From Metamaterial-Based to Metamaterial-Inspired Miniaturized Antennas: a Possible Procedure and Some Examples

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Abstract

In this contribution, we present the procedure employed by our research group to go from *metamaterial-based* to *metamaterial-inspired* miniaturized antennas. The concepts of microwave metamaterial-based and metamaterial-inspired antennas and components are firstly reviewed. Then, we address the main issues to tackle when going from metamaterial-based to metamaterial-inspired miniaturized antennas. The first issue is related to the anisotropy of the inclusions, which is not usually considered in the preliminary analysis of metamaterial-based antennas. The solution of this issue is given in terms of a deep, though approximated, analysis of the near field distribution of the antennas. The second issue is related to the dimensions of the inclusions, which should be much smaller than the operating wavelength. The solution in this case is found in the miniaturization of the isolated inclusions through different methods. Finally, the third issue is related to the definition of the constitutive parameters of the sample made of a given arrangement of inclusions. An operative solution of this issue is related to the comparison between the transmission and reflection properties of the inclusion-made and the ideal isotropic metamaterial sample. A few design examples are also presented to show the procedure proposed through the paper.

1. Introduction

The use of volumetric and transmission-line metamaterials turns out in several interesting properties for microwave antennas. In this contribution, we refer to the class of *volumetric metamaterials* that are to be realized in practice through properly designed inclusions. One of the most interesting features enabled by the employment of volumetric metamaterials in the field of antennas is the possibility to get electrically small resonating radiators with acceptable performances, that can be useful for microwave sensors and RFID tags and radiators. The idea of using metamaterials to squeeze the dimensions of microwave components has been proposed for the first time in [1] in the case of 1D resonators. The concept presented in [1] has been extended by some groups worldwide to obtain miniaturized dipole and monopole [2], patch [3], and leaky-wave [4] antennas.

In these theoretical works metamaterials are usually considered as ideal homogeneous and isotropic samples with electrically small dimensions and described by homogenized constitutive parameters following given dispersion laws. The interesting features of the metamaterials enabling the miniaturization of the antennas are strongly related to both the geometrical dimensions of the metamaterial samples and the values of the homogenized constitutive parameters at the frequency of interest. In order to reproduce the same features in real-life antennas, we have to fabricate the needed metamaterial samples through proper inclusions.

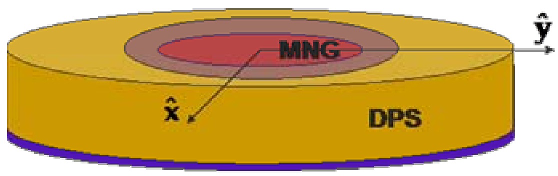
Anyway, when considering the antennas with inclusion-made metamaterials a few questions arises. First of all, since the volume of the antenna (and, thus, of the metamaterial sample) is electrically small, the metamaterial is made by a few inclusions. This leads to the fundamental question if this kind of antenna can be referred to as a metamaterial antenna anymore. It seems, in fact, that the antenna is rather just a regular antenna loaded with a few metallic inclusions (split-rings, spirals, wires, etc.) On the other hand, it is true that the designs of those antennas have been obtained through an application of the metamaterial concepts or, even more, in some cases it would not have been able to get that specific design without starting from the metamaterial concepts. Another fundamental question is again related to the electrically small dimensions of these antennas: how is it possible to define a homogenized material with given constitutive parameters in these electrically small volumes?

Recently, a distinction between *metamaterial-based* and *metamaterial-inspired* antennas has been proposed to solve some of these formal ambiguities [5]. According to that definition, metamaterial-based antennas are those ones made of ideal homogenized metamaterials. In the case of miniaturized antennas, the class of metamaterial antennas is made of just ideal components with the exception of the metamaterial radiators realized through the plasma-tube technology [6]. In this latter case, in fact, the epsilon-negative behavior is obtained through plasmas, which behaves more or less as ideal epsilon-negative metamaterials described by a Drude dispersion model. On the other hand, metamaterial-inspired antennas are all those radiators obtained applying the metamaterial concepts but that in reality consist of regular antennas just loaded with a few metallic inclusions. Therefore, almost all the miniature antenna experimental designs proposed so far in the literature can be considered, indeed, as metamaterial-inspired antennas.

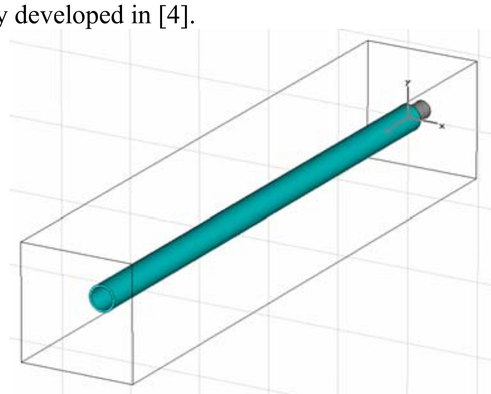
In this work, we outline the main issues to be solved when going from the metamaterial-based antennas to the metamaterial-inspired counterparts. Some examples concerning the design of patch and leaky wave radiators will be given.

2. From metamaterial-based to metamaterial-inspired antennas: the main issues to be solved

In Fig. 1 we present two designs of metamaterial-based antennas. The one in Fig. 1a is the sub-wavelength circular patch antenna presented in [3]. The inner part of the substrate is made of an ideal isotropic and homogeneous mu-negative metamaterial having a given value of the permeability at the working frequency. At that frequency, it has been shown in [3] that the antenna resonates and radiates, even if the dimensions are much smaller than half-wavelength, which is the typical resonant dimension of a patch radiator [3]. In Fig. 1b, instead, we reproduce the leaky wave cylindrical antenna presented in [4]. Such an antenna is made of an epsilon-negative cylindrical shell, whose thickness is a very small fraction of the operating wavelength. Again, the metamaterial is assumed to be an ideal homogeneous and isotropic material described by Drude's dispersion law, such that, at the working frequency, the permittivity of the sample is the one needed according to the theory developed in [4].



a)

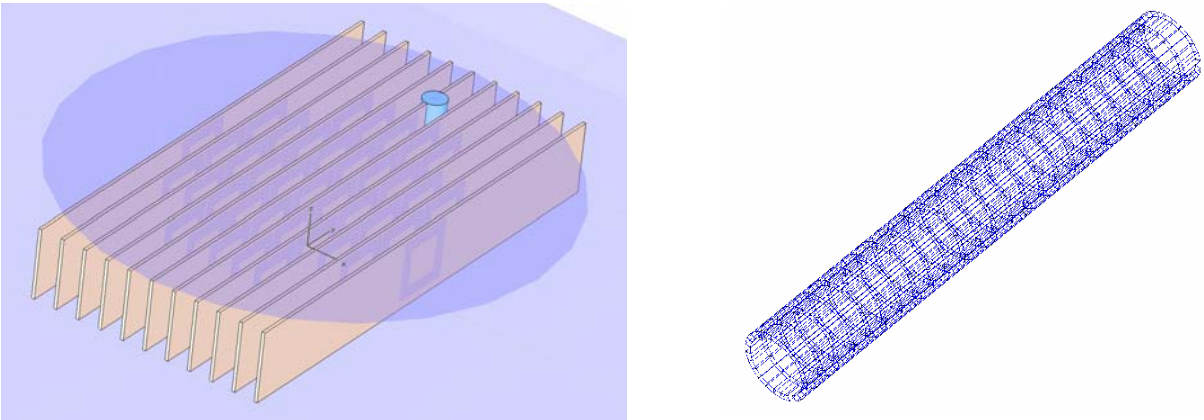


b)

Figure 1 – a) Miniaturized patch antenna loaded with a mu-negative (MNG) metamaterial substrate (the figure is from [3]). b) Leaky-wave cylindrical antenna made by an epsilon-negative (ENG) metamaterial shell (the figure is from [4]).

When going towards a practical implementation of these antennas through real-life inclusions, the first issue to solve is the inherent anisotropy of the inclusion-made metamaterial sample. A fully 3D-isotropic metamaterial is very hard to be produced, especially in the electrically small volume occupied by the antenna. Anyway, this difficulty can be smartly overcome looking at the near-field distribution of the resonating modes in the two structures of Fig. 1. The theoretical analysis developed in [3] and [4], in fact, allows to predict the distribution of the resonant modes, which are responsible for the operation of the two antennas and dominate the total field distribution in a full-wave scenario. Looking at these distributions, we found out that the electric and magnetic fields of the resonating modes are mostly polarized along given direction in the near field. In [7] and [8], therefore, we have shown that a possible anisotropy of the mu-negative and epsilon-negative metamaterials, respectively, does not affect the operation of the two radiators. Therefore, the issue of the inherent anisotropy of the inclusions can be solved just aligning properly the inclusions, according to the main polarizations of the fields in proximity of the metamaterial sample. In the case of the antennas in Fig. 1, the corresponding alignment of the inclusions is shown in [7]-[8].

The second issue to tackle in the design of miniaturized metamaterial-inspired antennas is the size of the inclusions to fit the electrically small volume of the radiators. The theoretical results presented in [3]-[4] show that in principle there is no limit in the size of the metamaterial samples loading the two antennas depicted in Fig. 1. The patch radius can be even with vanishing size, as well as the thickness of the cylindrical shell. Anyway, this is only a theoretical speculation and, when dealing with the inclusions, indeed, there is a limit in their smallest achievable dimensions. Therefore, ever more miniaturized inclusions are needed, in order to replicate the great miniaturization performances expected from the theoretical analysis of the corresponding metamaterial-based antennas. Some examples of miniaturized artificial magnetic inclusions are reported in [9]-[10]. Possible implementations of miniaturized artificial electric inclusions are found in [11]-[12]. Of course, in these cases, the electrically smaller the inclusions are, the narrower the operation bandwidth is. This further optimization issue is left to the final designer, according to the applications the radiators are designed for. Anyway, since we deal with miniaturized antennas it is evident that the corresponding applications are inherently narrowband. The metamaterial-inspired antennas corresponding to the ones reported in Fig. 1 are shown in Fig. 2.



a) b)

Figure 2 – a) Actual implementation of the miniaturized antenna depicted in Fig.1a. b) Actual implementation of the leaky-wave cylindrical antenna depicted in Fig. 1b.

Once the anisotropy issue has been solved and miniaturized inclusions are available, a third difficulty comes from the design of the inclusions in order to get the same needed value of permeability or permittivity derived from the theoretical analysis of the components. As previously anticipated, it is hard to speak about effective constitutive parameters when the homogenization volume is electrically small and the inclusions are not densely packed together. When the dimension of the inclusion, in fact, is a fraction of the wavelength and the metamaterial sample is very thin, the granularity of the material cannot be neglected anymore and classical homogenization procedures fail. The parameters retrieved through the classical methods are usually non-physical and non-local and, thus, may vary, for instance, with the angle of incidence. Some papers have considered recently this problem from a theoretical point of view and the interested reader is remanded to [13]-[14].

In the case of the metamaterial-inspired antennas it can be easily shown that there is not an urgent need of a theoretically correct definition of the effective parameters of the sample made by a few inclusions. The reason is again in the small volume occupied by the sample and the near-field distribution of the electromagnetic field interacting with the inclusions. In most cases as the ones reported in Fig.1, the fields interacting with the inclusions are almost linearly polarized in the near-field. This means that the only need is that for that particular polarization and angle of incidence, the arrangement of the inclusions has the same transmission and reflection properties of the ideal isotropic and homogeneous metamaterial counterpart. Therefore, the procedure to design the inclusions is straightforward. The inclusion-based metamaterial sample should behave exactly as the ideal metamaterial for the particular polarization and angle of incidence needed. The retrieved parameters of the sample, of course, cannot be considered as the real epsilon and mu of the metamaterial made of a set of inclusions. The obtained parameters, in fact, are subject to vary with the size of the sample, and with polarization and angle of incidence of the impinging field. Nevertheless, the retrieved parameters are very useful from the practical point of view, since they allow to obtain a quick and effective design of the inclusions. In other words, the parameters retrieved in this way cannot be considered as constitutive parameters of the medium, but represent an operational definition of the effective parameters for the specific problem at hand. The results presented in [7] for the case of the patch antenna and in other papers [15]-[16] for different microwave components confirm the validity of the proposed approach.

3. Acknowledgments

This work has been partially supported by the European Commission through the Network of Excellence METAMORPHOSE and the project ECONAM, grant number FP7-NMP-CSA-1-218696.

4. Conclusions

In this contribution, we have revised the concepts of metamaterial-based and metamaterial-inspired antennas, outlined the main issues to tackle when going from ideal metamaterial designs to the actual implementation of miniaturized radiating components through the proper inclusions. The problem considered in this work: a) anisotropy of the inclusion-based metamaterial; b) dimensions of the inclusions; c) design of the inclusions and values of the constitutive parameters. Solutions to these problems have been proposed through a couple of examples concerning a miniaturized patch and a leaky wave cylindrical antenna.

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