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# Fiber-microsphere system at cryogenic temperatures toward cavity QED using diamond NV centers

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**Abstract:** The coupling of a microsphere resonator to a tapered fiber was demonstrated at cryogenic temperatures (8 - 13 K) and investigated with a probe laser light whose frequency around the zero phonon line of nitrogen vacancy centers in diamond (638 nm). For this purpose, a liquid-helium-flow cryostat with a large sample chamber is developed and a resonance dip with a  $Q$  of  $2 \times 10^6$  is observed. The resonance frequency and the coupling condition are found to be stable for a period of one hour.

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**OCIS codes:** (060.5565) Quantum communications; (120.6780) Temperature; (270.5565) Quantum communications.

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## 1. Introduction

A silica microsphere resonator coupled to a tapered fiber is an ideal microcavity system. Microspheres have small mode volumes and Q-factors as high as  $9 \times 10^9$  [1]. Input-output efficiencies of nearly 100% are possible [2,3]. Such fiber-coupled microspheres have application in various optical devices, such as low-threshold lasers [4–8], biochemical sensors [9], and nonlinear optical devices [10,11]. These systems have also attracted interest for solid-state devices using cavity quantum electrodynamics (CQED) for photonic quantum information technology. Recently, Wang *et al.* observed strong coupling between a single nitrogen vacancy (NV) center and a microsphere resonator using a visible probe beam (at 638 nm) via far-field coupling at 10 K [12]. The poor coupling efficiency (of a few percent) due to the far-field coupling could be dramatically improved if a fiber-microsphere system were available at cryogenic temperatures. In this context, Srinivasan *et al.* demonstrated the coupling of a bent tapered fiber to an AlGaAs microdisk cavity at 14 K for wavelengths of 1.2–1.5  $\mu\text{m}$  [13]. In addition, Kippenberg *et al.* has demonstrated the coupling of a tapered fiber to silica microtoroid resonators at 1.46 K using near-infrared probe radiation at 780 nm [14]. However, the property of the fiber-microsphere system for a probe light with shorter wavelengths than NIR region has not been explored.

In this paper, we investigated a fiber-microsphere system at cryogenic temperatures (8–12 K) using a probe light at 638 nm whose frequency around the zero phonon line of nitrogen vacancy centers in diamond. A resonance dip with a  $Q$  of  $2 \times 10^6$  was observed and was stable for over an hour. Such a system would be directly applicable for CQED experiments using NV centers. We achieved fine control of the gap distance between the fiber and the sphere. Technical details of the liquid-helium-flow cryostat having a large sample chamber equipped with optical-fiber ports are also presented.

## 2. Experimental setup and sample preparation

Figure 1(a) sketches the cryostat system having eight optical-fiber ports, so that experiments at different wavelengths can be performed. Optical losses can be significant for quantum optics experiments. To minimize such losses, optical fibers have been directly installed in the sample chamber and connected to the tapered fiber using a fiber splicer. Inside the cryostat, between the fiber port and the sample chamber, the fibers are protected by stainless pipes with metal bellows to reduce the heat shrinking.

Inside the large sample chamber (20-cm diameter and 10-cm tall), a microsphere with a stem is attached to a three-dimensional piezoelectric stage (from Attocube Systems) and positioned next to the tapered fiber. The large size of the chamber permits the straight tapered fiber (~8 cm taper) to be installed without bending, to avoid degradation of the polarization. The piezoelectric stage was operated in a coarse positioning mode with a minimum resolution of 10 nm. Contact between the microsphere and the tapered fiber was monitored using a CCD camera with a telescope through the top and side viewports.

The samples were cooled with exchange helium gas (500 mbar at room temperature) inside the chamber. The lowest achieved temperature was around 5 K. The temperature stability of the sample chamber was better than 0.1 K.

In order to probe the coupling between the tapered fiber and the microsphere, tunable single frequency diode lasers at 638 nm (New Focus TLB-6304) and at 1562 nm (Santec TSL-210V) were used. In order to avoid damage to the tapered fibers, the optical power coupled in was kept below 1 nW. The output light was measured using high-sensitivity photodetectors (New Focus models 2151M and 2153M).

The microsphere with a stem was formed by melting the edge of a tapered fiber using radiation from a CO<sub>2</sub> laser. Tapered fibers were fabricated by heating a single-mode fiber with a ceramic heater and stretching the end of the fiber [15,16]. The low-loss (<10%) tapered fibers were fixed on silica glass substrates using UV adhesives. To enhance the robustness at

cryogenic temperatures, silicone polymer or epoxy adhesives (STYCAST) were overcoated onto the UV adhesives.

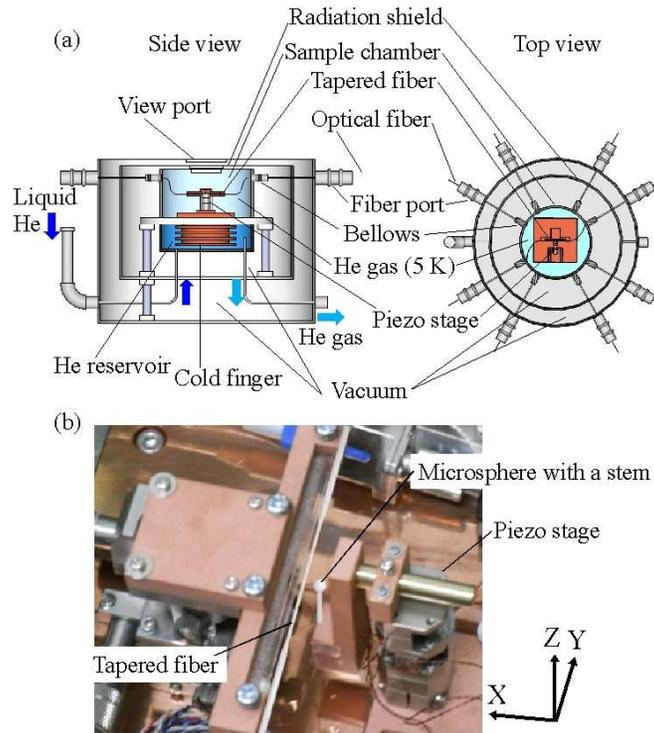


Fig. 1. (a) Cutaway diagram of the cryostat system. It has a top view port and two side view ports (not shown). (b) A photograph inside the sample chamber.

### 3. Experimental results

The change in the spectrum was monitored while controlling the gap distance between the fiber and the sphere at cryogenic temperatures. For this test, a probe laser at telecom wavelengths (1562 nm) was used. Figure 2 shows transmittance spectra at 10 K. The diameters of the microsphere and of the tapered fiber were about 70  $\mu\text{m}$  and 1  $\mu\text{m}$ , respectively. The microsphere was approached to the tapered fiber by 10 nm step with measuring the transmittance spectra. The distances mentioned below is measured from the position where the transmittance spectrum suddenly changed (Fig. 2, 0 nm). The transmittance (~90%) of the tapered fiber was almost constant between room temperature and 10 K.

When the distance between the microsphere and the tapered fiber was 400 nm or more, no resonant dip could be observed. At a distance of 200 nm, a sharp dip with a linewidth of 34 MHz appeared, corresponding to  $Q = 5.1 \times 10^6$ .

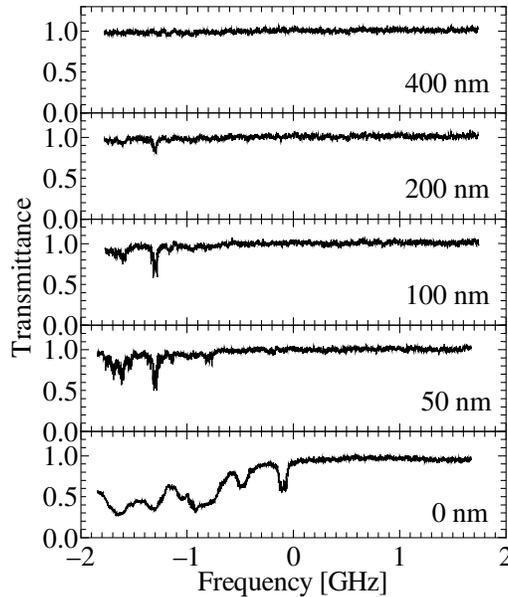


Fig. 2. Variation in the transmittance spectrum with the separation between the microsphere and the tapered fibers at 1562 nm and 10 K.

As the gap distance decreased to 50 nm, the dip grew stronger while maintaining the same linewidth. When the microsphere was moved even closer to the tapered fiber, the shape of the spectrum suddenly changed and numerous broad lines appeared. Since the spectrum did not further change when the microsphere was moved more, we believe the microsphere was in contact with the tapered fiber. Note that the tapered fiber is elastic for a small deformation up to tenth of nanometers. The reason of the sudden change in the spectrum may be due to the coupling of inner low- $Q$  modes, which have broad resonant spectra. We have observed similar phenomena when the taper-fiber diameter (1  $\mu\text{m}$  in this experiment) is relatively small to the wavelength of the probe laser (1.55  $\mu\text{m}$ ). It is because inner low- $Q$  modes have small evanescent field outside of the cavity and able to couple to the tapered-fiber mode only when the microsphere is touching on the tapered fiber. The change in the coupling conditions may also contributes to this phenomenon.

Next we attempted to achieve stable coupling of the microsphere resonator and the tapered fiber at cryogenic temperatures (8 - 12 K) for visible light (638 nm). For this purpose, a tapered fiber with a moderate diameter (1  $\mu\text{m}$ ) which is larger than the wavelength of the probe laser was used. In this condition, sharp resonance peaks can be observed even when the microsphere contacts the tapered fiber, because the evanescent field from the tapered fiber is small and thus the low- $Q$  inner modes inside the microsphere cannot couple to the mode inside the tapered fiber. The diameter of the microsphere was 50- $\mu\text{m}$ . The polarization of the input light was optimized, to decrease the amplitude of the resonant peak, using a halfwave plate and two quarter-wave plates.

Figure 3(a) shows the transmittance spectrum of the tapered-fiber in contact with the microsphere at 8 K. A sharp resonant dip with a linewidth of 210 MHz was observed, corresponding to  $Q = 2.2 \times 10^6$ . No recognizable changes in the shape of this resonant spectrum were observed during an hour. Figure 3(b) shows temperature dependence of the spectrum between 11.5K and 13.0K. The observed resonant frequency shift was less than  $\pm 0.05$  GHz within this temperature region. In our additional experiment (not shown), the resonant frequency did not change much (less than  $\pm 0.2$  GHz) for temperatures between 8K and 25K but became sensitive to the temperature increase over 25K ( $-0.20\text{GHz/K}$  average shift between 25K and 50K). This behavior is similar to the one observed with a silica

microtoroidal resonator [17], where reported shift of the resonant frequency was  $-0.135$  GHz/K at 30K and almost 0 at around 13 K. This optical frequency shift originates both from the thermal expansion of the microsphere and a change in the effective reflective index [17,18]. The stability of the depth of the resonant peaks in Fig. 3(b) also suggests that the polarization in the apparatus (including the tapered fiber inside the cryostat) was almost constant during the measurement. We think that the large size of the sample chamber helps reduce stresses in the tapered fiber, which would otherwise cause temperature-dependent birefringence. These features ensure that this fiber-microsphere system would be advantageous for cavity QED experiments using diamond NV centers at cryogenic temperatures.

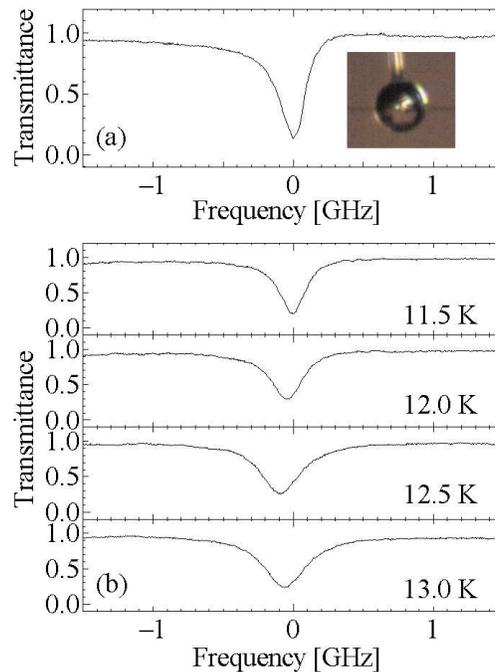


Fig. 3. (a) Transmittance spectrum at 638 nm and 8 K. The inset is a microscope image of the fiber coupled microsphere at 8 K. (b) Dependence of the spectrum on the temperature in the range from 11.5 to 13.0 K.

#### 4. Conclusion

In conclusion, we have demonstrated the stable coupling of a microsphere resonator to a tapered fiber at cryogenic temperatures (8 - 12 K) using visible light. A resonance dip having  $Q = 2 \times 10^6$  was observed using a probe laser at 638 nm, and was stable for over an hour. This system would thus be useful for CQED experiments using NV centers in diamond. We also demonstrated fine control of the gap distance between the fiber and sphere at cryogenic temperatures.

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