Simultaneous Measurement of Strain and Temperature Using a Single Emission Line

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***Abstract*—In this study, we present and demonstrate a novel sensor system for simultaneous measurement of strain and temperature through a unique combination of a long period grating and a fiber laser based on a fiber Bragg grating. In order to achieve this, a new erbium-doped fiber laser structure is created, showing an optical signal-to-noise ratio of 55 dB and a peak power measured on the optical spectrum analyzer between −5 and 0 dBm. The strain and the temperature information can be obtained by using a unique emission line through monitoring both the fiber laser wavelength shift and the change of the power level, both of which showing a clear linear behavior.**

***Index Terms*—Erbium lasers, fiber Bragg gratings (FPG), fiber lasers, long period gratings (LPGs), LPG coupling.**

I. Introduction

FIBER Bragg gratings (FBGs) have played an important role in communication systems, fiber lasers and optical fiber sensing since the 1980s. They have been widely used as optical fiber sensors due to their advantages demonstrated over their electrical counterparts, such as immunity to electromagnetic interference, compactness, multiplexing capability, resistance to harsh environments and low cost. As a result, FBGs have been widely used for structural health monitoring, oil pipe leak detection and gas detection [1]. Some applications have involved the use of FBGs to form laser-based sensor systems, taking full advantage of the narrow spectra of FBGs which are suitable for laser wavelength selection [2]. Compared to FBG-based sensor systems, these fiber laser-based sensor systems have shown many advantages including a higher resolution for wavelength shift identification, higher optical signal-to-noise ratio (OSNR) and enhanced capability for remote sensing. As an example a fiber laser-based sensor can be used to monitor as far as 200 km without any external amplification [3], in contrast, a FBG-based sensor illuminated by a broadband light source can only reach a maximum distance up to 25 km, limited by Raylegh Scattering [4].

This work was supported by the Spanish Government projects TEC2010-20224-C02-01, TEC2013-47264-C2-2-R, the FEDER funds, and by the European COST action TD1001.

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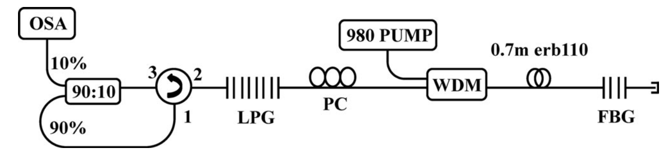

Fig. 1. Schematic diagram of the experimental setup.

A common issue of using FBGs as sensing devices is the cross-sensitivity between the measurands, i.e. strain and temperature. A number of techniques have been reported in order to overcome this limitation and thus to achieve simultaneous measurement of strain and temperature. These systems include those using photonic crystal fibers [5] and multimode fibers [6], in combination with FBGs [7] or long period gratings (LPGs) [8] among others. Most of these systems, however, have a low resolution and are fragile showing some difficulty in splicing or handling if a microstructured fiber is used. Other techniques include the use of specifically designed FBGs [9], [10] or gratings written into special fibers [11] or the combination of a grating and some other physical property like the dependence of the modes beating frequency on the laser cavity [12]. Few papers have been published considering both the simultaneous measurement and fiber lasers. These schemes have interesting features, for example, a high signal-to-noise ratio would allow the sensors to be interrogated over tens of kilometers [12], [13].

In this paper we present a new sensor system based on an erbium doped fiber (EDF) laser involving a FBG and coupled with a LPG, for simultaneous measurement of strain and temperature. Both parameters can be simultaneously measured, because they induce both a fiber laser wavelength shift and a change of the power level coupled out by the LPG. The utilization of a unique emission line for measuring both parameters allows a more efficient use of the optical spectrum, which is an important factor for sensor multiplexing using wavelength division multiplexer (WDM) techniques [14].

II. Principle of Operation

The experimental setup is shown in Fig. 1. The laser gain medium is a 0.7 m EDF Er110, provided by Liekki and pumped by a 980 nm laser with a maximum output power of 500 mW. This fiber was chosen due to its flat gain profile around 1535–1540 nm and the high gain provided.

As shown in Fig. 1, a WDM couples the 980 nm pump-light into the linear laser cavity, with a FBG being connected to the other end of the EDF. The FBG also acts as a temperature/strain sensor in this work. The FBG studied is centered at

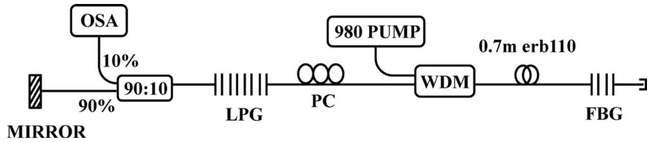

Fig. 2. Scheme of the experimental setup using a mirror instead of a circulator.

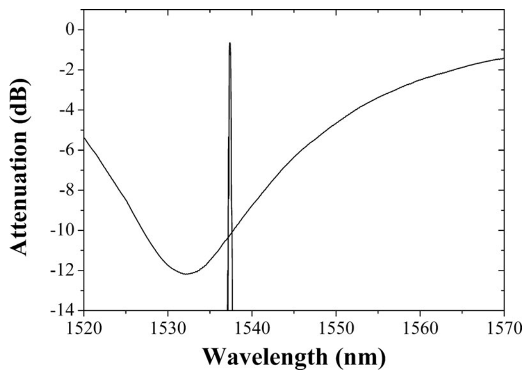

Fig. 3. Superimposed optical transmitted and reflected spectra of LPG and FBG respectively.

1536–1537 nm with a reflectivity higher than 95% and the free termination was immersed in a refractive-index-matching gel to avoid undesired reflections. The reflected laser light travels back through the WDM and a polarization controller (PC) to the LPG where the signal is partially attenuated due to the mode coupling between the fiber core and the cladding of the LPG. The PC is included in the system to minimize the polarization dependence of the LPG, which was induced by the UV exposure during the fabrication process in a non-polarization-maintaining fiber [15]. This polarization dependence may be eliminated by writing the grating on photosensitive PM-fiber.

Finally, as indicated in Fig. 1, a circulator is used to couple the light into the cavity and to extract a 10% of the power to be monitored by an optical spectrum analyzer (OSA). The circulator shown in Fig. 1 can be replaced by a silver-coated fiber optic mirror as illustrated in Fig. 2. Both options have been analyzed in this work showing similar results. Therefore, the first scheme was used to demonstrate the proof of concept.

The LPG used in the setup is centered at 1532 nm and both the FBGs and the LPGs were fabricated at City University London. The grating wavelengths were chosen in order to place the spectral profile of the signal reflected by the FBG at the linear slope of the LPG. In this way when the LPG shape shift occurs due to a temperature/strain change the amplitude of the laser varies linearly. Fig. 3 shows the superimposed optical spectra of the LPG and FBG. As can be seen in the figure, the reflected peak of the FBG is placed at the slope of the LPG.

In order to validate the sensing technique a series of experiments has been undertaken. Even though the system is designed to discriminate temperature from strain when both FBG and LPG were subject to the same strain and temperature conditions, there is, however, some difficulty in performing these measurements thus in this work an indirect method is used for verification of the sensing principle proposed. First of all, the sensitivities of the wavelength and peak power of the laser

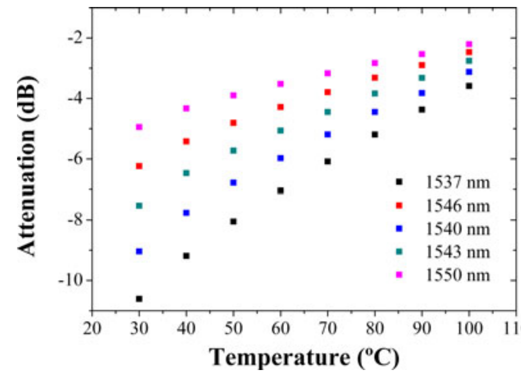

Fig 4. Relationship between temperature and transmitted power of the LPG for different FBG wavelengths.

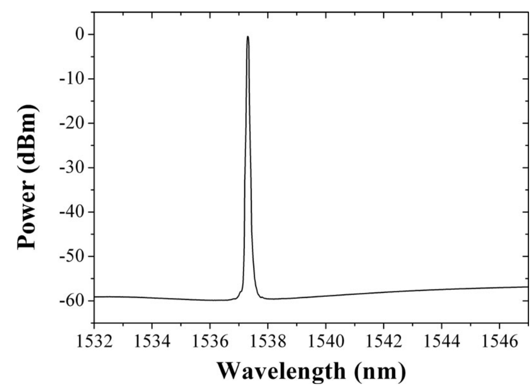

Fig. 5. Spectrum of the laser output signal on the OSA.

to strain and temperature were measured independently. Afterwards the proper behavior of the laser was verified when both sensors are subjected to changes simultaneously. Finally the equations to obtain $\Delta\varepsilon$ and ΔT from the wavelength and the peak power of the emission line are described.

III. Experimental Verification

Before setting up the fiber laser, in order to obtain an optimal wavelength value for the FBG, a study of the attenuation given by the LPG at different FBG wavelengths was carried out as a function of the temperature. To perform the study a LPG centered at 1532 nm was heated in a climatic chamber from 30 to 100 °C. The attenuation given by the LPG was measured at different wavelengths every 10 °C (see Fig. 4) This study shows that a higher dynamic range and sensitivity can be achieved by using a FBG with a central wavelength situated at around 1536 −1537 nm as indicated in Fig. 4. Thus these were the wavelengths chosen for the FBGs fabricated for this work. In addition to the sensitivity discussed, the sensing range has also been considered by carefully locating the Bragg wavelength of the FBG within the linear slope of the LPG thus to optimize both the sensitivity and sensing range.

By using the set-up shown in Fig. 1, the laser output can be measured on the OSA as shown in Fig. 5. The properties of the EDFL were studied resulting in an OSNR that is higher than 55 dB and a peak power measured on the OSA between −5 and 0 dBm. This peak power coupled out of the LPG, however,

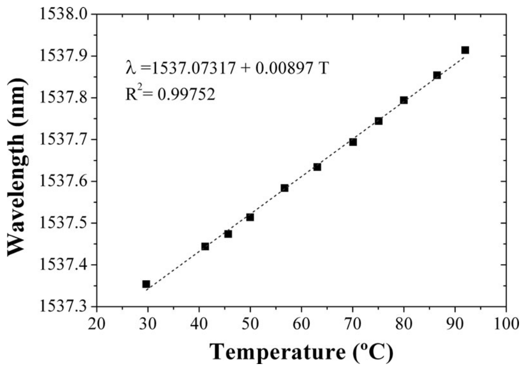

Fig. 6. Relationship between the fiber laser wavelength and temperature applied to the FBG (LPG was kept steady at room temperature).

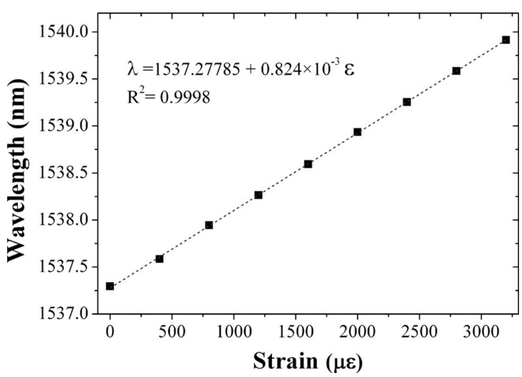

Fig. 7. Relationship between the fiber laser wavelength and strain applied to the FBG (LPG was kept steady at room temperature).

depends on the temperature and strain of the LPG although its wavelength is still dependent both on the temperature and the strain applied to the FBG.

Four tests were undertaken in order to obtain the wavelength and the peak power response of the system to temperature and strain variations applied to one sensor independently each time. For the strain tests, the gratings were glued to a translation stage which allowed the strain to be set with an error of $\pm 6\ \mu\varepsilon$. The temperature tests were performed in a climatic chamber with a resolution of ± 0.1 °C.

The first two tests studied the dependence of the laser wavelength as a function of the strain and temperature variation surrounding the FBG. The FBG was heated in a climatic chamber while the LPG was kept at room temperature. No strain was applied to any of them. The response is clearly linear with a typical sensitivity $k_{\lambda T} = 8.97$ pm/°C with a square of the correlation coefficient $\mathrm{R}^2 = 0.997$ (see Fig. 6). Similarly a strain sweep was conducted to the FBG while the LPG remained steady. Both of them were kept at room temperature. The strain sensitivity from the FBG had a linear behavior with a sensitivity $k_{\lambda\varepsilon} = 0.824$ pm/$\mu\varepsilon$ with a $\mathrm{R}^2 = 0.999$ (see Fig. 7).

In the same manner, two tests were carried out to study the changes on the peak power of the laser caused by the variation of temperature and strain applied on the LPG. In the first test the LPG was heated in the climate chamber while the FBG was kept at room temperature (both of them suffered no strain). Again a linear behavior can be observed with a power sensitivity

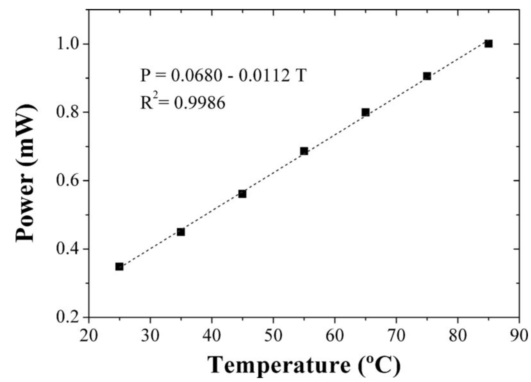

Fig. 8. Relationship between the fiber laser peak power and temperature applied to the LPG (FBG was kept steady at room temperature).

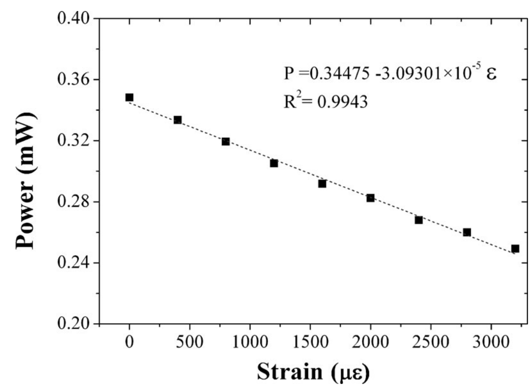

Fig. 9. Relationship between the fiber laser peak power and strain applied to the LPG (FBG was kept steady at room temperature).

$k_{PT} = 0.0112$ mW/°C with a $\mathrm{R}^2 = 0.998$ (see Fig. 8). In the last experiment the LPG was placed on the translation stage where a strain sweep was performed. Meanwhile the FBG remained steady and both of them were kept at room temperature. As shown in Fig. 9 the sensitivity measured was $k_{P\varepsilon} = -3.09 \times 10^{-5}$ mW/$\mu\varepsilon$, $\mathrm{R}^2 = 0.994$.

After the completion of the performance evaluation of individual sensitivities, a study of the combined sensor response to temperature/strain variations was carried out. It is important to stress that the aim of this test was to assure the proper response of the laser when both the laser wavelength and power variation occurred due to changes in the two sensors simultaneously. Given the sensitivity of both FBG and LPG on strain and temperature and for ease of the implementation, in this work the power change induced by the LPG was controlled by the temperature variation and the shift of the FBG was controlled by strain variation. To achieve this, the LPG was heated in the climatic chamber meanwhile the FBG was strained using the translation stage.

In the first test 63 samples were taken for both temperature and strain sensing using the LPG and the FBG respectively (see Fig. 10). The temperature of the LPG was set between 25 and 85 °C with a step change of 10 °C (no strain was applied to the LPG). For every temperature step a strain sweep was performed

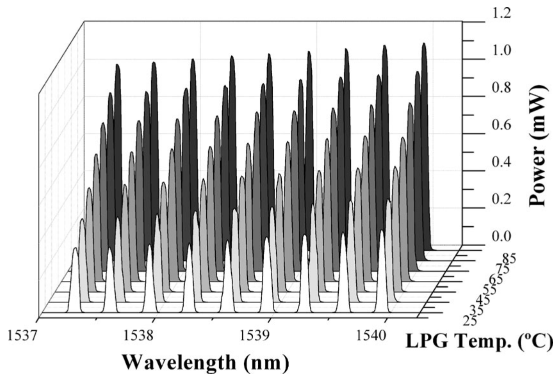

Fig. 10. Power and wavelength variation of the output signal when different temperature and strain was applied to the FBG and LPG respectively (no strain or temperature changes applied to the LPG and FBG respectively).

to the FBG centered at $\lambda = 1537.3$ nm from 0 to 3200 $\mu\varepsilon$ with a step change of 400 $\mu\varepsilon$ (FBG remained at room temperature).

As shown in Fig. 10, the wavelength and the power of the output signal change linearly with the strain applied to the FBG. Based on the experimental data obtained, the LPG sensitivity for strain $k_{\lambda\varepsilon}$ is 0.824 pm/$\mu\varepsilon$ and for temperature k_{PT} 0.011 mW/°C, as it was expected.

However, even though the power variations for a fixed wavelength are linear, there is also an additional power growth with the wavelength increase. As can be seen in the Figs. 10 and 11, as the wavelength of the laser increases because of a strain change in the FBG at a constant LPG temperature, the power of the emission line rises slightly too. This is due to the fact that a positive displacement of the laser wavelength in the linear slope of the LPG (because of a change in the FBG sensor) increases the power in the same manner as if a negative displacement of the LPG shape occurred due to a temperature or strain variation at the LPG.

Consequently, when the wavelength varies, the power varies as well apart from the variation related to the temperature increase at the LPG. This increment must be quantified and corrected in order to get a proper temperature reading from the sensor. This linear dependence was measured as $k_c = 0.0369$ mW/nm.

Because of this, as it is shown in Fig. 11(a) if the peak power of the laser is represented for every strain (on the FBG) and temperature (on the LPG) value, a shift can be seen in the power measured for an identical temperature. However, after subtracting the correcting factor, a unique fit line can be used with a sensitivity of $k_{PT} = 0.011$ mW/°C [see Fig. 11(b)].

At this point the sensitivities of the wavelength and the peak power of the emission line due to temperature and to strain variations can be measured. In addition, the linear behavior of the wavelength and peak power of the laser when both vary simultaneously has been observed as a function of physical changes at the LPG and FBG. Finally, the relationship between the sensitivities and the output signal has been studied when both sensor are subjected to identical strain and temperature values simultaneously.

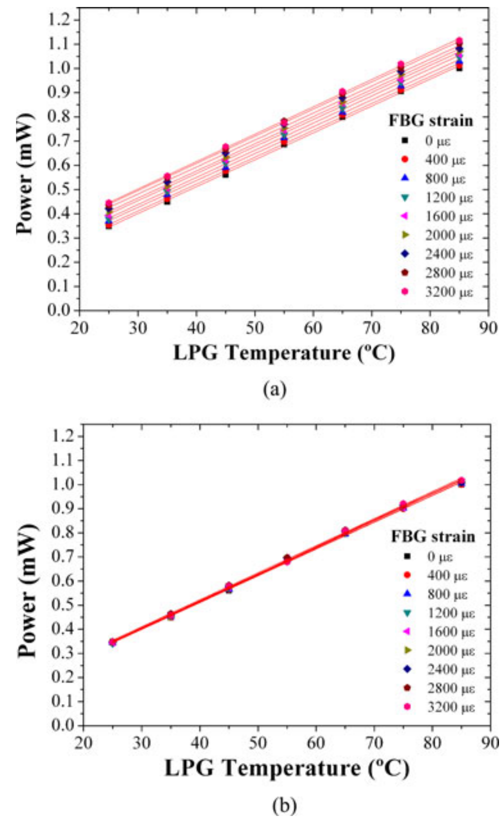

Fig. 11. Output power variation for different temperature and strain applied to the FBG and LPG respectively before (a) and after the correction (b).

The variation of the wavelength ($\Delta\lambda$) and the peak power (ΔP) coupled out of the LPG as a function of the variation of the temperature (ΔT) and strain ($\Delta\varepsilon$) measured can be written as follows:

$$\Delta\lambda = \Delta T \cdot k_{\lambda T} + \Delta\varepsilon \cdot k_{\lambda\varepsilon} \tag{1}$$

$$\Delta P = \Delta T \cdot k_{PT} + \Delta\varepsilon \cdot k_{P\varepsilon} + k_c \cdot \Delta\lambda \tag{2}$$

where $k_{\lambda\varepsilon}$ and $k_{\lambda T}$ are the laser wavelength sensitivities to strain and temperature respectively. Similarly $k_{P\varepsilon}$ and k_{PT} are the laser peak power sensitivities to strain and to temperature. The power increase due to the wavelength shift is given by the correcting factor k_c.

Equivalently, this relationship can be deducted from (1) and (2) and represented using a matrix form:

$$\begin{pmatrix} \Delta\lambda \\ \Delta P - k_c\Delta\lambda \end{pmatrix} = \begin{pmatrix} k_{\lambda T} & k_{\lambda\varepsilon} \\ k_{PT} & k_{P\varepsilon} \end{pmatrix} \cdot \begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = [K] \cdot \begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix}. \tag{3}$$

Accordingly the temperature and the strain are given by

$$\begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = \frac{1}{|K|} \begin{pmatrix} k_{P\varepsilon} & -k_{\lambda\varepsilon} \\ -k_{PT} & k_{\lambda T} \end{pmatrix} \cdot \begin{pmatrix} \Delta\lambda \\ \Delta P - k_c\Delta\lambda \end{pmatrix} = \dots$$
$$= \frac{1}{k_{\lambda T} \cdot k_{P\varepsilon} - k_{\lambda\varepsilon}k_{PT}} \begin{pmatrix} k_{P\varepsilon} + k_{\lambda\varepsilon}k_c & -k_{\lambda\varepsilon} \\ -k_{PT} - k_{\lambda T}k_c & k_{\lambda T} \end{pmatrix} \begin{pmatrix} \Delta\lambda \\ \Delta P \end{pmatrix}. \tag{4}$$

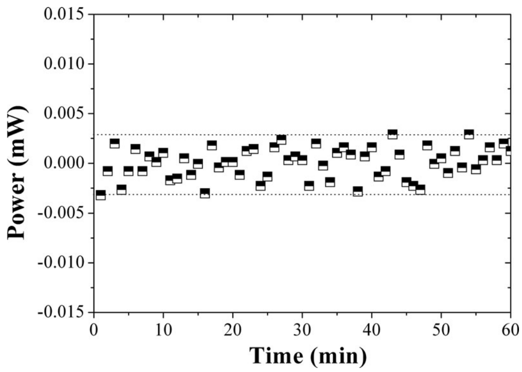

Fig 12. Power instability of the laser in 1 h.

Finally, using the previously measured sensitivities, temperature and strain applied simultaneously to the sensors can be deducted from the laser wavelength and peak power as follows:

$$\begin{pmatrix} \Delta T \\ \Delta\varepsilon \end{pmatrix} = \begin{pmatrix} 0.052 & 86.682 \\ 121.303 & -943.617 \end{pmatrix} \begin{pmatrix} \Delta\lambda \\ \Delta P \end{pmatrix} \tag{5}$$

where wavelength shift $\Delta\lambda$ is expressed in nanometers (nm), the peak power variation ΔP is in miliwatts (mW), the strain variation ($\Delta\varepsilon$) in microstrain ($\mu\varepsilon$) and the temperature variation (ΔT) is expressed Celsius degrees (°C).

To ensure the accuracy and repeatability of the measurements, it is important to assess the fiber laser power instability as the LPG sensor information is encoded in the amplitude of the signal obtained. Therefore, an instability study was carried out by measuring the output peak power once every minute until 1 h (see Fig. 12). This study shows that the peak power of the laser had very good power stability with an average variation of 1.31 μW and a maximum variation of 3.17 μW in 1 h. Consequently, the peak power instability of the laser is not a limiting factor and the peak power of the laser can be used for sensing applications.

The same experimental process has been repeated multiple times and it is good to see that repeatable results have been obtained, showing a good repeatability of the measurements. In the final test, a FBG centered at 1536.2 nm was used to replace the FBG at 1537.2 nm. The results agreed well with those obtained in the first test, although the measurement range and the constants used in the above equations were slightly different.

It is worth mentioning that once this technique has been validated, the results obtained can be easily adapted and improved by means of changing the gratings specifications. Since the sensing technique relies on the wavelength and the power of the laser, there are some key parameters of the gratings that must be taken into account for an appropriate design of the system. One of these parameters is the bandwidth of the LPG that determines the span of the linear slope in which the FBG must be constantly placed in order to get a correct reading. Therefore, the highest and the lowest possible wavelength of the emission line must be placed at the right and at the left limit of the linear slope of the LPG respectively in a worst case scenario. That is the reason why the Bragg wavelength of the FBG is also a critical parameter. In the proposed experiment, the FBG centered at 1537 nm was proved to stay within the linear part of the LPG shape from 0 $\mu\varepsilon$ and 25 °C (lowest emission wavelength, Fig. 3) to 3200 $\mu\varepsilon$ and 90 °C (highest emission wavelength). Another important parameter that is required to be considered for the design of the laser is the attenuation of the rejected band of the LPG. A higher attenuation implies an increase in the slope of the linear part of the LPG shape; consequently it increases the sensitivities related to the power $k_{P\varepsilon}$ and k_{PT}.

As a result, different gratings must be employed depending on the required accuracy and measuring range of temperature and strain. In this study the right slope of the LPG rejected band has been used to modulate the power of the laser but equally the left slope, with a different sensitivity, can also be utilized.

IV. Conclusion

A new sensor system based on an EDF laser has been presented and demonstrated. The temperature and strain information are included in the fiber laser wavelength and in the peak power level using a unique emission line. The fiber laser has an OSNR higher than 55 dB and a power instability of 3.17 μW in 1 h. The temperature and strain applied to the FBG shifts the wavelength of the laser with a sensitivity of 0.894 pm/$\mu\varepsilon$ and 8.97 pm/°C respectively. On the other hand the peak power of the laser increases linearly with the LPG temperature with a sensitivity of 0.0112 mW/°C and also decreases linearly with the strain applied with a sensitivity of -3.09×10^{-5} mW/$\mu\varepsilon$. Extensive tests have been undertaken in this work to verify the sensing principle, underpinning the system operation by applying physical variations to both sensors simultaneously. The power increase due to the wavelength shift has been also measured ($k_c = 0.0369$ mW/nm) and taken into account in the measurements. Finally equations have been derived for the effective calculation of the strain and the temperature as a function of the peak power and the wavelength of the emission line. The main advantage of this technique is that just one emission line is needed in order to monitor two parameters. This economic bandwidth usage enables multiplexing of a larger number of sensors within a certain optical bandwidth. Moreover, the high OSNR obtained allows the system to be used for remote sensing applications.

Acknowledgment

The authors would like to thank Liekki for providing the Erbium doped.

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