Compact MIMO Antenna Arrays Using Metamaterial Hybridization Band Gaps

Geoffroy Lerosey[1,*], Christian Leray[2], Fabrice Lemoult[1], Julien de Rosny[1], Arnaud Tourin[1] and Mathias Fink[1]
[1] Institut Langevin, ESPCI ParisTech - CNRS UMR 7587, 10 rue Vauquelin, 75005 Paris, France, geoffroy.lerosey@espci.fr
[2] Time Reversal Communications, Parc Saint Christophe, 10 Avenue de l'Entreprise 95861 Cergy Pontoise Cedex

Abstract: In this talk, we show how the concept of hybridization band gap in metamaterials can be utilized to create antennas for MIMO applications. Those strongly decoupled antennas present at the same time a very small form factor and a very low correlation. To that aim, we first explain briefly the concept of hybridization between a resonator and the free space waves continuum. Then we expose the methodology we use to design multi-ports antennas based on that concept. We present results of several antennas designed using this idea, especially in the wifi bands, and give potential solutions for multi-band compact MIMO antennas for LTE applications.

1. Introduction

It is well known that in order to be efficient for MIMO communications, antenna arrays must present very low correlation coefficients. This can be achieved by separating the antennas of the array by a distance higher than half a wavelength at the operating frequency [1]. Yang has proposed, based on a structure investigated by Sievenpipper, to decouple even better patch antennas from surface waves using mushroom type electromagnetic band gap structures [2,3]. There has also been some proposals in order to decouple antennas using slabs of metamaterial which present an effective negative permeability or permittivity [4]. Yet none of those approaches ensure antennas with a very small form factor. Here we propose a very general approach based on the concept of hybridization band gaps that permit to design antennas with any type of resonant element. Using those subwavelength resonant elements, it is possible to design antenna arrays which present a small form factor and low correlations and inter-antenna coupling. In the first part of the paper, we explain the concept of hybridization in terms of Fano resonances, and underline why resonant elements create band gaps that forbid the propagation of waves. We explain how one can take advantage of those properties to realize compact antenna arrays for MIMO applications. Then we propose various designs of antennas based on this concept, and underline their performances in terms of coupling, efficiencies and form factors.

2. Hybridization band gaps

2.1 Metamaterials and photonic crystals

In a recent paper [5], we have shown that there is a very close relation between metamaterials and photonic crystals. Those two different kinds of manmade materials are not governed by the same phenomena, but they can present the same properties. In the case of photonic crystals, interferences between scattered and transmitted waves, known as Bragg interferences, can result in the inhibition of the propagation of waves in certain frequency ranges. One very interesting feature of photonic crystals [6] is that since propagating waves only govern their properties, one can locally modify these materials without destroying the band gaps they offer, in order for instance to create cavities, filters, waveguides, and so on. These crystals, although presenting many applications, can very limitedly be used in the radio frequency domain since their typical scale is of the order of the wavelength. Metamaterials [7], on the contrary, present much smaller spatial scale.

This is due to the fact that their unit cell is generally resonant, and hence can have a typical width much smaller than the wavelength. They are usually used for their effective properties, for instance negative permeabilities or permittivities, and hence as slabs or bulky pieces. This can be explained by the common belief that the unit cells of metamaterials are strongly near field coupled, and that no local modification of a metamaterial can be done, such as changing a single or a few unit cells, without altering the properties of the whole material. Hence, there has been no tentative to transpose the concepts explored in the photonic crystal field to that of metamaterials. In the antenna community, electromagnetic band gap materials (EBG) have been proposed independently to decouple antennas, which present spatial scales relatively smaller than those of photonic crystals. Again, the latter are usually used as isolating surface between antennas, and the typical separation between uncoupled antennas remains quite large, of the order of half a wavelength, even though the coupling can be drastically reduced.

2.2 Metamaterial as hybridization band gap materials

In order to explain the relation between photonic crystals and metamaterials, we have adopted the notion of hybridization. This phenomenon occurs when a local resonance hybridizes with the continuum of the plane waves of a homogeneous medium, giving raise to a binding and an anti-binding branches, that are separated by the so-called hybridization band gap. This effect is usually rather elusively justified by a level repulsion between the wave, that is, the photon or the phonon, and a local resonance. This notion has been particularly studied in the acoustics community, and is rather unknown in the electromagnetic one. We have studied many unit cells of metamaterials using a willingly simplified quasi 1D model [5], and shown that many features of the latter can be attributed to a far field type of coupling between unit cells, namely, to the hybridization concept.

The principal results of this study are as follow. For most media made out of resonant and subwavelength unit cells, even organized on a deep subwavelength scale, at the first order only propagating waves participate to the coupling between unit cells. The dispersive nature of the medium made of those unit cells can be attributed to a Fano interference between the wave incoming on a resonator and going through it without interacting, and the wave that “excites” the resonator and that is re-emitted by it. Therefore, the dispersive nature of the metamaterials, which includes high permittivity or permeability parts of the spectrum, and negative permittivity or permeability parts of the spectrum, can be attributed solely to far field components. This is of course not valid for all unit cells since some present high near field couplings, that is, capacitive or inductive couplings, but for most. This has a very important consequence: most resonant metamaterials present band gaps (those negative effective properties frequency windows), which simply rely on far field components of the spatial spectrum. Conversely, most metamaterials can be understood just like conventional photonic crystals, albeit of much smaller spatial scales, and governed by different physical phenomena. This has led us to introduce the notion of defect in metamaterials band gaps, and to demonstrate a very deep subwavelength cavity in the microwave domain, with unprecedented small mode volume [8].

2.3 Hybridization band gap materials for antenna applications

Photonic or microwave band gaps are obviously very useful for many applications, and present great advantages for antenna applications, as demonstrated by electromagnetic band gaps. Indeed, such media present the ability to stop the propagation of waves in certain frequency ranges. Our approach, which uses any subwavelength resonator as a building block for designing a subwavelength scaled hybridization band gap, takes advantage of this property. An international patent application has been filled on this idea.

Basically, an hybridization band gap based on a metamaterial that can be linear, 2D, or 3D, provides the following outcomes. The wave emitted by a feed that is placed in the direct vicinity of such medium cannot enter the medium, and hence tend to be emitted in the direction opposite to that of the band gap. This gives the possibility to engineer the radiation pattern of an antenna in order to emit waves in preferred directions of space. Consequently, one can design antenna arrays, each antenna emitting with quasi orthogonal radiation patterns, for example for MIMO applications. In this case, the MIMO takes advantages of radiation diagram diversity, rather than from uncorrelated points in space, that require a much larger spacing between the antennas. Naturally, because the waves cannot penetrate the metamaterial, two ports placed very closely but separated by a few unit cells of the hybridization band gap are strongly decoupled, the coupling being lower and lower as the number of unit cells is increased. The second advantage of this approach is that since those resonant unit cells can be of deep subwavelength size, efficient antenna arrays with orthogonal radiation diagrams and very good decoupling can be realized on very small dimensions compared with the wavelength. Using a linear chain of unit cells one can design a 2 antenna array, using a square of unit cells one obtains a 4 antenna array, and so on, without using any polarization degree of freedom.

A very convenient way of realizing such an antenna is to design a band gap using a given unit cell, and to use the same unit cell as an antenna, by slightly changing its dimension such that its resonant frequency falls in the band gap of the metamaterial. For instance, if one creates a line of identical passive resonant wires very closely spaced that give a band gap above their resonant frequency, putting two shorter wires on each side of the line gives the possibility to create a 2 antenna array of deep subwavelength dimension, by connecting the shorter wires to an RF stage and matching their impedance.

3. Practical antenna designs

Of course, using an array of wires to design a multi-port antenna for MIMO applications is not very convenient since its fabrication is complicated and costly. In the rest of the talk, we will present various practical antenna designs based on the idea of hybridization band gaps. To that aim, we will first introduce a planar type antenna design, directly printed on a PBC, whose unit cell consists in a quarter wavelength high resonant slit, that is, a very subwavelength resonator. A typical example of such antenna is provided in Figure 1. It shows a compact 4 antennas array with gains around 2 dBi for each port. Its principle is very simple considering the concept of hybridization band gap metamaterials. We use quarter wavelength slits whose resonant frequency is around 2.2 GHz and which are printed on a single side PCB. The 4 ports antennas is made using two 2 ports antennas polarized along the x and y directions. Each of these two ports antennas consists of 4 of the aforementioned slits which create an hybridization band gap, and on each side of this band gap medium, two fed ports which are the antennas. Thus, the two antennas are decoupled by the 4 slits band gap medium. In order to decouple even more the two orthogonally polarized yet small 2 ports antennas, we place again a four slit band gap medium in between them.

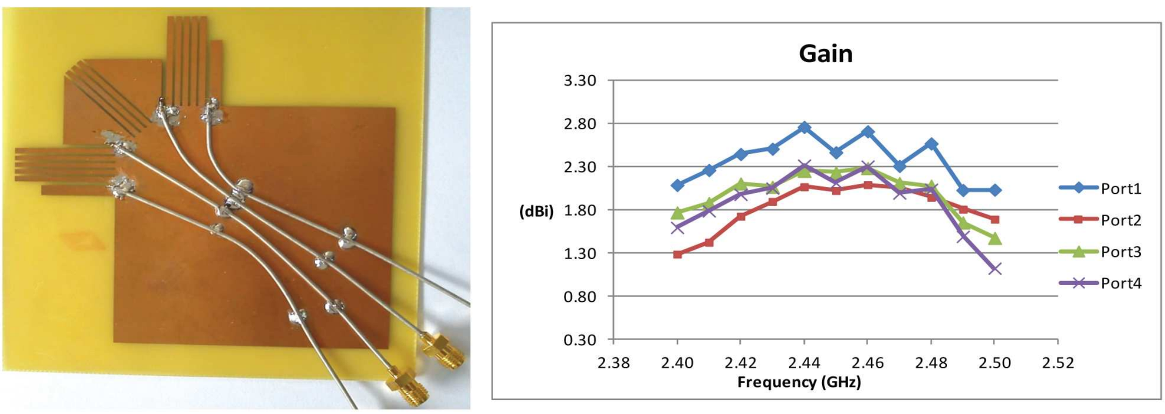

Figure 1: a 4 ports MIMO antenna for WIFI applications. The antenna size is around 5cm*5cm and it displays typical gains between 2 and 2.8 dBi.

In Figure 2, we map the 3D radiation pattern of one of the 4 ports of this compact MIMO antenna. It is clear that thanks to this structure, and because of the resonant deep subwavelength band gap medium created by the resonant slits, a very directional emission is realized by this antenna despite its very small size. The 3 other radiation patterns are as directive as the one presented here, yet they point in different directions. This is verified by the correlation plot presented in Figure 2 as well, which shows that the 4 antennas are very well decoupled.

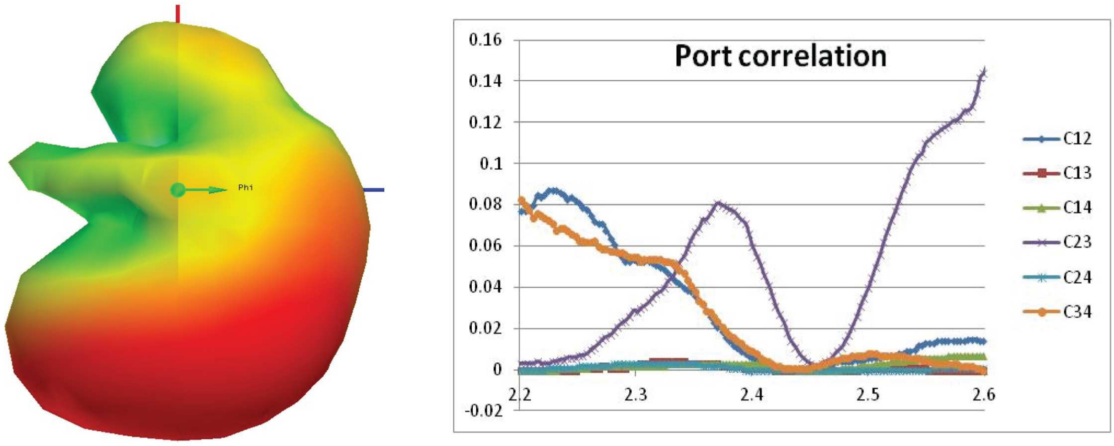

Figure 2: typical radiation pattern of the left bottom port of the previous MIMO antenna array, clearly displaying a good directivity. The measured correlations between the 4 antennas, plotted on the left curves, show a very good decoupling between the 4 antennas despite the very small form factor of the array

This is one example of the use of hybridization band gap media to realize very compact, efficient and decoupled MIMO antenna arrays. We will present other types of 2, 3 and 4 ports antennas based on various designs, as well as discuss the possibility to realize multi-band multi-ports MIMO antennas for instance for LTE applications

Acknowledgments

We acknowledge funding of French “Agence Nationale de la Recherche” (ANR) under project TRIMARAN.

References

[1] A. Paulraj, R. Nabar and D. Gore. Introduction to Space-Time Wireless Communications, Cambridge Univ. Press, (2003).
[2] D. Sievenpiper et al. *IEEE Trans. on Microwave Theory and Techniques*, **11**, 2059, (1999).
[3] F. Yang and Y. Rahmat-Samii. *IEEE Trans. on Antennas and Propagation*, **51**, 2936, (2003).
[4] CC. Hsu et al., Antennas and Propagation Society International Symposium, APS-URSI- IEEE (2009).
[5] F. Lemoult, M. Fink and G. Lerosey, arxiv.org/pdf/1112.2524 (2011).
[6] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, Photonic Crystals: Molding the Flow of Light (Second Edition) (Princeton University Press, 2008).
[7] N. Engheta and R. Ziolkowski, eds., Metamaterials: physics and engineering explorations (John Wiley & Sons & IEEE Press, 2006).
[8] F. Lemoult, M. Fink and G. Lerosey, arxiv.org/pdf/1112.2524 (2011).