Magnet-less Non-reciprocal Metamaterials with Magnetic or Electric Gyrotropy

Toshiro Kodera #1, Dimitrios L. Sounas *2, Christophe Caloz *3

Department of Electrical Engineering, Yamaguchi University, Ube, 7558611 Japan
[1] tk@yamaguchi-u.ac.jp

* *Department of Electrical Engineering, École Polytechnique de Montréal, Montréal, QC, H3T 1J4 Canada*
[2] dimitrios.sounas@polymtl.ca
[3] christophe.caloz@polymtl.ca

***Abstract*—Two magnet-less non-reciprocal metamaterials with magnetic or electric gyrotropy are presented. Both are based on the traveling-wave resonance of transistor-loaded rings, accompanied by rotating magnetic or electric dipole moments. Their gyrotropic properties are validated by measuring Faraday rotation of a wave reflected by or transmitted through them.**

I. Introduction

Magnetic gyrotropy is the key phenomenon enabling non-reciprocal devices, such as isolators and circulators, which are ubiquitous in communications systems. At microwave frequencies, ferrites have been the essential commercial gyrotropic materials since the 1950's, due to their high-power capability and operation stability [1] and due to the absence of alternatives. However, ferrites require a static magnetic field for biasing bias. This field is usually produced by a permanent magnet, which results in bulky components, high fabrication cost and upper-frequency limitations for resonant-type devices.

The letter presents two recently introduced metamaterial structures that provide *non-reciprocal gyrotropy without ferrites and without magnets*. We refer to these metamaterials as *magnet-less non-reciprocal metamaterials (MNMs)*. The first one exhibits *magnetic gyrotropy* via the traveling-wave resonance of transistor-loaded microstrip-line ring resonator particles [2], where rotating magnetic dipole moments mimic the operation of a biased ferrite. This artificially created magnetic gyrotropy is validated through reflection-type Faraday rotation (or magneto-optic Kerr effect). The second structure exhibits *electric gyrotropy* via the traveling-wave resonance of transistor-loaded slot-ring resonator particles[3], where rotating electric dipole moments mimic cyclotron orbits in plasmas. In contrast, to the magnetically gyrotropic structure, the electrically gyrotropic structure is electromagnetically transparent, thus providing transmission-type Faraday (real Faraday) rotation, also verified experimentally.

II. Magnetically Gyrotropic Traveling-Wave Microstrip-Line Ring Resonator Particle

A. Principle

Figure 1 shows the principle of the magnetic magnet-less non-reciprocal metamaterial (M-MNM). Magnetic moment precession associated to electron spin precession in a ferrite material, illustrated in Fig. 1(a), is mimicked by a microstrip-line ring resonator loaded by a unilateral element, as depicted in Fig. 1(b). This results in a traveling-wave resonance, as shown in Fig. 1(c), where the electrical circumference of the ring is a multiple of 2π but where the wave is traveling (as opposed to standing) due to the presence of the unilateral element. The corresponding magnetic dipole moment rotation is illustrated in Fig. 1(d).

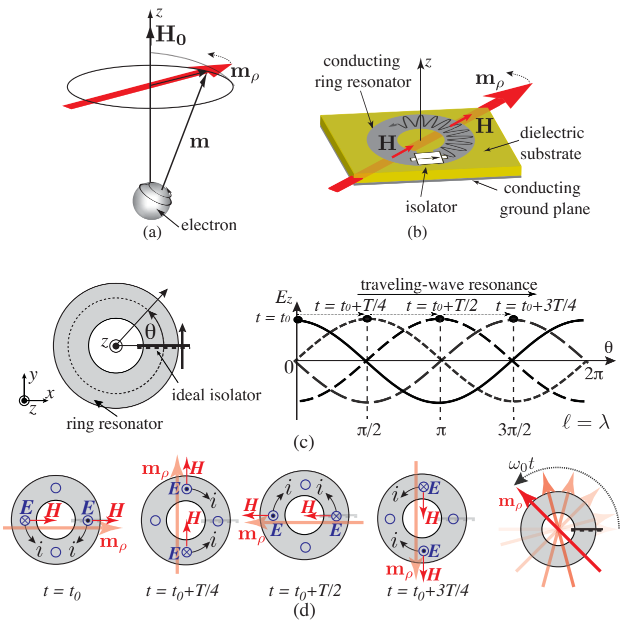

Fig. 1. Principle of the magnet-less non-reciprocal metamaterial providing *magnetic* gyrotropy (M-MNM). (a) Rotating magnetic moment in a ferrite. (b) Rotating magnetic moment in the proposed M-MNM structure, corresponding to the local rotating electromagnetic field of the traveling-wave resonance. (c) Time evolution of the electric field along the ring resonator at four quarter-period spaced time instants for a ring loaded with an ideal isolator. (d) Electromagnetic field between the ring and the ground plane and corresponding effective magnetic moment at the time instants of Fig. 1(c).

B. Prototype

Figure 2 shows an M-MNM prototype based on the principle in Fig. 1. The structure consists of two dielectric layers and three metallic layers, where the former two are used as substrates. The top layer consists of the FET-loaded microstrip-ring resonators. Resistors of 100 Ω and 68 Ω are inserted at the gate and drain of the FETs for matching. In order to achieve equal orthogonal-polarization responses, a super-cell consisting of four rings with 90° symmetry is used. The middle metallic layer is a uniform metal layer acting as a ground plane for the microstrip rings of the top layer. The bottom metallic layer contains the bias network of the FETs with meander-line chokes and by-pass capacitors.

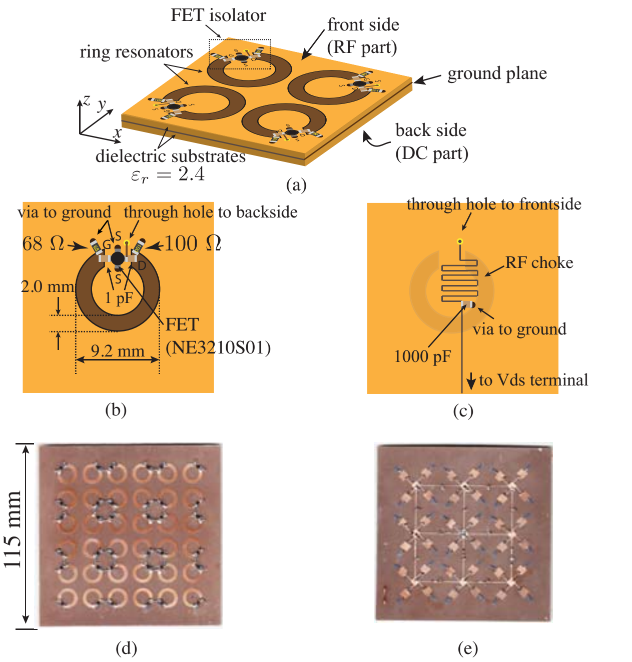

Fig. 2. M-MNM prototype. (a) Unit super-cell consisting of 4 rings in a 90°-symmetric configuration. (b) RF part of the structure at the front side. (c) DC biasing network at the back side. (d) Front side of the prototype consisting of 3×3 super-cells. (e) Back side.

C. *Reflection-type Faraday rotation (magneto-optic Kerr effect) experiment*

Figure 3 shows the measurement setup, which consisting of two horn antennas facing the prototype of Fig. 2. The antenna at port #1 has a fixed polarization, while the antenna at port #2 has a variable polarization, with θ being the angle between the polarizations of the two antennas. The transmission characteristics between ports #1 and #2 are measured for different θ's.

Figure 4 plots the measured transmission responses between the two horn antennas involving M-MNM reflection, S_{21} and S_{12}, for different θ's. In the co-polarized case ($\theta = 0°$) [Fig. 4(a)], we have $S_{21} = S_{12}$. For $\theta = +75°$ [Fig. 4(b)], $S_{21} > S_{12}$ and $S_{21} < S_{12}$ below and above $f = 7.58$ GHz, respectively. For $\theta = -75°$ [Fig. 4(c)], the transmission direction is reversed over the entire frequency range compared to the case $\theta = +75°$ [Fig. 4(b)]. This behavior is identical to that of a biased ferrite grounded slab [1], and therefore indicates non-reciprocity. The M-MNM was theoretically analyzed in [4], and was applied to a non-reciprocal magnet-less CRLH leaky-wave antenna in [5].

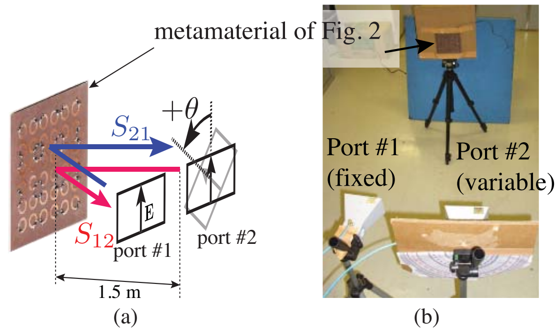

Fig. 3. Measurement setup, consisting of two horn antennas facing the prototype. (a) Port and angle definitions. (b) Photograph.

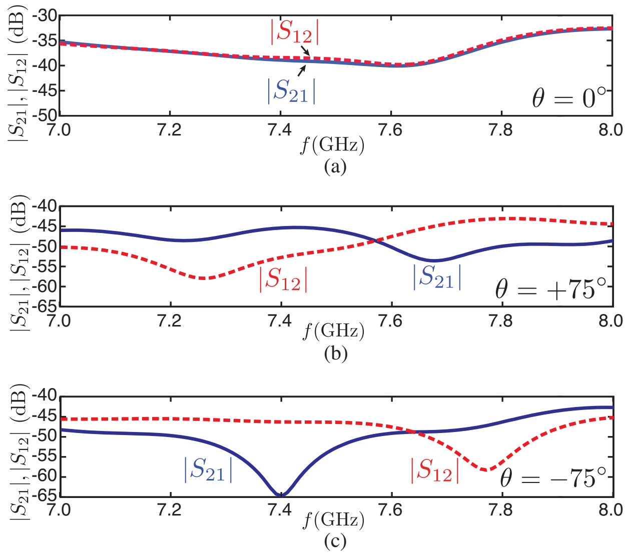

Fig. 4. Measured transmission response using the setup of Fig. 3 for different θ's. (a) $\theta = 0°$. (b) $\theta = +75°$. (c) $\theta = -75°$.

III. Electrically Gyrotropic Traveling-Wave Slot-Line Ring Resonator Particle

A. *Principle*

In the M-MNM, the middle conductive plane is required as a ground for the microstrip-line ring resonators. Such a ground restricts the operation of the M-MNM to a reflective operation. The microstrip-ring resonator may be replaced by a slot-ring resonator, not requiring any conductive plane, and thus enabling transmissive operation. Since the electric field of a slot-ring is radial, it is a rotating *electric* dipole moment that is generated in this case, and this result in an electric magnet-less non-reciprocal metamaterial (E-MNM).

Figure 5 depicts the principle of the E-MNM. Electric moment precession associated to electron cyclotron orbiting in a plasma, illustrated in Fig. 5(a), is mimicked by a slot-line ring resonator loaded by a unilateral element, as depicted in Fig. 5(b). This results in a traveling-wave resonance, as shown in Fig. 5(c), the corresponding electric dipole moment rotation is illustrated in Fig. 5(d).

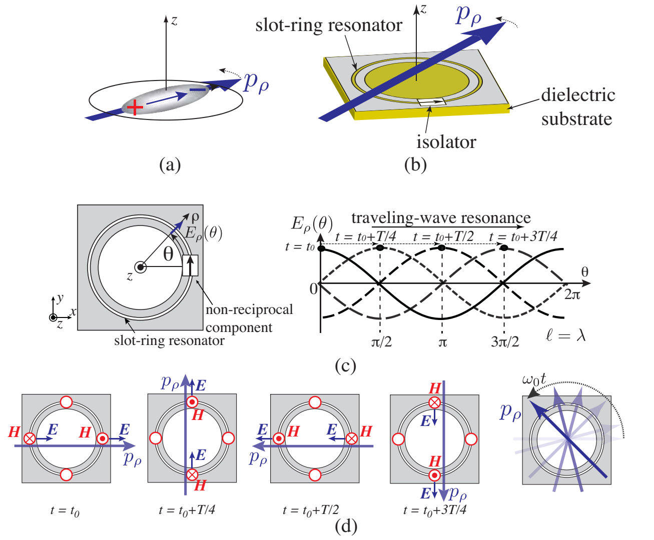

Fig. 5. Principle of the magnet-less non-reciprocal metamaterial providing *electric gyrotropy*. Rotating electric moment in (a) magnetic materials at optical frequencies, and (b) the proposed metamaterial structure consisting of slot-ring resonator loaded with an ideal isolator. (c) Slot-ring geometry and fields along the ring at four quarter-period spaced time instants. (d) Electric field in the slot-ring and the corresponding electric dipole moment p_ρ.

B. Prototype

Figure 6 shows an E-MNM prototype based on the principle in Fig. 5. Here, the structure consists of just two-layers, one dielectric layer and one metallic layer. The top layer contains the E-MNM elements, including the slot-ring resonator, the FET isolator, the matching resistors (100 Ω, 68 Ω) and the bias network.

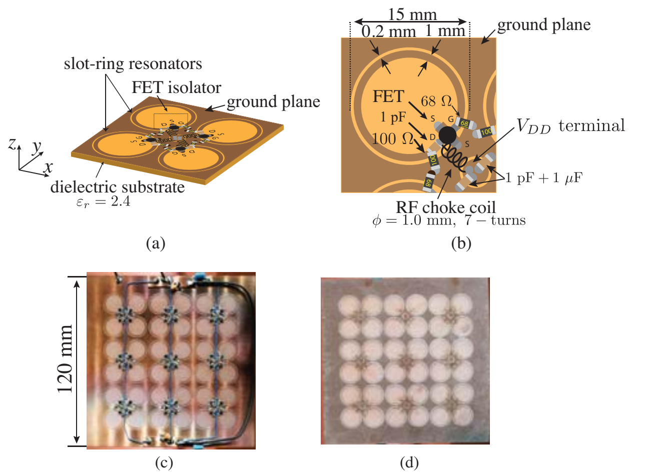

Fig. 6. E-MNM prototype. (a) Unit super-cell consisting of 4 rings in a 90°-symmetric configuration. (b) Dimensions and parameters of the traveling wave resonator. (c) Front side of the prototype consisting of 3 x 3 unit cells. (d) Back side of (c).

C. Transmission-type Faraday rotation experiment

Figure 7 shows the experimental setup, which consists of two face-to-face horn antennas with the prototype of Fig. 6 placed in between. The antenna at port #2 has a fixed polarization, while the antenna at port #1 has a variable polarization, θ, corresponding to the angle between the polarizations of the antennas. The transmission responses between port #1 and #2 are measured for different θ's.

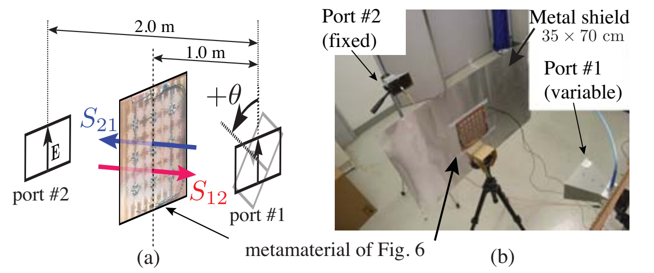

Fig. 7. Measurement setup, consisting of two face-to-face antennas with the prototype place in between. (a) Port and angle definitions. (b) Photograph.

Figure 8 plots the measured transmission responses between the two horn antennas across the prototypes, S_{21} and S_{12}, for different θ's. In the co-polarized case ($\theta = 0°$) [Fig. 8(a)], we have $S_{21} = S_{12}$. For $\theta = +45°$ [Fig. 8(b)], $S_{21} < S_{12}$ around $f = 7.6$ GHz. For $\theta = -45°$ [Fig. 8(c)], the transmission direction is reversed compared to the $\theta = +45°$ case. This transmission-direction reversal is the same as in the biased ferrite slab case.

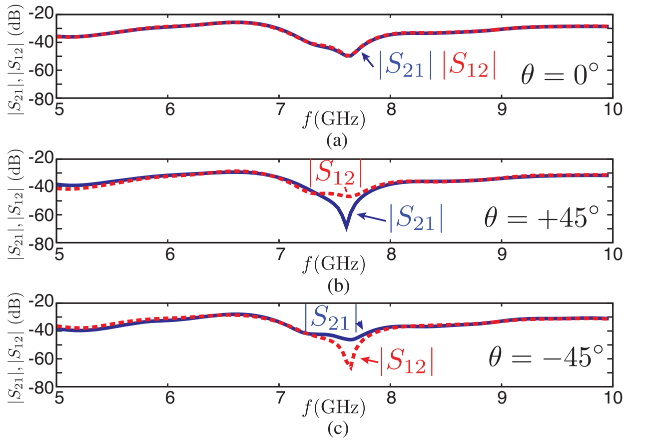

Fig. 8. Measured transmission parameters between the two horns for different θ, $V_{DS} = 0.48$ V and $I_{DD_{total}} = 1.22$ A. (a) $\theta = -45°$. (b) $\theta = 0°$. (c) $\theta = 45°$.

IV. Conclusion

Magnet-less non-reciprocal metamaterials (MNMs) providing magnetic or electric gyrotropy have been introduced. The non-reciprocal gyrotropic properties of the MNMs were validated through reflection-type and transmission-type Faraday-rotation experiments.

ACKNOWLEDGMENT

This work was supported by the NSERC Discovery Accelerator Supplement Grant # 396116-10 and by the KAKENHI Grant-in-Aid # 23686054.

REFERENCES

[1] B. Lax and K. J. Button, *Microwave Ferrites and Ferrimagnetics*, McGraw-Hill, 1962.
[2] T. Kodera, D. L. Sounas, and C. Caloz, “Artificial Faraday rotation using a ring metamaterial structure without static magnetic field,” *Appl. Phys. Lett.*, vol. 99, pp. 031114:1-3, July 2011.
[3] T. Kodera, D. L. Sounas, and C. Caloz, “Faraday Rotation by artificial electric gyrotropy in a transparent slot-ring metamaterial structure, in *IEEE APS Int. Symp., Chicago, IL, USA*, July 2012.
[4] D. L. Sounas, T. Kodera, and C. Caloz, “Electromagnetic modeling of a magnet-less non-reciprocal gyrotropic metasurface,” *IEEE Trans. Antennas and Propagations*, in press.
[5] T. Kodera, D. L. Sounas, and C. Caloz, “Non-Reciprocal Magnet-less CRLH Leaky-Wave Antenna based on a Ring Metamaterial Structure,” *IEEE Antennas Wireless Propagat. Lett.*, vol. 10, pp. 15511554, Jan. 2012.