Entwined spiral arrays on ferrite substrates

G. Cochet[1,3], A. Vallecchi[2], A. G. Schuchinsky[1], P. Queffelec[3]

[1]ECIT, School of Electronics, Electrical Engineering & Computer Science, Queen's University Belfast
Belfast, BT3 9DT, United Kingdom
Fax: + 44 28 9097 1702, Email: gcochet01@qub.ac.uk, a.schuchinsky@qub.ac.uk
[2]Department of Information Engineering, University of Siena
Siena, IT-53100, Italy, Email: andrea.vallecchi@unisi.it
[3]LEST, University of Brest, France
Fax: +33 2 9801 6395, Email: Patrick.Queffelec@univ-brest.fr

Abstract

The properties of metasurfaces formed by the entwined spiral arrays on normally magnetised ferrite substrates have been explored. It is shown that the coupling between the array fundamental topological resonance and the ferromagnetic resonance of the ferrite substrate leads to significant increase of the fractional bandwidth (FBW). The features of resonance transmittance assisted by the volume spin waves excited by the entwined spirals in the ferrite substrate are discussed.

1. Introduction

Metasurfaces formed by the doubly periodic patterns of convoluted printed conductors have recently attracted increasing interest [1]-[4]. The sub-wavelength response was originally achieved using the constituent elements with complex shapes tightly filling a unit cell. However realisation of the intricate conductor layouts was often impaired by their sensitivity to fabrication tolerances and defects of the periodic patterns. An alternative approach, based upon interweaving the conductor patterns occupying several unit cells, alleviates these difficulties and allows not only further reduction of unit cell size but also broader fractional bandwidth (FBW) with less stringent constraints on the unit cell layout. The doubly periodic arrays of planar intertwined spirals with the arms interleaved into adjacent unit cells represent an important class of such metasurfaces with the unit cell size smaller than 1/30 of wavelength [4]-[6].

The sub-wavelength response of the intertwined spiral arrays with the unit cell shown in insert in Fig. 1(a) is enabled by the distributed coupling between the reference spiral and the counter-wound spiral arms extended from the adjacent unit cells. Interleaving of the conductor patterns alters both the equivalent capacitance and inductance of the whole unit cell but in different ways [4]. Therefore when the interwoven conductors are deployed on dielectric substrate, the capacitance is further increased while the inductance is affected only marginally due to the field redistribution. This leads to broadening FBW but causes degradation of the angular and polarisation stability of the resonance response. The use of ferrite substrates, which combine the variable frequency dependent permeability with the high dielectric permittivity, may provide better control of the magnetic response and alleviate the shortcomings of the interwoven arrays on purely dielectric substrates. The utility of ferrites in application to miniaturisation of the broadband antennas was recently demonstrated in [7].

The objective of this work is to explore the properties of metasurfaces comprised of the intertwined quadrifilar spiral arrays on normally magnetised ferrite substrates. The effects of the ferrite dispersion and gyrotropy on the transmittance and reflectance characteristics of the right (RCP) and left (LCP) circular polarised incident waves are discussed and illustrated by simulation results.

ISBN 978-952-67611-2-1

2. Intertwined quadrifilar spiral arrays on ferrite substrates

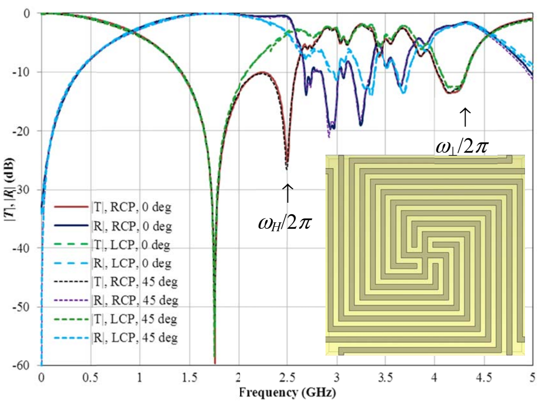
The doubly periodic arrays of intertwined quadrifilar spirals described in [4] are formed by extending the arms of a reference spiral into the gaps between the spiral arms in the adjacent unit cells. Four additional strips are counter-wound inside the basic reference spiral in the unit cell as shown in insert of Fig. 1(a). It is important to note that the counter-wound spiral arms not only increase the total capacitance but also produce negative mutual inductance, which reduces the total inductance of the unit cell. The ferrite substrate also has qualitatively different effect on the unit cell capacitance and inductance because the ferrite permittivity is constant in the frequency range of interest, whereas the permeability may rapidly vary with frequency. Therefore the interwoven spirals on ferrite substrates open new interesting opportunities for shaping the array resonance response by tailoring the capacitive and inductive reactances of the unit cell somewhat independently.

In order to gain insight in the effect of ferrite substrate on the properties of the intertwined spiral arrays, their transmittance and reflectance have been simulated in CST Microwave Studio. In the case of ferrite substrate magnetised normally to its surface (along the z-axis), the relative permeability is described by the Polder tensor

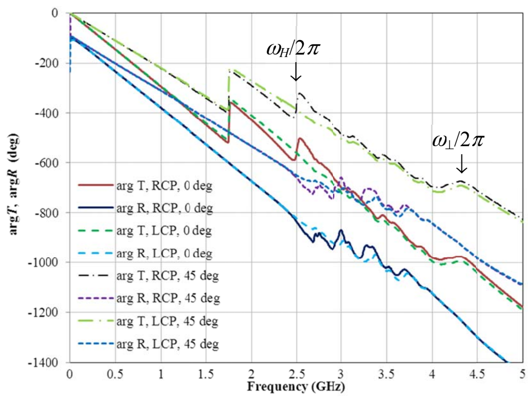
$$\mathbf{\mu}_r = \begin{pmatrix} \mu & -i\kappa & 0 \\ i\kappa & \mu & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (1)$$

where $\mu = 1 + \frac{\omega_H \omega_M}{\omega_H^2 - \omega^2}$, $\kappa = \frac{\omega \omega_M}{\omega_H^2 - \omega^2}$; ω is angular frequency, $\omega_M = \gamma 4\pi M_s$, $\omega_H = \gamma\left(H_0 + i\Delta H\right)$; H_0 is an internal dc magnetic bias, ΔH is the ferromagnetic resonance linewidth, $4\pi M_s$ - the saturation magnetisation of ferrite and the gyromagnetic ratio γ=5.6$\pi\times10^6$rad$\times$s^{-1}/Oe. To discriminate the magnetic effect of the ferrite substrate, its relative dielectric permittivity was artificially set at ε_r=1.

The RCP and LCP waves represent a natural set of eigenwaves travelling in gyrotropic medium along the magnetisation direction. Since the stand-alone entwined spiral arrays exhibit polarisation invariance in a broad range of incidence angles [4], the scattering characteristics of RCP and LCP waves can be analysed separately in order to elucidate the main properties of the resonance response of the intertwined spiral arrays on ferrite substrates.



(a)



(b)

Fig. 1: Transmittance and reflectance of RCP and LCP plane waves at normal incidence on the intertwined quadrifilar spiral array on ferrite substrate: (a) magnitude and (b) phase of the transmission T and reflection R coefficients. The square unit cell shown in the insert has the size p = 5.7 mm and contains 5-fold fully intertwined spirals with the widths of strips (s) and gaps (g) equal s=g=0.15 mm. The ferrite substrate of thickness 1 mm has the following parameters: $4\pi M_s$=1780 Gs, H_0=893 Oe, ΔH=70 Oe, permittivity ε_r = 1.

ISBN 978-952-67611-2-1

3. Simulation results and discussion

The simulation results presented in Fig. 1 demonstrate that the permeability of ferrite substrate has strong impact on the array characteristics at the frequencies close to the ferromagnetic resonance, $\omega = \omega_H$, and in the range $\omega_H < \omega < \omega_H + \omega_M$, corresponding to the bandgap of RCP wave in ferrite medium. Indeed, as expected the RCP wave in the normally magnetised ferrite layer exhibits higher reflectance and resonant absorption at $\omega \rightarrow \omega_H$-0, whereas the array response to the LCP wave is just weakly perturbed by the ferrite permeability, see the transmittance phase plots in Fig. 1(b). However at frequencies $\omega > \omega_H$, the reflectance and transmittance of both LCP and RCP waves qualitatively differ from those for a ferrite layer or a stand-alone entwined spiral array. In the frequency band $\omega_H < \omega < \omega_\perp = \sqrt{\omega_H \left(\omega_H + \omega_M\right)}$, a fine pattern of the entwined spirals' near-field created in the ferrite substrate facilitates excitation of the volume spin waves, which render the resonance transmittance at the frequencies of the RCP bandgap. Even though the transmittance resonances of both LCP and RCP waves are well correlated, the RCP wave exhibits considerably smaller reflectance and greater phase variations which can be attributed to its stronger coupling to the spin waves in the ferrite substrate. It is noteworthy that the cross-polarisation between the RCP and LCP waves remains very low, less than -40 dB, at normal incidence and its peak values increase to about -15 dB at oblique incidence of 45° across the entire frequency range presented in Fig. 1.

Since the ferromagnetic resonance frequency is determined by the dc magnetic bias, ω_H can be tuned close to the frequency of the topological resonance of the intertwined spiral array. In this case, the FBW of the RCP reflectance dramatically increases without inflicting significant increase of losses as can be observed in Fig. 1(a).

Finally, it is necessary to remark that the excellent angular stability of the intertwined spiral array observed for the stand-alone arrays proved to be unaffected by the presence of the ferrite substrate in the entire range of the considered frequencies including the ferromagnetic resonance and bandgap. As illustrated in Fig. 1(a), the transmittance and reflectance magnitudes calculated at normal and 45° wave incidence are practically indistinguishable for both RCP and LCP at all the simulated frequencies.

Acknowledgment

The work of G. Cochet is supported by the DGA-DSTL PhD scholarship in the framework of the UK-France defence cooperation.

References

[1] S. Barbagallo, A. Monorchio, and G. Manara, Small periodicity FSS screens with enhanced bandwidth performance, *Electronics Letters*, vol. 42, pp. 382–384, 2006.

[2] F. Huang, J. C. Batchelor and E. A. Parker, Interwoven convoluted element frequency selective surfaces with wide bandwidths, *Electronics Letters*, vol. 42, pp. 788-790, 2006.

[3] B. Sanz-Izquierdo, E. A. Parker, J.-B. Robertson, and J. C. Batchelor, Singly and dual polarized convoluted frequency selective structures, *IEEE Trans. Antennas Propagat*, vol. 58, no. 3, pp. 690-696, 2010.

[4] A. Vallecchi and A. G. Schuchinsky, Entwined planar spirals for artificial surfaces, *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 994-997, 2010.

[5] A. Vallecchi and A. G. Schuchinsky, Metasurfaces with intertwined conductor patterns, Proceedings of *Metamaterials' 2011*, Barcelona, Spain, 10-15 Oct. 2011.

[6] A. Vallecchi and A. G. Schuchinsky, Artificial surfaces formed by tessellations of intertwined spirals, Proceedings of *5th European Conference on Antennas and Propagation*, *EuCAP 2011*, Rome, Italy, 11-15 Apr. 2011, pp. 1846-1848.

[7] E. Irci, K. Sertel, J. L. Volakis, Antenna miniaturization for vehicular platforms using printed coupled lines emulating magnetic photonic crystals, *Metamaterials*, vol. 4,no. 2–3, pp. 127-138, 2010

