Laser Scanning Microscopy of Superconducting Electromagnetic Metamaterials

Alexander P. Zhuravel
B. Verkin Institute for Low Temperature Physics & Engineering (ILTPE)
National Academy of Science of Ukraine (NASU)
UA-61103 Kharkov, Ukraine
zhuravel@ilt.kharkov.ua

Alexey V. Ustinov
Physikalisches Institute
Karlsruhe Institute of Technology (KIT)
76131 Karlsruhe, Germany
National University of Science and Technology (MISIS)
119049 Moscow, Russia

Steven M. Anlage
CNAM, Physics Department
University of Maryland
College Park, Maryland 20742-4111, USA

***Abstract*— Sub-wavelength superconducting rf meta-materials have evident advantages over their normal metal counterparts for strong diamagnetism, low-loss and intrinsically nonlinear tunability with temperature, dc magnetic, and rf electromagnetic field. These microwave properties are uniquely controlled through the spatial distribution of super-fluid density in the superconductor. The technique of low-temperature Laser Scanning Microscopy (LSM) is applied to investigate local contribution of these effects onto global rf response of superconducting meta-materials having different geometry of artificially structured magnetic meta-atoms. The main capabilities of the LSM technique for noncontact spatially resolved characterization of such structures are reviewed.**

***Keywords*— metamaterials; nonlinearity; superconductors; microwave devices; laser scanning microscopy**

I. Introduction

Recently, there has been increasing interest in superconducting (SC) meta-materials due to their strong diamagnetic response, low loss, ultra-compact design and capability for a controllable tuning by temperature, rf current and dc magnetic field. Several conceptual papers on the development and applications of SC meta-materials are now available [1-7]. There has been a noted upturn in the number of publications on using of the SC quantum meta-material [8-12]. In contrast to their normal metal counterparts, advantages of almost all of SC meta-materials are limited by moderate rf powers. These may quench the SC state as a result of extremely strong current densities arising locally in some areas of thin-film unit cells. This, in turn, produces local sources of microwave nonlinearity and dissipation that are non-uniformly distributed over planar structure of SC unit cells (so-called meta-atoms). Therefore, identification of these *microscopic* sources, as well as clarification of their distinct role playing in the manifestation of *macroscopically* averaged (global) response of SC meta-atoms, is a vital issue of fundamental and applied research for SC meta-materials in high-frequency fields. In addition, improvement of electromagnetic meta-material technology comes from a thorough understanding of the contribution of different defects, the topology normal and SC rf transport, as well as geometrical and structural features of unit cell design based on thin-film SC material. Therefore it is a great need for using of advanced methods of spatially-resolved analysis capable to find the 2D distribution of rf current density establishing direct origin of the local sources of microwave nonlinearity and dissipation. It has been shown earlier that the technique of low-temperature Laser Scanning Microscope (LSM) is a powerful nondestructive instrument for non-contact 2D probing of the local rf current density, $J_{rf}(x, y)$ in thin SC films and microwave devices [13-15]. Furthermore, the LSM method was successfully used for simultaneous imaging of optical, thermal, and microwave properties of a large-scale (up to 10x10 mm^2) SC structures in their operating conditions at $T < T_c$, with micron-scale spatial resolution [16]. In addition, a procedure of spatially-resolved separation of resistive and inductive components of LSM photo-response (PR) was developed in [13], while a procedure of LSM PR(x, y) calibration to determine the absolute amplitude of $J_{rf}(x, y)$ and the changes in the surface resistance δR_s is outlined in [15]. In this extended abstract, the target application of the LSM methods is briefly reviewed with focusing the main attention on investigation of SC meta-materials.

II. Experimental Details

A. Samples

Initially, a single $YBa_2Cu_3O_{7-\delta}$ split-ring resonator (SRR) is LSM examined as samples under test to reveal the current distribution in the rings [17]. A double planar SRR structure of a superconducting *Nb* film symmetrically located around a normal-metal (Au) strip it will be investigated thereafter as meta-molecule of metal-superconductor hybrid meta-material

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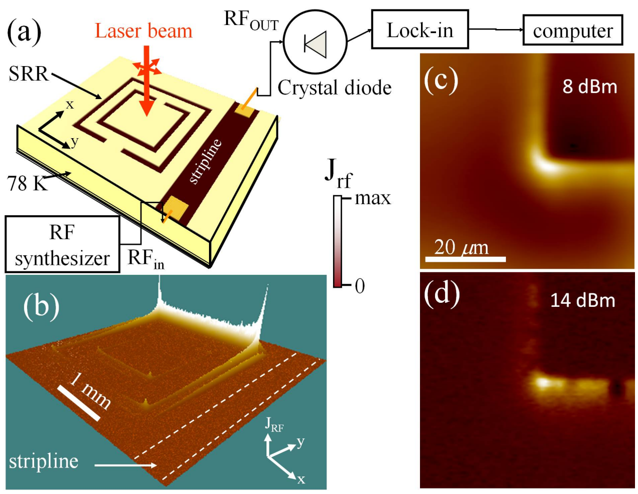

Fig. 1. a) Experimental LSM setup for the photoresponse imaging of a single $YBa_2Cu_3O_{7-\delta}$ SRR along with (b) 2D LSM presentation of $J_{rf}(x, y)$ distribution at 78 K and at P_{rf} = 8 dBm. Parts (c) and (d) show detailed $J_{rf}(x, y)$ for a close-up of an inside corner of the inner ring, at 5.146 GHz measured at P_{rf} = 8 dBm and P_{rf} = 14 dBm, correspondly.

[18]. The next set of the samples are ultra-compact *Nb* and $YBa_2Cu_3O_{7-\delta}$ magnetically active planar resonators based on a thin film Archimedean spiral geometry [16, 19]. Besides, a two-dimensional regular array of SQUIDs is LSM characterized as an example of a tunable SC meta-surface [20].

B. *LSM technique*

The LSM technique uses a focused laser beam for scanning the surface of a planar SC meta-material with the propagating microwave signal. In the area illuminated by the laser beam, the superconductivity is locally suppressed by generation of the quasi particles, by breaking of the Cooper pairs and by heating effect of the laser irradiation. The microwave current is also generating quasi-particles due to the ac losses in superconductor. The combined effect of laser irradiation and rf signal is the signal of photo response (PR) that is proportional to the square of the amplitude of the rf current density. In LSM measurement, the transmitted (or reflected) microwave signal amplitude is registered and mapped after reconstruction as a function of the laser beam position, resulting effectively in imaging of the amplitudes of the microwave currents or local surface resistance in area of SC circuit. For more details on the LSM technique and methods, see [13-16].

III. Results and Discussion

Typical examples for the imaging of the microwave properties of SC meta-material are illustrated below. Chronologically, the implementation of negative index media (of electromagnetic meta-materials) has been performed with SRRs and thin wires [21]. The rings are used to synthesize some kind of magnetic plasma is needed to create the media with a negative permeability in a narrow rf band above resonance, where signal propagation is inhibited. A typical SRR is made of two concentric rings, separated by a small gap that radically decreases the resonance frequency of the system. Thus, one can possible to obtain resonant unit cells of meta-material structure with dimensions only a tenth of the corresponding wavelength, compared to a half of a wavelength for the individual ring. Further, design of such unit cells was significantly revised to arrange more compact sub-wave magnetic meta-atoms in a lattice with special emphasis on its tenability. Thus, the illustrated examples are listed as they have been occurred during the progress of SC meta-materials.

A. *Single $YBa_2Cu_3O_{7-\delta}$ split-ring resonator*

Fig. 1(a) shows design of the $YBa_2Cu_3O_{7-\delta}$ SRR that is coupled to an $YBa_2Cu_3O_{7-\delta}$ micro-strip carrying the microwave signal. Advantage of such structure is the ability to tune the frequency by using three (unique to superconductors) methods: temperature, dc magnetic field, and rf magnetic field [22]. The LSM photo-response indicates the build-up of $J_{rf}(x, y)$ in the inside corners over both rings of the single SRR for the fundamental mode of 5.146 GHz as viewed in Figs. 1(b, c). In area of the inside corners, the maximum of $J_{rf}(x,y)$ may create an overcritical state of the SC film leading to a more linear (normal-metal like) behavior of the local sources of rf nonlinearity that is seen as a black (zero-response) zones in Fig. 1(d)]. In contrast, the remaining critical-state regions give a maximum value to the LSM PR. The results show that the dominant sources of microwave nonlinearity and dissipation are strongly localized in the resistive domains leading to a problem of severe degradation of the resonator *Q*.

B. *Superconductor/metal hybrid metamaterial*

Alternatively, some advantages can be gained from below demonstrated effects of the enhanced $J_{rf}(x,y)$ at sharp square interior corners of thin film SSR. Fig. 2(a) shows the first mode standing wave pattern of $J_{rf}(x,y)$ distribution across area of meta-molecule originally designed for an electromagnetic response analogous to media exhibiting electromagnetically induced transparency (EIT)—a narrow transparency window with large group delay [23]. The unit cells [see Fig. 2(b)] contain a 200 nm-thick SRR (dark element) pair made from Nb symmetrically located around a 2 μm-thick cut wire made from Cu (radiative element) on a quartz substrate [18]. Again, there are a few anomalously high $J_{rf}(x,y)$ values visible in the LSM PR image plotted over the whole resonator topology due

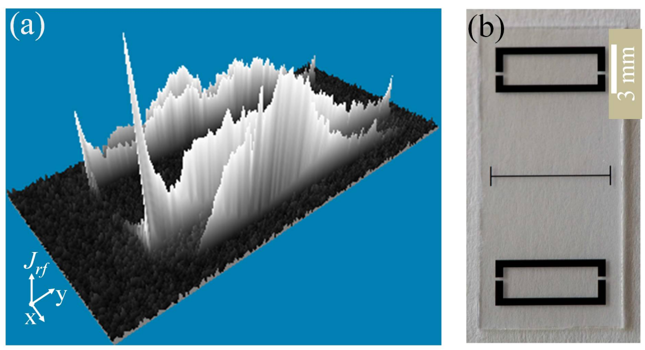

Fig. 2. (a) rf current densities $J_{rf}(x, y)$ in the upper ring of the SRR is shown in (b) photograph of the sample with the cut wire and the SRR pair. The LSM image was acquired in fundamental resonance mode of 9.747 GHz at input power of +18 dBm, and a temperature of 7 K.

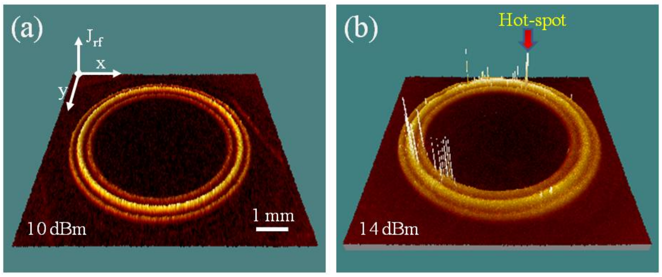

Fig. 3. 2D LSM images showing rf current distributiob in a *Nb* spiral resonator with an outer diameter of 6 mm and 40.5 turns, at the third resonant mode of 355 MHz, T = 4.5 K and at (a) P = 10 dBm and (b) P = 14 dBm. Photorespose peaks in (b) are circularly aligned along center crest of the $J_{rf}(x,y)$ standing wave pattern.

to modulation of super-fluid density at the edges and corners of the superconducting SRR. If the enhanced currents at the corners can reach the critical current density of the superconductor, the nonlinear regime might become accessible with the moderate microwave power levels. The effect was confirmed in [18] to demonstrate sharp switching event of the transparency windows at high microwave powers, resulting in a nonlinear switchable meta-material without the use of varactors or other lumped elements.

C. Magnetically active planar spiral

An extremely compact form of magnetic meta-atom has been made possible by the development of planar spiral unit cells with diameter as small as $d \sim \lambda/658$, where λ is the free space wavelength [24]. Such resonators have an expedient geometry in which the currents flowing in neighboring strips are in the same direction and approximately equal in magnitude, eliminating rf current buildup at the edges of the windings [25]. This provides the distribution of total current density to be relatively smooth within the sample as shown in Fig. 3(a). At overcritical current densities, a hot-spot formation inside a Nb thin film is evident [see Fig. 3(b)] establishing direct link between microscopic and macroscopic manifestations of nonlinearity in such structures.

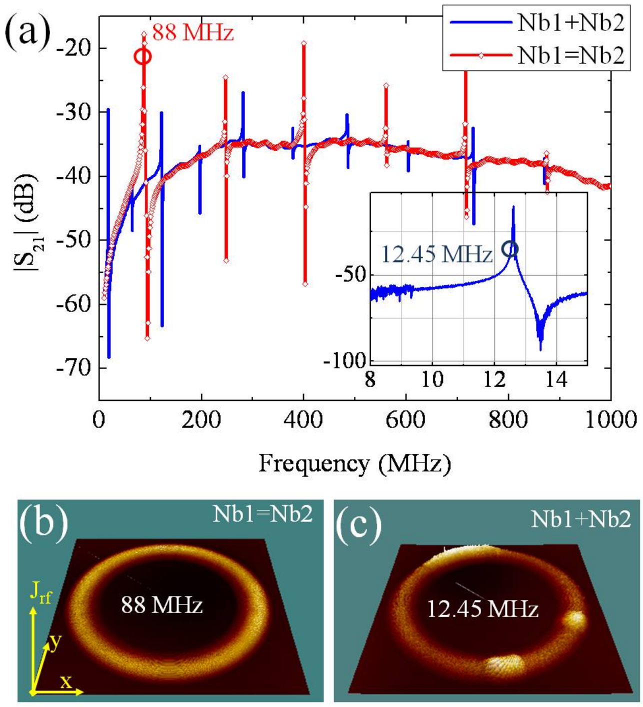

Fig. 4. (a) Typical transmission data for two identical single spirals samples *Nb1*, *Nb2* and their joint *Nb1+Nb*2 structure along with LSM images showing $J_{rf}(x,y)$ distribution in fundamental resonant mode of (b) individual spiral *Nb1* at 88 MHz and (c) double-spiral combination at 12.45 MHz respectively. Detailed view of the first mode resonance of the double-spiral structure is shown in the inset.

D. Double-spiral structure

A dual-layer design of highly sub-wavelength magnetic meta-materials has been proposed in [26]. Practically the same result was obtained by us using a very simple design of two identical SC *Nb* spirals that are face-to-face capacitive coupled through thin layer of vacuum grease. These plane-coupled spiral resonators are found to have the resonances occurring at a much lower frequencies than ones of the originally designed separate spirals [see Fig. 4(a)]. The statement is confirmed by LSM imaging as seen in Figs. 4(b, c). We imaged a resonant frequency of 12.45 MHz corresponding to d ~ $\lambda/4000$ instead of its non-optimized design.

E. Regular array of rf SQUIDs

In the present experiment, we demonstrate a method to analyze the contribution of individual superconducting meta-atoms to the collective response of a two-dimensional microwave meta-surface. The structure under investigation is an array of 27 x 27 Nb SQUIDs each containing one Nb-AlOx-Nb Josephson junction. For small excitations signals, they are treated as magnetic field tunable resonators [20, 27,

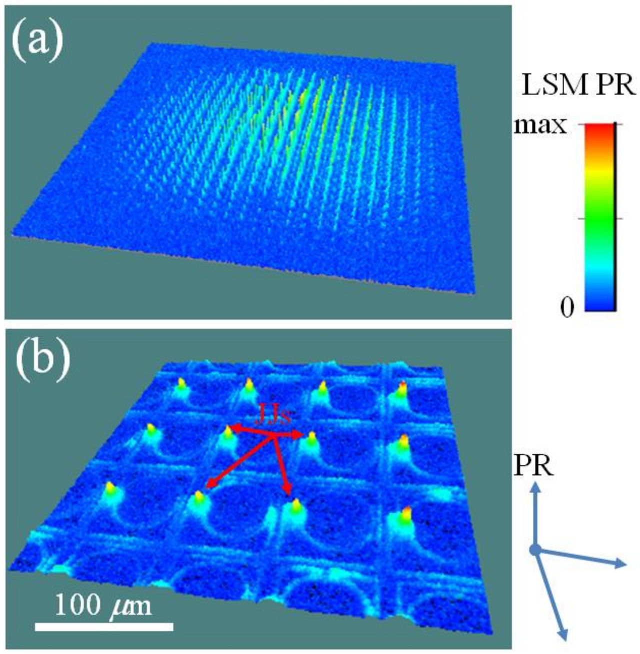

Fig. 5. Three-dimensional LSM photo-response map of 27 x27 SQUID structure at f = 17.955 GHz imaged through (a) the whole area and (b) small central part. The magnitude of the PR is color-coded using the color-scale on the right where red and blue stand for high and low photo-response, respectively..

28]. The *PR(x,y)* at *f* = 17.955 GHz in Fig.5(a) is expected coherent response of the array similar to that theoretically predicted assuming nearest neighbor coupling in a 2D array of rf-SQUIDs [28]. However, the result is dramatically changing when a weak dc magnetic field is applied. More details on imaging of microwave response of rf-SQUID meta-surface in dc magnetic field are discussed in separate talk is presented at this symposium.

IV. Summary

Advantages of the LSM technique are illustrated on a few examples of superconducting meta-materials which microwave properties were investigated spatially with a micron-scale resolution. It was shown that the LSM is a power nondestructive evolution technological tool as well as it can be applied to understand a number of fundamental problem as tuning and nonlinear behavior of meta-materials in rf fields.

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References

[1] S. M Anlage, "The physics and applications of superconducting metamaterials,", J. Opt., v. 13 pp. 024001 (1-10), April 2010.

[2] P. Jung, A. V Ustinov and S. M Anlage, "Progress in superconducting metamaterials," Supercond. Sci. Technol., vol. 27, pp. 073001 (1-13), May 2014.

[3] I. Smolyaninov and V. N. Smolyaninova, "Metamaterial superconductors," Phys. Rev. B, vol. 91, pp. 094501 (1-7), March 2015.

[4] V. Savinov, A. Tsiatmas, A. R. Buckingham, V. A. Fedotov, P. A. J. de Groot, and N. I. Zheludev, "Flux Exclusion Superconducting Quantum Metamaterial: Towards Quantum-level Switching," Sci. Rep. vol. 2, pp. 450 (1-5), June 2012.

[5] B.L.T. Plourde , H. Wang , F. Rouxinol , M.D. LaHaye, "Superconducting metamaterials and qubitsProc. SPIE 9500, Quantum Information and Computation XIII, vol. 95000M, May 2015.

[6] M. Ricci, N. Orloff and S. M. Anlage, "Superconducting metamaterials," Appl. Phys. Lett. vol. 87, 034102 (1-3), July 2005.

[7] H.-T. Chen, H. Yang, R. Singh, J. F. O'Hara, A. K. Azad, S. A. Trugman, Q. X. Jia, and A. J. Taylor, "Tuning the Resonance in High-Temperature Superconducting Terahertz Metamaterials," Phys. Rev. Lett., vol. 105, pp. 247402 (), Dec. 2010.

[8] C. Du, H. Chen, and S. Li, "Quantum left-handed metamaterial from superconducting quantum-interference devices", Phys. Rev. B, vol. 74, pp. 113105 (1-4), Sept. 2006.

[9] N. Lazarides and G. P. Tsironis, "rf superconducting quantum interference device metamaterials," Appl. Phys. Lett., vol. 90, 163501(1-3), April 2007.

[10] A. I. Maimistov, I. Gabitov, "Nonlinear response of a thin metamaterial film containing Josephson junctions," Opt. Commun. vol. 283, pp. 1633-1639, April 2010.

[11] P. Jung, S. Butz, S. V. Shitov, and A. V. Ustinov, "Low-loss tunable metamaterials using superconducting circuits with Josephson junctions," Appl. Phys. Lett., vol. 102, pp. 062601 (1-3), Feb. 2013.

[12] D. Zhang, M. Trepanier, O. Mukhanov, and S. M. Anlage, "Tunable Broadband Transparency of Macroscopic Quantum Superconducting Metamaterials," Phys. Rev. X, vol. 5, pp. 041045(1-6), Dec. 2015.

[13] A. P. Zhuravel, S. M. Anlage, and A. V. Ustinov, "Measurement of local reactive and resistive photoresponse of a superconducting microwave device," Appl. Phys. Lett., vol. 88, pp. 212503 (1-3), May 2006.

[14] A. P. Zhuravel, S. M. Anlage, and A. V. Ustinov, "Imaging of Microscopic Sources of Resistive and Reactive Nonlinearities in Superconducting Microwave Devices," IEEE Trans. Appl. Supercond., vol. 17, pp. 902 – 905, June 2007.

[15] A.P. Zhuravel, A. G. Sivakov, O. G. Turutanov, A. N. Omelyanchouk, S. M. Anlage, A. Lukashenko, A.V. Ustinov, and D. Abraimov, "Laser scanning microscopy of HTS films and devices," Low Temp. Phys. vol. 32, pp. 592-607, June 2006.

[16] A. P. Zhuravel, B. G. Ghamsari, C. Kurter, P. Jung, S. Remillard, J. Abrahams, A. V. Lukashenko, A. V. Ustinov, and S. M. Anlage, "Imaging the Anisotropic Nonlinear Meissner Effect in Nodal $YBa_2Cu_3O_{7-\delta}$ Thin-Film Superconductors," Phys. Rev. Lett. vol. 110, pp. 087002 (1-5), Feb. 2013.

[17] M. C. Ricci, H. Xu, R. Prozorov, A. P. Zhuravel, "Tunability of Superconducting Metamaterials," IEEE Trans. Appl. Supercond., vol. 17, pp. 918 – 921, June 2007.

[18] C. Kurter, P. Tassin, A. P. Zhuravel, L. Zhang, T. Koschny, A. V. Ustinov, C. M. Soukoulis, and S. M. Anlage. "Switching nonlinearity in a superconductor-enhanced metamaterial," Appl. Phys. Lett. vol. 100, pp. 121906 (1-4), Jan. 2012.

[19] C. Kurter, A. P. Zhuravel, J. Abrahams, C. L. Bennett, A. V. Ustinov, S. M. Anlage, "Superconducting RF Metamaterials Made With Magnetically Active Planar Spirals," IEEE Trans. Appl. Supercond., vol. 21, pp. 709 – 712, June 2011.

[20] A. S. Averkin, A. P. Zhuravel, P. Jung, N. Maleeva, V. P. Koshelets, L. V. Filippenko, A. Karpov, and A. V. Ustinov, "Imaging coherent response of superconducting metasurface," IEEE Trans. Appl. Supercond., vol. 26, pp. 1-3, Jan. 2016.

[21] . B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microwave Theory Tech., vol. 47, pp. 2075–2084, Nov.1999.

[22] M. C. Ricci, H. Xu, R. Prozorov, A. P. Zhuravel, A. V. Ustinov, and S. M. Anlage, "Tunability of Superconducting Metamaterials," IEEE Trans. Appl. Supercond., vol. 17, pp. 918 – 921, June 2007.

[23] C. Kurter, P. Tassin, L. Zhang, T. Koschny, A. P. Zhuravel, A. V. Ustinov, S. M. Anlage, and C. M. Soukoulis, "Classical Analogue of Electromagnetically Induced Transparency with a Metal-Superconductor Hybrid Metamaterial," Phys. Rev. Lett. vol. 107, pp. 043901 (1-4), July 2011.

[24] C. Kurter, J. Abrahams, and S. M. Anlage, "Miniaturized superconducting metamaterials for radio frequencies," Appl. Phys. Lett., vol. 96, pp. 253504 (1-3), June 2015.

[25] Alexander P. Zhuravel, Cihan Kurter, Alexey V. Ustinov, and Steven M. Anlage. "Unconventional rf photoresponse from a superconducting spiral resonator", Phys. Rev. B vol. 85, pp. 134535 (1-8), April 2012.

[26] W.-C. Chen, C. M. Bingham, K. M. Mak, N. W. Caira, and W. J. Padilla, "Extremely subwavelength planar magnetic metamaterials," Phys. Rev. B, vol. 85, pp. 201104 (R1-R5), May 2012.

[27] A. V. Ustinov, "Experiments With Tunable Superconducting Metamaterials," IEEE Transact. Terahertz Sci. and Technol., vol. 5, pp. 22-26, Dec. 2015.

[28] M. Trepanier, Daimeng Zhang, Oleg Mukhanov, and Steven M. Anlage, "Realization and Modeling of Metamaterials Made of rf Superconducting Quantum-Interference Devices," Phys. Rev. X, vol. 3, pp. 041029 (1-11), Dec. 2013..