博士論文要旨 (2017 年度)

A Study on Metamaterial Transmission Lines for RF and Microwave Applications

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1. Introduction

Metamaterial is a terminology to describe a composite material in form of effective medium with negative permittivity ε and/or negative permeability μ. In 1998, thin wire structures (TWs) exhibit a negative value of effective permittivity which was first demonstrated by Pendry [1]. In 1999, he presented split ring resonator structures (SRRs) with a negative value of effective permeability [2]. Shelby and Smith verified a negative index of refraction of negative ε and negative μ by constituting TWs and SRRs in 2001 [3]. Later, a transmission line approach for metamaterials was first introduced approximately at the same time in June 2002 by three different groups, Eleftheriades [4], Oliner [5], and Caloz [6]. The proposed structures consist simply of L-C elements loaded-transmission line networks and are called by left-handed transmission line (LH TL) or negative-refractive-index transmission line (NRI TL). In 2006, composite right/left-handed transmission line (CRLH TL) and dual composite right/left-handed transmission line (D-CRLH L) are presented by Caloz [7, 8]. The CRLH TL exhibits a LH band at low frequency, a RH band at high frequency, and is of pass-band while D-CRLH TL is in opposition. More recently, an extended-composite right/left-handed transmission line (E-CRLH TL) has been combined from CRLH and D-CRLH TLs to get more involved band structures [9]. This TL is also known as a generalized negative refraction index transmission line (NRI TL) [10].

Metamaterials have been applied in a large number of RF and microwave devices such as antennas, filters, power dividers, direction couplers, absorbers and microwave lens. With the unique electromagnetic properties, metamaterials seem to allow manufacturers to reduce the size of these devices while maintaining good performance at a low cost.

Therefore, in this thesis, a study on metamaterial transmission lines is presented to bring new research results and applications for E-CRLH TL, the most recent metamaterial TL. This study also paves the way for novel arbitrary dual-, tri- and quad-band RF and microwave devices. In addition, there is a growing demand for faster data transmission of ultra wide band (UWB) applications. Antipodal Vivaldi antenna is a candidate for UWB applications. With resonant metamaterial approach, the gain of the antipodal Vivaldi antenna is improved by using nearly zero-index metamaterial (ZIM) unit cell. Also, a new estimation method for low frequency end of antipodal Vivaldi antennas is presented in this study.

2. Metamaterial transmission lines

2.1 Analysis and design of E-CRLH TL with new closed-form solutions

Figure 1 shows the equivalent circuit of an E-CRLH TL unit cell [9, 10]. By applying the periodic boundary conditions related with Bloch-Floquet theorem [11], the dispersion relation is obtained as

$$\cos(\beta d) = 1 + Z_h Y_v, \qquad (1)$$

where β is the propagation constant for the Bloch waves and d is the length of the unit cell. An example of the dispersion diagram of the unbalanced E-CRLH TL ($f_{C5} \neq f_{C6}$ and $f_{C7} \neq f_{C8}$) is depicted in Fig. 2. The balanced E-CRLH TL is obtained when $f_{C5} = f_{C6}$ and $f_{C7} = f_{C8}$.

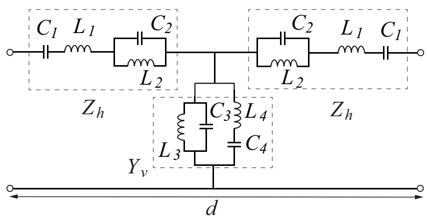

Figure 1: Equivalent circuit of an E-CRLH TL unit cell [9, 10].

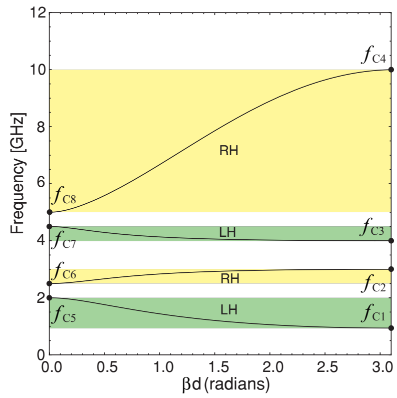

Figure 2: A typical dispersion diagram of E-CRLH TL in an unbalanced case [15].

The Bloch impedance is a quantity to use for the impedance matching. The Bloch impedance of the proposed metamaterial TL may be approximately calculated by the expression [10, 12]:

$$Z_B = \sqrt{\frac{2Z_h}{Y_v}}. \tag{2}$$

Most microwave application design with the E-CRLH TL are based on the controllability of the dispersion diagram, and the impedance matching consideration of the Bloch impedance. Therefore, it is important to find appropriate L–C elements to match the requirements. Previous studies for designing E-CRLH TL have presented for balanced cases and have seldom mentioned about unbalanced cases. Reference [13] presented a possible solution for a balanced case to achieve a desired phase at four specified frequencies. A balanced E-CRLH TL with arbitrary phase shifts at four arbitrary frequencies is reported in Ref. [14] by using the results of homogeneous E-CRLH medium. Homogeneous E-CRLH medium may be useful for idealization, but not for the case of a practical E-CRLH TL lumped implementation, since the unit-cells would sometimes cascaded periodically to build effectively the corresponding uniform TL structure [9].

In this study, a different approach is proposed to determine lumped elements of the equivalent circuit. Required L-C elements of the E-CRLH unit cell are calculated from the cut-off frequencies $f_{C1} \sim f_{C8}$. Moreover, we complement a mix case ($f_{C5} = f_{C6}$ and $f_{C7} \neq f_{C8}$), ($f_{C5} \neq f_{C6}$ and $f_{C7} = f_{C8}$), and a special case for a constant Bloch impedance. It shows a complete view of E-CRLH TLs. While a proper method for deriving the parameters of the unbalanced and mixed E-CRLH TLs is not yet reported, our closed-form solutions clearly have effectiveness for deriving these cases. By solving a set of equations explicitly, one can design easily a desired dispersion diagram and control Bloch impedance. To avoid complexity, References [9, 13, 14] have not characterized S-parameters of the E-CRLH TL in the unbalanced case. In our study, S-parameters of a periodic E-CRLH unit cell network have been investigated carefully for unbalanced, mixed, balanced and special cases. In addition, our method can be used for a desired phase characteristic, which is very useful for phase shift devices. Our calculated result covers the result of Ref. [13], in which the balanced case with some specified conditions is a special case in this study.

In conclusion, unlikely the previous methods, our method is in a general form and helpful for various cases. The numerical results has demonstrated the usefulness of the method. Thus this study contributes to the theory and applications of the E-CRLH TLs, and its results can be applied to design dual-, tri- and quad-band RF and microwave devices [15].

2.2 A compact metamaterial antenna based on asymmetric E-CRLH TL unit cell for multiband applications

For wireless communications, few antennas based on E-CRLH TL and NRI-TL were proposed up to now. Reference [16] presents a dual-band antenna based on a modified asymmetric NRI-TL unit cell. This antenna has a compact size, but exhibits a very low gain at the operating frequencies. More recently, a multiband antenna based on one asymmetric E-CRLH unit cell is designed for quad-band [17]. However, the resonant frequencies are not analyzed yet.

In this chapter, a compact quad-band antenna has been designed from one E-CRLH unit cell for GSM810, WLAN 2.45/5.5 GHz and WiMAX 3.5 GHz bands [18]. Asymmetric E-CRLH unit cell is chosen to design the antenna because of smaller configuration to compare with symmetric E-CRLH unit cell. The resonant frequencies of the proposed antenna have been predicted theoretically from L–C lumped elements and compared with simulated values. A photograph of the fabricated antenna is shown in Fig. 3. Figure 4 presents the measured return loss S11 of the antenna from 0.5 to 6 GHz. The measurements are executed by Agilent E8361A network analyzer in an anechoic chamber and compared with the corresponding HFSS simulated results. Our quad-band antenna has an electrical size $0.15\lambda_0 \times 0.08\lambda_0$ at the center frequency of the lowest band (GSM810) and its size is very small to compare with the previous quad-band antennas which designed by conventional methods. Although Reference [17] has made from the E-

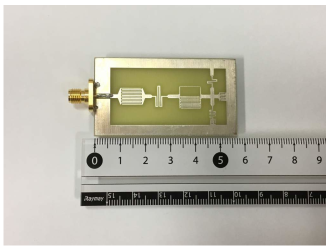
Figure 3: Fabricated antenna

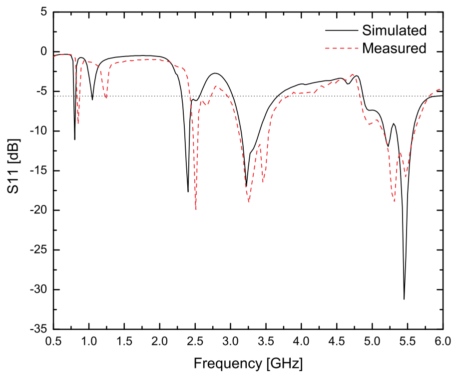

Figure 4: S11 characteristics of the fabricated antenna

CRLH unit cell, our antenna can be designed by roughly one half size. The gains of the proposed antenna are estimated as 3.66 dBi at 5.5 GHz, 1.46 dBi at 3.5 GHz, −1.31 dBi at 2.45 GHz and −8.12 dBi at 0.81 GHz. Due to the compact size, the gains of the antenna are quite low at low frequencies. At the higher frequencies, the gains of the antenna are enhanced and comparable with the previous quad-band antennas. In fact, the proposed antenna has a better gain at the low frequencies than the reported dual-band NRI-TL antenna (−17 dBi at 0.9 GHz and −8 dBi at 2.4 GHz) in Ref. [16].

In conclusion, the proposed antenna shows advantages of small size, omnidirectional radiation characteristics, and easy fabrication of single copper layer on the low cost of FR4 substrate. Basically, this antenna could be a candidate for multiband wireless communications.

3. Resonant metamaterials

3.1 Zero-index metamaterial (ZIM) unit cell for improving gain of antipodal Vivaldi antennas

The antipodal type of Vivaldi antennas (AVAs) offers broad bandwidth, minimal signal distortion, and high gain properties. However, the operation mechanism of the antipodal Vivaldi antenna is not well understood. Previously, antipodal Vivaldi antennas have been mainly designed by empirical methods without rigorous theory or formulas. While the operational upper frequency end of the antipodal Vivaldi antenna is theoretically infinity, the low frequency end has not been predicted and explained clearly. Therefore, the first objective of this study is to get better insight on the operation of the antipodal Vivaldi antennas, and to develop an accurate estimation of the low frequency end of the operational range [19].

Since the gain of the antipodal Vivaldi antenna is a very important parameter for UWB applications, many

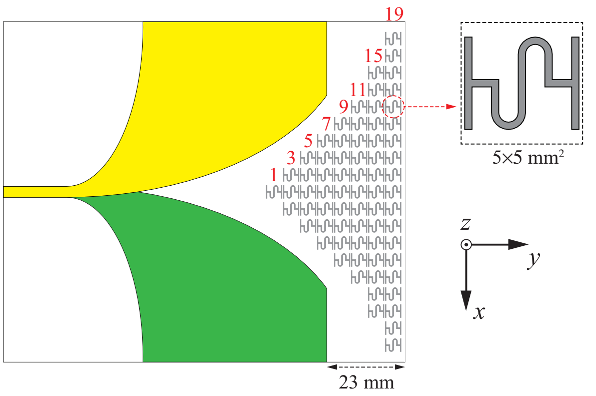

Figure 5: The configuration of the antipodal Vivaldi antenna with ZIM unit cell

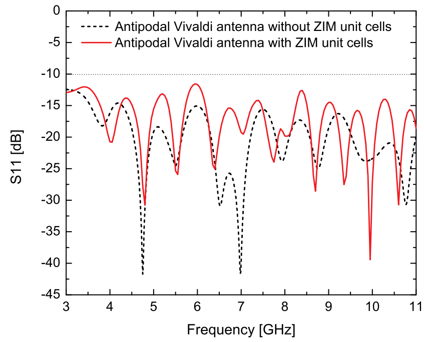

Figure 6: Simulated S-parameters for the antipodal Vivaldi antenna without and with ZIM unit cells

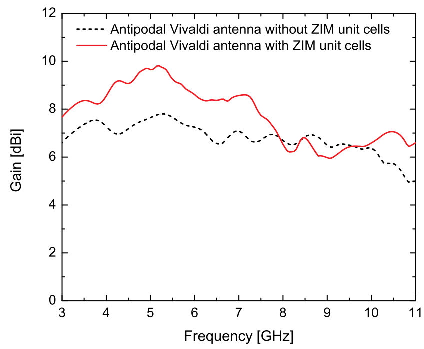

Figure 7: Simulated gains for the antipodal Vivaldi antenna without and with ZIM unit cells

studies have been carried out to enhance the gain of this antenna. Some methods have been proposed such as making corrugated structure at the edges of the Vivaldi antenna, and adding a high permittivity dielectric or a parasitic elliptical patch as a director in the aperture of the Vivaldi antenna. However, these methods increase the complexity and the cost for fabrication, and they elongate the antenna length too much for some applications. Hence, the second objective of this study is to enhance the gain of the antipodal Vivaldi antenna by using resonant metamaterials. A symmetric zero-index metamaterial (ZIM) unit cell is proposed in this study. The ZIM unit cell has anisotropic metamaterial characteristics. When wave propagation is along y direction and the electric field polarization is in x direction, the unit cell exhibits positive permittivity and permeability as a normal material. When wave propagation is along x direction and the electric field polarization is in y direction, the unit cell shows negative permittivity and has nearly zero-refractive index at a certain frequency range.

The ZIM unit cells are arranged to the aperture of AVA as shown in Fig. 5. This arrangement makes a stronger end-fire radiation in y direction because very few waves can propagate along x direction. The performance of the proposed configuration can be seen from Figs. 6 and 7. Even the AVA adds the ZIM unit cells, the S11 is lower than −10 dB in entire frequencies of UWB. It confirms that the proposed configuration has a very good impedance matching. In general, the gain of the designed AVA has been improved roughly 2 dB from 3.0 to 7.5 GHz.

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