OPTICAL REFLECTOMETRY IN THE FREQUENCY DOMAIN FOR THE INTERROGATION OF FIBRE BRAGG GRATINGS

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1. Introduction

Optical fibre optic sensors represent a powerful class of alternative technologies to the conventional electrical sensors thanks to their low-weight, small dimensions and immunity to electromagnetic interferences. Among all fibre optic sensors, those based on fibre Bragg gratings (FBG) have a significant potential and have been developed for a wide variety of mechanical and temperature sensing applications. These devices enable multi-point sensing as many gratings can be placed in cascade within a single fibre. To interrogate them, wavelength-division multiplexing (WDM) is the most commercially encountered method and it allows addressing a few tenths of gratings on a single fibre [1]. In this technology, the gratings must occupy different wavelength ranges, i.e. they must be characterized by different Bragg wavelengths (λ_B). When using the phase mask inscription technique, this means that a different phase mask must be used for the fabrication of each FBG of the cascade. In order to overcome this limitation, it has been proposed to use optical frequency domain reflectometry (OFDR) as the interrogating method instead of WDM [3]. Although several thousands identical (same λ_B) FBGs can be detected by OFDR, two crosstalk effects limits the maximum sensors that can be cascaded in practice. In this paper, after describing the OFDR measurement principle, we study the impact of two crosstalk effects (multi-reflection and spectral shadowing) on the number of FBGs that can be simultaneously addressed.

2. Theoretical background

2.1 Fibre Bragg gratings

In its simplest form, a fibre Bragg grating (FBG) is a permanent and periodic modification of the core refractive index along an optical fibre [2]. As a result from multiple reflexions and interferences within the structure, the Bragg grating acts as a wavelength selective mirror around a particular wavelength, called the Bragg wavelength (λ_B), that can be determined using $\lambda_B = 2n_{eff}\,\Lambda$ where n_{eff} is the effective refractive index of the fibre at the Bragg wavelength and Λ is the grating periodicity (typically 500nm). A remarkable feature of FBG for sensing applications is the linear dependency of its Bragg wavelength on temperature and axial strain. In the particular case of temperature sensing, a wavelength shift of about 10pm is observed for a temperature variation of 1°C.

2.1 Optical frequency domain reflectometry

The basic phenomenon behind the coherent OFDR is the frequency-modulated continuous wave (FMCW) interference (beating) that was originally investigated in electric radar systems. In the basic configuration, the coherent OFDR consists of a tuneable laser source (TLS) whose frequency can be swept continuously in time without mode hops and an optical interferometer (Michelson) comprising a reference path and a measurement path (see figure 1). The device under test (DUT) is connected to the measurement path whereas the reference path is used as local oscillator (by using a fixed mirror). The interferences between the reference signal from reference path and the reflected and/or backscattered signals coming from the DUT is electrically detected and a Fourier transform allows the visualization of beat frequencies. If the optical frequency of the TLS is modulated at a constant rate, beat frequencies are proportional to the optical path differences between the reflections in the DUT and the reference path. The proportionality is given by:

$$z = \frac{c}{2n_{eff}\gamma} f_b \tag{1}$$

where f_b is the beat frequency and γ the rate of change of the frequency emitted by the tuneable source in Hz/s. Using eq.(1), reflection along the DUT can be located. The key point of OFDR implementations is the requirement for high performance optical sources providing a fast and linear frequency sweeping over a broad frequency range. However, lasers exhibit in practice fluctuations in their optical frequency tuning rate and compensations techniques have to be implemented in practice [2]. OFDR can provide millimetre spatial resolution over a fibre length of a few hundreds of meters.

3. Principle of the quasi-distributed sensor

Using OFDR to interrogate a cascade of FBGs has been proposed in [3]. Figure 2 (top)

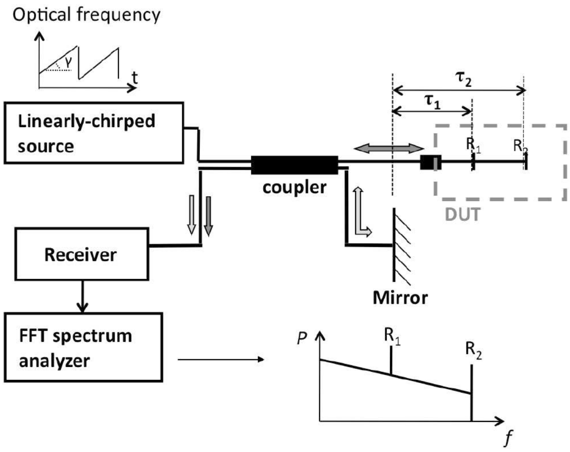


Fig.1: *OFDR set-up*

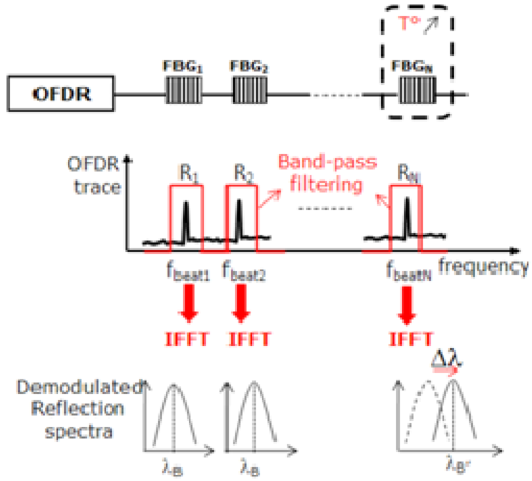


Fig.2: Principle of the sensor

shows the block diagram of the OFDR set-up for the interrogation of cascaded FBGs. The AC part of the interference signal detected at the photodiode (receiver) can be expressed as:

$$u(t) \propto \sum_{i=1}^{N} k_i a_i(\omega(t)) \cos\left(2\pi\gamma(\tau_i - \tau_{ref})t + \Phi(\omega(t)) + \varphi_i\right) \qquad (2)$$

where k_i is a constant representing all the fibre attenuation and coupling losses for FBG #i and ϕ_i is a constant phase. τ_i *and* τ_{ref} are the time delays corresponding to the roundtrip propagation to FBG #i and to the reference mirror of figure 1, respectively. $a_i(\omega(t))$ and $\Phi(\omega(t))$ represent the amplitude and phase of the FBG #i reflection spectrum, respectively. As the single arm reflections between different FBGs can be avoided in practice, they have been neglected in the equation. It can be seen from eq.(2) that the amplitude of the reflection spectrum of each FBG, $a_i(\omega(t))$, modulates a sinusoidal function with a unique beat frequency $(f_{bi} = \gamma(\tau_i - \tau_{ref}))$ that identifies the FBG (because it depends on τ_i). Therefore, when Fourier transform of the eq.(2) is taken to obtain the OFDR trace, discrete reflections of this trace contain in their sidebands (around their beat frequency) information about the Fourier transforms of the FBG reflection spectra (the relationship between ω and t is known from the linear variation of the source frequency with time). They can therefore be rebuilt as shown on figure 2. As a consequence, if a temperature/strain change is applied on one of the FBGs of the concatenation, the induced Bragg wavelength shift can be measured from the OFDR trace and the temperature/strain determined (thanks to a calibration stage). The experimental set-up has been tested for temperature measurement on a concatenation of 10 gratings. A maximum error of 1.5 degrees has been observed. In reference [3], it has been claimed that 3000 FBGs could be measured using OFDR interrogation. However, even if 3000 reflection peaks can indeed be detected by the OFDR apparatus, it does not necessarily mean that all of them can properly be demodulated, i.e. the measurand (temperature, strain,…) can be determined with a reasonable accuracy. Indeed, some crosstalk effects are inherent to the OFDR interrogation technique. In the remaining of this paper, their impacts are studied by means of simulations.

4. Multiple reflection crosstalk

Multi-reflection crosstalk can be defined as the following: in addition to the useful signal reflecting from the FBG under test, there exist many other signals which after several reflections arrive at the detector at the same time as the useful signal. These components added to the useful signal, could result in a measurement error after demodulation. We studied this problem considering 3-reflection components. We consider in the test arm N equally-spaced cascaded FBGs with identical power reflectivity, *r*. To be able to analyse the contributions of 3-reflection components on the signal, we take into account all the possible paths giving the same round-trip time as the useful signal. The simulated results presented in figure 3 ("equal" curve, for N=50 and a 20cm distance between FBGs) shows the case where the useful signal is the signal reflected from the last sensor of the concatenation (worst case). SMRR stands for Signal to Multi-Reflection crosstalk Ratio, defined as the ratio between the useful power and the power sum of all the multi-reflection contributions. In addition to the equal distance case, we conducted simulations for a uniform random distribution of the distances between two successive FBGs (between 10 and 30cm). The corresponding result is also represented in figure 3. By using such a figure, we can determine the reflectivity value required to obtain a given SMRR for a concatenation of 50 FBGs (as a rule of thumb, SMRR is usually fixed to 10). As expected, use of the uniform distribution provides better performance than the equally spaced sensing points. When the multi-reflections have a weight of 10% of the useful signal (SMRR=10), reflectivity values should be smaller than 5% for the uniform distribution case. This performance can be achieved by equally spaced sensors when the reflectivity is smaller than 1%. For different N values (and when the useful signal corresponds to FBG# N), figure 4 shows the SMRR versus reflectivity for the uniform distribution case. We can observe that 100 FBGs can be interrogated by using a reflectivity smaller than about 3% while keeping SMRR > 10, which is not possible to reach with the equal distance case.

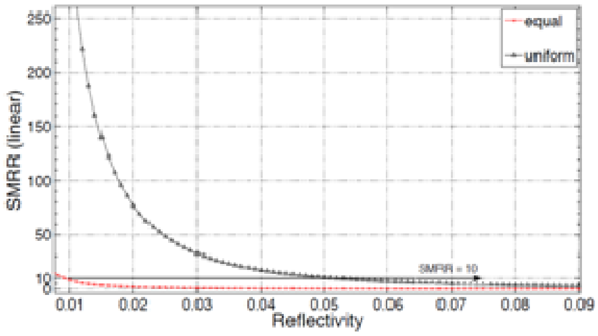


Fig.3: *SMRR for N=50*

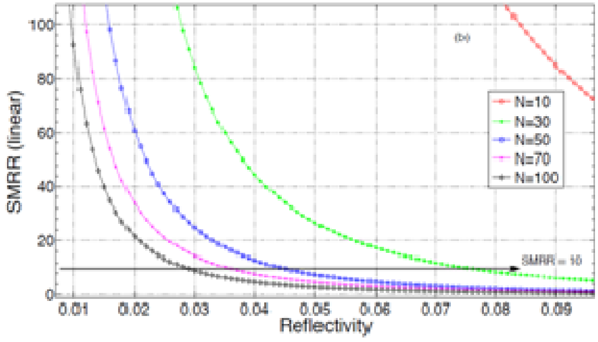
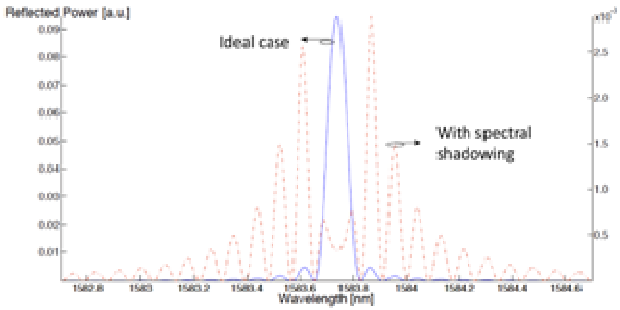


Fig.4: SMRR for the uniform distribution case and for various values of

5. Spectral shadowing crosstalk

Spectral-shadowing crosstalk occurs when a concatenation of gratings sharing the same spectral characteristics are addressed simultaneously. Distortion occurs in the downstream FBG's spectra due to light having to pass (twice) through all the FBGs located between the interrogator and the FBG under test. One can intuitively predict that the further the FBG under test, the more distorted the measured reflection spectrum (the more erroneous the demodulated measurand). We performed simulations to take into account this crosstalk effect in the frame of a quasi-distributed temperature sensor. In the analysis, all FBGs are assumed to be at room temperature and to have about identical spectral characteristics (Bragg wavelength around 1583.7nm at room temperature and reflectivity below 10%) with small fluctuations in the Bragg wavelength. These inevitable fluctuations due to fabrication process correspond to the specifications of the real gratings written in UMONS clean room facilities and can be modelled by a Gaussian distribution of the Bragg wavelengths with a standard deviation of 50 pm. Figure 5 shows (dashed line) the simulated reflection spectrum corresponding to the last sensor for a concatenation of 50 FBGs (N=50). It clearly demonstrates the modification in power and shape of the reflected spectra compared to the ideal case (without shadowing, full line). Because of the shape deterioration of the reflection spectrum, the determination of Bragg wavelength results in an inevitable error on the measured temperature. Simulations that use the centre of mass algorithm to determine λ_B, have provided mean measurement errors of 0.3, 0.7, 1.0, 1.2 and 1.4°C for N=10, 30, 50, 70 and 100 FBGs, respectively. The last FBG was supposed to be at 40°C while all the others were at room temperature (22°C). Figure 6 shows the error on the N^{th} FBG as a function of temperature deviation (temperature to be measured − mean temperature of all downstream

FBGs). In order to avoid high error values (values higher than 1.5°C, uncertainty inherent to our OFDR) on the measured temperature occurring in the problematic region ([1°C-18°C]) shown in figure 6, we adopted a modification on the measurement method using an enhanced algorithm. This enhancement, based on a bidirectional OFDR measurement and on a power analysis of the refection spectra, will be discussed during the talk.



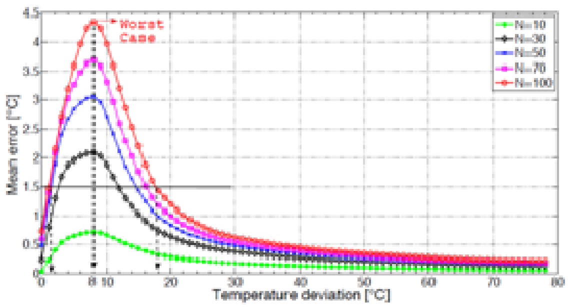


Fig.5: *Deformed reflection spectrum due to spectral shadowing*

Fig.5: Spectral shadowing-induced error as a function of temperature deviation

6. Conclusions

This paper proposes a quasi-distributed measurement scheme based on FBGs interrogated by optical frequency domain reflectometry. Although several thousands FBGs can be detected by the system, crosstalk effects limits the maximum sensors that can be cascaded in practice. We showed that about one hundred FBGs can be concatenated while keeping a measurement error less than 1.5°C for temperature sensing.

Acknowledgement

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