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Novel Passive and Active Transmission Line Metamaterial Devices

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ABSTRACT

This paper presents a number of metamaterial (MTM) structures and devices, with emphasis on the so-called transmission line (TL) MTMs, which have lead to most practical applications so far. Both results obtained from 2002 to mid-2005 [1] and recent advances over the past few months are described.

INTRODUCTION

The fact that electromagnetic metamaterials (MTMs) [1,2] constitute a new field in science and technology is largely recognized today. After only six years from their first experimental demonstration, they have generated to over 2000 publications (including in around 10 special issues), they occupy an important position in all major conferences on electromagnetics, and have drawn the attention of the entire scientific community. Beyond the academic arena, many companies, forseeing in MTMs the potential for a novel generation of microwave and optical devices, have started to show strong interest and motivation for investment in this new direction.

MTMs are artificial electromagnetic *effective (i.e. electromagnetically uniform)* structures exhibiting interesting and useful properties not readily available in nature. They include, left-handed (LH) or negative refractive index (NRI) MTMs, but are not restricted to these media. Any artificial effective structure with exotic properties (e.g. artificial magnetism in the THz/optics) can be termed MTM. In the opinion of the author, structures designed to operate in the Bragg-regime (e.g. photonic crystals) should not be called MTMs, although this is commonly done, because Bragg structures are not effective, and have been known from Newton and Brillouin under the simpler and more convenient name of periodic structures.

Today's MTMs may be classified in two categories, resonant-type (thin-wire / split ring resonator structures) and TL-type MTMs. While the former have been more popular in the physics community, the latter have lead to a larger range of practical applications; the present paper deals mostly with them. Resonant-type and TL-type MTMs are related in several ways and share many physical phenomena.

TRANSMISSION LINE (TL) METAMATERIALS (MTMs)

TL-MTMs [1] originated in 2002 from the simple observation that a hypothetical transmission line with series capacitance and shunt inductance would result into a propagation medium with negative propagation constant or, equivalently, anti-parallel phase and group velocities, which are the attributes of a LH or NRI medium. It was later realized that naturally right-handed (RH) parasitic were also necessarily present and contributed to the overall response of a TL medium in a very significant and interesting manner. This gave raise to the concept of composite right/left-handed (CRLH) MTMs, which has lead to wealth of novel electromagnetic concepts and applications [1].

MONO-DIMENSIONAL STRUCTURES, PASSIVE

Fig. 1 shows a number of *passive* mono-dimensional CRLH-TL-MTM structures. These structures generally exhibit a LH behavior at low frequencies and a RH behavior at high frequencies. In a so called-balanced condition (equal series and shunt resonances), the gap between the two bands closes up and creates a condition of infinite wavelength (or phase velocity) with non-zero group velocity; this allows a DC-like propagation, which allowed for the first-time broadside radiation in a leaky-wave antenna.

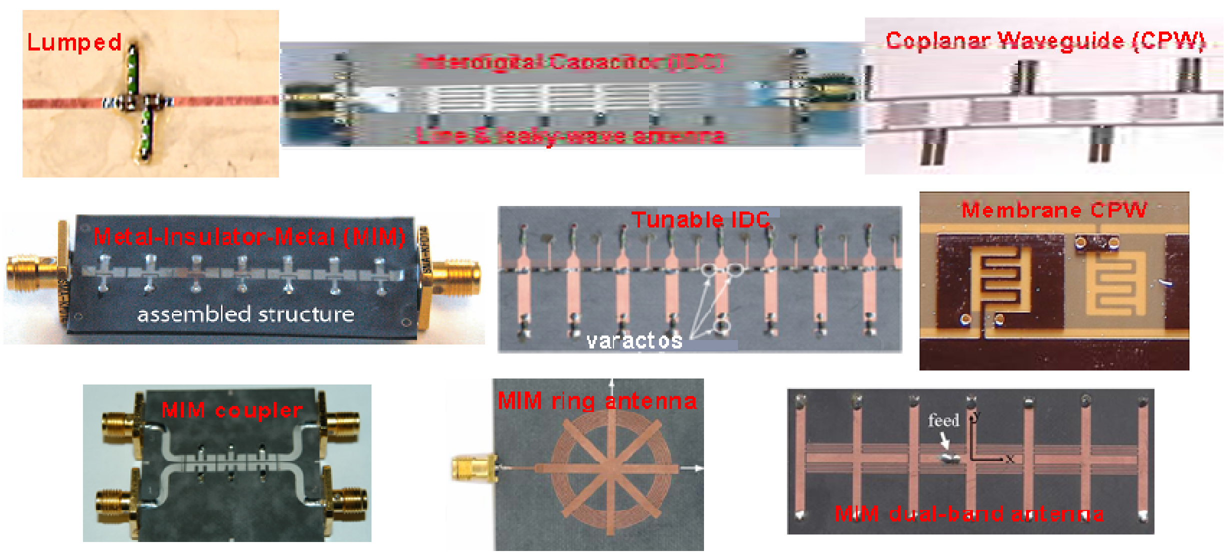

Figure 1. *Passive* mono-dimensional composite right/left-handed (CRLH) transmission line (TL) metamaterial (MTM) structures in planar technology.

The structures in Fig. 1 include inderdigital-capacitor (IDC) and metal-insulator-metal (MIM) implementation of CRLH-TLs. The MIM-CRLH is more compact, easier to design and free of spurious transverse resonances limiting the bandwidth of the IDC [3]. The following CRLH passive devices have been demonstrated: enhanced-bandwidth components, dual-band components, tight coupled-edge couplers, zeroth order resonators, UWB filters, beam-forming networks, backfire-to-endire frequency- and reflecto-directive systems.

MONO-DIMENSIONAL STRUCTURES, ACTIVE

Recently, *active* CRLH-MTM structures have also been demonstrated. For instance, a versatile distributed power-amplifier exhibiting dual-band characteristics and other exotic properties is presented in [4]. In [5] the novel active leaky-wave antenna shown in Fig. 2 is demonstrated. This structure integrates microwave amplifiers which regenerate the power level lost in the radiation process. In this manner, a very long radiation aperture and subsequently a very high directivity is attainable, without requiring a complex and lossy feeding network in contrast to conventional arrays. Moreover, since the far-field radiation patterns are the Fourier transforms of the near-field distribution along the structure, the shape of the beam can be reconfigured for different performances (e.g. maximum directivity with uniform profile or minimum side-lobes with binomial profile).

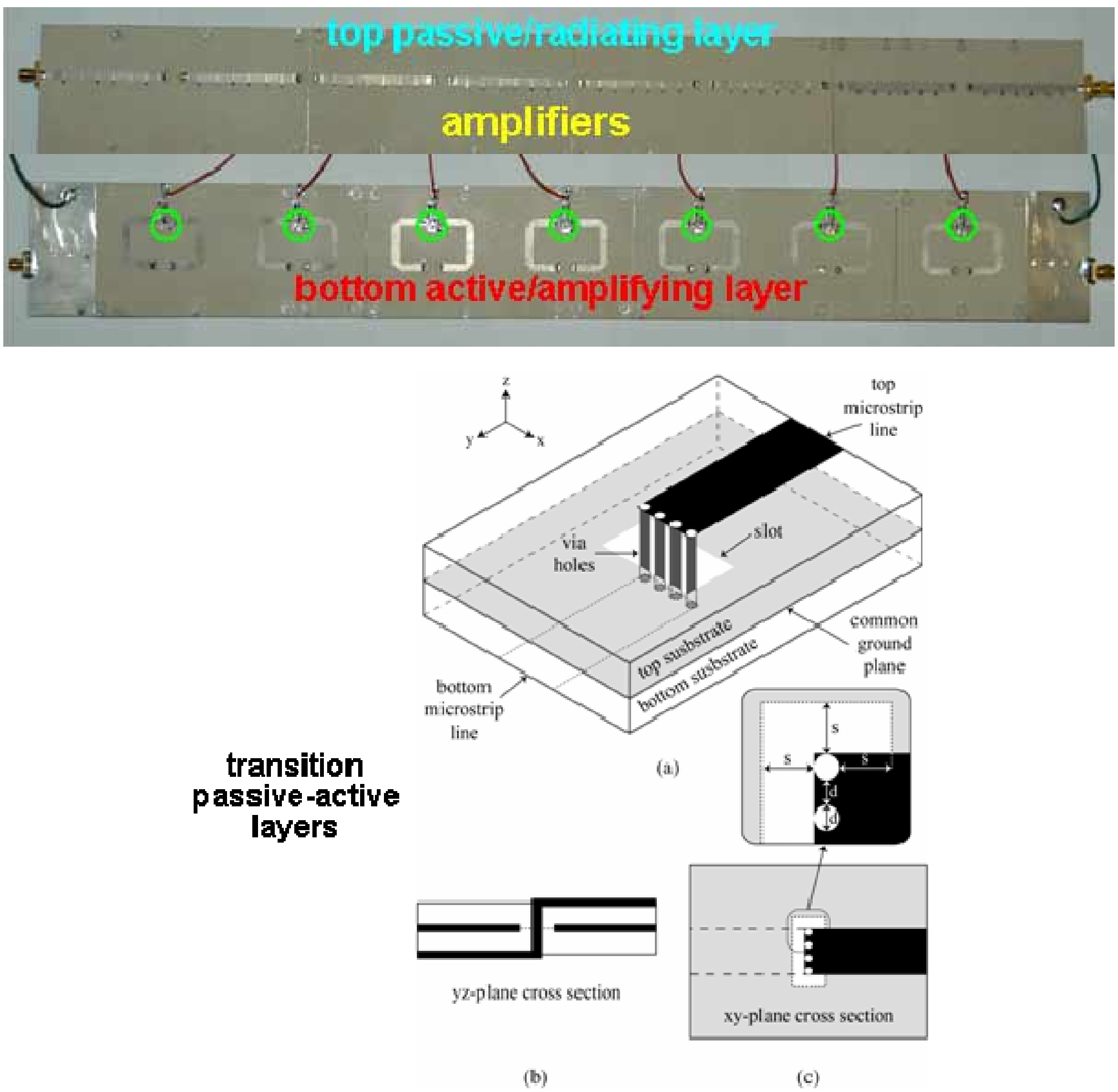

Figure 2. *Active* mono-dimensional CRLH-TL-MTM radiating structure with super-high directivity and beam-shaping capability.

TWO-DIMENSIONAL STRUCTURES

Fig. 3 shows planar MTM structures. At the top, one can see microstrip-type (open) and stripline-type (closed) LH mushroom structures. The open structure was initially introduced as a high-impedance surface for suppression of surface waves in patch antennas. By enhancing the series capacitance with a MIM configuration, left-handedness was achieved. For instance, the distributed flat NRI Veselago's "lens" and a "perfect" (exhibiting theoretically zero reflection) parabolic refractor shown in the middle of the figure were demonstrated. More recently, a dual-CRLH (D-CRLH) [6] metal wire substrate (MWS) [7] was invented. This structure is dual-CRLH in the sense that it has its LH band at high frequency and its RH band at low frequency [6]. Even in its RH band, it presents the interesting properties of providing a wide range of continuously controllable effective permittivity and permeability (both larger than the parameters of the host medium, i.e. dielectrico-magnetic, and therefore allowing circuit miniaturization). THE LH band is particularly interesting in the sense that, in contrast to that of the conventional CRLH, it is (theoretically, ignoring parasitics) unlimited toward high frequencies. Two-dimensional MTM structures have also lead to novel type of leaky-wave (e.g. conical-beam) antennas.

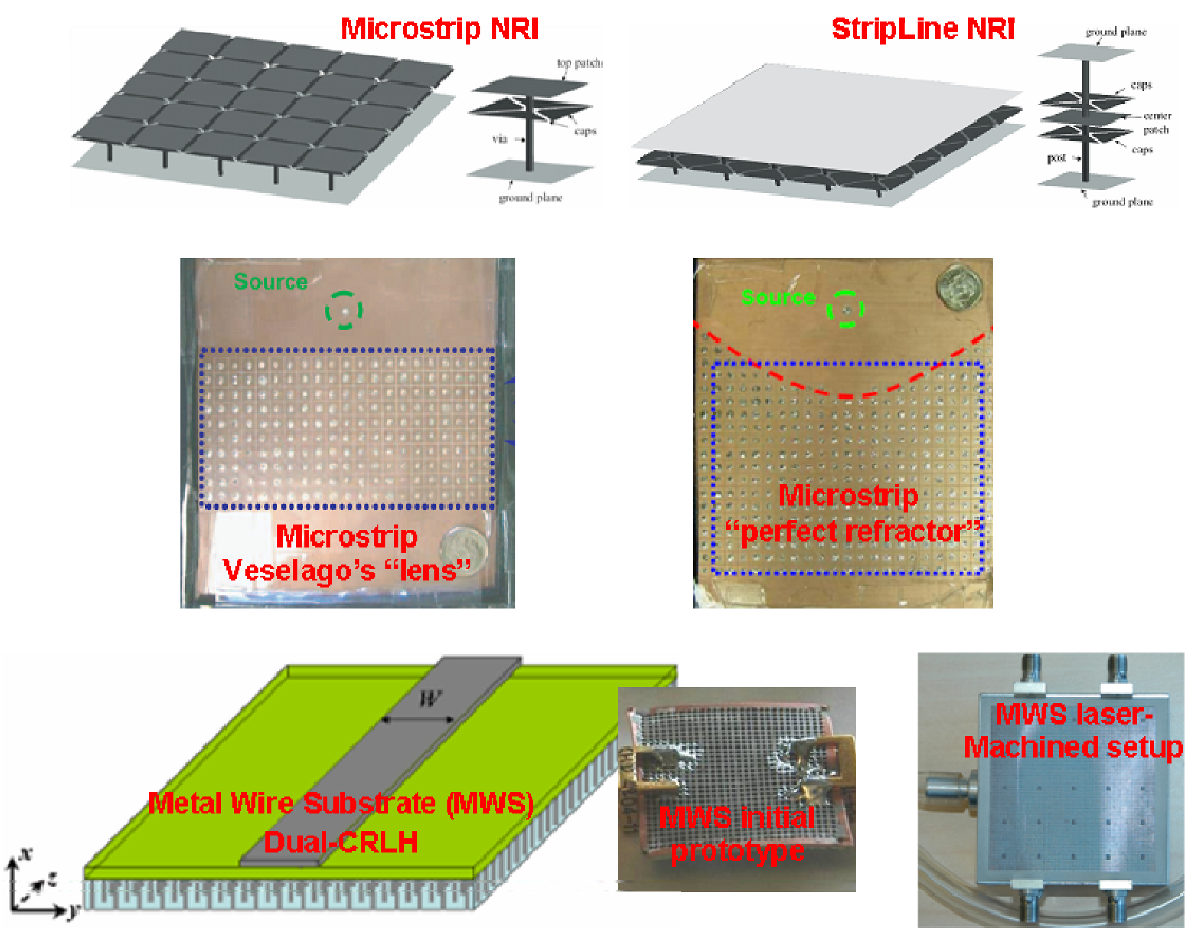

Figure 3. Two-dimensional MTM structures.

THREE-DIMENSIONAL AND DIELECTRIC STRUCTURES

To date, neither 3D nor optical MTMs (in particular NRI) are practically available. The discovery of such MTMs is still challenging and will represent a major breakthrough in this new field. Fig. 4 shows several structures currently investigated along this line. The TL-type 3D MTM structure shown in the upper right region part seems prohibitively complicated in terms of fabrication. A more realistic route in the quest of efficient 3D and optical MTMs consists in focusing on structures which can be actually fabricated and experimented in the lab. In this philosophy, we proposed the concept of clustered dielectric particle (CDP) MTM, as suggested in the other two parts of the figure. These structures are constituted of simple dielectric cubes (or more complex shapes) organized in clusters, as molecules in real material. When appropriately designed, these clusters may exhibit electric and magnetic loop modes associated with magnetic and electric dipole moments, respectively. If these dipoles oppose the excitation fields (i.e. are dia-magnetic and dia-electric, respectively) and if their susceptibilies are stronger than those of the host medium, they produce negative effective permeability and permittivity, i.e. negative refractive index. Such effects have already been observed numerically.

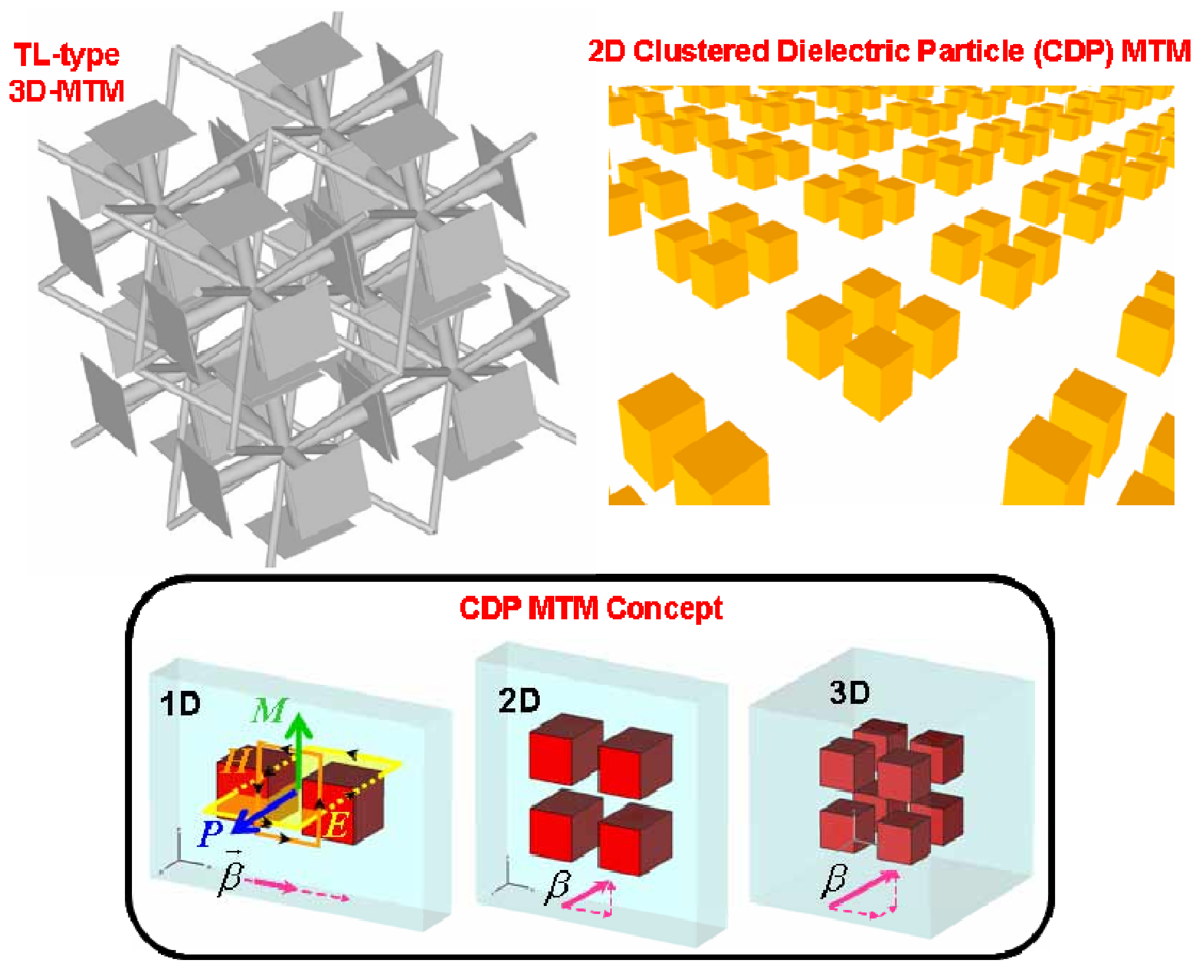

Figure 4. Three-dimensional and dielectric (optical) MTM structures.

CONCLUSIONS

Various mono-, bi- and tri-dimensional MTM structures and devices have been shown and described. A second “wave” of more sophisticated bulk MTM structures, benefiting from emerging novel micro- and nano-technologies, is expected in near future.

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