8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics - Metamaterials 2014
Copenhagen, Denmark, 25-30 August 2014

Inner modes of a compact spiral resonator suitable for metamaterial applications

N. Maleeva[1], **M. Fistul**[1,2], **N.N. Abramov**[1], **A. Averkin**[1], **A. P. Zhuravel**[3] **A. Karpov**[1], **and A. V. Ustinov**[1,4]

[1]National University of Science and Technology "MISIS", Laboratory of Superconducting Metamaterials, Leninsky Prospect, 119049, Moscow, Russia
[2]Theoretische Physik III,Ruhr-Universität Bochum, D-44801 Bochum, Germany
[3]B. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, Kharkov, 61103, Ukraine
[4]Physikalisches Institut, Karlsruhe Institute of Technology (KIT), Karlsruhe, 76131, Germany
m13@list.ru

Abstract – **Spiral resonators are ultra-compact magnetic components promising applications in negative refraction index metamaterials. We present an experimental study, numerical simulation and theoretical model of a planar monofilar Archimedean spiral resonator. We show that the analysis of electrodynamic properties of a spiral resonator is in good accord with direct numerical simulations and experimental data obtained with specifically designed magnetic scanning probe.**

I. Introduction

Electromagnetic metamaterial is normally made of resonant elements with predominant electric or magnetic field coupling, so-called meta-atoms [1]. In order to create an optically uniform media, the meta-atom size and spacing should be small, deeply in the sub-wavelength range. If the resonant frequencies of both types of meta-atoms coincide, the effective permeability and permittivity may both become negative simultaneously, resulting in effective negative refraction index giving unusual electrodynamics properties to the metamaterial. The first proposed magnetic meta-atoms were split-ring resonators [2]. Recently the usage of planar spiral resonators (SR) was proposed for magnetic meta-atoms [3, 4, 5], promising great reduction of the typical resonator's size to the wavelength ratio (R/λ).

First of all, a resonator is characterized by a set of resonant frequencies, which, in turn, strongly depends on a specific geometry of resonator. For example, in a one-dimensional transmission line with two identically open ends, the resonant modes can be excited at frequencies $f_n = f_1 n$, where $n = 1, 2....$ This relationship radically changes to the $f_n = (2n-1)f_1$ once the line is rolled in a ring-shaped SR [6, 7]. Relying on this facts we decided to study the resonant frequencies and corresponding current distributions of resonators made in the form of planar Archimedean spiral. Previously we have already presented the outline of our analytical model of the planar Archimedean SR [8]. Here we present an experimental study of microwave resonances of a single Archimedean SR by using RF magnetic probe scanning technique and direct numerical simulations. Our experimental and simulation results support the proposed electrodynamic model.

II. Experiment and discussion

Our test sample was fabricated as a copper printed circuit board (PCB) on a dielectric substrate RO4350B with dielectric constant $\epsilon_r = 3.48$ and thickness 0.765 mm. The Archimedean spiral has 23 turns with step $d = 0.7$ mm. The copper trace width is 0.3 mm and the external radius of the spiral $R_e = 16.25$ mm. The resonant frequencies of the SR are presented in Table 1. The resonant frequencies were detected by RF transmission measurements [7].

A sketch of the experimental setup is shown in Fig. 1. In order to excite the resonator, a 32 mm diameter shielded probe loop was used as excitation field source. The loop antenna was made from 2 mm semi-rigid 50

Table 1: Resonant frequencies of the SR obtained experimentally, numerically and analytically.

Mode number	Measured resonant frequency, MHz	Simulated resonant frequency, MHz	Analytical resonant frequency, MHz
1	80	80	69
2	180	179	172
3	268	266	245
4	353	351	341
5	437	434	416
6	522	518	511

ohm coaxial cable. It was positioned above the PCB at 30 mm from the plane of the SR to ensure a weak coupling. The local ac magnetic field component near the surface of the spiral was measured using a movable small loop antenna as a probe. The probe loop antenna of about 0.5 mm in diameter was formed on the end of 0.5 mm semi-rigid 50 ohm coaxial cable. This probe was placed at the distance of about 50 μm from surface of the SR and oriented perpendicular to the spiral radius. Thus, full distance from the center of the loop to the surface of the spiral was about 0.3 mm. A motorized linear drive was used to move the probe loop along the radius of the spiral and thus to measure the magnetic field spatial distribution. The excitation signal and measuring of the response from the probe loop were provided by a vector network analyzer. Both the motorized drive and the network analyzer were controlled by PC to perform automated measurements. In such an experimental setup an S_{21} transmission is proportional to the amplitude of a voltage generated in the probe loop (while the excitation amplitude was kept constant), and thus S_{21} is proportional to the amplitude of the magnetic flux through the loop. Spatial distributions of the radial component of the magnetic field for four eigenmodes ($n = 1, 2, 3$ and 6) are

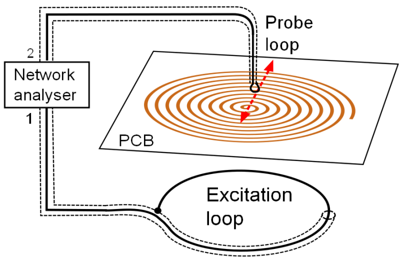

Fig. 1: Sketch of experimental setup for measuring of spatial distribution of the SR magnetic field.

presented in Fig. 2 (solid lines). Full electromagnetic simulation of the SR was performed in High Frequency Structure Simulator [9] (HFSS). For simulating the RF transmission measurements, the driven modal method was used. The SR was simulated as a perfect conductor with zero thickness on the substrate with ϵ_r placed between two RF excitation loops. The resonant frequencies, obtained as described above, are presented in Table 1 (column 4). Next, the magnetic field distribution at the distance $z = 0.3$ mm from the spiral plane was calculated for four modes $n = 1, 2, 3,$ and 6 (See Fig. 2 dashed lines). Doted lines in Fig. 2 show the prediction of the analytical model [8].

III. Conclusion

We studied electrodynamics of a compact Archimedean spiral resonator with predominant magnetic coupling to the external ac field. In spite of an early interest to this structure introduced by Nikola Tesla more than a century ago, the analytical model for a finite size spiral was missing. Our experimental study of the spectrum of the resonances and measurements of the profiles presented here of the standing waves allow for a detailed verification of the analytical calculations. Numerical modeling of the spiral resonator with HFSS program is in a good accord with the experimental data and the analytical model. The presented study supports the development

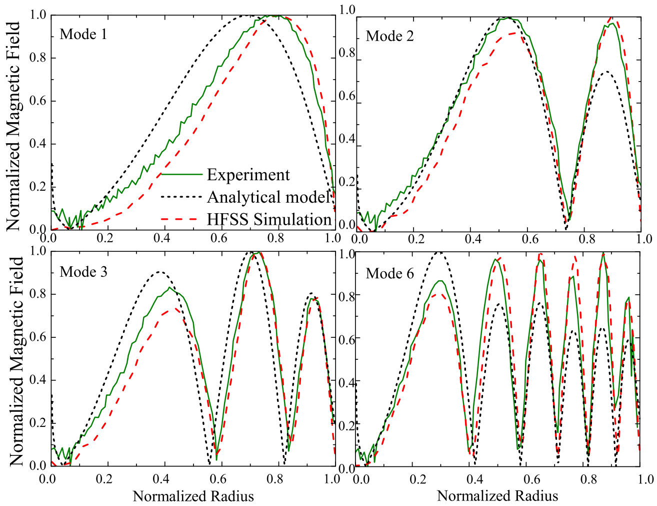

Fig. 2: The normalized radial component of the magnetic field for first, second, third and sixth modes. Green straight line corresponds to experiment results of the copper spiral, black dashed line corresponds to analytically obtained function $B_r(r, z)$ with $z = 0.3$ mm of the perfect conductor spiral and red dot-dashed line corresponds to the radial component of the magnetic field obtained by the simulation of the superconductive spiral. Simulated magnetic field was taken with $z = 0.3$ mm too.

of the ultra-compact antennas and the electromagnetic metamaterials.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education and Science of the Russian Federation Grant 11.G34.31.0062. N. Maleeva acknowledges the financial support from the Michail-Lomonosov-Forschungsstipendien und -aufenthalte.

REFERENCES

[1] N. Engheta and R. W. Ziolkowski, *Metamaterials: Physics and Engineering Explorations*, Wiley & Sons, New York, 2006; S. Zouhdi, Ari Sihvola, Al. P. Vinogradov, *Metamaterials and Plasmonics: Fundamentals, Modelling, Applications*, Springer-Verlag, New York, 2008.

[2] R. A. Shelby, D. R. Smith, S. C. Nemat-Nasser, S. Schultz, "Microwave transmission through a two-dimensional, isotropic, left-handed metamaterial", *Appl. Phys. Lett.*, 78, 489, 2001; R. A. Shelby, D. R. Smith, S. Schultz, "Experimental Verification of a Negative Index of Refraction", *Science*, 292, 77, 2001.

[3] J.D. Baena, R. Marques, F. Medina and J. Martel "Artificial magnetic metamaterial design by using spiral resonators", *Physical Review B* 69, 014402, 2004.

[4] C. Kurter, J. Abrahams and S. M. Anlage, "Miniaturized Superconducting Metamaterials for Radio Frequencies", *Appl. Phys. Lett.* 96, 253504, 2010.

[5] S. Massaoudi and I. Huynen, "Multiple resonances in arrays of spiral resonators designed for magnetic resonasnce imaging", *Microwave and Optical Tachnology Letters* 50, 7, 2008.

[6] N. Maleeva, M. V. Fistul, A. Karpov, A. P. Zhuravel, A. Averkin, P. Jung, and A. V. Ustinov, "Electrodynamics of a ring-shaped spiral resonator", *Journal of Appl. Phys.* 115, 064910, 2014.

[7] C. Kurter, A. P. Zhuravel, J. Abrahams, C. L. Bennett, A. V. Ustinov and S. M. Anlage, "Superconducting RF Metamaterials Made with Magnetically Active Planar Spirals", *IEEE Trans. Appl. Supercond.* 21, 709, 2011.

[8] N. Maleeva, M. Fistul, A. Averkin, A. Karpov and A. V. Ustinov, "Electrodynamics of a spiral resonator as a suitable magnetic component of metamaterials", Proceedings of *Metamaterials'2013,* pp. 474-477, Bordeaux, France, 16-19 September 2013.

[9] http://www.ansys.com