Fully-Printed Multilayer Metamaterial For Free-Space Excitation

Hoang-Linh Nguyen, *Student Member, IEEE,* and Ashwin Iyer, *Member, IEEE*

***Abstract*—The report presents a fully-printed biplanar design of a volumetric negative-refractive-index transmission-line (NRI-TL) metamaterial. The proposed structure employs dual-arm spiral inductors providing stronger loading inductance and leading to better matching to free space, while still possessing a small electrical length of one-eleven of the operating free-space wavelength.**

***Index Terms*—Metamaterials, fully-printed, left-handed (LH), negative refractive index (NRI), periodic structures, volumetric, transmission line.**

I. Introduction

NEGATIVE-Refractive-Index Transmission-Line (NRI-TL) Metamaterials are implemented by periodically loading conventional transmission lines (TLs) with series capacitors and shunt inductors at subwavelength intervals (period *d*) to negate the intrinsic parameters of the host TL, resulting in negative effective permittivity, permeability, and therefore a NRI [1]. Stacked layers of such planar metamaterials, which are termed multilayer or volumetric NRI-TL metamaterials, have been shown to interact with suitably polarized electromagnetic sources in free space [2].

In Ref. [3], a fully-printed multilayer metamaterial structure was proposed based on a biplanar 2D NRI-TL unit cell. This structure exhibited NRI characteristics at lower frequencies and a unit-cell electrical length of $d \approx \lambda_0/20$. As a result, this topology better adheres to the effective-medium condition, which could not be achieved by its fully-printed uniplanar counterpart ($d \approx \lambda_0/5$) [4]. On the other hand, the free-space metamaterial superlens [4], which employs discrete (surface-mount) inductors and capacitors in the uniplanar configuration, satisfies the effective-medium conditions ($d \approx \lambda_0/18$); however, the cost of such a structure is prohibitive due to both the price of loading components and the complexity of placing them. Therefore, the biplanar structure appears to be a low-cost solution suitable for free-space excitation, provided that it can be matched to free space.

In this report, we introduce a design (Fig. 1) based on the same biplanar topology, which has strong loads of inductance and capacitance. The proposed structure utilizes dual-arm spiral inductors, which have much larger inductance than meandered-line inductors, and MIM-type capacitors. Although the unit-cell size must be increased to accommodate these inductors, the expanded interior region allows larger loading metal-insulator-metal- (MIM-) type capacitors, resulting in a lower NRI frequency range and, therefore, a comparable electrical length ($d \approx \lambda_0/18$).

The authors are with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada.

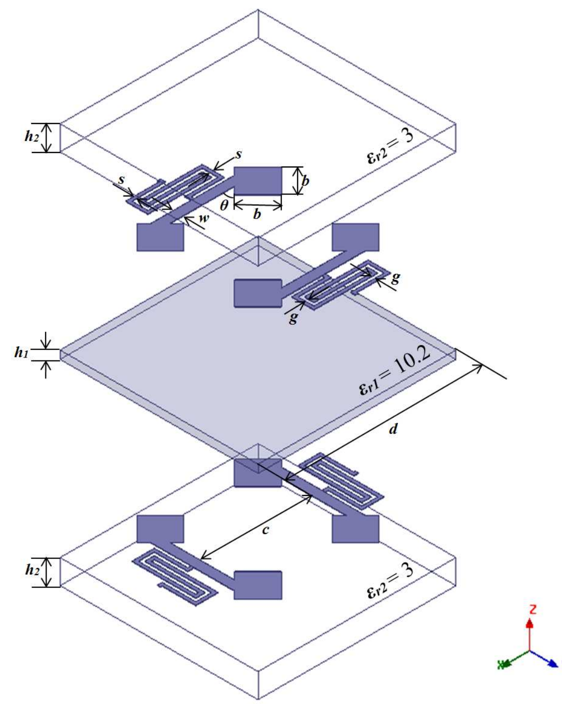

Fig. 1. An exploded view of the proposed structure with a period of 6.2 mm.

II. Design

The design employs larger physical unit-cell dimensions than that presented in [3], which provides more room for the printed inductor, and bigger loading capacitors, Fig.1. The dielectric layer hosting the MIM-type capacitors is made of Rogers RT/duroid 6010/6010LM (thickness $h = 10mil$, $\varepsilon_r = 10.2$, $tan\delta = 0.0023$), and is separated from adjacent layers by Rogers RO3003 (thickness $h = 60mil$, $\varepsilon_r = 3$, $tan\delta = 0.0013$), creating a vertical period of $p = 70mil$.

The dielectric gaps are chosen to be thicker than the unit-cell layers in order to minimize unwanted coupling between the layers. Additionally, the pads of the MIM-type capacitance are rotated by an angle of $\theta = 45^o$ to mitigate parasitic capacitance formed between adjacent pads across two neighbouring unit cells. The crucial change in the new design is the substitution of dual-arm spiral inductors (arm width $w = 0.1mm$, gap $g = 0.1mm$) for meandered-line inductors.

III. Simulations and Results

The goal of the project is to find the optimum dimension of the loading MIM-type capacitors, dual-arm spiral inductors, and CPS width, resulting in appropriate capacitance and inductance values. A parametric study was conducted to search for these dimensions. The simulation aimed at verifying the matching of the structure to free space was created using full-wave simulator HFSS.

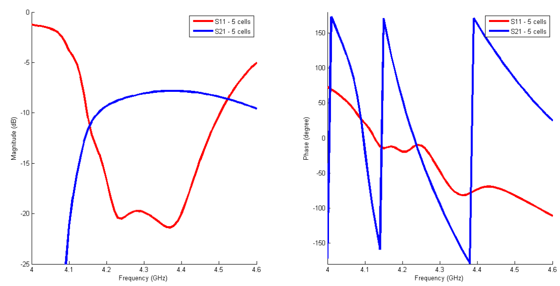

Fig. 2. Reflection and transmission data measured when plane wave hits a transversely infinite and 5-unit-cell long slab

In the simulation, a suitably polarized plane wave excited in free space was launched toward an transversely infinite, and 5-unit-cell long slab consisting of the proposed unit cell. The scattering parameters were collected to measure the matching degree, and also to extract the effective permittivity and permeability of the slab.

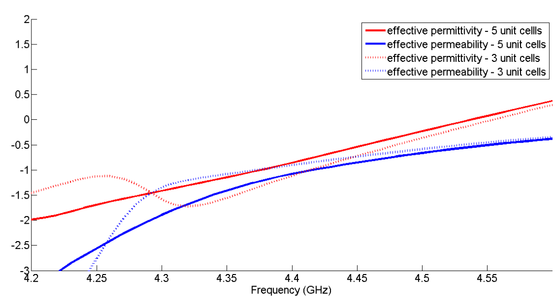

Fig. 3. Extracted effective permittivity and permeability

The structure exhibits the NRI properties from 4.2 GHz to 4.5 GHz. At the frequency of 4.4 GHz, the structure obtains good matching to free space ($S_{11} \approx 19dB$) as shown in Fig.2, and the extracted effective permittivity and permeability are 0.98 and 1.08 in Fig.3 , respectively, which are close to -1, explaining the impedance matching to free space as shown in the return loss. The extraction procedure was applied to slabs with length of 3 unit cell and 5 unit cell.

IV. Conclusion

The proposed volumetric NRI-TL metamaterial structure in the project employs fully printed loads. The unit cell obtained a small electrical length of $\lambda_0/11$ at 4.4GHz, rendering a material an effective medium, which allows the permittivity and permeability extraction procedure to work properly. It also has a good free-space matching, at which its effective permittivity and permeability are close to -1.

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