Dynamic Range Enhancement in Fiber Bragg Grating Sensors Using a Multimode Laser Diode

P. J. Moreira, L. A. Ferreira, J. L. Santos, and F. Farahi

***Abstract*—A signal processing scheme for fiber Bragg grating sensors based on the utilization of adjacent modes of a multimode laser diode light source is demonstrated which allows high sensitivity to be obtained over a large measurement range. For strain measurements, a range of 4800 $\mu\varepsilon$ is achieved with a resolution of 0.08 $\mu\varepsilon/\sqrt{\text{Hz}}$, yielding a dynamic range of 95 dB.**

***Index Terms*—Bragg gratings, demodulation, multimode laser diode, optical fiber, optical fiber sensor.**

I. Introduction

FIBER Bragg grating (FBG) has been the most attractive intrinsic fiber sensor in recent years [1]–[4]. One of the major advantages of this type of sensor is attributed to wavelength encoded information provided by the Bragg grating when affected by the measurand. Since the wavelength is an absolute parameter, the signal returned from a Bragg grating only depends on the measurand status. In addition, information remains immune to power fluctuations along the optical path. Other advantages are the small size, rugged and intrinsic nature of these structures, as well as their multiplexing capability.

In order to fully utilize the advantages offered by this type of sensor, it is essential to develop a demodulation scheme that translates the wavelength encoded signal from the sensor into a correspondent signal more amenable to conventional electronic processing. This has been an active research field regarding fiber Bragg sensors. Schemes have been proposed based on bulk filters [5], fiber edge filters [6]–[8], edge optical source spectrum [9], edge fiber grating spectrum [10], edge detector spectral response [11], tunable fiber filters [12], tunable acoustooptic filters [13], tunable wavelength-division multiplexing (WDM) [14], tunable single-mode laser diodes [15], receiving FBG's [16]–[18], interferometric detection [19], fiber lasers [20] and Fourier techniques [21], [22].

In a previous letter, the authors proposed a demodulation scheme for FBG sensors based on a receiving grating with its Bragg wavelength ramped by a strain induced sawtooth waveform [23]. The measurand information has been recovered by measuring the phase difference between the first harmonic (carrier) of the signal reflected by the receiving grating and the first harmonic of the sawtooth waveform. The main characteristic of that scheme was the fact that both the sensor status and the sensor sensitivity to the measurand action were found to be independent of the optical power level in the system (for power levels larger than the equivalent noise power level). However, the dynamic response of such a system was limited due to practical constrains in modulating the wavelength via periodic application of strain to the reference grating. This problem was later solved by using a ramped multimode laser diode and eliminating the reference grating [24]. The advantages of using a multimode laser diode are low cost, high sensitivity, capability of wavelength tuning by acting on the laser diode injection current, insensitivity of its spectrum to back reflected light from the system (specially when edge longitudinal modes are considered), easy laser temperature control and stabilization of its spectrum, and the potential to extend the measurement range by using more than one mode of the laser spectrum. In this letter, we report experimental results that demonstrate enhanced measurement range using several adjacent modes of a multimode laser diode.

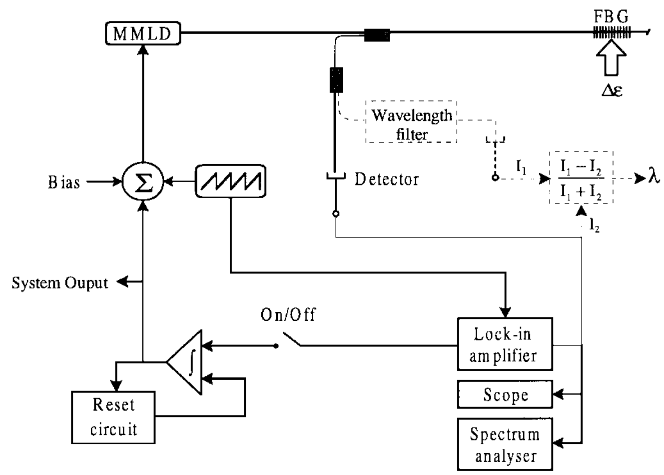

Fig. 1. Experimental setup.

II. Experiment, Results and Discussion

The experimental setup is shown in Fig. 1. A pigtailed multimode laser diode (FUJITSU FLD130C2LK/352) with spectrum centered at 1318 nm at 25 °C was used to illuminate

Manuscript received December 11, 1998; revised March 11, 1999. The work of P. J. Moreira and L. A. Ferreira was supported by the "Programa PRAXIS XXI". The work of F. Farahi was supported by the National Science Foundation under Grant DMI-9 413 966.

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Publisher Item Identifier S 1041-1135(99)04252-4.

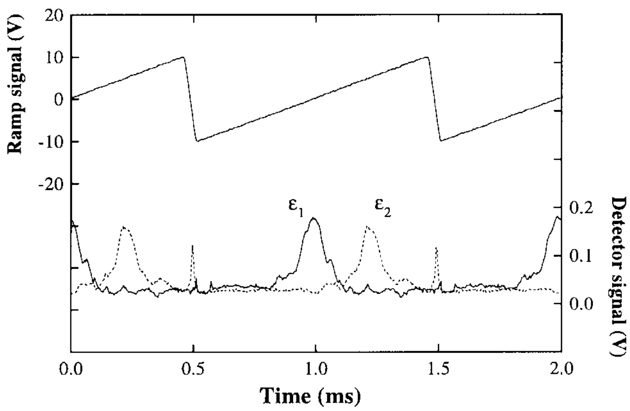

Fig. 2. Effect on the detected waveform of a strain change in the sensor head of $\varepsilon_2 - \varepsilon_1 = 223\ \mu\varepsilon$.

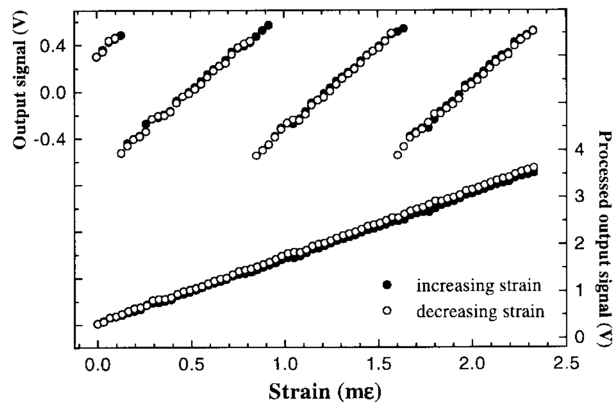

Fig. 3. Processed system output versus strain applied to the sensing grating (increasing and decreasing).

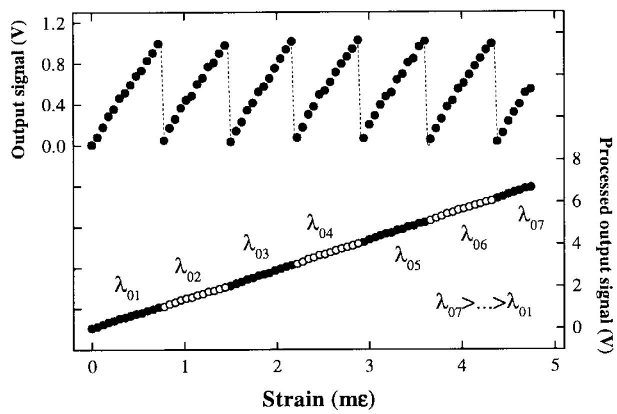

Fig. 4. Processed system output versus applied increasing strain up to its maximum value.

the sensing FBG through a 3-dB coupler. With no strain applied, the grating spectral characteristics were $\lambda_B = 1304.4$ nm and $\delta\lambda \approx 0.2$ nm. By tuning the laser temperature, its spectrum was shifted to ensure that longitudinal modes in one of the edges of the laser gain curve were always present in the Bragg wavelength interval defined by the strain measurement range. The use of these modes also minimizes system sensitivity to back-reflected light into the laser cavity.

The laser spectrum was ramped by applying a sawtooth waveform to the injection current. Light reflected by the grating was detected and after amplification the phase of the detected signal was compared with the phase of the sawtooth waveform using a lock-in amplifier. Fig. 2 illustrates the basic working principle of the interrogation technique. It shows the system output for two different values of strain applied to the sensing head when operating in open loop ($\varepsilon_2 - \varepsilon_1 = 223\ \mu\varepsilon$). The strain was applied using a translation stage with micrometer precision. From this figure, the phase shift of the detected waveform relative to the laser diode modulation sawtooth waveform is evident. In a closed loop operation, the lock-in voltage output, proportional to the phase shift, acts as an error signal to the servo. This produces a change in the laser injection current and keeps the relative position of the laser spectrum and grating wavelength unchanged. To utilize more than one mode of the laser, the servo output (also system output, $V_{\rm out}$) was allowed to change only in the interval [−0.57 V, 0.57 V], corresponding to a laser diode injection current variation of ≈70 mA (which induces a spectrum shift of ≈0.8 nm, slightly larger than the laser mode separation, 0.75 nm). When $V_{\rm out}$ reaches one of the limits of the above interval, a reset circuit sets $V_{\rm out}$ to the symmetric limit and the system is locked to an adjacent mode. The bandwidth of the tracking system is ≈1 Hz, essentially defined by the time constants of the integration circuit and lock-in amplifier.

Fig. 3 shows the system output when increasing and decreasing strain is applied to the sensing grating in a range large enough to sweep four laser modes. When the discontinuities associated with the laser mode jumps are eliminated, a linear behavior results, which is evident when the lines for increasing and decreasing strain are shown. The small hysteresis observed was attributed to the mechanical system utilized to apply strain to the grating. Clearly important for the proposed demodulation technique is to evaluate the maximum strain measurement range achievable. Toward that goal, the fiber containing the sensing grating was continuously stretched until it broke at an applied strain value of 4800 $\mu\varepsilon$. As can be observed in Fig. 4, seven laser modes were swept for the system to operate over the entire range of applied strain. The linear behavior of the measurement system up to these large strain values is evident (with a slope of 1.41 V/mε). The static strain resolution was found to be 0.08 $\mu\varepsilon/\sqrt{\rm Hz}$, essentially limited by the electronic noise of the processing system. From these values, the system dynamic range was evaluated as 95 dB.

It has been shown that when sensing gratings are illuminated by optical sources emitting polarized light, aleatory measurement errors can occur [25]. This happens because, in general, the grating fabrication process generates structures that are anisotropic. Therefore, the characteristics of light reflected by these devices will depend on the polarization of light incident on them, which changes randomly under the effect of perturbations coupled to the lead fiber. Naturally, it is highly desirable to have a FBG demodulation scheme that is immune to these phenomena. Since the multimode laser diode utilized in the experiment is a polarized optical source, the performance of the proposed demodulation scheme to the effect described

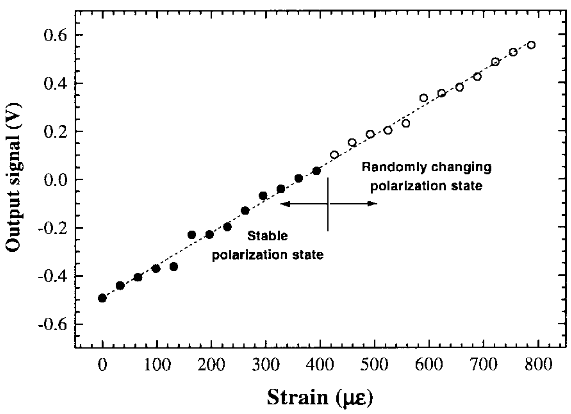

Fig. 5. System behavior for stable and randomly changing input polarization states.

above could be easily tested, by randomly changing the input polarization state with a polarization controller during a strain measurement cycle (Fig. 5). It was observed that the shape of the waveform returned by the grating is indeed dependent on the input polarization state. However, within the experimental margin of error the phase of the first harmonic of this waveform showed no sensitivity to variations of that state, which explains the effectiveness of the proposed demodulation scheme under these conditions. When considered in the basic form shown in Fig. 1, the system studied has the problem of identifying the locked laser mode when the system is turned on. For a large range of strain measurements, this feature is not desirable. However, it can be overcome by combining the proposed configuration with a low-resolution wavelength filter discriminator, like a fiber biconical filter [8], able to identify the laser mode locked by the high-resolution phase measurement system presented here. This approach is feasible since the diode laser temperature is kept at a fixed value, which permits one to know in advance and with sufficient accuracy the wavelength region of the laser spectrum. The dashed part of Fig. 1 shows a possible implementation of this concept.

III. Conclusion

An extended range interrogation scheme for FBG-based sensors using a multimode laser diode was demonstrated. A dynamic range of 95 dB was achieved. It was also verified that a fiber Bragg sensor using this demodulation scheme is insensitive to variations in the state of polarization of input light.

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