

Probing dynamics of micro-magnets with multi-mode superconducting resonator

Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

© 2018 Author(s). In this work, we propose and explore a sensitive technique for investigation of ferromagnetic resonance and corresponding magnetic properties of individual micro-scaled and/or weak ferromagnetic samples. The technique is based on coupling the investigated sample to a high-Q transmission line superconducting resonator, where the response of the sample is studied at eigen frequencies of the resonator. The high quality factor of the resonator enables sensitive detection of weak absorption losses at multiple frequencies of the ferromagnetic resonance. Studying the microwave response of individual micro-scaled permalloy rectangles, we have confirmed the superiority of fluxometric demagnetizing factor over the commonly accepted magnetometric one and have depicted the demagnetization of the sample, as well as magnetostatic standing wave resonance.

<http://dx.doi.org/10.1063/1.5025028>

References

- [1] G. A. Prinz, *Science* 282, 1660 (1998). 10.1126/science.282.5394.1660
- [2] S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. von Molnár, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, *Science* 294, 1488 (2001). 10.1126/science.1065389
- [3] C. A. Ross, S. Haratani, F. J. Castaño, Y. Hao, M. Hwang, M. Shima, J. Y. Cheng, B. Vögeli, M. Farhoud, M. Walsh et al., *J. Appl. Phys.* 91, 6848 (2002). 10.1063/1.1452247
- [4] O. Rousseau, B. Rana, R. Anami, M. Yamada, K. Miura, S. Ogawa, and Y. Otani, *Sci. Rep.* 5, 9873 (2015). 10.1038/srep09873
- [5] E. C. Gingrich, B. M. Niedzielski, J. A. Glick, Y. Wang, D. L. Miller, R. Loloee, W. P. Pratt, Jr., and N. O. Birge, *Nat. Phys.* 12, 564 (2016). 10.1038/nphys3681
- [6] B. Baek, W. H. Rippard, S. P. Benz, S. E. Russek, and P. D. Dresselhaus, *Nat. Commun.* 5, 3888 (2014). 10.1038/ncomms4888
- [7] V. V. Ryazanov, V. A. Oboznov, A. Y. Rusanov, A. V. Veretennikov, A. A. Golubov, and J. Aarts, *Phys. Rev. Lett.* 86, 2427 (2001). 10.1103/PhysRevLett.86.2427
- [8] L. R. Tagirov, *Phys. Rev. Lett.* 83, 2058 (1999). 10.1103/PhysRevLett.83.2058
- [9] A. K. Feofanov, V. A. Oboznov, V. V. Bol'ginov, J. Lisenfeld, S. Poletto, V. V. Ryazanov, A. N. Rossolenko, M. Khabipov, D. Balashov, A. B. Zorin et al., *Nat. Phys.* 6, 593 (2010). 10.1038/nphys1700
- [10] H. Hilgenkamp, V. V. Moshchalkov, and P. Kes, *Science* 302, 1159 (2003). 10.1126/science.1092038
- [11] J. E. Villegas, S. Savel'ev, F. Nori, E. M. Gonzalez, J. V. Anguita, R. García, and J. L. Vicent, *Science* 302, 1188 (2003). 10.1126/science.1090390
- [12] D. P. de Lara, M. Erekhinsky, E. M. Gonzalez, Y. J. Rosen, I. K. Schuller, and J. L. Vicent, *Phys. Rev. B* 83, 174507 (2011). 10.1103/PhysRevB.83.174507
- [13] *Ferromagnetic Resonance-Theory and Applications*, edited by O. Yalcin (InTech, 2013).
- [14] I. Neudecker, G. Woltersdorf, B. Heinrich, T. Okuno, G. Gubbiotti, and C. Back, *J. Magn. Magn. Mater.* 307, 148 (2006). 10.1016/j.jmmm.2006.03.060

- [15] S. S. Kalarickal, P. Krivosik, M. Wu, C. E. Patton, M. L. Schneider, P. Kabos, T. J. Silva, and J. P. Nibarger, *J. Appl. Phys.* 99, 093909 (2006). 10.1063/1.2197087
- [16] C. Kittel, *Phys. Rev* 73, 155 (1948). 10.1103/PhysRev.73.155
- [17] N. Álvarez, G. Alejandro, J. Gòmeza, E. Goovaerts, and A. Butera, *J. Phys. D: Appl. Phys.* 46, 505001 (2013). 10.1088/0022-3727/46/50/505001
- [18] Y.-C. Chen, D.-S. Hung, Y.-D. Yao, S.-F. Lee, H.-P. Ji, and C. Yu, *J. Appl. Phys.* 101, 09C104 (2007). 10.1063/1.2711072
- [19] Y. V. Khivintsev, L. Reisman, J. Lovejoy, R. Adam, C. M. Schneider, R. E. Camley, and Z. J. Celinski, *J. Appl. Phys.* 108, 023907 (2010). 10.1063/1.3435318
- [20] J. Wei, Z. Zhu, C. Song, H. Feng, P. Jing, X. Wang, Q. Liu, and J. Wang, *J. Phys. D: Appl. Phys.* 49, 265002 (2016). 10.1088/0022-3727/49/26/265002
- [21] H. Puzkarski and P. Tomczak, *Sci. Rep.* 4, 6135 (2014). 10.1038/srep06135
- [22] H. Puzkarski, P. Tomczak, and H. T. Diep, *Phys. Rev. B* 94, 195303 (2016). 10.1103/PhysRevB.94.195303
- [23] M. Donahue and D. Porter, "OOMMF user's guide, version 1.0," Interagency Report No. NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD, 1999.
- [24] J. E. Miltat and M. J. Donahue, "Numerical micromagnetics: Finite difference methods," in *Handbook of Magnetism and Advanced Magnetic Materials* (John Wiley & Sons, Ltd., 2007), Vol. 2.
- [25] V. Novosad, F. Y. Fradin, P. E. Roy, K. S. Buchanan, K. Y. Guslienko, and S. D. Bader, *Phys. Rev. B* 72, 024455 (2005). 10.1103/PhysRevB.72.024455
- [26] A. A. Awad, K. Y. Guslienko, J. F. Sierra, G. N. Kakazei, V. Metlushko, and F. G. Aliev, *Appl. Phys. Lett.* 96, 012503 (2010). 10.1063/1.3268453
- [27] G. N. Kakazei, G. R. Aranda, S. A. Bunyaev, V. O. Golub, E. V. Tartakovskaya, A. V. Chumak, A. A. Serga, B. Hillebrands, and K. Y. Guslienko, *Phys. Rev. B* 86, 054419 (2012). 10.1103/PhysRevB.86.054419
- [28] N. Ross, M. Kostylev, and R. L. Stamps, *J. Appl. Phys.* 116, 113909 (2014). 10.1063/1.4895984
- [29] K. Y. Guslienko, G. N. Kakazei, J. Ding, X. M. Liu, and A. O. Adeyeye, *Sci. Rep.* 5, 13881 (2015). 10.1038/srep13881
- [30] J. Ding, P. Lapa, S. Jain, T. Khaire, S. Lendinez, W. Zhang, M. B. Jungfleisch, C. M. Posada, V. G. Yefremenko, J. E. Pearson et al., *Sci. Rep.* 6, 25196 (2016). 10.1038/srep25196
- [31] E. V. Skorohodova, R. V. Gorev, R. R. Yakubov, E. S. Demidov, Y. V. Khivintsev, Y. A. Filimonov, and V. L. Mironov, *J. Magn. Magn. Mater.* 424, 118 (2017). 10.1016/j.jmmm.2016.10.024
- [32] Y. Li, Y. Lu, and W. E. Bailey, *J. Appl. Phys.* 113, 17B506 (2013). 10.1063/1.4794876
- [33] I. A. Golovchanskiy, V. V. Bolginov, N. N. Abramov, V. S. Stolyarov, A. B. Hamida, V. I. Chichkov, D. Roditchev, and V. V. Ryazanov, *J. Appl. Phys.* 120, 163902 (2016). 10.1063/1.4965991
- [34] C. S. Chang, M. Kostylev, A. O. Adeyeye, M. Bailleul, and S. Samarin, *EPL* 96, 57007 (2011). 10.1209/0295-5075/96/57007
- [35] K. Vogt, H. Schultheiss, S. J. Hermsdoerfer, P. Pirro, A. A. Serga, and B. Hillebrands, *Appl. Phys. Lett.* 95, 182508 (2009). 10.1063/1.3262348
- [36] T. Sebastian, Y. Kawada, B. Obry, T. Brächer, P. Pirro, D. A. Bozhko, A. A. Serga, H. Naganuma, M. Oogane, Y. Ando et al., *J. Phys. D: Appl. Phys.* 48, 164015 (2015). 10.1088/0022-3727/48/16/164015
- [37] K. Perzlmaier, M. Buess, C. H. Back, V. E. Demidov, B. Hillebrands, and S. O. Demokritov, *Phys. Rev. Lett.* 94, 057202 (2005). 10.1103/PhysRevLett.94.057202
- [38] H. T. Nembach, J. M. Shaw, C. T. Boone, and T. J. Silva, *Phys. Rev. Lett.* 110, 117201 (2013). 10.1103/PhysRevLett.110.117201
- [39] T. Mewes, J. Kim, D. V. Pelekhov, G. N. Kakazei, P. E. Wigen, S. Batra, and P. C. Hammel, *Phys. Rev. B* 74, 144424 (2006). 10.1103/PhysRevB.74.144424
- [40] O. Klein, G. de Loubens, V. V. Naletov, F. Boust, T. Guillet, H. Hurdequint, A. Leksikov, A. N. Slavin, V. S. Tiberkevich, and N. Vukadinovic, *Phys. Rev. B* 78, 144410 (2008). 10.1103/PhysRevB.78.144410
- [41] H.-J. Chia, F. Guo, L. M. Belova, and R. D. McMichael, *Phys. Rev. Lett.* 108, 087206 (2012). 10.1103/PhysRevLett.108.087206
- [42] S. Tamaru, K. Yakushiji, A. Fukushima, S. Yuasa, and H. Kubota, *IEEE Magn. Lett.* 5, 3700304 (2014). 10.1109/LMAG.2014.2365435
- [43] S. Zhang, S. A. Oliver, N. E. Israeloff, and C. Vittoria, *Appl. Phys. Lett.* 70, 2756 (1997). 10.1063/1.118974
- [44] A. Banholzer, R. Narkowicz, C. Hassel, R. Meckenstock, S. Stienen, O. Posth, D. Suter, M. Farle, and J. Lindner, *Nanotechnology* 22, 295713 (2011). 10.1088/0957-4484/22/29/295713
- [45] C. Schoeppner, K. Wagner, S. Stienen, R. Meckenstock, M. Farle, R. Narkowicz, D. Suter, and J. Lindner, *J. Appl. Phys.* 116, 033913 (2014). 10.1063/1.4890515

- [46] S. E. Barnes, M. Aprili, I. Petkovic, and S. Maekawa, *Supercond. Sci. Technol.* 24, 024020 (2011). 10.1088/0953-2048/24/2/024020
- [47] S. Mai, E. Kandelaki, A. F. Volkov, and K. B. Efetov, *Phys. Rev. B* 84, 144519 (2011). 10.1103/PhysRevB.84.144519
- [48] I. A. Golovchanskiy, N. N. Abramov, V. S. Stolyarov, O. V. Emelyanova, A. A. Golubov, A. V. Ustinov, and V. V. Ryazanov, *Supercond. Sci. Technol.* 30, 054005 (2017). 10.1088/1361-6668/aa66a9
- [49] M. Göppl, A. Fragner, M. Baur, R. Bianchetti, S. Filipp, J. M. Fink, P. J. Leek, G. Puebla, L. Steffen, and A. Wallraff, *J. Appl. Phys.* 104, 113904 (2008). 10.1063/1.3010859
- [50] D. M. Pozar, *Microwave Engineering*, 4th ed. (John Wiley & Sons, Inc., 2011).
- [51] H. Huebl, C. W. Zollitsch, J. Lotze, F. Hocke, M. Greifenstein, A. Marx, R. Gross, and S. T. B. Goennenwein, *Phys. Rev. Lett.* 111, 127003 (2013). 10.1103/PhysRevLett.111.127003
- [52] Y. Tabuchi, S. Ishino, T. Ishikawa, R. Yamazaki, K. Usami, and Y. Nakamura, *Phys. Rev. Lett.* 113, 083603 (2014). 10.1103/PhysRevLett.113.083603
- [53] X. Zhang, C.-L. Zou, L. Jiang, and H. X. Tang, *Phys. Rev. Lett.* 113, 156401 (2014). 10.1103/PhysRevLett.113.156401
- [54] C. Song, T. W. Heitmann, M. P. DeFeo, K. Yu, R. McDermott, M. Neeley, J. M. Martinis, and B. L. T. Plourde, *Phys. Rev. B* 79, 174512 (2009). 10.1103/PhysRevB.79.174512
- [55] A. Aharoni, *J. Appl. Phys.* 83, 3432 (1998). 10.1063/1.367113
- [56] A. Aharoni, L. Pust, and M. Kief, *J. Appl. Phys.* 87, 6564 (2000). 10.1063/1.372771
- [57] S. O. Demokritov, B. Hillebrands, and A. N. Slavin, *Phys. Rep.* 348, 441 (2001). 10.1016/S0370-1573(00)0011-2
- [58] J. H. Kwon, S. S. Mukherjee, P. Deorani, M. Hayashi, and H. Yang, *Appl. Phys. A* 111, 369 (2013). 10.1007/s00339-012-7542-x
- [59] P. Deorani, J. H. Kwon, and H. Yang, *Curr. Appl. Phys.* 14, S129 (2014). 10.1016/j.cap.2013.11.008
- [60] A. A. Serga, A. V. Chumak, and B. Hillebrands, *J. Phys. D: Appl. Phys.* 43, 264002 (2010). 10.1088/0022-3727/43/26/264002
- [61] P. Wessels, A. Vogel, J.-N. Tödt, M. Wieland, G. Meier, and M. Drescher, *Sci. Rep.* 6, 22117 (2016). 10.1038/srep22117
- [62] See <http://www.femm.info/wiki/HomePage> for FEMM software details.
- [63] J. H. Kwon, J. Yoon, P. Deorani, J. M. Lee, J. Sinha, K.-J. Lee, M. Hayashi, and H. Yang, *Sci. Adv.* 2, e1501892 (2016). 10.1126/sciadv.1501892
- [64] K. G. Fedorov, S. V. Shitov, H. Rotzinger, and A. V. Ustinov, *Phys. Rev. B* 85, 184512 (2012). 10.1103/PhysRevB.85.184512
- [65] A. L. Pankratov, K. G. Fedorov, M. Salerno, S. V. Shitov, and A. V. Ustinov, *Phys. Rev. B* 92, 104501 (2015). 10.1103/PhysRevB.92.104501
- [66] J. R. Clem, *J. Appl. Phys.* 113, 013910 (2013). 10.1063/1.4773070
- [67] D. C. Mattis and J. Bardeen, *Phys. Rev.* 111, 412 (1958). 10.1103/PhysRev.111.412
- [68] C. P. McClay, S. Soares, and P. S. Weitzman, *Superconducting Microwave Transmission Lines* (John Wiley & Sons, Inc., 1991).
- [69] D. Janjusevic, M. S. Grbic, M. Pozek, A. Dulcic, D. Paar, B. Nebendahl, and T. Wagner, *Phys. Rev. B* 74, 104501 (2006). 10.1103/PhysRevB.74.104501
- [70] N. Samkharadze, A. Bruno, P. Scarlino, G. Zheng, D. P. DiVincenzo, L. DiCarlo, and L. M. K. Vandersypen, *Phys. Rev. Appl.* 5, 044004 (2016). 10.1103/PhysRevApplied.5.044004