Plasmonic properties of superconducting niobium in the optical part of the spectrum


1. Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK
2. Department of Physics, National Taiwan University, Taipei 10617, Taiwan
3. Centre for Disruptive Photonic Technologies, TPI, SPMS, Nanyang Technological University, Singapore 637371
4. School of Physics and Astronomy, University of Southampton, SO17 1BJ, UK
5. Department of Physics, Loughborough University, Loughborough, LE11 3TU, UK
6. Research Center for Applied Sciences, Academia Sinica, Taipei 115, Taiwan

We show for the first time that, contrary to common expectations, transition to superconductivity affects plasmonic behaviour of niobium at optical frequencies. This result is unexpected as photon energy is orders of magnitude higher than the binding energy of the Cooper pairs, the superconducting charge carriers.

We study temperature-induced variation in the optical properties of a nanostructured superconducting metamaterial. In non-superconducting metamaterials, temperature-related changes in optical response tend to saturate below 50K. In contrast, both the position and the strength of our metamaterial's resonances exhibit a pronounced critical dependence on temperature down to a few Kelvin. Niobium is a well-known low-temperature superconductor, well-described by the Bardeen-Cooper-Schrieffer theory. Our results shed new light on this material and theory, suggesting that superconductivity may play a role in optical dielectric response near the superconducting transition.

The superconducting metamaterial (Fig. 1a), was created by focused ion beam (FIB) milling 250 nm deep V-grooves in a 300 nm thick niobium (Nb) film on a sapphire substrate. Niobium is a type-II superconductor with transition temperature at 9.2K, below which it exhibits zero DC and low microwave resistance. The binding energy of the Cooper pairs in Nb is just few meV so the response at optical frequencies will be lossy, since each optical-range photon carries sufficient energy (~1eV) to break Cooper pairs and therefore to locally suppress superconductivity.

The metamaterial was placed in an optical cryostat and its reflectivity was measured from room temperature down to 6K (Fig 1b). Two broad resonant dips are observed in all spectra (Fig. 1b), one at ~1100-1300 nm and another at 1400-1600 nm. As temperature decreases, one initially observes a red-shift in the position of the latter as well as a decrease in the depth of the reflectivity dip, however at ~9-10K, as Nb enters the superconducting state, both trends are reversed. Furthermore, we also observed such a critical behaviour in the experimentally measured dielectric constants of an unstructured Nb film around the transition temperature. We explain the experimentally observed critical dependence of the metamaterial resonance position on the transition temperature of Nb by means of a thermodynamics-based model that takes into account the change in the free energy of the metamaterial resonator between the normal and superconducting states. We argue that this is a signature of the transition to the superconducting state, which is detected by infrared photons.