A STUDY OF METAMATERIAL BASED ELECTRICALLY SMALL ANTENNA TO ENHANCE GAIN

Gagandeep Kaur and Nitin Shankar Singh
Department of Electronics and Communication Engineering, Lovely Professional University, Jalandhar, India

ABSTRACT

This is a review paper in which electrically small metamaterial-based antennas are discussed from the industrial point of view using mobile phones as the application example and dual band microstrip antenna with metamaterial structure for dual band operation. The most interesting feature of the design is the ability of enhancing the gain and total efficiency of the antenna without affecting the other important parameters like bandwidth and directivity. The double negative (DNG) properties of metamaterial (-ε and -μ) have been proved by simulated S-parameters showing improved results in form of power gain and efficiency. Metamaterial (MTM) in antennas is proposed for better improvement in the impedance bandwidth and reduction in the return loss at operating frequencies. It appears that despite the interesting theoretical findings, the commercial acceptability of these antennas is low. Some of the issues possibly leading to this situation are addressed. Discussion topics range from challenging application environment, through the response of finite-size composite-material samples, all the way to the required constructive criticism and acknowledgement of prior art. Selected issues are discussed in more details, and proposals how to possibly improve the commercial acceptability of metamaterial-based antennas are made.

KEYWORDS: *MTMs, DPS, DNG, Rectangular Microstrip Patch Antenna, S-parameters, Metamaterials.*

I. INTRODUCTION

So-called metamaterials (MTMs) are engineered media whose electromagnetic responses are different from those of their constituent components. There are several classifications of metamaterials. We choose to name them based on their fundamental properties, i.e., by the signs of their permittivity and permeability. The double positive (DPS) metamaterials have both the permittivity and permeability positive, i.e., $\varepsilon>0$, $\mu>0$. The double negative (DNG) metamaterials have both the permittivity and permeability negative, i.e., $\varepsilon<0$, $\mu<0$.The number of papers about electrically small metamaterial-based antennas is big and steadily growing, e.g. [1], [2],[3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13],[14],[15],[16] and the references therein. Interesting theoretical discussions predict great advantages from metamaterials in small-antenna design. For example, resonant conditions for strongly sub wavelength patch antennas, or possibilities to overcome the small-antenna Q−limit have been discussed.

Undoubtedly, metamaterial-inspired theoretical ideas can offer new points of view in the “traditional” small-antenna design. Also, many of the theoretical works are already backed up with prototypes experimentally verifying the proposed ideas. However, to push the proposed antennas in commercial applications (e.g., in mobile phones), it is necessary to properly demonstrate the practical benefits of metamaterial-based antennas when compared with “traditional” reference antennas for the same application. Unfortunately, at the time being, solid comparative demonstrations can hardly be found in the literature.

What is the root cause for the lack of these demonstrations? Understanding this is very important as convincing experimental demonstrators are essential to maintain the industrial interest in small-antenna enhancement using metamaterials. Below we discuss some challenges for the utilization of meta-materials in mobile-phone antennas, and address some other issues that might be hindering the commercial acceptability of these design schemes. While enhancing the beamwidth Return loss , S-parameters and directive gain. Previously, some challenges related to metamaterials in small-antenna design have been discussed, e.g., in [17], [18].

II. METAMATERIALS IN RECTANGULAR PATCH ANTENNAS AND MOBILE-PHONES: GENERAL OBSERVATIONS

Wireless communications is just one of the applications of metamaterial, such as the implementation of 4G communication systems. A metamaterial antenna is a very small and powerful antenna that can be manufactured onto the surface of a circuit board. It is composed of meta-material, which is made up of microscopic elements that allow radio frequency waves to pass through at a higher efficiency than with traditional materials. Classified as a near-zero index material, it bends and reflects electromagnetic radiation perpendicular to the substrate.

The main drawback of Patch Antenna is less impedance bandwidth. The insertions of Inspired Metamaterial Structure at various layer on Rectangular Microstrip Patch Antenna ultimately lead to Reduction of Return Loss and Enhances Bandwidth significantly[12],[13],[14],[15].This reduction of return loss indicates that only small amount of reflection waves were returned back to the source and most of the power will be radiated from the patch. The reduction of return loss ultimately improves gain of patch antenna which makes patch antenna more directive. The development of system such as satellite communication, highly sensitive radar, radio altimeters and missiles systems needs very light weight antenna which can be easily attached with the systems and which does not make the system bulky.

The goal of the here is to realize the manipulation of ε andμ through specific inclusion of metal in dielectrics to achieve a desired substrate properties in order to yield optimum radiation characteristics. Recent advances in Left-Handed Metamaterials (LHM) provided the technology to design and implement such structures. Combining analytic method for analyzing radiation for homogeneous anisotropic slab, optimization of structure becomes possible Hence LHM technology is adapted and optimized for metamaterial substrate design. We show that metamaterials can be approximated as being anisotropic homogeneous materials, not only in scattering (reflection/transmission) phenomenon, but also in embedded radiation.

1. Mobile phone is a very challenging application environment for artificial composite materials.
    - Available volume in the vicinity of antennas is only a small fraction of free-space wavelength.
    - Antenna manufacturing complexity should be kept Low.
    - Spatial near fields exciting finite-size material samples are highly complex.
    - Some of the antennas need to couple strongly enough to the rest of phone mechanics to gain Sufficient Bandwidth.
2. Resonant nature of typical metamaterials is challenging.
    - Interesting material phenomena tend to occur in the vicinity of the resonance.
    - Effect of dispersion and resonant losses can be strong.
    - Non-radiating resonances coupled with antenna resonances are unwanted.
3. Metamaterial-based antennas are rarely fully benchmarked against reference antennas.
    - Full experimental characterization in the real application environment is always needed.
    - Reference antenna should be targeted (desirably already being used) for the same application.
    - Proper figure-of-merit should be used: bandwidth comparison is not enough if efficiency Degrades.
4. Occasionally self-driven constructive criticism towards metamaterial-based antennas is missing.
    - Why should the proposed antenna be actually used, instead of “traditional” antennas?
    - Possible drawbacks (increased weight, cost etc.) of the proposed designs should be openly Stated.

III. RECTANGULAR PATCH ANTENNA AND MOBILE ANTENNAS AS AN APPLICATION

The concept of such antennas though introduced in early 1950‟s in US by Deschamps & in France by Gutton & Baissinot, it was in 1970‟s only that with advent of Printed Circuit technology. The micro strip antennas are the present day antenna designer's choice. Low dielectric constant substrates are generally preferred for maximum radiation. The conducting patch can take any shape but rectangular and circular configurations are the most length of the antenna is nearly half wavelength in the dielectric; it is a very critical parameter, which governs the resonant frequency of the antenna. There are no hard and fast rules to find the width of the patch. There are many kinds of materials used to improve the gain of microstrip patch antenna. Among them, Metamaterial [4-6] are found most suitable. Metamaterials have opened an exciting field to realize unexpected physical properties and applications, which are not possible from naturally occurring materials.

The largest dimensions of a mobile phone are roughly $\lambda 0/3...\lambda 0$ over the commonly used communications frequencies ($\lambda 0$ is the free-space wavelength). The volume reserved, e.g., for the cellular antenna is therefore only a small fraction of the wavelength. In addition to this, the spatial near-field pro-file in the vicinity of the antenna is typically highly complex due to the antenna pattern details, and closely located mechanics components (display, speakers, etc.) Thus, it is impossible to create the ideal homogenization conditions assumed in many theoretical works. Also, due to the very small volume reserved for the antenna, the whole phone is typically utilized as a radiator in order to increase the obtainable bandwidth [18]. Apparently, the difference between the response (even the goal of the desired response) of a free-standing antenna element, and the element mounted in a real mobile phone can be significant. To promote the findings successfully from the commercial point of view, it is therefore essential to make sure that the proposed antenna offers the best size-vs.-performance characteristics also in the real phone environment. To maintain low manufacturing complexity (and associated costs), a big portion of mobile phone antennas is still implemented on planar surfaces. Even though 3D composite material covers (e.g. [1], [6], [10]) would allow (in theory) to obtain natural matching for a highly sub-wavelength antenna, it is difficult to envision the actual realization of such covers in low-volume and low-cost applications. At the end, the performance enhancement obtained even with planar substrates under volumetric antenna elements (e.g., planar inverted F-antenna) should clearly outweigh the increased manufacturing process complexity (costs), increased weight, and implications of the reserved volume.

IV. ON THE RESONANT NATURE OF TYPICAL METAMATERIALS

Typical realizations of metamaterials proposed for electrically small antennas are composite substrates or superstrates based on resonant inclusions. For example, Lorentz-type resonant magnetic behaviour is achieved with a lattice of broken loops, and Drude type artificial permittivity behaviour is achieved with a lattice of thin wires. Alternatively, transmission-line meshes can be used to create high−k (k is the propagation constant in the mesh) appearance for a wave oscillating in the mesh with the goal to obtain size reduction. Even when excluding the above described challenges related to the mobile-phone volume constraints, there remain some fundamental questions on other challenges. For example, artificial magnetic have no natural magnetic polarization, thus, work has to be done to polarize the loops to obtain collective microwave response. Moreover, the loops are electrically very small, thus, their contribution to total radiation is typically negligible. Rather, the loops tend to store energy in the near field around them. How could this kind of material help boosting the performance of the main radiator whose main loss mechanism should come through radiation. In general, typically the exotic, "metamaterial-like" phenomena occur in the vicinity of the material resonance, thus, such a material possesses strong dispersion and resonant losses. Coupling this kind of materials with inherently rather high Q antennas creates some apparent challenges: strong dispersion further increases the antenna Q (most often un-desirable, example discussion in [17]), or a discrete collection of inclusions acts more as a non-radiating parasitic resonator than a "true" material load [18]. In the latter case, it some-times becomes difficult to identify the differentiating advantage offered by metamaterial-based antenna implementations when compared to "traditional" solutions utilizing parasitic resonators to boost the bandwidth. Moreover, due to very tight system requirements for the radio performance, non-radiating resonances only boosting the impedance bandwidth (and not the radiation efficiency bandwidth) are typically unwanted.

V. PROPER EXPERIMENTAL ANTENNA PERFORMANCE BENCHMARKING IS ESSENTIAL

How to get new antenna concept adopted in commercial use, e.g., in mobile phones? First, the benefits (smaller volume or improved performance with a fixed volume, etc.) stemming from the proposed solution should clearly enough outweigh the possibly associated challenges (increased weight, complexity and cost, etc.). Second, given the performance of the proposed antenna seems feasible, this performance should be compared with the performance of a reference antenna being used for the particular application. Below we list some general issues that help to build a convincing demonstration. The antennas are completely characterized.

1.) A topology optimized metamaterial-based electrically small antenna configuration that is independent of a specific spherical and/or cylindrical metamaterial shell design is demonstrated. Topology optimization is shown to provide the optimal value and placement of a given ideal metamaterial in space to maximize far-field radiated power.

2.) An indigenous low-cost metamaterial embedded wearable rectangular microstrip patch antenna using polyester substrate for IEEE 802.11aWLAN applications easily work for the metamaterial applications.

3.) Only the absolute value of S11−parameter is clearly a non-complete description of small-antenna performance.

• Measured efficiency and input impedance behaviour should be presented, Value of the results is further increased by considering also the user effect on the antenna performance.

4.) Proper figure-of-merit is used in the performance comparison.

• For single-resonant antennas proper figure-of-merit de-scribing size-vs.-radiation bandwidth characteristics is the radiation quality factor.

• For multi-band antennas, possibly accompanied with a matching circuit, determining a proper figure-of-merit becomes more challenging.

• Often in these cases performance has to be evaluated as a compromise between required volume, impedance behaviour, total efficiency, tolerance effects of matching components, tolerance to user effects, and manufacturing complexity and cost.

5.) Both the benefits and drawbacks of the proposed solution are fully reported.

VI. SELF – DRIVEN CONSTRUCTIVE CRITICISM TOWARDS THE PROPOSED SOLUTIONS

The world is full of differently seeming electrically small antennas. Evidently, a lot of attention has been paid to the selection of certain antennas for the use in mobile phones. Some of the issues typically affecting this selection process have been described above. Therefore, as metamaterial-based antennas are being proposed for mobile phones, the proposal should first clearly answer to the question: “Why the proposed antenna should be used over all the other alternatives?”

Especially in the beginning of metamaterial research these materials were in many occasions advertised to provide characteristics not found in nature. Such advertisements, accompanied with some first theoretical studies based on simplified material models, have created a lot of expectations towards metamaterials also in the field of small antennas. It is apparent, however, that as we approach the experimental realization of antennas utilizing these materials, inevitable performance restrictions (e.g., dispersion and losses) are strongly limiting the actual performance. Therefore it is important to understand and openly state the practical limitations even in the case of (typically the first) most theoretical studies, not to create hypothetical expectations. For example, for some time artificial magnetic materials were considered as a very good miniaturization technique for microstrip antennas due to the low-loss nature of the corresponding microwave (artificial) magnetism (background for magnetic materials with microstrip antennas is available, e.g., in [19]). However, the experimental demonstrations available in the literature were incomplete, or failed to validate the observations based on simplified analysis [20]. When the inherent material dispersion (coming as an inevitable side result of the experimental realization) was included into the analysis, it was revealed that such materials can never outperform reference antennas.

VII. APPLICATIONS AND RESEARCH AREAS OF METAMATERIALS

Metamaterial antennas are a class of antennas which use metamaterials to enhance or increase performance of the system. The metamaterials could enhance the radiated power of an antenna. Materials which can attain negative magnetic permeability could possibly allow for properties such as an electrically small antenna size, high directivity, and tunable operational frequency, including an array system. Furthermore, metamaterial based antennas can demonstrate improved efficiency-bandwidth performance. Metamaterials are manufactured materials that exhibit properties not found in nature. A significant improvement in antenna performance is predicted for a class of metamaterials exhibiting a negative electric permittivity, (ENG), a negative magnetic permeability (MNG), or both (ENG/MNG). Antennas constructed from metamaterials have revolutionary potential of overcoming restrictive efficiency-bandwidth limitations for natural or conventionally constructed electrically small antennas. Metamaterial antennas, if successful, would allow smaller antenna elements that cover a wider frequency range, thus making better use of available space for small platforms or spaces.

Metamaterials employed in the ground planes surrounding antennas offers improved isolation between radio frequency or microwave channels of (multiple-input multiple-output) (MIMO) antenna arrays. Metamaterial, high-impedance ground planes can also be used to improve the radiation efficiency, and axial radio performance of low-profile antennas located close to the ground plane surface. Metamaterials have also been used to increase the beam scanning range by using both the forward and backward waves in leaky wave antennas. Various metamaterial antenna systems can be employed to support surveillance sensors, communication links, navigation systems, command and control systems.

VIII. ACKNOWLEDGING PRIOR WORKS AND PROPER MARKETING

The history of artificial materials in microwave engineering is very long, especially when it comes to the utilization of artificial dielectrics [21]. Also, the transmission-line and resonator theories have been well established for several decades ago. Thus, as already outlined above, some of the realizations of metamaterial-based antennas might bear strong resemblance with the "traditional" solutions. However, still in this case the proposed antennas might offer some benefits not seen in the prior solutions. Nevertheless, when introducing the proposed antennas it is important to understand and respect the prior works, to be able to clearly highlight the differentiating aspects of the proposed solution.

Other issues possibly helping to improve the commercial acceptability of metamaterial based antennas through better understanding relate to using consistent terminology. Currently, confusion is created as occasionally non-standard evaluation measures are used (for related criticism see, e.g., [22]), or widely studied structures are called differently in different sources. For example, despite the different terminology being used, all the structures considered in, physically boil down to a periodic array of broken loops (authors of [23] further call a principally similar substrate "magnetic metamaterial" substrate). A reader not experienced with the progress in this field might have the illusion that different structures are studied in all of these papers.

It is also common that many antenna structures available in the recent literature are called "metamaterial-based antennas" or simply "metamaterial antennas", even though the actual structures do not contain anything that can be described as (artificial) material according to general definition. Examples of such antennas include, e.g., microstrip antennas utilizing only one discrete resonant grid as a superstrate, or antennas utilizing few discrete resonators (often broken loops) within the antenna volume. For many people having background in the field of small antennas (but not necessarily in the field of metamaterials) the use of such terminology might create the feeling of an attempt to hide traditional antenna features behind newly established terminology.

IX. SOME CONCLUDING REMARKS

Several issues possibly affecting the fact that, despite interesting theoretical findings, the commercial use of metamaterial-based antennas, e.g., in mobile phones is low. Some of the issues, like the challenging application environment, cannot be affected. Other issues, like the proper experimental characterization of the proposed antennas, will have a clear impact when trying to push these antennas to commercial applications. To improve above problems a topology optimized metamaterial-based electrically small antenna configuration that is independent of a specific spherical and/or cylindrical metamaterial shell design can be analysed and designed. Topology optimization can be to provide the optimal value and placement of a given ideal metamaterial in space to maximize far-field radiated power of an antenna. Also An application mode for optimization in COMSOL Multiphysics 3.4a beta combined with axi-symmetric two-dimensional (2D) RF application mode is ideally suited to design the highly resonant, rotationally symmetric metamaterial-based electrically small antenna models that require a dense finite element meshing to correctly resolve the EM fields.

X. FUTURE WORK

Several improvements to enhance the gain and characteristics of the metamaterial based antenna can be taken into consideration for future research. The metamaterial can be designed using FR4 glass epoxy substrate on PCB sheet. Circular patch antenna and feeding techniques may affect the performance of the antennas and simulate the result with the IE3D SI simulator for their directivity, gain and bandwidth. Despite of using single unit cell, a combination of a number of unit cells can be applied in designing the antenna on metamaterial substrate.

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AUTHORS

Gagandeep Kaur was born at 1st October, 1989 in Sriganga nagar. She had completed her B.tech degree in E.C.E. from MIMIT, Malout (PTU) India. Currently she is pursuing her M.tech degree in E.C.E. from Lovely Professional University, Phagwara, India. Her area of specialization is Antenna and wave propagation.

Nitin Shankar Singh was born at Jhansi in 1990.He had completed his B.tech degree in E.C.E. from P.S.I.T., Kanpur. Now, he is pursuing his M.tech degree in E.C.E from Lovely Professional University Phagwara, India. His area of specialisation is Optical Communication.