Abstract—A system for the interrogation of multiplexed fiber Bragg sensors (FBG) based on a mechanically tuned erbium doped fiber (EDF) laser is presented. A Bragg grating imprinted in a standard, single-mode optical fiber is used as a cavity tunable element, mechanically coupled to a piezoelectric actuator (PZT) with flexure hinges. A laser wavelength sweeping interval of 7.4 nm is achieved by inducing a controlled strain on the tunable FBG. The spectral position of the FBG sensors is inferred from the first derivative of the detected optical signal with no need of extra, expensive devices as a lock-in amplifier, optical filters or special fiber gratings.

Index Terms—Erbium doped fiber laser, FBG, multiplexed fiber sensors, tunable laser.

I. INTRODUCTION

Optical fiber sensors have been developed in the last thirty years for several applications, showing remarkable advantages over conventional sensors [1]. Many techniques for interrogating optical sensors have been proposed, particularly those that are able to address several sensors simultaneously. Fiber Bragg gratings (FBG) are widely used due to its intrinsic characteristic of shifting the wavelength of reflected light when the fiber is subjected to temperature or strain variations, typically with sensitivities of 10 pm/°C and 1.2 pm/με in the Bragg wavelength near 1550 nm [2], [3].

Probably the simplest way to detect Bragg wavelength shifts is to launch a broadband light into the fiber grating and then observe the reflected spectrum with an optical spectrum analyzer (OSA). However, this is not the best alternative to monitor optical sensors, for many reasons. For instance, the OSA is a bulky, expensive instrument with a high time response. Also, the sensor reflects only a small amount of light and the detected signal may show a low signal-to-noise ratio. Alternatively, one may use Fabry-Perot tunable filters, interferometric methods or tunable lasers, that are also able to address multiplexed FBG sensors in a wide wavelength interval [4], [5]. Among these approaches are the ones that use tunable EDF lasers with an FBG at one or both ends of the laser cavity, instead of a broadband light source. In this case, the FBG may work either as a sensor of the system or as a tunable element, once that induced strain applied on the FBG shifts its Bragg wavelength and so the peak wavelength of the fiber laser [6]-[10]. The controlled strain of the FBG induced by a stretching device and used as part of the cavity feedback, as proposed first by Ball and Morey [6], allow the peak
wavelength of the laser to be tuned over a spectral range suitable for FBG sensors interrogation. This method is similar to one used in spectroscopy, and it was proposed by Wetjen et al [10] for detection of acetylene and ammonia, once these gases have absorption lines within the sweeping interval of a tunable EDF laser. In that case, the sweeping wavelength interval was only 3 nm.

Unfortunately, tuning the laser by means of a stretching device that induces a controlled strain on the FBG that is part of the cavity has its own drawback, either due to stretching limits of the device as well as physical constraints on the optical fiber into which the Bragg grating is imprinted. Since the FBG cannot be stretched indefinitely, its tunable bandwidth is limited to few nanometers and to low sweeping frequencies. Wider intervals, as 40 nm achieved by Song et al [8], are possible when special fibers with high-strength gratins are used, although not in dynamic measurements.

In this work we used a very simple apparatus that is capable of addressing up to three multiplexed FBG sensors with wavelength spacing of 2.4 nm between the peaks of the spectra. An FBG imprinted in standard, single-mode hydrogenated optical fiber was used as part of the laser cavity and connected to a PZT-driven flexure hinge with parallelogram design able to stretch the FBG in a controlled manner, providing a mechanical way to tune the laser and sweep the wavelength of grating sensors. A computer-based algorithm is used to establish with better precision the peak of the sensors spectra, based on the first derivative of the detected signal.

II. SYSTEM DESCRIPTION

The interrogation system is composed of an optical circuit with the linear cavity EDF laser and the tunable fiber Bragg grating (TFBG), an optoelectronic circuit for the detection of the optical signal and a personal computer that filters the detected signal twice and determines the measure values associated with the wavelengths of the sensors perturbed by an external effect (for example, temperature variation or longitudinal strain on the sensor). Fig. 1 shows a diagram representing the setup used in the characterization of the system. The linear cavity laser has a total length of eight meters, with six meters of erbium doped fiber. The EDF has a concentration of 330 ppm, numerical aperture of 0.21 and wavelength cutoff of 880 nm. Light emitted by a 1480 nm pump laser diode is launched into the EDF through a WDM coupler. An optical isolator is also used to protect the pump laser from cavity laser radiation. One end of the cavity is performed by a gold coated optical tip, with reflectivity of 70% in the C band, which provides cavity feedback. The other end of the cavity is performed by the TFBG, bonded with cyanoacrylate adhesive on the PZT-driven mount, with Bragg wavelength of 1544.5 nm, a 95% reflectivity and bandwidth of 0.3 nm FWHM. All gratings sensors used in the characterization had approximately the same bandwidth.

Lasing occurs at a wavelength that matches the peak wavelength of the TFBG, which depends on the aperture of the PZT-driven mount, controlled by a high voltage amplifier with 1 Hz triangular waveform output. The ramp peak voltage is adjustable from few volts up to 100 V, which corresponds to the maximum displacement of the PZT and so the maximum laser tuning range. The laser
efficiency was calculated to be 2.5 % and lasing occurs for a pump power of 39 mW. It is worth mentioning that these values are related to the characteristics of the TFBG used in the laser cavity, namely its reflectivity and bandwidth.

Fig. 1. Diagram representing the setup used in the characterization of the interrogation system (IMG: index matching gel).

The PZT-driven mount has an intrinsic hysteresis that induces some difference in the displacement between the ascending and descending ramp voltage, however this difference is not relevant because the system accounts only for the optical signal acquired during the ascending ramp applied to the PZT, thus any hysteresis effect can be neglected. In an earlier approach, a sawtooth waveform was applied to the PZT in order to highlight only the ascending ramp in the system, but using this kind of waveform implies that the movement of closing the flexure hinges would be much faster than the movement of opening them. In such case, the glued fiber may undergo a peak of released stress in every period of the waveform, which could break the TFBG after some time of operation, especially if the system is set to work with higher sweeping frequencies. Although we did not investigate the aspects of different waveforms and frequencies of operation over the system performance, we concluded that a triangular waveform was a better choice for the signal applied to the PZT than a sawtooth waveform.

Owing to the fact that the cavity is several meters long, the laser signal is heavily multi-moded. When the gain medium overcomes the cavity losses, a mode can oscillate if it satisfies the cavity resonance condition, given by

\[ \lambda = \frac{2nL}{m} \]  

where \( \lambda \) is the resonant laser mode wavelength, \( n \) is the refractive index of the medium, \( L \) is the laser cavity length and \( m \) is a positive integer. If \( \Delta \lambda \) is the spectral range between two consecutive
longitudinal modes, it follows that
\[
\Delta \lambda = \frac{2nL}{m} - \frac{2nL}{m+1} = \frac{2nL}{m(m+1)}
\]
In cases where the laser has a long cavity, \( m \) is a large number and we may consider \( m + 1 \approx m \):
\[
\Delta \lambda = \frac{2nL}{m^2}
\]
Combining (1) and (3) results in
\[
\Delta \lambda = \frac{\lambda^2}{2nL}
\]
For the fiber laser used in the system, we found \( \Delta \lambda \) to be only 0.103 pm and more than 2,900 modes are able to lase inside the cavity for the FWHM of the TFBG. Several approaches can be found in the literature describing how to achieve single-mode oscillation in an EDF laser [8], [11]-[13] by using unpumped EDFs as saturable absorbers, resonator filters and so on. Nonetheless, the multi-modal characteristic of the EDF laser does not play a crucial role in the sensing system because the laser spectral linewidth is approximately ten times narrower than the spectral linewidth of the interrogated gratings (the laser linewidth acquired with an optical spectral analyzer was less than 0.06 nm).

The system interrogates all grating sensors connected to the port 2 of the optical circulator. At port 2 of the circulator a 3 dB coupler is connected and separates a sensor grating (BGS) from another unperturbed reference BGS, which will serve as a reference for the spectral position of the BGS to be interrogated. This BGS is bonded over a moveable platform electronically controlled by a step-motor. A broadband light source (SLED) was used to enable the recording of the gratings spectra by the OSA and the data were compared with the results obtained with the acquisition system.

III. RESULTS AND DISCUSSION

To characterize the system a low frequency triangular waveform is applied to the PZT that opens and closes the flexure hinge in a one-second cycle, promoting the continuous and linear scanning of the laser signal produced by the EDF cavity. Through the optical circulator, the laser signal illuminates the sensor grating (\( \lambda = 1545.7 \) nm) and the reference grating (\( \lambda = 1547.8 \) nm), convolving with their spectra according to the sweeping promoted by the PZT. In doing so, the photo-detected signal obtained from the port 3 of the circulator is an electrical and temporal representation of those spectra, meaning that the reflection peak wavelength of the sensor grating can be inferred from the time difference between the detected peaks of the two grating spectra if the peak wavelength of the reference grating is known. Keeping both gratings close to each other provides temperature compensation, as temperature variations shift the peak wavelength of both gratings equally, not affecting the temporal difference between them.

In order to better discriminate the spectral peak of the gratings, a first derivative technique was applied to the photo-detected signal [4], once that zero-crossing points are easier to detect by an
electronic circuit than peak points. The process is achieved by filtering the photo-detected signal with a low-pass digital filter (order 48 and cutoff frequency of 10 Hz) and by a first-order notch filter that eliminates the DC component of the signal. The use of digital filters for processing the photo-detected signal was very effective in reducing the optical and electrical noise of the system. Besides, the filter parameters can be easily adjusted if the system worked with a different sweeping frequency.

Fig. 2 presents three graphs, the first one with the triangular waveform applied to the PZT, the second one with the photo-detected signal and the third one with the first derivative of the signal. The spectra of two gratings can be seen from this figure, being interrogated either in the ascending ramp as in the descending ramp applied to the PZT. When the voltage ramp is ascendant the wavelength increases, so the left spectrum has lower wavelength than the right one. For the descending ramp the opposite occurs.

Fig. 2 shows also that the first derivative of the signal is not perfectly symmetric to the zero level. This may happen when the spectra of interrogated gratings are not perfectly symmetric or due to the time constants chosen for the digital filters. In fact, the notch filter does not give a perfect first derivative of the photo-detected signal but a signal that is proportional to the first derivative. Also, it can be noticed that the first derivative of one of the gratings obtained with the ascending ramp is linked to its first derivative obtained with the descending ramp. This occurs when the grating peak wavelength is too close to the maximum or minimum sweeping wavelength of the laser. This situation could be avoided with an electronic control that blocks the signals acquired during the descending ramp. Furthermore, the main feature to be determined is the zero-crossing points of the photo-detected signal, given that it is from these points that the system evaluates the spectral peak position of the interrogated gratings.

The BGS was stretched by a moveable platform in steps of 35 με up to 945 με. These induced strains were then compared with the temporal difference Δt between the spectral peaks of the BGS and the reference grating, given by the zero-crossing points in the first derivative of the photo-
detected signal. The result shows a direct linear relation, as it can be seen in Fig. 3. As the induced deformation applied to the interrogated BGS increases, its peak wavelength gets closer to the reference BGS. It follows that the difference between their zero-crossing points is reduced and the graph in Fig. 3 shows that by using negative values of $\Delta t$ in the x-axis. The RMS fluctuation indicates a system dynamic resolution of 4.6 $\mu e/\sqrt{Hz}$.

![Graph](image1)

**Fig. 3.** Time difference between the zero-crossing points of the interrogated BGS and reference BGS versus the induced deformation applied to the interrogated BGS.

Fig. 4 shows the temporal position of the first derivative of the photo-detected signal for three different values of strain applied to the BGS, as well as the first derivative of the static BGS. Fluctuations in the signal amplitude are caused by noise in the electronic and optical parts of the system but this does not impair the determination of the zero-crossing points. Also, we notice that the zero-crossing point for the reference BGS shows a slight difference between the three plotted curves. This difference could be caused by a slight temperature variation in the laboratory during the system characterization.

![Graph](image2)

**Fig. 4.** First derivative of the photo-detected signal from the digital filters for three values of applied strain on the BGS. Black line: 70 $\mu e$, red line: 455 $\mu e$, blue line: 805 $\mu e$. 
The PZT-driven mount used in the system is the same one described by Paterno et al. [14], which utilized the ramp signal modulated with a 900 Hz, low-amplitude sinusoidal signal (dither). That modulation was necessary in order to obtain the first derivative of the photo-detected signal from a lock-in amplifier. In the present work, the same first derivative detection was obtained with digital filters, which are simpler than the lock-in amplifier. Furthermore, the interrogation of sensors is not constrained by the time constant of the lock-in amplifier (nearly one second), making the sweeping rate adjustable upon changing the frequency of the PZT ramp signal. We could not get satisfactory interrogation with frequencies over 40 Hz due to the limited bandwidth of the photo-detector used, but later experiments using a better photo-detector showed that reliable sensor interrogation is accomplished for frequencies below the resonance frequency of the PZT [15].

In order to determine the larger possible sweeping range for the system proposed in this work, more than 30 TFBG imprinted in standard, single-mode hydrogenated fibers were tested. We have concluded from the empirical data that a variation of 7.4 nm in the laser wavelength can be achieved with less risk of breaking the TFBG. This result is more than twice the ones reported in the literature for tunable fiber lasers in the same configuration. Sweeping ranges up to 12 nm were observed, but the gratings would break after some time of operation, variable from seconds to a couple of hours. It is likely that this limit could be considerably improved by utilizing gratings imprinted in other types of fibers (polymeric fibers) or draw-tower fiber Bragg gratings (DTG), manufactured during the fiber drawing process by a single UV laser pulse [16], [17].

IV. FINAL CONSIDERATIONS

We have proposed a system for the interrogation of up to three sensors based in Bragg gratings, multiplexed with a 2.4 nm difference between their spectral peaks and interrogated by an EDF laser tuned by an FBG imprinted in standard, single-mode optical fiber. The digital processing of the photo-detected signal uses an algorithm that minimizes the necessity of expensive equipments such as optical spectrum analyzer, lock-in amplifier or tunable optical filters. A good discrimination of interrogated grating spectra was obtained. For strain sensing, the temperature compensation is inherent to the system if the reference grating is kept under the same temperature of the strain sensors. For temperature sensing the reference grating must be submitted to controlled temperature.

ACKNOWLEDGMENT

The authors thank the Agência Nacional do Petróleo (ANP), Fundação Araucária, CNPq, Capes and the Financiadora de Estudos e Projetos (Finep) for the financial support by means of the Human Resources Program of the ANP in the Gas and Oil Sector (PRH-ANP/MCT – PRH10-UTFPR).

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