A Metamaterial for Directive Emission

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In this paper we present the first results on emission in metamaterial. We show how the specific properties of metallic composite material can modify the emission of an embedded source. We show that under proper conditions the energy radiated by a source embedded in a slab of metamaterial will be concentrated in a narrow cone in the surrounding media. An experimental demonstration of this effect is given in the microwave domain, and the constructed antenna has a directivity equivalent to the best reported results with photonic-crystal-based antennas but using a completely different physical principle [B. Temelkuaran *et al.*, J. Appl. Phys. **87**, 603 (2000)].

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Periodic metallic structures have the ability to simulate various homogeneous materials whose specific properties eventually do not exist for natural materials. It has been shown that a structure composed of a periodic mesh of metallic thin wires, when its characteristic dimensions (period, section of the wires) are small in comparison to the wavelength, behaves as a homogenous material with a low plasma frequency [1,2]. It means that the dispersion relation of the propagating modes in this structure is shaped like in plasmas of electron gas. This opened the field of composite materials or metamaterials for microwaves and optical applications. Several structures have been proposed to simulate materials with a dielectric or a magnetic plasma frequency or even both together (always using nonmagnetic conducting structures) [3]. A special case of the latter is known as a left-handed metamaterial, as under proper conditions a propagating plane wave in this media is such that **E**, **H**, and **k** form a left-handed system, **k** being the wave vector. Left-handed metamaterials have been the subject of intensive research in the past few years [4]. In terms of application, the amazing refractive properties of the metamaterials and, more specifically, the left-handed material have excited the imaginations of the physicists, and ideas proposed by Vesalgo long before the availability of such a material are taken up nowadays and extended [5]. For example, Pendry has proposed left-handed material to build perfect lenses that are not limited to the usual wavelength limits but are able to focus even evanescent waves [6].

Regarding the control of emission two features are of interest: the enhancement of the emission rate and the control of the direction of emission. Several solutions have been proposed to these problems, such as microcavities that can enhance spontaneous emission or photonic crystals that are probably the best candidates to inhibit, enhance, and control emission. For that matter, photonic crystals have been first proposed for the inhibition of the spontaneous emission [7]. Let us recall that basically a tridimensional photonic crystal is a dielectric or metallic periodic structure whose period is of the order of magnitude but smaller than the wavelength for use. The difficulties encountered to realize such periodic structures in the optical domain have slowed down the development of the applications, but recent works have shown that they are now available [8,9].

The antennas also benefit from the properties of photonic crystals: they have been first proposed as a substrate for planar antennas in order to suppress the surface modes on a conventional metallic ground plane [10]. The second idea was to use planar defects in a photonic crystal to design directive antennas [11,12]. The planar cavity acts in that case as a Fabry-Perot resonator, and the similitude is even clearer for monodimensional photonic crystals that are strictly equivalent to the classic Fabry-Perot filter realized using dielectric optical thin films and often used as an optical spectral filter.

Our aim in this paper is to show how a metamaterial allows us to control the direction of emission of a source located inside the material in order to collect all the energy in a small angular domain around the normal. To our knowledge, it is the first time that the metamaterials are considered to modify the emission of a source.

In this paper we will consider the simplest class of metamaterial: a metallic mesh of thin wires (with wires in the three directions of space). Theoretical and experimental works have shown that such arrays of continuous thin wires are characterized by a plasma frequency [1,2,13]. Both approximate analytical theory and rigorous homogenization theory show that the equivalent permittivity has a behavior governed by a plasma frequency in the microwave domain:

$$\epsilon_{\text{eff}} = 1 - \omega_p^2/\omega^2, \tag{1}$$

where ω_p is the plasma frequency and ω the frequency of the electromagnetic wave.

The first consequence of the existence of this microwave plasma frequency is that the equivalent permittivity is negative when the frequency is below ω_p. It has been discussed and, for example, surface modes has been shown to exist when $\omega_s = \omega_p/\sqrt{2}$ [1]. But one other extraordinary property of such material has been less discussed: the permittivity just above the plasma frequency can be positive and less than one (still real as long as the materials are lossless). That is to say, the optical index is less than one, eventually very close to zero. This property opens many opportunities as the relevant parameter is often the contrast between the permittivities rather than the permittivity itself (for example, in optical application). It has been shown that a dielectric photonic crystal, when the frequency is chosen at the band edge, can also simulate a low-index material [14]. Then a very low optical index is a very good candidate to design, for example, extremely convergent microlenses.

How will this property help us in the control of the emission of a source? Let us now consider a point source inside a slab of near-zero index material surrounded by a homogeneous isotropic material (supposed to be the vacuum here). We will first give a naive geometric image of the principles of this control (see Fig. 1, top). We consider an incident ray on an interface (the upper face of the slab) with grazing incidence that comes from a source inside the slab of metamaterial. The Snell-Decartes laws imply that with a near-zero index the ray in the media above the slab will be refracted in a direction very close to the normal (lower is the optical index; closer is the direction to the normal). Then all the refracted rays will be in almost the same direction around the normal as illustrated in Fig. 1, top.

Figure 1, bottom, illustrates the same idea but with a more rigorous point of view: an harmonic source with frequency ω radiates in all the modes (plane waves) with tangential components on the interfaces of the slab included in the range $-k_0 n_{\mathrm{eff}}$, $k_0 n_{\mathrm{eff}}$ ($n_{\mathrm{eff}}^2 = \epsilon_{\mathrm{eff}}$ and $k_0 = \omega/c$). As the tangential components of the wave vector are continuous on the interfaces (as long as the slab is infinite along the x and y axes defining the plane of the interface), the emitted field in the media around the slab must have k_x and k_y components included in the same range. We have assumed that the point source radiates in all the propagative modes and that the emission in evanescent modes is negligible as these modes are exponentially attenuated in the slab and will be negligible on the interfaces as soon as the distance between the source and the interface is sufficiently large. If the optical index of the metamaterial is very small, then the emitted field is concentrated around the normal of the slab. This is summarized in Fig. 1, bottom, where the small circle has a radius proportional to the effective index of the metamaterial, in fact, $k_0 n_{\mathrm{eff}}$. This small circle is the constant frequency dispersion diagram in the metamaterial. The large circle has a radius proportional to the index of the media around the slab (k_0 for vacuum, the constant frequency dispersion diagram of the surrounding media). For the sake of clarity two-dimensional diagrams are presented, but, in fact, these circles are nothing other than a section in the $k_y = 0$ plane of the isofrequency dispersion diagram, i.e., are given by $\omega(k_x, k_y, k_z) =$ const. In the case of an homogeneous isotropic media with optical index n_{eff}, this diagram is a sphere with a radius equal to $k_0 n_{\mathrm{eff}}$.

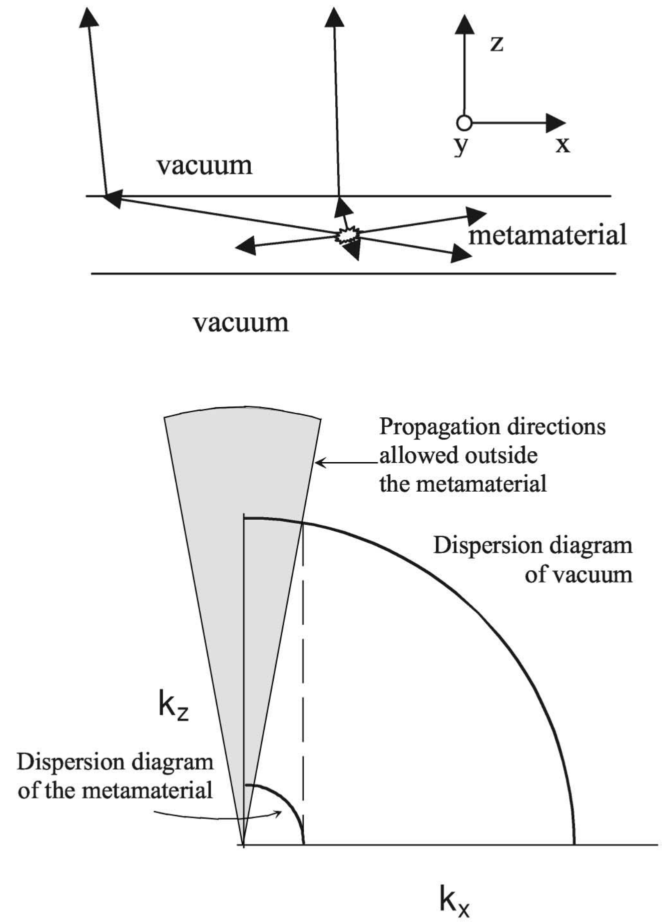

FIG. 1. Top: geometrical interpretation of the emission of a source inside a slab of metamaterial whose optical index is close to zero. From the Snell-Decartes laws even the grazing rays are refracted in a direction close to the normal. Bottom: Construction in the reciprocal space. The circles are the isofrequency dispersion diagrams for the vacuum (large circle with radius k_0) and the metamaterial (small circle with radius $k_0 n_{\mathrm{eff}}$). The conservation of the tangential components of the wave vector and the assumption that the source emits only in the propagating modes is traduced by the fact that only the modes whose tangential components are smaller than the radius of the small circle (the dashed line) are excited in the surrounding media.

Similar considerations have been developed theoretically using dielectic photonic crystals, and the richness of the dispersion relation of these structures gives more possibilities such as antennas radiating in off-axis directions [15].

The ideas developed here have been applied in the microwave domain to realize a directive emitter using metallic grids. The metamaterial is composed of copper grids made using the conventional printed circuits technology of electronics and slices of foam whose permittivity is close to 1 ($\epsilon = 1.08$ at 14.6 GHz). Figure 2 shows a schematic view of the structure composed of six identical grids with a square lattice embedded in foam essentially for its mechanical properties (the parameters are given in the figure caption).

In our realization of the metallic mesh the vertical wires have been suppressed, and, from a theoretical point of view, the material is no longer isotropic. However, several remarks justify that it has little influence on the radiation properties of the device. First, the isotropy of the material is not needed and it is required only that the dispersion diagram of the metamaterial is included in a small range of k_x and k_y. Second, the monopole symmetries imply that the component of the total electric field along the z direction is negligible; thus the interaction with the vertical wires is also negligible (it has been numerically verified). And it must be noticed that the realization of the structure with the wires in the three directions is much more complicated.

The transmission of the structure has been measured, of course, without the ground plane and without the monopole represented in Fig. 2. The low frequency stop band confirms that the metamaterial possesses a microwave plasma frequency at about $f = 14.5$ GHz (see Fig. 3). Note that the experimental transmission is defined by the quotient of the measured field with and without the structure (i.e., the slab of metamaterial) when it is placed in the front of the reception antenna and the emission antenna is located at about 12.5 m. The antennas are both ridged horn antennas linearly polarized and the measurements are realized with a network analyzer. Since the structure has a limited extent, this "transmission" is not required to be lower than one. Some focusing effect can lead to transmission greater than unity, and this effect can explain the transmission greater than one in Fig. 3 and can be observed theoretically for finite size structures [16]. The experimental results are in good agreement with the numerical simulations given in the same figure. The numerical results are obtained for a periodic structure along the x and y axes (and thus infinite) using the method of moments in the thin wire approximation. For the higher frequencies some discrepancies can be noted. We have conducted experiments that consist of measuring the transmission spectra for several distances between the reception antenna and the crystal. It appears that the discrepancy can be attributed to the coupling between the reception horn and the crystal. Of course, this coupling is negligible when the transmission of the photonic crystal is quasinull, and then the discrepancies disappear in the gap region. Indeed, we have checked that the numerical limit of the gap matches the experiments whatever the distance between the crystal and the horn.

In order to validate our approach we have built an antenna with this slice of metamaterial lying on a metallic plane surface, acting as a ground plane for our antenna (see Fig. 2). The structure is excited with a simple monopole introduced between the third and the fourth grids. The position of the monopole in the plane centered between the two grids is chosen in order to optimize the performances of the antenna, since its input impedance is quite sensitive to this position.

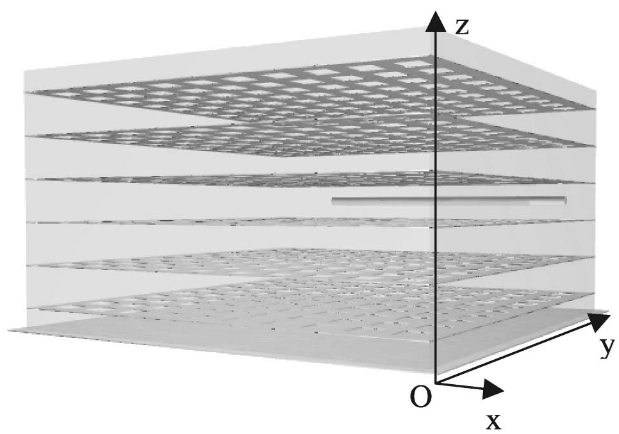

FIG. 2. Schematic representation of the structure. The metamaterial is composed of copper grids with a square lattice and whose period is equal to 5.8 mm (in the x-axis and y-axis directions). The grids' spacing in the z-axis direction is 6.3 mm, and the grids are separated with foam represented in light grey on the figure. The edge of the square holes of the copper grids is 4.95 mm. The edge of the square grids is about 226 mm. To complete the antenna the metamaterial is placed on a metallic ground plane (represented by the gray plane below the metamaterial) and is excited by a monopole antenna (represented by the wire between the 3rd and the 4th grids). In fact, the emitting part of the monopole is approximatively centered on the square antenna and the wire represents the coaxial cable which feeds the monopole. Note that the dimensions are arbitrary on the figure and are chosen for the sake of clarity of the figure.

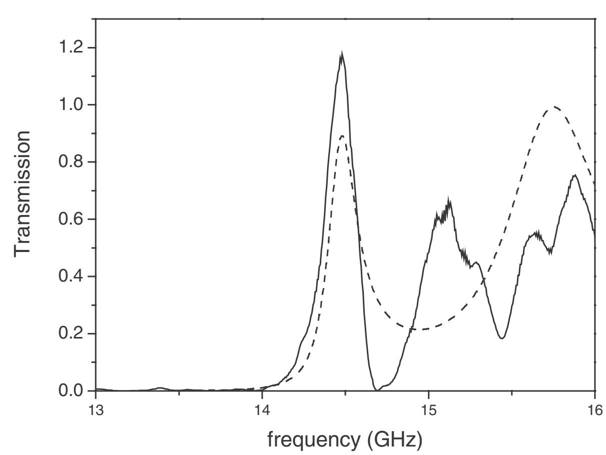

FIG. 3. Experimental (solid line) and theoretical (dashed line) transmission of the slab of metamaterial for a normal incidence.

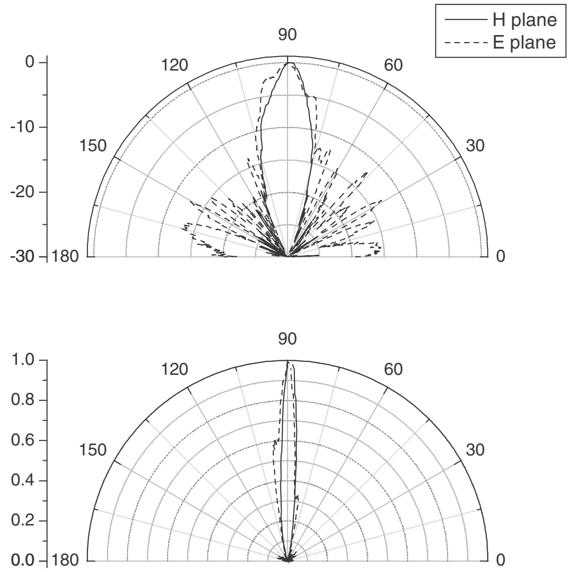

FIG. 4. Diagram of emission of the antenna in dB scale (upper figure) and linear scale (lower figure) in the H plane (solid line) and the E plane (dashed line).

Figure 4 shows the emission diagram in both linear and dB scales of the structure for the optimal frequency ($f = 14.65$ GHz chosen to obtain the best directivity). The diagram has been measured in the same anechoic chamber at a distance of about 10.5 m (in order to be in a far field configuration). Again the reception antenna is a ridged horn and the network analyzer is used for the measurements. The diagram of emission has been measured in two orthogonal planes: one is the yOz plane (orthogonal to the coaxial cable, the H plane) and the other the xOz plane (the coaxial cable is in this plane, the E plane), and both the copolarized field (the monopole is parallel to the axis of polarization of the horn) and cross-polarized field (the monopole is orthogonal to the axis of polarization of the horn) have been measured. As expected, the emission of the structure is concentrated in a narrow lobe around the normal of the structure and moreover is linearly polarized. The cross-polarized field is not represented and is always less than 20 dB lower than the copolarized field. The half-power beamwidth is about $\Delta\theta_1 = 8.9°$ in the H plane and $\Delta\theta_2 = 12.5°$ in the E plane. Using the classical formulas valid for the directional patterns $D = 4\pi/(\Delta\theta_1\Delta\theta_2)$, the directivity D is found to be equal to 372, that is equivalent to the best directivity reported to our knowledge for a photonic-crystal-based antenna but using a defect resonance [11]. The asymmetry observed on the emission diagram (Fig. 4) is due to the coaxial cable feeding the monopole the antenna. We think that a more elaborate device, for example, a patch, should improve the directivity, and from the presented results a directivity of more than 500 can be expected.

The results presented in this Letter validate the concepts of our approach to control the emission, and we think that they can be applied in other domains, such as optical sources, or in the domain of thermal coherent sources.

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