Some New Strategies for Practical Realization of Metamaterial-Based Devices

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Abstract

In this paper, we discuss some new strategies for designing devices such as lenses, cloaks, near-field imaging systems, etc., that are based on the use of dispersion-engineered materials *aka* Metamaterials (MTMs). Historically, the design of these devices has largely been based on the use of double-negative (DNG) type of materials that have been typically found to be highly dispersive, narrowband, angular-sensitive and polarization-dependent. Techniques for mitigating these problems with DNG materials are being actively researched, though successes have been rather limited to-date. In this paper, we look at some alternate strategies from a practioner's viewpoint that lead to the realization of MTM-devices which suffer little from the drawbacks alluded to above. Some illustrative examples of devices fabricated by using these new strategies are included in the paper.

1. Introduction

The concept of a flat, Veselago-type superlens, realized by using a DNG material is highly attractive and has drawn the attention of many researchers, including the modern-day pioneers in the area, like Pendry and Smith [1,2,3] and several other active workers in the field [4,5]. Some of the fundamental roadblocks that have stood in the way of practical realization of these lenses—and getting them to perform in the same way as predicted theoretically by assuming ideal DNG characteristics—include losses, dispersion, narrow bandwidth and anisotropy, all of which have adverse effects on the performance of the DNG flat lens. Although there have been many attempts by researchers in the field to circumvent these problems with the DNG lenses realized, for instance, by using SRRs or Fishnet type inclusions embedded in a background medium that do indeed display DNG characteristics—albeit over a narrow frequency band and only for near-normal incidence—few have been successful to date, and the quest for low-loss, wideband, angular-independent DNG materials remains unabated and continues to be pursued vigorously today.

Before proposing any new strategies, or 'magic bullets', which would solve the problems alluded to above that plague the present design for metamaterials in general, which not only include the DNG but the ENG and MNG as well, we back up a step and look first at the end objectives that we are trying to achieve by examining the intended applications of MTMs, suggested in the metamaterial literature in recent years. These may be categorized in broad groups as follows: (i) near-field imaging; (ii) far-field focusing for performance enhancement of small radiators; and (iii) cloaking. We argue, first of all, that perhaps the "one size fits all" strategy that has been followed in the past, in which MTMs—primarily DNGs—have been proposed as "catch-all" solutions for all of the applications mentioned above, should be re-examined and that the strategies should be tailor-made to fit the specific applications to get the best results and to avoid the problems encountered with the conventional MTMs, such as high dispersion, narrow bandwidth, etc. The primary objective of this paper is to describe these strategies that we have developed for the various applications mentioned above and to provide examples that illustrate how these strategies are applied to meet our goals.

2. Proposed Strategies

We begin with the problem of far-field focusing of fields radiated by an elemental source, such as a dipole or a horn feed. Rather than viewing it as an imaging problem where the elemental source is to be focused at infinity by using, say, a DNG, ZIM (zero index medium) or LIM (low index medium) lens, we treat it as a “field transformation” problem instead, where the spherically divergent fields from the dipole or a horn feed are to be transformed by the dispersion-engineered flat lens into an aperture distribution that is as close to uniform as possible, both in terms of amplitude and phase [6]. Thus, we do not search for media with certain effective medium characteristics; instead, we design the lens to have scattering matrix characteristics that vary in the radial direction by taking a cue from the ray optical techniques typically employed to design conventional spherical lenses, and adapting them for the flat lens problem at hand. Additionally, we develop a multilayer design that enforces the matching condition both at the front and back surfaces of the lens in order to ensure low reflection at these interfaces (see Figs.1 and 2). An example design of a flat lens that is based on this concept will be presented in the paper.

Alternatively, we may want to design a superstrate for an elemental radiator, such as a printed dipole on a microstrip patch, to enhance its directivity [7,8], to reduce its profile by using a substrate [9], or to even attempt to increase its bandwidth [10]. Here, again, one finds that using a DNG material is not the best approach and, furthermore, the use of effective medium theories can sometime lead to erroneous conclusions.

In the near-field imaging, all we are looking to do is to capture the field information on a plane located as close to the original source-plane as possible, and process it in a suitable manner, say by using a back-propagation algorithm to recover and reconstruct the original information. The DNG slab has been proposed for this task as well, with the expectation that it would take a point source and generate a virtual image inside the slab as predicted by negative refraction in a DNG medium, and that this virtual image would then be re-imaged outside, once again via the process of negative refraction. However, as before, a close examination reveals that in practice things do not work quite the way described above; and, in fact, it has been demonstrated that even a thin plasmonic slab of silver, for instance, can be used for the problem at hand, and that it is altogether unnecessary to insist on negative refraction for the near-field imaging problem we are considering here. Returning to the back-propagation approach, it is certainly possible to reproduce the source distribution in the image plane such that it is close to the original one, and the issue of diffraction-limited imaging is not as relevant for this type of field reconstruction as it is for imaging with a conventional lens. It should also be realized that the imaging systems that have been proposed for near-field imaging are unable to handle the situation when dealing with buried objects, since the so-called “lens” must be placed as close to the source plane as possible to be effective. This can be explained once we understand the phenomenological aspects of the problem of near-field imaging, which differs from that of lensing in the conventional sense.

Finally, let us turn to the problem of cloaking, which typically relies upon “transformation optics” [11-15] for its design and calls for the use of an inhomogeneous medium, derived via the transformation of Maxwell’s equations from one co-ordinate system to another, to accomplish its goal. The limitations of this approach are well known, and some of them are: difficulty in physical realization; narrow bandwidth (~2.5%); and deterioration of performance when either the incident angle or the polarization is changed. If we modify our design goal slightly to be in line with what is needed in real-world applications in radar and EMI areas, and set it instead to be the reduction of scattering from a given object when it is coated with a suitable material that we will design, then our strategy for achieving this goal becomes very different from what it has been employed in the past to realize cloaks, where only the transformation optics approach has been utilized to design them. In the proposed approach, we begin by designing a multilayer coating, comprising of realistic lossy dielectric and magnetic materials that we can realize in practice. In the next step, we combine these layered materials with one or more specially designed metamaterial screens with relatively broadband absorption characteristics to enhance the performance of the absorber even further. Examples of such absorbers will be included in the presentation in which as much as 9:1 bandwidth has been achieved [16, 17], several orders of magnitude higher than is realizable for cloaks designed by using the transformation approach, even for arbitrarily shaped objects and for arbitrary angles of illumination, neither of which can be handled by the existing designs of cloaks without encountering a serious compromise of their performances.

Before closing, we mention that while using effective medium theories [4] can be helpful for initial design, and for gaining physical insights, these designs must be simulated by using rigorous CEM (Computational Electromagnetics) tools such as GEMS [18] to verify the validity of the results generated by using the effective medium approach. The author is also pleased to acknowledge partial support of this research from King Fahd University of Petroleum and Minerals (KFUPM).

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[18] GEMS, 3-D High Performance parallel EM simulation software, www.2comu.com.

Figures

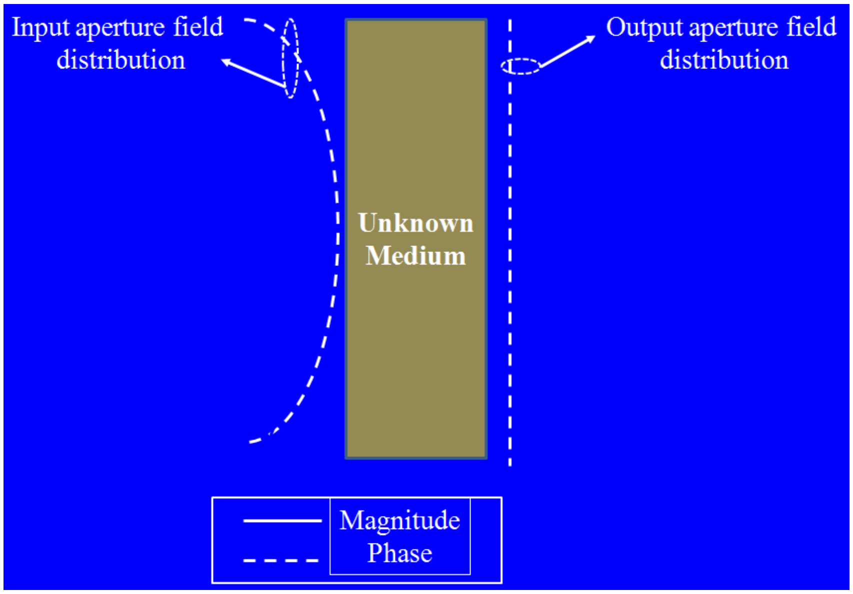

Fig.1. Schematic Diagram of Field Transformation Approach

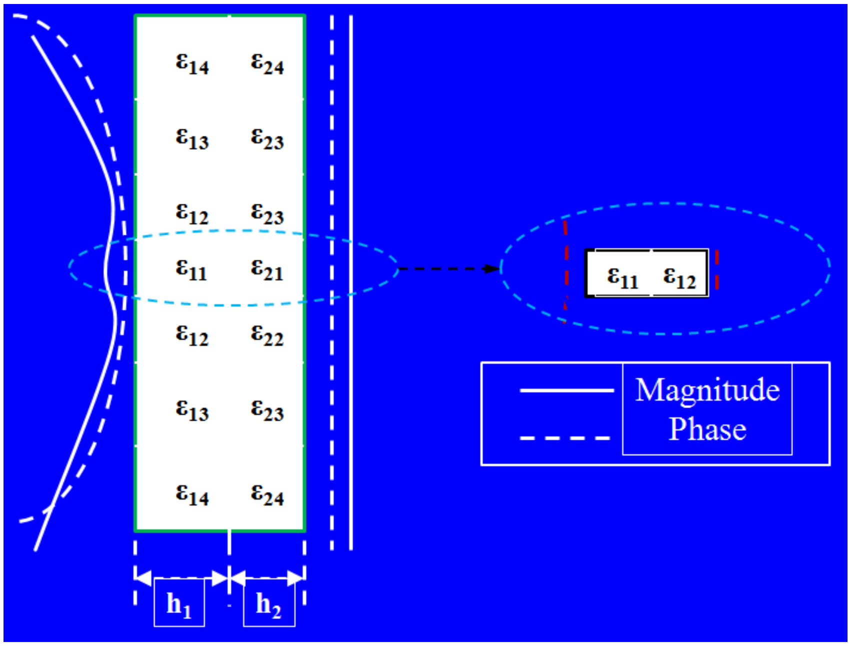

Fig.2. Zoned Dual-Layer Slab designed by using the Field Transformation approach