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Dual-lens beam compression for optical coupling in superconducting nanowire single-photon detectors

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Abstract The optical coupling of superconducting nanowire single-photon detectors (SNSPDs) has always been restricted to a single-mode fiber for a limited detection area. In this study, for enhancing photon coupling, a dual-lens system operating at 2.2 K was used to compress the beam size on the basis of the Gaussian beam theory and geometric approximation. A magnification of approximately 0.3 was obtained, and a focused spot with diameter of approximately 10 μm was measured from a multimode fiber. Assisted with the compressed beam, a system efficiency of 55 % (1550 nm) was achieved for a SNSPD with a detection area of 10 μm × 10 μm and 62.5 μm multimode fiber coupling. At the same time, a high speed of 106 MHz was measured with the proposed system. The realization of a highly compressed optical beam reduced the optical coupling requirement and helped maintain a high speed for the SNSPD.

Keywords Superconducting nanowire · Single-photon · Infrared detector · Large detection area

1 Introduction

Superconducting nanowire single-photon detectors (SNSPDs) have shown promise for applications in quantum communication and computation [1–9]. In particular, they have been developed because they offer the advantages of a low dark count rate (DCR), a short time jitter, broadband response, and a high repetition rate [10–14]. An SNSPD is typically covered by a uniform superconducting nanowire with a meandering structure over the detection area. Numerous research groups have adopted a detection area of 10 μm × 10 μm for both easy fabrication and optical coupling in single-mode fiber.

In practical applications, the SNSPD should have a sufficiently large detection area to cover the incident beam. Several research groups have reported SNSPDs with a large detection area [15–17]. However, fabricating an SNSPD with a large detection area increases the kinetic inductance [18], which determines the repetition rate of the SNSPD, and increases the difficulty encountered during microfabrication. A superconductor nanowire array [19] was recently developed for covering a large detection area (63 μm × 63 μm). A complex readout based on rapid single-flux quantum signal processing circuit was required in the array SNSPD. During review of this paper, we became aware of recent related experimental work of another superconductor nanowire array [20] with integrated multiplexed readout. In another study, an aspheric lens was introduced in an SNSPD to couple photons from a 50 μm multimode fiber to a detection area of 15 μm × 15 μm [21].

In this study, we designed and developed a dual-lens system on the basis of the Gaussian beam theory and geometric approximation. The beam was focused to be approximately 10 μm when 62.5 μm multimode fibers were adopted for photon coupling. The use of lenses facilitates multimode fiber coupling and reduces the detection area required in free-space applications.

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2 Device fabrication

A standard process was used for fabricating an SNSPD as Refs. [22, 23]. A silicon substrate with both sides polished was adopted. First, silicon oxide layers were grown on both sides of the silicon substrate by the thermal oxidation method. Subsequently, niobium nitride (NbN) films were deposited on a silicon oxide layer by using DC reactive magnetron sputtering. A nanowire with a width of 50 nm was patterned on the NbN films by e-beam lithography and reactive ion etching. Finally, another silicon oxide film and an Au film were grown over the detection by plasma-enhanced chemical vapor deposition and e-beam evaporation, respectively.

The fabricated 50-nm NbN superconductor nanowire covered a detection area of 10 µm × 10 µm. The critical current of the fabricated superconductor nanowire was 5.6 µA at 2.2 K. In photons detection, the nanowire was illuminated from the substrate side. Therefore, the device structure was similar to an optical structure, and the efficiency was enhanced at the designed wavelength. The cavity structure was simulated using finite-difference time-domain (FDTD) method and optimized at a wavelength of 1550 nm with an absorption efficiency of 97 %.

3 Coupling settings

A fiber-coupled SNSPD is always adopted for high-temperature stability and a low DCR [11, 24, 25]. To couple photons to the detection area efficiently, the beam from the fiber should be smaller than the detection area of SNSPD. Two methods can be used to compress the optical beam. In one method, optical components are used in free space, whereas, in the other method, a multimode fiber and optical components at the cold head of the cooler are used. The numerical aperture (NA) of the communication fiber was limited to approximately 0.2. In geometric optics, an optical component with a higher NA typically produces a smaller spot. For obtaining a highly compressed beam, we adopted the latter, where dual lenses were installed in front of the SNSPD detection area at the cold head of the cryocooler. Figure 1 depicts a schematic of photon coupling.

In this study, the SNSPD was designed using a closed-cycle cryocooler featuring photon transmission through a fiber in the temperature ranging from room temperature to approximately 4 K. A multimode fiber with a length of 2 m was used to guide photons from the atmosphere into a vacuum. The laser beam in free space was directly coupled to the fiber. The beam from the fiber was focused on the detection area of the SNSPD by using lenses after compression. The output port of the fiber was fixed in an objective position of the lenses, and the detection area was fixed in an image position by using a package system monitored with the aid of an infrared microscope as shown in Fig. 1.

The propagation of the output beam of the fiber in paraxial approximation was similar to that of a Gaussian beam. The output beam from the fiber was focused on the detection area of the SNSPD. The output beam passed through lenses and a substrate, closing to the principal axis of lenses. The electric and magnetic fields of the optical beam could be described using vector wave equations. In a cylindrical coordinate system, the wave equations can be rewritten as scalar equations by using the Borgnis function, and they can be solved using the paraxial approximation. Here, the solution of wave equations indicated that the optical beam (ω) conformed to a Gaussian distribution as

$$\omega = \omega_0 \sqrt{1 + \left[\frac{2(z - z_0)}{k\omega_0^2}\right]^2}. \tag{1}$$

Here, z_0 and ω_0 are the position and size of the waist (defined at $1/e$), respectively. The Gaussian distribution of the optical beam from the lenses was verified using a beam profiler. The optical intensity in the x and y directions was closely fitted by a Gaussian distribution. The spatial resolution of the beam profiler was insufficient to measure the distribution at the waist; however, the distribution was measured at a position in the far field where the beam diverged. The beam can be deduced to be a Gaussian beam from the far-field result in Fig. 2.

Therefore, the compressed beam was analyzed using the transformation theory of Gaussian beams with lenses. On the basis of the transformation theory of Gaussian beams, the beam waist can be expressed as follows:

$$\omega_0' = \frac{\lambda f}{\pi\omega_0 \sqrt{1 + \left(\frac{\lambda s}{\pi\omega_0^2}\right)^2}}, \tag{2}$$

where f denotes the focal length of lensed, ω_0' denotes the compressed size of the waist, and s denotes the object distance. Equations (1) and (2) show that Gaussian beam maintained a Gaussian distribution in the xy plane when traveling along the z-axis. Furthermore, Eq. (2) shows that the beam size can be reduced by: (1) choosing lenses that have short focal distances (f), (2) increasing the object distance (s), and (3) increasing the divergence angle ($2\theta = 2\lambda/\pi\omega_0$).

Because of the limited space at the cold head, the object distance cannot be too large. Therefore, a lens with a short focal length was positioned on the side close to the detection area, and the divergence angle was increased by installing another lens on the side close to the optical fiber as shown in Fig. 1. On the basis of the aforementioned transformation theory, we selected commercially available lenses with focal lengths of 18 and 6 mm and fixed them by using stainless steel housings, as shown in Fig. 1. The