Left-handed metamaterial at D-band using single circular split-ring resonators

A. Elhawil, J. Stiens, C. De Tandt, W. Ranson, B. Zhu, and R. Vounckx

Department of Electronics and Informatics (ETRO),
Laboratory for Micro- and Photonelectronics (LAMI),
Vrije Universiteit Brussel (VUB), Pleinlaan 2, B-1050 Brussel, Belgium

This paper demonstrates a negative refractive index material composed of an array of circular single split-ring resonators. We discuss in details the design and its features. The reflection and transmission spectra are measured using quasi-optical technique with normal incidence. The measured magnetic resonant frequency that is excited by the electric field is 142 GHz. Moreover, we study the various parameters of the design such as the refractive index, figure of merit, group velocity and phase velocity. The obtained results from the measured data are in good agreement with that retrieved from the simulations.

Introduction

Split ring resonators (SRRs) have shown fascinating properties, especially negative refractive index. They were first introduced by Pendry *et al*. in 1999 [1]. So far, many designs have been developed and extensively studied in different frequency ranges. In 2004 Katsarakis *et al*. [2] demonstrated experimentally that the magnetic resonance can be excited by the electric field. This new finding allow designing SRRs with small dimensions. However, square split-ring resonators have been employed and many detailed studies have been provided on SRRs that resonate with normal incidence in terahertz and far-infrared frequency range [3]-[6]. The aim of this paper is to investigate a circular split-ring design that resonant in w-band, and provide a detailed study about the effective parameters such as the refractive index (n), the permeability (μ),the permittivity (ε) , the group delay and the group velocity. We also demonstrate the performance of the design using the figure of merit (FOM).

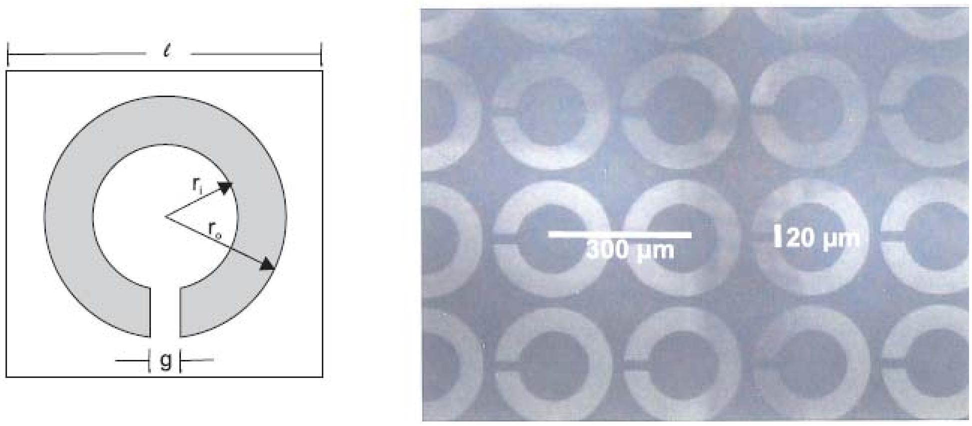


Fig. 1: Geometry and microscopic image of SRR array: l = 300 μm, r_o = 130 µm, r_i = 70 μm, and g = 20 μm.

Fabrication and structure

The negative-index metamaterial presented in this paper consists of an array of circular split rings. Fig. 1 shows the schematic and geometric parameters. The fabrication process has been performed using the positive photolithography. After exposing the photoresist using UV light, the sample with the aluminium layer of 0.65 μm thick are etched. Finally, the photoresist is stripped with acetone then the sample is cleaned using Isopropyl Alcohol (IPA).

Simulation and Experiments

The simulations were carried out by the transient solver in CST Microwave Studio. The optical dispersion properties of aluminium are computed using the Drude Model. On the other hand, the experiments were performed using AB millimetre 8-350-2 vector network analyser [7] in the D-band radiation (110-170 GHz). The boundary conditions are set for normal incidence where the wave propagates perpendicularly to the plane of SRRs and the electric field is parallel to the gap. Figs. 2a and c depict the measured and simulated transmission spectrum. As it can be seen, the *LC* resonance is excited by the electric field, which couples to the capacitance, inducing a circular current in the coil and leading to an oscillatory magnetic dipole moment perpendicular to the SRR plane [8]. This produces a LC-resonance at 142 GHz. Rotating the sample 90° and measuring the reflection and the transmission causes the dip to disappear, as shown in Figs. 2b and d, because the electric field cannot couple to the LC circuit. Furthermore, both Figures demonstrate a good agreement between the simulated and the measured results.

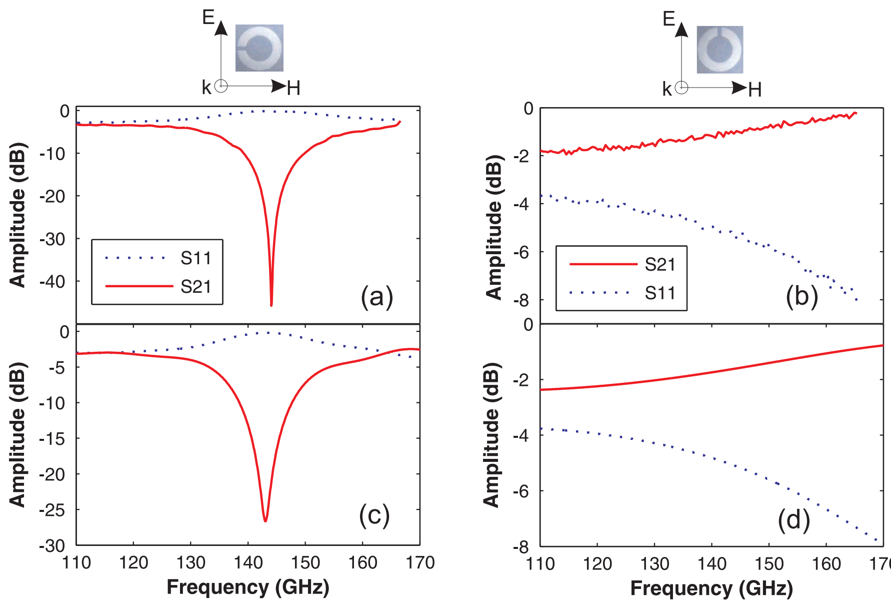
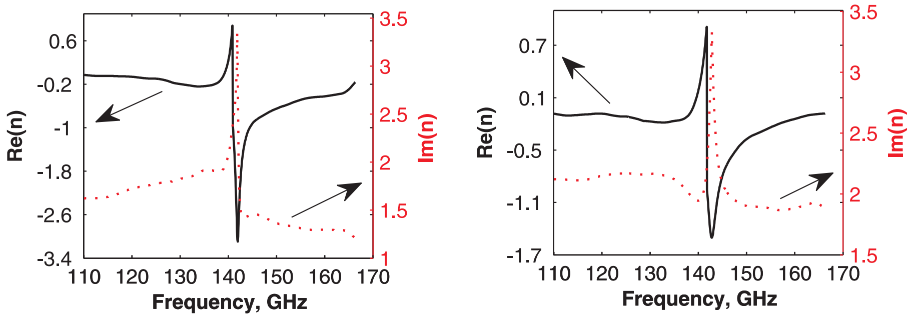


Fig. 2: a) and b) measured, c and d) simulated transmittance (solid) and reflectance (dotted) spectra.

The refractive index is extracted from the reflection and transmission coefficients using the method described in [9]. As it can be seen from Fig. 3, the minimum value of the retrieved refractive index is about -3 around 142 GHz. In order to characterize the



(a) (b)

Fig. 3: Real part (solid) and imaginary part (dotted) of the retrieved refractive index from a) measured b) simulated data.

performance of our structure, the figure of merit (FOM) ($-Re(n)/Im(n)$) is calculated from the retrieved refractive index (n). The value for FOM is 1.4.

The phase velocity and group delay

The group delay (λ_g) is defined as the difference between the propagation time of a pulse with group velocity υ_g to travel a distance z and the time it takes to travel the same distance in vacuum:

$$\lambda_g = \frac{z}{\upsilon_g} - \frac{z}{c} \tag{1}$$

where c is the light speed and υ_g is given by [11]

$$\upsilon_g = \frac{d\omega}{dk} = \frac{c}{Re(n) + \omega \frac{dRe(n)}{d\omega}} \tag{2}$$

where k is the wave number and ω is the angular frequency. For abnormal group velocity, the group delay is negative [10] [11]

$$\lambda_g = \frac{z}{\upsilon_g} - \frac{z}{c} = \frac{d}{d\omega}(\omega\frac{z}{c}[Re(n(\omega)) - 1]) \equiv \frac{d\phi}{d\omega} < 0 \tag{3}$$

where ϕ is the unwrapped phase of the transmission coefficient. On the other hand, the phase delay is expressed as $\lambda_p = -\phi/\omega$. The measured transmission phase and the calculated group delay are depicted in Fig. 4. As it can be seen, in the frequency range between 141 to 143.4 GHz the slope of the phase is positive indicating a negative group delay. Since the real part of the refractive index is negative in this region, therefore ($dRe(n)/d\omega$) is negative and as a consequence υ_g in this range is also negative.

Conclusion

In conclusion, we investigated a circular split ring resonator design. The extracted parameters from the simulated and measured data show that the SRRs exhibit a negative refractive index in the frequency range of 141-143 GHz. This also has been verified by the extracted group delay. There is a good agreement between the measured and simulated data. Moreover, the design has acceptable figure of merit which is 1.4.

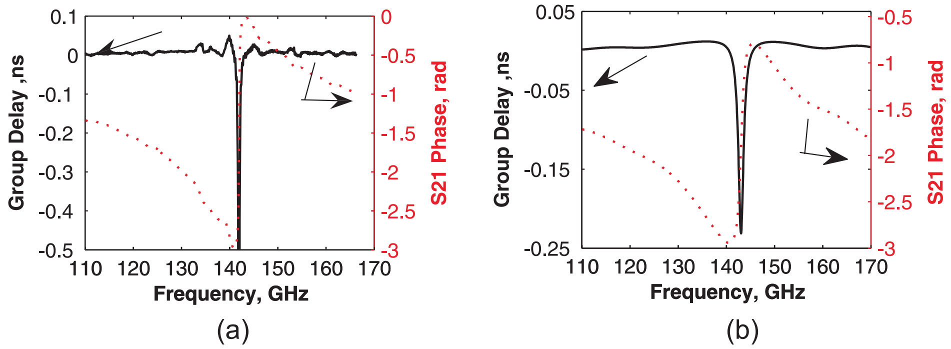


Fig. 4: Retrieved group delay and phase from a) measured and b) simulated data

Acknowledgement

This work was partially funded by Libyan Ministry of Higher Education, Flemish Fund for Scientific Research (FWO-G.0230.08), the Flemish Institute for the encouragement of innovation in science and technology (IWT-SBO 231.011114).

References

[1] J. B. Pendry, A. J. Holden, D. J. Robbins, and J. W. Stewart ,"Magnetism from conductors and enhanced nonlinear phenomena",*IEEE Trans. Microw. Theory Tech.*,vol. 47, pp. 2075, 1999.

[2] N. Katsarakis, T. Koschny and M. Kafesaki, E. N. Economou, and C. M. Soukoulis, "Electric Coupling to the Electric Resonance of Split-Ring Resonators",*Appl. Phys. Lett.*,vol. 84, pp. 2943-2945, 2004.

[3] S.G. McMeekin, A. Z. Khokhar, S.G. McMeekin, B. Lahiri, R.M. De La Rue and N.P. Johnson, "Investigating Split Ring Resonators from 1.3 to 10 microns",*Optics and Optoelectronic*, pp. 6581,2007.

[4] N. Katsarakis, G. Konstantinidis, A. Kostopoulos, R. S. Penciu, T. F. Gundogdu, M. Kafesaki, E. N. Economou, T. Koschny, and C. M. Soukoulis, "Magnetic response of split-ring resonators in the far-infrared frequency regime",*Opt. Lett. 30*, vol. 11, pp. 1348-1350, 2005.

[5] Z. Jiangfeng, K. Thomas and C. M. Soukoulis,"Magnetic and electric excitations in split ring resonators", *Opt. Express*, vol. 15, 26, pp. 17881-17890, 2007

[6] C. Rockstuhl, T. Zentgraf, H. Guo, N. Liu, C. Etrich, I. Loa, K. Syassen, J. Kuhl, F. Lederer, and H. Giessen, "Resonances of split-ring resonator metamaterials in the near infrared",*Appl. Phys. B 84*, pp. 219-227, 2006.

[7] AB millimetre, available at: http://www.abmillimetre.com

[8] M. W. Klein, C.Enkrich,M. Wegener and S.Linden,"Second-Harmonic Generation from Magnetic Metamaterials", *Science*,vol. 313, 5786, pp. 502-504, 2006.

[9] D. R. Smith and S. Schultz, "Determination of effective permittivity and permeability of metamaterials from reflection and transmission coefficients",*Phys. Rev. B 65*, 195104, 2002.

[10] G. V. Eleftheriades and K. G. Balmain,Negative-Refraction Metamaterials: Fundamental Principles and Applications, IEEE Press - Wiley-Interscience, Hoboken, New Jersey, 2005.

[11] G. Dolling,C. Enkrich, M. Wegener,C.M. Soukoulis and S.Linden "Simultaneous Negative Phase and Group Velocity of Light in a Metamaterial",*Science*, vol. 312, 5775, pp. 892-894, 2006.