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**PHOTONIC SENSORS**

# Long term stability of spectral measurement systems for Fiber Bragg Grating sensors

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**Abstract:** This paper addresses the metrological stability of spectral measurements performed with a smart FBG sensing instrument. With a sophisticated tracking system based on real-time drift compensation, we obtained, during 16 days, an unrivalled measurement stability, as low as: 0.0074 fm/h with a standard deviation: 0.032 pm. This level of performance opens the way, not only to high quality metrology, but also to long-term structure monitoring in many sectors.

**Keywords:** Optical Fiber Sensor, Fiber Bragg Grating, spectral measurement, stability, drift, resolution, Metrology

## 1. Introduction

After the 90's, dedicated to Fiber Bragg Grating (FBG) developments, the 2000's allowed both to the R&D laboratories and the SMEs involved in Optical Fiber Sensors (OFS) to develop appropriate FBG-based sensors and measurement systems [1]. Today, some techniques, prototypes, and commercially available products exist, and may be compared in terms of performances, ergonomy and price, prior to be used in industrial applications. Classically, some metrological parameters are put forward by academic people or developers: *e.g.* spectral resolution, optical source spectrum FWHM (and so the number of sensors), measurement rate... but almost never the long-term stability, *i.e.* the lack of drift, parameter which is an important matter of concern for many end-users. After a brief reminder on the FBG sensing technology, we focus on recent results and improvement obtained in terms of stability of spectral measurements for FBGs.

## 2. Fiber Bragg Grating sensing

FBGs are well-known diffraction gratings realized by photo-writing interferences with (UV, fs…) lasers within fibers, often germanosilicate type for their good photosensitivity. They consist in a sub-micronic modulation of the fiber core refractive index. In practice, a few millimeters-long FBG is made of several thousand periods of index modulation. And so, it reflects a very narrow spectral band centered at $\lambda_B = 2.n_e.\Lambda$ with $\Lambda$ (~ 0.5 µm) and $n_e$ the effective index (~ 1.4672) of the propagation mode. Any change in these parameters induces a spectral shift $\delta\lambda_B$ whose spectral monitoring enables the measurement of the requested parameter(s) (intrinsically temperature, strain or pressure, and some others like curvature, liquid/polymer refractive index, force, acceleration... depending on the FBG constitution and packaging). Moreover, FBGs offer the advantage to be multiplexable. For this purpose, several FBGs

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characterized by a specific $\lambda_{Bi}$, may be put in series and analyzed by the optoelectronic system (which plays the role of Optical Spectrum Analyzer) around their wavelength $\lambda_{Bi}$. The incident light is then reflected at $\lambda_{B1}$, $\lambda_{B2}$ ... $\lambda_{BN}$ by such a sensing network, and fine spectral variations of these wavelengths are analyzed by the instrument. To be more complete: spectral measurement of $\lambda_{Bi}$ represents the FBG # i address, while accurate determination of $\delta\lambda_{Bi}$ provides the measurement itself. Applications involving FBGs are numerous, but many of them can be linked to the concept of SHM (Structural Health Monitoring). Let us mention several industrial fields in which we were involved: mining & ground monitoring [2], underground storage [3], civil engineering [4], nuclear energy [5-6], high temperature environments [7], railway industry [8], composite materials [9], smart structures [10], Biophotonics [11-12], safety & security [13]…

## 3. Highly-stable measurement system

Requested performances vary from one sector to another, but some trends are emerging, and customers require ever-increasing performances. Although a few years ago they could be satisfied with a few pm resolution (*i.e.* a few µm/m in terms of strain, or a few tenths of °C), a measurement rate of 1 kHz, and multiplexing capabilities of a dozen of sensors, there are now more and more applications that go beyond these specifications. As an example, the need for no drift measurements is a matter of concern for long-term applications, and becomes challenging for system developers. Beyond the fact that in next paragraphs we will only talk about the interrogator performances, we must never forget that such sensing technology is part of a “metrological chain”, including FBGs, pigtails, and many optical and electronic components, each of them involved in the resulting "quality" of the measurement. In this study, the more relevant metrological specifications are: drift (lack of), stability, fidelity: their definitions can be found in current standards.

### 3.1 FBG measurement system stabilization

The OFS measurement system is based on a tunable source: each FBG transducer becomes therefore reflective when the wavelength emitted by the source equals its characteristic wavelength. Thus, during a complete scan of the source spectrum, each FBG photo-written in the fiber under test reflects light at slightly different moments, defined by their spectral spacing.

Once a grating is, for instance, strained, its spectral shift $\delta\lambda_B$ is increased proportionally to the applied strain $\delta\varepsilon$ and, correspondingly, its Bragg wavelength $\lambda_B$ becomes reflective later, since the source needs a time delay to reach this new wavelength. Once calibrated and synchronized, the difference in these moments (when reflection takes place between a first reference spectrum and a second spectral measurement) enables to determine the spectral shift $\delta\lambda_B$ and thus the evolution of the parameter (here the strain variation: $\delta\varepsilon = \delta L/L$).

The measurements quality is therefore based on the scan linearity, but also on the spectral stability of the whole system. Unfortunately, in industrial environments especially when surrounding conditions change (*e.g.*: temperature), system transfer function drift is inevitable, especially on long term applications.

In this project, our objective was to achieve an instrument able to self-learn the transfer function of its tunable source, to linearize the measurement response. It may be shown that in order to reduce the sampling budget, a truly linear scanning source may allow the use of constant spectral sampling steps, to guaranty the same level of performances over the full spectrum.

Our optoelectronic instrument includes: a narrow tunable source, a compact and tunable etalon Fabry-Perot interferometer operating in reflection whose temperature is stabilized at ± 1 mK, and an FBG whose wavelength is known, but without any accuracy.

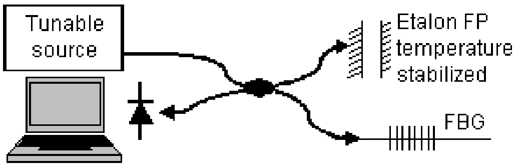
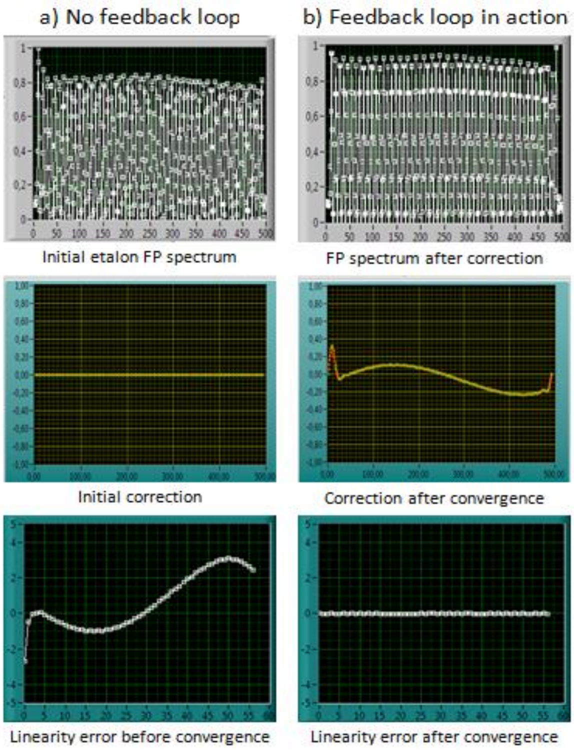


Fig. 1 Simplified diagram of the smart measurement system including the self-learning function software.



Initial etalon FP spectrum

FP spectrum after correction

Initial correction

Correction after convergence

Linearity error before convergence

Linearity error after convergence

Fig. 2 Transfer function linearization procedure steps.

### 3.2 Spectral measurement stability improvement

To assess the stability of the self-controlled measurement system, we set up a second FP etalon stabilized at ± 1 mK too. This provides a comb spectrum, as should do a fiber sensing line made of several FBGs. The only difference is due to the fact that every spectral line is stable at ± 10 fm. Thus, the spectral comb being very stable, monitoring of residual spectral drifts describes the intrinsic performances of the self-learning system. Among the 50 spectral lines measured, Fig. 3 shows the stability of one given line over a 400 h period (16 days) and Fig. 4a exhibits room temperature where the system is operating. Thus, in spite of circadian oscillations up to 5°C, the drift of our measurement system does not exceed - 0.0074 fm/h, *i.e.* - 3 fm after 400 h, and a standard deviation as low as 32 fm.

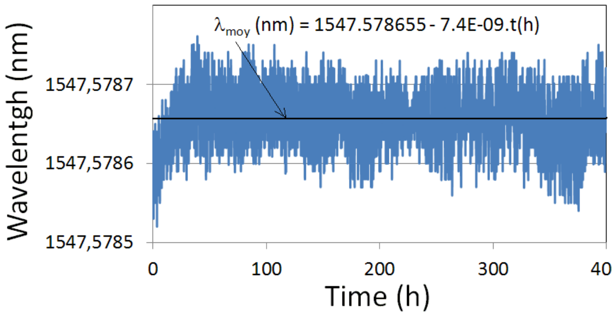


Fig. 3 Spectral measurement *versus* time.

A CUSUM curve (CUmulative SUM [14, 15]) was used to highlight the singular points of the spectral measurement (Fig. 4b). Its interpretation is based on the detection of slope discrepancies, the theory showing that any difference between each slope can be interpreted as a change in the behavior of the optoelectronic measurement system.

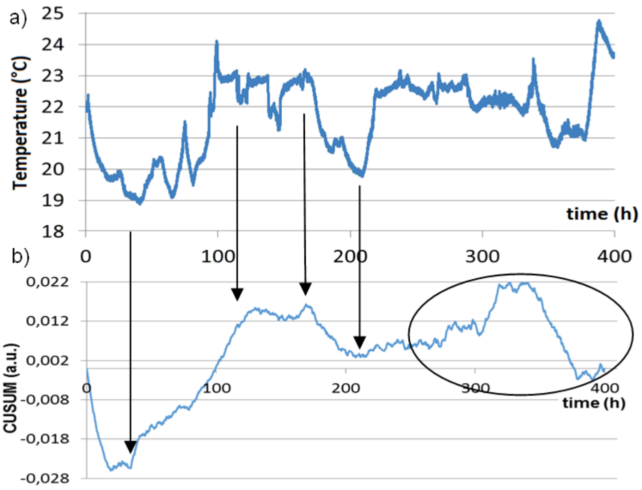


Fig. 4 a) Room temperature *vs* time and b) CUSUM curve

If the measurement system is equipped with sensors able to monitor its internal parameters (*e.g.* components' temperature, driving currents…), sensing data can be matched with singular points of the CUSUM curve. Once the process identified, corrective actions may be implemented (*e.g.*: critical components thermalization) through a continuous improvement process. In our case, at least four singular points were identified during the first 200 hours (Fig. 4 b, left side).

These 4 points compared to room temperature records point out the influence of this parameter on the stability of wavelength measurements. However, there is no obvious correspondence in the second half of the CUSUM: the cause is probably different (see the oval on Fig. 4b). Its identification based on an internal diagnostics, will then be achieved to determine the origin of these residual drifts to improve the stability of the current system.

### 3.3 Allan Variance

The Allan variance is a measure of frequency stability in clocks, oscillators and amplifiers [16, 17]. For n samples to consider, it is expressed as:

$$\sigma_y{}^2 = \frac{1}{2.n}\sum_{i=0}^{n-1}(y_{i+1} - y_i)^2 \quad \text{….. (1)}$$

The Allan deviation $\sigma_y(\tau)$, the square root of Allan variance, is also known as *sigma-tau*. The *M-sample variance*, expressed as $\sigma^2_y(M, T, \tau)$, is a measure of stability using M samples, time T between measures and observation time $\tau$. Both $\sigma^2$ and $\sigma$ describe the system stability: If a signal is submitted to a Gaussian noise, its Allan deviation will be characterized by a straight line with a negative slope, whose origin is the variance reduction by averaging. If the signal has a long-term drift, it will appear as a straight line of positive slope for long times.

In our experiment: $n = 14400$ samples, $\tau = T = 100$ s.

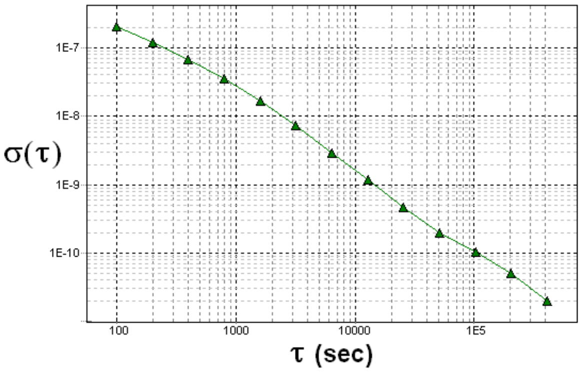


Fig. 5 Allan standard deviation of one given spectral line.

Fig. 5 shows the Allan deviation for a particular wavelength among 55 lines acquired during the 16-days period. For these lines, the quasi-linear decrease observed is in relation with a Gaussian noise.

### 3.4 Repeatability after shut down &disconnection

An important aspect, for end users, concerns the stability of measurement at any time, which means in any circumstances including potential shut down of the equipment, *i.e.* the repeatability after the measurement system by restarted or when the fiber link is disconnect and reconnected.

To check the influence of these two types of events on spectral measurement stability, we applied the following protocol:

1. Day 1, 9:00: fiber connection to the instrument,
2. From 9:00 to 12:00: instrument warm up,
3. From 12:00 to 12:30: spectral lines recording,
4. 12:30: Instrument shut down + optical fiber disconnection, *up to next day,*
5. Day 2, up to Day 10: the procedure is repeated.

In such a way, the FBG instrument was only in action 4.5 h a day, and full stopped 19.5 h. On Fig. 6 ten periods of 30 min acquisitions (protocol step 3) are concatenated to shows the spectral stability, for a given spectral line. A very slight influence of shut down and fiber disconnection may be observed.

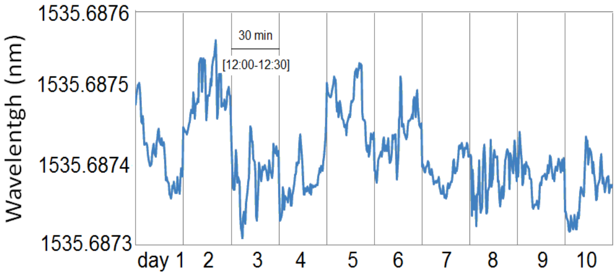


Fig. 6 Ten 30 min-long wavelength measurement periods, shared by shut downs and sensing fiber disconnections.

On Fig. 7 the spectral stability is depicted. The mean standard deviation $\sigma = 93$ fm is obtained on the central part of the spectrum, ranging from 1538 nm to 1570 nm, while outside, standard deviation may reaches 200 fm. As optoelectronic system need about 24 h to be stabilized (Fig. 2), spectral stability results should have been better with longer warm-up periods.

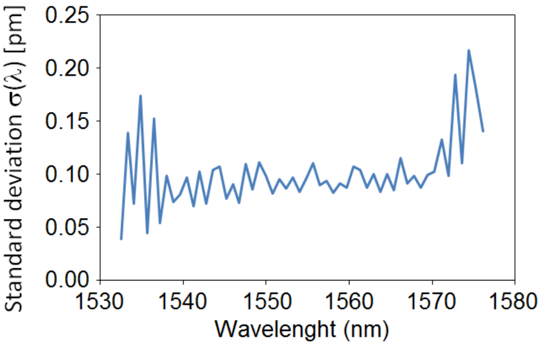


Fig. 7 Spectral measurement Repeatability.

## Conclusion

We have been working on improving the metrological performances of our FBG measurement systems for several years. Our activities have been focused on the measurement rate, others on the integration for embeddability, some others on the spectral range, etc. In this paper, we have presented our latest results related to the improvement of the spectral sensing stability. A smart self-learning system has been implemented, allowing us to achieve better performances to date, namely - 3 fm drift over 400 h and a standard deviation as low as 32 fm, despite surrounding temperature variations up to 5°C. Repeatability including fiber disconnection and system shut down has also been evaluated. In such conditions, standard deviation being 3-5 times worse: 93 fm on 80 % of the spectrum and maximum 200 fm on spectrum edges.

For users, access to such performances, based on an absolute internal wavelength referencing in real time, now paves the way to an accurate Metrology and to high quality long-term monitoring applications. Moreover, as residual drifts are partially linked to surrounding temperature changes, a much better stability may also be achieved if a cabinet with stabilized temperature is used to build the measurement system.

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