Superconducting plasmonics and metamaterials: from extraordinary transmission to Fano resonances

A. R. Buckingham[1], A. Tsiatmas[2], V. A. Fedotov[2], Y. Chen[3], P. A. J. de Groot[1] and N. I. Zheludev[2]

[1]School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom, Tel. +44 23 80592104, arb202@soton.ac.uk

[2]Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom

[3] Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot, OX11 0QX, United Kingdom

Abstract: By varying temperature superconductors can be converted from lossy to ideal metals, permitting the control of both extraordinary transmission in arrays of subwavelength holes, and quality factors of Fano resonances in superconducting metamaterial films.

Superconductors may be considered as plasmonic media, exhibiting both a negative dielectric constant and a dominant kinetic resistance. Use of superconductors in metamaterials permits the control and reduction of the hereditary Joule losses, paving the way for low-loss, high Q-factor metamaterials.

Metamaterials supporting Fano-type resonances have attracted considerable attention for use in sensor, nonlinear and switching applications due to their sharp dispersion. In an asymmetric split ring (ASR) the resonance lifetime and the Q-factor are controlled by the ring asymmetry, and in the absence of Joule losses may be made infinitely high. Thus control of the Joule losses through the use of high-temperature superconducting (HTS) materials is important in achieving a sharp resonant response. Furthermore, the plasmonic properties of superconductors can be investigated when considering the temperature-dependent effects of extraordinary transmission. We show that the unusual optical properties can be attributed to the resonant coupling of light with plasmons mediated by the periodic patterning of the HTS films.

We report on free-space measurements of the temperature dependent transmission of millimetre waves in HTS metamaterials. HTS films of $YBa_2Cu_3O_{7.5}$ have been lithographically structured into arrays of both ASR and holes. In the ASR arrays, Fano resonances at 87GHz become substantially stronger as the superconducting critical temperature (T_C) is reached (Figure 1). These experimental results are in good agreement with the simulated data and we conclude that this provides a route towards high Q-factor spectral filters for the millimetric wave part of the spectrum [1]. In the hole array, the experimental data show extraordinary transmission peaks which dramatically increase in amplitude as T_C is reached, where we observe a Q-factor exceeding 250 due to plasmonic interactions (Figure 2). As the temperature is reduced below T_C the transmission amplitude decreases slowly. The origin of this effect is in the collective interaction between the holes. Above T_C the material behaves like a lossy metal the long-range interaction between neighbouring holes is suppressed, inhibiting extraordinary transmission. Our results show that the extraordinary transmission effect does not require surface plasmons to exist, but the effect is further enhanced in the regime whereby the media may be considered plasmonic [2]. Further to this we report on recent measurements on Nb based superconducting metamaterials where losses may be reduced further still, and on arrays of interacting superconducting disks whereby enhancement of the incident electromagnetic field is strong enough to break superconductivity leading to non-linear responses in metamaterials.

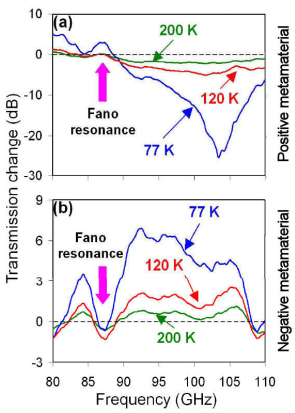

Figure 1: Experimental verification of Fano resonances in positive (graph a) and negative (graph b) ASR metamaterial arrays fabricated from HTS films.

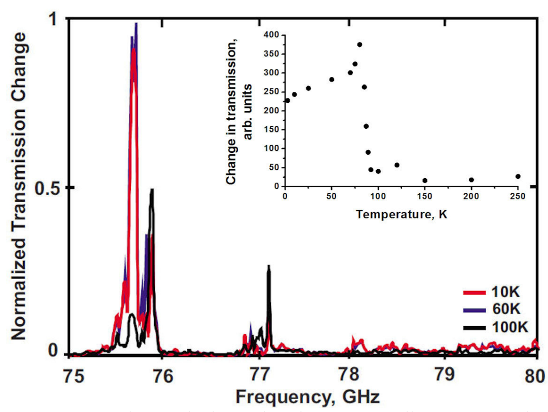

Figure 2: Experimental data showing extraordinary transmission peaks in a HTS hole array metamaterial. Inset shows increase in transmission at 81 GHz relative to room temperature transmission.

[1] V.A. Fedotov, A. Tsiatmas, J. H. Shi, R. Buckingham, P. de Groot, Y. Chen, S. Wang and N.I. Zheludev, Opt. Exp. **18** (9), 9015 (2010)
[2] A. Tsiatmas, A. R. Buckingham, V. A. Fedotov, S. Wang, Y. Chen, P. A. J. de Groot and N. I. Zheludev, Appl. Phys. Lett. **97** (1), 111106 (2010)