Unidirectional Loop Metamaterials (ULM) as Magnetless Artificial Ferrimagnetic Materials: Principles and Applications

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Abstract—This paper presents an overview of Unidirectional Loop Metamaterial (ULM) structures and applications. Mimicking electron spin precession in ferrites using loops with unidirectional loads (typically transistors), the ULM exhibits all the fundamental properties of ferrite materials, and represents the only existing magnetless ferrimagnetic medium. We present here an extended explanation of ULM physics and unified description of its component and system applications.

Index Terms—Unidirectional Loop Metamaterials (ULM), nonreciprocity, ferrimagnetic materials and ferrites, gyrotropy, Faraday rotation, metamaterials and metasurfaces, transistors, isolators, circulators, leaky-wave antennas.

I. INTRODUCTION

Over the past decades, nonreciprocal components (isolators, circulators, nonreciprocal phase shifters, etc.) have been almost exclusively implemented in ferrite technology [1]–[8]. This has been the case in both microwaves and optics, despite distinct underlying physics, namely the purely magnetic effect (electron spin precession) in the former and optics, despite distinct underlying physics, namely the purely magnetic effect (electron spin precession) in the former and magneto-optic effect (electron spin precession) in the latter case. However, ferrite components suffer from the well-known issues high-cost, high-weight and incompatibility with integrated circuit technology, and magnetless nonreciprocity has therefore long been considered a holy grail in this area [14], [15].

There have been several attempts to develop magnetless nonreciprocal components, specifically

1) active circuits [16]–[21], and space-time [15] 2) modulated structures [22]–[27] and 3) switched structures [28] (both based on 1950ies parametric (e.g. [29], [30]) or commutated (e.g. [31]) microwave systems). All have their specific features, as indicated in Tab. I.

TABLE I

| Comparison (Typical and Relative Terms) Between Different Magnetless Nonreciprocity Technologies Plus Ferrite. |
|---|
| material | $P_{\text{comm}}$ | bias | cost | noise |
| ferrite | yes | zero | magnet | high | N/A |
| act. circ. | no | low | DC | low | low |
| switched | no | med. | RF | high | high |
| modulated | no | med. | RF | med. | med. |
| ULM | YES | low | DC | low | med |

We introduced in 2011 [32] in a Unidirectional Loop Metamaterial (ULM) mimicking ferrites at microwaves and representing the only artificial ferrite material, or metamaterial, existing to date. This paper presents an overview of the ULM and its applications reported to date.

II. OPERATION PRINCIPLE

A Unidirectional Loop Metamaterial (ULM) may be seen as a physicomimetic artificial implementation of a ferrite in the microwave regime. Its operation principle is thus based on microscopic unidirectionality, from which the macroscopic description is inferred upon averaging.

A. Microscopic Description

Microwave magnetism in a ferrite is based on the precession of the magnetic dipole moments arising from unpaired electron spins about the axis of an externally applied static magnetic bias field, $\mathbf{B}_0$, as illustrated in Fig. 1(a), where $\mathbf{B}_0 \parallel \hat{z}$. This is a quantum-mechanical phenomenon, that is described by the Landau-Lifshitz-Gilbert equation [3], [10], [33]

$$\frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{B}_0 + \frac{\alpha}{M_s} \mathbf{m} \times \frac{d\mathbf{m}}{dt},$$

(1)

where $\mathbf{m}$ denotes the magnetic dipole moment, $\gamma$ the gyromagnetic ratio, $M_s$ the saturation magnetization, and $\alpha$ the Gilbert damping term. Equation (1) states that the time-variation rate of $\mathbf{m}$ due to a transverse RF magnetic field signal, $\mathbf{H}_0^{\text{RF}} (\parallel \hat{t}, \hat{t} \perp \hat{z})$, is equal to the sum of the torque exerted by $\mathbf{B}_0$ on $\mathbf{m}$ (directed along $+\hat{z}$, $\hat{z}$ azimuth angle), and a damping term (directed along $-\hat{\theta}, \hat{\theta}$ elevation angle) that reduces the precession angle, $\psi$, to zero along a circular-spherical trajectory (conserved $|\mathbf{m}|$) when the RF signal is suppressed (relaxation).

Classically, magnetic dipole moments can be associated with current loop sources, according to Ampère law. Decomposing a ferrite magnetic moment, $\mathbf{m}$, into its longitudinal component, $m_z$, and transverse component, $m_\perp$, as shown in Fig. 1(a), one may thus invoke the effective current loops $I_{\text{eff}}^{m_z}$ and $I_{\text{eff}}^{m_\perp}$ as source models for the corresponding moments. Among these currents, only $I_{\text{eff}}^{m_z}$ matters in terms of magnetism, since $I_{\text{eff}}^{m_\perp}$, as the source associated with $\mathbf{H}_0^{\text{RF}}$, does not induce any precession (Footnote 2). $I_{\text{eff}}^{m_z}$ is thus the current one has to mimic to devise an "artificial ferrite." This current, as seen in Fig. 1, has the form of a loop tangentially rotating on an imaginary cylinder of axis $z$.

Footnote 1: The adjective "physicomimetic" is meant here, from etymology, as "mimicking physics."

Footnote 2: The longitudinal ($z$) component does not contribute to precession, and hence to magnetism. Indeed, since $\mathbf{B}_0 \parallel \hat{z}$, the $z$-component of $\mathbf{m}$ produced by $\mathbf{H}_0^{\text{RF}}$ would lead to $m_z^{\text{RF}} \times (\mathbf{B}_0 + \mu_0 \mathbf{H}_0^{\text{RF}} \parallel \hat{z}) = (m_z^{\text{RF}} (B_0 + \mu_0 H_0^{\text{RF}}) (\hat{t} \times \hat{z}) = 0$, the only torque being produced by the transverse component ($\mathbf{H}_0^{\text{RF}}$, $\hat{t} \in xy$-plane), $m_\perp^{\text{RF}} \times (\mathbf{B}_0 + \mu_0 \mathbf{H}_0^{\text{RF}}) = (m_\perp^{\text{RF}} B_0) (\hat{t} \times \hat{z}) \neq 0$. In the rest of the text, we shall drop the superscript "RF," without risk of ambiguity since $\mathbf{m}$, is exclusively produced by the RF signal.

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B. Macroscopic Description

Since it mimics the relevant magnetic operation of a ferrite at the microscopic level, the unit-cell particle in Fig. 1(b) must lead to the same response as bulk ferrite at the macroscopic level when repeated according to a subwavelength 3D lattice structure so as to form a metamaterial as shown in Fig. 2(a).

The ULM in Fig. 2(a), just as a ferrite, forms a 3D array of magnetic dipole moments, $m_i$, whose average over a subwavelength volume $V$, 

$$ M = \frac{1}{V} \sum_{i=1}^{\rho} m_i = \left( \frac{1}{V} \sum_{i=1}^{\rho} m_{i,p} \right) \hat{\rho} = M_{p,\hat{\rho}} $$

(2)

corresponds to the density of magnetic dipole moments, or magnetization, as the fundamental macroscopic quantity describing the metamaterial.

From this point, one may follow the same procedure as in ferrites [8], [37] to obtain the Polder ULM permeability tensor

$$ \bar{\mu} = \begin{bmatrix} \mu & j \kappa & 0 \\ -j \kappa & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix} $$

(3a)

with $\mu = \mu_0 \left( 1 + \frac{\omega_0 \omega_m}{\omega_0^2 - \omega^2} \right)$ and $\kappa = \mu_0 \frac{\omega_m}{\omega_0^2 - \omega^2}$, 

(3b)

where $\omega_0$ and $\omega_m$ are the ULM resonance frequency (or Larmor frequency) and effective saturation magnetization frequency, respectively [8], that will be derived in the next section. As in ferrites, the effect of loss can be accounted for by the substitution $\omega_0 \leftarrow \omega_0 + j \alpha \omega$, where $\alpha$ a damping factor in (1) [8].

So, a ULM may really be seen as an artificial ferrite material producing magnet-less artificial magnetism. However, its nonreciprocity is achieved from breaking time-reversal (TR) symmetry by a TR-odd current bias, originating in the transistor (DC) biasing, instead of a TR-odd external magnetic field [14].

ULMs have been implemented only in a 2D format so far. The corresponding structure is shown in Fig. 2(b), and may

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1. The difference is essentially quantitative: while in the ferrite $p/\lambda < 10^{-6}$ ($p$: molecular lattice constant), in the ULM $p/\lambda \approx 1/10 - 1/5$ ($p$: metamaterial lattice constant or period), but homogenization works in both cases.
2. Whereas in a ferrite, we have $M = M_s + M_{RF} = (M_s + M_{RF}) \hat{z} + M_{RF} \hat{p}$, where $M_s$ is the saturation magnetization of material, in the ULM $M_s = 0$. We shall subsequently drop the superscript “RF” also in $M_s$.
3. In a ferrite, $\omega_0 = \gamma B_0$ and $\omega_m = \gamma \mu_0 M_s$. 

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Fig. 1. “Physicomimetic” construction of the Unidirectional Loop Metamaterial (ULM) “meta-molecule” or particle. (a) Magnetic dipole precession, arising from electron spinning in a ferrite material about the axis (here $z$) of an externally applied static magnetic bias field, $B_0$, with effective unidirectional current loops $i_{\text{eff}}$ and $i_{\text{off}}$, and transverse radial rotating magnetic dipole moment $m_{\rho}$ associated with $i_{\text{eff}}$, (b) ULM particle [32], typically (but not exclusively [34]) consisting of a pair of broadside-coupled transistor-loaded rings supporting antisymmetric current and unidirectional current wave (shown here with exaggeratedly small wavelength for the sake of visibility), with resulting radial rotating magnetic dipole moment emulating that in (a).

Fig. 2. ULM structures obtained by periodically repeating the unit cell with the particle in Fig. 1 (a) Metamaterial (3D), described by the Polder volume permeability [33], (b) Metasurface (2D metamaterial), described by a surface permeability [36].
be referred to as a Unilateral Loop Metasurface (ULMS). Section IV will present ULMS Faraday rotation and Sec. V-A will discuss related applications.

III. ULM PARTICLE AND DESIGN

ULMs may be implemented in different manners. Figure 5 shows a ULM particle implemented in the form of a microstrip transistor-loaded single ring placed on PEC plane. Assuming a distance much smaller than the wavelength between the ring and the PEC plane, the structure is equivalent, by the image principle, to the antisymmetric double-ring structure in Fig. 1(b) [35].

The transistor-loaded ULM particle in Fig. 3 or Fig. 1(b), is essentially a ring resonator, whose total electrical size is given by [38]

$$\beta_{ms} \alpha (2\pi - \alpha_{TR}) + \varphi_{TR} = 2\pi, \quad \beta_{ms} = k_0 \sqrt{\varepsilon_c} \frac{\omega}{c} \sqrt{\varepsilon_c},$$

where $\beta_{ms}$ is the microstrip line wavenumber ($\varepsilon_c$: effective relative permittivity), $\alpha$ is the average radius of the ring, $\alpha_{TR}$ is the geometrical angle subtending the transistor chip, and $\varphi_{TR}$ is the phase shift across it. Solving Eq. 4 for $\omega$ provides the resonance frequency of the resonator, and hence the ULM resonance frequency,

$$\omega_0 = \frac{(2\pi - \varphi_{TR})c}{\sqrt{\varepsilon_c}(2\pi - \alpha_{TR})},$$

in (3). The parameter $\omega_m$ in the same relations follows from the mechanical orientation of the moments, as explained in Sec. II-B although we do not have here a saturation magnetization $M_s$ leading to the frequency parameter $\omega_m = \gamma \mu_0 M_{m}$ in the ferrite, we have an equivalent phenomenological parameter $\omega_m$ associated with the orientation of the rings, which may be found by extraction, as will be seen in Sec. IV.

Note that ULMs may be designed for multi-band operation and enhanced-bandwidth operation. The former, in contrast to ferrites that are restricted to a single ferromagnetic resonance $\omega_0 = \gamma B_{eq}$, can in principle accommodate multiple resonances by simply incorporating rings of different sizes, as illustrated in Fig. 4. The latter, in contrast to ferrite whose bandwidth is inversely proportional to loss due to causality, can be achieved by leveraging overlapping coupled resonances [2].

This restriction can be somewhat overcome in a structured ferromagnetic structure, such as a ferromagnetic nanowire supporting a remanent bistable population of up and down magnetic dipole moments with corresponding resonances $\omega_0^+ = \gamma \mu_0 H_{0}^+$ and $\omega_0^- = \gamma \mu_0 H_{0}^-$ [39, 40].

IV. FARADAY ROTATION

Faraday rotation is one of the most fundamental and useful properties of magnetic materials. Given their artificial ferrite nature (Sec. III), ULMs can readily support this effect. The Faraday angle is given by [3, 8]

$$\theta_F(z) = -\left(\sqrt{\frac{\beta_{+} - \beta_{-}}{2}} \right),$$

where $\mu$ and $\kappa$ are the Polder tensor components in (3b), with the resonance $\omega_0$ given by (5) and the saturation magnetization frequency $\omega_m$ discussed in Sec. III. Interesting, the ULM allows the option to reverse the direction of Faraday rotation by simple voltage control (instead of magnet mechanical flipping in a conventional ferrite) using an antiparallel transistor pair load, as demonstrated in [42].

Figure 6 shows a reflective Faraday ULM metasurface (ULMS) structure, based on the particle in Fig. 3 and response, initially reported in [32]. The results confirm that the ULM works exactly as a ferrite, whose equivalent parameters are given in the caption.

ULM Faraday rotation has also been reported in transmission, using the circular-slot ULM structure mentioned at the
Using slots, and hence equivalent magnetic currents, instead of rings supporting electric currents, that structure really operates as an artificial magneto-optic material, with a permittivity tensor replacing the magnetic tensor in (3a). A similar Faraday rotation effect may also be achieved using arrays of twisted dipoles loaded by transistors [43].

V. APPLICATIONS

A. Metasurface Isolators

The transmissive ULMS in [41] can be straightforwardly applied to build a Faraday isolator [3], [4], [44], [45], as shown in Fig. 6. As the wave propagates from the left to the right, its polarization is rotated 45° by the left ULMS in the rotation direction imposed by the transistors (here, clock-wise). It thus reaches the polarizer with its electric field perpendicular to the conducting strips and therefore unimpededly crosses it. It is finally rotated back to its initial (vertical) direction by the right ULMS, whose rotation direction is opposite to the left one (here, counter-clockwise). In the opposite direction, the right ULMS rotates the wave polarization in such a manner that its electric field is parallel to the conducting strips of the polarizer, so that the wave is completely reflected. It is then rotated again by the right polarizer and gets back to the right input orthogonal to the original wave.

Faraday rotation is not the only approach to realize spatial isolation, as in Fig. 6. Such isolation may be simply achieved, without any gyrotropy but still magnetlessly, with a metasurface consisting of back-to-back antenna arrays interconnected by transistors [47]; this nonreciprocal metasurface may exhibit an ultra wideband response and provide transmission gain.

B. Nonreciprocal Antenna Systems

The ULM structure may be used in various nonreciprocal radiating (antenna, reflector and metasurface) applications. Figure 7 shows a nonreciprocal antenna system and its response [48]. The structure [Fig. 7(a)] is a ULM magnetless version of the nonreciprocal ferrite-loaded Composite Right/Left-Handed (CRLH) open-waveguide leaky-wave antenna introduced in [49], [50], with the ferrite material replaced by a 1D ULM structure. This structure may be used as a nonreciprocal full-space scanning antenna [Figs. 7(b) and (c)], whose unidirectionality provides protection against interfering signals, or as an antenna diplexer system, where nonreciprocity effectively plays the role of a circulator with highly isolated uplink (3 → 1) and downlink (2 → 3) paths.

C. Isolators and Circulators

ULM technology also enables various kinds of nonreciprocal components. Figure 8(a) shows a ULM microstrip isolator [38]. The ULM structure below the microstrip line is composed of two rows of transistor-loaded rings with opposite biasing, and hence opposite allowed wave rotation directions. As the wave from the microstrip line reaches a ring pair, its mode is coupled into a stripline mode with strip pair constituted by the longitudinal sections of the overlapping rings, and usual antisymmetric currents. In the propagation direction where these currents are co-directional, with allowed rotation direction of the ULM, the stripline mode is allowed to propagate, whereas in the opposite propagation direction, it is inhibited and dissipates in matching resistors on the rings. Figure 8(b) shows a ULM microstrip circulator [38], which is based on mode-split counter-rotating modes as all circulators.

VI. CONCLUSION

We have presented an overview of ULM structures and applications. The ULM physics has been described in great details, revealing that the ULM really represents an artificial ferrite medium. It is in fact the only existing medium of the kind. It has been pointed out that the ULM may offer unique extra benefits compared to ferrites, such as a multiband operation, ultra broadband and electronic Faraday rotation direction switching.
