Topology and Design of Wide-Band 3D Metamaterials made of Periodically Loaded Transmission Line Arrays

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***Abstract* — We propose a new topology for realizing artificial microwave materials that exhibit a negative refractive index over a wide frequency band. These metamaterials consist of a three-dimensional transmission line mesh that is loaded with reactive series and shunt elements to create negative permittivity and permeability. The cubic-cell transmission line host network is a physical realization of the 3D distributed node TLM lattice which has the same low-frequency properties as the FDTD Yee scheme. This paper describes the topology, the theory, the design, and possible realizations of such a metamaterial. Its wave properties are validated by full-wave simulations using the time domain electromagnetic field simulation tool MEFiSTo-3D Pro.**

***Index Terms* — Artificial materials, left-handed materials, metamaterials, negative refractive index materials, periodic structures, transmission line networks.**

I. Introduction

Extensive research efforts are underway worldwide to create artificial materials that exhibit negative refractive index. One can classify existing approaches into two general categories, namely resonant and non-resonant periodic structures. Among the latter category belong the periodically loaded transmission line networks that have been demonstrated in 2002 by Iyer and Eleftheriades [1], [2], Caloz and Itoh [3], and Oliner [4]. They consist of host transmission line networks with embedded lumped series capacitors and shunt inductors. These periodic structures are capable of supporting backward waves as discussed by Ramo, Whinnery, and Van Duzer [5]. Analytical, numerical and experimental studies have confirmed that these loaded transmission line models exhibit indeed the peculiar properties predicted by Veselago [6].

Inspired by these realizations, So, Du and Hoefer [7] have created TLM-based 2D and 3D computational models of metamaterials, but so far, only one- and two-dimensional metamaterials have actually been realized in transmission line technology. In this paper we demonstrate for the first time how the transmission line approach can be extended to three space dimensions. Like the 1D and 2D cases, this 3D metamaterial is a realizable network of transmission lines with embedded series capacitances and shunt inductances. We present the theoretical concept, validate its wave properties through full-wave transient electromagnetic modeling, and develop a methodology for designing such a 3D metamaterial.

II. Theoretical Foundations

The 3D distributed TLM node [8] is a realizable network model of Maxwell's equations. It has the same staggered (distributed) topology as the well-known FDTD scheme proposed by Yee. Its main advantage for the purpose of metamaterial design is that it can actually be built. Therefore, it is perfectly suitable as a host network for a transmission-line based metamaterial. All that is needed is the strategic embedding of reactive elements into this network. We will first summarize the wave properties of a 3D distributed node TLM network that consists of ideal transmission line sections, and determine the embedded reactive element values required to achieve a desired negative refractive index and wave impedance. We will then deal with the issues that arise when such networks are realized in a particular technology. Specifically, we must account for the effect of the shunt and series junctions that form the nodes of the real network, and the placement and implementation of the reactive embedded elements, and undesirable parasitic interactions between them.

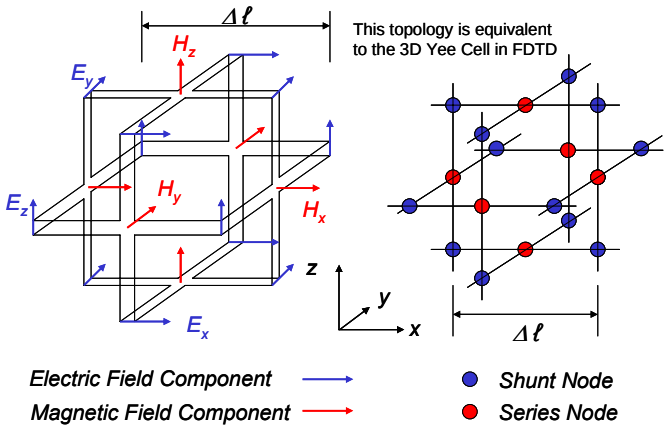

Fig. 1. Unit cell of the 3D distributed node TLM network, consisting of staggered series and shunt connections of ideal transmission line sections. The field components are sampled at the same locations as in the FDTD Yee scheme.

Fig. 1 shows the unit cell or building block of the 3D distributed node TLM network. It consists of three shunt and three series nodes per cell - oriented in the three coordinate directions - that connect the lossless transmission line or link