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Recent Progress on Nonreciprocal CRLH Metamaterials for Antenna Applications

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1. Introduction

Metamaterials are artificial electromagnetic structures that can control permission/prohibition of electromagnetic wave propagation in order to realize unique and fascinating electromagnetic phenomena, and to invent state of the art functional circuits and antennas in the microwave region. The concept of metamaterials has been applied to various kinds of waves, not only for electromagnetic/light waves, but also for acoustic and other waves. Composite right/left handed (CRLH) metamaterials are one of the most instructive and useful concepts in that they can model complex phenomena of wave propagation simply with the use of equivalent circuit models verifying physical mechanisms, and that they are employed to practically design artificial materials and microwave circuits. Metamaterials were also combined with other physical phenomena, systems, or functionalities, such as quantum mechanics/optics, nonlinear systems, and so forth. Non-reciprocity, to be discussed here, is one of the attractive physical phenomena, which shows differences appearing in transmission coefficients between two anti-parallel propagation directions. It manifests itself by a combination of broken time reversal symmetry and broken spatial inversion symmetry. The broken time reversal symmetry has been realized by using the gyro-tropic materials, such as ferrites in the microwave region and magneto-optic media in optics. In recent years, the solid-state technologies including PIN diodes, FETs, and time-varying switches, instead of gyro-magnetic materials, also play the same role in achieving off-diagonal components in permittivity or permeability tensors. On the other hand, broken spatial inversion symmetry can be realized by the use of geometrical asymmetries in the wave-guiding structures. In this paper, we focus on the nonreciprocal CRLH metamaterials realized by a combination of metamaterials and non-reciprocity. For most cases, non-reciprocities appearing in magnitude of transmission coefficients have been discussed for applications to isolators and circulators. These circuits operate in the vicinity of magnetic resonant frequency, and then suffer from significant magnetic losses. At frequencies far from the resonances, nonreciprocal phenomenon becomes weaker, but we can still utilize non-reciprocity appearing in phase of transmission coefficients. By using such a phase-shifting non-reciprocity in metamaterials, we can have situations where forward wave propagation with positive refractive index is dominant in one propagation direction, while backward wave propagation with negative refractive index is dominant in the opposite direction [1]. For specific cases, we can have unidirectional wavenumber vectors independently of the propagation directions at a given frequency. Under the condition with unidirectional wave number vectors, traveling wave resonators can be constructed showing that the resonant frequency is independent of the resonator's size, and that magnitude of the field profile is uniform, and gradient of phase distribution is tunable independently of the resonant conditions [2]. The resonators with tunable phase gradient were implemented into antenna applications to steer the beam. However, we still have difficulties in achieving wide scanning angles and in overcoming beam squint problem showing that the beam angle varies with the operational frequencies. In this paper, we review the recent progress on the nonreciprocal CRLH metamaterials for enhancement of non-reciprocities and for dispersion-less phase-shifting non-reciprocities to eliminate the beam squint [3].

2. Design of Phase-shifting Non-reciprocity

Non-reciprocity manifests itself as a result of a combination of two factors; broken time reversal symmetry and broken spatial inversion symmetry. The former can be realized by the use of gyro-tropic materials in the wave-guiding structures, specifically, the use of transversely magnetized ferrite, which causes field displacement effect showing that the field profile varies with wave propagation direction. The latter factor is achieved by providing geometrical asymmetry to the transverse cross section of the transmission line with respect to the plane including propagation direction and the gyro-tropic axis, i.e., magnetization of the ferrite. Phase-shifting non-reciprocity $\Delta\beta$ can be approximately derived from the dispersion relation for asymmetric microstrip lines on the normally magnetize ferrite substrate and is given by

$$\Delta\beta \approx \frac{\omega_m}{c}\frac{(B_1 - B_2)}{2Y_0}\frac{l_{NR}}{p} \qquad (1).$$

where quantities B_1 and B_2 denote a pair of susceptance surfaces on side walls of the microstrip line, $\omega_m = \gamma\mu_0 M_{ef}$ corresponding to effective magnetization in ferrite, as shown in Fig. 1(a). Therefore, (1) clearly shows the non-reciprocity occurs as a result of a combination of two factors; the gyro-magnetic characteristic and geometrical asymmetry.

3. Dispersion of Non-reciprocity [3]

When considering modulated signals in the pseudo-traveling wave resonance for beam-scanning antennas, we need to take into account frequency dependence of beam direction, that is, beam squint problem. In order to eliminate the beam squint, we need to minimize the dispersion of phase-shifting non-reciprocity $\Delta\beta$. By using (1), dispersion-less nonreciprocity can be designed for the CRLH metamaterials. It is noted that the difference of susceptances on the side walls (B_1-B_2) should be proportional to the operational frequency, i.e., capacitive surfaces are desired. Therefore, we insert inductive stubs symmetrically to the CRLH lines in order to achieve negative permittivity as well as to prevent the influence on the non-reciprocity. In addition, capacitive stubs are asymmetrically inserted to provide dispersion-less non-reciprocity. Figure 2 clearly demonstrates dispersion-less phase-shifting non-reciprocity in the CRLH metamaterials.

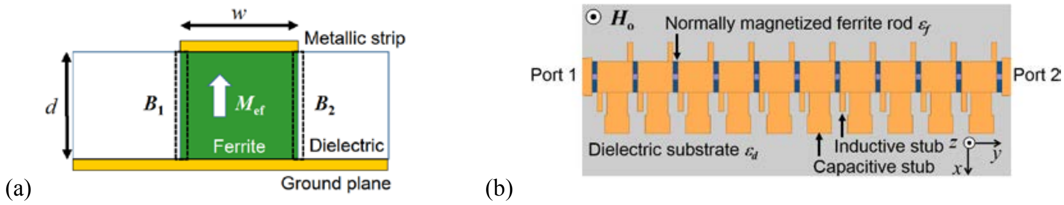

Figure 1. Geometry of the nonreciprocal CRLH metamaterials. (a) Transverse cross section of the microstrip line on the normally magnetized ferrite substrate. (b) Top view of the CRLH metamaterials with dispersion-less non-reciprocity.

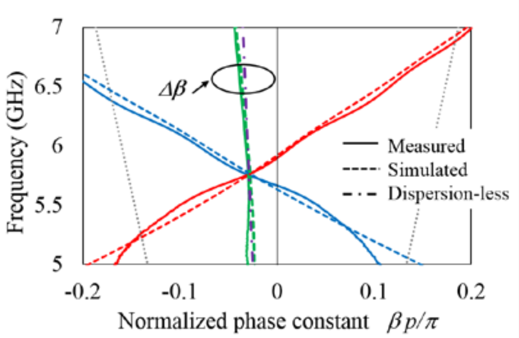

Figure 2. Dispersion diagram for dispersion-less phase-shifting non-reciprocity in CRLH metamaterials.

4. Conclusions

Recent progress on nonreciprocal CRLH metamaterials was reviewed. Enhancement of magnitude in phase-shifting non-reciprocity and their dispersion were designed for antenna applications.

5. Acknowledgements

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6. References

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