Optical range plasmonics around superconducting transition temperature of niobium metamaterial

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Abstract: By measuring the reflectivity of a nanostructured niobium film, we demonstrate a critical dependence of niobium's optical response on its superconducting transition temperature around 9K. Our results 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, despite the expectations to the contrary, superconductivity does affect the plasmonic behaviour at optical frequencies. We study the temperature-induced change in the optical properties of a nanostructured superconducting metamaterial. In non-superconducting metamaterials, the temperature-related variations of the optical response tend to saturate at temperatures below 50K. In contrast, both the position and the strength of our metamaterial's resonances exhibit a pronounced critical dependence on temperature down to few Kelvin. Our results suggest there might exist a new mechanism that plays role in forming optical dielectric response near the superconducting transition.

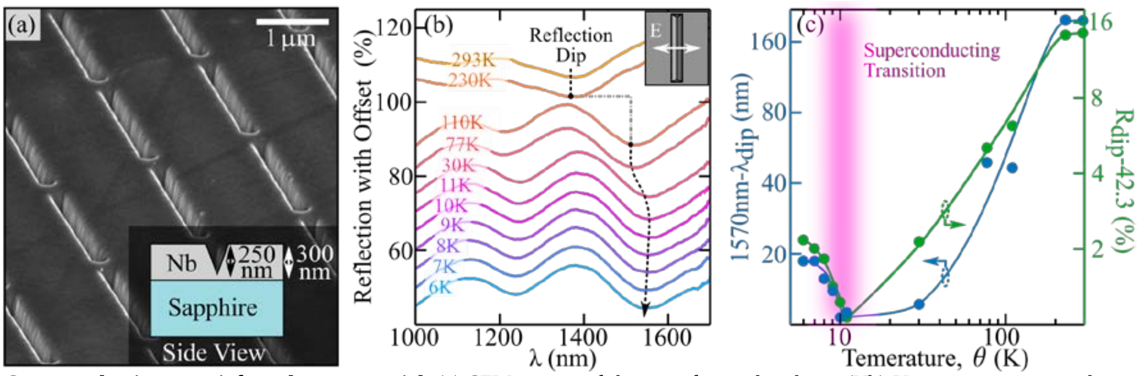

Fig. Superconducting near-infrared metamaterial. **(a)** SEM picture of the manufactured niobium (Nb) V-groove metamaterial with composition and geometry shown inset. **(b)** Reflectivity spectra of the metamaterial at different substrate temperatures for light polarized perpendicular to the V-grooves (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, shown in Fig. 1a, was fabricated by Focused Ion Beam (FIB) milling 250nm deep V-grooves in 300nm thick niobium film on sapphire substrate. Niobium is a type-II superconductor with transition temperature at 9.2K in which the binding energy of the Cooper pairs is just a few meV. Therefore, its optical response will be lossy, since each optical-range photon will carry sufficient energy (~1eV) to split Cooper pairs and therefore to locally supress the superconductivity.

The metamaterial was placed into an optical cryostat and its reflectivity was measured at temperatures from 6K to room temperature. The results are shown in Fig 1b. Two broad resonant dips can be observed in all spectra, one at ~1100nm-1300nm and another at 1400-1600nm (the latter is highlighted by the dashed line in Fig. 1b). The depth and position of the long-wavelength resonance are shown in Fig. 1c as a function of temperature. As temperature is lowered, one can initially observe a red-shift of the position as well as decreasing depth of the reflectivity dip, however at ~9-10K, as niobium 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.