Channelling plasmons in nanostructured superconducting waveguides

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Abstract

We show that superconductors are intrinsic low-loss plasmonic media able to support highly confined plasmonic excitations. We identify several promising superconducting waveguide configurations that provide nanoscale localization of plasmons at frequencies up to few THz and support their dispersion-less propagation for tens of centimetres.

1. Introduction

Surface plasmon polaritons (or simply plasmons) are electromagnetic waves coupled to collective oscillations of the conduction electrons that propagate along the surface of a medium with negative permittivity, such as a metal or a semiconductor.

Due to their bounded nature plasmons are able to confine and route light at the nanometre scale, offering an intriguing opportunity to bridge the gap between current electronic and photonic technologies, and transform chip-scale data transport paradigm towards faster, smaller, and more efficient electronics.

Practical applications of plasmons, however, are hampered by dissipative losses, which are an inherited feature of all metal (or semiconductor)-based plasmonic waveguides. Possible solutions that are widely considered at present include compensation of losses with gain [1] and search for new, better plasmonic materials [2].

Here we show that superconductors represent unique low-loss plasmonic media, which can support virtually dispersion-less propagation of plasmonic waves at terahertz frequencies (and below), with an unprecedented degree of confinement - several thousand times larger than possible with the noble metals at optical frequencies.

2. Superconducting plasmonics

The plasmonic regime in the noble metals manifests itself just below the plasma frequency, when the free electrons driven by an electromagnetic wave oscillate so rapidly that almost no collisions happen during one period of oscillations. Correspondingly, oscillations of all the electrons become coherent and their acceleration is determined by the strength of the incident field and kinetic inductance of the electrons. At frequencies below few THz the response of metals is controlled by frequent electron-electron collision events (Ohm's law regime), which destroy the coherence and diminish the coupling of electrons with the electromagnetic wave thus prohibiting efficient plasmonic excitations.

Intriguingly, in superconducting state the absence of electron scattering and the dominant kinetic inductance of the charge carriers are natural, resulting from the formation of Cooper-pairs, which should allow the existence of efficient plasmonic excitations, much like optical plasmons, at frequencies ranging from few Hz up to the superconducting gap frequency (around few THz for high-temperature superconductors).

Indeed, recent experiments on temperature control of Fano resonances in superconducting metamaterials [3] and on extraordinary transmission through perforated superconducting films [4] have indirectly shown the existence of plasmonic excitations, which were held responsible for the effects upon superconducting transition. Unfortunately, electromagnetic fields are almost completely expelled from the superconductors, making plasmonic excitations loosely bounded to the surface and weekly localized, and therefore unsuitable for guiding applications.

We found that plasmonic fields can be spatially squeezed on the scale of just few tens of nanometers in properly structured superconducting waveguides, where plasmons are still able to propagate for hundreds of wavelengths adding up to several centimetres.

3. Superconducting plasmonic waveguides

The simplest structure that can support propagation of highly localized superconducting plasmons is the parallel-plate waveguide, where two superconducting plates are separated by nanometer-thick dielectric layer (see Fig. 1(a)). The effective refractive index of the guided plasmonic mode here is significantly higher than that of the dielectric material filling the gap. It is controlled by both the size of the gap and temperature of the superconductor, as illustrated for YBCO in Fig. 1(b). Experimental demonstration of such a remarkable guiding regime is conducted using a two-slit Fabry-Perot interferometer shown in Fig 1(c).

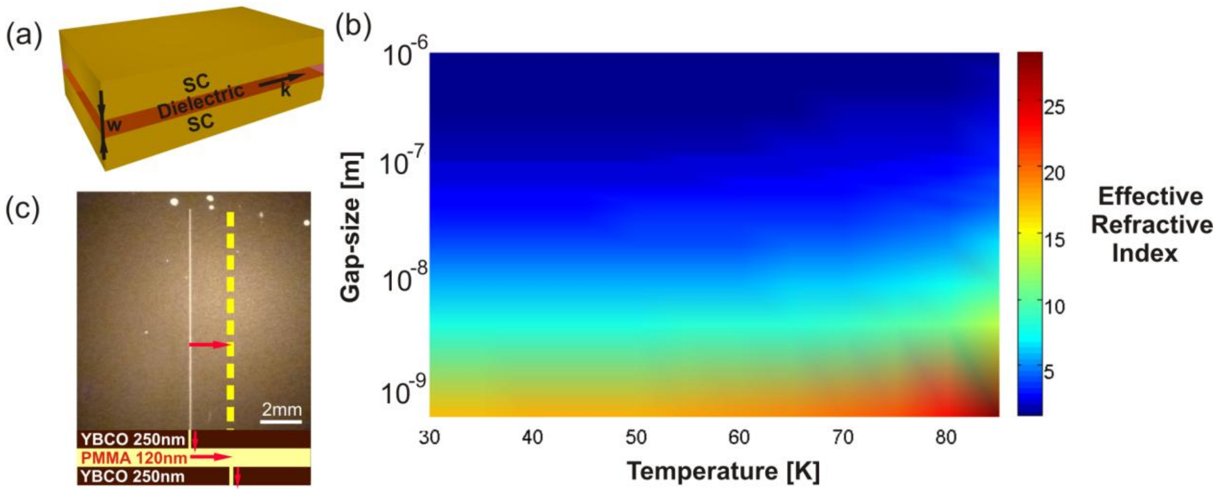

Fig. 1: (a) Schematic of the parallel-plate superconducting waveguide structure. (b) Effective refractive index of the plasmonic mode guided at 100 GHz as a function of the waveguide temperature and air-gap size. (c) Photograph of two-slit Fabry-Perot interferometer based on YBCO parallel-plate waveguide. The dashed yellow line indicates the position of the complimentary slit in the lower YBCO layer, while red arrows show the route of the propagating mode.

Another important waveguide configuration, which allows extreme localization and propagation of plasmonic waves, is a bundle of parallel superconducting micro-wires. Here the number of wires, their radius and separation control the number of supported plasmonic modes, their effective refractive index and propagation length. This is illustrated in Fig. 2 for the case of two YBCO wires that are just-touching.

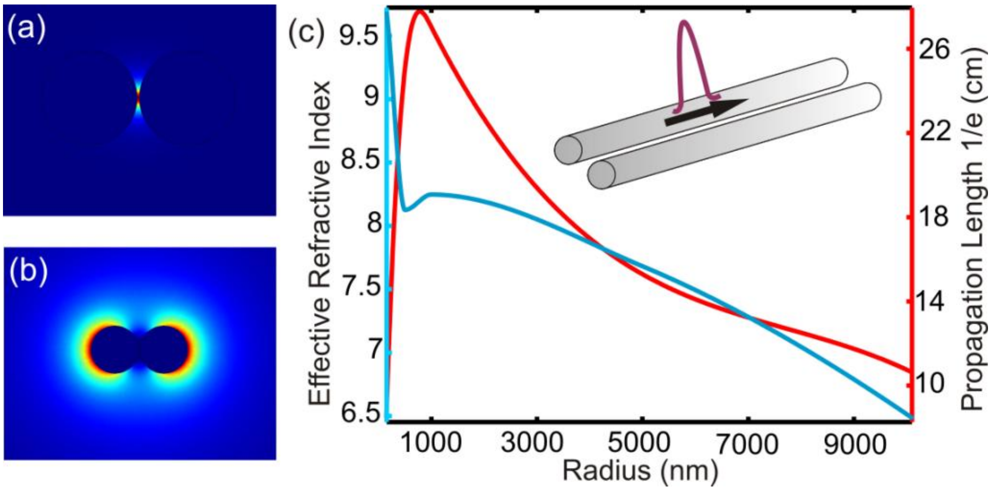

Fig. 2: Panels (a) and (b) show the modes supported by two parallel touching superconducting YBCO wires. (c) Effective refractive index and propagation length of the mode shown in panel (a) plotted at 100 GHz and 30K as a function of the wire radius.

Nanoscale lateral confinement of the plasmonic mode can also be conveniently achieved in a slot waveguide configuration shown in the inset to Fig. 3(a). For example, a 100 nm wide groove made in 500 nm thick YBCO film kept at 30K will support a mode that at 100 GHz propagates for a distance of more than 10 cm with the effective refractive index of 1.5 (see Fig. 3(a)). Remarkably, the cross-section of such a superconducting plasmonic waveguide is about $2x10^7$ times smaller than that of the conventional millimetre-wave frequency waveguides. Furthermore, the plasmonic mode in this wave-guide, as well as in the gap and wire waveguides considered above, propagates with no dispersion (as evident from Fig. 3(b)) paving the way towards dispersion-less plasmonics.

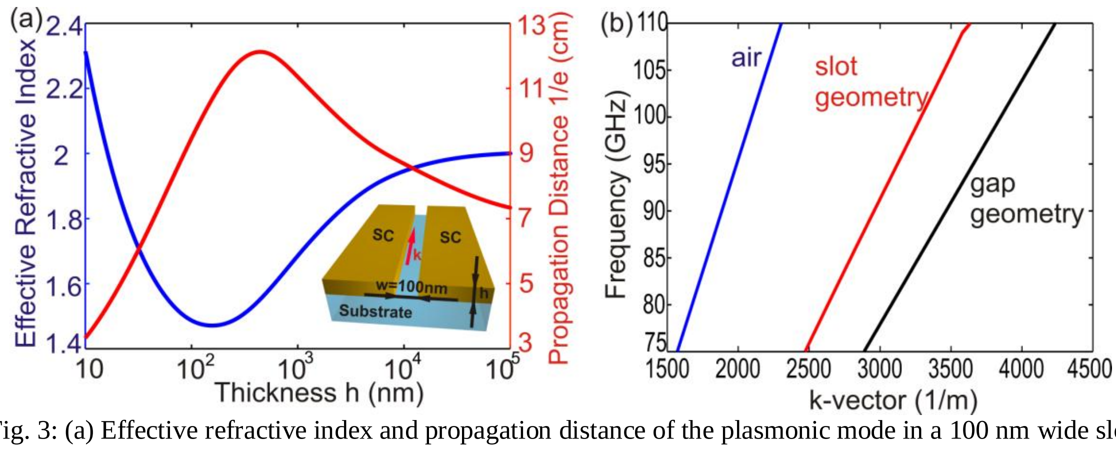

Fig. 3: (a) Effective refractive index and propagation distance of the plasmonic mode in a 100 nm wide slot waveguide plotted as a function of the superconducting film thickness. (b) Dispersion relations of the electro-magnetic waves propagating in a slot and parallel-plate (gap) superconducting waveguides and free space (air).

References

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