Faraday-effect current sensor with improved sensitivity-bandwidth product

Kent B. Rochford, Allen H. Rose, Merritt N. Deeter, Gordon W. Day


Event: 10th Optical Fibre Sensors Conference, 1994, Glasgow, United Kingdom
Faraday effect current sensor with improved sensitivity-bandwidth product

K.B. Rochford, A.H. Rose, M.N. Deeter, and G.W. Day
Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, CO 80303

Abstract: We report a new design for a Faraday effect current sensor based on yttrium iron garnet. The improved sensor has substantially greater bandwidth than previous designs and is considerably easier to fabricate. The measured sensitivity is 0.7°/A with a -3 dB bandwidth of 500 MHz, giving a factor of 45 increase in sensitivity-bandwidth product. A noise-equivalent current of 840 nA/Hz was measured at 1.8 kHz using difference-over-sum processing. The use of newly developed turning prisms with phase-preserving coatings greatly simplifies construction, improves electrical isolation, and increases sensitivity through proximity effects.

Recently, a current sensor made from gallium-substituted yttrium iron garnet (Ga:YIG) having a sensitivity of 3°/A and a -3 dB bandwidth of 2.6 MHz was leading to a sensitivity-bandwidth product of 7.8 MHz°/A. In this paper we demonstrate further increases in sensitivity-bandwidth product by using an iron garnet with slightly lower magneto-optic sensitivity than Ga:YIG but substantially increased bandwidth. Also, we report a simplified design for bulk optical current sensors that significantly eases fabrication. This improvement results in a more compact device with increased sensitivity and electrical isolation.

A Faraday effect current sensor can be constructed by arranging a closed path of magneto-optic material around a conductor and measuring the net Faraday rotation along this path. For sensors using bulk transducers, reflectors such as turning prisms or polished surfaces are used to redirect light from one bulk piece to the next and form a closed optical path. Total internal reflection (TIR) can impart a linear retardance which decreases sensitivity. Using Jones calculus, we find that the sensitivity is reduced by a factor \( F = \frac{(\cos 3\delta + \cos 2\delta + \cos \delta + 1)}{4} \) for a sensor path of four active pieces and three turning prisms with equal retardance \( \delta \). Less than 10° retardance at each prism is required to obtain a sensitivity that is at least 95% of the zero-retardance sensitivity.

The requirement for low-retardance reflections motivated the use of complementary-prism-pair reflectors in the device of [1]. In the sensor reported here we use single turning-prisms with low TIR retardance. The retardance is minimized by a multi-layer dielectric coating that is applied to the hypotenuse of a right-angle BaK-1 prism and equalizes the s- and p-polarization reflected phase shifts at the desired angle of incidence. The retardance measured at 1.3 µm for the coated prism reflection is compared to calculated retardance for an uncoated prism in Figure 1. This approach results in simplified assembly since one prism is required at each turn and the incidence angle tolerance is greatly increased. The amount of Faraday-inactive prism material in the optical path is also reduced and this improves electrical isolation to currents and fields outside the path.

Figure 1. Retardance for coated and uncoated prism reflection. Less than 10 degrees retardance is required for 95% of zero-retardance sensitivity.
Bulk crystals of YIG, or \( \text{Y}_3\text{Fe}_5\text{O}_{12} \), typically exhibit a linear magneto-optic response for fields much less than a saturation field \( H_s \). Though less sensitive than Ga:YIG, pure YIG exhibits a much higher bandwidth\(^7\) and a magneto-optic sensitivity that can be over 10 000 times greater than that of \( \text{SiO}_2 \). For the device reported here, YIG cylinders with 2.5 mm length and 2.0 mm diameter were chosen. For this size and shape the demagnetization factor \( N_d \approx 0.22 \),\(^8\) and the calculated length-normalized magneto-optic sensitivity \( S' \approx 0.49 \, ^\circ/(\text{mT}\cdot\text{mm}) \). Four cylinders were arranged as shown in Figure 2, with three coated turning prisms (2 mm by 2 mm right-angle prisms) positioned to direct the optical beam through each YIG piece. Assuming each YIG piece has normalized sensitivity \( S' \) and the prisms contribute negligible Faraday rotation and linear retardance, the calculated sensitivity of this device is \( 0.4^\circ/\text{A} \).

Sensor performance was evaluated at 1.3 \( \mu \text{m} \). A collimated, linearly polarized beam was input to the device. A Wollaston polarizer separated light exiting the sensor into orthogonal polarizations, and each beam was detected. A half-wave plate located just before the Wollaston polarizer was rotated to bias the sinusoidal transfer function of the polarimetric system to the linear operating point. For low frequency measurements, both signals were processed with a difference-over-sum amplifier to minimize the effects of laser power fluctuations.

The measured sensitivity of the assembled current sensor was \( 0.7^\circ/\text{A} \), a factor of 1.8 greater than the predicted value of \( 0.4^\circ/\text{A} \). This increase is due to the proximity of the YIG pieces and apparently arises from demagnetization effects. The demagnetization factor of an assembled sensor is not adequately described by treating the four YIG cylinders as isolated pieces because a magnetic circuit is formed by the loop of YIG pieces and interactions are not limited to a single cylinder.

The noise-equivalent current (NEI) was measured by applying a 1 mA rms AC current at 1.8 kHz through the device and monitoring the difference-over-sum output with a spectrum analyzer. Figure 3 shows a noise floor that is 61.8 dB lower than the signal for a 0.94 Hz measurement bandwidth. The resulting NEI is 840 nA/Hz\(^{1/2} \), about a factor of four greater than the previous Ga:YIG sensor,\(^1\) and corresponds to a noise-equivalent rotation of \( \sim 1 \times 10^8 \, \text{rad}/\text{Hz}^{1/2} \).

YIG has a saturation Faraday rotation of 220°/cm,\(^7\) so 220° rotation is expected from four 2.5 mm long cylinders at saturation. Extrapolating the measured \( 0.7^\circ/\text{A} \) small-signal sensitivity to estimate the

---

Figure 2. YIG current sensor with coated prisms. The device measures 6.5 mm \( \times \) 6.5 mm \( \times \) 2 mm with an inner aperture that can accommodate a 2.4 mm conductor.

Figure 3. Difference-over-sum output spectrum for 1 mA rms excitation at 1.8 kHz.
saturation current yields ~ 300 A. However, a simple polarimetric sensor biased at the linear operating point has a sinusoidal transfer function, so response is linear within 1% for rotations $\theta < 7^\circ$. Thus the device is expected to have 1% linearity over a ±10 A current range. If we define the measured NEI for a 1 Hz bandwidth as the lowest detectable current and 10 A as the maximum current, this sensor should exhibit ~140 dB dynamic range for 1% linear response.

One requirement for device insensitivity to external magnetic fields and currents is that the optical beam travel a closed path with uniform magneto-optic sensitivity. This condition is not fulfilled in our present device because the turning prisms have negligible sensitivity compared to the YIG cylinders. Electrical isolation was determined by comparing the sensor signal obtained from a 1 mA rms current at 1.8 kHz passing through a conductor outside the sensor with the signal obtained when the same current was passed through the center of the sensor. With the conductor just touching the outside of the sensor, the isolation for various positions ranged from 14 dB to 31 dB, with the poorest isolation occurring with the conductor nearest the last YIG piece in the optical path. Repeating the measurements with the conductor 5 mm from the sensor gave isolations ranging from 27 dB to 56 dB, with the worst isolation again at the last YIG piece. Though this device exhibits less isolation than the 56 dB measured isolation of a 55-turn silica fiber sensor, this represents a significant improvement over the isolation exhibited by the complementary-prism-pair device. We believe that this improvement is due to the reduced optical path between YIG pieces that the single-prism design allows.

Frequency response was measured by placing the sensor in a coaxial travelling-wave cell and recording the rotation signal with one high-bandwidth photodiode for excitation frequencies between 1 MHz and 1 GHz. (Difference-over-sum processing was not used due to bandwidth limitations of this circuit.) The spectrum exhibits ±0.6 dB ripple from 1 to 100 MHz, a +3.8 dB resonance at 200 MHz and a -3 dB bandwidth of 500 MHz. (Figure 4). The bandwidth is less than the 700 MHz measured for a single YIG cylinder, and the reduction is thought to be due to proximity effects among the YIG pieces. For this device, the calculated sensitivity-bandwidth product is 350 MHz°/A, a factor of 45 improvement over the 7.8 MHz°/A product measured for the Ga:YIG device, and a greater improvement over the transit-time-limited 1.5 MHz°/A product for a silica-fiber current sensor with a 5 mm diameter fiber coil.

The response to a 9 ns (FWHM) 345 mA peak current pulse was also measured. Single pulse data exhibited signal-to-noise ratios greater than 7. A measurement of 32 averaged pulses is shown in Figure 5 to demonstrate pulse fidelity. Slow drift in the laser power is evident since the current was pulsed at a low repetition rate.
Compatibility with optical fiber pigtails has been demonstrated. Quarter-pitch graded-index lenses were attached to polarization-maintaining fibers for beam collimation and lens/fiber pigtail assemblies were aligned to the sensor. A glass cube attached to the sensor ports allows unobstructed optical access and provides surfaces for fixturing and mounting. Figure 6 shows a photograph of the pigtailed device. Excess loss as low as 2 dB was measured, and most of this is attributed to Fresnel losses at the YIG interfaces \( n = 2.23 \) at \( \lambda = 1.3 \mu m \). Permanent attachment with cured adhesive resulted in 3 dB total insertion loss.

In conclusion, a simplified iron garnet current sensor using phase-preserving coatings on single turning prisms has been demonstrated. These low-retardance reflectors considerably ease fabrication of bulk current sensors. The sensor is more compact and exhibits increased electrical isolation and proximity effects that increase the magneto-optic sensitivity over that of isolated pieces. Selection of YIG as a transducer material has provided a large increase in bandwidth with a relatively small loss of sensitivity compared to a previous Ga:YIG device and allows a significant increase in sensitivity-bandwidth product.

We thank David Smith of Opticoat Associates for design and deposition of the phase-preserving coatings. This work is sponsored in part by the Defense Nuclear Agency under DNA IACRO #93-806 and work unit 0002. This paper is a publication of the U.S. Government and is therefore not subject to copyright.

References