Faraday Rotation by Artificial Electric Gyrotropy in a Transparent Slot-Ring Metamaterial Structure

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***Abstract*—A non-reciprocal metamaterial structure composed of a 2D periodic array of slot ring resonators including each a semiconductor-based isolator is introduced and experimentally shown to produce Faraday rotation. In contrast to previously reported non-reciprocal metastructures, which were of microstrip type and were limited to the reflection mode, the proposed slot line type structure is transparent, as the wave can pass through the slots, and therefore it operates in the transmission mode. The metamaterial exhibits the same response as a magnetically biased ferrite or plasma, but without the need of a biasing static magnetic field.**

I. Introduction

Recently, artificial *magnetic* non-reciprocal gyrotropy, based on the rotation of the dynamic magnetic field in semiconductor-loaded metamaterial ring particles, was introduced in [1], [2]. The properties of the resulting metastructures were shown to be essentially similar to those of magnetically biased ferrites in the microwave region. One of the practically most interesting features of these metastructures is the fact that they require neither magnetic materials nor magnets, so that they can be fully integrated in MICs and MMICs, and so that their loss does not scale linearly with the operation frequency, in contrast to ferrites, which become impractical toward millimeter waves due to prohibitive loss [3].

Artificial magnetic gyrotropy has been demonstrated in several applications [1], [2], [4], [5]. However, the metastructures reported in these papers are of microstrip line type. They are thus backed by a full metal conducting ground plane, which makes them opaque to waves incident upon them. In this work, the ring resonators are *slot* rings. Therefore, wave penetration through the structure is allowed and the structure can operate in the transmission mode. In contrast to its magnetic predecessors, this structure utilizes *electric gyrotropy*. Its operation is demonstrated by the inspection of Faraday rotation across it.

II. Electric Gyrotropy by Semiconductor-Loaded Slot-Ring Metastructure

Figure 1 shows the analogy between the operation of natural electric gyrotropic materials, such as ferrites at optical frequencies [6], and the proposed magnetless gyrotropic metamaterial. In the former case, depicted in Fig. 1(a), electric moment precession, and subsequent electric moment rotation, is produced at the molecular scale in the presence of a biasing static magnetic field. In the latter case, illustrated in Fig. 1(b), natural electric moment precession is mimicked by a magnetic current traveling along the slot ring, enabled by the presence of a unidirectional semiconductor element, and electric dipole rotation is subsequently produced, at a metamaterial scale, where an electrostatic voltage suffices to bias the semiconductor elements. At the macroscopic scale, a similar response is obtained in both cases, from the similar rotating electric dipole moments at the microscopic scale.

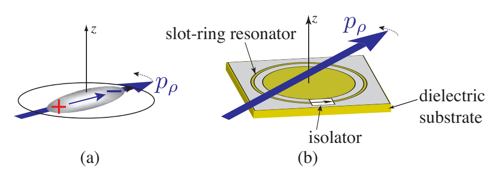

Fig. 1. Rotating electric moment (a) in an electric gyrotropic material and (b) in the proposed magnetless gyrotropic metastructure.

The generation of the rotating electric moment in the proposed metastructure is further explained in Fig. 2 for the case of an ideal isolator. Each ring is loaded with a semiconductor-based unidirectional element, such as a field-effect transistor, in order to produce a traveling-wave regime. The slot-ring resonates when its circumference equals the guided wavelength. Figure 2(a) depicts the time evolution of the radial electric field magnitude in the ring at quarter-period spaced instants, while Fig. 2(b) shows the corresponding vector field evolution and effective electric moment p_ρ.

The radial electric moment rotates around the axis of the ring with an angular velocity equal to the resonance angular frequency of the ring, and, assuming a right-handed directed unidirectional semiconductor element with respect to z, the effective electric susceptibility tensor of the metastructure reads

$$\overline{\overline{\chi}} = \begin{bmatrix} \chi_1 & j\chi_1 & 0 \\ -j\chi_1 & \chi_1 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \qquad (1)$$

The electric polarization $\boldsymbol{P}$ rotates then in the right-handed direction with respect to z in xy plane, as may be verified from the polarization relations $P_x = \chi_1 E_x + j\chi_1 E_y$, $P_y = -j\chi_1 E_x + \chi_1 E_y$.

As in the ferrite case [3], the dispersion relations for the right-handed and left-handed circularly polarized waves

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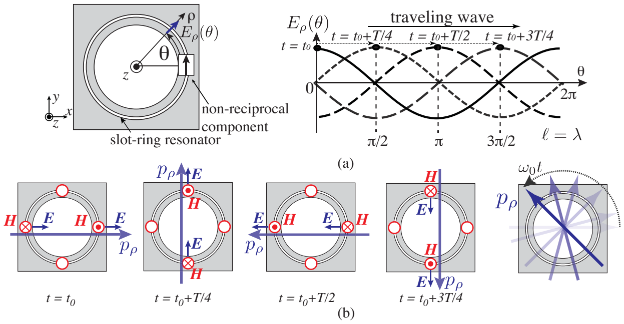

Fig. 2. Slot-ring resonator loaded with an ideal isolator. (a) Slot-ring geometry and radial electric field magnitude along the ring at four quarter-period spaced time instants. (b) Corresponding vector field evolution and effective electric moment p_ρ.

across the structure can be derived from (1). They read $\beta_\pm = \omega\sqrt{\mu\varepsilon_0[(1+\chi_1)\pm\chi_1]}$, and Faraday rotation as produced as a result of the difference between the phase constants $\beta_\pm$.

III. Experimental Validation

Fig. 3 shows a practical implementation of the proposed metamaterial structure. It consists the repetition of a four-ring super-cell with 90° rotational symmetry in terms of the placement of the unidirectional elements are isolators. These isolators are realized by common-source field-effect transistors (NE3210S01) connected to the ring via a DC decoupling capacitor of 1 pF. Moreover, two resistors, of 68 Ω and 100 Ω respectively, are connected to the ground from the gate and the drain for the impedance matching. The static voltage V_{DD} is applied through the RF choke coil together with two shunt capacitors of 1 pF and 1 μF, respectively.

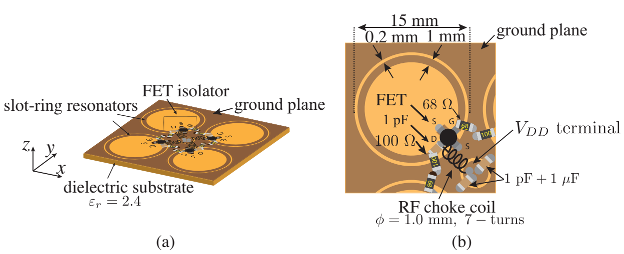

Fig. 3. Practical implementation of the proposed metastructure. (a) Four-ring super-cell with 90° symmetry. (b) Dimensions and parameters of each ring.

Fig. 4 shows the measurement setup, which consists of two horn antennas facing each other through the structure. The structure is placed in a 12 cm square window of an aluminum plate of 35 × 70 cm, to avoid direct coupling between the antennas. Antenna #2 has a fixed (linear) polarization, while antenna #1 rotates so as to present a variable polarization with respect to antenna #2. The distance between each antenna and the structure is 1.0 m (= $25\lambda_0$ at 7.5 GHz), which is well beyond the near-field limit. The antennas are connected to vector network analyzer using time gating function for better signal discrimination.

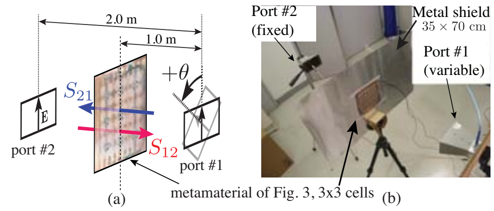

Fig. 4. Measurement setup. (a) Two horn antennas, one with fixed polarization and the other one with variable polarization, facing each other through the metastructure under test. (b) Whole setup showing the two horn antennas and the structure.

Figure 5 shows the measured S-parameters for a bias voltage $V_{DD} = 0.48$ V (maximum voltage before instability) and several angles θ between the polarizations of the two antennas. Comparing Figs. 5(a) and (c) shows complementary responses for the transmission curves of opposite directions under opposite antenna relative angles, which is an expected manifestation of non-reciprocal rotation. When the antennas are co-polarized, the response naturally reciprocal, as shown in Fig. 5(b). The observed Faraday rotation responses are identical to those that would be obtained with a ferrite slab [3].

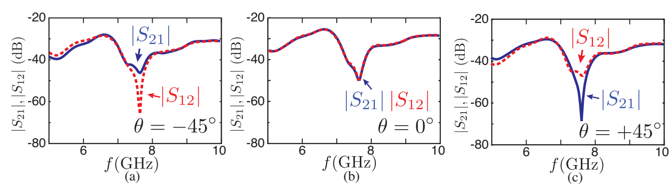

Fig. 5. Measured transmission parameters between the two horns for different θ and $V_{DS} = 0.48$ V, $I_{DD_{total}} = 1.22$ A. (a) $\theta = -45°$. (b) $\theta = 0°$. (c) $\theta = 45°$.

IV. Conclusion

Faraday rotation by artificial electric non-reciprocal gyrotropy has been demonstrated experimentally in a novel transparent slot-ring metamaterial structure.

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