A Novel Broadband Fractal Metamaterial Unit Cell

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***Abstract*—A fractal inspired metamaterial structure based on the electric LC resonator (ELC) described in [1] is presented. The proposed unit cell was built with a larger physical size to shift the frequency of operation to lower frequencies, and a partial repetition of the basic I–shape was inserted in each capacitive gap. The resulting structure was simulated in HFSS, and the relative permittivity and permeability values were extracted from the simulations. The structure was found to have negative permittivity over the range 1.3 GHz – 1.75 GHz, which corresponds to a percent bandwidth of 29.5% with a unit cell that is smaller than $\lambda_\circ/10$.**

I. Introduction

Metamaterials have been the focus of significant research in recent years because of the promise of such lofty notions as cloaking, faster than light travel, and flat lenses. To realize these technologies, negative values of relative permittivity are necessary, and some metamaterial structures have given enticing glimpses of achieving this goal with typically narrow band performance. Thus, one significant goal of research in this area is to achieve wideband performance.

This paper begins with the electric LC resonator (ELC) first described by Liu et. al. [1]. The original unit cell geometry was designed to provide negative permittivity across the band 10.8 GHz – 13 GHz to achieve 18.5% bandwidth; the unit cell that achieved this response required an electric length of approximately $\frac{\lambda_\circ}{7.6}$ at midband. The proposed geometry exploits fractal notions to modify the ELC structure with additional features in the vertical direction to achieve increased bandwidth and decreased electrical size.

II. The Geometry of the Fractal Structure

One of the best unit cell geometries to achieve negative permittivity is the Electric Disk Resonator [2]. This structure provides a large surface to interact with the incident electric field, and often exhibits a moderate frequency range over which an effective negative permittivity is attainable. Unfortunately, this structure is not easily manufactured because of its three dimensional shape. To simplify manufacturing and implementation, this structure may be approximated with an I-beam, which is simply a two-dimensional rendering of the three-dimensional geometry. This 2D structure has been explored and found to effectively induce negative permittivity, although its bandwidth is narrower, and the field interaction is weaker, than the three-dimensional version.

To broaden the bandwidth of this structure, [3] proposed a fractal expansion of the basic I-beam shape with additional replicas of this shape that would resonate at different frequencies. Unfortunately, the proposed fractal structure lacked continuous bandwidth, and instead exhibited multiple bands over which the desired response was achieved. The current paper intends to combine the work of [3] and [1] with modification of the individual lengths of each part of the geometry, as well as the addition of discrete capacitively coupled resonators that broaden the bandwidth of this structure significantly.

Fig. 1 shows a unit cell of the ideal fractal metamaterial structure under consideration. The conductive traces have a thickness of 0.035 mm, and are positioned on a substrate of FR4 epoxy with a thickness of 0.079 mm. The I-beam initiator is central to the structure with four secondary I-beams on the ends of the initiator. To further increase bandwidth of this structure, two additional I-beams were added in the middle of each side and are capacitively coupled to the primary fractal structure. The lengths of each section were chosen to resonate at closely related frequencies to widen the bandwidth over which the effective permittivity is negative. To improve performance of this unit cell, and reduce overall size, the geometry of Fig. 1 was modified by truncation of the grayed-out sections to form the final structure shown in Fig. 2

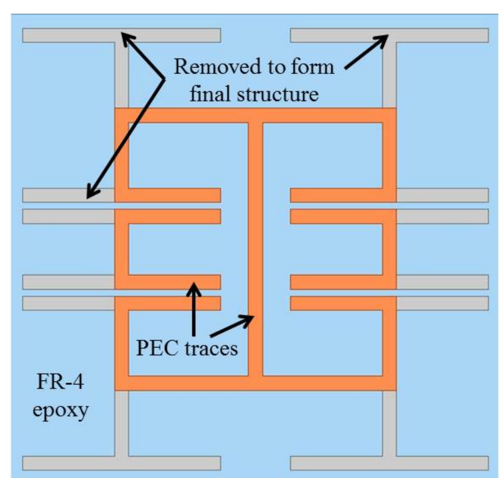

Fig. 1. The ideal fractal metamaterial unit cell.

III. Simulation Results

The response of the metamaterial structure described above was simulated within a vacuum filled parallel plate waveguide

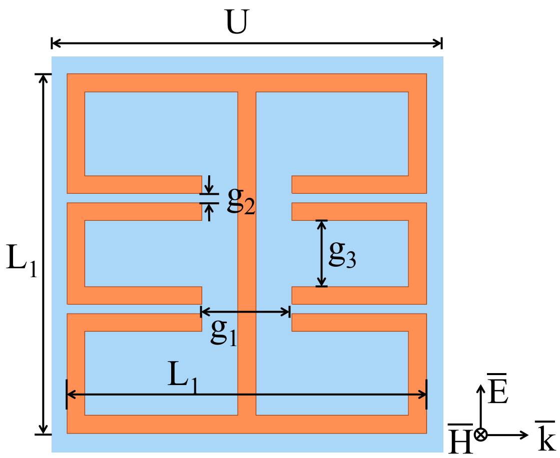

Fig. 2. The proposed reduced fractal metamaterial unit cell, where $L_1 = 20$ mm, $U = 22$ mm, $g_1 = 5$ mm, $g_2 = 0.5$ mm, and $g_3 = 3.67$ mm; all traces are 1 mm wide.

using Ansys HFSS; the parallel plate waveguide was 10 mm wide and 25 mm high. The reflection and transmission resulting from simulation of this metamaterial are shown in Fig. 3. As shown, the first resonance occurs at 1.45 GHz where the unit cell size is slightly less than $\lambda_\circ/10$, and has a -10 dB bandwidth over the range 1.3 GHz – 1.6 GHz. A second resonance occurs between 2.05 GHz and 2.25 GHz. The fields in the parallel plate waveguide are shown in Fig. 4. In this figure, it is shown that the incident and transmitted waves both point downward, but the electric fields inside the unit cell point upward. Thus, the effective permittivity of the material at this frequency is negative.

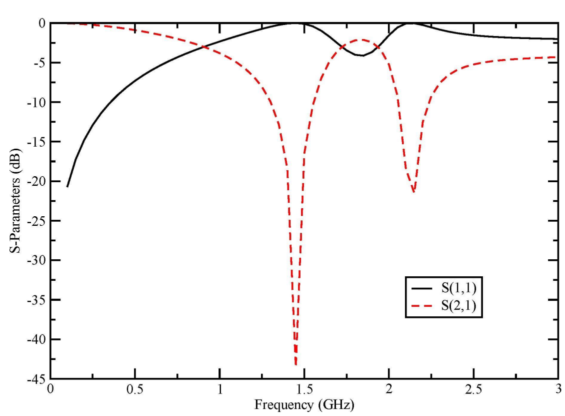

Fig. 3. The reflection and transmission resulting from simulation of the metamaterial.

The relative permeability and permittivity of this metamaterial structure were calculated from the simulated S parameters using the extraction algorithm described in [4]. Fig. 5 shows the extracted relative permeability and relative permittivity. As expected from the field plot of Figure 4, the permittivity is negative in the range 1.3 GHz – 1.75 GHz, which corresponds to a bandwidth of 29.5%. Although this structure was primarily intended to provide negative permittivity, there is also a region of negative permeability in the range 2.05 GHz – 2.45 GHz, corresponding to a bandwidth of 17.8%. This effect corresponds to a mode structure that looks more like that of a split ring resonator. It should be noted that in this region of negative permeability the unit cell is approximately $\lambda_\circ/7$ and thus may not be considered to be electrically small.

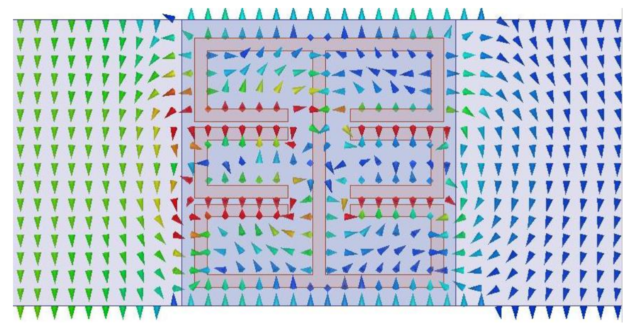

Fig. 4. The field structure inside the waveguide at 1.45 GHz.

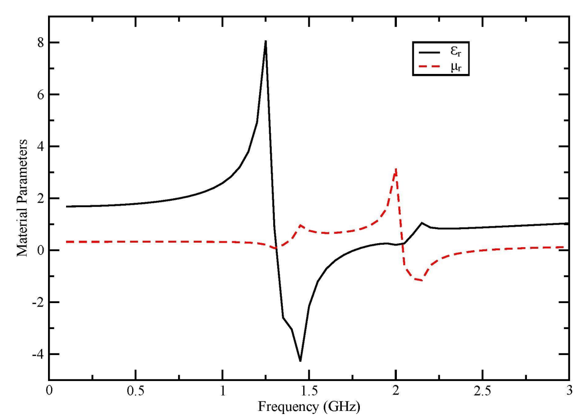

Fig. 5. The real part of the extracted permeability and permittivity.

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