Smart Interrogation of Fiber Bragg Grating Sensors

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Abstract

The fiber Bragg grating sensing technology has been popularized with wavelength-division-multiplexed sensors cascaded along an optical fiber and remotely interrogated by a unique device. Recent trends confirm the interest in producing cost-effective and smart interrogators enabling to measure only a few distributed sensors along a single optical fiber link. To this aim, we have developed an original miniaturized spectrometer comprising a VCSEL emitting around 1550 nm and a photodiode, driven by a robust micro-processor unit. A specific read-out technique based on the Hilbert transform and centroid method was implemented. It allows visualizing the Bragg wavelength evolution as a function of time with an acquisition rate of 100 Hz. The performances of this new interrogation device are discussed in the paper.

Introduction

A fiber Bragg grating (FBG) is a distributed mirror in a short segment of the optical fiber, reflecting a limited wavelength range around the so-called Bragg wavelength and transmitting all others [1]. The physical phenomenon behind this is a periodic and permanent modification of the core refractive index along the optical fiber axis induced by exposure of the core under ultraviolet light of an intense interference pattern. The index change is possible due to the fiber photosensitivity at a wavelength around 240 nm thanks to the presence of germanium oxide dopants inside the core. An FBG is defined by some physical parameters: the grating length L, the grating period Λ and the refractive index modulation δn. Optically, an FBG behaves as a narrow-band reflective filter around the Bragg wavelength:

$$\lambda_B = 2\left(n_{eff} + \delta n\right)\Lambda \approx 2n_{eff}\Lambda \qquad (1)$$

where n_{eff} is the effective refractive index of the optical fiber. Any change of the effective refractive index or the grating period will induce a shift of the Bragg wavelength which can be used to sense temperature, axial strain or pressure. The FBG sensitivity to strain or temperature is linear and without hysteresis. Typical values of axial strain and temperature sensitivity at 1550 nm are 1.2 $pm/\mu\varepsilon$ and 10 $pm/°C$, respectively [2].

Numerous methods for peak-tracking exist in the state of the art and are reviewed in [3]. This paper describes the main features of the optical interrogator under development, from the components to the signal processing methods used as well as the performances obtained. For the aim of the smart interrogator, the Hilbert transform and the centroid method were used for their simplicity, rapidity and efficiency of implementation. In our work, all the demodulation process was done in Python language.

Two graphical user interfaces have been developed in order to provide a real-time spectrometer and to monitor the evolution of Bragg wavelengths as a function of time. The first one consists of a program in Python language that runs on a Raspberry Pi 4 and the second one consists of an Android application based on a Bluetooth communication with the smart interrogator.

Experimental setup

The smart interrogator under development is presented in Fig. 1. The light source is a Vertical Cavity Surface Emitting Laser (VCSEL). The VCSEL has numerous advantages (serial manufacturing, low threshold current, reduced footprint and low electrical power consumption) that establish it as a low-cost device [6,7]. The VCSEL used in this study is a narrowband source driven in current over a spectral range of 10 nm, allowing maximum four or five Bragg gratings cascaded along the fiber. An electrical driving unit is needed to modulate the electrical current in the VCSEL, consequently activating the VCSEL wavelength redshifting [1]. An isolator is placed in front of the laser to avoid reinjection of light into the laser cavity, which changes or degrades the laser light's characteristics. The circulator aims to separate the forward signals from the source and the backwards signals from the Bragg gratings. The photodetector is an InGaAs PIN photodiode that converts the optical power into an electric signal processed by the micro-controller unit. The output of the setup is a reflection spectrum composed of 200 data points obtained during the laser sweep period. It is then sent either to a computer or a Raspberry Pi 4 with a USB cable (serial protocol). The Raspberry Pi 4, located at the same position as the interrogator, is used for a sake of mobility where a remote user can visualize on his laptop (via a VNC connection) what is happening at the measurement points. The use of such a remote connection protocol tends to a smarter interrogator.

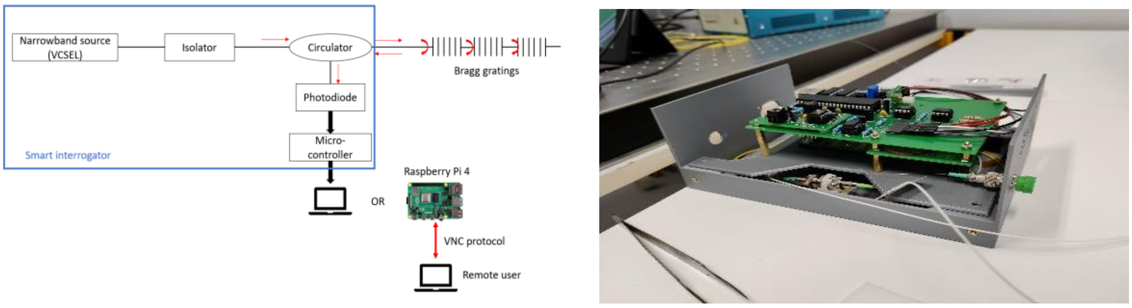

Fig. 1. Operating principle of the VCSEL-based micro-spectrometer (left) and picture of the current development without the Raspberry Pi 4 (right).

Processing algorithm

The Hilbert transform is a mathematical tool used in Wavelength Division Multiplexing (WDM) systems where the optical fibers contain more than one Bragg grating. Indeed, the centroid method can only be used if there is only one peak in the investigated wavelength span. The Hilbert transform will make it possible to separate each of the peaks in the reflection spectrum in a quite precise way. The central wavelength of each reflection peak can be judged through the zero-crossing point of the transformed signal [3,4,5] as presented in Fig. 2. Around the zero-crossing points, the slope of the signal is very steep and by applying a condition in the data processing, it is therefore possible to separate each peak and observe them in a dedicated window in wavelengths.

The centroid method is a widely used method for peak detection where the Bragg wavelength is determined as the center of mass of the reflection peak [3,5]. To implement this method, as in Fig. 3, the first step is to determine the maximum of the peak. Then, a threshold must be set from the maximum which is generally at -3 dB or half the power of the peak. All the data points above the threshold are used to compute the Bragg wavelength by:

$$\lambda_B = \frac{\sum_{i=1}^{N} \lambda_i I_i}{\sum_{i=1}^{N} I_i} \tag{2}$$

where N is the number of data points above the threshold and I_i is the amplitude of reflectivity.

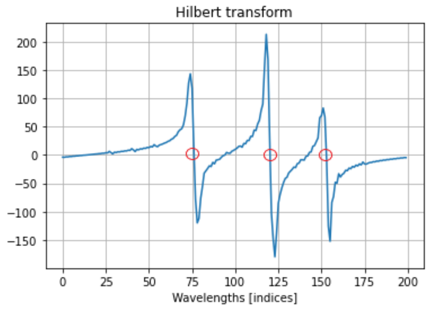

Fig. 2. Hilbert transform of three Bragg gratings. The zero-crossing points are represented by circles.

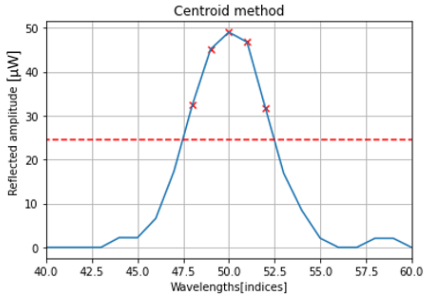

Fig. 3. Centroid method applied on a Bragg grating. The dotted line represents the threshold, and the crosses are the data points used in (2).

Thanks to these methods, it is possible to process a spectrum in real-time in such a way as to accurately identify its peaks. The demodulation operates in successive steps. First, the data vector will undergo a Hilbert transform which will be followed by a recovery of its intersections with the horizontal axis. The detected peaks can then be separated into different windows. Each window passed into the centroid method will then deliver the wavelength of the peak in question. Finally, the outputs for each window are recombined into a list containing the N peaks of the incoming signal.

Additional signal processing methods have been applied to improve the results of the interrogator. The first method allows to compensate for the non-constant VCSEL output power as a function of the wavelengths. The solution is to implement a compensation window in amplitude that represents a multiplicative factor to be applied for each index of the data vector, taking care to not amplify noise unnecessarily. The second processing allows to have more precision with the centroid method. Indeed, as seen in Fig. 3, the centroid method is based on a few data points. Thanks to interpolation on a peak, it is possible to resample the number of data points to be more resolved. The detrimental effect is that the interpolation increases slightly the computation time of the algorithm. The last signal processing method developed is the exponential smoothing on Bragg wavelengths that acts as a low-pass filter. This is used to mitigate the slight oscillations of Bragg wavelengths during the measurements. The exponential smoothing is defined by:

$$\lambda_B(t) = \alpha\lambda_B(t-1) + (1-\alpha)\lambda_B(t) \tag{3}$$

where α is the smoothing factor (between 0 and 1). Eq. (3) means that the Bragg wavelength depends on a weight average of the current observation and the previous one.

Performances

The objective of the smart interrogator under development is to reach a trade-off between rapidity and accuracy. Actually, the acquisition rate of the interrogator is around 100 Hz but future improvements on the hardware part are possible to increase this value. Regarding the software part in the Python language, the algorithm for the centroid peak detection method is very fast and lasts less than 1 ms (for a Raspberry Pi 4). This time can be reduced if more powerful resources are employed. A higher acquisition rate would allow to be even more reactive to events on the fiber, which is quite critical for strain sensors but not really for temperature sensors.

Two parameters are important when studying the system performances: stability and repeatability. The stability can be measured by calculating the deviation of the Bragg wavelengths over time when the fiber is at rest and maintained at a specific temperature. Fig. 5 depicts the signal measured with a smoothing factor of 0.7. In this case, the deviation remains below 20 pm. Depending on the weight that can be given to exponential smoothing, it is possible to reduce considerably the oscillations. For example, for a static temperature sensor, a high smoothing factor can be used due to thermal inertia. The repeatability of the Bragg grating is the ability to return to a state of rest after an applied stress and this for successive measurements carried out under the same experimental conditions. The results obtained in Fig. 6 are very satisfactory. Let us note that a slight sliding phenomenon appears due to the equipment used for the experience.

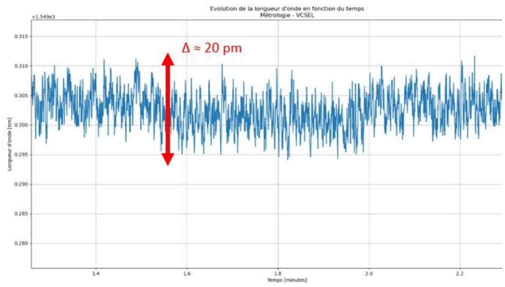

Fig. 5. Stability of the Bragg wavelength detection with a smoothing factor of 0.7.

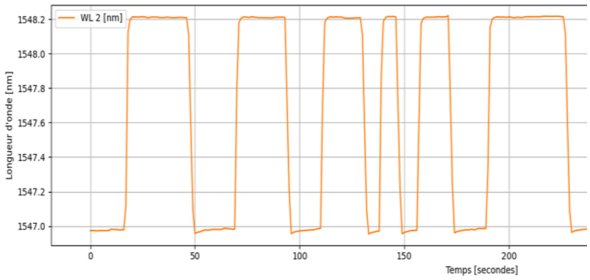

Fig. 6. Repeatability of the Bragg wavelength detection.

Conclusion

As a summary of our work, we have developed a complete single channel optical interrogator which can lead to new trends in the democratization process of fiber Bragg grating technology compared to classical interrogators in the industry. Our smart interrogator is based on the use of a VCSEL and a PIN photodiode, combined with powerful processing techniques such as the Hilbert transform and the centroid method. The whole forming a robust tool for Bragg wavelengths detection in real time.

References

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