All-fiber optical magnetic-field sensor based on Faraday rotation in highly terbium-doped fiber

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Abstract: An all-fiber optical magnetic field sensor is demonstrated. It consists of a fiber Faraday rotator and a fiber polarizer. The fiber Faraday rotator uses a 2-cm-long section of 56-wt.%-terbium–doped silicate fiber with a Verdet constant of $-24.5 \text{ rad/(Tm)}$ at 1053 nm. The fiber polarizer is Corning SP1060 single-polarization fiber. The sensor has a sensitivity of 0.49 rad/T and can measure magnetic fields from 0.02 to 3.2 T.

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Magnetic field sensors have been widely used for navigation, vehicle detection, current sensing, and spatial and geophysical research. Many electronic techniques for magnetic field sensors have been developed, including superconducting quantum interference devices (SQUID’s), search coils, fluxgates, Hall-effect sensors, anisotropic magnetoresistive devices, and giant magnetoresistive devices [1]. All-fiber optical magnetic field sensors are desirable because of their immunity to electromagnetic interference, low weight, small size, and long-distance signal transmission for remote operation.

Many all-fiber magnetic field sensors use material coatings. For example, if a magnetostrictive or metal jacket is deposited on the fiber, the optical phase can be changed by strain or Lorentzian force, respectively, when immersed in a magnetic field [2,3]. A fiber end can be coated with a composite material and butt coupled to another fiber. The optical
Coupling between the fibers changes with the transverse displacement of the coated fiber in the magnetic field [4]. Iron film has been deposited on a side-polished fiber Bragg grating. The reflective wavelength of the fiber grating shifts with the strain induced by a magnetic field [5].

Faraday rotation can be used for magnet sensors. Because the Verdet constant of silica fiber is small [~1.1 rad/(Tm) at 1064 nm], the fiber is usually coiled with multiple turns to increase the polarization rotation angle. This kind of magnet sensor is often used for current sensing [6,7]. However, bend-induced linear birefringence affects the state of polarization and quenches the desired Faraday effect. In this paper, an all-fiber optical magnet sensor based on Faraday rotation is demonstrated. The device is made of a fiber Faraday rotator spliced to a fiber polarizer. The fiber Faraday rotator is a 2-cm-long terbium-doped (Tb) fiber, which is sufficiently short to avoid bending. The Verdet constant of this Tb fiber is $-24.5 \pm 1.0$ rad/(Tm) at 1053 nm, which is the largest Verdet constant ever reported in optical fiber. The fiber polarizer is a length of Corning SP1060 single-polarization fiber (PZ).

The magnetic sensing principle is shown in Fig. 1. Linear-polarized input light from the laser source was transmitted to the Tb fiber via polarization-maintaining (PM) fiber. The polarization of the light rotated when the Tb fiber experienced a magnetic field parallel to the axis of light propagation. The light then passed through the fiber polarizer, which extinguished light whose polarization was not aligned to its principle axis. The PM fiber transmitted the remaining light to a detector. Because of the polarizer, the power received at the detector was a function of the polarization rotation angle given by Malus’s Law [8]. Since the polarization rotation angle in the Tb fiber is related to the magnetic field strength by the Faraday effect, the magnetic field can be measured by monitoring the output power of the sensor.

![Fig. 1. Sensing principle of an all-fiber Faraday magnet sensor.](image)

Terbium doping is an effective way to increase the Verdet constant in the fiber to reduce the fiber length and avoid coiling. Highly terbium-doped silicate glasses were designed and fabricated. Boron oxide and aluminum oxide were added into the glass composition to improve the solubility of terbium oxide. 56 wt.% terbium-oxide-doped glass is used as the core glass. The rod-in-tube technique was used for single-mode fiber fabrication. The fiber pulling temperature is around 1000°C. The N.A. and diameter of the core are 0.14 and 4 µm, and cladding diameter of the fiber is 130 µm. The propagation loss of the fiber is measured to be 0.11 dB/cm at 1310 nm using cut-back technique. The effective Verdet constant was measured to be $-24.5 \pm 1.0$ rad/(Tm) at 1053 nm, using the measurement technique described in Refs. 9 and 10. This Verdet constant is 4 × that of the Tb fiber previously reported [9] and a 22% increase from the previously highest reported Verdet constant in optical fiber [11].

Single-polarization fiber is a type of fiber in which only one polarization mode can propagate. It has large birefringence to separate the two orthogonal polarization modes so that each has a different cutoff wavelength. Within a certain wavelength region, one polarization mode propagates while high loss eliminates the other. In this way, the fiber functions as a polarizer. Such large birefringence can be introduced via stress from boron-doped rods, elliptical core/cladding, or air holes.

In this experiment, Corning SP1060 fiber was used as the polarizing element [12]. With two air holes on either side of an elliptical core, large birefringence and therefore spectrally...
separated fundamental-mode cutoff were achieved. The core diameter along the major axis was 8 μm, and the clad diameter was 125 μm, with a core N.A. of 0.14. The propagation loss of the surviving mode was 0.1 dB/m at 1060 nm. The center wavelength was 1065 nm, and the bandwidth was 25 nm. The polarization extinction ratio depends on the length of the fiber. The 1-m PZ fiber used in the experiment was coiled with a 15-cm diameter to shift the PZ bandwidth toward the shorter wavelength, resulting in an extinction ratio >16 dB at the 1053-nm working wavelength.

The experimental configuration used to test the sensor is shown in Fig. 2. A 2-cm section of Tb-doped fiber, spliced between the PM fiber and 1-m section of PZ fiber, passed through a magnet tube. Linearly polarized 1053-nm light was launched into the PM fiber. The polarization directions of the PM and the PZ fibers were aligned with a rotational difference of θ₀, which should be set between 20° to 70° to obtain a nearly linear response curve of magnetic field strength as a function of measured power. The N48 NdFeB magnet tube was 4 cm long with inner and outer diameters of 5 mm and 6 cm, respectively. As the magnet was translated along the fiber, the magnetic field imposed on the Tb fiber changed.

![Fig. 2. Experimental configuration of an all-fiber magnet sensor. PM: polarization maintaining fiber; PZ: polarizing fiber.](image)

The magnetic fields can be readily calculated by using the geometrical shape of the magnet [13]. The axial component of the magnetic field distribution along the central axis of the magnet tube is derived to be

\[
B_z(z) = \frac{B_r}{2} \left\{ \frac{z + l/2}{\left[ a_1^2 + (z + l/2)^2 \right]^{3/2}} - \frac{z + l/2}{\left[ a_2^2 + (z + l/2)^2 \right]^{3/2}} \right\} - \frac{z - l/2}{\left[ a_1^2 + (z - l/2)^2 \right]^{3/2}} + \frac{z - l/2}{\left[ a_2^2 + (z - l/2)^2 \right]^{3/2}},
\]

(1)

where \(a_1\) and \(a_2\) are the inner and outer radii, respectively, \(l\) is the length of the magnet, and \(B_r\) is the residual magnetic flux density. Figure 3 shows the calculated \(B_z(z)\) for the N48 magnet used in the experiment (\(B_r = 1.35\) T) along with the measured magnetic field outside the magnet. The physical ends of the magnet are also shown for reference. A commercial Hall-effect sensor was used to measure the magnetic field. Because it was larger than the hole in the magnet (radius, \(a_1\)), the field could only be measured outside the magnet. As shown in Fig. 3, the measured result agreed very well with the theoretical curve calculated from Eq. (1). The averaged magnetic density flux \(B_{av}\) experienced by the 2-cm length of Tb fiber (calculated in the center of Tb fiber) is also shown in the figure. Since the subsection of \(B_{av}\) from \(-3\) to \(-1\) cm along the \(z\) axis is nearly linear and includes both the maximum and minimum of \(B_{av}\), this region is used in the measurement to validate the operating principle of the device.
After considering the extinction ratio (Ex) of the polarizing fiber, the relative transmission through the PZ fiber is derived as \[ \frac{I}{I_0} = \cos^2 \left( \theta_0 + \theta \right) + \sin^2 \left( \theta_0 + \theta \right) 10^{\text{Ex}/10}, \] where \( \frac{I}{I_0} \) is the measured output power normalized to its maximum \( I_0 \); \( \theta = VB_{av}L \) is the Faraday rotation angle in the Tb fiber; and \( V \) and \( L \) are the effective Verdet constant and the length of the Tb fiber, respectively. In the experiment, \( \text{Ex} = 18 \, \text{dB} \) and \( \theta_0 = 50^\circ \). The experimental and theoretical curves of the relative transmission are shown in Fig. 4. The error was determined to be 0.01 by a polarization-stability measurement. The experimental data agree well with the theoretical curve, both of which show a nearly linear response. The nominal transmission loss through the device was 10 dB, mainly induced by the mode mismatch between the PZ fiber and Tb fiber, and splicing loss between the Tb fiber and silica fiber.

Using Eq. (2), the measured Verdet constant of the device and the relation \( \theta = VB_{av}L \), \( B_{av} \) is measured in the linear response region using the all-fiber sensor. Figure 5 shows that the
measurement agrees exceptionally well with the theoretical curve, derived from the solid curve in Fig. 3.

![Fig. 5](image_url)

**Fig. 5.** Measured (circles) and theoretical (solid) \(B_{av}\) as a function of the \(z\) axis. The dashed lines represent the end of the magnet.

The sensitivity of the all-fiber sensor is given as \(d\theta/dB_{av} = V_L = 0.49\) rad/T. This can be increased by increasing the effective Verdet constant and/or the length of the Tb fiber. Since the polarization rotation may go beyond 90°, a maximum detected magnetic field \(B_{max} = (\pi/2)/V_L\) of 3.2 T can be measured in this configuration without ambiguity. A larger magnetic field could be measured by decreasing the effective Verdet constant or the length of the Tb fiber.

The resolution of the magnetic sensor is obtained by taking the derivative and absolute value of both sides of Eq. (2):

\[
\Delta B = \frac{\Delta I}{I_0 V_L \sin \left[ 2(\theta_0 + \theta) \right] \left[ 1 - 10^{-\text{Ex/10}} \right]} = \frac{\Delta I}{I_0 \pi \sin \left[ 2(\theta_0 + \theta) \right] \left[ 1 - 10^{-\text{Ex/10}} \right]} = \frac{2B_{max}}{I_0 \pi \sin \left[ 2(\theta_0 + \theta) \right]}.
\]

In the approximate form of this equation, the effect of the extinction ratio is neglected, which is appropriate for \(\text{Ex} \geq 18\). Increasing the effective Verdet constant and the length of the Tb fiber could increase the resolution, at the expense of reducing \(B_{max}\). In the experiment, the length of the Tb fiber is set to 2 cm to act as a point sensor. The factor \(\Delta I/I_0\) is limited by the laser source noise. If the noise is assumed to around 1%, the minimum measurable magnetic field is 0.02 T. This number can be substantially reduced by providing a reference measurement for the laser source, eliminating the intensity fluctuations of the source from the measurements. In this case, detection at the nW level (with \(I_0\) at the mW level) yields a sensor resolution of \(2 \times 10^{-6}\) T. If higher resolution and higher \(B_{max}\) are both required, two all-fiber magnetic field sensors could be co-located. In this scenario, one sensor would have a large \(V_L\) product to obtain the desired resolution; the other would have a small \(V_L\) product to obtain the desired maximum detected magnetic field by removing the ambiguity of the other sensor.

The Verdet constant of the Tb fiber depends on temperature; for example, \(1/V dV/dT\) is around \(10^{-4}/\text{K}\) for silica [15]. To mitigate the impact of temperature on measurement results, a fiber-grating temperature sensor could be cascaded or co-located with the magnetic field sensor to monitor the temperature near the magnetic field sensor. In this way, the sensor can give accurate results, providing the device has been calibrated as a function of temperature.
Although the resolution of this intensity-based sensor cannot exceed that of interference–
based sensors, this all-fiber magnetic-field sensor is extremely suitable for environments
containing strong electromagnetic fields, such as nuclear facilities and magnetic levitation
(e.g., high-speed trains). Apart from the sensing element, the rest of the proposed sensing
system is silica fiber, which is immune to perturbations by electromagnetic fields, unlike
electronic–based sensors. The proposed sensor is compact and robust compared with bulk
optics–based sensors. Additionally, it has a simple structure and does not need material
coatings, which will result in a low-cost device.

Since the all-fiber magnetic field sensor can only measure magnetic fields parallel to it
axis, three orthogonally oriented sensors could be combined together to provide a complete
three-dimensional magnetic field sensor.

In conclusion, an all-fiber optical magnetic field sensor has been demonstrated. It consists
of a fiber Faraday rotator and a fiber polarizer. The fiber Faraday rotator uses a 2-cm-long
section of 56-wt.-%-terbium–doped silica fiber with a Verdet constant of –24.5 rad/(Tm) at
1053 nm. The fiber polarizer is Corning SP1060 single-polarization fiber. The sensor has a
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