We demonstrate high-resolution magnetic field imaging with a scanning fiber-optic probe which couples nitrogen-vacancy (NV) centers in diamond to a high-numerical-aperture photonic-crystal fiber integrated with a two-wire microwave transmission line. Magnetic resonance excitation of NV centers driven by the microwave field is read out through optical interrogation through the photonic-crystal fiber to enable high-speed, high-sensitivity magnetic field imaging with sub 30 μm spatial resolution. © 2016 Optical Society of America

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Remarkable spin properties of nitrogen-vacancy (NV) centers in diamond offer unique opportunities for high-sensitivity, ultrahigh-resolution, room-temperature magnetic field [1–4], and temperature [5] measurements and suggest the ways toward solid-state spin qubits [6–8] and single-photon sources [9]. Although the highest sensitivities of NV-diamond-based magnetic field sensing and gradiometry have been achieved in a confocal microscopy scheme [5], integration of an NV-diamond sensor with a fiber-optic interface is often needed for a practical implementation of NV-diamond-based sensing in a variety of environments, including magnetic field and temperature measurements in biological systems. Optical detection of a magnetic resonance (ODMR) induced in NV centers in diamond on a fiber-optic platform [10] has been recently shown to provide a compact and powerful solid-state tool for room-temperature magnetic field imaging [11], magnetic gradiometry [12], and thermometry of single biological cells [13].

The trade-off between the spatial resolution and sensitivity is crucial for the performance of fiber-optic NV-diamond magnetometers. While a submicron resolution can be achieved with NV-diamond nanoparticles coupled to the tip of a tapered fiber [14,15], real-life applications, including optical magnetometry and thermometry of biological cells, often dictate a more durable design of a fiber–NV-diamond interface. As shown in the earlier work [11], a fiber-optic probe integrating an NV-diamond microcrystal and a standard multimode optical fiber can enable magnetic field imaging with a ~150 μm spatial resolution and sensitivity of the order of 10 pT · Hz⁻¹/².

Here, we show that the spatial resolution of fiber-optic magnetic field imaging can be further improved without compromising the durability of the fiber probe by using a magnetometer that integrates an NV diamond with a properly designed high-numerical-aperture photonic-crystal fiber (PCF). In experiments presented below in this Letter, we demonstrate high-resolution magnetic field imaging using a scanning fiber-optic probe which couples NV centers in diamond to a high-numerical-aperture photonic-crystal fiber integrated with a two-wire microwave transmission line. Magnetic resonance excitation of NV centers driven by the microwave field is read out through optical interrogation through the photonic-crystal fiber to enable high-speed, high-sensitivity magnetic field imaging with sub 30 μm spatial resolution.

The fiber magnetometer used in our experiments (Figs. 1 and 2) consists of an NV-diamond microcrystal approximately 25 μm in diameter and a photonic-crystal fiber with a 30 μm diameter core integrated with a two-wire microwave transmission line. A diamond microcrystal with a density of NV centers of the order of 10¹⁸–10¹⁹ cm⁻³ (at least two orders of magnitude higher than in Ref. 11) was carefully positioned at the center of the fiber core with a high-precision mechanical manipulator under a microscope and attached to the fiber with a cyanoacrylate glue [10].

A 50 μm diameter copper wire running along both sides of the fiber and making a loop around the fiber tip [Fig. 2(a)]
served as a transmission line delivering a microwave field driving the magnetic resonance in NV centers. This magnetic resonance is read out by the 10 mW, 532 nm second-harmonic output of a continuous-wave Nd:YAG laser [10,11]. This laser induces a photoluminescence (PL) of NV centers within the 630–800 nm wavelength range, which is collected by the PCF and transmitted along the fiber in the backward direction toward the detection system (Fig. 1). The PL beam coupled out of the fiber is collimated with a micro-objective and separated from laser radiation with a dichroic mirror to give a signal that reaches the detection system, consisting of a photodetector and a lock-in amplifier (Fig. 1).

ODMR is implemented in our experiments by measuring the intensity of the PL signal $I_{PL}$ as a function of the frequency of the microwave field $\Omega$, which is scanned through a resonance with a transition between the $m = 0$ and $m = \pm 1$ sublevels of the spin-triplet ground state of NV centers (Figs. 3(a)–3(d)). In the absence of an external magnetic field, the ODMR spectrum $I_{PL}(\Omega)$ features a two-peak profile [Fig. 3(b)], reflecting residual strain in the crystals in the diamond crystal, removing the degeneracy of $m = +1$ and $m = -1$ sublevels. The two peaks observed in the ODMR spectrum $I_{PL}(\Omega)$ in the absence of an external magnetic field are still fourfold degenerate as each of these peaks represents the PL response from NV centers with four different orientations allowed by the crystal lattice of diamond [Fig. 3(a)]. An external magnetic field $B_0$ would generally give rise to four peaks in the ODMR spectrum [Fig. 3(c)], corresponding to generally different projections of $B_0$ on four possible directions of the N–V axis in the crystal lattice of diamond. The sensitivity of magnetic field measurements performed on a weak external field $B_j$ with a magnitude $B_j \ll B_0$, can thus be improved by applying a well-characterized bias magnetic field $B_0$ to remove the four-field degeneracy of the zero-field ODMR spectrum [Figs. 3(c) and 3(d)].

In our experiments, the bias field $B_0$ was induced by a homemade solenoid and had a magnitude of 2–3 mT. To define the orientation of this field, we introduce the polar and azimuthal angles, $\theta$ and $\varphi$, respectively, of the $B_0$ vector measured relative to the laboratory system of coordinates whose $y$–$z$ plane is chosen in the plane of a pair of 40 $\mu$m diameter copper wires used to induce a weak external magnetic field $B_j = B_1 + B_2$, where $B_1$ and $B_2$ are the magnetic fields induced by individual wires (Fig. 1). The ODMR spectra are controlled by varying the $\theta$ and $\varphi$ angles, as well as the orientation of the fiber probe. The respective changes in the ODMR spectra, shown in Figs. 3(b)–3(d), can be best understood in terms of the angles $\alpha_j (j = 1, 2, 3, 4)$ that the magnetic field $B_0$ makes with the four N–V axes in the diamond lattice [Fig. 3(a)]. The outer peaks in the ODMR spectra correspond to minimum values of $\alpha_j$ or $\pi - \alpha_j$. An accidental degeneracy may occur when two or more $\alpha_j$ values are close to each other [Figs. 3(c) and 3(d)]. For a given magnitude of the bias field $B_0$, the maximum $B_0 = 0$ shift of the outer ODMR peaks and, hence, the maximum sensitivity of $B_j$ measurements is achieved with $B_0$ aligned with one of the N–V axes in the diamond lattice, i.e., with one of $\alpha_j$ close to zero.

![Fig. 1. Experimental setup: Nd:YAG SH, Nd:YAG laser source with a second-harmonic output; PD, photodetector; DAC, digital-to-analog converter.](image1.png)

![Fig. 2. (a) Sketch of a fiber-optic magnetometer integrating an NV-diamond sensor, a high-NA PCF, and a two-wire microwave transmission line. (b), (c) Scanning microscope images of a high-NA photonic-crystal fiber: (b) cross section of the fiber and (c) close-up view of the air cladding, $d \approx 30 \mu$m, $w \approx 1.5 \mu$m, $t \approx 300$ nm.](image2.png)

![Fig. 3. (a) Bias magnetic field $B_0$ and N–V axes in the crystal lattice of diamond. (b)–(d) Intensity of photoluminescence from NV centers in diamond collected through the optical fiber as a function of the frequency of the driving microwave field with (b) $B_0 = 0$, (c) $B_0 = 2.1$ mT, $\theta = -58^\circ$, $\varphi = 30^\circ$, $\alpha_1 = 7.3^\circ$, $\alpha_2 = 113.8^\circ$, $\alpha_3 = 112.2^\circ$, $\alpha_4 = 102.1^\circ$, and (d) $B_0 = 2.6$ mT, $\theta = 36^\circ$, $\varphi = 97^\circ$, $\alpha_1 = 27.3^\circ$, $\alpha_2 = 123.6^\circ$, $\alpha_3 = 126.4^\circ$, $\alpha_4 = 75.0^\circ$.](image3.png)
With the bias field $B_0$, known, the field $B_1$ is measured by detecting a small shift $\Delta$ of the peaks in the ODMR spectra relative to their central frequency $D$. With $B_1$, aligned with one of the N–V axes in the diamond lattice, the characteristic equation for the spin Hamiltonian of an NV center [3] dictates the following relation between $B_1$ and $\Delta$ [11,16]: $[\mu_B(B_0 + B_1)]/2 = \Delta^2 - E^2$, where $E$ is the zero-field splitting parameter, $\mu_B$ is the Bohr magneton, $h$ is the Planck constant, and $g$ is the electron g-factor ($g \approx 2.0$).

Two-dimensional profiles of the magnetic field are taken by scanning the fiber-optic magnetometer relative to the copper conductors inducing the magnetic field (Fig. 1). The magnitude of the magnetic field $B_1$ is controlled by the electric current flowing through the conductors, which is varied in our experiments from 0.1 to 0.2 A. For high-speed magnetic field imaging, the lock-in amplifier served to select the frequency-modulated component of the ODMR signal from NV centers resonantly driven by a frequency-modulated microwave field [11,17].

The spatial resolution of this imaging technique is determined by the size of the NV-diamond crystal and the diameter of the fiber core the NV-diamond crystal is attached to. A higher spatial resolution can be achieved by reducing the NV-diamond crystal and the fiber core. However, this improvement in spatial resolution comes at the expense of a lower PL signal in spatial resolution comes at the expense of a lower PL signal.

In our search for a high-NA waveguide structure, we resort to the air-clad photonic-crystal fiber design [18,19], which falls into a more general class of double-clad fibers [20,21]. In the air-clad PCF design best suited for the purposes of our work [Figs. 2(b) and 2(c)], the diameter of a silica core, $d \approx 30 \mu$m, is accurately matched with the diameter of the NV-diamond crystal and the core is surrounded by a ring of air holes with a width $w \approx 1.5 \mu$m, separated by silica bridges with a thickness $t \approx 300 \text{ nm}$, connecting the fiber core to the outer part of the cladding. Unlike the standard regime of double-clad PCF operation, where the circular air holes in the central part of the fiber [Figs. 2(b) and 2(c)] serve as a part of the inner fiber cladding, the role of these air holes in our fiber probe is to improve the adhesion of the NV-diamond microcrystal to the fiber tip covered with cyanoacrylate glue.

Since the thickness of the silica bridges in the outer part of the fiber cladding is less than the PL wavelength $\lambda_{PL}$, which ranges from 630 to 800 nm, the outer cladding strongly confines PL light to the 30 $\mu$m diameter core. Indeed, with $t < \lambda_{PL} < w$, the PL light is trapped in the fiber core, as the sub-wavelength silica bridges are too thin ($t < \lambda_{PL}$) and the air gap between the core and the outer part of the fiber is large enough ($\lambda_{PL} < w$) to avoid excessive radiation loss from the fiber core. The numerical aperture of such a fiber at the center of the PL wavelength silica bridges are too thin ($t < \lambda_{PL}$) and the air gap between the core and the outer part of the fiber is large enough ($\lambda_{PL} < w$) to avoid excessive radiation loss from the fiber core.

The solid lines in Figs. 4(a) and 4(b), we present typical images of two-dimensional distributions of the magnetic field $B_1$, induced by a pair of copper conductors with a bias magnetic field $B_0 = 2.1 \text{ mT}$, $\theta = -58^\circ$, $\varphi = 30^\circ$ [Figs. 4(a) and 4(c)] and $B_0 = 2.6 \text{ mT}$, $\theta = 36^\circ$, $\varphi = 97^\circ$ [Figs. 4(b) and 4(d)]. Figures 4(c) and 4(d) display one-dimensional profiles of the magnetic field measured by scanning the fiber-optic magnetometer along the directions shown by dashed vertical lines in Figs. 4(a) and 4(b), respectively. The errors of magnetic field measurements [shown by error bars in Figs. 4(c) and 4(d)] are only a few percent larger than the standard deviations found from the analysis of noise traces of the lock-in output measured with $B_1 = 0$ [Figs. 4(e) and 4(f)]. This finding shows that the errors of magnetic field measurements in our experiments are mainly due to the noise of the microwave source.

The solid lines in Figs. 4(c) and 4(d) show the distribution of the magnetic field calculated for the pair of copper conductors used in experiments. Results of calculations are seen to agree well with experimental measurements. With the bias magnetic field $B_0 = 2.6 \text{ mT}$, $\theta = 36^\circ$, $\varphi = 97^\circ$, the total magnetic field from the two conducting wires features a well-pronounced maximum with a width of 27 $\mu$m. This feature, as can be seen from Figs. 4(b) and 4(d), is clearly resolved in the magnetic field distributions measured by the fiber-optic
NV-diamond magnetometer. With $B_0 = 2.1$ mT, $\theta = -58^\circ$, $\varphi = 30^\circ$, the conducting wires give rise to a fine feature with a full width of about 30 μm [Figs. 4(a) and 4(c)]. This feature is also reliably resolved in the profiles of the magnetic field measured by the fiber-optic NV-diamond probe.

Advanced PCF technologies [23] allow PCFs with submicron core diameters to be fabricated without loss in functionality [24]. The core-cladding refractive-index steps close to that of the silica–air interface have been achieved for such PCF structures [25,26], maximizing their numerical aperture. On the other hand, NV centers in diamond nanocrystals with their spins manipulated by properly optimized electron-spin-resonance pulse sequences have been shown to enable room-temperature magnetometry with a sensitivity at the fT (Hz)$^{-1/2}$ level [1–3]. Integration of this technique with high-index-step submicron-core PCFs thus opens a route toward fiber-based magnetometry with a submicron spatial resolution and sensitivity comparable to or even surpassing the magnetic field sensitivity of superconducting quantum interference devices (SQUIDs) [27].

To summarize, we have demonstrated high-resolution magnetic field imaging with a scanning fiber-optic probe which couples NV centers in diamond to a high-numerical-aperture PCF integrated with a two-wire microwave transmission line. Magnetic resonance excitation of NV centers driven by the microwave field is read out through optical interrogation through the photonic-crystal fiber to enable high-speed, high-sensitivity magnetic field imaging with a sub 30 μm spatial resolution. Along with the quantitative improvement in the spatial resolution of fiber-based optical magnetometry, the results presented in this work outline a strategy for the development of fiber-optic magnetometers combining submicron spatial resolution with a sensitivity at the level of the sensitivity of SQUID magnetometers.

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