Fiber Bragg grating laser sensor

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Abstract. An erbium-doped fiber laser utilizing a broadband mirror as the end reflector and an intracore Bragg grating as the output coupler is designed and developed. This arrangement is used as a laser sensor to improve interrogation efficiency of intracore Bragg gratings over broadband sensor interrogation methods. Wavelength tuning of the fiber laser has been achieved by varying the temperature and strain on the Bragg grating, demonstrating an improved SNR with respect to the previous techniques that use broadband interrogation of the Bragg grating sensor.

Subject terms: fiber lasers; erbium-doped fibers; laser sensors; intracore Bragg grating.

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1 Introduction

Over the past few years the introduction of single-mode fibers with rare-earth dopants (neodymium and erbium) has made possible the successful demonstration of fiber lasers with very low thresholds and high gains. Furthermore, the recent technology of intracore fiber Bragg gratings incorporated in these systems allows for narrow linewidth laser sources that will potentially find a great many applications in fiber sensor and telecommunication systems.[1]

Optical fiber Bragg gratings can be made by producing periodic variations in the index of refraction along a short section in the core of an optical fiber. Photorefractive formation of Bragg gratings in germanosilicate fibers was first observed by Hill et al.[2,3] Later, Meltz et al.[4] were able to demonstrate the successful fabrication of intracore gratings using transverse illumination of the fiber with two UV (245-nm) interfering beams. The successful fabrication of these gratings with their inherent dependence on the optical properties of the fiber has lead to their immediate consideration as sensing devices. That is, because the Bragg grating will reflect only a narrow band of incident light, which depends on the periodic change in the index as well as the refractive index of the fiber core, the grating can be exploited as a temperature and strain sensor. In spite of all the advantages that the intracore Bragg grating sensors offer, their utilization has been limited by the inability to effectively and practically demodulate the wavelength-encoded temperature and strain information. The recent development of a wavelength demodulation system (WDS) for Bragg grating sensors overcomes this problem by simply splitting the backreflection generated from the grating into two beams; one of which serves as an intensity reference and the other passes through a wavelength-dependent transmission filter? The ratio of these two signals provides fluctuation-free decoded wavelength information, from which strain or temperature can be inferred. The developed system, however, utilizes a broadband light source to interrogate the Bragg grating sensor and determine the exact wavelength of the grating. Clearly, because the Bragg grating reflects only a small portion of the broadband incident light (as imposed by its narrow spectral response), one inherent problem with this system is the very low signal levels sent to the detectors, which results in a low SNR. The low SNR compromises the resolution and the dynamic range of the sensor system [an absolute strain resolution of 28 microstrain ($\mu\varepsilon$) with a dynamic range of 25.5 dB have been reported using such a system[6]].

In this paper, we report on the development of an erbium-doped fiber laser that utilizes a broadband mirror as the high reflector in the laser cavity and an intracore Bragg grating serving the dual purpose of output coupler and a sensor. The wavelength as well as the linewidth of the fiber laser are dictated by characteristic spacing and length of the Bragg grating. The Bragg grating was fabricated to have a reflective wavelength at approximately the center of the erbium-doped fluorescence and formed the output mirror of the laser cavity. This intracore Bragg grating fiber laser allows the construction of a sensor with improved interrogation efficiency over broadband systems.

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2 Fiber Laser Sensor

The characteristic broadband gain profile of the erbium-doped fiber around the 1550-nm region makes it a potentially useful tunable light source. Employing this doped fiber in an optical cavity as the lasing medium along with some tuning element will result in a continuously tunable laser source over its broad gain profile. In fact, a tunable erbium-doped fiber with an external grating was reported in 1986 by Reekie et al.[7] Recently, the use of intracore Bragg gratings as internal mirrors for a lasing cavity have been demonstrated by Ball and Morey.[1] In light of this fiber laser technology, a simple way to overcome the low SNR associated with the WDS is to use an intracore Bragg grating (with the appropriate wavelength) as an output coupler and a broadband mirror as the end reflector in a fiber laser assembly. This arrangement forces the lasing to occur at the Bragg wavelength. Because the grating dictates the lasing wavelength, any changes in the Bragg grating (caused by temperature- or strain-induced effects) results in a change of the lasing wavelength. Thus, monitoring the output wavelength of the fiber laser is effectively the same as tracking the center wavelength of the Bragg grating. In this arrangement, the WDS detectors monitor the lasing signal, which is, obviously, much stronger than the previous narrow-band reflection that was observed by utilizing the broadband source. This will, in effect, result in a greatly improved SNR and allow more efficient wavelength determination by the WDS.

A change in the temperature of the fiber produces a shift in the Bragg wavelength because of thermal expansion, which changes the index of refraction and the grating spacing. The wavelength shift resulting from temperature change AT is approximately given by the following simple expression?

$$\mathrm{AX}_{\mathrm{Bragg}} = \lambda_{\mathrm{Bragg}}(\alpha + \xi)\Delta T \ , \qquad (1)$$

where ξ is the thermo-optic coefficient, which is approximately 8.3×10^{-6} for the germanium-doped silica fiber core, and α is the thermal coefficient of expansion for the fiber, which is 0.55×10^{-6} for silica. Clearly, from these numbers, the change in the index of refraction is the dominant effect. Therefore, one would expect a change of approximately 13.7 pm in the lasing wavelength as a result of 1” change in temperature on a grating with a center wavelength of 1550 nm.

When a fiber is strained, the Bragg wavelength varies because of the change in the grating spacing and the photoelastic induced change in the refractive index. This shift in wavelength due to a longitudinal strain ε is approximately given by the following equation*:

$$\Delta\lambda_{\mathrm{Bragg}} = \lambda(1 - p_e)\varepsilon \ , \qquad (2)$$

where p_e is the photoelastic constant given by

$$p_e = \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})] \ , \qquad (3)$$

where p_{11} and p_{12} are components of the strain optic tensor, n is the index of the core, and ν the Poisson’s ratio. From Eqs. (2) and (3), one would expect 1.21 pm change in the lasing wavelength as a result of applying 1 $\mu\varepsilon$ to the Bragg grating with center wavelength at 1550 nm.

3 Experiment

A schematic diagram of the experimental setup is shown in Fig. 1. A continuous wave Ti:sapphire laser was used to pump an erbium-doped fiber with a core diameter of 3.1 μm and erbium concentration of 450 ppm. A neutral density filter was placed just outside of the Ti:sapphire laser to allow for a continuous variation in the laser power. A wedge beamsplitter was positioned after the neutral density filter. Its first surface reflection was directed into a wavemeter, whereas the second surface reflection was directed into a power meter for continuous monitor of the pump laser wavelength and power. The laser beam was coupled into a wavelength division multiplexer (WDM) with a 20 x objective lens. The coupling efficiency of pump laser light into the doped fiber was approximately 10%, and the most efficient wavelength for pumping this particular Er^{+3}-doped fiber was determined to be 976 nm. A five-meter section of the erbium-doped fiber was fusion spliced onto the output port of the WDM, forming the gain medium of the laser cavity. The other end of the doped fiber was coated with a silver nitrate solution,’ which acted as the broadband end reflector for the laser system. The optical fiber containing the Bragg grating was fusion spliced to the 1550-nm port of the WDM, which behaved as the output coupler to the fiber laser cavity. The broadband mirror and the Bragg grating (with the WDM in between) simply define the laser cavity as shown in Fig. 1. The output from the laser cavity was then collimated and directed into a Fourier transform IR (FTIR) spectrometer, which had a resolution of 0.5 cm^{-1} (or 0.11 nm at 1550 nm). This allowed continuous monitoring of the output wavelength and intensity from the fiber laser sensor assembly.

The Bragg grating temperature was varied using a heat-bath assembly. This system consisted of a 400-ml Pyrex container filled with 200 ml of diffusion pump oil (this oil was chosen because of its high boiling point and noncorrosive nature), which was heated by a temperature controlled hot plate. A thermocouple was placed in the oil bath to allow for continuous monitoring of the temperature, which was varied between 20 and 160°C. The Bragg grating section of the fiber laser was immersed in the oil bath and carefully positioned close to the thermocouple. This oil heat-bath arrangement for varying the temperature provided accurate measurements of the fiber core temperature of the Bragg grating.

To further test and characterize the erbium-doped fiber laser sensor the Bragg grating was strained. The Bragg grating was surface-adhered along the centerline of a cantilevered aluminum beam that could be loaded in flexure, allowing the Bragg grating to be strained in both tension and compression. A resistive foil strain gauge of similar gauge length as the grating was bonded symmetrically to the underside of the beam to serve as a strain reference. The wavelength from the strain laser sensor was determined with the FTIR spectrometer as described above.

4 Results

Utilizing a Bragg grating with an 85% reflectivity as the output coupler in the described experimental arrangement (Fig. 1), the coupling power into the fiber laser was kept to a minimum value, that is, below lasing threshold, which was determined to be between 2.2 and 2.6 mW. The broadband fluorescence obtained from the fiber assembly under these

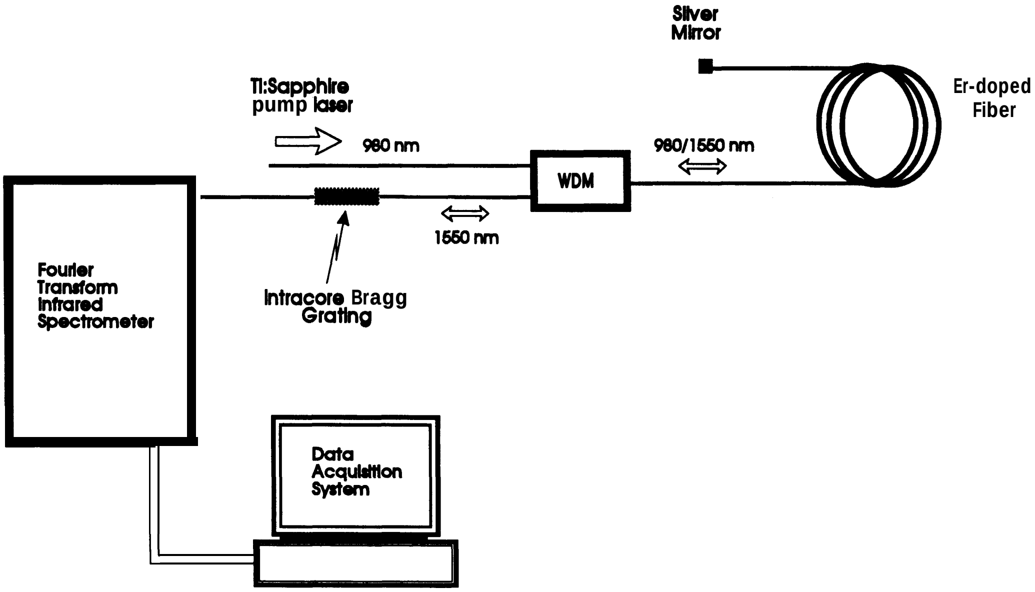


Fig. 1 Schematic diagram of the Bragg fiber laser sensor. The laser cavity is defined by the broadband silver mirror and the Bragg grating reflector and contains the WDM within the cavity.

conditions is shown in Fig. 2. The spectrum is the typical characteristic broadband gain profile from an erbium-doped fiber spanning a range of several tens’ of nanometres, namely between 1.50 and 1.57 μm. Superimposed on the gain profile is a notch at 1550 nm corresponding to the reflection of the fluorescence from the Bragg grating. With increasing incident pump power, the losses in the fiber laser cavity are overcome and lasing begins. At pump powers just above threshold value, due to the Bragg grating, the notch begins to grow in the positive direction and as the pump power increases further the laser line grows even stronger (this effect is clearly shown in Fig. 3). In this figure, the output spectrum from the erbium-doped fiber laser is shown for various coupled pump powers into the doped fiber, starting below lasing threshold at 2.2 to 2.6 and 2.8 mW, where the laser line at 1550 nm begins to grow. Pure lasing occurs at 4.8 mW, as indicated in the indented graph at the upper right corner (Fig. 3), where the third graph shows a vertical line at 1550 nm representing the lasing wavelength with no background fluorescence.

Temperature tuning of the laser sensor was achieved by positioning the Bragg grating in an oil heat bath next to the thermocouple. This experimental arrangement ensured that thermocouple will read the temperature of the Bragg grating, which is exactly the temperature of the heated oil bath. It is important to note that the Bragg grating utilized in this part of the experiment had a 50% reflectivity at 1550 nm. The temperature of the Bragg grating was varied between 20 to 160°C in approximately 30°C steps. The resulting peak lasing

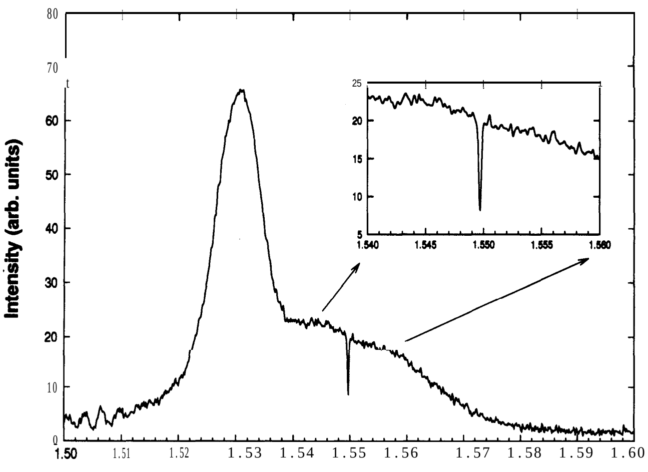


Fig. 2 Characteristic broadband fluorescence spectrum of the erbium-doped fiber with the Bragg grating as the end reflector. The indented figure at the upper right corner shows an expanded scale of the spectrum near the Bragg wavelength.

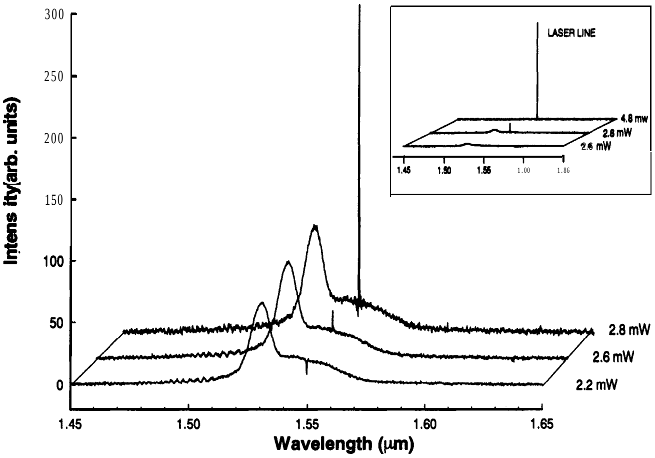


Fig. 3 Output spectrum from the erbium-doped fiber laser sensor at coupled input powers varying from below lasing threshold 2.2 mW, nearly lasing at 2.6 and 2.8 mW. The indented figure at the upper right corner shows the lasing spectrum as a function of coupled pump power of 2.6, 2.8, and 4.8 mW. Complete lasing occurs at 4.8 mW coupled pump power in the erbium-doped fiber laser system.

wavelengths as a function of these different temperatures are shown in Fig. 4(a). These results imply a tuning range of 12.5 pm in the center laser line for 1°C variation in temperature, which is in approximate agreement with the calculated value from Eq. (1). Because the behavior of the lasing spectrum is important in terms of sensor characterization, the FTIR spectra for some of the temperatures of Fig. 4(a) are shown in Fig. 4(b). It is clear from these data that both the amplitude and the linewidth of the laser remain nearly constant over the indicated temperature range. This seems to suggest that the reflectivity of the grating remains constant for a 200°C change in temperature, because the gain profile of the erbium-doped fiber is practically flat over the few nanometers within the lasing region.

Strain tunability of the Bragg grating fiber laser was achieved using the cantilevered aluminum beam as described in the experimental section of this paper. The result of the measurement of peak lasing wavelength as a function of strain on the Bragg grating ranging between − 2500 to 2500 με is shown in Fig. 5. The strain sensitivity of the fiber laser was measured to be approximately 1.20 pm per microstrain, which is in good agreement with the value predicted from Eq. (2).

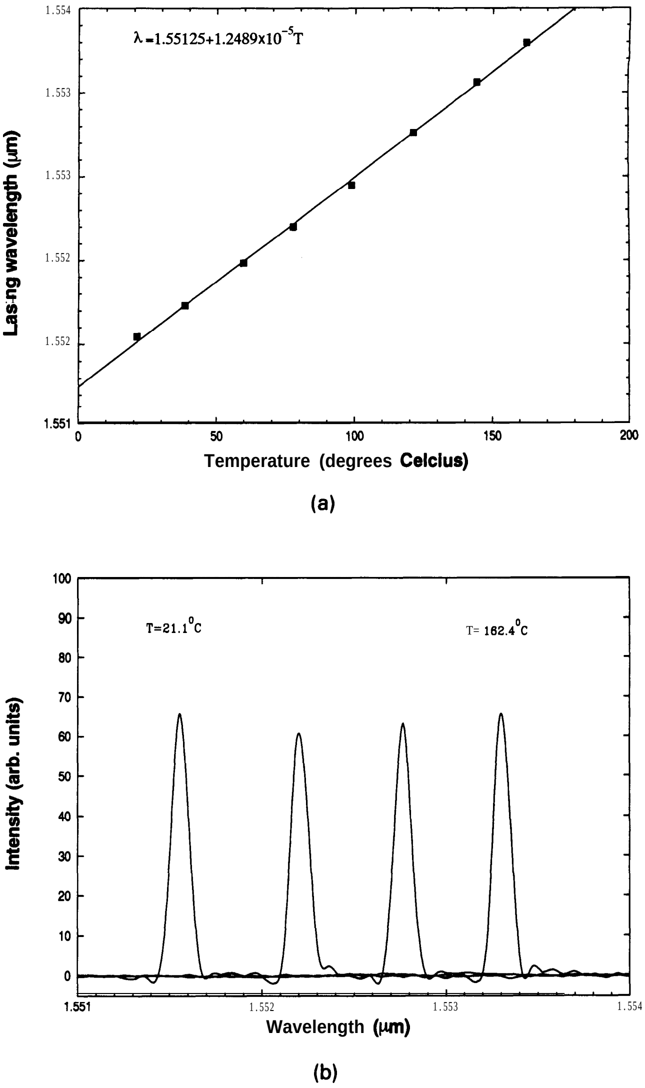
Finally, a wavelength demodulation system (WDS) developed previously[5] was used to determine the wavelength of the Bragg-tuned fiber laser sensor. The WDS splits the light from the fiber laser using a fiber optic 2 X 2 coupler. The light exiting one arm of the coupler is filtered in direct proportion to its wavelength using a bulk optic filter and detected by a photodetector. The light from the other arm of the coupler is detected unfiltered and is used to cancel out any intensity fluctuations in the source, coupling losses, or microbend losses. The wavelength of the fiber laser λ is then given by

$$\frac{I_F}{I_R}=A\left(\lambda-\lambda_0+\frac{\Delta\lambda}{\sqrt{\pi}}\right) , \qquad (4)$$

where I_F and I_R are the filtered and unfiltered optical signals, A and λ_0 are constants determined by the filter characteristics, and AX is the laser linewidth. An interference filter with a bandpass center wavelength of 1560 nm was used in the WDS. This filter was angle tuned so that its front slope provided an equal range of linear filtering on either side of the fiber laser center wavelength. The WDS used provided a total wavelength measurement range of approximately 0.5 nm, limited by the filter characteristics. This can be increased by using a high-pass interference filter with a broader range of linear filtering tailored to the desired operating wavelength linearities. The result from the WDS that was utilized to track the wavelength shift is shown in Fig. 6. The limiting factor in the resolution of this system is electrical noise from the signal processing of the WDS. This corresponds to approximately 5.5 με resolution for the strain sensor, or approximately 0.4°C for the temperature sensor and a bandwidth of 13.0 kHz.

5 Conclusion

An erbium-doped fiber laser that utilizes a broadband mirror as the high reflector and an intracore Bragg grating as the output reflector was designed and successfully demonstrated. The development of this tunable fiber laser in which a Bragg



(a)

(b)

Fig. 4 (a) Peak lasing wavelength as a function of temperature and (b) lasing spectrum for various temperatures.

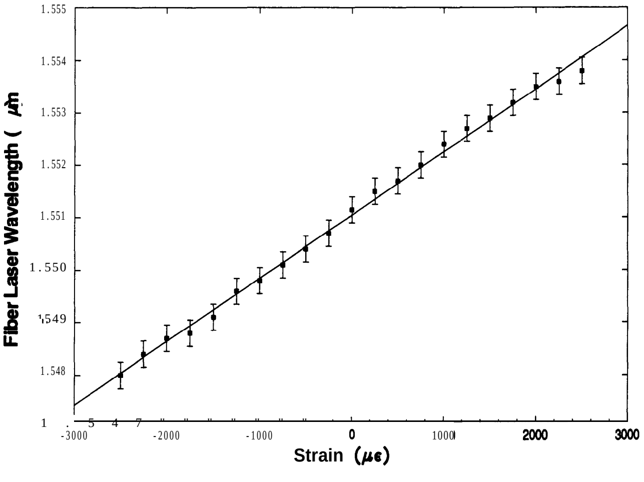


Fig. 5 Fiber laser output wavelength as a function of strain on the Bragg grating.

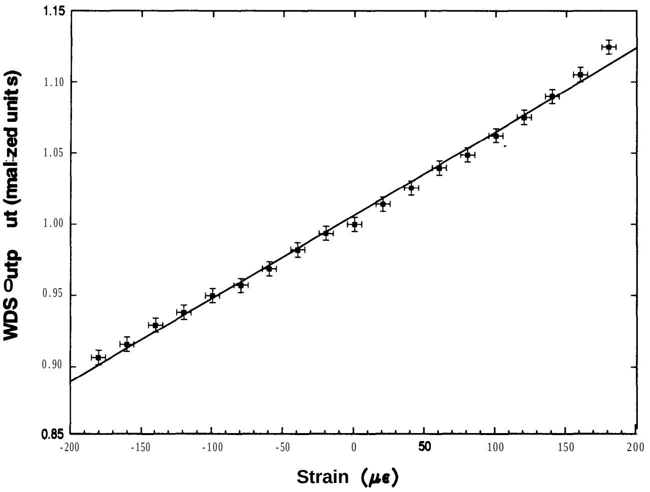


Fig. 6 Wavelength tracking of the fiber laser wavelength as a function of strain on the Bragg grating with the WDS.

grating is employed as an output coupler permits the efficient interrogation of the Bragg grating and allows the system to be used as a fiber laser sensor.

Experimental results indicate temperature tuning of 12.5 pm over 1°C change in temperature and strain tuning of 1.2 pm over 1 $\mu\epsilon$. It has been determined that the minimal doped fiber length for successful operation is 1.5 m. An input coupled pump power of 4.8 mW will be required to completely deplete the broadband fluorescence spectrum for this doped fiber length.

The fiber laser sensor greatly enhances the performance of the wavelength demodulation system (WDS), which originally analyzed signals from Bragg gratings interrogated with a broadband light source. We have demonstrated successful implementation of a fiber laser sensor that uses a broadband mirror and a fiber Bragg grating as an end reflector in conjunction with a wavelength demodulation system to form a fiber laser strain sensor. This strain sensor system could measure strain with resolution of approximately 5.5 $\mu\epsilon$ (corresponding to 0.4°C resolution for a temperature sensor) and a bandwidth of 13.0 kHz.

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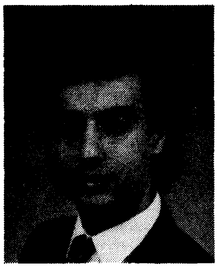
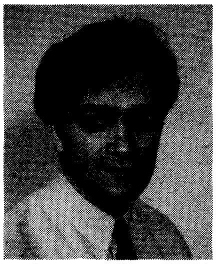


Andreas Othonos received his BSc, MSc, and PhD degrees in physics from the University of Toronto in 1984, 1986, and 1990, respectively. His doctoral dissertation research was conducted in the area of carrier and phonon dynamics in semiconductors. Since 1990, he has been with the Ontario Laser and Lightwave Research Centre as a research scientist. His current research interests are ultrafast carrier-phonon dynamics, ultrafast optics, nonlinear optics, and fiber optic lasers.



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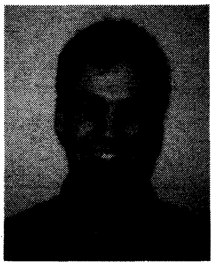

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Raymond M. Measures is a professor at the University of Toronto Institute for Aerospace Studies and the director of the Fiber Optics Smart Structures Laboratory, which he established in 1988. He obtained his PhD from Imperial College, London University, in 1964. Dr. Measures developed the concept of laser saturation spectroscopy as a localized diagnostic technique and demonstrated that laser resonance saturation represents an extraordinarily efficient method of creating a plasma. He spent a sabbatical year at the Royal Institution in London (1972 to 1973) and led the development of the first airborne laser fluorosensor. He also authored the first comprehensive monograph on laser remote sensing. Professor Measures is currently directing a major program devoted to the development of structurally integrated fiber optic sensors with the goal of creating smart materials and intelligent structures. He has coauthored over 70 papers and has contributed to several books and patents. He is also on the editorical board of the *Journal of Intelligent Material Systems and Structures* (Technomic Publishing Co. Inc.) and the *Smart Materials and Structures Journal* (Institute of Physics).