A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

LETTER

Split ring resonators made of conducting wires for performance enhancement

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

April 2017

EPL, **118** (2017) 24002
doi: 10.1209/0295-5075/118/24002

www.epljournal.org

Split ring resonators made of conducting wires for performance enhancement

K. S. UMADEVI[1,3], SREEDEVI P. CHAKYAR[2], SIKHA K. SIMON[2], JOLLY ANDREWS[2] and V. P. JOSEPH[2]

[1] *Department of Physics, Newman College, Mahathma Gandhi University - Thodupuzha, Kerala, India*
[2] *Department of Physics, Christ College (Autonomous), University of Calicut - Irinjalakuda, Kerala, India*
[3] *Department Electronics, Prajyoti Niketan College, University of Calicut - Thrissur, Kerala, India*

received 28 January 2017; accepted in final form 8 June 2017
published online 26 June 2017

PACS 41.20.Jb – Electromagnetic wave propagation; radiowave propagation
PACS 42.60.Da – Resonators, cavities, amplifiers, arrays, and rings

Abstract – This paper introduces a negative permeability metamaterial structure —Wire Split Ring Resonator (WSRR)— constructed using conducting wires and experimentally investigates its tunable properties at microwave frequencies. The structure is fabricated by fixing conducting rings made of copper wires on a thin flexible polymer film. The resonance properties of a single WSRR are studied by placing it between two monopole antennas connected to a vector network analyser. For the analysis of bulk samples, two horn antennas are used. The structure shows strong magnetic response with high-quality factor and is observed to be very sensitive to parameter variations. A comparitive study with conventional SRR is made and the results are verified by simulation. The proposed WSRR structure is easy to construct and is superior to conventional SRR in frequency selective and tunable applications.

Introduction. – The emerging field of metamaterials has significantly raised the interest of researchers in various fields of science and engineering due to its unique properties and manifold applications. This new class of artificially engineered materials with negative parameters (permeability μ, permittivity ϵ and refractive index n) may be even described as the material of the millennium. The realisation of this negative refractive index material by Smith *et al.* in 2000 has triggered immense research activities in this new field [1].

The two constituents of negative-index metamaterial structures are negative permeability and permittivity counterparts. The first negative permeability structure called Split Ring Resonator (SRR) was proposed by Pendry [2]. SRR which is also called Edge Coupled SRR (ECSRR) is usually fabricated on planar dielectric substrates. As the name suggests, they consist of two concentric metallic flat rings of circular or rectangular shape with negligible thickness each having small splits situated at opposite ends. Resonance properties of such metamaterial structures entirely depend upon their structure, substrate and other dielectric environments [3–8].

In order to overcome the limitations of SRR-like bianisotropy, lower limit for resonant frequency, etc., several other designs have been proposed and analysed. Broad side Coupled SRR (BCSRR) proposed in 2002 [9] is one among the most explored structures. The two rings of the BCSRR are fabricated on either sides of the substrate coaxially with the splits at opposite ends. Studies have shown that BCSRR has smaller resonant frequency, higher Q value, smaller electrical size and higher isotropy in the plane of the structure than the ECSRR [10,11]. Another structure called Double sided SRR (DSRR), studied by different researchers, is a mixture of both ECSRR and BCSRR, where two ECSRRs are placed on the two sides of a dielectric substrate [12]. A comparative study using numerical simulation of SRR, DSRR and BCSRR structures showed that DSRR can provide better miniaturization and have wider half-power bandwidth as compared to conventional SRR (ECSRR) [5]. Effects of substrate parameters on resonant frequency of DSRR structures under magnetic and electrical excitations are also investigated [13].

Other types of SRR structures explored are Complimentary SRR (CSRR), multiple ring SRR and labyrinth-based metamaterial structures [14–17]. Some other structures of different forms like S-shaped, V-shaped, C-shaped and Ω-shaped resonators are also attempted [18–23].

In this paper we propose a new split ring resonator structure, named as Wire Split Ring Resonator (WSRR),

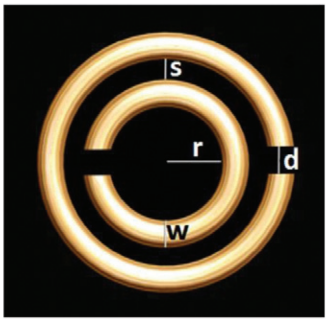

Fig. 1: (Colour online) Schematic representation of the proposed Wire Split Ring Resonator (WSRR) with structural parameters.

constructed using thin metallic wires. Even though the shape of this structure is similar to conventional SRR, its theoretical analysis and resonant properties show a marked deviation from the conventional one. The highlight of this proposed novel structure is that they are fabricated devoid of any solid substrate which makes it self-standing and thereby avoiding the constraints associated with a supporting substrate and hence the intrinsic resonant properties of the SRR can be directly obtained. The changes induced on the resonant frequency due to the interaction of the excitation field with the supportive dielectric substrate of the existing SRRs are avoided here. Any conventional SRR, if fabricated without a rigid substrate with the intention to use it in the field of sensors, is prone to sudden changes in resonant frequencies for even minor structural fluctuations because of its thin metallisation. This limitation is avoided in the case of WSRR due to the comparatively rigid nature of the wire metallisation. This may also lead to possible applications in various fields where our WSRR can be used as a movable sensor probe. Since wires are used for the fabrication of the proposed SRR, structural refinements aiming at frequency tunability can be more easily realized. Here we analyse the resonant behaviour of the proposed WSRR by varying its structural parameters and make a comparative analysis with the resonant properties of the conventional SRR along with its confirmation by simulation.

Design and fabrication of the structure. – In the presence of the magnetic-field components of an external applied electromagnetic wave, the SRR structure undergoes resonant absorption. The resonant frequency f in terms of the total capacitance C between the rings and the effective inductance L can be obtained using the equation

$$f = \frac{1}{2\pi\sqrt{LC}}. \qquad (1)$$

The schematic representation of the proposed WSRR unit cell is shown in fig. 1. The structural parameters are inner radius r, diameter of wire w, spacing between rings s and split width d. The fabrication method of this negative permeability structure is quite simple compared to other SRR structures since no procedures like photo masking, chemical etching, etc., are involved. The WSRR unit cells are constructed using small pieces of copper wires bent into the form of split rings using a cylindrical-cavity–shaped mold and fixing them on a thin adhesive polymer film. The flexibility of the polymer film is an added advantage of the structure. WSRR unit cells having different inner radii and gap distances are constructed using copper wires of diameter 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm and 0.8 mm. The thickness of the supporting polymer film used is 18 μm. The WSRR units are fixed periodically on the polymer sheet in the form of two-dimensional array. Such layers are arranged side by side to form a two-dimensional bulk WSRR medium. The photograph of the WSRR units constructed in planar and bulk form are given in fig. 2. We can reduce the small asymmetries observed in the structure by employing any standard engineering procedures. For comparing the resonance behaviour of WSRR with conventional SRR, we fabricated a SRR structure on another piece of the same polymer film. The two flat rings of the conventional SRR are fabricated by the chemical etching process using a thin copper sheet of 20 μm thickness [7].

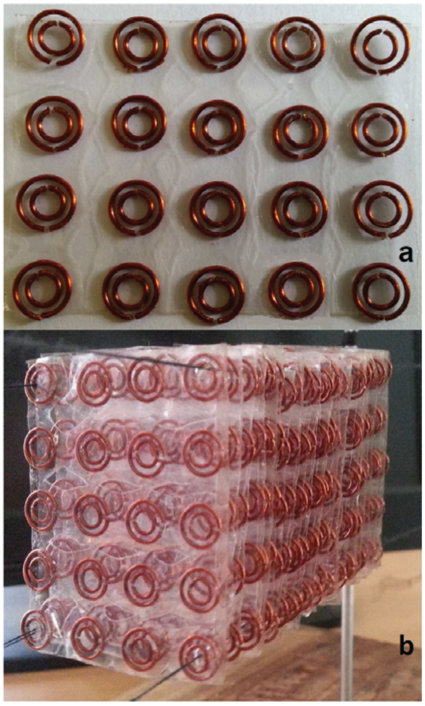

Fig. 2: (Colour online) Photograph of the WSRR constructed with structural parameters $w = 0.4$ mm, $r = 1.68$ mm, $s = 0.5$ mm, $d = 0.5$ mm. (a) Two dimensional array with periodicity of 10 mm × 10 mm; (b) bulk medium with periodicity of 10 mm × 10 mm × 10 mm.

Measurements and results. – Two monopole antennas connected to a Vector Network Analyser (VNA) are used to study the transmission properties of the WSRR unit cell structure [4,24]. Figure 3(a) depicts a schematic representation of the experimental arrangement with the

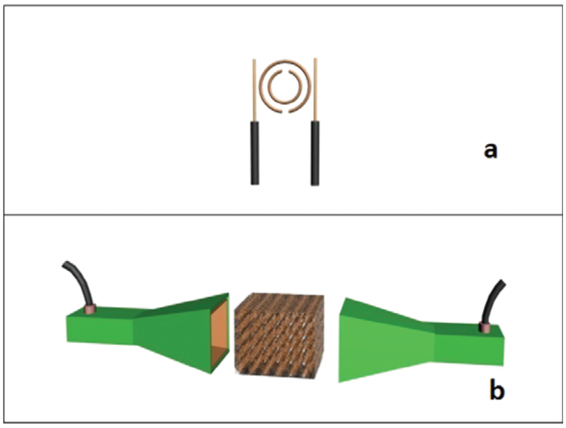

Fig. 3: (Colour online) Schematic representation of the experimental setup: (a) single WSRR between transmitting and receiving probes; (b) bulk WSRR medium placed between transmitting and receiving horn antennas.

WSRR unit cell kept between the transmitting and the receiving probes. For measuring the absorption properties of bulk WSRR medium, a sample of dimension $50\,\text{mm} \times 40\,\text{mm} \times 100\,\text{mm}$ is placed between two horn antennas, one acts as the transmitter and the other as the receiver (fig. 3(b)).

Transmission spectra. The measured transmission spectra of a typical WSRR unit cell is shown in fig. 4(a). The geometrical parameters of the structure are $r = 2.45\,\text{mm}$, $s = 0.8\,\text{mm}$, $w = 0.7\,\text{mm}$ and $d = 0.5\,\text{mm}$. The result shows sharp resonant absorption of power at 3.64 GHz. For comparative study, a conventional SRR structure with the same values for r, s and d is fabricated. The width of the conventional SRR is taken equal to the wire diameter w of the WSRR. The resonant graph of the equivalent SRR is shown along with that of the WSRR in fig. 4(a). It is evident from the figure that the bandwidth of the WSRR is quite smaller than that of the SRR which is indicative of a high-Q resonance performance. The verification of experimental results by simulation is performed using Ansoft HFSS and both results are found quite in agreement (fig. 4(b)). Figure 5 gives transmission spectra obtained for the bulk medium which also shows strong absorption dip (5.39 GHz). Structural parameters selected for fabricating the bulk medium are $w = 0.4\,\text{mm}$, $r = 1.68\,\text{mm}$, $s = 0.5\,\text{mm}$, $d = 0.5\,\text{mm}$ and periodicity is $10\,\text{mm} \times 10\,\text{mm} \times 10\,\text{mm}$.

Effect of structural parameters. Absorption curves of different WSRR units with varying values for w, r and s are examined and the effects of these structural parameters on the resonance frequency are analysed.

The split width d is kept constant (0.5 mm) since its effect on resonance frequency is comparably less. The variation of resonance frequency with inner radius r for two different values of w, by keeping the spacing between the rings s constant is plotted in fig. 6. It shows that irrespectively of the value of w, as r increases the

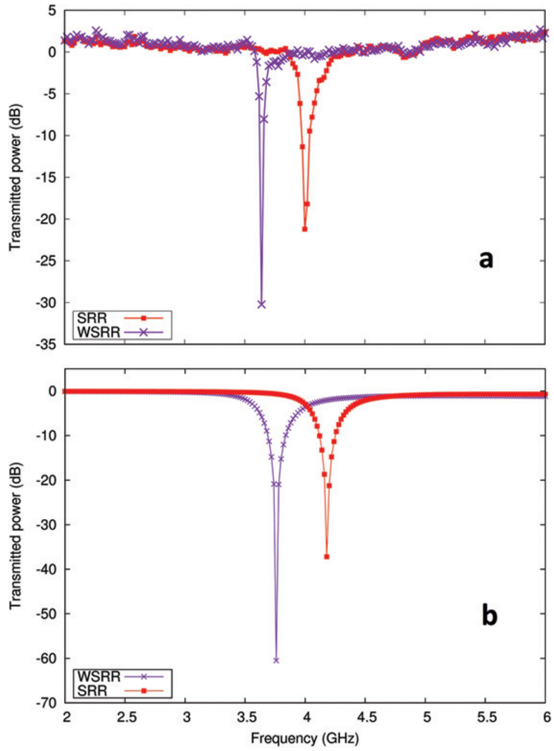

Fig. 4: (Colour online) Transmission spectra of Wire SRR (WSRR) and conventional SRR with the same structural parameters r, s, d and width w equal to the diameter of the wire: (a) experimental, (b) simulation.

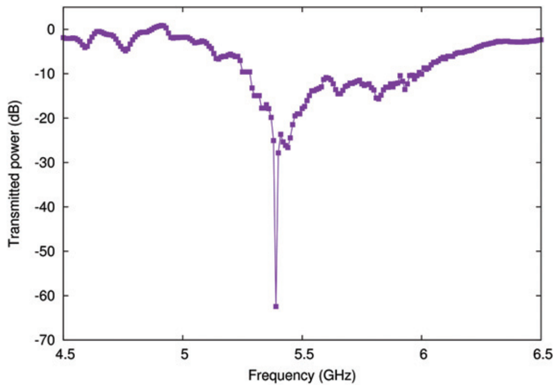

Fig. 5: (Colour online) Experimental transmission spectra of WSRR bulk medium.

resonance frequency decreases —a result similar to conventional SRR [4], but showing higher variations. Figure 7 demonstrates the effect of s on the resonance frequency for different r, when w is kept constant. As s increases, due to the decrease in effective capacitance and mutual inductance between the two rings of SRR, the resonance frequency shifts towards the high-frequency region. This result also is qualitatively similar to that of a conventional SRR. Figure 8 is a similar graph which depicts the dependence of the resonance frequency on the diameter of the wire w. As is evident from the figure, for an increase of

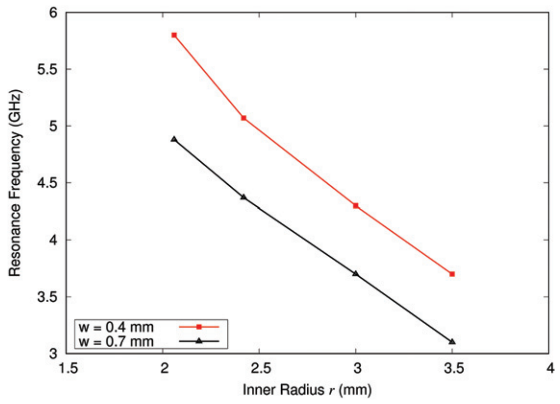

Fig. 6: (Colour online) Variation of resonance frequency of WSRR with inner radius r for two different wire diameters w keeping spacing between the rings s constant (0.97 mm).

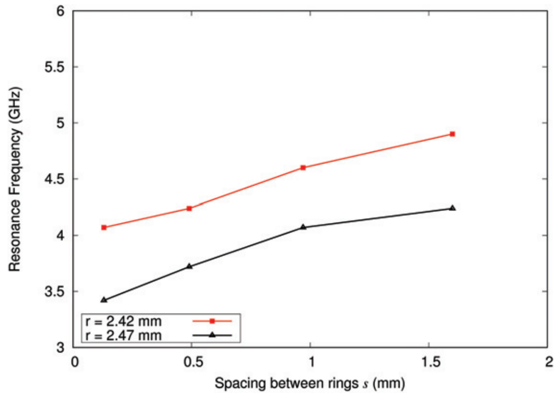

Fig. 7: (Colour online) Variation of resonance frequency of WSRR with the spacing between the rings s for two different inner radii r keeping wire diameter w constant (0.6 mm).

the wire diameter the resonant frequency is seen decreasing. In the case of SRR, the enhancement of the width of the ring results in an increase in the resonant frequency, whereas for the WSRR it behaves oppositely —*i.e.*, as the wire diameter increases the resonant frequency decreases. This may be due to the variation in effective capacitance occurred due to the structural difference between SRR and WSRR.

Significant characteristics of WSRR. – Apart from the above-mentioned variations of structural dependent resonant properties of WSRR in comparison with the conventional SRR, the following points are worth mentioning. WSRR shows a very high Q value compared to SRR of the same structural dimensions where the width is replaced with the diameter of WSRR. This may be due to the higher volume of metallisation of the WSRR leading to increased induced current flow through the rings. Since the cross-sectional area of the WSRR rings is much greater than that of the SRR, the Ohmic loss is very much reduced. Another possible reason which may lead to the enhancement of the Q value can be explained by analysing

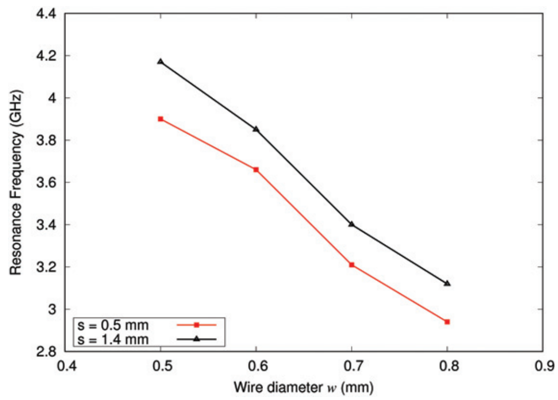

Fig. 8: (Colour online) Variation of resonance frequency of WSRR with wire diameter w for two different values of s keeping inner radius r constant (2.2 mm).

the region of field concentration between the rings of the structure. In the case of conventional SRR, due to the flat nature of the rings the supportive film is in tight contact with the metallisation and a significant portion of the electric field passes through the dielectric [24]. But the capacitance contribution in WSRR is mainly by the curved semi-spherical portions of the rings facing each other and only a minor portion of the field passes through the thin supporting polymer substrate film, which is attached at the bottom part of the SRR ring. So the dielectric loss which adversly influences the quality factor of the resonator is negligibly small for the WSRR case. This new SRR may find potential applications in fields of sensor devices, material characterization studies, frequency selective surfaces, etc. Secondly we noticed that the dependence of structural parameters on the resonant frequency of WSRR is much greater than that of a conventional SRR. This greater tunability of WSRR also finds specific applications in various fields. In addition to this, non-requirement of any solid substrate removes the loss factors and constraints associated with them and thereby enhances the sensitivity of our structure in the external excitation field. The flexibility properties of the film used for fixing the rings in order to maintain the structural parameters of individual units and periodicity of bulk samples is another added advantage in selected fields of applications.

Conclusion. – The fabrication method and resonance characteristics of a novel flexible negative permeability split ring resonator structure made of conducting wires (WSRR) for microwave frequencies are presented. The resonant properties of this proposed structure are analysed both by experiment and simulation. The frequency tunability of WSRR by structural parameter variations is also analysed. A comparative study with conventional SRR shows higher structural dependent frequency tunability for our structure. The other noticeable characteristics of the WSRR are the enhanced quality factor and the absence of any rigid supporting substrate and hence may have potential applications in the field of sensors, material characterisation studies, etc. Fabrication of this newly proposed metamaterial element is much easier and cost effective. The design may be extended to the fabrication of bulk negative-index metamaterials.

* * *

We are thankful to Prof. K. T. Mathew, Department of Electronics, Cochin University of Science and Technology, for providing us with technical support in performing the simulation works.

REFERENCES

[1] Smith D. R., Padilla W. J., Vier D., Nemat-Nasser S. C. and Schultz S., *Phys. Rev. Lett.*, **84** (2000) 4184.

[2] Pendry J. B., Holden A. J., Robbins D. and Stewart W., *IEEE Trans. Microwave Theory Tech.*, **47** (1999) 2075.

[3] Sheng Z. and Varadan V. V., *J. Appl. Phys.*, **101** (2007) 014909.

[4] Aydin K., Bulu I., Guven K., Kafesaki M., Soukoulis C. M. and Ozbay E., *New J. Phys.*, **7** (2005) 168.

[5] Ekmekci E. and Turhan-Sayan G., *Prog. Electromagn. Res. B*, **12** (2009) 35.

[6] Chakyar S. P., Andrews J. and Joseph V. P., *World Acad. Sci. Eng. Tech. Int. J. Mech. Aerospace Ind. Mechatron. Manuf. Eng.*, **10** (2016) 1030.

[7] Ragi P. M., Umadevi K. S., Nees P., Jose J., Keerthy M. V. and Joseph V. P., *Microwave Opt. Tech. Lett.*, **54** (2012) 1415.

[8] Zhu J., Li D., Yan S., Cai Y., Liu Q. H. and Lin T., *EPL*, **112** (2015) 54002.

[9] Marqués R., Medina F. and Rafii-El-Idrissi R., *Phys. Rev. B*, **65** (2002) 144440.

[10] Lee H.-J., *J. Korean Phys. Soc.*, **55** (2009) 1596.

[11] Marqués R., Mesa F., Martel J. and Medina F., *IEEE Trans. Antennas Propag.*, **51** (2003) 2572.

[12] Sauviac B., Simovski C. and Tretyakov S., *Electromagnetics*, **24** (2004) 317.

[13] Ekmekci E., Averitt R. and Turhan-Sayan G., *Effects of substrate parameters on the resonance frequency of double-sided srr structures under two different excitations*, in *PIERS Proceedings, Cambridge, USA, 2010*, pp. 538–540.

[14] Baena J. D., Bonache J., Martin F., Sillero R. M., Falcone F., Lopetegi T., Laso M. A., Garcia-Garcia J., Gil I., Portillo M. F. *et al.*, *IEEE Trans. Microwave Theory Tech.*, **53** (2005) 1451.

[15] Bilotti F., Toscano A. and Vegni L., *IEEE Trans. Antennas Propag.*, **55** (2007) 2258.

[16] Ozbay E., Bulu I. and Caglayan H., *Phys. Status Solidi B*, **244** (2007) 1202.

[17] Bulu I., Caglayan H. and Ozbay E., *Opt. Express*, **13** (2005) 10238.

[18] Liu Z., Li H., Zhan S., Cao G., Xu H., Yang H. and Xu X., *Opt. Mater.*, **35** (2013) 948.

[19] Ekmekçi E. and Turhan-Sayan G., *Investigation of effective permittivity and permeability of novel v shaped metamaterial using simulated s parameters*, in *Proceedings of the 5th International Conference on Electrical and Electronics Engineering, Bursa, Turkey, 2007*, pp. 251–254.

[20] Saadoun M. M. and Engheta N., *Microwave Opt. Tech. Lett.*, **5** (1992) 184.

[21] Aydin K., Li Z., Hudlička M., Tretyakov S. and Ozbay E., *New J. Phys.*, **9** (2007) 326.

[22] Aydin K., Li Z., Bilge S. and Ozbay E., *Photon. Nanostruct. - Fundam. Appl.*, **6** (2008) 116.

[23] Chen H., Ran L., Huangfu J., Zhang X., Chen K., Grzegorczyk T. M. and Kong J. A., *Phys. Rev. E*, **70** (2004) 057605.

[24] Chakyar S. P., Sikha S. K., Bindu C., Andrews J. and Joseph V. P., *J. Appl. Phys.*, **121** (2017) 054101.