Fast, Sensitive Magnetic-Field Sensors Based on the Faraday Effect in YIG

M. N. DEETER, A. H. ROSE, AND G. W. DAY

***Abstract*—We characterize magnetic-field sensors based on the Faraday effect in ferrimagnetic iron garnets in terms of their sensitivity, speed, and directionality. Signal-to-noise measurements at 80 Hz on small (typically 5 mm diameter × 3 mm long) samples of yttrium iron garnet (YIG) yield noise equivalent magnetic fields of 10 nT/$\sqrt{\text{Hz}}$. Frequency response measurements exhibit virtually flat response to approximately 700 MHz.**

I. INTRODUCTION

APPLICATIONS of the Faraday effect to magnetic-field sensing are growing rapidly, particularly in situations where size, weight, speed, and immunity to electromagnetic interference are important considerations [1]. Most of these applications have used diamagnetic materials. However, other classes of magnetic materials offer the possibility of greater sensitivity, though perhaps at some cost in stability, speed, or other properties. One particularly interesting class of materials is the ferrimagnetic iron garnets. Although the unique magneto-optical properties of these materials have been employed in several applications, including magnetic-field sensing [2]–[6], little information on the performance limitations of such sensors is available.

In this paper, we report the results of an investigation of some of the properties and limitations of magnetic-field sensors based on yttrium iron garnet (YIG), one of the most readily available ferrimagnetic iron garnets.

II. FERRIMAGNETIC FARADAY-EFFECT SENSORS

In ferrimagnetic materials, an applied magnetic field tends to align the magnetic dipoles of the individual domains which make up the material. The Faraday rotation angle Θ_F is proportional to the magnetization component parallel to the direction of propagation of the electromagnetic wave. At saturation, the domains are completely aligned, and the Faraday rotation angle Θ_F^{sat} is given by the product of the specific Faraday rotation F (which is constant for a particular material at a specified wavelength), and the sample length L.

In SI units, the magnetic field H_{sat} at which ferrimagnetic materials saturate, is given by the relation

$$H_{\mathrm{sat}} = M_{\mathrm{sat}} N_D \tag{1}$$

where M_{sat} is the material's saturation magnetization, and N_D is the demagnetization factor, which depends only on the sample's shape and orientation. The demagnetization factor accounts for the difference between the applied field and the actual field within the sample, which is smaller. Ideally, the Faraday rotation in ferrimagnetic materials is linear with H_z, the component of the applied field parallel to the propagation direction. Thus, for $H_z < H_{\mathrm{sat}}$

$$\Theta_F = \Theta_F^{\mathrm{sat}}(H_z/H_{\mathrm{sat}}) \tag{2}$$

or

$$\Theta_F = H_z(FL/M_{\mathrm{sat}}N_D). \tag{3}$$

In terms of rotation per unit applied field (assuming the same interaction length), yttrium iron garnet (YIG) is two to three orders of magnitude more sensitive than typical diamagnetic materials, such as glasses [5]. Other iron garnets are potentially more sensitive [6]–[9]. Furthermore, because the saturation field H_{sat} depends directly on the geometrical demagnetization factor, the sensitivity can be tailored to meet specific requirements.

One problem with ferrimagnetic materials, however, is the inherent nonlinear and hysteretic response of the individual ferrimagnetic domains. In one of the first papers to consider the use of iron garnets as magnetic-field sensors, Massey *et al.* [2] found it necessary to apply a transverse saturating bias field to a YIG sensor in order to align the domains within the sample. While this technique for eliminating problems caused by domains is effective, it is not practical for many applications in which the sensor should be passive and should not itself be a source of magnetic fields. Later, Holm *et al.* [4] showed that, using a differential detection system similar to that shown in Fig. 1, the effects of individual domains were apparent only when the probing beam was significantly smaller than the sensing element. When the light beam was collimated and uniformly sampled the entire YIG element, the signal response became quite well behaved.

III. SENSOR RESPONSIVITY

To verify Holm's results and (3), we determined the response of three samples[1] of single-crystal YIG ($Y_3Fe_5O_{12}$) at a wavelength of 1.3 μm. This wavelength

Manuscript received January 9, 1990; revised July 23, 1990.
The authors are with the Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, CO 80303.
IEEE Log Number 9038960.

---

[1] YIG samples were obtained from Deltronic Crystal Industries, Incorporated, Dover, NJ. This does not constitute a recommendation or endorsement. Samples from other suppliers may perform as well or better.

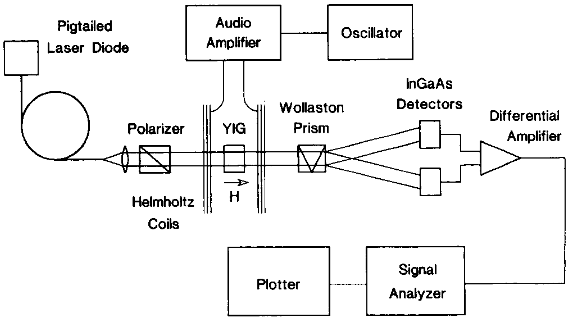

Fig. 1. Experimental system for measuring YIG sensitivity. The Wollaston prism, dual InGaAs detectors, and differential amplifier constitute a differential detection system which produces a linear signal for small Faraday rotation angles.

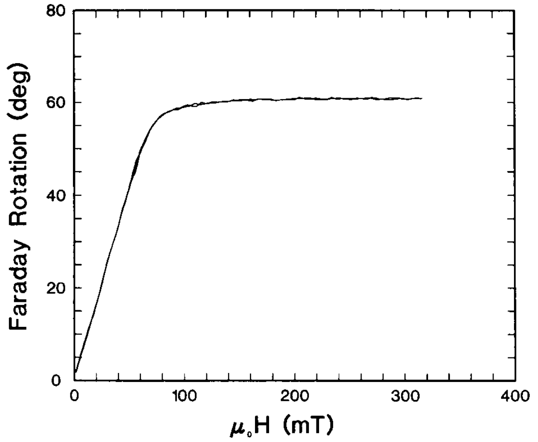

Fig. 2. Faraday rotation versus applied field for 3-mm-long sample. Note the lack of hysteresis and the linearity which is maintained until very near saturation.

lies well beyond the YIG absorption edge near 1 μm [10], yet still in a region where the specific Faraday rotation is quite high [11]. All the samples were 5-mm-diameter cylinders; the lengths were 1, 3, and 5.6 mm. In order to minimize domain effects, we made the beam diameter approximately equal to the crystal diameter. The Faraday rotation data shown in Fig. 2 for the 3-mm-long YIG sample were obtained by sweeping the applied field from 0 to approximately 255 kA/m (corresponding to a free-space flux density of 320 mT) and back to 0. In order to produce a graph of Θ_F rather than sin $(2\Theta_F)$, which corresponds to the actual output of the detection system, the data were mathematically inverted.

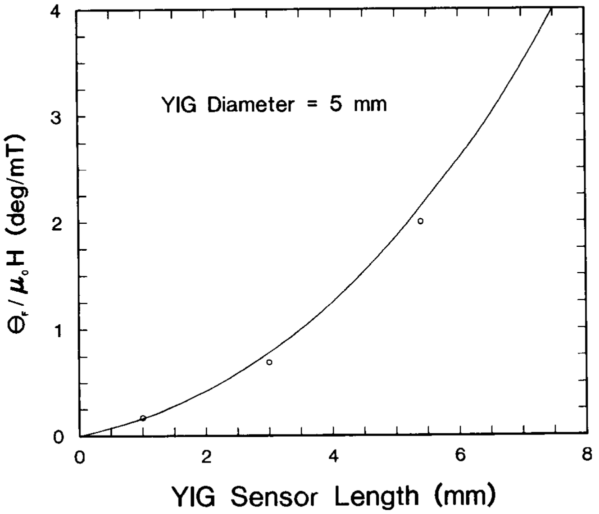

Fig. 3. Geometrical dependence of YIG sensor response. YIG samples were all 5 mm in diameter. The solid theoretical curve was calculated using demagnetization factors of ellipsoidal samples with the same length to width ratio as cylindrical samples (see [12]).

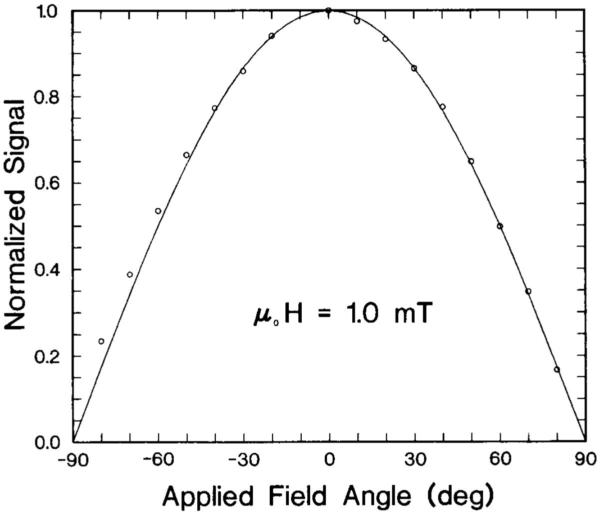

Fig. 4. YIG sensor directionality. The YIG sample was 5 mm in diameter and 5.6 mm long. The modulus of the applied magnetic field was 800 A/m ($\mu_o H$ = 1.0 mT).

In agreement with [4], the data in Fig. 2 exhibit linearity (for $\mu_o H \leq 60$ mT) and no hysteresis. The results on all three samples, in terms of sensor response (the ratio of the Faraday rotation to free-space flux density $\Theta_F/\mu_o H$) versus crystal length are plotted in Fig. 3. The solid line is a theoretical curve based on values of N_D calculated using the equivalent ellipsoid approximation (see for example [12]). The specific Faraday rotation for YIG at 1.3 μm was taken as 220°/cm [13]. Despite the departure of the data from the theoretical curve, the overall trend of the data follows the theory well.

IV. DIRECTIONALITY

Sensor directionality is an important issue for any application in which the direction of the applied field might not necessarily coincide with the propagation direction of the optical beam. In ferrimagnetic materials, unlike diamagnetic materials, the longitudinal magnetization component, and thus the Faraday rotation, are sensitive to both

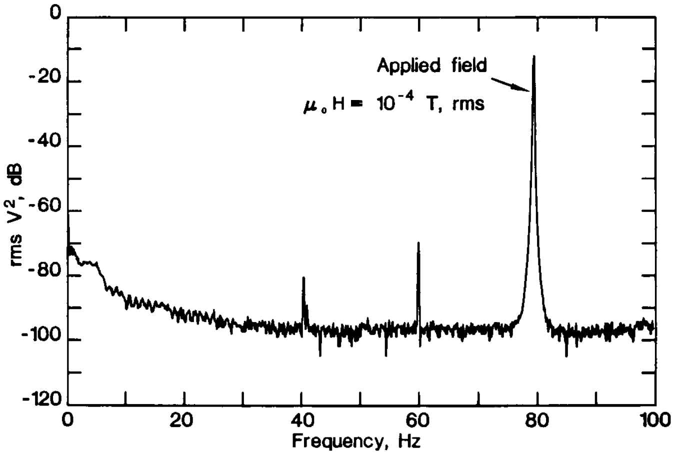

Fig. 5. Typical noise spectra for applied field of $\mu_o H$ = 1.0 mT (rms) taken with a noise bandwidth of 0.187 Hz. The low-frequency (0-40 Hz) noise is believed to be primarily caused by detector responsivity drift. Above 40 Hz, the noise floor is appoximately 10 nT/√Hz.

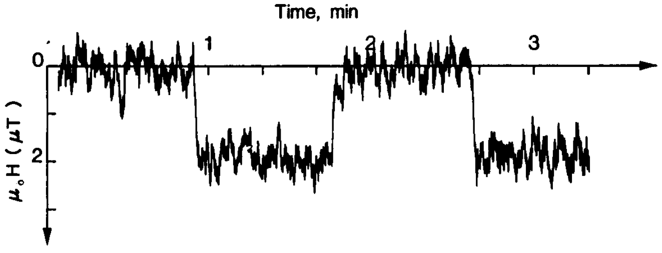

Fig. 6. DC output of YIG sensor obtained by intensity modulation and lock-in detection. A magnetic field of $\mu_o H$ = 2 μT was switched on and off at intervals of approximately 1 min. The minimum detectable field in this case appears to be on the order of 100 nT/√Hz.

the longitudinal and transverse-field components. The origin of this effect lies with the Zeeman energy term which couples the magnetization vector to transverse as well as longitudinal applied fields. As a function of applied-field angle, this effect should manifest itself as a distortion of the ideal cosine response function. On the other hand, preliminary calculations predict that the magnitude of this distortion should be small when the modulus of the applied field is much less than the saturation field H_{sat}. These calculations will be published elsewhere.

Signal directionality measurements were performed with two orthogonal pairs of Helmholtz coils arranged to independently produce longitudinal and transverse field components. The applied-field angle was controlled by calculating and applying the proper amount of current for each pair of calibrated Helmholtz coils for the given field angle and fields modulus. Directionality data for the 5.6-mm-long sample and an applied field of 800 A/m ($\mu_o H$ = 1.0 mT) are shown in Fig. 4, along with an ideal cosine response curve. At this field strength, the measured response closely follows the ideal cosine response curve.

V. NOISE-EQUIVALENT FIELD

To determine the minimum detectable magnetic field, noise spectral data were taken with the 3-mm-long YIG sample using the system shown in Fig. 1. The source was a pigtailed 1.3-μm laser diode with approximately 0.3-mW optical power. For calibration, ac current oscillating at 80 Hz was applied to a pair of Helmholtz coils producing a magnetic field of 80 A/m ($\mu_o H$ = 0.10 mT) amplitude (rms) along the axis of the sample. Typical spectra are shown in Fig. 5. The noise bandwidth was 0.187 Hz. The signal-to-noise ratio at 80 Hz is approximately 87 dB, corresponding to a noise floor of approximately 10 nT/√Hz. This is about a factor of 6 above the shot-noise limit for our experimental parameters. We think this difference is due primarily to laser noise and excess amplifier noise.

Below 40 Hz, the rise of the noise floor probably has at least two components. The first, ambient magnetic noise, arises because of insufficient magnetic shielding around the experiment. The remaining component, associated with the detection system, is more significant. If this noise source were additive, it would be possible to extend the noise performance obtained at 80 Hz to lower frequencies by modulating the source and measuring the signal at the modulation frequency.

To investigate this possibility, dc data were taken by chopping the source at 100 Hz, while switching a dc field of approximately 1.6 A/m ($\mu_o H$ = 2.0 μT) on and off at about 1-min intervals. A lock-in amplifier with a noise

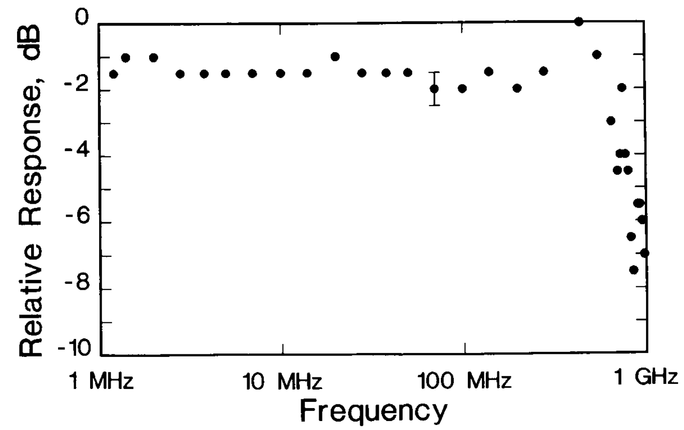

Fig. 7. Frequency response of the YIG sensor for applied magnetic field of $\mu_o H \approx 0.5\ \mu$T. The −3-dB rolloff frequency is approximately 700 MHz. The approximate measurement uncertainty is shown by the error bar.

bandwidth of 2 Hz and a chart recorder were used to record the data. The results are shown in Fig. 6. Although there is no evidence of long-term signal drift, the minimum detectable dc field is of the order of 0.08 $(\mathrm{A/m})/\sqrt{\mathrm{Hz}}$ (or 100 $\mathrm{nT}/\sqrt{\mathrm{Hz}}$) which is about a factor of 10 greater than for the ac case. Since ambient magnetic-field fluctuations are not generally of this order of magnitude [14], we think that the increased noise at low frequencies is due primarily to some type of multiplicative noise, such as detector responsivity drift caused by small temperature variations.

This explanation was first proposed by Holm *et al.* [15]. Small, time-varying differences in the temperature of the detectors are difficult to avoid, even if, as in our case, the detectors are mounted closely together on a thermally conducting substrate. For certain Ge detectors, a relative temperature drift of 1 °C will change the relative response by 0.3%. This amount of drift is sufficient to overwhelm very small differential signals for which the intensities at the two detectors are nearly equal. On the other hand, this type of noise is apparently not a problem for ac measurements above about 40 Hz.

VI. FREQUENCY RESPONSE

The frequency response of a magnetic-field sensor is of concern in many applications. Unfortunately, very little work has been done in measuring the frequency response of bulk iron garnets. Moreover, much of the work that has been done has exploited the phenomenon of ferrimagnetic resonance, in which magnetic samples are simultaneously subjected to orthogonal dc and RF magnetic fields. Resonance in the amplitude of magnetization oscillations at the RF frequency occurs at a frequency determined by the strength of the dc field. Results from this configuration have little relevance to our situation, in which we are primarily interested in the response of the magnetization of an unsaturated sample to a pure RF field [16].

We determined the response of a specimen to fields at frequencies from 1 MHz to 1 GHz. In this experiment, the applied RF magnetic field was produced by current passing through a copper strip about 15 mm wide and 4 cm long, and mounted within a grounded aluminum box. The axis of the cylindrical YIG sample was positioned approximately 5 mm above the transversely mounted copper strip. The transmission line was well terminated at each end to avoid reflections. Current was supplied to the strip at discrete frequencies by an RF synthesizer; the longitudinal magnetic field was calculated to be about 0.4 A/m (or 0.5 μT), rms. The frequency response of the detection system, which employed a Ge avalanche photodiode, was independently measured to be flat within ±2.5 dB to 1.2 GHz. The response of the 5.6-mm-long YIG specimen is shown in Fig. 7; the −3-dB point is approximately 700 MHz. The mechanism limiting the frequency response has not been investigated.

VII. DISCUSSION

Massey *et al.* [2] calculated that the noise-equivalent magnetic field for a YIG sensor 2 mm in diameter and 1 cm long with a shot-noise limited optical system should be on the order of 100 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$. Such a sensor, for which $\mu_o H_{\mathrm{sat}} \approx 10$ mT, would possess a dynamic range of 160 dB (for a noise bandwidth of 1 Hz). Although our experimental noise-equivalent magnetic field (in the ac case) is about 100 times larger, it is certainly conceivable that, through the choice of optimum sensor design and material, Massey's figure may be reached or even surpassed.

As suggested by (4), there are several ways to increase the sensitivity of magnetic-field sensors based on iron garnets. The most obvious way is by increasing the length L which, as seen in Fig. 2, increases the sensitivity superlinearly because of the dependence of the demagnetization factor on L. Another technique is to employ iron garnets with larger values of the ratio F/M_{sat}. Of course, a decrease in either the demagnetization factor or saturation magnetization will also decrease H_{sat} and therefore limit the maximum measurable magnetic field.

In general, both F and M_{sat} strongly depend on iron garnet composition and temperature, and F is also a strong function of wavelength. This suggests the possibility of tailoring the iron garnet composition to optimize specific sensor parameters, such as sensitivity or temperature stability. For example, substitution of tetrahedral iron sites in YIG by certain diamagnetic ions, such as gallium, can be used to reduce M_{sat} substantially. Although F is also reduced somewhat by this method, a net increase in the ratio F/M_{sat} is achieved [7]. An even greater enhancement is achieved in various bismuth-substituted iron garnets [8], [9], for which F can be as much as ten times greater than for the associated pure iron garnet. Finally, still another composition has been used to decrease the temperature dependence of the output of a magnetic-field sensor by matching the temperature dependences of F and M_{sat} at a specific wavelength [3], [5].

VIII. CONCLUSION

The data presented here suggest that sensors based on the Faraday effect in YIG can be very successful in many applications requiring measurements of low to moderate field strengths ($10 \text{ nT} < \mu_o H < 100 \text{ mT}$) over broad frequency ranges (dc-700 MHz). While they are not as sensitive as fiber magnetic-field sensors based on the magnetostrictive effect [17], they offer much wider bandwidth and higher spatial resolution, and are much simpler. Furthermore, it should be possible to extend their sensitivity substantially by using different sensing element geometries and other related materials.

REFERENCES

[1] G. W. Day and A. H. Rose, "Faraday effect sensors: The state of the art," in *Proc. SPIE*, vol. 985, 1988, p. 138.

[2] G. A. Massey, D. C. Erickson, and R. A. Kadlec, "Electromagnetic field components: Their measurement using linear electrooptic and magnetooptic effects," *Appl. Opt.* vol. 14, p. 2712, 1975.

[3] O. Kamada, H. Minemoto, and S. Ishizuka, "Mixed rare-earth iron garnet (TbY) IG for magnetic field sensors," *J. Appl. Phys.*, vol. 61, p. 3268, 1987.

[4] U. Holm, H. Sohlström, and T. Brogårdh, "YIG-sensor for fibre optical magnetic field measurements," in *Proc. SPIE*, vol. 514, 1984, p. 333.

[5] O. Kamada, Y. Tsujimoto, and Y. Hayashi, "Fiber-optical current sensors using mixed rare-earth iron garnet crystals," in *Proc. 3rd Sensor Symposium*, 1983, p. 167.

[6] K. Matsuda and S. Ishizuka, "Integration of a faraday rotator and a mode selector for a magnetic field sensor," *Appl. Phys. Lett.*, vol. 55, p. 610, 1989.

[7] R. C. LeCraw, "Wide-band infrared magneto-optic modulation," *IEEE Trans. Magn.* (Abstract), vol. 2, p. 304, 1966.

[8] S. H. Wemple, J. F. Dillon, Jr., L. G. Van Uitert, and W. H. Grodkiewicz, "Iron garnet crystals for magneto-optic light modulators at 1.064 μm," *Appl. Phys. Lett.*, vol. 22, p. 331, 1973.

[9] H. Takeuchi, S. Ito, I. Mikami, and S. Taniguchi, "Faraday rotation and optical absorption of a single crystal of bismuth-substituted gadolinium iron garnet," *J. Appl. Phys.*, vol. 44, p. 4789, 1973.

[10] R. C. LeCraw, D. L. Wood, J. F. Dillon, Jr., and J. P. Remeika, "The optical transparency of yttrium iron garnet in the near infrared," *Appl. Phys. Lett.*, vol. 7, p. 27, 1965.

[11] G. B. Scott and D. E. Lacklison, "Magnetooptic properties and applications of bismuth substituted iron garnets," *IEEE Trans. Mag.*, vol. MAG-12, p. 292, 1976.

[12] D. J. Craik, *Structure and Properties of Magnetic Materials.* London: Pion Limited, 1971, p. 22.

[13] YIG data sheet, Deltronic Crystal Industries, Inc., Dover, NJ.

[14] W. H. Campbell, in *Physics of Geomagnetic Phenomena*, S. Matsushita and W. H. Campbell Eds. New York: Academic, 1967, p. 823.

[15] U. Holm, H. Sohlström, and T. Brogårdh, "Measurement system for magneto-optic sensor materials," *J. Phys. E.*, vol. 17, p. 885, 1984.

[16] P. K. Tien, D. P. Schincke, and S. L. Blank, "Magneto-optics and motion of the magnetization in a film-wavelength optical switch," *J. Appl. Phys.*, vol. 45, p. 3059, 1974.

[17] D. M. Dagenais, F. Bucholtz, K. P. Koo, and A. Dandridge, "Demonstration of 3 pT/√Hz at 10 Hz in a fibre-optic magnetometer," *Electron Lett.*, vol. 24, p. 1422, 1988.

*

M. N. Deeter received the B.S. degree in physics, and the M.S. and Ph.D. degrees in optical sciences from the University of Arizona, Tucson, in 1984, 1986, and 1988, respectively. In 1987, he was awarded an IBM Fellowship to study magneto-optical materials for optical data storage, which later became the subject of his Ph.D. thesis.

In 1988, he joined the National Institute of Standards and Technology, Boulder, CO, where he is currently engaged in the research and development of fiber-optic electric and magnetic-field sensors. His research interests include fiber optics, magneto-optical materials, integrated optics, and optical fiber sensors.

Dr. Deeter is a member of the Optical Society of America.

*

A. H. Rose received the B.S. degree in physics at Abilene Christian University, Abilene, TX, in 1981 and the M.S. and Ph.D. degrees in physics at the University of Arkansas, Fayetteville, in 1983 and 1986 respectively. He then took an NRC postdoc at the U.S. Army's Ballistic Research Laboratory. His graduate research was the development and application of photo-deflection and photo-acoustic spectroscopy for combustion diagnostics. His postdoc research was on molecular spectroscopy.

In 1987 he joined National Bureau of Standards (NBS), which became National Institute of Standards and Technology (NIST), Boulder, CO, to work on the development of optical fiber sensors that measure electric and magnetic fields.

*

G. W. Day received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana, in 1966, 1967, and 1970, respectively.

In 1969, he joined the National Bureau of Standards as an NBS/NRC Postdoctoral Fellow and has remained with that organization, now called the National Institute of Standards and Technology, Boulder, CO. His research has spanned a wide range of problems in the characterization of optical electronic devices and components, focusing especially on optical detectors and optical fiber. Since 1982 he has been responsible for research on optical fiber sensors, primarily for electromagnetic measurements. He has been an Adjunct Professor of Physics at the Colorado School of Mines, a Visiting Fellow at the University of Southampton and a Visiting Lecturer in Electrical Engineering at the University of Colorado. In 1980 he helped organize the first biennial Symposium on Optical Fiber Measurements, and continues as its program chairman.

Dr. Day has received both the Gold and Silver Medals of the U.S. Department of Commerce and an IR-100 Award from Industrial Research Magazine for his research.