Nonreciprocal Metamaterials and Their Applications to Antennas

#Tetsuya Ueda [1]

[1] Department of Electronics, Kyoto Institute of Technology
Matsugasaki Sakyo-ku, Kyoto 606-8585, Japan, Email: ueda@kit.ac.jp

Abstract

This paper reviews recent progress on nonreciprocal metamaterials, especially with the nonreciprocity in the phase characteristics of transmission coefficients, and their applications to antennas. The nonreciprocal metamaterials are implemented into leaky wave antennas, new type of traveling wave resonators, and resonant-type beam-steering antennas.

Keywords: Metamaterials, Composite Right/Left Handed Transmission Lines, Nonreciprocal Devices, Leaky Wave Antennas, Travelling-Wave Resonators.

1. Introduction

Composite right/left handed transmission lines (CRLHTL) are one of the most available and practically useful concepts, based on transmission-line theory in designing various metamaterials [1]. The transmission lines can describe metamaterial structures in terms of equivalent circuit models and provide physical meanings and mechanism of wave propagation in the composite structures. Nonreciprocal metamateials have been studied for applications to nonreciprocal devices and antennas with the help of the CRLHTL concept. The early work [2] focused on nonreciprocal characteristics appearing in magnitude of the transmission coefficients for applications to isolators and circulators. On the other hand, it is the fact that most of basic concepts of metamaterials utilize their intrinsic phase characteristics, as seen from terminologies, such as forward wave, backward wave, right/left handed, as well as in cloaking technology and transformation optics. From a phase-controlling point of view, a new type of nonreciprocal metamaterials have been recently proposed and demonstrated, which have the nonreciprocity in the phase characteristics of the transmission coefficients, based on the CRLHTL concept [3], [4]. The nonreciprocal transmission line can support dominant right-handed mode propagation in one direction of power flow and dominant left-handed mode propagation in the opposite power direction simultaneously. In special cases, wavenumber vectors of dominant modes propagating along the nonreciprocal transmission line can be the same for two different power directions without significant coupling [3]. By employing the nonreciprocal transmission lines, we can enhance leaky wave radiation by constructive interference of the radiations from incident waves and the reflected waves at the terminal [5]. In the second, a simple straight and finite-long transmission-line resonator which is composed of nonreciprocal phase-shift CRLHTL provides automatic phase-matching condition and behaves as a traveling-wave resonator with uniform magnitude and phase gradient in the field distribution [6]. The unique characteristic of the resonator is that the resonant frequency does not depend on the resonators size, but on the configuration of the unit cell. Therefore, the resonator’s size can be independently selected without change in the operational frequency and gradient of the phase distribution. The phase gradient can be controlled by changing the nonreciprocity of the nonreciprocal phase-shift CRLHTL employed in the resonator. When the operational frequency is in the fast wave region of the transmission line, the leaky wave radiation from the resonator with uniform field profiles leads to the beam forming, the radiation angle of which directs obliquely with regards to the broadside direction and can be controlled by changing the phase gradient on the resonator. Thus, the resonator can be implemented into applications to beam-steering antennas [7].

2. Nonreciprocal Phase-Shift CRLHTL

Simple equivalent circuit models of a unit cell of conventional reciprocal CRLHTL and the proposed nonreciprocal phase-shift CRLHTL are shown in Fig. 1. Both are composed of transmission line sections and lumped elements. The series capacitance and shunt inductance are inserted to achieve negative permeability and permittivity. For the nonreciprocal cases as shown in Fig. 1(b), the transmission line arm sections support forward wave mode propagation in both propagation directions, but the phase constants differ. This equivalent circuit model under periodic boundary condition provides nonreciprocal dispersion relations, as shown in Fig. 2. The simple formula shows that the vertical symmetric axis of the dispersion curves shifts to the right or left in the horizontal direction, with regards to the cases for conventional reciprocal CRLHTL. In the same manner as the reciprocal cases, the band gap between lower (mainly left-handed modes) and upper (mainly right-handed modes) bands can be designed, based on the impedance matching condition between the characteristic impedance of the center transmission line and the ratio of inserted lumped inductive and capacitive elements [3]. In the nonreciprocal phase-shift CRLHTL, we have a frequency region where a right-handed mode is dominant in the positive power direction, whereas another left-handed mode is dominant in the negative power direction along the CRLHTL at the same frequency.

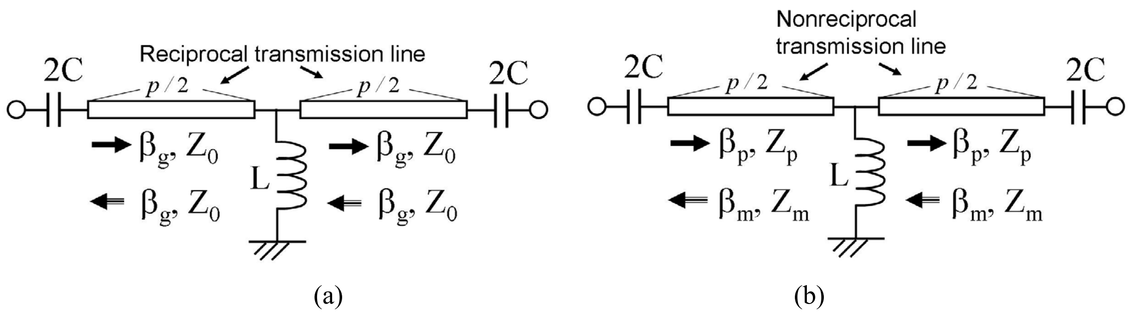

Fig. 1. Schematic of equivalent circuit model for the unit cell in nonreciprocal phase-shift CRLHTL. (a) Reciprocal case. (b) Nonreciprocal case.

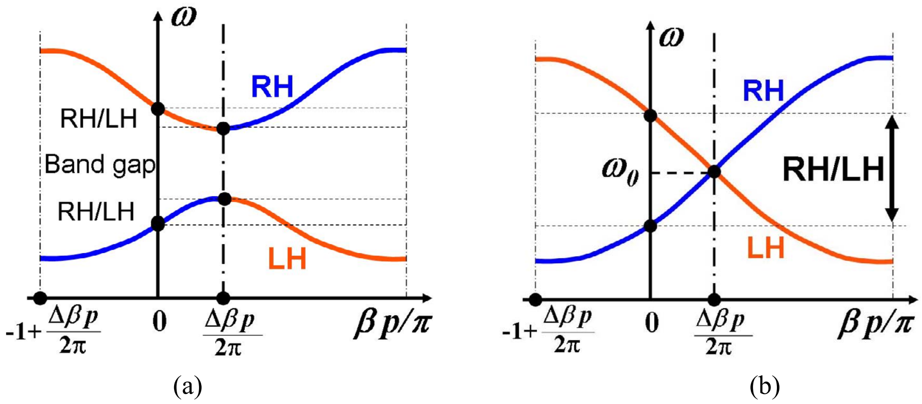

Fig. 2. Schematic of dispersion diagram of the nonreciprocal phase-shift CRLHTL. (a) Unbalanced case with band gap. (b) Balanced case without band gap.

3. Leaky Wave Antenna Application

In the fast wave region of dispersion diagram, we may have leaky wave radiation from transmission lines with open boundaries, as shown in Fig. 3. For right-handed wave propagation in the lines, we have forward wave (endfire) radiation, as shown in Fig. 3(a), whereas a backward wave (backfire) radiation is found for left handed mode propagation, as shown in Fig. 3 (b). When the nonreciprocal phase-shift CRLHTL under consideration is utilized as leaky wave antennas in the

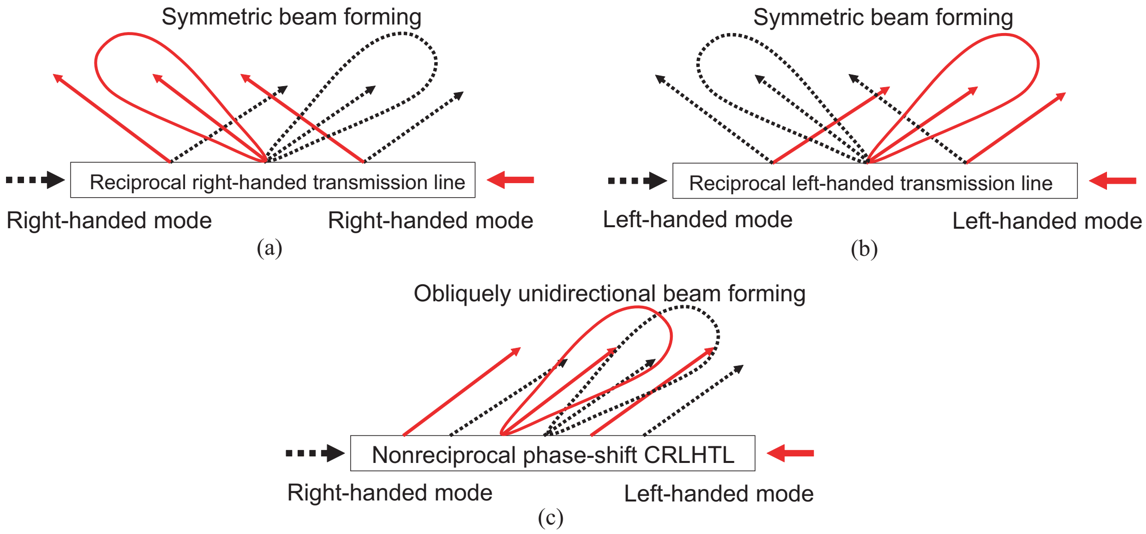

Fig. 3. Schematic of leaky wave radiation from transmission lines. (a) Reciprocal right-handed transmission lines. (b) Reciprocal left-handed transmission lines. (c) Nonreciprocal phase-shift CRLHTL. (After [3] ©2009 IEEE)

fast wave region, we may have nonreciprocal leaky wave radiation, in which we can have forward wave radiation for the positive power flow of the guided mode along the line, while backward wave radiation is seen for the negative power flow at the same operational frequency. As a result, the radiation angles for two different power directions along the line can be set to the same, independent of selection of power direction of the guided modes, as shown in Fig. 3 (c). When an input signal is incident at an input port and the terminal is not impedance-matched to the line, the incident wave is reflected at the terminal. In conventional leaky wave antennas, the reflection at the terminal causes secondary leaky wave radiation and forms undesired sidelobes. On the other hand, for the present nonreciprocal transmission lines, the secondary leaky wave radiation from the reflected waves directs to the same direction with the oblique angle as the primary radiation from the incident waves. Therefore, these radiations can interfere constructively with each other, which results in the enhancement of the radiation gain and directivity, compared to the radiation only from one-way propagation cases. That is, we can utilize not only the radiation from incident waves, but also from the reflected waves along the transmission lines [5].

4. Travelling-Wave Resonators and Their Applications to Beam-Steering Antennas

At specific frequencies where the wavenumber vectors are quite the same for two different power directions along the nonreciprocal transmission line, as found in Fig. 2, we can set up a new

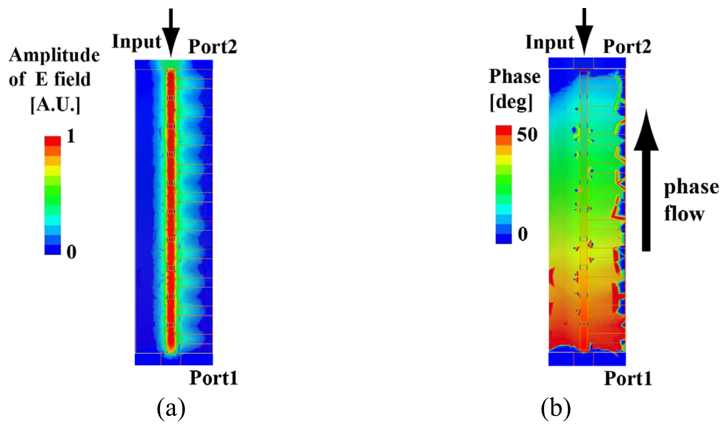

Fig. 4. Numerical simulation results for field profiles on the travelling wave resonators. (a) Magnitude distribution. (b) Phase distribution. (After [6] ©2010 IEEE)

type of traveling-wave resonators. The resonator is composed of a finite-long and straight nonreciprocal phase-shift CRLHTL with both ends open or shorted. Since the dominant mode is right-handed in the positive power direction, the phase shift shows the delay as the wave goes away from the input port. On the other hand, the dominant mode is left-handed in the negative power direction, and the phase shift of the reflected waves shows the advance as the wave returns to the input port. Therefore, the phase delay in the positive power direction along the CRLHTL is completely compensated by the phase advance in the negative power direction. In this case, the resonant condition automatically holds independently of the length of the transmission line for the proposed nonreciprocal phase-shift CRLHTL. The unique characteristic of the resonator is that the resonant frequency is independent of the resonator's size. The field profiles show that the magnitude profiles is uniform and the phase distribution linearly varies along the resonator, as shown in Fig. 4 [6]. Therefore, the nonreciprocal transmission-line resonator behaves as traveling-wave resonators. In addition, when the traveling-wave resonator operates in the fast wave region, it can radiate leaky waves. The leaky wave radiation from the resonator with uniform field profiles leads to the beam forming. The beam direction depends on the gradient of the phase distribution along the resonator, and the phase gradient is determined by the nonreciprocity in the phase characteristics of the line employed in the resonator. Therefore, the beam direction can be controlled by changing the phase nonreciprocity of the transmission lines [7].

5. Conclusions

In this paper, recent progress on nonreciprocal metamaterials has been introduced, especially with the nonreciprocity in the phase characteristics of transmission coefficients, and their applications to antennas. The nonreciprocal metamaterials were implemented into leaky wave antennas, new type of traveling wave resonators, and resonant-type beam-steering antennas.

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