All-fiber optical magnetic field sensor based on Faraday rotation

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Abstract: An all-fiber optical magnetic field sensor with a sensitivity of 0.49 rad/T is demonstrated. It consists of a fiber Faraday rotator (56-wt.%-terbium–doped silica fiber) and a fiber polarizer (Corning SP1060 fiber).

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Magnetic field sensors based on Faraday rotation are widely used. 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. Because the Verdet constant of silica fiber is very small [~1.1 rad/(Tm) at 1064 nm], standard silica fiber must be long and coiled multiturn to increase the polarization rotation angle. However, bend-induced linear birefringence affects the state of polarization and quenches the desired Faraday effect. In this paper, an all-fiber optical magnet field 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 fiber polarizer is a Corning SP1060 single-polarization fiber (PZ).

Terbium doping is an effective way to increase the Verdet constant in the fiber and avoid coiling. The multicomponent silica fiber used here was 56 wt.% terbium doped, resulting in 0.14 numerical aperture (N.A.). Core and cladding diameters were 4 μm and 130 μm, respectively, and the propagation loss was 0.11 dB/cm at 1310 nm. The effective Verdet constant was measured to be –24.5±1.0 rad/(Tm), using the measurement technique described in Ref. [1,2]. Corning SP1060 fiber was used as the fiber polarizer. This fiber has different cutoff wavelengths for the two orthogonal linear polarization directions [3], making it possible to transmit light in only one linear polarization within a certain wavelength band.

The experimental configuration used to test the sensor is shown in Fig. 1. A 2-cm section of Tb-doped fiber, spliced between a polarization-maintaining (PM) fiber and a 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 θ_0, 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. The magnetic field distribution along the axis of the magnet tube can be derived as in Ref. [1].

Linear-polarized input light was transmitted to the Tb fiber via the PM fiber. The polarization of the light rotated when the Tb fiber experienced a magnetic field along the axis of light propagation. The light then went 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 is a function of the polarization rotation angle given by Malus' Law. 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.

After considering the extinction ratio (Ex) of the polarizing fiber, the relative transmission through the PZ fiber is derived as [4]

$$I/I_0 = \cos^2(\theta_0+\theta) + \sin^2(\theta_0+\theta)10^{(-\mathrm{Ex}/10)}, \tag{1}$$

where I/I_0 is the measured output power normalized to its maximum I_0; $\theta = VB_{\mathrm{av}}L$ is the Faraday rotation angle in the Tb fiber; and V, B_{av}, and L are the effective Verdet constant, average magnetic flux density on the Tb fiber, and the length of the Tb fiber, respectively. The experimental and theoretical curves of the relative transmission are shown in Fig. 2. In the experiment, Ex = 18 dB and θ_0 = 50°. The error was determined to be 0.01 by a polarization stability measurement, and the experimental data agreed well with the theoretical curve.

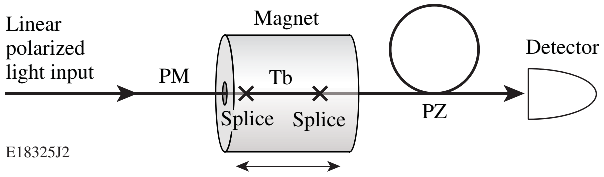

Fig. 1. Experimental configuration of an all-fiber magnet sensor. PM is polarization maintaining fiber, and PZ is polarizing fiber.

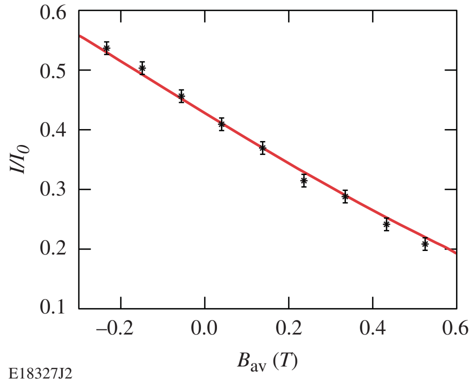

Fig. 2. Measured and calculated relative transmission of an all-fiber magnet sensor.

The sensitivity of the all-fiber sensor is given as $\mathrm{d}\theta/\mathrm{d}B_{av} = VL = 0.49\ \mathrm{rad}/T$. This can be increased by increasing the effective Verdet constant and/or the length of the Tb fiber. Since the polarization rotation can go beyond 90°, a maximum detected magnetic field $B_{max} = (\pi/2)/VL$ of 3.2 T can be measured in this configuration without ambiguity. A larger 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. (1):

$$\Delta B = \frac{\Delta I}{I_0 VL \sin\left[2\left(\theta_0+\theta\right)\right]} = \frac{\Delta I}{I_0}\,\frac{2B_{max}}{\pi \sin\left[2\left(\theta_0+\theta\right)\right]}\,. \tag{2}$$

The effect of the extinction ratio was neglected in this derivation, which is appropriate for Ex > 18 dB. Increasing the effective Verdet constant or the length of the Tb fiber could also increase the resolution, at the expense of reducing B_{max}. The most effective way to increase the resolution is to decrease the ratio $\Delta I/I_0$. For example, if the detector resolution is at the nW level, increasing I_0 to the mW level yields a sensor resolution of 2.0×10^{-6} T, with B_{max} still 3.2 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 has a large *VL* product to obtain the desired resolution, while the other one has a small *VL* product to obtain the desired maximum detected magnetic field by removing the ambiguity of the other sensor.

The Verdet constant of the Tb fiber is temperature dependent; for example, $1/V\ \mathrm{d}V/\mathrm{d}T$ is around 10^{-4}/K for silica. To mitigate the impact of temperature on the 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.

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

In conclusion, an all-fiber optical magnetic field sensor with a sensitivity of 0.49 rad/T is demonstrated. It consists of a fiber Faraday rotator (56-wt.%-terbium–doped silica fiber) and a fiber polarizer (Corning SP1060 fiber).

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