Metamaterials-based Antennas: Translation from Physical Concepts to Engineering Technology

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***Abstract*— In this paper, I would like to share my thoughts about the applications of metamaterials in innovative antenna designs from an engineering perspective. Based on my understanding of metamaterials, we have translated the physical concepts of metamaterials in the laboratory to innovative antenna technologies for practical applications. The technologies have been successfully developed, in particular at microwave and millimeter-wave bands, to greatly improve key performances of antennas, such as operating bandwidth and efficiency, and to also significantly reduce the volume of antennas. Some of the latest antenna designs based on metamaterials are included.**

***Index Terms*—metamaterials (MTM), antennas, operating bandwidth, efficiency, gain, miniaturization.**

I. INTRODUCTION

When I first came to know about metamaterials from a seminar by presented a physicist in early 2000, the unique electromagnetic properties of the metamaterials grabbed my attention as a new promising paradigm in electromagnetics, in particular, antenna engineering. Since that time, more and more theoretical studies of new physical concepts and phenomena has led to many exciting scientific findings [1-5]. I have monitored the progress in researching metamaterials with strong interest because we as antenna engineers have long been searching for technical breakthroughs that would help us meet increasing challenges in antenna designs in wireless systems. Before 2010, when I was with Institute for Infocomm Research (I^2R), A*Star Singapore I have partnered with some researchers from universities to explore the possibilities of applying the metamaterials in antenna or electromagnetic engineering. However, our experience with this research effort, and its outcomes were very disappointing from an engineering point of view, to say the least. It confirmed my concerns, again and again that the existing metamaterials, namely double negative (DNG) materials typically suffer from narrow operating bandwidths, high ohmic losses and high fabrication and/or material costs because they are usually formed by using the single or arrays of elements that exhibit strong resonances. These drawbacks prevent the use of metamaterials in practical applications, because they play a very critical role in any wireless system design.

In 2010, I began to rethink about how to incorporate metamaterials in antenna designs by translating the scientific concepts of metamaterials to practical technologies. What prompted me to revisit this issue was that I had just secured a new research project on metamaterials funded by A*Star. Even though I myself was not involved in this particular aspect of antenna research prior to this, and the pressure was on me to deliver something interesting and useful. Here, I will attempt to share my thoughts as well as my experience with this effort.

II. GENERALIZED METAMATERIAL CONCEPT

Before thinking about how to make an impact in this exciting field, albeit as a latecomer, I thought that I should ask myself the basic question: "What are metamaterials?" I found that typically the researchers associate metamaterials with negative index characteristics and, hence, limit themselves to double-negative (DNG) materials even though a number of other definitions could be found in the literature. For example, the following definitions have been popularly cited:

1. Metamaterials are artificial media structured on a size scale smaller than the wavelength of external stimuli. Materials of interest exhibit properties not found in nature, such as negative index of refraction. They are cellular assemblies of multiple elements fashioned from materials including metals and plastics, arranged in periodic patterns. Metamaterials gain their properties not from their constituents, but from their exactingly-designed structures. Their precise shape, geometry, size, orientation and arrangement can affect light or sound in a manner that is unachievable with conventional materials [6].

2. (Metamaterial is) a synthetic composite material with a structure such that it exhibits properties not usually found in natural materials, especially a negative refractive index [7].

3. Metamaterials are exotic composite materials that display properties beyond those available in naturally occurring materials. Instead of constructing materials at the chemical level, as is ordinarily done, these are constructed with two or more materials at the macroscopic level. One of their defining characteristics is that the electromagnetic response results from combining two or more distinct

materials in a specified way which extends the range of electromagnetic patterns because of the fact that they are not found in nature [8].

Therefore, the "metamaterials" can be briefly described as *artificial structures* engineered to provide electromagnetic (EM) properties *not readily available* in nature. We adopted this definition of metamaterials and began to review what metamaterials or artificial structures we could work on in terms of permittivity (or relative permittivity, ε_r) and permeability (or relative permittivity, μ_r). We should mention that there are other ways to categorize a material, for example, in terms of its refractive index (product of permittivity and permeability) or in terms of its linearity/non-linearity, and so on.

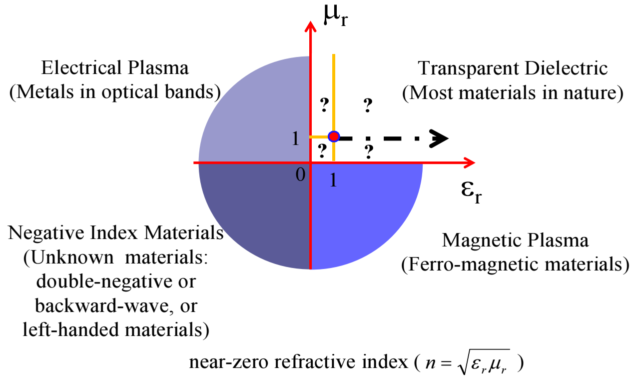

Fig. 1 Classification of materials in terms of permittivity and permeability

I found that either a real or artificial material whose electromagnetic properties belong to Quadrants I and III (see Fig. 1) are of much interest from an engineering perspective over those belonging to Quadrants II and IV.

It is obvious that all artificial materials or structures falling in Quadrant III can be categorized as metamaterials. Owing to their unique of double-negative (DNG) refraction index, their backward wave propagation or left-hand wave transmission characteristics, these materials appear to have a much higher potential for applications in innovative electromagnetic engineering. A huge amount of research funding has been invested in research into DNG and similar materials and a very large number of publications have appeared in prestigious journals.

Unfortunately, however, although scientific findings about metamaterials have been very exciting, the same cannot be said about their success in industrial applications, which have been very few and far between indeed. I conjecture that this is because although the physical concepts of metamaterials appear to have a huge potential, the technology needed to implement these concepts are not yet ready for practical applications. The primary reason for this, I believe, is that metamaterials, especially DNG metamaterials typically comprise of elements/structures which exhibit strong resonances, and which, in turn, result in narrow bandwidths and high ohmic losses caused by sharp electric currents induced in the structures near resonances that render them impractical to use in real-world engineering applications, unless we can find new ways to realize them such that these problems are mitigated.

On the other hand, a commonly acceptable definition of metamaterials also tells us that all structures with arbitrary permittivities and permeabilities can be considered as metamaterials if the EM properties of such artificial structures are not found in any nature materials. Thus, we decided to review the materials with the properties belonging only to Quadrant I, namely ($\mu_r \geq 0$, $\varepsilon_r \geq 0$).

From the above study, I found that the EM properties of existing natural materials are all associated with a relatively small zone in Quadrant I (μ_r, ε_r)≥ 1 where μ_r is usually close to unity. This suggests that we still have considerable room to research into and develop new artificial structures, metamaterials that belong to Quadrant I, so as to realize unique EM properties that could help improve real-world antenna performance. It would include, for instance, the structures falling in the zones of *a.* $0 \leq \mu_r < 1$; *b.* $0 \leq \varepsilon_r < 1$; *c.* either μ_r or $\varepsilon_r >> 1$; and *d.* both μ_r and $\varepsilon_r >> 1$.

The structures with the above properties are of special interest in microwave engineering including antenna and circuit designs because of several reasons. For example, there are no materials featuring the properties associated with in Zones *a* and *b* which affect EM wave propagation significantly, and it is impossible to fabricate a dielectric such as existing FR4, which can achieve arbitrary dielectric constants as desired. Also, to our knowledge, no material can provide arbitrary permeability as desired in many application, at least at radio frequencies higher than 1 GHz. Although some thin films can realize very high values of permeability or permittivity, or both, the same cannot be said for the films of practical thickness that we need to use in real-world applications..

It is also worthwhile to mention that, the artificial structures also can realize some unique EM properties, such as chirality and anisotropy, which affect the EM wave propagation in non-conventional ways.

One more issue that we need to be aware of when translating metamaterial concepts to technology is that it has been difficult for the engineers from the industry to fully understand the metamaterials that have been described by using many physics-based terms such as refraction index, permittivity or permeability, instead of engineering parameters such R, C, and L or S-parameters. Also, we need to see a direct link between the scientific phenomena or concepts of metamaterials to well-defined engineering designs, based on the use of backward waves and so on.

As a result, I worked out my own strategy to conduct the translational research of metamaterials in antenna engineering. We have focused on developing artificial structures which feature unique EM properties in Quadrant I. Also, we are still exploring new non-resonant ways to realize the structure /materials with desired properties unique to Quadrant III.

III. SOME SUCCESS STORIES

Following our strategy, we have thought out-of-the-box to develop metamaterials-based technology for innovative antenna design. Listed below are some of these that have been successfully developed and translated to applications in the industry.

A. Zero-Phase-Shift Line Based Antennas:

Zero-phase-shift segmented loop antennas are able to generate uniform magnetic field in an electrically larger zone with a perimeter of two operating wavelengths for near-field RFID applications at ultra high frequency (UHF) bands [9-11]. The zero-phase-shift line is also used to form the circularly polarized omni-directional antenna for wireless local area network (WLAN) applications [12].

B. Anisotropic High-Permittivity Loaded Antenna

A dipole antenna loaded with an anisotropic high-permittivity planar structure was designed for multiple-input-multiple-output (MIMO) systems [13]. The antenna achieved a wide bandwidth of 44.4% (1.67-2.69 GHz) with gain of 14.2 dBi, aperture efficiency of 94%. The design concept was also applied in other antenna arrays for cellular base-station with great thickness reduction.

C. Mushroom Antenna

An antenna comprising of an array of mushroom cells as radiators was developed for WiFi applications [14]. The composite right/left-handed antenna with a low profile of $0.06\lambda_0$ and a ground plane of $1.10 \times 1.10\lambda_0$ was able to achieve 25% bandwidth ($|S_{11}| < -10$ dB), 9.9-dBi average gain, and cross-polarization levels of <-20 dB across the bandwidth.

D. Gap-Capacitor Loaded Antenna

The antenna is composed of a slotted patch in which the series zero-order resonance (ZOR) and antiphase TM_{10} mode are simultaneously excited due to the introduction of the series gap-capacitive loading on the center and the radiating edges of the patch. The antenna achieved a bandwidth of 20% with a profile of 0.04 operating wavelengths and efficiency of 90%. This antenna found application in an L-band radar system.

IV. CONCLUSIONS

Metamaterials are of high potentials not only in scientific research but also engineering applications. In particular, the concepts of metamaterials have opened up a new window and opportunities to develop innovative technologies. More importantly, it has taught us to think out-of-the-box to explore new ways to bridge the gap between the physical concepts and engineering technology, and thereby translate scientific findings in the laboratories to industry designs in market. Our experience has given us much confidence to translate research to development to commercialization (R&D&C) in the context of metamaterials.

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