Characterization of a multipoint sensor based on fiber Bragg gratings

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ABSTRACT

The industrial processes need to control many variables such as temperature, flow, pressure, position, etc. For this reason, one sensor is required for each signal to be controlled. Therefore, multipoint sensors that can measure different signals in the same system have been proposed. In this work a multipoint sensor, which consists of a fiber laser with two Fabry-Perot cavities based on fiber Bragg gratings was studied. The sensor operation principle is based on the overlapping of the gratings reflection spectra, which produce a laser emission with a wavelength of 1536 nm. For this kind of sensors, various detection methods to identify and quantify the signals from its intermodal frequencies, have been used which employ some circuits like PLL (Phase Loop Lock), lock-in amplifiers and electrical spectrum analyzers. However these equipments are quite expensive. Therefore in the present work signal analysis with Fourier discrete transform to identify and quantify the sensor signals based on the laser intermodal frequencies is proposed. Such frequencies were 200 and 800 kHz corresponding to cavities of 500 and 130 m length, respectively.

Keywords: Multipoint sensor, Fourier discrete transform fiber Bragg grating, intermodal frequency

1. INTRODUCTION

Multipoint sensors based on optical fiber have advantages to measure one or multiple variables in different points (temperature, pressure, flow etc.) since they are immune to electromagnetic interference, moreover owing to the fact that they are electrically isolated, they can be used in high voltage zones.

Laser sensors based on optical fiber present a disadvantage when it is question of constructing multipoint sensors, i.e., it is difficult to interrogate various Bragg gratings (FBG) in the same system if some of them are being affected by some physical parameter. To solve this, various methods have been proposed. From mode locked lasers [1], lasers with different emission wavelength [2], the use of tunable filters to select the adequate laser emission for each sensor [3]. However the above mentioned techniques to interrogate each sensor in multipoint systems are quite complicated and expensive.

In the present work, a method based on an optical fiber laser is proposed. The arrangement consists of an optical fiber laser with two cavities formed by one reference FGB in one end, and two sensor FBGs in the other end. The laser gain medium is an erbium doped fiber. Each cavity formed by the correspondent sensor FBG and the reference FBG will produce different intermodal frequencies when the FBGs spectra overlap. In a previous work, this principle was already reported and used as flow sensor [4]. In these cases the laser output intensity was used to quantify the FBG stretching. However, if the optical power varies as the result of the stretching of both FBGs, it is not possible to discriminate between both sensors and the determination of the intermodal frequencies becomes necessary. The intermodal frequency gives the cavity length and the position of the sensor that has been actived. The obtained optical signal intensity was measured by a conventional photodetector and in order to determine the intermodal frequency, Fourier analysis was performed using MATLAB. There was also used the fact that the magnitude of the central mode varies as the stretching is applied and therefore it would be possible not only to discriminate the sensor that is active, but also to quantify the physical variable magnitude.

The important elements in the development of the sensor, high reflection mirrors, can be substituted by FBGs, since they can be also used as sensors. The FBG comprises a short portion of single-mode optical fiber in which the refractive index of the core is periodically modulated. Light is guided along the fiber core and when the Bragg condition is satisfied, the

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contribution of each light reflection of the grating planes are constructively added to form a reflection peak with a central wavelength defined by the grating parameters as is shown by Equation 1. The Bragg wavelength of the grating is the central wavelength of the light reflected by an FBG, and it depends on the core refractive index and grating periodicity.

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the grating and Λ is the modulation period of the refractive index.

The effective refractive index as well as the period between grating planes can be affected by changes in the longitudinal stretching and the grating temperature, which affects the Bragg wavelength, as is shown by Equation 2 [5].

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T \tag{2}$$

$\Delta\lambda_B$ can be used to measure physical parameters related to stretching and/or temperature. An example is its application in a water flow sensor based on an optical fiber laser [6].

The cavity of an optical fiber laser can be constituted by two FBGs used as mirrors, which provide optical feedback into a gain media, in this case an optical fiber doped with rare earth ions like erbium (Er^{3+}), neodymium (Nd^{3+}) or ytterbium (Yb^{3+}). An optical pumping is commonly used.

The laser output has certain characteristics such as power output, resonant modes frequency, phase and polarization that depend of the gain media (doped fiber), wavelength pumping (1480 or 980 nm), as well as cavity length.

When the signal propagating within the cavity reaches a standing-wave condition determined by the mirrors separation (L), the cavity resonates and an integer number (m) of half wavelengths in the region between the mirrors would be produced. The condition is simply that there must be a node at each mirror, and this can only happen when L equals an integer number of $\lambda/2$ (where $\lambda = \lambda_o/n$) as is shown in Equation 3:

$$m = \frac{L}{\lambda/2} \tag{3}$$

and

$$\nu_m = \frac{mv}{2L} \tag{4}$$

Where v is speed in the medium and ν_m is the intermodal frequencies.

Therefore there are an infinite number of possible oscillatory longitudinal cavity modes, commonly known as intermodal frequencies ν_m. Consecutive modes are separated as is described by Equation 5[7]:

$$\nu_{m+1} - \nu_m = \Delta\nu = \frac{v}{2L} \tag{5}$$

It was mentioned above that the use of intermodal frequency can help to discriminate which sensor is active. To measure this frequency it can be used a PLL (Phase Loop Lock), a lock-in amplifier or a spectrum analyzer. In this work a mathematical tool known as Fourier discrete transform was employed. The common use of the Fourier transform is to determine the signal frequency components.

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Almost any mathematical function can be expressed as the superposition of sinusoidal functions. The superposition form depends on whether the signal is periodical or not. For periodical signals, there is a direct addition known as a Fourier series. However if it is not periodical, the superposition has an integral form called Fourier transform.
The Fourier discrete transform (Equation 6), is a particular kind of Fourier transform, which converts a function in the time domain to another in the frequency domain. It requires a discrete function and non zero values with finite duration.

(6)

Where

2. EXPERIMENTAL SETUP

The setup of the sensor is shown in Figure 1. The fiber laser consists of a pumping laser diode with wavelength of 980 nm and a power of 37 mW. As gain medium, 6.8 m of erbium doped fiber was used and the Fabry-Perot cavities were constituted by three FBGs (BRAGG PHOTONICS), one as a reference (FBG3 with λ_B=1536 nm) and two used as sensors (FBG2 with λ_B=1535and FBG1 with λ_B=1534). The cavities consisted of 130 and 500 m of single mode fiber (SMF-28), respectively. The output signal was obtained from the 10% port of a 90:10 coupler and it was measured by a FGA10 (Thorlabs Inc.) conventional photodiode. The optical output was converted to voltage using an operational amplifier in current/voltage converter configuration. The analogical voltage signal was monitored with an oscilloscope (Tektronix TDS 2002) and it was acquired through the RS232 port in a PC. A MATLAB algorithm was designed to apply the Fourier discrete transform to this signal in order to determine the intermodal frequencies. Finally, such frequencies were displayed in a graphic way. The stretching was applied with a drive micrometer (Thorlabs Inc.) with a resolution of 10 μm.

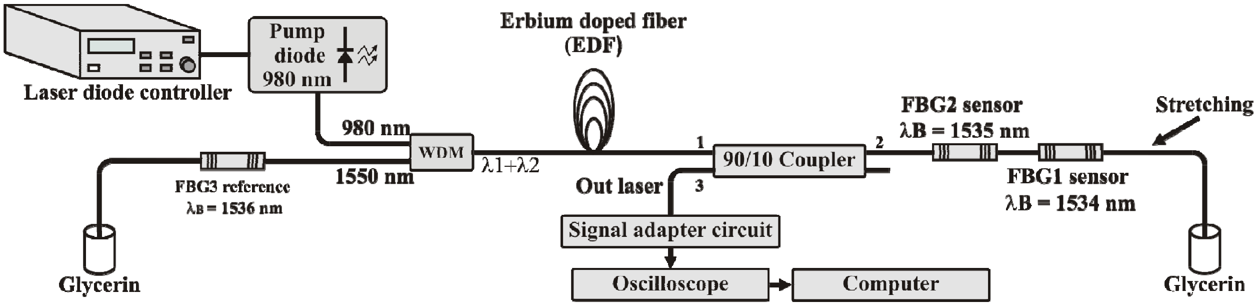

Figure 1. Multipoint sensor.

3. RESULTS

The characterization of each cavity was performed in an independent way and after that, both were coupled to perform the measurements simultaneously. Figure 2 shows the output spectrum of the laser intermodal frequencies correspondent to the cavity 1, which was formed by the reference grating (FBG3) and the sensor grating (FBG1) and had a length of 500 m. A separation of consecutive modes of 200 kHz was calculated using Equation 5. Such value was according to the experimental values found as can be observed from the figure. In a similar way, the characterization of the cavity 2 (formed by FBG1 and FBG2) which has an intermodal frequency of 800 kHz was performed. After the cavities characterization, the fundamental peak of the intermodal frequency, which was the one with the maximum amplitude on the spectrum was selected to monitor its magnitude variation produced by the FBG stretching.

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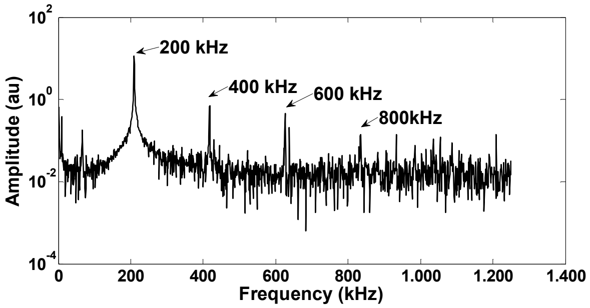
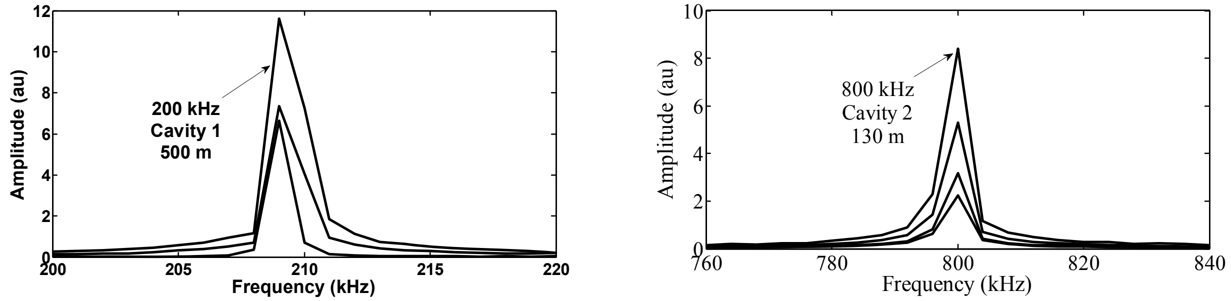


Figure 2. Intermodal laser frequencies of cavity 1.

As it was already mentioned in the experimental section, the FBG stretching was applied by a micrometer drive in a range from 0 to 1 mm with 50 μm steps, which produce an increase of the intermodal frequency peak amplitude of each cavity, as is shown in Figure 3. In Figure 3b can be also observed that the peak amplitude increases uniformly, while the peaks in the Figure 3a do not present such behavior. This is probably due to the shape of the reflection spectrum of the FBGs, which present some irregularities such as small perturbations. Therefore the overlapping of the spectra of the reference FBG and the sensor (FBG1) was not uniform for the case of cavity 1 as it was the case of cavity 2. Because of this, the selection of the FBG spectra must be performed carefully in order to obtain linear behavior in the sensor response, as it was already reported in previous works [7]. With this information, it can be mentioned that the resolution and the active range depends on such spectra shapes, for instance with the cavity 2 is possible to measure smaller variations of physical variables (temperature, water flow, pressure, displacements, etc.), while for the cavity 1 the resolution would be lower.

Finally, the signal voltage and the magnitude of the intermodal fundamental peak variations as a stretching was applied to FBG1 were measured. The results are shown in Figure 4. Figure 4a shows that the output voltage variations, which is a measure of the laser output, are quite regular which is in agreement with former results. However, the intermodal peak amplitude variation is quite noisy. This is probably due to the magnitude of the signal, which is quite small. An average of the signal during the acquisition was performed; however it seems that is not enough and that it would be necessary to perform such average in a different way. From the figure, it can be observed that the peak magnitude behavior resembles that of the voltage variation in a range of 0.5 mm of FBG stretching and there is a linear behavior in the range from approx. 0.2 to 0.5 mm. Therefore, it can be said that is possible to determine the variation of a physical variable from the amplitude of the fundamental intermodal peak. Furthermore an important aspect is that the quantification of the physical variables can be performed with the same arrangement at the same time, which can be observed in Figure 5, where is possible to observe the intermodal frequency peaks of both cavities.



(a) (b)

Figure 3. Intermodal laser frequencies of every cavity.

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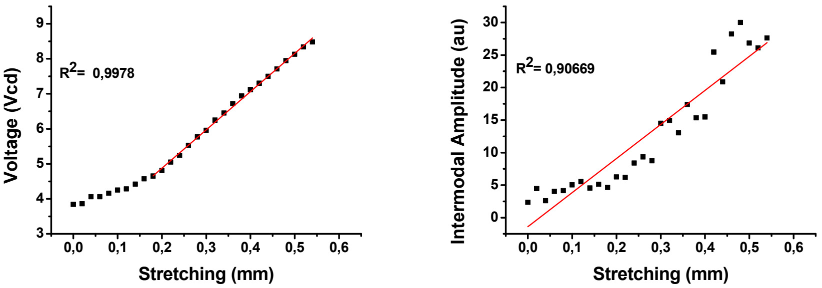

(a) (b)

Figure 4. (a)Voltage vs FBG1 stretching (b) Intermodal amplitude vs FBG1 stretching.

4. CONCLUSIONS

The study of a multipoint sensor to monitor two variables was performed using two laser cavities in the same arrangement through an algorithm designed in MATLAB using the Fourier discrete transform to determine the intermodal frequency of the laser cavities in a simple way. The operation frequency for every cavity was around 200 and 800 kHz for cavity lengths of 500 and 130 m, respectively. In general, the results are focused just in determining which sensor was activated by the measurement of the intermodal frequency. However, in this work it was proposed that is possible to quantify the change of both physical variables simultaneously, which would improve the system performance for its application as flow, pressure or temperature sensors. The noise in the intermodal frequency amplitude may be reduced applying an average of the acquired signal in a more effective way. Currently, a research on the sensor application and an increment in the sensor number is under progress.

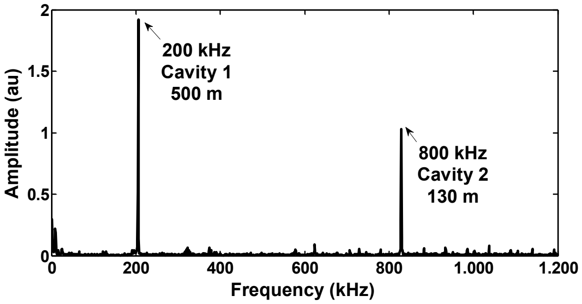

Figure 5. Intermodal laser frequencies of two cavities.

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