Optical range plasmonics of niobium around the superconducting transition temperature

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Abstract: We show that a niobium metamaterial exhibits optical plasmonic resonances which change in a critical way near the superconducting transition temperature of 9K. This suggest a hitherto unknown link between superconductivity and optical range plasmonics.

Superconductivity is commonly expected to be insignificant in optics, where photon energy is orders of magnitude higher than the binding energy of the Cooper pairs, the superconducting charge carriers. Here we show that, contrary to this expectation, superconductivity does affect plasmonic behaviour at optical frequencies.

We study temperature-induced changes in the optical properties of a nanostructured superconducting metamaterial. In non-superconducting metamaterials, temperature-related variations 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.

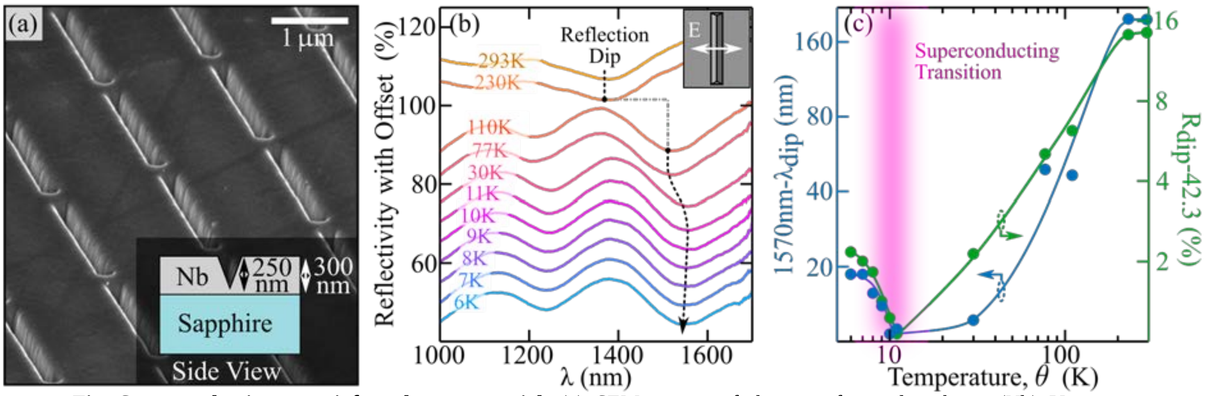

Fig. Superconducting near-infrared metamaterial. **(a)** SEM picture of the manufactured niobium (Nb) V-groove metamaterial with composition and geometry shown inset. **(b)** Reflectivity spectra of the metamaterial at different substrate temperatures for light polarized perpendicular to the V-grooves (as illustrated inset; 'E' denotes electric field). Traces are sequentially offset vertically by 5% upwards for clarity. The black dashed line highlights the change in the spectral position of the long-wavelength resonant dip as a function of temperature. **(c)** The position (blue; left axis) and depth (green; right axis) of the long-wavelength resonant dip in metamaterial reflectivity as a function of temperature. The pink vertical stripe highlights the transition temperature of niobium.

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 split Cooper pairs and therefore to locally supress 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. We argue that this is a signature of the transition to the superconducting state, which is detected by infrared photons. The critical dependence of resonance position and strength on the transition temperature of Nb is likely to be related to increased order parameter fluctuations around the superconducting transition.