Guiding of terahertz photons in superconducting nano-circuits

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***Abstract*— The field of plasmonics, as one of the fascinating areas of photonics, has received great attention for its capability of deep subwavelength confinement. We present a nanoscale plasmonic slot waveguide based on high transition temperature (T_c) superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO). The effect of geometrical parameters on the modal properties of the BSCCO plasmonic slot waveguide and the thermal tuning of the modal properties of the waveguide are explored. It is shown that the rising of temperature results in increasing the mode effective refractive index in exchange for decreasing the propagation length of surface plasmon polaritons (SPPs). Our proposed plasmonic waveguide paves the way for the development of the BSCCO based THz photonic integrated circuity at the nanoscale.**

Keywords*— quantum emitters, high-temperature superconductor, $Bi_2Sr_2CaCu_2O_{8+\delta}$ quantum material, plasmonic waveguides, terahertz integrated circuitry, on-chip light sources, and detectors.

I. Introduction

The intrinsic Josephson junctions (IJJs) terahertz (THz) emitters based on the high transition temperature (T_c) superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) quantum materials offer frequency tunability that covers the entire THz gap [1]–[25]. Such devices can be operated as both quantum THz emitters and surface current sensitive detectors on a single chip, paving the way for the realization of integrated low-loss mm-waves to THz photonic integrated circuitries for applications in quantum information processing, on-chip communication, and spectroscopy.

Plasmonic nanocircuits can manipulate the flow of electromagnetic waves between the light sources and detectors but they suffer from the plasmon propagation loss which is inherent to their material building block. Such plasmonic circuitry is usually based on semiconductors, noble metals, and graphene. Utilizing the superconducting materials with their zero resistance for DC signals and their low-loss response to high-frequency signals below their gap frequency offer the real-time control of plasmonic properties through the application of external perturbation such as temperature, magnetic field, intense light, and current. So superconducting materials have the potential to be considered as alternative platforms for the realization of low-loss or loss-less plasmonic circuitry below their critical temperature, magnetic field, and gap frequency.

Here, we demonstrate a plasmonic slot waveguide, a deep subwavelength air slot, formed between thin superconducting films of slightly underdoped BSCCO with T_c=85 K. Our proposed waveguide is compatible with the IJJs based THz devices. We analyze the effect of structural dimensions on the modal characteristic of the waveguide including the effective refractive index, the propagation length of surface plasmon polaritons (SPPs), and mode energy confinement, all at frequency f=0.3 THz. Furthermore, we investigate the thermal properties of the excited SPPs.

II. Results and Discussion

The schematic of the proposed plasmonic slot waveguide based on superconducting BSCCO is shown in Fig. 1(a). The waveguide is a deep subwavelength air slot of width w in a thin film of BSCCO with a thickness of h. The generated SPPs propagate through the air slot, as schematically shown in Fig. 1(a). The *a-b* plane complex conductivity of BSCCO is extracted from the THz time-domain spectroscopy (TDS) data and was discussed in our earlier work [25].

We employ the numerical finite element simulation method and calculate the effective refractive index (N_{eff}) of the supported mode of the waveguide and propagation length (L_p) of the SPPs using the following equations

$$N_{\mathrm{eff}} = Real\ (\beta)/k_0, \quad (1)$$

$$L_{\mathrm{p}} = 1\ /\ (2\ Imag(\beta)), \quad (2)$$

where β and k_0 are complex propagation constant of the traveling SPPs mode and the free space wavevector, respectively [26].

Furthermore, we examine the energy confinement of the SPPs mode (Γ) in the slot, to find out how well the modal field is confined in the gap. This is defined as the ratio of the power flow in the slot ($w \times h$ area) to the total power flow normal to the *x-z* plane [27]:

$$\Gamma = \frac{\int_{slot} Re\{E\times H^{*}\cdot n\}\, dA}{\int_{total} Re\{E\times H^{*}\cdot n\}\, dA} \quad (3)$$

where E and H are the electric and magnetic field vectors, respectively, and n is the normal unit vector in the y-direction (as shown in Fig. 1(a)).

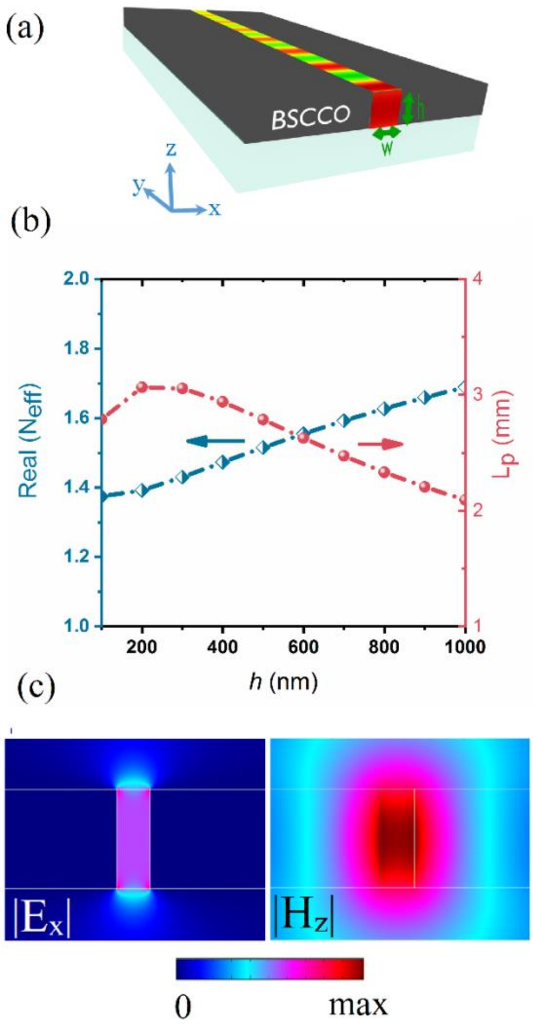

Fig. 1. (a) Schematic diagram of the superconducting THz plasmonic slot waveguide circuitry at the nanoscale. The BSCCO film is shown in grey, and the generated SPPs (colored area) are propagating through the air gap, (b) real part of the mode effective refractive index (N_{eff}), and propagation length (L_p) of THz plasmonic waveguide as a function of BSCCO thickness h for slot width w=100 nm, and (c) x-component of the electric field distribution and z-component of the magnetic field distribution of TEM-like mode at w=100 nm and h=300 nm. All curves are for frequency f=0.3 THz and temperature T=10 K.

We then investigate the properties of the proposed waveguide as a function of BSCCO film thickness (h). There are two superconductor/air interfaces at the slot region, and the SPPs are formed at each interface. As $h \rightarrow 0$, the excited SPPs' coupling becomes weaker, therefore propagation length decreases.

On the other hand, at higher h, SPPs couple and form a quasi-transverse electromagnetic (TEM) like mode. Therefore, due to the increase of the portion of the superconductor, the net refractive index (the mode effective refractive index) gets larger, and SPPs propagation length decreases. The results follow the characteristics of a subwavelength plasmonic slot waveguide [28].

In the rest of the paper, we focus on the characteristics of a superconducting waveguide nano-circuit of w=100 nm and h=300 nm. The x-component of the electric field and z-component of the magnetic field distributions of the fundamental supported mode of the proposed superconducting plasmonic waveguide at temperature T=10 K, far below the BSCCO superconductor transition at T_c=85 K, are shown in Fig. 1(c).

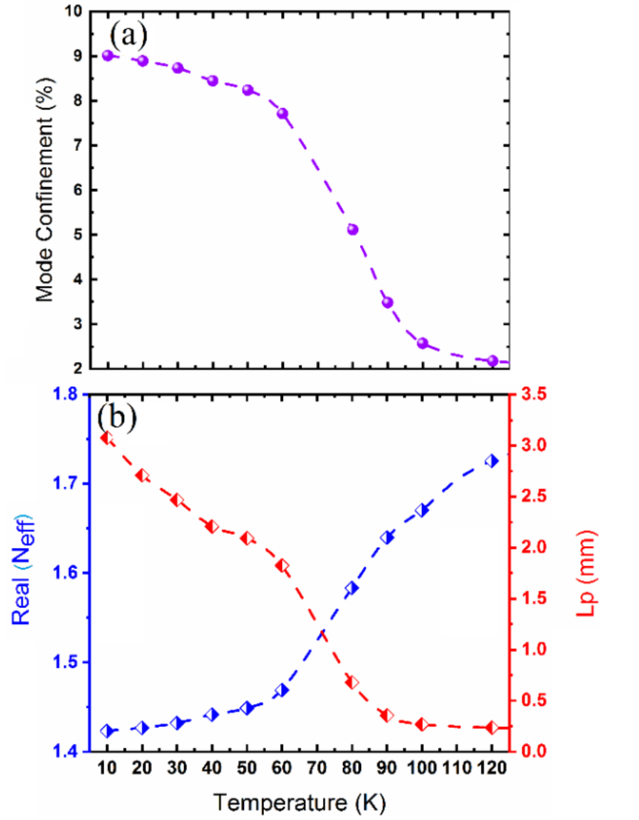

Fig. 2. The temperature dependent (a) mode confinement, and (b) real part of the mode effective refractive index (N_{eff}) and the SPP propagation length (L_p) of the superconducting THz plasmonic waveguide circuitry, at frequency f=0.3 THz and temperature T= 10 K, for the slot dimensions of w=100 nm and h=300 nm.

The dominant components of these fields are perpendicular to the direction of propagation. Therefore, the modes are quasi-TEM modes, and their energy is highly distributed within the slot region.

In the following, we study the temperature dependence of the mode confinement, N_{eff}, and L_p of the SPPs. The temperature-dependent mode confinement of the waveguide is shown in Fig. 2(a). By increasing the temperature, the inductive part of BSCCO permittivity ($|\varepsilon_1|$) decreases [25] which results in a more modal field penetration into the material. Therefore, the higher modal field is within the superconductor at high temperatures. As a result, the mode confinement within the air slot is decreased at higher temperatures (see Fig. 2(a)). On the other hand, a greater penetration of the modal field in the superconductors results in an increase of N_{eff} and consequently a decrease of L_p, as shown in Fig. 2(b) (according to equation (1) and (2)).

III. Conclusion

We proposed a plasmonic waveguide circuitry based on high-T_c superconductor BSCCO with operational frequency f= 0.3 THz. We calculated the modal properties which are supported by the plasmonic waveguide, including the effective refractive index, propagation length, and mode confinement. We first investigated the effect of the variation of the structures' parameters on the characteristics of the supported mode. We then studied the modal properties over a range of temperatures, from T= 10 to 120 K. Our investigation of the superconducting plasmonic waveguide at the nanoscale may be useful for the development of a fully integrated BSCCO THz circuitry for possible applications in on-chip low-loss communication, spectroscopy, and quantum processing.

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