All-Fiber Isolator Based on Faraday Rotation

Linear polarized light

Polarizing fiber

Magnet

Tb fiber

Polarizing fiber

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An all-fiber optical Faraday isolator is demonstrated for the first time with 17-dB isolation

- All-fiber isolators are required for high-power applications
- The all-fiber isolator is made of a fiber Faraday rotator and two pieces of polarizing fiber
- The fiber Faraday rotator uses a 56 wt% Terbium-doped multicomponent silica fiber
  - effective Verdet constant = $-22.3 \pm 0.8 \text{ rad/(Tm)}$
- Corning SP1060 fiber is used as the polarizing fiber
  - extinction ratio >17 dB at 1053 nm for 1-m-long PZ
- 17-dB isolation is measured for all back-injected polarization states
Faraday isolators are critical components in many optical systems and are still based on bulk optics.

- Faraday isolators are used in optical communication systems, high-power laser systems.
- Faraday rotation is the result of circular birefringence induced by a magnetic field applied along the axis of light propagation.
- The angle of rotation is given by
  \[ \theta = VBL \]
  
  - \( V \): Verdet constant
  - \( B \): magnetic-field flux density
  - \( L \): length of the crystal
- A rotation angle of 45° is required for most applications.
The small Verdet constant in standard silica fibers is the bottleneck to realizing all-fiber Faraday isolators.

- Faraday isolators based on bulk optics are limited in high-power applications
  - material/air interfaces, surface reflections, epoxy problem

- No commercial all-fiber Faraday rotators are available
  - \( V = 1.1 \text{ rad/(Tm)} \) in silica at 1064 nm
  - \( V = -40 \text{ rad/(Tm)} \) in TGG (terbium gallium garnet) at 1064 nm
  - for a conventional magnet (\( B = 0.2 \text{ T} \)), 4 m of fiber is required for a rotation angle of 45°
  - such a long fiber length is impractical in terms of magnet size and polarization mixing
56 wt% terbium is doped in the Silica fiber to increase the Verdet constant

- **Core:** 56 wt% terbium
  4-\(\mu\)m diameter

- **Cladding:** 55 wt% terbium
  130-\(\mu\)m diameter

- **N. A.** = 0.14

- **Loss** = 0.11 dB/cm at 1310 nm

- **Effective Verdet constant**
  \[-22.3 \pm 0.8 \text{ rad/(Tm)}\] at 1053 nm
  \(20 \times\) larger than silica fiber

*\(^{*}\)L. Sun et al., Opt. Lett. 34, 1699 (2009).*
The magnetic-field distribution of a magnet along the axis direction can be accurately derived.

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

\[ B_r = 0.95 \ T \text{ (residual flux density)} \]
\[ a = 15 \ \text{cm}, \ b = 15 \ \text{cm}, \ L = 25 \ \text{cm} \]

The prediction matches the measured magnetic field outside the magnet.
45° rotation in an all-fiber Faraday rotator can be achieved with 20-cm Tb-doped fiber in the magnet.

- 20-cm Tb-doped fiber is placed in the magnet
- Theoretical maximum rotation angle >50°
- Meets 45° requirement for all-fiber Faraday rotator

\[ z = \text{distance between the center of the magnet and the center of the Tb fiber} \]
The fiber polarizers are made from Corning SP1060 polarizing fiber (PZ fiber)

Only one linear polarization can propagate.

- Core: 8 (2.6) μm diameter
- Cladding: 125 μm diameter
- N. A. = 0.14
- Loss = 0.1 dB/m at 1060 nm
Transmission spectrum of orthogonal polarizations in PZ fiber shows an extinction ratio $>15$ dB

- Extinction ratio $>15$ dB
- Bandwidth = 25 nm
- Sufficient extinction for all-fiber polarizers
An all-fiber Faraday isolator is built by combining a fiber Faraday rotator and fiber polarizers.

- Two sections of the PZ fiber are aligned through the Tb-fiber with a 45° rotation angle and fusion spliced.
- Each section of the PZ fiber is 1 m (extinction ratio >17 dB at 1053 nm).
- The position of the magnet is adjusted to obtain 45° polarization rotation.
The extinction ratio of the isolator is measured to be 17 dB for all back-injected polarization states.

![Graph showing isolation vs rotation angle]

Isolation = 17.0±0.4 dB

- The isolation is measured while rotating the polarization direction of the back-injected light
The required magnet dimensions can be reduced to a few centimeters.

With cm-scale magnets, all-fiber Faraday devices become practical.
All-fiber Faraday isolators have advantages over bulk-optics–based isolators

- All-fiber isolators have low cost compared with bulk-optics isolators
  - Automated, pre-programmed fiber splicing instead of manual alignment

- All-fiber isolators are suitable for high-power applications
  - no material/air interfaces, no reflection surfaces, no epoxy

- All-fiber isolators are ideal for large-scale integration
  - hundreds of fiber isolators can be packaged in a single magnet
Summary/Conclusions

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