Passive and Active Metamaterial Constructs and Their Impact on Electrically Small Radiating and Scattering Systems

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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 in the VHF, UHF and microwave regimes and of electrically small scatterers in the optical regime. 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 resonant (and in some instances, non-resonant) 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 of our initial electric and magnetic metamaterial-based electrically small antenna designs have been realized through the introduction of the corresponding metamaterial-inspired near-field resonant parasitic element antennas. Their further miniaturization at HF, VHF and UHF frequencies has been enabled by introducing lumped and distributed elements to achieve the highly subwavelength ENG, MNG, and DNG unit cells that form the near-field resonant parasitic elements. Many of these metamaterial-inspired electrically small antenna designs have now been fabricated and tested; the measurement results are in very nice agreement with their predicted behaviors. While these initial efforts emphasized high overall efficiencies without using any external matching networks, more recent resonant near-field parasitic designs have also explored increasing their bandwidths and, hence, lowering their Q values. Higher bandwidth approaches include introducing active (non-Foster) elements to overcome standard passive system

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constraints. Further 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. These and other results summarized in Fig. 1 will be given 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 silica core of a silver (or gold) coated nano-particle, the intrinsic absorption in the plasmonic shell can be overcome and new optical properties can be observed in the scattering and absorption cross-sections of these active CNPs. Applications include highly subwavelength lasers and amplifiers. These active CNPs 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. Gain media have also been introduced successfully into other metamaterial unit cells by several research groups.

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 recently investigated [9]. The dipole can represent any quantum two-level system or classical nano-antenna 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 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.

3. References

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4. Acknowledgments

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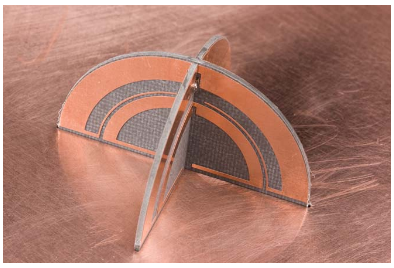
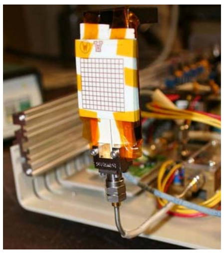
Electrically small resonators
Lower frequencies

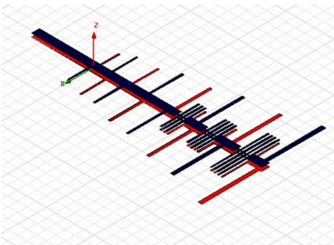
2D Transmission line MTMs	**3D Volumetric MTMs**
Lenses	Lenses
Phase shifters	Waveguiding devices
Filters	Artificial magnetic conductors
Diplexers	Cloaking devices
Leaky wave antennas	Antennas

Metamaterial-inspired constructs:

- Infinite wavelength devices
- Electrically small antennas
- High directivity antennas
- Compact multi-frequency antennas







Dispersion Engineering:

- Time delay lines
- Group velocity control
- Antenna phase center control

Active elements

- Low loss metamaterials
- Fast wave transmission lines
- Broad bandwidth electrically small antennas

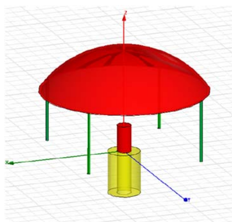


Fig.1. Summary of several lower frequency metamaterial concepts, constructs and applications.

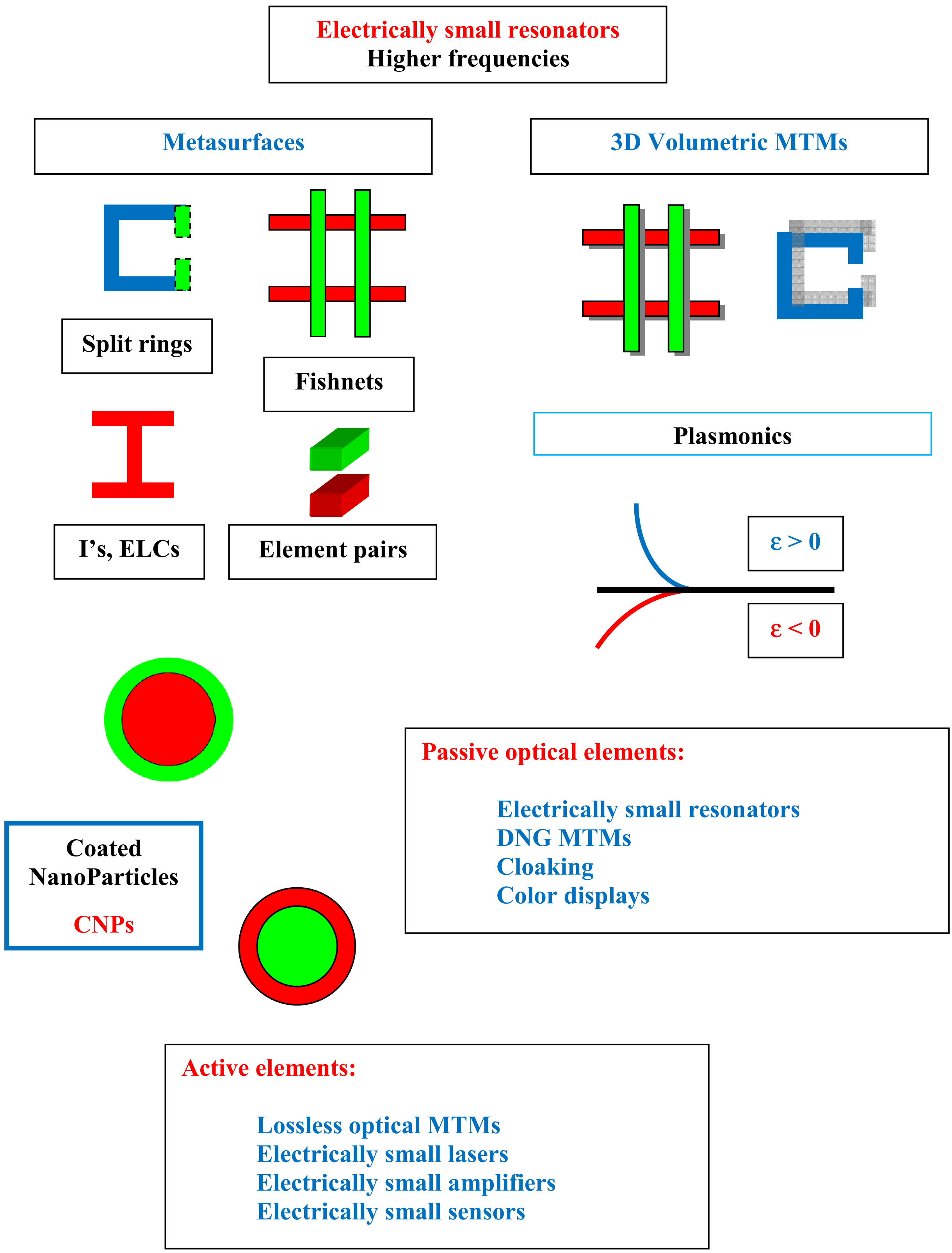


Fig.2. Summary of several higher frequency metamaterial concepts, constructs and applications.