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A Multiplexed Bragg Grating Fiber Laser Sensor System

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***Abstract*—A technique for multiplexing Bragg gratings in a fiber laser arrangement is described. This technique has successfully been used to multiplex two and three Bragg gratings with very little crosstalk. The Bragg grating laser sensors were used to measure both strain and temperature. Independent strain and temperature tuning of the gratings shows no crosstalk.**

I. Introduction

INTRACORE fiber Bragg gratings may be used as sensors in which the measurand-induced effect is encoded as a shift in the narrow-band spectrum of the back-reflected light [1]. Mechanical robustness, inherent interrupt immunity, and its wavelength-encoded measurand information are features that make the Bragg grating sensor especially attractive for practical applications. Traditionally, some form of spectrum analyzer, such as a monochromator, has been used to determine the wavelength of the back-reflected Bragg spectrum. Clearly, practical applications require a compact, robust, and inexpensive method of demodulating the Bragg grating sensor signals. The recently developed passive ratiometric wavelength demodulation system [2] (WDS) for Bragg grating sensors addresses these issues.

The use of an intracore Bragg grating as an end-reflector of a laser 'greatly enhances the performance of the WDS by improving the sensor's signal-to-noise ratio [3]. Here the Bragg grating performs the dual functions of a cavity end-reflector and a sensor where the measurand controls the laser wavelength. The continuous gain profile of an erbium-doped fiber around the 1550-nm region has been used as the active medium in a tunable fiber laser arrangement [4], [5]. The improved performance of a single Bragg grating as cavity end-reflector in a tunable fiber laser has already been demonstrated [6]. In this letter, we report on a multiplexed Bragg grating fiber laser sensor arrangement.

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II. Multiplexed Fiber Laser Strain Sensor

Clearly, in order for fiber-optic sensors to compete with conventional technology and be considered viable for practical applications, the cost per sensor must be reduced. The major cost of the fiber laser sensor (FLS) system is buried in the pump laser and the wavelength division multiplexer (WDM) needed for pumping the erbium-doped fiber. A multiplexed sensing architecture reduces the high cost associated with the one-sensor FLS since the same pump and WDM may be used in the multisensor configuration.

Theoretically, erbium represents a homogeneously broadened medium that supports only one lasing line. To produce several laser lines within a single length of optical fiber, a section of erbium-doped fiber is placed between the successive Bragg gratings. With sufficient pump power and enough separation between the Bragg grating center wavelengths, a multiplexed FLS is possible. The maximum number of sensors would depend on the total pump power, the required dynamic range, and finally the gain profile of the active medium. The typical 50-nm-wide gain spectrum of the erbium-doped fiber would allow four Bragg gratings in series, assuming 12-nm tuning range for each (this would correspond to 10 000 $\mu\epsilon$ when used as a strain gauge).

In the first experimental arrangement [7], two 2.2-m lengths of Er-doped optical fiber (450 ppm Er and core diameter 3.1 μm) are pumped with a 980-nm laser diode through one port of a WDM. A short length of optical fiber containing a Bragg grating with a center wavelength of about 1550 nm was fusion spliced to each 2.2-m section of Er-doped optical fiber. The 1550-nm input side of the WDM was silvered using a chemical deposition technique. A Fourier transform infrared (FTIR) spectrometer with a resolution of 0.15 nm was used to examine the output spectrum of the multiplexed sensor arrangement.

In order to test the individual performance of each sensor in the array, both temperature and strain tuning were tried. Exposing the Bragg grating to a change in temperature shifts its center wavelength λ_B according to [1]

$$\frac{\Delta h_B}{\lambda_B} = (a + \xi)\Delta T \qquad (1)$$

where a is the coefficient of thermal expansion and ξ is the thermooptic coefficient. Each degree Celsius change of temperature translates the laser wavelength by 13.7 pm. When the Bragg grating is strained, its wavelength varies due to the change in the grating periodicity and the photoelastic induced change in the refractive index. This translation in wavelength for a longitudinal strain ϵ is given by the following equation [1]:

$$AA_{Bragg} = \lambda(1 - p_e)\epsilon \qquad (2)$$

where the term p_e is the effective photoelastic constant. Using the above equations, one would expect a change of **1.21** pm per microstrain in the lasing wavelength with an intracore Bragg reflector centered at 1550 nm.

III. Experiments

To determine the level of crosstalk in a two-element multiplexed FLS, the second grating in the sequence was bonded onto a cantilever beam and loaded (in both tension and compression) where the relative wavelengths of both lasing lines were recorded with the FTIR spectrometer. The low-crosstalk exhibited in this experiment can be seen from Fig. 1. To demonstrate the independent function of the two sensors, the first sensor in the sequence was immersed in a 400-mL Pyrex container filled with 200 mL of diffusion pump oil and heated by a temperature-controlled hot plate. A thermocouple was placed in the oil for accurate and continuous monitoring of the temperature. The oil temperature was varied from 20 to 160°C and the output spectrum recorded by the FTIR. At the same time, the second grating was strained to different values for each temperature reading. The results of this experiment are shown in Fig. 2. Again the low level of crosstalk and the independent function of the two sensors is evident. It should be noted that the relative amplitude of the laser lines tends to fluctuate with strain and temperature. At present, it is believed that the reason for this change is directly tied to the wavelength of the lasing line, its spatial relation with respect to the gain medium, and the spectral content of the Bragg grating. In fact, it has been shown that erbium is not completely homogeneous, and multiple lasing lines are possible [S]. Further experiments and analysis will be necessary to thoroughly understand this new type of sensor and the complex interactions involved. It should be noted that such fluctuations do not represent a problem for a WDS.

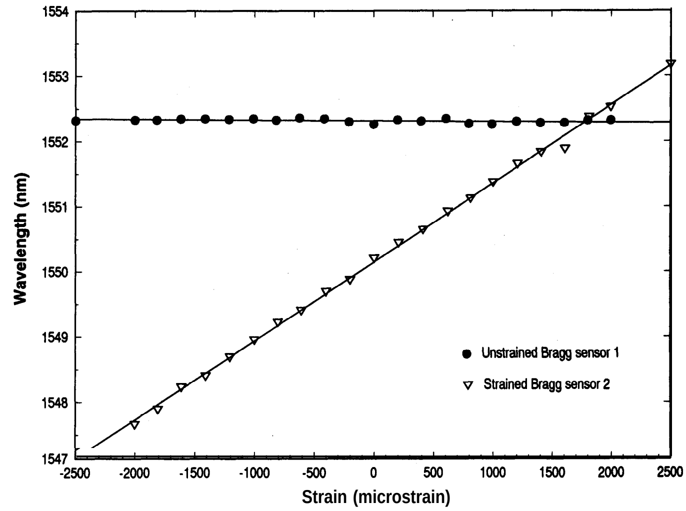

Fig. 1. Measure of the Bragg center wavelength as a function of strain for the two-element multiplexed FLS.

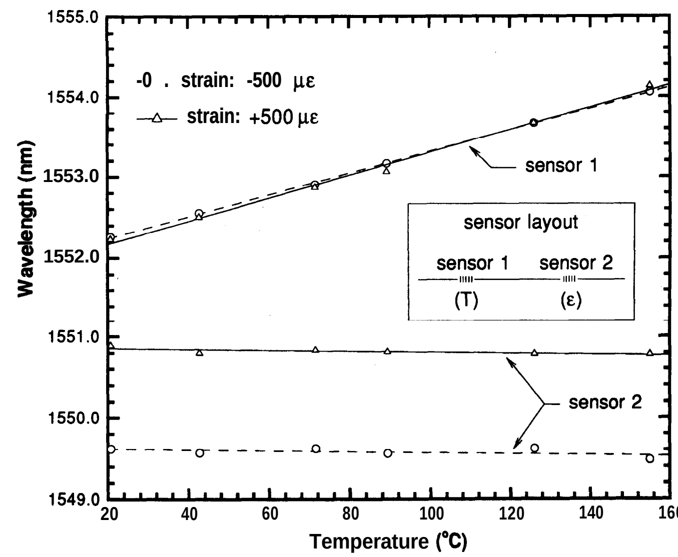

Fig. 2. Independent wavelength response of sensors 1 and 2 as a function of applied temperature on sensor 1 with application of strain -on sensor 2. The inset indicates the application of the measurands on the respective sensors.

In a second arrangement, a third section of 1.2-m length of erbium-doped fiber fusion spliced to a third Bragg grating was added to the two-element arrangement described above. Further increase of the pump power was necessary to obtain simultaneous lasing at all three Bragg wavelengths. For completeness, the third Bragg grating in this three-element array was strain tuned to show a good correlation with theory and a low level of crosstalk. These data are presented in Fig. 3.

IV. Results and Discussions

Since erbium represents a theoretically homogeneous medium, separate gain regions are required for each laser

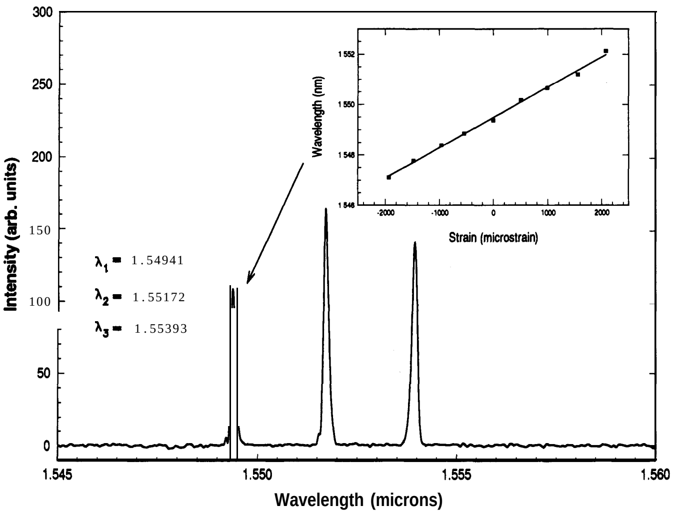

Fig. 3. The output spectrum of the three-element multiplexed FLS. The inset shows the tuning response of the last sensor in series with respect to strain.

line. This is especially true if the Bragg gratings are to be interrogated simultaneously in a serially multiplexed architecture. A mode-locking arrangement may be employed, which eliminates the need for additional gain sections [9]. Although Ball et *al.* [5], [10] also used Bragg gratings to control the wavelength of their fiber laser, their arrangement requires two gratings to define the cavity, which must be in the same strain or temperature state. This is not the case in our configuration, as each cavity is defined by one Bragg grating and a broad-band mirror. We have observed that less than 30 mW of pump power at 980 nm was required for the three-element serial multiplexed FLS described above.

In the serial multiplexed configuration the cavities are coupled so their respective gains are not independent. In fact, some gain coupling was observed for both the two- and three-element arrays. Although this phenomenon is interesting and affords further investigations, it does not compromise the performance of the intended multisensor system, as the WDS is immune to amplitude fluctuations. As with most wavelength division ‘multiplexing architectures, channel crosstalk was minimal. Within the limits of the FTIR, no crosstalk could be measured. Individual sensor performance for the measurement of strain and temperature was compared to the theoretical predictions of (1) and (2). The total error for temperature measurement was less than 9%, which could be attributed to the absolute accuracy of the FTIR and small fluctuations in the temperature of the hot plate. Strain sensing yielded similar results.

We also undertook experiments aimed at assessing the need to use a gain section between two consecutive Bragg gratings and found that for two Bragg gratings with center wavelengths at 1536 and 1550 nm, only the first (after the gain section) would lase. On the other hand, when we used gratings at 1548 and 1550 nm, severe mode hopping occurred, especially if one of the gratings was strained.

V. Conclusions

A serially multiplexed Bragg grating FLS that uses a broad-band mirror and a set of intracore Bragg gratings has been built and tested. Each Bragg grating is used to linewidth narrow and tune a different fiber laser in the arrangement. Two- and three-element fiber laser sensor sequences were used to demonstrate the multiplexing potential of the FLS. Multiple lasing lines were sustained within erbium’s homogeneously broadened gain curve by inserting extra sections of the doped fiber between the gratings. Experiments were performed that show how the power in each line varies with the different pump energies. For the two-element serial multiplexed system, the gratings were independently strain and temperature tuned to demonstrate the low crosstalk between the two laser lines even when their wavelengths coincided. This multi-lasing architecture represents a novel approach to multiplexing of Bragg grating sensors and will be investigated further. However, the number of sensors in series is likely to be limited by avoidance of laser line crossover. For a 50-nm-wide gain curve and a 12-nm range for each sensor (corresponding to 10 000 $\mu\epsilon$), four sensors at most can be serially multiplexed.

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