

Fiber-integrated diamond-based magnetometer

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We demonstrated a fiber-integrated diamond-based magnetometer in this paper. In the system, the fluorescence of nitrogen vacancy (NV) centers in nanodiamonds deposited on a tapered fiber was coupled to the tapered fiber effectively and detected at the output end of the fiber. By using this scheme, optically detected electron spin resonance spectra were recorded for single NV centers. The results confirmed that such a tapered fiber-nanodiamond system can act as a magnetometer. Featured with excellent portability, convenient fabrication, and potential for further integration, the constructed system has been demonstrated to be a practical magnetometer prototype. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4823548>]

The negatively charged nitrogen vacancy center (NV⁻) in diamond has increasingly attracted attention in recent years due to its excellent properties like photostability, biocompatibility, and chemical inertness. These properties imply that the nitrogen vacancy (NV) (refer to NV⁻) center embedded nanodiamond could act as an ideal photon source in bioimaging, scanning fluorescence resonance energy transfer microscopy, and cavity quantum electrodynamics (QED) research.^{1–6} More importantly, besides the advantage of its long room temperature spin coherence time, the electron spin of the NV center has shown feasibility of optical polarization, optical detection, and coherent manipulation. Various promising applications based on these properties have been exploited, such as single photon source generation, quantum information processing, and high sensitivity magnetometer.^{7–10} Among these applications, the magnetometer is very promising and has been investigated in diverse respects. For example, there have been reports of magnetic field imaging with nanoscale spatial resolution, high sensitivity detection of single electron spins and nuclear spins magnetically, and vector magnetometer using an ensemble of NV centers in a bulk diamond.^{3,11–15} In addition, various methods have been employed to improve the magnetometer sensitivity, such as complex pulsed decoupling technique, using sample of isotopically pure diamond, infrared-absorption detection, etc.^{16,17} In short, the magnetometers based on NV centers have demonstrated the unprecedented combination of spatial resolution and magnetic sensitivity at ambient condition.^{8,11} However, the application of such kind of magnetometer is severely limited owing to the inconvenience in operation and macroscopic laboratory optical setups. The integration and commercialization of diamond-based magnetometers is still a challenge.

In this work, we explored the implementation of a tapered fiber technique^{18,19} in the design of NV center based magnetometer. The nanodiamonds with NV centers were

deposited on a tapered fiber, such that the fluorescence from the NV centers can be coupled into the fiber forming an integrated NV center-fiber system. The optically detected electron spin resonance spectra of a single NV center in a nanodiamond on the tapered fiber were measured via the tapered fiber, which demonstrated the realization of a fiber-integrated diamond-based magnetometer. The fluorescence from the same nanodiamond was counted through both tapered fiber and confocal microscope for the comparison of photon counts and magnetic sensitivity. It is confirmed that the tapered fiber based magnetometer is particularly promising for practical application because of its excellent portability, convenience in fabrication and operation, which provides a promising way for further developing fully integrated magnetometer.

To fabricate tapered fibers, standard single-mode optical fibers (630 HP) were heated by a hydrogen microtorch and carefully stretched to the opposite directions using two translators.²⁰ Fig. 1(a) shows the SEM image of the thinnest part of a typical tapered fiber used in our experiment, with a diameter of 390 nm and transmittance of 34%. The transmittance of the prepared tapered fibers was distributed between 15% and 70%, in respect to the fiber diameter between 300 and 1000 nm. The optical measurements were performed approximately in a sealed plexiglass box in a class 10 000 clean room to effectively limit transmittance degradation.²¹

In order to precisely deposit the nanodiamonds on the tapered area, a method, as described below, was applied. First, a nanodiamond suspension of required concentration was prepared,^{2,22} in which the most probable size of the nanodiamonds was about 25 nm. Subsequently, the tip, heat pulled to about 40 μm outer diameter, of a capillary was used to transfer prepared nanodiamond suspension onto the tapered fiber. As shown in Fig. 1(b), using a precise linear stage, the tip of the capillary was positioned right on the tapered section of the fiber. A micro-drop of the nanodiamond suspension was then squeezed over the tapered fiber forming an about 40 μm coverage. When the solvent dried

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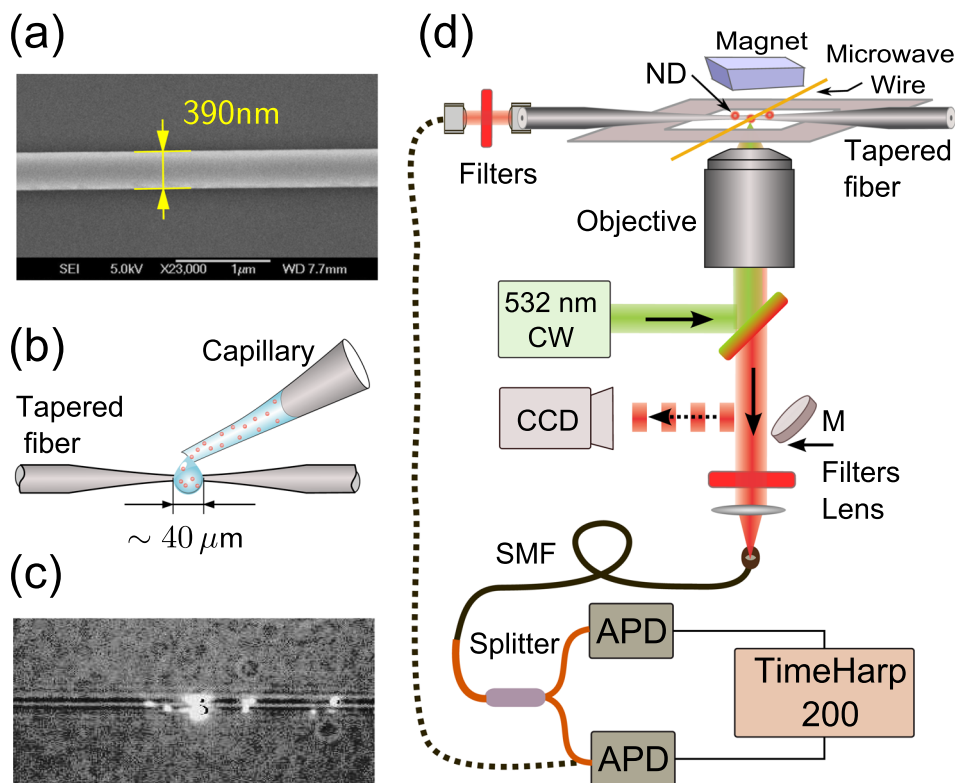


FIG. 1. (a) SEM image of the thinnest part of the tapered fiber. The taper diameter is 390 nm. (b) A diagram of the method to prepare the nanodiamond-tapered fiber system. (c) Microscopic image of the tapered fiber taken with a CCD camera. (d) A schematic diagram of the experimental setup.

out, a few nanodiamonds with single NV centers were randomly deposited on the 40 μm section of the tapered fiber.

Fig. 1(d) schematically depicts the experimental setup for optical measurements. A 532 nm laser (green beam) was focused on the nanodiamond with an $100\times$, $\text{NA} = 0.9$ objective. The fluorescence was exported through both the confocal microscope (the optical path was shown by the red beam at the lower part of the figure) and one end of the tapered fiber (red beam to the left). For the confocal optical route, the fluorescence was collected by the same objective and then sent to two avalanche photodiodes (APD) via a single-mode fiber (core size: 9 μm) that also acted as a pinhole. A time-correlated single photon counting module (TimeHarp 200, PicoQuant) was used for measuring the second-order correlation function of the collected fluorescence signals. In addition, the fluorescence collected by the objective can also be sent to a CCD camera by inserting a reflecting mirror M. To make the nanodiamonds deposited on the fiber optically visible on the CCD, a red laser beam was sent through the fiber. The scattered light from several scatters (nanodiamonds/impurities) were displayed in Fig. 1(c). In order to perform optically detected electron spin resonance (ESR) spectroscopy measurement, as a transmitter antenna, a 20 μm copper microwave wire was carefully shifted orthogonally to the tapered fiber as close as possible using a 3-axis linear stage.

Figs. 2(a) and 2(b) show the scanning fluorescence images of the single NV centers in nanodiamonds deposited on the tapered fiber, for which the fluorescence was collected through the confocal microscope and the tapered fiber, respectively. Both the methods detected the same NV centers

on the tapered fiber. Focusing on the bright spot marked with green circle in Figs. 2(a) and 2(b), the fluorescence counts of this center collected via the objective was about 20 K counts/s (i.e., 40 K counts/s for total collected photons, since the fluorescence beam was split into 50:50 for second-order correlation function measurement), while the photon counts of about 40 K counts/s was obtained by collecting photons at one end of the tapered fiber (i.e., the total photon count rate would be about 80 K counts/s considering two fiber ends). The photon count rate recorded through the tapered fiber was about two times as large as that obtained by the objective. Sometimes the difference in photon count rate could even be more than two times. The photon count rate generally depends on the transmittance and the diameter of the tapered fiber, the location of the NV center on the tapered fiber, the dipole moment orientation of the NV center, etc. It should be possible to get better photon collection efficiency than that obtained above.

To prove the single photon statistics of the NV center, the second-order correlation function $g^2(\tau)$ between photons both from the objective via a splitter (Fig. 2(c)), and between photons from the objective and one fiber end (Fig. 2(d)) was measured. For these two cases, the anti-bunching dip $g^2(0)$ were 0.08 and 0.22, respectively. This clearly proves single photon statistics for both collection methods. It is worth to point out that the anti-bunching dip in Figure 2(d) is less pronounced. This indicates that, in respect of the single photon emission, a relatively higher ratio of background fluorescence was coupled into, or generated in, the tapered fiber. Fortunately, as shown in Fig. 3, there is no distinguishable influence observed in the optically detected ESR spectroscopy measurement.

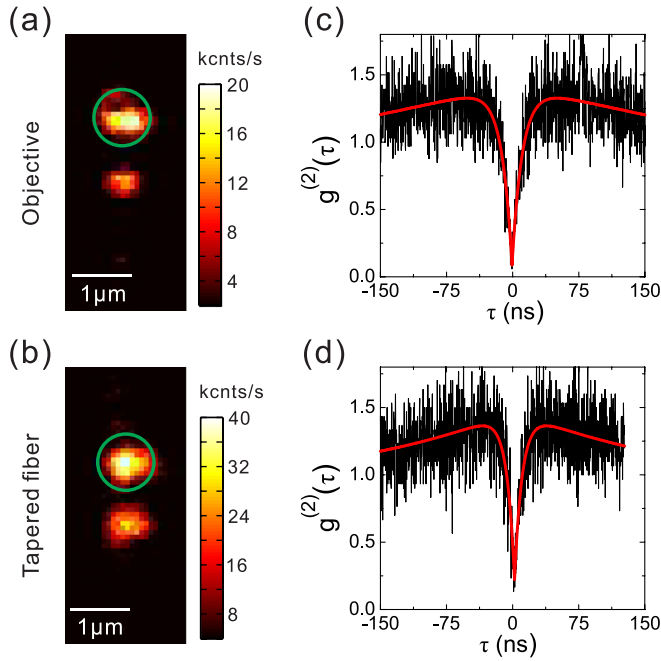


FIG. 2. Scanning images of the single NV centers in nanodiamonds deposited on the tapered fiber, in which the fluorescence was detected through (a) the confocal microscope and (b) the tapered fiber, respectively. (c) and (d) The normalized second-order correlation functions measured from the NV center marked by the green circles accordingly. The photons of (c) are both from confocal objective via a splitter, while the photons of (d) are from the objective and one fiber end.

The NV center based magnetometer is realized, in general, by using optically detected ESR spectroscopy measurement over a single NV center, which records the photoluminescence (PL) intensity of the NV center against the frequency of the applied microwave field. When the microwave frequency is resonant with the transition between $m_s = 0$ and one of the $m_s = \pm 1$ states, a dip of the PL signal appears. When the external magnetic field is changed, the resonant frequencies corresponding to $m_s = \pm 1$ states are changed accordingly, namely, the Zeeman shift of the ESR lines. This frequency shift can thus act as an indicator of the external magnetic field, which allows the NV center to be used as a magnetometer.

The spin Hamiltonian of the NV center can be written as^{11,23}

$$H = D[S_z^2 - S(S+1)/3] + E(S_x^2 - S_y^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}, \quad (1)$$

where D and E are the zero-field splitting parameters, z is the NV center quantization axis, μ_B is the Bohr magneton, g is the electron g -factor ($g \approx 2.0$), $\mathbf{B}$ is the applied external magnetic field and $\mathbf{S}$ is the electron spin of the NV center.

The optically detected ESR spectra were measured at various external magnetic fields by using the tapered fiber configuration, as well as the confocal configuration for comparison. In the microscope configuration, the collected photons were sent to an APD via a single-mode fiber without using a fiber splitter, while for the tapered fiber configuration, the photons were still collected at one end of the fiber. It is possible to collect photons from both ends of the fiber to get higher collection efficiency using a fiber combiner. Because the main topic of the work was not photon

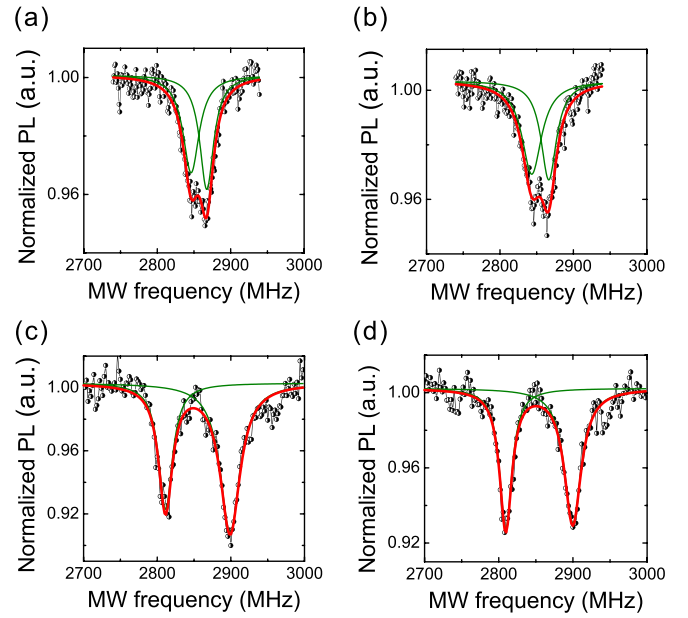


FIG. 3. Optically detected ESR spectra of a single NV center measured without applying any external magnetic field (a) and (b), and with an external static magnetic field B (c) and (d), respectively. Among these four spectra, (a) and (c) were collected via the confocal microscope, while (b) and (d) were collected via the tapered fiber.

collection efficiency, for which some methods have been reported,^{18,19,24–26} in this work, we simply collected photons only from one end of the fiber for convenience.

Figs. 3(a) and 3(b) show the optically detected ESR spectra of a single NV center at magnetic field $B = 0$ obtained by using confocal microscope and tapered fiber to collect fluorescence, respectively. The splittings in these zero-field spectra are due to the fact that the local axial C_{3v} symmetry is broken and the zero-field splitting parameters E is not zero any more. According to the result of the Lorentz fit of the data, D is 2854.7 MHz and E is 11.4 MHz.

Optically detected ESR spectra of the same NV center measured under an external static magnetic field $\mathbf{B}$ are shown in Figs. 3(c) and 3(d). In these two ESR spectra, we can see clearly the Zeeman shifts of the ESR lines induced by the magnetic field. The positions of the two ESR resonances are $\nu_1 = 2809.5$ MHz and $\nu_2 = 2900.0$ MHz, respectively. The magnitude of the external magnetic field can be calculated according to¹¹

$$(g\mu_B B)^2 = \frac{1}{3}(\nu_1^2 + \nu_2^2 - \nu_1 \nu_2 - D^2) - E^2. \quad (2)$$

Substituting the obtained values of various parameters into the equation, the magnetic field $B = 1.6$ mT was obtained. The orientation of the magnetic field can also be determined through the method described by Balasubramanian *et al.*¹¹ The result is $\theta \approx 17^\circ$, in which θ is the angle between magnetic field $\mathbf{B}$ and the NV center quantization axis.

To evaluate the magnetometer sensitivity, the shot-noise-limited magnetic field sensitivity η_B is approximated through the following equation:^{23,27}

$$\eta_B \approx 0.77 \frac{h}{g\mu_B C \sqrt{R}} \frac{\Delta \nu}{\nu}, \quad (3)$$

where h is the Planck constant, R is the rate of detected photons, C is the contrast of the dip in the measured optically detected ESR spectra, and $\Delta\nu$ is the dip linewidth (FWHM).

For the confocal microscope configuration, the measured optically detected ESR spectrum, as shown in Fig. 2(c), gave $C = 0.086$, $R = 40$ kcnt/s, $\Delta\nu = 27.8$ MHz. According to Eq. (2), the corresponding magnetometer sensitivity was deduced to be $\eta_B \approx 57 \mu T/\sqrt{Hz}$.

With regard to the tapered fiber configuration, the measured optically detected ESR spectrum, as depicted in Fig. 2(d), gave $C = 0.0725$, $R = 40$ kcnt/s, $\Delta\nu = 23.8$ MHz. The corresponding magnetometer sensitivity was calculated to be $\eta_B \approx 58 \mu T/\sqrt{Hz}$.

From the above results, we find that the magnetometer sensitivity obtained from the tapered fiber configuration is at the same level as that from the confocal microscope. It confirmed the feasibility of the magnetometer based on the coupled NV center/tapered fiber.

For this tapered fiber based system, there are some predominant advantages. First, it is compact and portable in comparison with the conventional confocal microscope system. Second, the fabrication of the coupled tapered fiber/NV center system is quite convenient. Furthermore, this tapered fiber-nanodiamond system can be packaged by using a low refractive index ultraviolet glue as the coating material.²⁸ Then the system would be isolated from surrounding pollution, and applied with great flexibility and mobility. The last but most important advantage of the magnetometer constructed here is its suitability for further integration. More specially, the single NV center embedded nanodiamond on the tapered fiber can be excited from one end of the tapered fiber with green laser, while the fluorescence from the NV center is collected from the other end. Up to date, such configuration is still under optimization against strong fluorescence background, which overwhelmed the fluorescence from the single NV center.

In summary, we investigated fiber-integrated diamond-based magnetometer, in which a single NV center embedded nanodiamond was attached on the tapered fiber and the fluorescence of the single NV center was coupled into the tapered fiber. Magnetic field measurement was realized by monitoring the variation of the optically detected ESR signal of the NV center via tapered fiber. The results confirmed the feasibility of the constructed magnetometer. Thus constructed fiber-integrated magnetometer is promising because of its excellent portability, flexibility, as well as the convenience in fabrication and operation. Moreover, this setup has the potential to be developed into a portable universal magnetometer.

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