Am. A*, vol.14, pp.3323-3332, 1997.

[3] B. Gralak, S. Enoch and G. Tayeb, "Anomalous refractive properties of photonic crystals," *J. Opt. Soc. Am. A*, vol.17, pp.1012-1020, 2000.

[4] G. Guida, D. Maystre, G. Tayeb, P. Vincent, "Electromagnetic modelling of three-dimensional metallic photonic crystals," *Journal of Electromagnetic Waves and Applications*, vol.12, pp.1153-1179, 1998.

[5] N. Guérin, S. Enoch and G. Tayeb, "Combined method for the Computation of the Doubly Periodic Green's Function," *Journal of Electromagnetic Waves and Applications*, vol.15, pp.205-221, 2001.