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Microfiber-coupled Superconducting Nanowire Single-Photon Detector

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Abstract**—***High-efficiency Superconducting Nanowire Single-Photon Detectors (SNSPDs) have enabled numerous experiments and applications especially in modern quantum optics and quantum communication. Two types of SNSPDs have been developed so far. One is the standard-fiber-coupled SNSPD with the fiber vertically illuminating the meandered nanowires, the other is waveguide-coupled SNSPD with the nanowires fabricated on the surface of the waveguide which guides photons while the fiber is coupled to the waveguide. Here we propose a new type of SNSPD integrated with microfiber. The photons are guided by a microfiber and evanescently absorbed by the nanowire of SNSPD when the microfiber is atop the superconducting NbN nanowires. The room-temperature optical experiments indicated a coupling efficiency of up to 90% with a 1.3-μm-diameter microfiber for the wavelength of 1550 nm. We were able to demonstrate that the microfiber-integrated detectors achieved a system detection efficiency (SDE) of ~20% at the wavelength of 1550 nm at a system dark count rate (DCR) of 100 Hz with a 2-μm-diameter microfiber. We expect the microfiber-integrated high-efficiency SNSPDs may extend to more applications such as micro-nano optics.*

keywords—SNSPD; microfiber; nanowire

I. INTRODUCTION

Ever since superconducting nanowire single-photon detectors (SNSPDs or SSPDs) were proposed, they have attracted much attention due to the detectors' promising intrinsic properties that include high detection efficiency (DE), low dark count rate (DCR), broadband sensitivity, and low timing jitter. The system detection efficiency (SDE) has been improved to over 90% with a wavelength of 1550 nm in a fiber-coupled system by embedding the SNSPD in an optical cavity [1,2]. The system dark count rate (SDCR) has also been reduced to sub-1 Hz using various methods such as on-chip bandpass filter, bending fiber, and cold filters. On the other hand, the intrinsic broadband sensitivity of SNSPD is suppressed due to the bandwidth of optical cavity, even though several designs of broadband SNSPD have been proposed. Furthermore, with a “fiber-core size” active area of meandered nanowires in the fiber-coupled system, the long nanowires lead to a large kinetic inductance of SNSPD and subsequently a low maximum counting rate and large timing jitter.

An impressing waveguide-coupled SNSPD has been developed in recent years [3]. With SNSPD atop the optical waveguide, photons propagating in the waveguide could be evanescently absorbed to the nanowires within a few tens of microns in length. The on-chip detection efficiency (OCDE) has been estimated to be over 90%, indicating a high absorptance and intrinsic DE of the devices. By correctly dimensioning the waveguide and the nanowire, the absorptance could be over 90% for a wavelength range of more than 700 nm [7]. Furthermore, the length of the nanowire is much shorter comparing to the fiber-coupled SNSPD, leading to a higher counting rate and lower timing jitter (~18 ps). However, the unsatisfactory coupling loss between optical fiber and waveguide lowers the SDE of the waveguide-coupled system (~10%), which limits the application of the waveguide-coupled SNSPD to quantum photonics integrated circuits (QPIC).

In 2003, Tong first demonstrated low-loss optical waveguiding in microfibers and nanofibers (MNFs) with diameters far below the wavelength of the guided light [4], which attracts much research interests in MNFs. MNFs show excellent properties such as strong evanescent fields, tight optical confinement, and small mass or weight, which are appealing for applications such as optical sensing and coupling. Here we report the fabrication and characterization of a new type of SNSPD coupled with microfiber, which has been proposed by our group recently [5]. The simulation results give a minimal total nanowire length of about 300 µm at an absorption rate of 90%. The microfiber-coupled SNSPD might obtain the superior performance of waveguide-coupled system while still has a high coupling efficiency from standard fiber to the microfiber. we fabricated a microfiber atop the SNSPD with a low-refractive-index adhesive cladding, and characterized the absorptance of the nanowire and the overall system detection efficiency. The room-temperature optical experiments indicated an absorptance rate of up to 90% with a 1.3-µm-diameter microfiber for the wavelength of 1550 nm. We were able to demonstrate that the microfiber-coupled detectors achieved a maximal SDE over 20% at the wavelength of 1550 nm with a 2-µm-diameter microfiber.

II. *Method*

We fabricated SNSPDs on 6.5-nm-thick NbN films deposited on MgF2 (001) single crystal substrates (the detailed fabrication process is reported in ref [6]). The low-refractive-index MgF2 was used as substrate to guarantee light transmission in the microfiber. The films were patterned into meandered nanowires with a linewidth and pitch of both 100 nm using electron beam lithography and reactive ion etching. The active area of the nanowires was designed to be 3 lines×100 µm, 3 lines×250 µm, 11 lines×20 µm, and 11 lines×50 µm, to verify the simulation results for microfiber–nanowire absorptance. The contact pad was carefully designed not only to meet the requirements for microfiber coupling, but also to reduce the electrostatic charge on the non-conductive MgF2 substrate (further details of the contact pad design are reported in the Supporting Information). We fabricated a 1.3-µm-diameter microfiber from the standard optical fiber using the flame-heated taper drawing method. With a cladding of low-refractive-index adhesive, we fabricated fixed the 1.3-µm-diameter microfiber atop the SNSPD, as shown in Fig. 1.

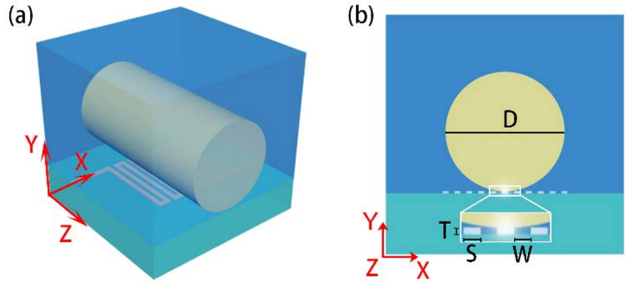

Fig. 1. *(a) Schematic diagram of the microfiber-integrated SNSPD . (b) Cross section of the structure. Inset indicates the interface between microfiber and NbN nanowires.*

III. *Result*

We measured the SDE and DCR of our devices as a function of normalized bias current (I_b/I_{sw}, I_{sw} is the current for SNSPD to switch from superconducting state to normal state) at a wavelength of 1550 nm, the result is shown in Fig. 2. The SDE of the device 2# reaches 18.2% at 100Hz DCR. The low-temperature optical loss and the coupling loss between microfiber and nanowire both may make SDE lower than expected. In addition, due to the fabrication process imperfections, the curve at 1550 nm wavelength is not saturated, which also leads to a lower SDE.

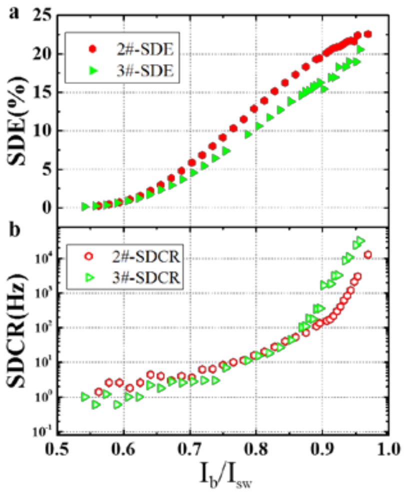

Fig. 2. *SDE (a) and SDCR (b) as functions of the normalized bias current (Ib/Isw) for two microfiber-coupled SNSPD*

The low SDE can be explained by the following reasons: (1) the η_{int} of the SNSPD hasn't saturated to 100% because of the fabrication process imperfections; (2) the large optical loss at 2.2 K due to the difference between the refractive indices of the substrate and the adhesive; (3) the larger fiber diameter and low-temperature refractive indices difference both lead to a smaller microfiber–nanowire absorptance. We expect the high-efficiency microfiber-coupled SNSPDs may extend to more applications such as micro–nano optics.

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