Accuracy issues for a quasi-distributed sensor based on the concatenation of identical fibre Bragg gratings

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A quasi-distributed temperature monitoring system based on the concatenation of identical Fibre Bragg Gratings is proposed. The system is interrogated by a wavelength-tuneable Optical Time Domain Reflectometer (OTDR). The demodulation method consists, for each grating of the concatenation, in fitting the measured data by the reference data obtained during the calibration process. In this paper, the effect of the measurement time and the demodulation method are analysed for accuracy purpose.

State-of-the-art of FBG-based quasi-distributed sensors

The application of Fibre Bragg Gratings (FBG) for sensing purposes is based on the dependence of the Bragg wavelength on strain and temperature. Indeed, the Bragg wavelength shifts linearly and without hysterisis when the FBG is exposed to temperature or strain changes [1]. Moreover, the overall reflection spectrum is conserved. The FBG sensitivity to temperature is of the order of 10 pm/°C.
Fibre Bragg Gratings (FBG) implemented within quasi-distributed sensors are mainly, not to say only, multiplexed into the frequency domain [2]. Consequently, in order to discriminate the information received from all the sensing points, a unique range of operating wavelengths is dedicated to each grating of the concatenation. Therefore, the number of sensing points is directly limited by the spectral bandwidth of the source, the resolution of the interrogating unit, and the wavelength spacing between two gratings - related to the maximum possible temperature excursion before superimposition of the reflection spectra.

Proposed solution and related advantages

In this paper, the authors propose a temperature monitoring system based on the concatenation of low reflective (<10%) identical FBG's, i.e. with the same Bragg wavelength at room temperature. The system is interrogated in the time domain by a wavelength-tuneable Optical Time Domain Reflectometer (λ-OTDR).
The OTDR is commonly used to analyze the light loss in a fibre in optical network trouble shooting. It injects an intense and short light pulse into the optical fibre and measures the backscattered and reflected light as a function of time. The signal is then analyzed to determine the location of optical fibre defaults.
As the OTDR returns the position of reflective events on an optical fibre, it may interrogate a concatenation of gratings. But a classical OTDR is not able to interrogate a concatenation of gratings. The main reason is because the spectral bandwidth of a standard OTDR (of around 10 nm) is way too large to detect the Bragg wavelength shift, as the FBG spectrum is usually less than 1 nm wide. Then, as a standard OTDR is not wavelength tuneable, it cannot follow the wavelength evolution of the heated Bragg grating. In our sensor, a classical OTDR has been extended to a wavelength tuneable one, with a much narrower bandwidth. For each programmed wavelength, it launches pulses, interprets the backscattered and reflected signals and records the OTDR traces.

With the proposed sensor, the interrogation time is constant whatever the number of interrogated points, and is proportional to the number of emitted wavelengths, i.e. to the range of studied temperatures. A simple calculation shows that a 40 dB dynamic OTDR allows the visualization of roughly 90 gratings characterized by the same Bragg wavelength, 10% reflective, and all subject to the same temperature in the worst case (i.e. all presenting a reflection peak of maximum height at the same wavelength). This is an important improvement when compared to frequency-domain interrogated FBG's. In that case, about fifteen gratings can be addressed on a single fibre. [2]

Sensor principle

The sensor principle is schematized in figure 1. The automated λ-OTDR can be understood as a device sending series of spectrally narrow optical pulses at well known wavelengths, and storing the corresponding traces. This device interrogates a concatenation of low reflective and identical FBG's – i.e. with the same Bragg wavelength (1535 nm at room temperature).

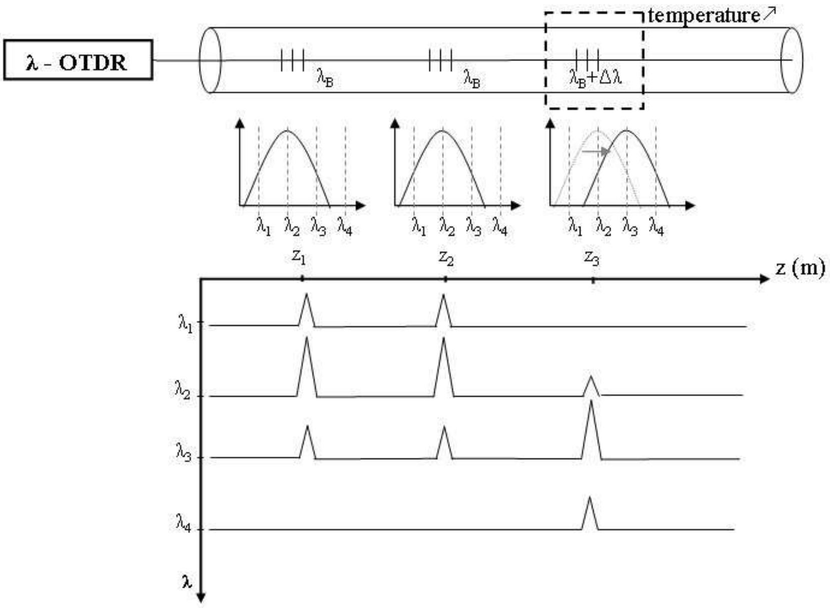

Figure 1: Sensor principle: when the λ-OTDR emitted wavelength is included within the reflection spectrum of one of the gratings, the OTDR trace contains a reflection peak located at this FBG's position. For each FBG, the reflection spectrum is rebuilt from the different magnitudes of the reflection peaks corresponding to each wavelength emitted by the λ-OTDR

Whereas the first two gratings of the schematized sensor on the figure 1 are subject to identical temperature conditions (room temperature), the third one undergoes a temperature increase. Its Bragg wavelength is therefore shifted to higher values. When the λ-OTDR emitted wavelength is included within the reflection spectrum of one of the concatenated gratings, the OTDR trace contains a reflection peak located at this FBG's spatial position. On figure 1, λ_1 is part of the first two FBG reflection spectra, although it is out of the third one. Therefore, the corresponding λ-OTDR trace contains two reflection peaks located at the first two gratings positions whereas the third grating is not visible. When the λ-OTDR emitted wavelength exactly corresponds to the resonance wavelength of one of the gratings, the λ-OTDR trace exhibits a reflection peak of maximum height at the grating position. It is the case for the λ_2 related trace in the figure

2, for the first two gratings positions. The third grating is visible on the trace but the magnitude of its reflection peak is not maximum as we didn't reach resonance yet. Then, when the λ-OTDR emits pulses at λ_3, as it corresponds to the Bragg wavelength of the third grating but is almost out of the first two reflection spectra, the height of the reflection peaks on the λ_3-related trace contains a peak of maximum height located at the third FBG position, whereas the first two peaks present a lower magnitude (as compared to the λ_2 case). Finally, at λ_4, the first two spectra are no more visible but the third FBG still presents a reflection peak. Consequently, when a sufficient wavelength range (2 nm in our case) is swept, the OTDR traces analysis permits to redraw the reflection spectrum of all the concatenated FBG's. Indeed, for each FBG, the reflection spectrum is rebuilt from the different magnitudes of the reflection peaks corresponding to each wavelength emitted by the OTDR.

Demodulation technique

During the calibration stage, for each concatenated grating, a reference spectrum, i.e. an accurately measured reflection spectrum at a well known temperature, is stored. The demodulation technique consists in comparing, for each FBG, the measured reflection spectrum with its reference.

When the measured temperature is different from the reference one, the associated FBG reflection spectra are translated with respect to one another by a $\Delta\lambda$ amount, which is directly proportional to the temperature difference between both data. The goal of the demodulation technique is to find this amount back.

For that purpose, the reference reflection spectrum is mathematically gradually wavelength shifted by a fixed step and compared to the measured data for each step. The comparison criterion is based on minimizing of the sum of the least square differences. It is computed for each translation of the reference reflection spectrum.

Accuracy issues

Different parameters can be modified in the set-up: the wavelength sampling rate (i.e. the wavelength spacing between two emitted wavelengths by the λ-OTDR), the wavelength step used in the demodulation and the measurement time for each OTDR trace (related to the number of consecutive averaged traces). The influence of the wavelength sampling rate has already been studied [3]. It has been optimised to 200 pm. Indeed, as the concatenated gratings are all roughly 250 pm wideband, the reconstructed spectrum contains at least two data points within the central lobe. This way, there is no uncertainty on the maximum position. In the following, the other parameters are studied for accuracy purpose.

Accuracy and demodulation wavelength step

Repeatability measurements (on 20 samples) were undertaken at 3 different temperatures: 50, 70 and 90 °C. The data was demodulated with 4 different wavelength steps: 10, 5, 2 and 1 pm. Repeatability statistics are presented in table 1. Although one might legitimately assume that decreasing the demodulation wavelength step would increase the accuracy of the measured temperature, the analysis of the table 1 shows that there is no direct link between accuracy and wavelength step. The worst temperature deviation is of 1.6 °C.

Temperature vs. wavelength step	10 pm		5 pm		2 pm		1 pm	
	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]
50.0°C	48.7	1.5	49.0	1.5	48.9	1.5	48.9	1.6
70.0°C	70.0	1.0	70.4	0.7	70.4	0.7	70.4	0.7
90.0°C	91.0	0.0	91.0	0.2	91.2	0.1	91.2	0.1

Table 1: Demodulated temperatures with corresponding demodulation wavelength step

Accuracy and measurement time

Repeatability measurements (on 20 samples) were conducted at 70°C with different measurement times (for each OTDR trace): 6, 10, 30, and 60s. The data were demodulated with a wavelength step of 10 pm. Repeatability statistics are presented in table 2, where a 30 seconds measurement time presents the best statistics with an accurate demodulated temperature and a standard deviation of 1.0°C. The complete measurement time can be roughly estimated as the product of one OTDR trace measurement time (30 s) by the number of needed traces, as data processing is very fast. For a 200°C temperature variation study, 10 traces are needed leading to a 5 minutes measurement time, whatever the number of interrogated gratings.

Temperature vs. Measurement time	6s		10s		30s		60s	
	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]	Mean value [°C]	Standard deviation [°C]
70.0°C	66.2	3.6	69.5	2.1	70.0	1.0	70.1	1.4

Table 2: Demodulated temperatures with corresponding measurement times

Conclusion

This paper presents a quasi-distributed temperature sensor based on the interrogation of identical fibre Bragg gratings by a wavelength-tuneable OTDR. The optimization of the set-up parameters leads to accurate measured temperatures to within 1.6°C the worst. The measurement time is of 5 minutes, whatever the number of interrogated gratings - that can be extended up to about 90.

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