A Novel Planar Left-Handed Transmission Line Using Defected Ground Structure with Inter-Digital Gap

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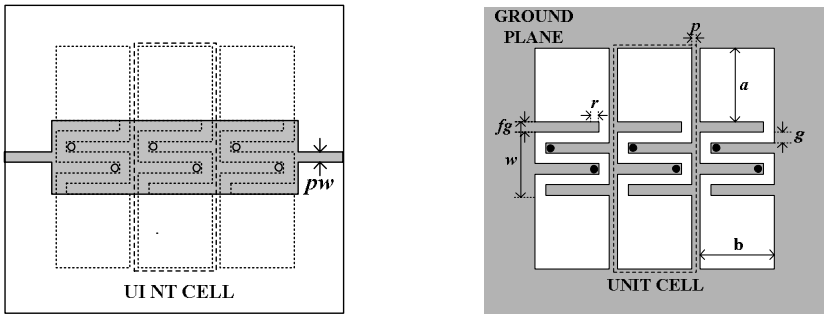
I. INTRODUCTION

There has been a growing research for various meta-materials with simultaneously negative values of effectively permittivity and permeability. In particular, because planar type of one-dimensional CRLH TL can be simply fabricated and has a wide application, RF-devices such as band stop/pass filters, couplers, backward antennas, and resonators are developed and their characteristics are analyzed [1]. Also, defected ground structure (DGS) is realized by etching off defected pattern on the ground plane of 1-D transmission line. The pattern usually adds an extra lumped capacitance to the lines by controlling the current paths on the ground. Generally, DGS is modeled as a parallel resonant circuit connected in series on transmission lines with characteristic impedance. Recently, to enhance performance of the RF devices and reduce their sizes, DGS is extensively studied [2].

In this paper, a novel left-handed transmission line (LH TL) is proposed using defected ground structure (DGS) with inter-digital gap (IDG). The conventional DGS has low series capacitance value by connecting slot between the defected areas. However, because the IDG is used, the proposed structure has the lower resonance frequency and higher series capacitance value than those of the conventional DGS in case of the same defected area. Therefore, IDG in the ground can make the required range of negative permeability in low frequency range where permittivity has negative, which is obtained by the grounded via hole.

II. STRUCTURE AND EQUIVALENT CIRCUIT OF PROPOSED LH TL



(a) (b)

Fig. 1 Proposed LH TL. (a) Top view. (b) Bottom view.
(***a*** = ***b*** = 5mm, ***w*** = 7.1mm, ***g*** = 0.1mm, ***fg*** = 0.5mm, ***r*** = 0.3mm, ***pw*** = 0.6mm, ***p*** = 0.25mm and number of finger pairs = 6)

Fig. 1 shows the proposed LH TL structure. The unit cell consists of a DGS with connecting inter-digital gap between two defected rectangular areas in the ground and via. As it is known well, compliment sprit ring resonator (CSRR) is also defected on ground

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but has property of effective negative permittivity in specific frequency band due to the electrically coupling among the host transmission line, patch and ground [4], while the proposed LH TL has effectively negative permeability in specific frequency band because of the capacitance of the series resonance tank. The effective negative permeability of the LH TL is implemented by the grounded via hole. Consequently, the LH TL has effective – μ and – ε due to series capacitance of inter-digital gap in the ground and shunt inductance of via, respectively

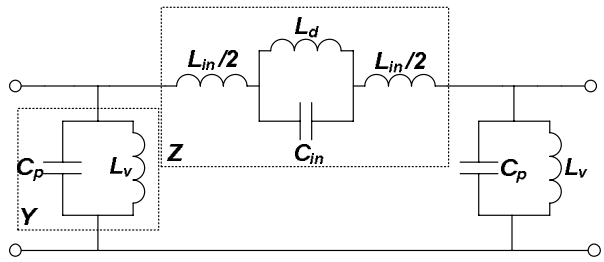

Fig. 2 Equivalent circuit of unit cell for proposed structure

Fig. 2 shows the equivalent circuit of unit cell for proposed LH TL. In an equivalent circuit of the unit cell, C_{in} and L_{in} express capacitance and inductance of an IDG, respectively. L_d express additionally induced inductance due to two defected rectangular areas of DGS Also, L_v and C_p are inductance of a via and capacitance between IDG and signal line. Z and Y are the series impedance and shunt admittance, respectively.

III. ANALYSIS AND MEASUREMENT

Fig. 2 shows the equivalent circuit which represents an effective double negative property in the specific frequency range, i.e., Z acts as a capacitance and Y does as an inductance in the specific frequency band. In Fig.2, the series impedance and shunt admittance can also be obtained as,

$$Z(\omega) = \frac{j\omega L_{in}\left(1-\omega^2 C_{in} L_d\right) + j\omega L_d}{1-\omega^2 C_{in} L_d} \quad \text{and} \quad Y(\omega) = j\omega C_p + \frac{1}{j\omega L_v} \tag{1}$$

The effective permeability and permittivity values are obtained by the equation (1) as

$$\mu_{eff} = \frac{Z(\omega)}{j\omega} \quad \text{and} \quad \varepsilon_{eff} = \frac{Y(\omega)}{j\omega} \tag{2}$$

In the modeling, each parameter is extracted from full wave simulated results of unit cell. The extracted circuit parameters are C_{in} = 3.2 pF, L_{in} = 1.68 nH, C_p = 3.31 pF, L_v = 1.43 pF, and L_d = 16.82 nH. Fig.3 shows the imaginary part of the impedance and admittance values. The whole frequency range can be divided into four regions bounded by the critical frequency points ω_r, ω_1, and ω_2. ω_r, ω_1, and ω_2 are points where the imaginary part of impedance is infinite, the imaginary part of admittance is zero, the imaginary part of impedance is zero, respectively. The values are obtained by

$$\omega_r = \frac{1}{\sqrt{C_{in} L_d}}, \omega_1 = \frac{1}{\sqrt{C_p L_v}}, \text{ and } \omega_2 = \frac{\left(L_{in} + L_d\right)}{\sqrt{C_{in} L_d L_{in}}}.$$

As shown in Fig. 3, below ω_r, since the shunt admittance has negative imaginary value, the region is ε-negative (ENG). The region between ω_r and ω_1 is double negative (DNG)

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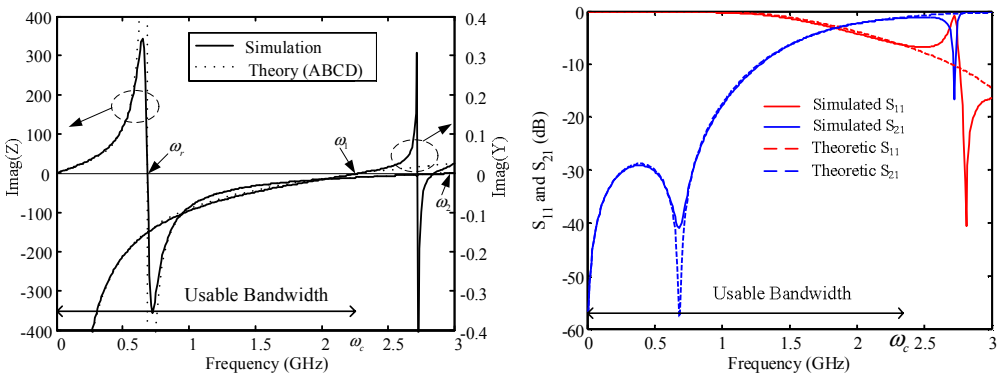
because the series impedance and shunt admittance has negative imaginary value. From ω_1 and ω_2, since the series impedance has negative imaginary value, the region is μ-negative (MNG). Finally, above ω_2, this region is double positive (DPS). Because a spurious resonance of the IDC appears above ω_c, the circuit model is valid in the frequency range between 0 and ω_c, called as the usable bandwidth as indicated in Fig.3.



(a) (b)

Fig. 3 (a) Imaginary part of impedance and admittance (b) Dispersion diagram

However, the DNG region exists below this frequency as shown in Fig. 3. By applying the periodic boundary conditions related with Bloch-Floquet theorem to the unit cell, the dispersion relation is obtained as,

$$\beta(\omega) = \frac{1}{d}\cos^{-1}\left(1 + ZY\right) \qquad (3)$$

where β is propagation constant for Bloch waves and d is the period of the structure.
As shown in Fig. 3, the results of theory (ABCD matrix) and full wave simulation show good agreements.

(a) (b)

Fig. 4 Fabricated 3stage CRLH TL. (a) Top view (b) bottom view
(Rogers Ro 3010 substrate: h= 0.64mm and ε_r = 10.2)

The photograph of the fabricated 3 stage LH TL is shown in Fig. 4. The input and output ports are fabricated using 50 Ω coaxial connector. There needs no tapering to the feed line because total impedance of the structure is about 50 Ω even though width of input signal line is corresponding to impedance of 10 Ω.

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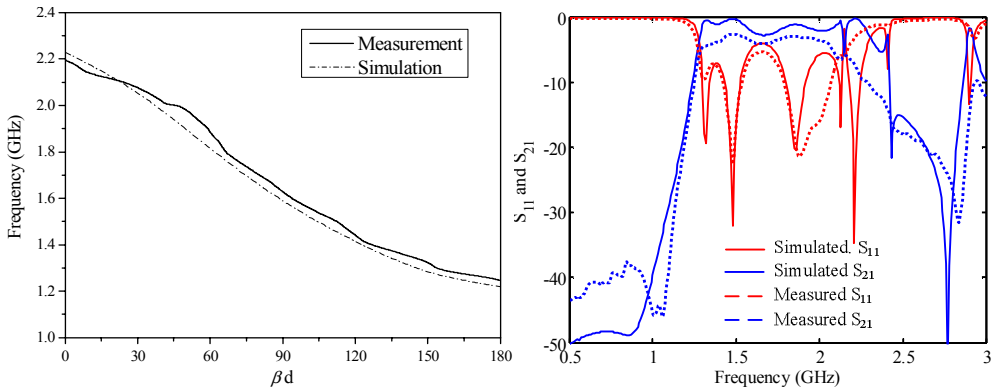

(a) (b)

Fig.5 Measured and Simulated (a) dispersion relation for LH band and (b) S-parameter

In order to measure the dispersion curve, 3, 4, and 5 stage CRLH TL has been fabricated. The phase of S_{21} of each stage CRLH TL at the same frequency has been measured. Then, the propagation constant of β is extracted from the measured phase of S_{21}. The dispersion curves obtained from full wave simulation assuming the infinite periodic structure and from measurement have been compared in Fig. 5 (a). As shown in Fig. 5, the results of full wave simulation and measurement show good agreements. The simulated and measured LH frequency bands are from 1.22 GHz and 2.23 GHz (58.7%) and from 1.24 to 2.2 GHz (55.8%), respectively.

V. CONCLUSION

In this paper, a novel LH TL is proposed using DGS with IDG. The required shunt inductance and series capacitance for LH TL are provided by via and inter-digital gap on ground line, respectively. Due to the IDG, the proposed structure has the higher capacitance and the lower resonance frequency than the conventional DGS. It can provides the LH frequency band in the relatively lower frequency region. The dispersion relations are analyzed using the derived equivalent circuit and Bloch-Floquet theory. The measured results of dispersion curves of LH TL have good agreements with those of simulation.

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