Wideband Left-handed Transmission Lines with Crossly Connected Circuit

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Abstract

Two wideband left-handed (LH) transmission lines are presented. A pure LH transmission line (PLH TL) materialized by a defected ground structure with an inter-digital capacitor on a microstrip line has a wide LH propagation region without a right-handed (RH) branch in the reduced Brillouin zone. Another is a broadband LH rectangular waveguide utilized by a shorted stub and twisted E-plane posts. Two LH transmission lines which can be represented by crossly connected circuits have wide LH fractional bandwidths of 143.5% (PLH) and 26.5% (LH waveguide), respectively.

Keywords : Left-handed transmission line Metamaterials Crossly connected circuit

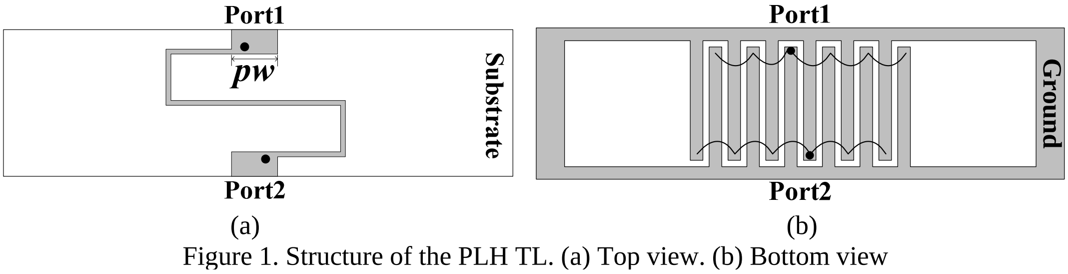
1. Introduction

Over the past decade, various meta-structures have been developed due to anomalous properties of metamaterials such as inverse Snell's low, backward wave propagation, infinite wavelength wave propagation, and others [1]. Most of metamaerial transmission lines have a limited LH band because a spurious RH branch due to an inherent series inductance and shunt capacitance occurs [2-3]. If a spurious RF branch were removed, a broader LH band would be obtained. Thus, in this paper, a pure LH transmission line having a broad LH band without a spurious RH branch in the reduced Brillouin zone (BZ) is presented [4]. The PLH TL is realised using a defect ground structure (DGS) with a wire bonded inter-digital capacitor (WBIDC) and cross-connected vias on a microstrip line. The structure gives rise to the negative values of inductance and capacitance which make the effective negative epsilon, resulting in the suppression of a RH branch.

As another wideband LH transmission line, a LH rectangular waveguide with a shorted stub and twisted E-plane posts is designed. In case of a rectangular waveguide, attempts to make a LH transmission line have been restrictively accomplished because of a limitation of the waveguide structure itself. Actually, previously reported metamaterial waveguides have very narrow LH bandwidth, i.e., less than 5% [5-6]. The novel LH waveguide is constructed with a cross-connected structure which is broadening and down-shifting a region of negative permeability. To analyze two wideband LH transmission lines, crossly connected circuits are derived. Their properties will be discussed in section 2 (PLH TL) and 3 (LH waveguide), respectively.

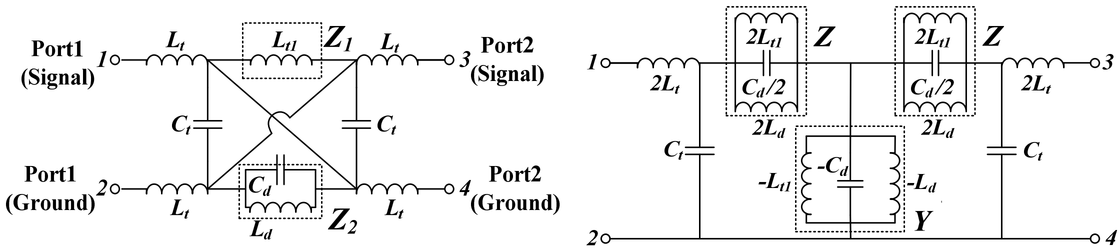
2. Pure Left-handed Transmission Line

Fig. 1 shows the unit cell of a PLH TL consisting of a DGS with WBIDC, shunt vias and meander signal line. The WBIDC is employed to remove spurious modes of the inter-digital capacitor. The position of the vias is very important in the design of the PLH TL. That is, the via near port 1 of the signal line is connected to the ground plane which links to port 2 and vice versa, as shown in Fig. 1. Consequently, the unit cell of the PLH can be exactly represented by a 4-termial network with crossly connected circuit as shown in Fig 2(a). In the equivalent circuit, the parallel resonance



(a) (b)

Figure 1. Structure of the PLH TL. (a) Top view. (b) Bottom view



(a) (b)

Figure 2. Equivalent circuit of the PLH TL. (a) Crossly connected circuit. (b) Modified equivalent circuit.

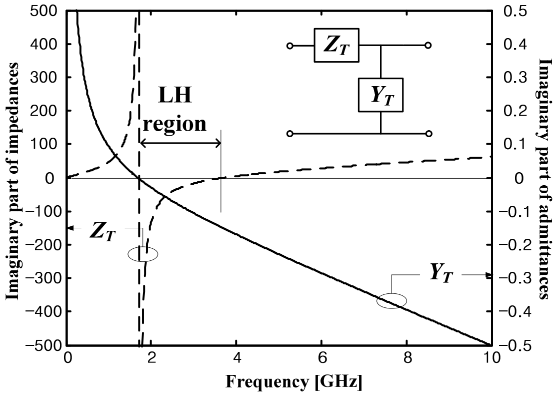


Figure 3. Imaginary part of impedance and admittance of the PLH TL.

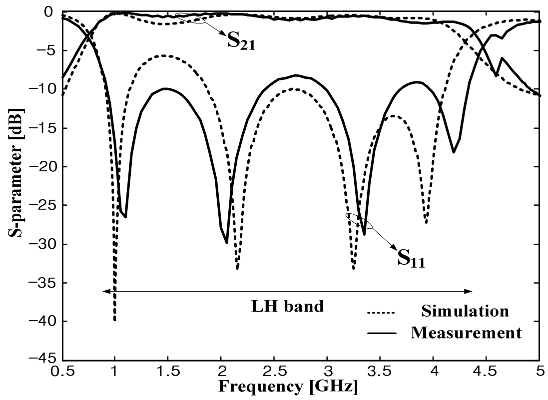


Figure 4. S-parameters of the PLH TL.

circuit of C_d and L_d is corresponding to the DGS and L_{t1} is determined by the length of the signal line between vias. Also, C_t and L_t of the host TL are parasitic elements of the PLH TL. From a rearrangement and Π-T transformations of the circuit, the crossly connected circuit is represented as Fig. 2(b) [4]. Then, the admittance (*Y*) has the most important information, that is, shunt admittance corresponding to effective epsilon has negative value of parallel composition of $-L_{t1}$, $-C_d$, and $-L_d$. From the modified equivalent circuit of the PLH TL, the impedance (*Z*) and admittance (*Y*) are expressed as the following

$$Z = \frac{2\omega^2 L_{t1} L_d}{j\omega(\omega^2 C_d L_{t1} L_d - L_{t1} - L_d)} \tag{1}$$

$$Y = \frac{j\omega(\omega^2(-C_d)(-L_{t1})(-L_d) - (-L_{t1}) - (-L_d))}{\omega^2(-L_{t1})(-L_d)} \tag{2}$$.

Fig. 3 shows the imaginary part of the impedance (Z_T) and admittance (Y_T) of a ladder circuit for unit cell, corresponding to effective permittivity and permeability, respectively. As shown figure, Im(Y_T) monotonically decreases with negative sign as the frequency increase above cut-off frequency (f_c) whereas that of a CRLH TL [2-3] increases as the frequency increases. Therefore, the PLH TL cannot have the positive permittivity due to the negative elements of $-L_{t1}$, $-C_d$, and $-L_d$ and supports only the LH propagation in BZ. Also, the negative permeability region determining the LH band of the PLH TL is controlled by the parameters of L_t and L_{t1}. That is, fractional LH bandwidth increases in proportion to the L_{t1} and in inverse proportion to L_t. Thus, obtain the broader LH band, the signal line is realized with a meander line (larger L_{t1}) and the wider connecting part to feed line (*pw*) is optimized (smaller L_{t1}) as shown in Fig. 1. The measured and simulated S-parameters for 2-stage PLH TL are displayed in Fig. 4. The implemented substrate is RT/duroid 5880 with a thickness of 0.787mm and relatively permittivity of 2.2. The results indicate that the PLH TL presents the broad LH fractional bandwidth of 143.5% (0.74GHz~4.47GHz) without a RH band. Moreover, the fabricated PLH TL has good transmission characteristics with the attenuation constant of below 1.5dB/λ_0 in the whole LH band.

3. Wideband LH Rectangular Waveguide

In this section, a wideband LH rectangular waveguide with crossly connected circuit will be discussed. Fig. 5 shows the unit cell of a cross-connected structure in a rectangular waveguide and its equivalent circuit. In general, a shorted stub in a rectangular waveguide which is represented by a parallel circuit of L_s and C_s acts as a resonator with negative value of effective permeability near the resonance frequency similar to a SRR. An E-plane post in a waveguide modelling as a T-equivalent circuit of L_p and C_p performs a negative value of effective permittivity by the shunt inductance (L_p). Specially, two twisted E-plane posts of the proposed structure crossly connect the top plane and bottom plane of the waveguide on both side of the shorted stub. Thus, the shunt inductances (L_p) of the equivalent circuit are cross connecting port 1 and 2 with respect to the stub as shown in Fig. 5(b). Additionally, to complete a circuit modelling, the inherent elements of L_w and C_w which are obtained by transmission line parameters of a rectangular waveguide should be added. The L_w and C_w depending on the waveguide structure is calculated as follows [7]

$$L_w = L'l \quad , \quad C_w = C'l \tag{4}$$

$$L' = Z_0\sqrt{\mu\varepsilon} \quad , \quad C' = \frac{1}{Z_0}\sqrt{\mu\varepsilon}\left(\frac{\beta}{k}\right)^2 \text{ (for TE mode)} \tag{5}$$

where L' and C' are per unit length inductance and capacitance of a rectangular waveguide, respectively. k is given by $\omega\sqrt{\mu\varepsilon}$, β is propagation constants of a TE_{10} mode, Z_0 is characteristic impedance, and l is the physical length of a unit cell. In order to design of a broad LH waveguide, the imaginary part of impedance of a transmission line corresponding to the effective permeability should have a wider negative region since the imaginary part of admittance (Y_T) corresponding to the effective permittivity keeps a negative value in the frequency band of interest. The imaginary part of impedance of LH waveguides using a stub and E-plane posts is approximated as follows,

$$\mathrm{Im}(Z_T) \approx \omega L_w / 2 + \frac{\omega L_s}{1-(\omega/\omega_r)^2} \tag{6}$$

where, ω_r is the angular resonance frequency of a parallel circuit of L_s and C_s. To obtain a negative permeability, the frequency should be larger than the resonance frequency and the inductance of L_s should be large enough to overcome the inherent waveguide inductance of L_w in (6). This suggests that the larger L_s is advantageous for the broad region of negative permeability when the frequency is above the resonance frequency. However, the general LH waveguide consisting of a shorted stub and straight E-plane post, the L_s of the resonant circuit is small because two surface currents oppositely flow between a shorted stub and two straight posts, resulting in the reduced H-field, as shown in Fig. 6(a). Thus, the LH waveguide using straight E-plane posts has a narrow region of negative permeability due to the decreased inductance. On the other hand, in case of the cross-connected LH waveguide, the double loops of surface currents are flowing in the same direction along two twisted posts and the stub, enhancing the H-field in the LH structure as shown in Fig. 2(b). Therefore, as the inductance becomes large, the negative permeability band of the crossly connected structure is down-shifted and broadened as shown in Fig. 7. This enhanced inductance also can make a compact LH waveguide be smaller according to down-shifted resonance frequency [8]. To investigate the transmission property of the LH structure, the periodic structure composed of 5 unit cells is implemented and fabricated. The LH bands by the simulation (7.53GHz~9.92GHz) and measurement (7.54GHz~9.84GHz), as shown in Fig. 6, are in good agreements with those of the negative permeability region in Fig. 7.

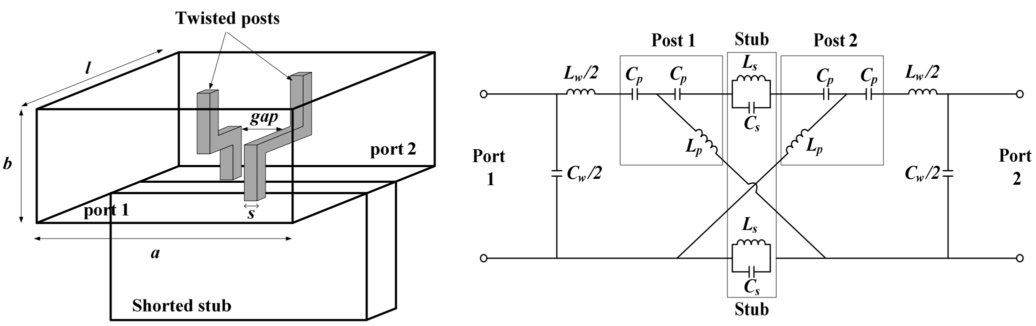


Figure 5. Wideband LH waveguide. (a) Unit-cell structure. (b) Crossly connected circuit.

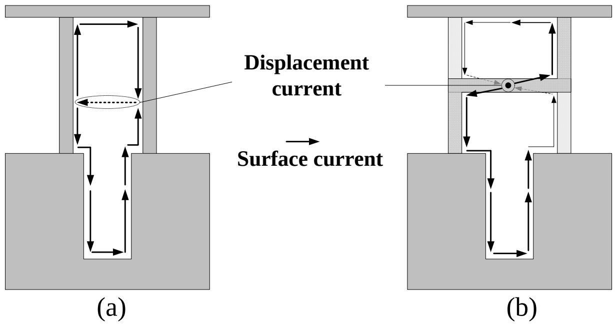


Figure 6. Surface current of the LH waveguide. (a) Non-cross type. (b) Cross type.

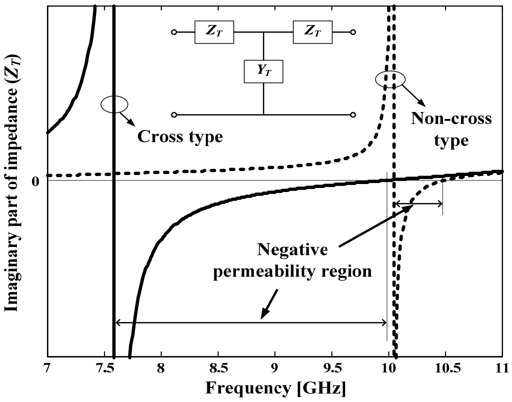


Figure 7. Im(Z_T) of the LH waveguide.

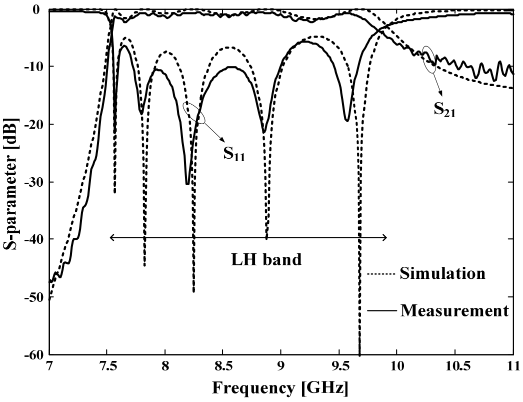


Figure 8. S-parameters of the LH waveguide.

4. Conclusion

In this paper, two wideband LH transmission line with crossly connected circuit constructed in a microstrip line and a rectangular waveguide, respectively, are presented. One is a PLH TL that has only a LH band without a parasitic RH branch. The cross-connected vias of the PLH TL make the negative components of inductance and capacitance. Thus, the LH transmission line removes the parasitic RH branch and has a wide LH propagation band. Second, the wideband LH rectangular waveguide using a shorted stub and twisted E-plane posts is designed. The twisted posts of a cross-connected structure make the double loops of surface currents between posts and stub and enhance the inductance of the stub. This peculiarity of the structure down-shifts and broadens a region of negative permeability. Therefore, the LH waveguide has a compact size as well as a broad LH band. The design results of the LH transmission confirm that two transmission lines with crossly connected circuit have wide LH band, compared with the previously reported metamaterial transmission lines.

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Acknowledgments

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