Fiber-optic Faraday-effect magnetic-field sensor based on flux concentrators

Merritt N. Deeter

The principles and performance of a fiber-optic Faraday-effect magnetic-field sensor designed around an yttrium-iron-garnet (YIG) sensing element and two flux concentrators are described. The system design exploits the technique of polarization-rotated reflection in which a single polarization-maintaining optical fiber links the sensor head to the optical source and detection system. In the sensing head, ferrite flux concentrators are magnetically coupled to the YIG sensing element to achieve maximum sensitivity. The system exhibits a noise equivalent field of 6 pT/$\sqrt{}$Hz and a 3-dB bandwidth of ~10 MHz. © 1996 Optical Society of America

1. Introduction

Faraday-effect sensors based on iron-garnet crystals are particularly useful as passive magnetic-field sensors in applications requiring high sensitivity, wideband frequency response, and compatibility with fiber optics.[1–3] Magnetic-flux concentrators have been employed to increase the sensitivity of these sensors further. A laboratory system (lacking fiber-optic links between the source, head, and detection system) incorporating such concentrators exhibited a noise equivalent field of 1.4 pT/$\sqrt{}$Hz at 2 kHz.[4]

In this paper the design and performance of a packaged and fiber-pigtailed magnetic-field sensor based on yttrium iron garnet (YIG) are described. The sensor architecture, shown schematically in Fig. 1, exploits the concept of polarization-rotated reflection (PRR).[5] The PRR design requires only a single polarization-maintaining optical fiber to link the sensor head to the source and detection system. A beam splitter positioned in the collimated beam between the source and input objective lens separates a fraction of the backward-traveling signal beam from the forward-traveling source beam and directs it to a polarimetric detection system.

The PRR design permits a complete analysis of the polarimetric signal from the head through a cancellation of the phase errors that accumulate in the polarization-maintaining optical fiber in the forward and backward optical paths.[5] Initially light from a linearly polarized source enters the fiber pigtail polarized at 45° relative to the axes of the polarization-maintaining optical fiber. At this point both the amplitudes and the phases of the components traveling along the fast and the slow axes of the fiber are equal. Propagation through the fiber produces a net phase shift between these components at the point where the light leaves the fiber and enters the head. A quarter-wave plate in the head converts these orthogonally polarized linear states into left and right circularly polarized states. Magnetic circular birefringence (a manifestation of the Faraday effect) in the magneto-optic sensing element produces another phase shift between the two circularly polarized states. This phase shift is doubled (because of the nonreciprocal nature of the Faraday effect) when the mirror reflects the light back through the sensing element. The quarter-wave plate then converts each circularly polarized component back to a linear state polarized perpendicular to that component's original state.

Therefore the component that initially traveled to the head polarized along the fiber's fast axis goes back along the slow axis and vice versa. When the two components finally emerge from the fiber, each has made exactly one pass along the slow axis and one pass along the fast axis. In this way all relative phase shifts induced by the fiber itself are canceled. The only residual phase shift is that caused by the Faraday effect, which is the desired signal.

Unlike standard Faraday-effect sensors, however, in which the magnetic field (the measurand) induces a polarization rotation, in the PRR design the mag-

The author is with Optoelectronics Division, National Institute of Standards and Technology, MS 814.02, 325 S. Broadway, Boulder, Colorado 80303-3328.

Received 21 March 1995; revised manuscript received 29 August 1995.

0003-6935/96/010154-04$06.00/0

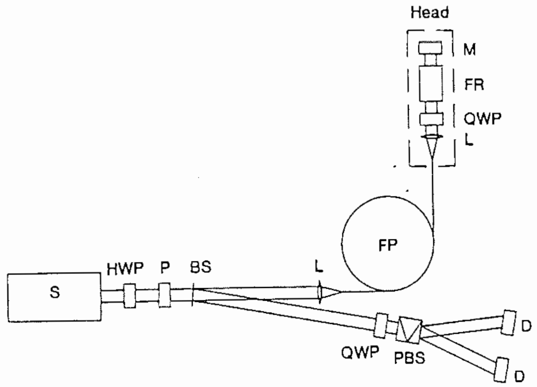

Fig. 1. Polarization-rotated reflection sensor system: S, source (laser or light-emitting diode); HWP, half-wave plate; P, polarizer; BS, beam splitter; L, lenses; FP, high-birefringence fiber pigtail; QWP, quarter-wave plates; FR, Faraday rotator; M, mirror; PBS, Wollaston polarizing beam splitter; D, detectors.

netic field generates a phase shift between linearly polarized components. The system thus behaves polarimetrically more as a conventional electro-optic (Pockels cell) modulator than a conventional magneto-optic modulator. Linearity requirements for such a system necessitate the use of an additional quarter-wave plate in the detection system as a polarimetric biasing element.

2. Head Design and Assembly

Optical, magnetic, and mechanical considerations influenced the design of the sensing head. A scale drawing of the unpackaged head is shown in Fig. 2. The optical elements include a gradient-index (GRIN) lens to collimate the fiber output, a quarter-wave plate (required by the PRR scheme), and a mirror-coated YIG crystal. For sensitivity enhancement, two tapered-cylinder ferrite flux concentrators were included. In the original YIG/flux-concentrator experiment,[4] axial holes in both concentrators were necessary to permit collimated light from the source to transmit through the YIG crystal to the detection system. An advantage of the PRR design is that only one of the concentrators requires such a hole. The second concentrator can therefore abut directly against the end of the mirror-coated end of the YIG crystal. This design provides significantly better magnetic coupling than is possible with the original transmissive flux-concentrator design. Moreover, because the second concentrator is completely isolated from the optical path, its position can easily be varied as a means for tuning the magneto-optic sensitivity of the head.

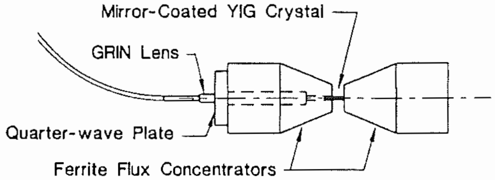

Fig. 2. Sensor head. Packaging is not shown.

The system was designed to operate with a source emitting at a wavelength of 1320 nm. At this wavelength, many iron garnets (including YIG) exhibit both large saturation Faraday rotation values (up to hundreds or even thousands of degrees per centimeter) and extremely low absorption.[6] Moreover commercial high-power diode-pumped Nd:YAG lasers with low-noise characteristics are available at this wavelength.

The single-crystal YIG sensing element measured 1.0 mm in diameter and 4.92 mm in length. The flux concentrators were fabricated from a commercially available nickel–zinc ferrite composition.[7] As shown in Fig. 2, each concentrator included both a cylindrical and a conical segment of equal length (12.7 mm). The diameter of the cylindrical section was 16.5 mm and narrowed to a minimum of 6.4 mm at the endface of the conical segment. To simplify fabrication of the concentrator, the diameter of the optical access hole was not uniform. Within the last 6.4 mm of the conical segment the hole diameter was 1.0 mm, thus matching the diameter of the YIG crystal. Throughout the remainder of the concentrator the hole diameter was 3.0 mm. As the final step of the assembly stage the YIG sensing element was inserted into the flux concentrator to a depth of 0.4 mm and secured in place with UV-setting optical adhesive.

The head was pigtailed with a 2.2-m polarization-maintaining fiber that terminated in an angle-polished FC/PC connector. The purpose of the angle-polished connector was to separate the signal beam (returning from the head) spatially from the Fresnel reflection generated by the source beam at the termination. These two waves, which are of comparable magnitude because of the optical losses within the head, would otherwise interfere in the detection system and thus corrupt the signal. For protection the entire head was fixed inside a plastic package. The dimensions of the packaged head were 2.5 cm × 2.5 cm × 8.1 cm.

3. Experimental

No attempts were made to make accurate calibrations of the magnetic fields generated in the response function, frequency response, or noise-equivalent-field experiments. Rather, measurements of electric current or power were converted to values of magnetic field by standard formulas. The accuracy of these indirect measurements is ~5%.

The system response functions were measured by recording the separate detector outputs as the applied magnetic field was stepped through a complete cycle. The applied field was generated by Helmholtz coils fed by a computer-controlled dc power supply. Response function data were recorded for several values of maximum applied field $H_{\max}$ and YIG/flux-concentrator separation d.

Figure 3 shows response function data recorded in the maximum sensitivity configuration ($d = 0$) for $\mu_0 H_{\max} = 1.9$ mT. The multiple peaks in each

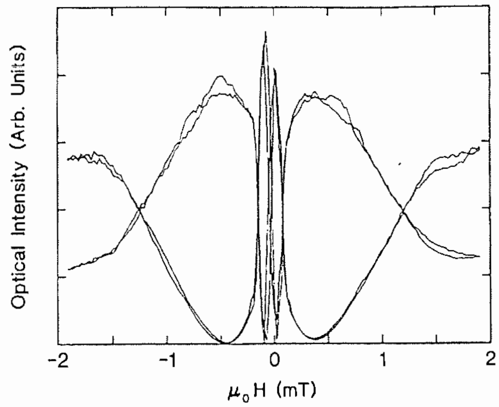

Fig. 3. Response function curves for the head in the maximum sensitivity ($d = 0$) configuration and maximum field $|\mu_0 H_{max}| = 1.9$ mT.

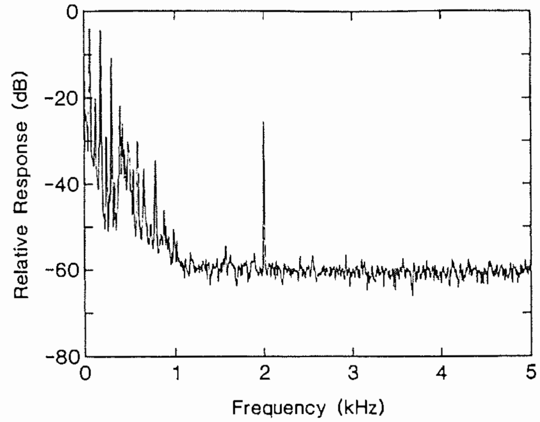

Fig. 4. Sensor output spectrum recorded while a 1.1-nT test signal is applied to the head at 2 kHz.

channel are typical of polarimetric detection systems. For magneto-optic materials exhibiting a purely linear relationship between the magnetic field and Faraday rotation (e.g., diamagnetic materials), response function data generally appear sinusoidal. The hysteresis and nonperiodicity of the peaks evident in Fig. 3 probably result from nonlinearity of the garnet/concentrator system's magnetization curve. Data sets recorded for values of $\mu_0 H_{max} > 1.9$ mT exhibited substantially less hysteresis than that seen in Fig. 3. In part, the hysteresis is thought to be due to optical undersampling of the YIG crystal's ferrimagnetic domains.[2] Saturation appears to occur near 1.8 mT. The sensor exhibited maximum magneto-optic sensitivity (Faraday rotation per unit magnetic field for values of $|\mu_0 H|$ less than ~0.2 mT). Within this range the magneto-optic sensitivity was ~1000°/mT. The measured value for the YIG crystal without the concentrators was 24°/mT. The field amplification provided by the flux concentrators was therefore a factor of ~40.

Noise-equivalent-magnetic-field measurements were performed by exposing the sensor head to a calibrated ac magnetic field (again with Helmholtz coils) and measuring the output signal-to-noise ratio on a spectrum analyzer. The Helmholtz coils were constructed around a nonmetallic frame to prevent the generation of eddy currents. The actual electrical signal in this experiment was formed by a differential amplifier fed by the outputs of the two detectors. These measurements require that the system be operated at quadrature, near the midpoint of the response function. Both hysteresis effects and sufficiently large dc magnetic fields can potentially bias the system well away from quadrature. Active magnetic-field biasing was used to maintain the system at quadrature in this experiment.

Figure 4 shows the output spectrum resulting from a 1.1-nT (rms) magnetic field applied to the head at 2 kHz. The signal-to-noise ratio was ~35 dB and the spectrum analyzer's noise bandwidth was 9.4 Hz. The noise equivalent field was therefore ~6 pT/$\sqrt{\text{Hz}}$. The calculated shot-noise-limited noise floor is 1.1 pT/$\sqrt{\text{Hz}}$. Other noise sources, including laser noise, magnetic domain noise (both in the garnet and concentrators), and electronic noise probably account for most of the difference between the theoretical and experimental noise floors. Much of the low-frequency noise in Fig. 4 (and particularly the obvious spikes) disappeared when the head was inserted into a three-layer μ-metal magnetic shield. Thus much of this low-frequency noise was caused apparently by environmental magnetic fields.

The incident beam power (measured just before the beam splitter) for this measurement was 6.3 mW, whereas the total detected power was ~0.22 mW. The system coupling efficiency was therefore 3.5% as opposed to the ideal value of 25% (limited only by the two passes through the 50/50 beam splitter). Fiber-coupling losses, reflection losses, and domain-scattering losses[8] are all contributing sources of excess optical loss.

Frequency-response measurements between 40 kHz and 250 MHz were conducted with the aid of a synthesizer, rf amplifier, TEM cell, high-speed optical receiver, and electrical spectrum analyzer. Only one of the optical signals generated by the polarimet-

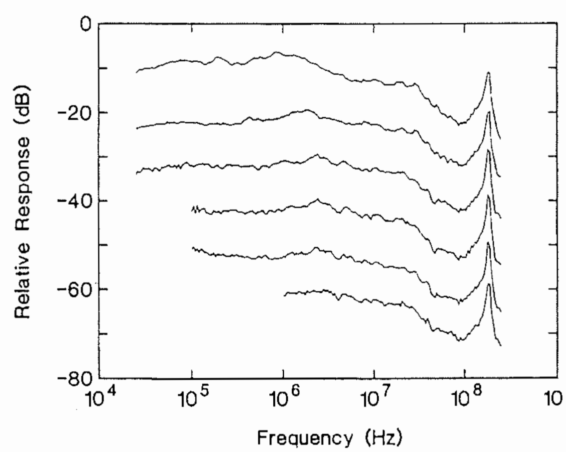

Fig. 5. Frequency response of the sensor head. The field amplitude was decremented in steps of 10 dB between runs. The top curve was recorded at a field strength of 6.8 μT (rms).

ric detection system was required for this experiment. A multimode optical fiber delivered the optical signal to the shielded, ac-coupled receiver. For each successive run, the field strength was decremented in steps of 10 dB from a maximum field amplitude of 6.8 μT (rms).

Several data sets recorded with the sensor configured for maximum sensitivity ($d = 0$) are shown in Fig. 5. Linear response is indicated in this figure by the observation that reduced field amplitudes produced only corresponding simple vertical shifts in the frequency-response data. The only exception to this behavior is seen in the top curve, which exhibits enhanced response below 1 MHz compared with all the other curves. The obvious peak near 200 MHz in all the runs is probably a domain wall motion resonance in the YIG crystal.[9] As indicated by the −3-dB frequency in all the data sets, the sensor bandwidth is of the order of 10 MHz.

4. Conclusion

A fiber-optic magnetic-field sensor based on a YIG sensing element and a simple single-fiber system design was demonstrated. Flux concentrators were exploited to enhance the YIG crystal's magneto-optic sensitivity. The system exhibited a noise equivalent field of 6 pT/$\sqrt{\text{Hz}}$ and a bandwidth of ~10 MHz.

Several design enhancements would increase the utility of this sensor even further. As noted above, active magnetic-field biasing was necessary to maintain quadrature operation for the frequency response and noise-equivalent-field measurements. Because of the ultrahigh magneto-optic sensitivity of the head, even small dc magnetic fields (for example, the Earth's field) have the potential to produce substantial polarimetric bias. On the other hand, such polarimetric bias errors could probably be compensated while still preserving the passive nature of the sensing head. One such compensation scheme might involve an electrically controlled variable retarder (for example, a Pockels cell) as a replacement for the quarter-wave plate in the detection system. This retarder would be integrated in a feedback loop fed by an error signal formed by the PRR output signal passed through a low-pass amplifier.

For applications requiring maximum sensitivity, the use of recently developed iron garnet compositions could probably improve performance by 1–2 orders of magnitude.[10] This would correspondingly reduce the sensor's noise equivalent field into the range of 100 fT/$\sqrt{\text{Hz}}$.

References and Notes

1. G. A. Massey, D. C. Erickson, and R. A. Kadlec, "Electromagnetic field components: their measurement using linear electro-optic and magneto-optic effects," Appl. Opt. **14,** 2712–2719 (1975).
2. K. Svantesson, H. Sohlström, and U. Holm, "Magneto-optical garnet materials in fiber optic sensor systems for magnetic field sensing," in *Electro-Optic and Magneto-Optic Materials II,* H. Dammann, ed., Proc. Soc. Photo-Opt. Instrum. Eng. **1274,** 260–269 (1990).
3. M. N. Deeter, "High sensitivity fiber-optic magnetic field sensors based on iron garnets," IEEE Trans. Instrum. Meas. **44,** 464–467 (1995).
4. M. N. Deeter, G. W. Day, T. J. Beahn, and M. Manheimer, "Magneto-optic magnetic field sensor with a 1.4 pT/$\sqrt{\text{Hz}}$ noise equivalent field at 1 kHz," Electron. Lett. **29,** 993–994 (1993).
5. A. Enokihara, M. Izutsu, and T. Sueta, "Optical fiber sensors using the method of polarization-rotated reflection," J. Lightwave Technol. **LT-5,** 1584–1590 (1987).
6. M. N. Deeter, G. W. Day, and A. H. Rose, "Magnetooptic materials: crystals and glasses," in *Handbook of Laser Science and Technology, Supplement 2: Optical Materials,* M. J. Weber, ed. (CRC Press, Boca Raton, Fla., 1995), pp. 367–402.
7. Flux concentrators were fabricated from a commercial nickel–zinc ferrite composition (C2050) sold by Ceramic Magnetics, Inc. The material exhibits an initial (low-frequency) permeability of 100, which rolls off to 50 at ~100 MHz.
8. M. N. Deeter, "Domain effects in Faraday effect sensors based on iron garnets," Appl. Opt. **34,** 655–658 (1995).
9. R. Wolfe, E. M. Gyorgy, R. A. Lieberman, V. J. Fratello, S. J. Licht, M. N. Deeter, and G. W. Day, "High frequency magnetic field sensors based on the Faraday effect in garnet thick films," Appl. Phys. Lett. **60,** 2048–2050 (1992).
10. M. N. Deeter, S. Milián Bon, G. W. Day, G. Diercks, and S. Samuelson, "Novel bulk iron garnets for magneto-optic magnetic field sensing," IEEE Trans. Magn. **30,** 4464–4466 (1994).