All-fiber optical isolator based on Faraday rotation in highly terbium-doped fiber

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An all-fiber isolator with 17 dB optical isolation is demonstrated. The fiber Faraday rotator uses 56 wt. % terbium (Tb)-doped silicate fiber, and the fiber polarizers are Corning SP1060 single-polarization fiber. The effective Verdet constant of the Tb-doped fiber is measured to be \(-24.5 \pm 1.0\) rad/(Tm) at 1053 nm, which is 20 times larger than silica fiber and 22% larger than previously reported results. © 2010 Optical Society of America

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Optical isolators are important components in optical communication networks and laser systems. Traditional optical isolators are based on bulk optics, which require free-space optical coupling for use with fiber-optic systems [1,2]. All-fiber optical isolators are highly desirable, particularly for high-power fiber-laser systems, where fiber termination and small free-space beams place restrictions on how much power can be transported through such components. The small Verdet constant \([-1.1\text{ rad/(Tm)}\) at 1064 nm] of silica fiber is the bottleneck to realize all-fiber Faraday isolators. Some research groups have demonstrated all-fiber Faraday rotators in silica fiber, using long lengths of silica fiber to increase the polarization rotation angle [3,4]. To use a reasonably sized magnet, the fiber is coiled multiple turns at several millimeters in diameter. Bend-induced linear birefringence, however, affects the state of polarization and quenches the desired Faraday effect. In this paper, we report on a highly terbium (Tb)-doped fiber with the highest reported Verdet constant in optical fibers (22% increase from previous results) and the first experimental demonstration of a fusion-spliced all-fiber Faraday isolator. Such an all-fiber isolator has significant potential for high-power fiber-laser systems.

Terbium doping is an effective way to increase the Verdet constant in the fiber. 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 NA and diameter of the core are 0.14 and 4 μm, and the 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 a cut-back technique. The fiber was fabricated at AdValue Photonics Inc., using in-house fiber-drawing facilities. Using the measurement technique described in [5], Fig. 1 shows the measured rotation angle and the corresponding curve fit at the measurement wavelength of 1053 nm, as the magnet is translated along the length of the fiber. In this figure, Δz is the relative distance between the centers of Tb fiber and the magnet along the center axis of the magnet. The error in the measured angle is primarily caused by air flow and is determined to be 1° by a polarization stability measurement.

In contrast to the experimental configuration in [5], two 15 cm pieces of straight single-mode (SM) fiber were used on either side of the Tb fiber. All other experimental components were identical to [5]. Since the axially integrated magnetic field inside and outside the magnet tube have opposite signs but identical absolute values, the measured Verdet constant consists of two parts, given by \(V_{\text{meas}} = V_{\text{Tb}} - V_{\text{silica}}\), where \(V_{\text{Tb}}\) and \(V_{\text{silica}}\) are effective Verdet constants of the Tb and the silica fibers, respectively. With the measured result \(V_{\text{meas}} = -25.7 \pm 1.0\text{ rad/(Tm)}\) at 1053 nm [6], \(V_{\text{Tb}}\) is determined to be \(-24.5 \pm 1.0\text{ rad/(Tm)}\), which is 22% larger than previous results.

![Fig. 1. (Color online) Measured rotation angle (circle) and corresponding curve fit (solid) at a wavelength of 1053 nm as a function of the magnet location along the fiber axis z.](image-url)
ously reported results [7]. This measurement is in reasonable agreement with a 27% increase in Tb\textsuperscript{3+} concentration, from \(0.66 \times 10^{22}\) in [7] to \(0.84 \times 10^{22}\) ions/cm\(^3\) in this Tb fiber.

In a single-polarization (PZ) fiber, only one polarization mode can propagate. This kind of fiber has a large birefringence to separate the two orthogonal polarization modes so that each has a different cutoff wavelength. Therefore, within a certain wavelength region, one polarization mode is eliminated due to high loss and the other propagates. In this way, the fiber functions as an all-fiber polarizer. Birefringence is usually introduced via stress from boron-doped rods, elliptical core/cladding, or air holes.

Corning SP1060 fiber is used here as the polarizing element [8]. With two air holes on either side of an elliptical core, a large birefringence and differential fundamental-mode cutoff are achieved. The core diameter along the major axis is 8 \(\mu\)m, and the clad diameter is 125 \(\mu\)m, with a core NA of 0.14. The propagation loss is 0.1 dB/m at 1060 nm. The measured transmission spectrum for two orthogonal polarization directions in 0.3-m-long SP1060 fiber, coiled with a 15 cm diameter, is shown in Fig. 2. The center wavelength is 1065 nm, and the bandwidth is 25 nm. The extinction ratio is >16 dB. The purpose of coiling the fiber is to shift the polarizing bandwidth toward shorter wavelengths, which will include the 1053 nm working wavelength. Since increasing the PZ fiber length will also increase the extinction ratio [8], 1 m of PZ fiber is used in the isolator.

The experimental isolator configuration is shown in Fig. 3. A 25 cm section of Tb-doped fiber, spliced between two 1 m sections of PZ fiber (with an extinction ratio of 18 dB at 1053 nm), goes through a magnet with a hole in the center. The N35 NdFeB magnet is \(15 \times 15 \times 25\) cm\(^3\) with a residual flux density \(B_r\) = 0.95 T. The inner diameter of this magnet is less than 2 mm, and its effect on the magnetic field is negligible. The 1-m-long PZ fiber is coiled with a 15 cm diameter. The polarization directions of the two sections of the PZ fiber are aligned with a rotational difference of 45°. The location of the magnet is adjusted with respect to the Tb fiber to achieve the 45° rotation.

Magnetic fields can be readily calculated by using the geometrical shape of the magnet [9]. The axial component of the magnetic-field distribution along the central axis of the magnet cube is derived to be

\[
B_z = \frac{B_r}{\pi} \left[ \tan^{-1} \left( \frac{ab}{2(z+l/2)[(4(z+l/2)^2+a^2+b^2)^{1/2]}^{1/2}} \right) - \tan^{-1} \left( \frac{ab}{2(z-l/2)[(4(z-l/2)^2+a^2+b^2)^{1/2]}^{1/2}} \right) \right],
\]

where \(a\) and \(b\) are the width and height of the magnet, respectively; \(l\) is the length of the magnet; and \(B_r\) is the residual magnetic flux density. Figure 4 shows the calculated \(B_z(z)\) for the N35 magnet used in the experiment along with the measured magnetic field outside the magnet. The physical ends of the magnet are also shown for reference. \(z\) is the distance from the center of the magnet along its central axis. The magnetic field, measured only outside the magnet because the magnetic field probe size is larger than the hole diameter, agrees very well with the theoretical curve calculated from Eq. (1). The maximum possible polarization rotation angle in the Tb-doped fiber is larger than 70° in this magnetic field.

The optical isolation at 1053 nm is measured to be 17 dB at room temperature, which is limited mainly

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**Fig. 2.** (Color online) Measured transmission spectra for two orthogonal polarization directions in 0.3-m-long SP1060 fiber coiled with a 15 cm diameter.

**Fig. 3.** (Color online) Experimental configuration of the all-fiber Faraday isolator.

**Fig. 4.** (Color online) Theoretical (solid) and measured (circle) magnetic-density flux distribution \(B_z\) along the center axis \(z\) of the magnet. The dashed lines represent the physical ends of the magnet.
by the extinction ratio of the fiber polarizers. The isolation can be increased using fiber polarizers with a larger extinction ratio. The loss of the isolator is 9 dB, including 0.2 dB of propagation loss in the total 2 m of the PZ fiber, 2.8 dB of propagation loss in Tb-doped fiber, and 3 dB from each splicing point between the PZ and the Tb-doped fiber. The loss contribution caused by the Tb-doped fiber could be decreased to under 0.5 dB using a high-grade magnet, which requires only a few centimeters of Tb-doped fiber. The loss induced by the mode mismatch between PZ and Tb-doped fiber is 1.8 dB per splicing point, which can be reduced via a fiber-mode converter. The remaining 1.2 dB loss per splice point is due to the splicing process. The melting points of the terbium-oxide-doped silicate fiber and silica fiber are 1200°C and 1650°C, respectively, making it difficult to melt them together using a conventional fusion splicer. Although this splicing loss is high, it could be decreased further by using a custom setup; for example, using a temperature-controllable heating filament.

The bandwidth of this isolator is 25 nm, limited by the bandwidth of the PZ fiber. The spectrum of the isolation has sharp edges, different from the Gaussian shape of other isolators. This feature makes it unique among optical isolators and can be leveraged for spectral filtering as an intracavity laser component; for example, in ring-cavity fiber lasers.

Apart from its generality, this all-fiber Faraday isolator will have the most significant impact in high-power fiber-laser systems. The magnet size can be reduced to a few centimeters by using a high-grade magnet, such as an N50 NdFeB magnet. For example, if the \( B_r = 1.45 \) T, the length and the width of the cubic magnet are less than 7 and 4 cm, respectively. There will be no material/air interfaces or epoxy problems found in bulk-optics isolators, which increases the power limits required for high-power applications. Since hundreds of pieces of Tb fiber can go through one magnet tube at the same time, many isolators can be integrated into a single magnet, which would reduce cost and size in large-fiber-array systems. Although this particular isolator was designed for 1053 nm, the concept could be applied in the telecom wavelength range if a larger or higher-grade magnet or terbium fiber with higher doping concentration is used.

In conclusion, an all-fiber isolator with optical isolation of 17 dB is demonstrated. The fiber Faraday rotator uses 56 wt. % terbium-doped silicate fiber, and the fiber polarizers are Corning SP1060 single-polarization fiber. The effective Verdet constant of the Tb-doped fiber is measured to be \(-24.5 \pm 1.0 \text{ rad/(Tm)}\) at 1053 nm, which is 20 times larger than silica fiber.

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