INVITED - TAILORING DOUBLE NEGATIVE METAMATERIAL RESPONSES TO ACHIEVE ANOMALOUS PROPAGATION EFFECTS ALONG MICROSTRIP TRANSMISSION LINES

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Abstract— **Several Double Negative (DNG) metamaterials, artificial materials with simultaneous negative permittivity and permeability, have been fabricated and tested experimentally at X-band frequencies. These include a negative index of refraction slab matched to free space and a perfect magnetic conducting slab. The basic concepts of propagation in DNG metamaterials, their designs and experimental verifications will be reviewed. These DNG metamaterials may indeed be very suitable for a variety of electromagnetic applications dealing with guided wave environments, sensors, and antennas. The use of a DNG metamaterial to tailor the propagation characteristics of a microstrip transmission line will be described in detail. It will be demonstrated that a DNG-loaded microstrip transmission line segment that exhibits a negative index of refraction can be matched to an ordinary microstrip line.**

I. INTRODUCTION

Double negative (DNG) metamaterials, i.e., materials with both negative permittivity and negative permeability [see, for instance, 1-3], have been a topic of high interest in recent years. These metamaterials are typically realized artificially as composite structures that are constructed from arrays of metallic inclusions in dielectric or magnetic substrates, and they exhibit unusual scattering and propagation properties within a particular frequency range. For instance, in contrast to a double positive (DPS) medium, i.e., a normal medium that has both positive permittivity and permeability, the wavenumber k in a DNG material is opposite to, rather than parallel to, the Poynting's vector associated with a plane wave propagating in it. Thus, the Poynting's vector is parallel to, and the wavenumber k is antiparallel to, the direction of causal power flow [3]. Several experimental verifications of the existence of the DNG metamaterials have been reported [4]-[6]. The property of interest to the microstrip transmission line application involves the possibility that the DNG metamaterial (MTM) could be matched to the intrinsic impedance of the transmission line and can then be used to achieve non-standard propagation characteristics along it.

II. MTM DESIGN

The DNG metamaterial components are derived from those successfully tested in [6]. There an integrated set of negative permittivity and negative permeability elements were used to obtain a negative index of refraction block at X-band that was matched to free space. The MTM elements considered here consist of a pair of capacitively loaded strips (CLS's) and a pair of oppositely oriented capacitively loaded loops (CLL's). They are embedded in a lossless dielectric characterized by the parameters $\varepsilon_r = 2.2$ and $\mu_r = 1.0$. These basic elements are shown in Figs. 1a and 1b, respectively. The sizes were determined to provide interesting responses in the 3-5 GHz frequency band. The incident quasi-TEM wave has its electric field polarized parallel to the strips (along the x-axis); its magnetic field is along the normal to the rings (along the y-axis). Its direction of propagation is along the capacitor legs (along z-axis). The CLL's in the pair are oppositely oriented to create a MTM element that, like the CLS pair, is reciprocal to a wave propagating from the left or the right. The integrated DNG block is shown in Fig. 1c. A 10 mil spacing between the CLS and CLL layers was assumed.

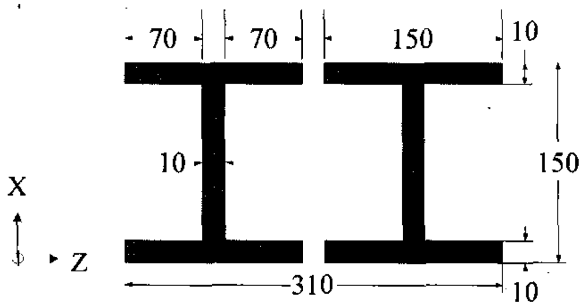

Fig. 1a. CLS unit cell (units = mils).

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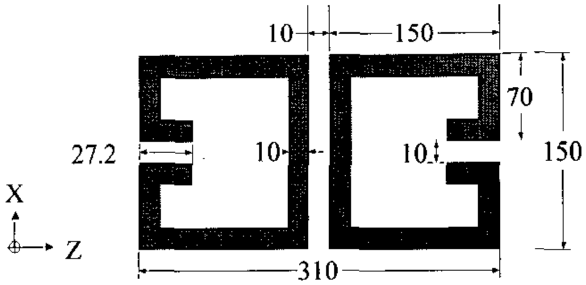

Fig. 1b. CLL unit cell (units = mils).

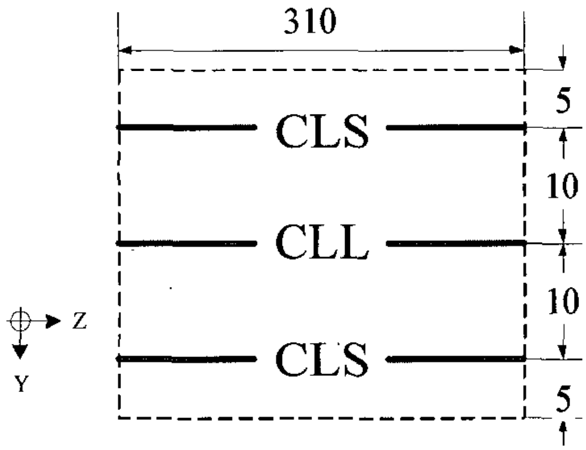

Fig. 1c. Top view of the unit MTM block (units = mils).

III. HFSS Results

Sixteen MTM blocks were then placed under a 50Ω microstrip transmission line as shown in Figs. 2a and 2b. The top and bottom edges of the CLS's were 5 mils from the ground plane and from the microstrip line. This geometry was entered into ANSOFT's High Frequency Structure Simulator (HFSS). Because of its symmetry, a vertical symmetry plane was inserted as shown and only half the MTM loaded transmission line structure was actually simulated. A 10 GHz single frequency was used to established the mesh. The simulation was swept from 2-5 GHz with 5000 steps. The number of tetrahedral was 99603. The magnitudes and phases of the HFSS predicted S_{11}, S_{12}, S_{21} and S_{22} values that have been normalized and de-embedded to the front and back edges of the MTM

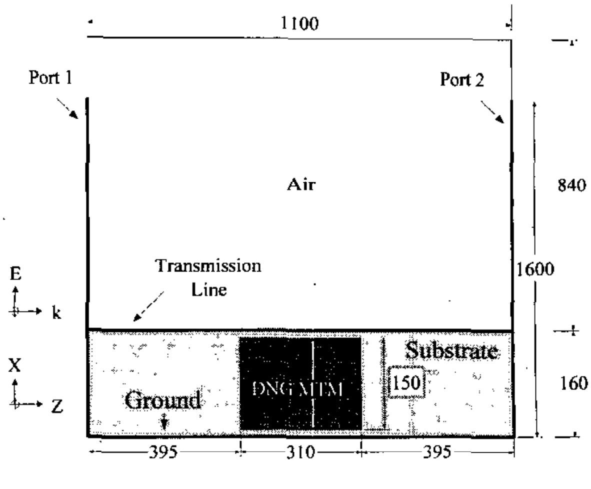

Fig. 2a. Side view of the designed MTM-loaded TL (units = mils).

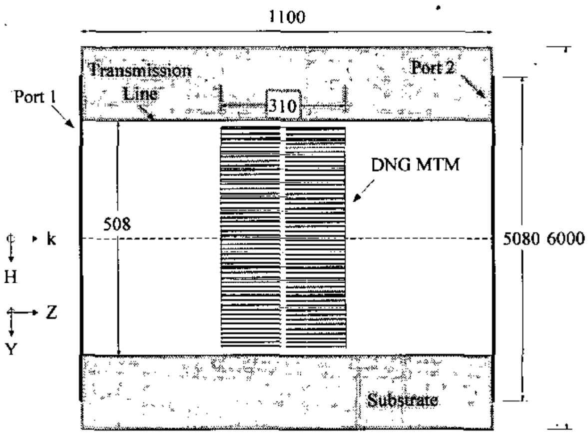

Fig. 2b. Top view of the designed MTM-loaded TL (units = mils).

block are shown in Figs. 3a and 3b. A passband exists in the frequency region, 3.4-3.6 GHz. The overall phase of S_{21} passes through 90° in the middle of this band at 3.53 GHz. Removing either of the CLS or the CLL elements caused a stop-band in this frequency region. The pass-band occurred only when both sets of elements were present. This behavior was analogous to that observed in the free space DNG modeling and experiments [6]. Consequently, we claim that the MTM block is acting as a DNG medium in this frequency region.

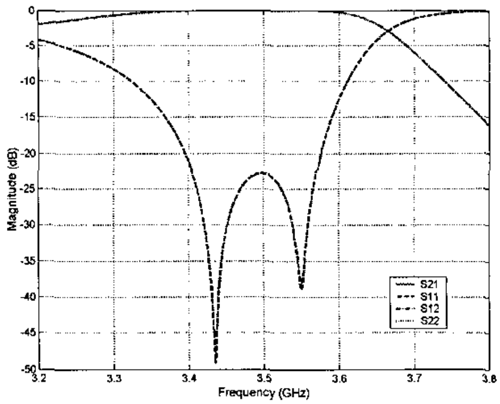

Fig. 3a. Magnitude of the HFSS S-parameter results.

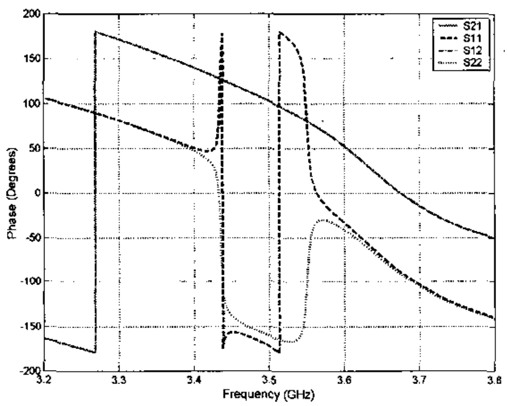

Fig. 3b. Phases of the HFSS S-parameter results.

IV. EFFECTIVE INDEX EXTRACTION

To substantiate this claim, we developed the two-port network representation shown in Fig. 4a for the MTM loaded transmission line section. The S-parameters were normalized at each frequency by the HFSS predicted values of the characteristic impedance of the transmission line, and the result was connected to the equivalent ABCD matrix via the standard expressions:

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}$$

$$B = Z_0 \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$$

$$C = \frac{1}{Z_0}\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}}$$

$$D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}$$

The resulting ABCD matrix was used to calculate the impedances Z_1, Z_2, and Z_3 of the two port network with the expressions

$$Z1 = \frac{(A-1)}{C}$$

$$Z2 = \frac{D-1}{C}$$

$$Z3 = \frac{1}{C}$$

The magnitudes and phases of the impedances Z_1, Z_2, and Z_3 are shown in Figs. 4b and 4c, respectively.

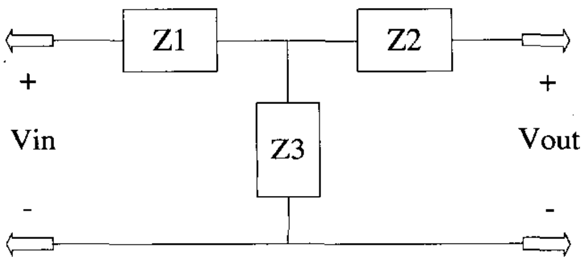

Fig. 4a. Two port network representation of the MTM loaded transmission line.

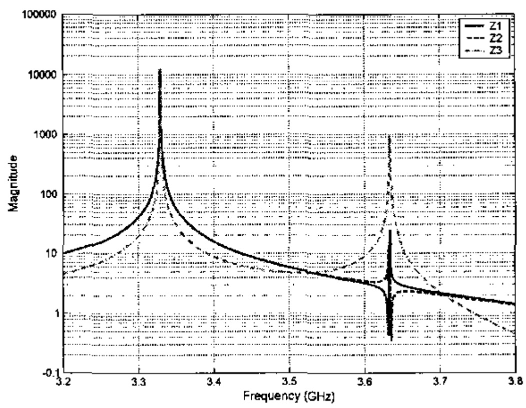

Fig. 4b. Extracted magnitudes of the impedances.

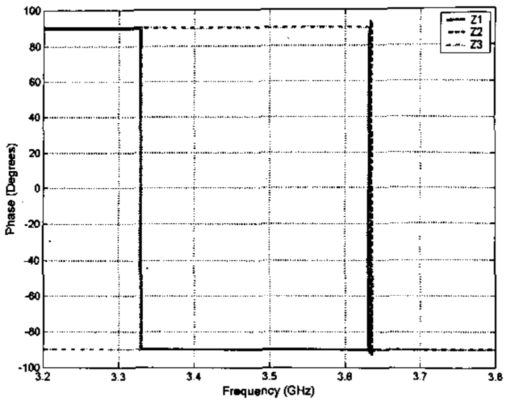

Fig. 4c. Extracted phases of the impedances.

It was found that the extracted impedances had large variations in their amplitudes across the frequency range. However, the impedances Z_1, Z_2 and Z_3 varied dramatically at the edges of the pass-band. From the extracted phases, one can see that the DNG MTM loaded transmission line can be represented as a normal L-C transmission line before the DNG pass-band. It switches to a C-L configuration in the DNG pass-band. It then switches to a C-C type of configuration after the DNG pass-band where complete reflectivity ($|S_{11}|\sim 1$) is exhibited. This C-L type of behavior has been shown in [5] to be characteristic of a planar DNG transmission line. As expected, it was found that propagating waves would only exist if both the L and C element characteristics were present.

It was also found that the impedance at the frequency 3.53 GHz is exactly 50Ω and A =0. This means $B \approx - Z_0 S_{12}$. The equivalent transmission line ABCD matrix then yields $B = jZ_0 \sin \beta l \approx - Z_0 S_{12}$. Since $\beta l = n2\pi l/\lambda$, this means $n < 0$ and $|n|=(m+1/4)\ \lambda/l$ or $n>0$ and $|n|=(m+3/4)\ \lambda/l$. Thus, the lowest order result indicates that the index of refraction is negative, i.e., n=-2.69 there. Further considerations have shown that negative values of the index occur within the DNG pass-band. This corresponds to the results shown in [3], i.e., a DNG medium has a negative index of refraction.

There are several interesting applications for a matched, negative index of refraction microstrip line element. The phase accumulation associated with propagation through the DNG region is opposite to that experienced in a normal DPS medium. The ability to load microstrip transmission lines with DNG segments thus suggests the possibility of phase compensation through the associated negative index of refraction. The dispersive properties of the DNG MTM loaded microstrip transmission line section could also be used to achieve dispersion compensation to improve pulse propagation along a normal DPS microstrip line.

V. CONCLUSIONS

A DNG MTM loaded transmission line was considered. Elements used successfully in previous DNG MTM experiments were modified to match the transmission line geometry. The structure was modeled with HFSS. An equivalent network representation of the MTM loaded transmission line structure was obtained and used to illustrate the DNG behavior. A negative index of refraction was realized with the DNG MTM elements. Phase and dispersion compensation are potential applications of such DNG MTM loaded microstrip transmission line segments.

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