Temperature control of Fano resonances and transmission in superconducting metamaterials

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Abstract: Losses are the main evil that limits the use of metamaterials in practical applications. While radiation losses may be controlled by design, Joule losses are hereditary to the metamaterial structures. An exception is superconducting metamaterials, where Joule losses can be uniquely controlled with temperature in a very wide range. We put this in use by demonstrating temperature-dependent transmission in the millimeter-wave part of the spectrum in high-Tc superconducting cuprate metamaterials supporting sub-radiant resonances of Fano type.

OCIS codes: (160.3918) Metamaterials; (000.4930) Other topics of general interest

References and links

1. N. Papasimakis, V. A. Fedotov, N. I. Zheludev, and S. L. Prosvirnin, “Metamaterial analog of electromagnetically induced transparency,” Phys. Rev. Lett. **101**(25), 253903 (2008).
2. S. Zhang, D. A. Genov, Y. Wang, M. Liu, and X. Zhang, “Plasmon-induced transparency in metamaterials,” Phys. Rev. Lett. **101**(4), 047401 (2008).
3. P. Tassin, L. Zhang, T. Koschny, E. N. Economou, and C. M. Soukoulis, “Low-loss metamaterials based on classical electromagnetically induced transparency,” Phys. Rev. Lett. **102**(5), 053901 (2009).
4. S. Y. Chiam, R. Singh, C. Rockstuhl, F. Lederer, W. L. Zhang, and A. A. Bettiol, “Analogue of electromagnetically induced transparency in a terahertz metamaterial,” Phys. Rev. B **80**(15), 153103 (2009).
5. N. Liu, L. Langguth, T. Weiss, J. Kästel, M. Fleischhauer, T. Pfau, and H. Giessen, “Plasmonic analogue of electromagnetically induced transparency at the Drude damping limit,” Nat. Mater. **8**(9), 758–762 (2009).
6. N. Papasimakis, and N. I. Zheludev, “Metamaterial-induced transparency,” Opt. Photonics News **20**(10), 22 (2009).
7. A. E. Miroshnichenko, S. Flach, and Y. S. Kivshar, “Fano resonances in nanoscale structures,” arXiv:0902.3014v4.
8. N. Liu, T. Weiss, M. Mesch, L. Langguth, U. Eigenthaler, M. Hirscher, C. Sönnichsen and H. Giessen, “Planar metamaterial analogue of electromagnetically induced transparency for plasmonic sensing,” Nano Lett. **9** (to be published).
9. B. Lahiri, A. Z. Khokhar, R. M. De La Rue, S. G. McMeekin, and N. P. Johnson, “Asymmetric split ring resonators for optical sensing of organic materials,” Opt. Express **17**(2), 1107–1115 (2009).
10. A. E. Nikolaenko, F. De Angelis, S. A. Boden, N. Papasimakis, P. Ashburn, E. Di Fabrizio, and N. I. Zheludev, “Carbon nanotubes in a photonic metamaterial,” Phys. Rev. Lett. (to be published).
11. Z. L. Sámson, K. F. MacDonald, F. DeAngelis, B. Gholipour, K. Knight, C. C. Huang, E. DiFabrizio, D. W. Hewak, and N. I. Zheludev, “Metamaterial electro-optic switch of nanoscale thickness,” Appl. Phys. Lett. **96**(14), 143105 (2010).
12. V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis, and N. I. Zheludev, “Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry,” Phys. Rev. Lett. **99**(14), 147401 (2007).
13. E. Plum, V. A. Fedotov, P. Kuo, D. P. Tsai, and N. I. Zheludev, “Towards the lasing spaser: controlling metamaterial optical response with semiconductor quantum dots,” Opt. Express **17**(10), 8548–8551 (2009).
14. M. A. Noginov, G. Zhu, M. Mayy, B. A. Ritzo, N. Noginova, and V. A. Podolskiy, “Stimulated emission of surface plasmon polaritons,” Phys. Rev. Lett. **101**(22), 226806 (2008).
15. D. A. Bobb, G. Zhu, M. Mayy, A. V. Gavrilenko, P. Mead, V. I. Gavrilenko, and M. A. Noginov, “Engineering of low-loss metal for nanoplasmonic and metamaterials applications,” Appl. Phys. Lett. **95**(15), 151102 (2009).
16. K. Boratay Alici, and E. Ozbay, “Low-temperature behavior of magnetic metamaterial elements,” N. J. Phys. **11**(4), 043015 (2009).
17. R. Singh, Z. Tian, J. G. Han, C. Rockstuhl, J. Q. Gu, and W. L. Zhang, “Cryogenic temperatures as a path toward high-Q terahertz metamaterials,” Appl. Phys. Lett. **96**(7), 071114 (2010).

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18. M. Ricci, N. Orloff, and S. M. Anlage, "Superconducting metamaterials," Appl. Phys. Lett. **87**(3), 034102 (2005).
19. F. Magnus, B. Wood, J. Moore, K. Morrison, G. Perkins, J. Fyson, M. C. K. Wiltshire, D. Caplin, L. F. Cohen, and J. B. Pendry, "A d.c. magnetic metamaterial," Nat. Mater. **7**(4), 295–297 (2008).
20. N. Klein, "High-frequency applications of high-temperature superconductor thin films," Rep. Prog. Phys. **65**(10), 1387–1425 (2002).
21. A. Tsiatmas, R. Buckingham, V. A. Fedotov, S. Wang, Y. Chen, P. de Groot, and N. I. Zheludev, "Superconducting plasmonics and extraordinary transmission," arXiv:1004.0729.
22. V. A. Fedotov, N. Papasimakis, E. Plum, A. Bitzer, M. Walther, P. Kuo, D. P. Tsai, and N. I. Zheludev, "Spectral collapse in ensembles of meta-molecules," arXiv: 0908.2533.
23. T. Van Duzer, and C. W. Turner, *Principles of Superconducting Devices and Circuits* (Elsevier, New York, 1981).
24. R. Schwab, E. Gaganidze, J. Halbritter, R. Heidinger, R. Aidam, and R. Schneider, "YBCO wafer qualification by surface resistance measurements combined with performance studies of microstrip resonators," J. Phys. C. Superconduct. Appl. **351**, 25–28 (2001).
25. J. Talvacchio, M. G. Forrester, J. R. Gavaler, and T. T. Braggins, "Large-area YBCO films for microwave applications," IEEE Trans. Magn. **27**(2), 978–981 (1991).

Metamaterials, supporting Fano resonances have recently attracted considerable attention for their sharp dispersion features making them ideally suited for slow light [1–7], sensor [8,9] nonlinear [10] and switching [11] applications. Such resonances appear as a result of interaction between a high- and low-quality excitation modes leading to asymmetric line profiles. An example of such system is an array of asymmetrically split rings, where anti-symmetric current mode corresponding to magnetic dipole excitation is coupled to a strongly radiating low-Q electric dipole mode [12]. The lifetime of such mode and the quality factor of the corresponding Fano resonance is controlled by the asymmetry of the metamaterial resonators and in the absence of dissipative losses can be made infinitely high.

In real metamaterial systems it is the dissipation that limits the maximum possible quality factor of the Fano resonances, and therefore controlling Joule losses is imperative for achieving sharp resonant response. The presently favored solution is to reduce dissipation by using optically-pumped gain media, such as semiconductor quantum dots [13], semiconductor quantum wells and organic dyes [14], embedded into metallic nanostructures (parametric gain systems are also under investigation, so far theoretically). While band-structure engineering of metallic alloys promises improved plasmonic media with low Joule losses [15], resistivity of metals can be reduces by cooling the latter to cryogenic temperatures [16,17]. The use of superconductors [18,19], in principle offers a practical way to completely eliminate Joule losses and provide by far much greater temperature control over dissipation than in metals. For instance, cuprate superconductors show lower surface resistivity than copper at frequencies below 200 GHz even at liquid nitrogen temperatures [20] and show intriguing plasmonic properties [21].

Here we report the first experimental study of *free-space* transmission of superconducting metamaterials, which was conducted in the millimeter-wave frequency

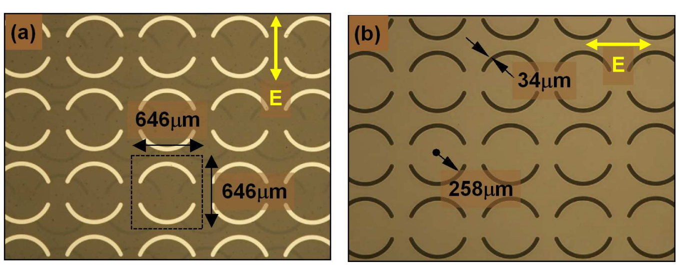

Fig. 1. Superconducting metamaterials. Panels (a) and (b) show photographs of correspondingly negative and positive forms of asymmetrically-split ring metamaterial. Dashed box indicates the metamaterial's unit cell.

range. Using YBCO films microstructured in the form of a *large double-periodic array* of asymmetrically-split-ring resonators we observed Fano resonances and showed that the

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strength of the resonances and transmission of the metamaterial arrays can be efficiently controlled by temperature.

Metamaterial structures were manufactured in 330 nm thick YBCO films deposited on 1 mm thick sapphire substrates. These cuprate films become superconducting below a critical temperature T_c ≈88 K and are characterized by relatively large porosity with an average lateral size of the pores of about 1 μm. Due to enhanced vortex pinning such porous films have typically lower surface resistance (R_s [77K, 10 GHz] < 300 μΩ) and can support larger critical currents (J_c [77K] > 3 MA/cm^2) than other forms of YBCO films, and are therefore better suited for applications in high-Q microwave devices. We have manufactured positive and negative forms of the asymmetrically split ring metamaterial, corresponding to square arrays of circular wires and slits (apertures in the cuprate film), as shown in Figs. 1(c) and 1(d) respectively. Each unit cell of the metamaterial arrays had the size of 646 μm x 646 μm and contained one pair of the circular elements with the arc length corresponding to 140 and 142 degrees, which formed an asymmetrically split ring resonator with the radius of 258 μm. Both positive and negative forms of the split ring resonators were wet-etched in the cuprate films following resist patterning with the use of e-beam lithography. The metamaterial arrays were 28 mm in diameter and contained 1400 asymmetrically split rings.

Transmission spectra of the cuprate metamaterials were measured in 80 – 110 GHz range of frequencies at temperatures above and below T_c using a vector network analyzer and linearly polarized horn antennas. Free-space measurements were performed with the samples placed in a liquid nitrogen flow optical cryostat located between the antennas. The polarization of the incident wave was set parallel to the split for positive split rings and perpendicular to the split in the case of negative split rings [as indicated in Figs. 1(c) and 1(d)], which was required for the excitation of the Fano resonances.

The results of transmission measurements are presented on Figs. 2(a) and 2(b), where we plotted changes in the transmission spectra of the metamaterials with decreasing temperature (down to 77 K) relative to their room temperature state. The measured changes clearly indicate the appearance of the Fano resonances at around 87 GHz, which become substantially stronger as the YBCO film becomes superconducting. In the case of positive asymmetrically split ring metamaterial the resonance emerges as a peak in the transmission change spectrum

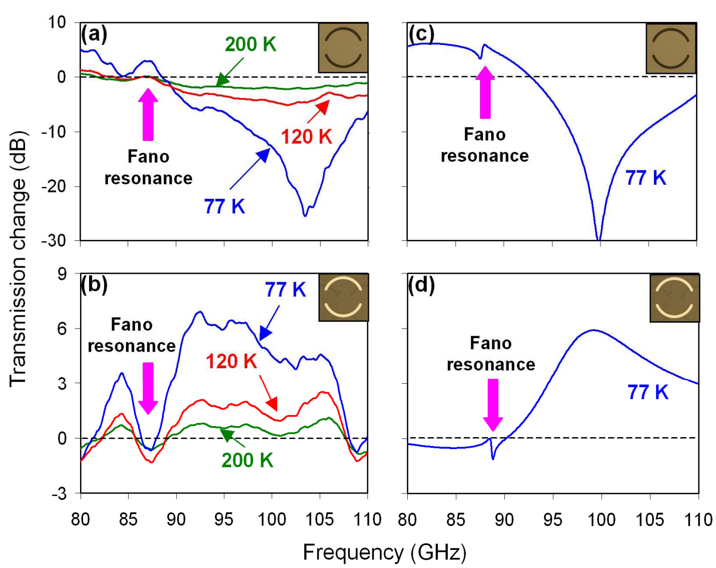

Fig. 2. Changes in transmission spectra of superconducting YBCO metamaterials relative to their room temperature state. Panels (a) and (b) present experimentally measured data for positive and negative metamaterial designs respectively, while panels (c) and (d) show corresponding results of numerical simulations.

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corresponding to increased transmission (metamaterial-induced transparency [6]), while the complementary (i.e. negative) version of the structure shows a pronounced dip corresponding to resonantly suppressed transmission (which fully agrees with the Babinet principle). Also, at frequencies away from this resonance the complementary metamaterial structures show gradual increase and decrease of the transmission levels with temperature and the changes become most pronounced upon superconducting phase transition. This is illustrated on Fig. 3 for the case of negative metamaterial, where we plotted its temperature-induced transmission change observed at 84 GHz.

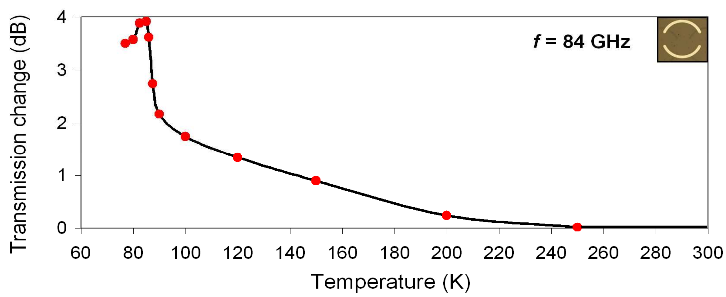

Fig. 3. Change of transmission measured at 84 GHz as a function of temperature for negative superconducting YBCO metamaterial (relative to its room temperature state). Experimental data is presented by red dots, while black curve provides guide for eye.

The results of our measurements appear to be in a good qualitative agreement with the simulated data, which we present in Figs. 2(b) and 2(c) for the case of liquid nitrogen temperature. Calculations of the transmission change were performed using 3D Maxwell equations solver integrated into commercially available Comsol Multiphysics modeling package. Each metamaterial structure was modeled as a single unit cell subjected to periodic boundary conditions in the lateral directions, which, given the size of the arrays, appears to be a good approximation for this type of metamaterials [22]. Electromagnetic properties of the superconductor were described by its surface impedance calculated from the resistivity data [23–25] using the standard two-fluid model. Although the position of the Fano resonances is very well predicted by our model the agreement between the simulated and experimental data is only qualitative showing the main trends. We believe that this is due to a great deal of uncertainty in retrieving modeling parameters for high-Tc superconducting films using the data available in the literature. Moreover, for temperatures above the critical point the surface impedance model may not work accurately enough because the skin depth in the cuprate film becomes comparable to the film thickness thus failing the impendence model. Periodic microstructuring of the YBCO films is likely to affect vortex pinning and therefore alter the superconducting state and could be another factor explaining some discrepancy between experimental and simulated data.

In conclusion, we have demonstrated that structuring of YBCO film with metamaterial pattern preserves its essential superconductor properties that allows treatment of such structure as a low-loss conductor. We have provided the first experimental demonstration of Fano resonances in superconducting cuprate metamaterials operating in the millimeter-wave frequency range at temperatures down to 77 K. The strength of the resonances is controlled with temperature and increases dramatically as the temperature of the metamaterials drops below the critical point. At frequencies away from the Fano resonance the complementary forms of the cuprate structures show gradual increase and decrease of transmission consistent with the Babinet principle. Out results provide optimism that high quality resonance spectral filters could be developed for the millimeter wave part of the spectrum with the use of high-temperature superconductors, lending to various security and sensor applications.

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