Metamaterial-Inspired Engineering of Electrically Small Antennas from Microwave to Optical Frequencies

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Abstract

In the decade since the inception of the metamaterials field, there have been a number of exciting advances in understanding and confirming many of their exotic physics properties. Many of these attributes have led to the consideration of engineering metamaterials and metamaterial-inspired structures for a variety of applications. This includes the miniaturization of resonators and their use for improving the performance characteristics of electrically small antennas and scatterers from the microwave region to the millimetre wave region to the terahertz region and even up through to the optical region. Active metamaterial constructs have been introduced to increase the bandwidths at low frequencies and to overcome the losses at high frequencies. The theoretical designs of many of these highly subwavelength systems and their simulated performance characteristics have been confirmed experimentally. These concurrences between theory and experiment will be highlighted.

1. Introduction

While double negative (DNG) metamaterials (MTMs) were proposed several decades ago, they have been experimentally demonstrated only in the last decade. Many of the exotic properties of single negative (SNG), i.e., epsilon-negative (ENG) or mu-negative (MNG), and DNG metamaterials have been verified. Minute, moderate and extreme MTM properties have been investigated. These MTM concepts have guided a growing number of physics and engineering applications (see [1-4], and refs therein). These include, for example, flat lens, which depend on negative refraction effects; cloaking devices, which depend on epsilon or mu near-zero properties; artificial magnetic conductors, which depend on near-infinity properties (i.e., high impedance surfaces); and electrically small resonators and waveguides, which depend on the presence of both positive and negative MTM properties. Metamaterials have led to different paradigms for achieving electrically small radiating and scattering systems, which will be emphasized in my presentation.

2. Physics and Engineering Applications: Lower Frequencies

The adaptation of resonant (and in some instances, non-resonant) metamaterials or simply the corresponding electrically small metamaterial unit cells to achieve enhanced performance characteristics of antenna systems, has received considerable research attention. This includes studies, for instance, of small antennas; multi-functional antennas; infinite wavelength antennas; patch antennas; leaky-wave antenna arrays; higher directivity antennas; low profile antennas achieved with a variety of modified ground planes; and dispersion engineering of time domain antennas [1-3, 5, and refs. therein]. The proliferation of wireless devices for communication and sensor applications has re-stimulated interest in many different types of antennas. The often conflicting requirements, for instance, of efficiency, bandwidth, directivity, weight, and cost have made the design tasks onerous for antenna engineers with traditional schemes. The metamaterial-inspired engineering of antennas and their performance characteristics has provided an alternative approach to addressing these pressing issues. Many metamaterial-inspired electrically small antenna designs have now been fabricated and tested; the measurement results are in very nice agreement with their predicted behaviours. Considerations of multi-band, higher directivity, and circularly polarized systems within the same real estate allowance (electrical size or footprint), along with potential applications, have been considered. Higher bandwidth approaches include introducing active (non-Foster) elements to overcome standard passive system constraints. These and other results summarized in Fig. 1 will be discussed in my presentation.

3. Physics and Engineering Applications: Higher Frequencies

While nature provides us easy-to-access constructs that exhibit MNG properties (e.g., split rings) at low frequencies and ENG properties (e.g., noble metals such as gold or silver) at high frequencies, ENG properties at low frequencies and MNG properties at high frequencies are more difficult to realize. While highly subwavelength DNG unit cells have been achieved at low frequencies [6], they challenge available nanotechnology capabilities at optical (visible) frequencies. Nonetheless, inventive structures have led to MNG, as well as DNG effects at optical frequencies. However, using metals at optical frequencies introduces large losses; and, consequently, the figures of merit of optical metamaterials have generally been poor. It has been demonstrated [e.g., 7] that with the introduction of active materials into the metamaterial constructs, the intrinsic absorption of metals can be overcome and new optical properties can be observed in their scattering and absorption cross-sections. For instance, active coated nano-particles (CNPs) have been considered for applications include highly subwavelength lasers, amplifiers, sensors and impedance transformers. They have also been considered as inclusions in unit cells for optical two-dimensional (2D) meta-films and three-dimensional (3D) bulk metamaterials [e.g., 8], including periodic and random arrays. While plane wave excitations of these active CNPs were initially studied, the excitation of an active CNP with an electric Hertzian dipole (EHD), i.e., an infinitesimal electric dipole antenna, has been investigated [9]. The dipole can represent any quantum two-level system or classical nano-dipole structure. The combination of an EHD with the active CNP as a nano-amplifier has potential usefulness as a highly localized nano-sensor. The spatial near-field distributions, as well as the total radiated power, have been examined for a variety of configurations to understand the gain required to realize practical devices. Generalizations of nano-impedance transformers to related nano-antenna structures have also been considered. These and other higher frequency results, which are summarized in Fig. 2, will also be given in my presentation.

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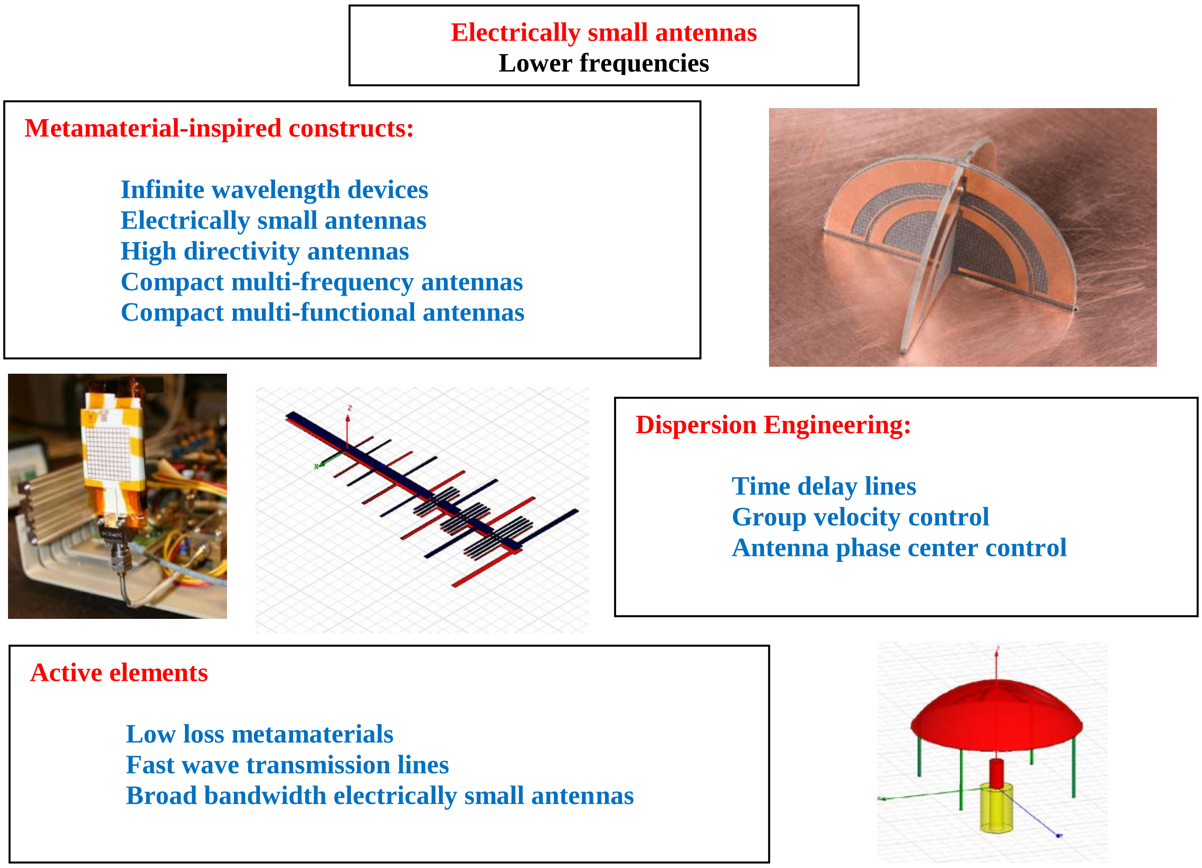

Fig.1. Several lower frequency metamaterial concepts, constructs and applications.

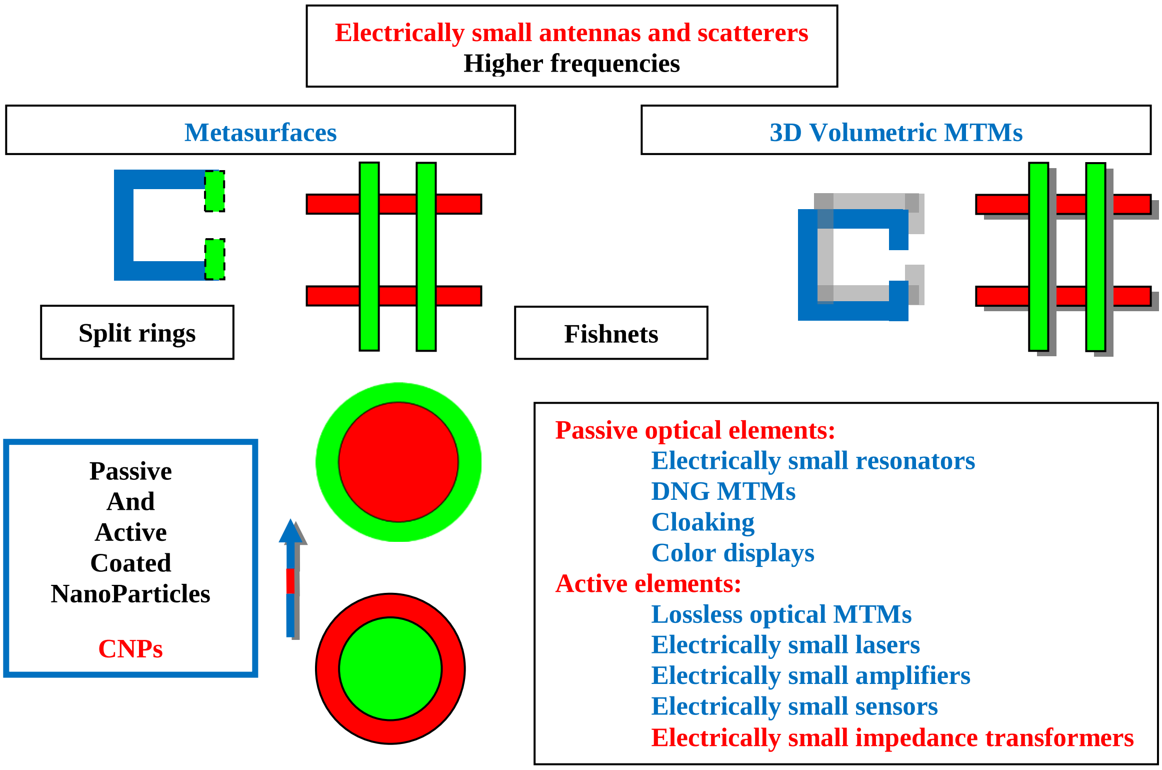

Fig.2. Several higher frequency metamaterial concepts, constructs and applications.

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