A compact directive antenna using ultrarefractive properties of metamaterials

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Abstract – **In this paper, we show that metallic photonic crystals can, in some particular conditions, behave as a metamaterial with effective optical index close to zero. We use these ultrarefractive properties to design compact directive antennas. We start from theoretical considerations, including modeling for 2D and 3D structures, and finally show experimental results.**

1 INTRODUCTION

Some recent works [1,2] describe the use of photonic crystals applied to the realization of directive antennas. In these works, the photonic crystal behaves as the mirrors of a resonant Fabry-Perot cavity.

In this paper we describe another way to get compact directive antennas using photonic crystals. In this case, we take profit of the ultrarefractive behavior of metallic photonic crystals at the vicinity of their low frequency gap. We describe our theoretical and numerical work, as well as our experimental results concerning the design of these directive antennas. One of the objectives is to obtain antennas much more compact than classical solutions. Another interesting feature is that these antennas can be excited by a single feeding device (patch, monopole). Such antennas could be useful for microwave telecommunications.

The antenna presented here uses a metamaterial that is a composite stack of metallic grids and foam layers. This metamaterial is analyzed using the techniques that we have developed for the study of photonic bandgap structures [3]. Near the band edge, it is shown that this material behaves as a homogeneous media with low optical index (much less than unity). We show that under proper conditions the energy radiated by a source embedded inside the structure is concentrated in a narrow emission lobe. Based on this analysis, we have build a device working in the microwave domain: a ground plane is covered by the metamaterial, with a monopole source embedded inside. The experimental measurements are in good agreement with the theoretical predictions.

For the study of this structure, specific numerical codes have been developed. The two-dimensional case is used for the preliminary studies [4]. 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 [5], but lead to huge numerical systems. In order to reduce the computational burden of the 3D codes, we have used a simplified modeling, assuming that the structure is infinite (in the two directions parallel to the ground plane), thus we take advantage of the periodicity to reduce the unknowns to one period only, using a fast bi-periodic Green's function [6].

2 ULTRAREFRACTIVE METALLIC METAMATERIAL

The behavior of the antenna presented in this paper is based on the properties of a stack of metallic grids, which can be considered as a photonic crystal, a grating, a metamaterial, a complex media, depending on the reader's habits. As well known, these grids have filtering properties. First, they completely filter the low frequencies that cannot propagate inside (low frequency bandgap). For our purpose, we are mainly interested in the small frequency range associated with the transition between the low frequency bandgap and the allowed propagating solutions. Several studies [7-9] have shown that in this frequency range where the wavelength is much greater than the period of the periodic media, the metamaterial can be homogenized in a material whose relative permittivity has a behavior governed by a plasma frequency in the microwave domain: $\varepsilon_{eff} = 1 - \omega_p^2 / \omega^2$. Of course, using this expression, one can check that the low frequencies see the metamaterial with a negative permittivity, i.e. a pure imaginary optical index, and so the only solutions are evanescent waves. But this expression also tells us that for frequencies just a little bit larger than the plasma frequency, the relative permittivity stays between 0 and 1, and the same is valid for the optical index. In this case where the metamaterial has an effective optical index which can be close to zero, one can expect ultrarefraction phenomena. This remarkable property is the key idea that governs the behavior of our antenna.

Another interesting feature of this device is its ability to generate a linearly polarized beam when

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the current in the exciting source flows parallel to a given direction. This is one of the reasons of our decision to use a monopole to feed the antenna. It means that all the currents in the metallic grids also flow parallel to this direction. The consequence is that the electric field inside the metamaterial is also nearly parallel to this direction. Since the grids are made with thin metallic crossed wires, it can be shown that the wires orthogonal to this direction have a very little influence on the antenna property. This feature is fundamental for the numerical study, since it proves that a two-dimensional modeling will allow us to anticipate the properties of the antenna with a good accuracy. One question arises: what is the usefulness of the wires in the orthogonal direction? The aim is to use another exciting source orthogonal to the first one, and to get two uncoupled problems generating two orthogonal linear polarizations. By this way, it should be easy to control the polarization of the emitted field.

Following this idea, the outline of our work stands out naturally: a numerical 2D study to understand and verify the global properties, and also to choose the convenient parameters; then a 3D study to check the parameters, and allowing us to verify that there is no cross polar; and finally an experimental realization concluded by the measurement of the radiation pattern.

3 TWO-DIMENSIONAL MODELING

The structure is modeled as a stack of metallic grids made with infinitely conducting wires. The infinitely conducting metal is indeed a good approximation in the range of wavelengths of interest. We suppose that a localized source is embedded in this metamaterial. According to the remark made above, when the frequency is in a convenient range where the metamaterial behaves as an ultrarefractive material with a positive effective efficiency $\varepsilon_{eff} = n_{eff}^2$ much less than unity, the Fourier components k_x and k_z of the propagative solutions in the metamaterial should stay smaller than $k_0\, n_{eff}$, and consequently much smaller than the wavenumber in vacuum k_0. It can be shown [3] that if the structure is infinite along the *x* direction, the tangential component k_x is continuous at the interface between the metamaterial and the vacuum, which means that the field in vacuum will have a k_x component much less than $k_0\, n_{eff}$. Consequently, the structure will radiate in directions very close to the normal to the structure (*z*-direction).

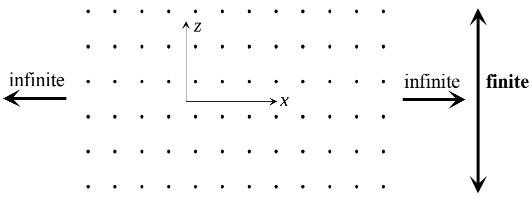

Fig.1. Schematic representation of a metamaterial made with a stack of 6 metallic grids.

We can also give another interpretation of this phenomenon using the transmission properties of the metamaterial. Fig. 2 shows the transmission of a plane wave through a stack of five grids parallel to the *y*-axis. We denote by d_x the period along the *x*-axis and by d_z the vertical spacing between two grids. In this case, the wires have a circular cross section. The polarization of the electric field is parallel to the wires. The figure shows clearly a large low-frequency gap, and a smaller gap for higher frequencies (not used in the present study). It also shows that the edge of the gap moves with the incidence. For instance, the wavelength associated with the vertical line passes through the stack in normal incidence, but is not transmitted for higher incidences. The reciprocity principle provides the link between these transmission properties and the emission of a source embedded in the metamaterial. This short and heuristic explanation can be put in a rigorous form using the dispersion curves of the Bloch modes inside the photonic crystal [3].

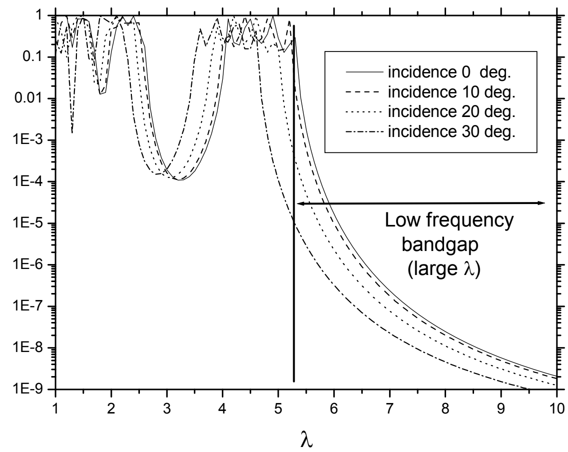

Fig.2. Transmission of a plane wave through a stack of 5 grids with $d_x = 1$ and $d_y = 2$. The radius of the wires is $r = 0.05$. All dimensions can be scaled by multiplication by an arbitrary factor.

Let us now turn to a model directly linked with the experimental study that we have realized. In the 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 14 GHz, 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 0.071 cm large (along the *x*-axis), $d_x = 0.58\ \text{cm}$, $d_z = 0.63\ \text{cm}$. This study is achieved with the help of a numerical code able to deal with a finite structure (finite number of wires). This code has been developed in our Laboratory, and is based on a rigorous modal method using the scattering matrices of each wire, the fields being expressed as Fourier Bessel series [4]. Fig. 3 shows the modulus and the lines of equal phase of the total field radiated by the structure made with 40×6 of these wires above a ground plane located at $z = 0$. The source is a wire antenna parallel to the *y*-axis placed in the middle of the metamaterial, with a wavelength $\lambda = 2.07$ cm. The most striking fact is the very slow variation of the phase inside the metamaterial, which is a proof that the effective index in this material is quite low. One can also notice that the phase of the emitted field is nearly constant on planes parallel to the emitting surface. The radiation pattern exhibits a narrow lobe (Fig.4), with a half-power beamwidth of 2×3.8°.

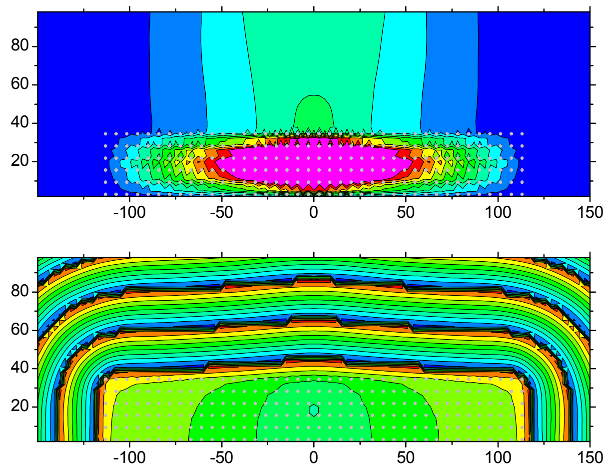

Fig. 3: Field modulus (top) and lines of equal phase (bottom) of the field radiated by the 2D antenna.

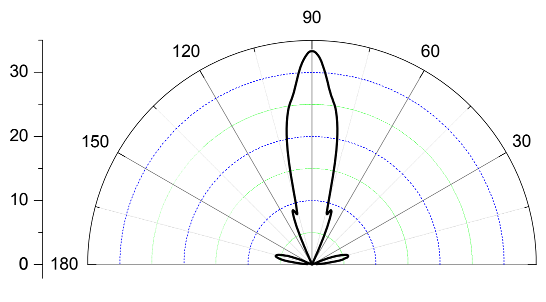

Fig.4: Radiation pattern for the device of Fig.3 (dB scale). The half-power beamwidth is 2×3.8°.

4 THREE-DIMENSIONAL MODELING

For this purpose, we use an integral method based on the Harrington's thin wire approximation [5]. In order to reduce the number of unknowns, 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 monopole in the absence of the grating. This field is transformed in a plane-wave packet using a FFT. To speed up the computations, we have developed a numerical technique for the efficient computation of the bi-periodic Green's function [6]. The results of this 3D modeling are given in Fig. 5. The half-power beamwidth are 2×2.0° and 2×2.6° in the H and E plane respectively. Of course, because of the various approximations done in this 3D modeling (Harrington's thin wire approximation, replacement of wires with rectangular cross section by equivalent wires with circular cross section, infinite extent in the *x* and *y* directions), the results give mostly qualitative information on the radiated field rather than quantitative ones.

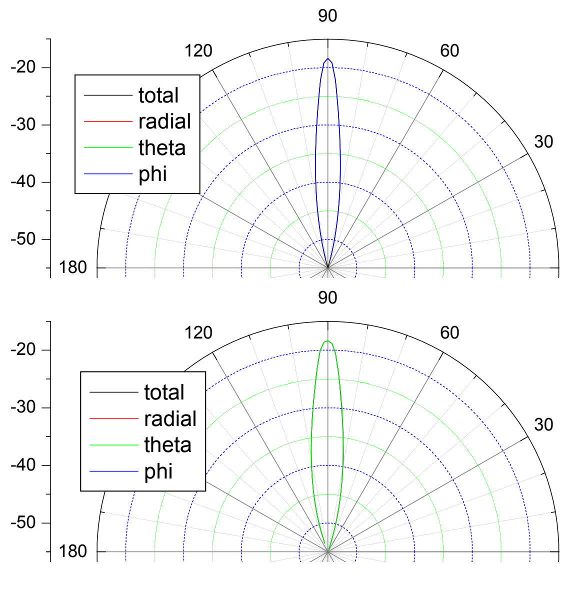

Fig.5: Radiation patterns in dB scale in the H plane (top) and the E plane (bottom), obtained by the 3D modeling.

5 EXPERIMENTAL REALIZATION

The experimental device is made of 6 grids etched from copper plates. The spacing between the grids is maintained by foam layers. The device is placed on a ground plane, and is fed by a monopole placed in the center. Fig. 6 gives the measured radiation pattern at 14.65 GHz. It shows the high directivity of the antenna and the good linear polarization of the emitted field. The measured half-power beamwidth is about 2×5°. The dissymmetry of the radiation pattern in the E plane is probably due to the coaxial cable which feeds the monopole. The cross-polar radiation is not shown on this figure, but it stays low: - 23 dB compared to the copolar level in the normal direction (maximum radiation), and about - 10 dB for directions far from the normal.

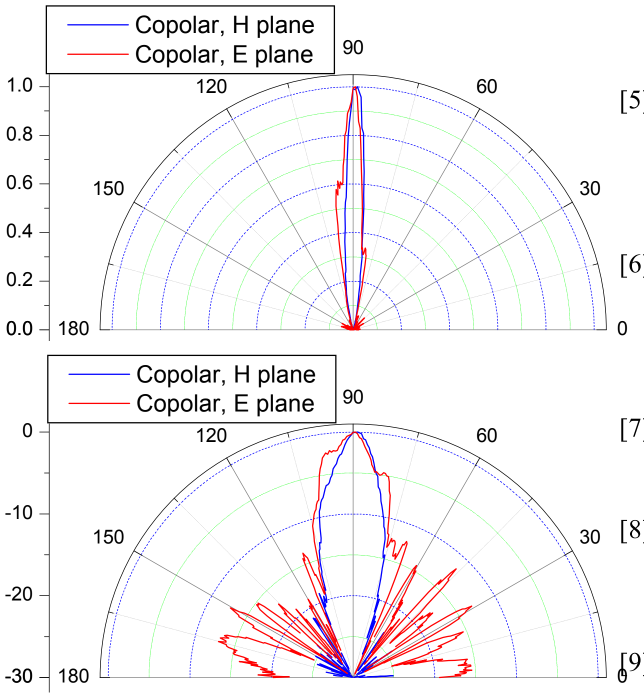

Fig.6: Experimental radiation pattern in linear scale (top) and dB scale (bottom).

CONCLUSION

This work proves that the concept of metamaterials for the realization of high directivity and compact antennas is relevant. Using the ultrarefractive properties of photonic crystals, we get a device which is not sensitive to the characteristics of the source which feeds the antenna.

Of course, since the properties of the metamaterial change rapidly with the frequency, this concept is not appropriate to design antennas working in a large bandwidth.

References

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