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Determining the Thermal Sensitivity of Optical Fibers Using High Order Fiber Bragg Gratings

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Abstract: The broadband wavelength-comb like response of high order Fiber Bragg Gratings is used to determine the intrinsic thermal sensitivity of the optical fiber material up to 900°C.

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1. Introduction

Optical fiber sensors (OFS) are nowadays commonly used for harsh environments monitoring thanks to multiple opportunities such as their low intrusivity in the probed environments or their insensitivity to electromagnetic interferences [1]. Distributed sensing can be performed using optical backscatter reflectometry based techniques and multi-point measurements are commonly performed using fiber Bragg gratings (FBGs) transducers. Measurement accuracy is, as with any physical transducer, determined partly by the calibration procedure [2,3].

Composed of a periodic refractive index modulation (RIM) written in the core of an optical fiber, FBGs are resonating structures that reflect light bands centered around Bragg wavelengths (λ_B) satisfying the well-known mode coupling condition [4] (Eq. 1).

$$\lambda_B = \frac{2 n_{\text{eff}} \Lambda}{m} \quad (1)$$

Where n_{eff} is the effective refractive index of the guided mode, Λ is the RIM period or grating's pitch and m is the harmonic order of the studied resonance.

Variations in external parameters, such as temperature, induce spectral shifts of the resonances which originate from two phenomena: on the one hand the increase in the effective refractive index (thermo-optic effect), and on the other hand the increase in the grating's pitch (thermal expansion). A key challenge in FBG-based measurements is that the spectral shift thermal sensitivity coefficient – typically expressed in pm/°C – depends on the resonance's Bragg wavelength itself. Common calibration methods hence rely on the determination of transducer-specific calibration laws [5]. In this case, thermal heterogeneities in the calibration volume may lead to notable errors in subsequent temperature estimation, considering highly multiplexed FBG arrays containing multiple transducers. In the case of small temperature variations (about 100°C), a constant spectral shift thermal sensitivity may be selected, with the obvious limit being the very reduced temperature span, not appropriate for harsh environments monitoring over 200°C. Recent works have proposed calibration models dependent on the initial wavelength of FBGs at a constant reference temperature [6], which is a first step towards an unified calibration law for FBG transducers.

In this work, we determine the intrinsic thermal sensitivity of the waveguide material by studying the broadband, wavelength comb-like response of a high order FBG (HO-FBG). This approach allows us to determine a generalized and material-dependent law up to 900°C, which can be used later on to perform temperature measurements with FBGs or any OFS technology relying on spectral shift calculations in the same fiber.

2. High order fiber Bragg gratings

As wavelength-multiplexed point transducers, FBGs are most commonly designed to present a unique resonance peak in the spectral window of interrogation. The latter is generally comprised between 1460 nm and 1620 nm (S, C and L telecom bands), but also in the 1260 nm to 1360 nm and 800 nm to 900 nm ranges. In the 1550 nm region, this corresponds to grating pitches ranging between 0.5 μm and 5 μm , generally with a grating order m_{inse} lower than 10 at the chosen wavelength, $\lambda_{B,\text{inse}}$. The distance to nearest orders (i.e. $m_{\text{inse}}-1$ and $m_{\text{inse}}+1$) can be tuned by writing at a higher grating order, that is to say $m_{\text{inse}} \geq 100$ typically. In this configuration, the nearest orders are present in the spectral bandwidth of interrogation, resulting in a wavelength comb-like spectral response (Fig. 1a). The spectral distance between resonances is hence tunable by adjusting the harmonic order at the wavelength of inscription, as presented in Fig. 1b.

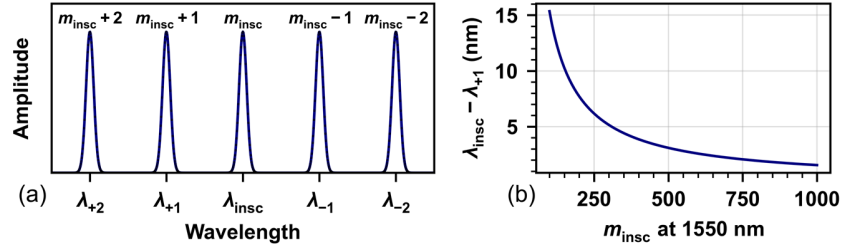


Fig. 1. (a) Reflected amplitude response of resonating structures such as FBGs. (b) Calculated spectral distance to the nearest higher order resonance for a FBG as a function of the harmonic order at an inscription wavelength of 1550 nm in fused silica fiber.

Contrary to typical low-order FBGs, HO-FBGs hence present pitches ranging from a few dozen micrometers to a few millimeters. In order to present sufficient reflectivity, they need to be composed of highly localized and contrasted RIMs. The manufacturing of such photonic components can be performed thanks to the recent advancements in femtosecond laser writing in silica optical fibers. HO-FBGs have for example recently been fabricated using the plane-by-plane method [7]. In this work, we focus on the point-by-point (PbP) technique. Both of these methods allow the manufacturing of high temperature resistant gratings (up to 1000–1100°C) [8]. Thanks to the broadband response of these components, we present in this work a new approach to calibrate OFS for temperature measurements, relying on the determination of a generalized sensitivity law which can be subsequently applied to any spectral shift response of, for example, wavelength-multiplexed FBG transducers.

In that prospect, we manufactured a 8 mm-long HO-FBG presenting a harmonic order $m = 250$ at 1550 nm, which corresponds to a grating pitch of about 134 μm in the SMF-28e fiber (Corning). It was written with the PbP method and using a 515 nm femtosecond laser with a pulse duration of 160 fs, focused in the core of the optical fiber using a microscope objective. The reflection spectra of the HO-FBG at room temperature (RT) is presented in Fig. 2, where 21 resonances are visible. For clarity purposes, some figures in the rest of this paper will only focus on six of these resonances, marked by squares in Fig. 2.

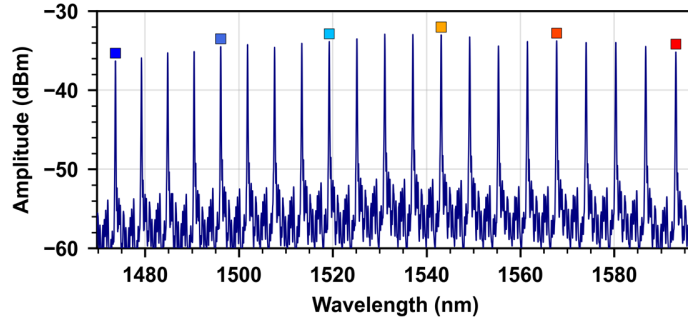


Fig. 2. HO-FBG spectrum (harmonic order $m = 250$ at 1550 nm).

3. Response under temperature: towards a generalized thermal sensitivity law determination

The 8 mm-long HO-FBG was submitted to temperatures steps from RT to 900°C in a calibration furnace. The Bragg wavelength shift (BWS) of six of its resonances (ranging from 1474 nm to 1593 nm at RT) as a function of temperature is presented in Fig. 3. As it is usually observed, the wavelength shift rate ($d\lambda_B/dT$) is dependent on the resonance's wavelength, leading here to a range in BWS values of 1 nm at 900°C between all the resonances. Indeed, it can be expressed as Eq. 2 [4]. We note that giving the typical spectral shift of a resonance from RT to 900°C (about 12 nm in the 1550 nm region), we approximate Eq. 2 by neglecting the effect of the chromatic dispersion.

$$\frac{d\lambda_B(T)}{dT} = \lambda_B(T) \cdot \left(\frac{1}{n_{\text{eff}}(T, \lambda_B)} \frac{dn_{\text{eff}}(T, \lambda_B)}{dT} + \frac{1}{\Lambda(T)} \frac{d\Lambda(T)}{dT} \right) \approx \lambda_B(T) \cdot (\xi(T) + \alpha(T)) = \lambda_B(T) \cdot \beta(T) \quad (2)$$

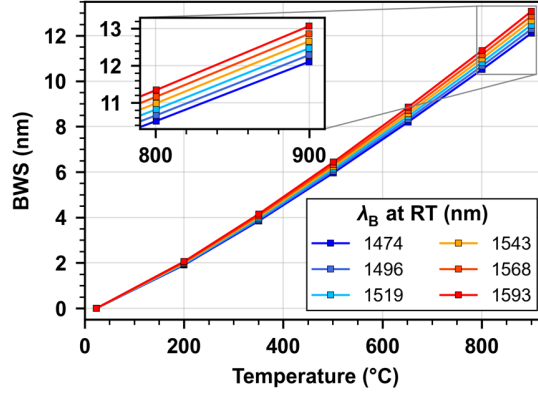


Fig. 3. Bragg wavelength shift response of six HO-FBG resonances from RT to 900°C.

As introduced previously, we identify the two contributions to spectral shift under temperature: the change in effective refractive index through the thermo-optic coefficient (ζ) and the change in grating pitch through the linear thermal expansion coefficient (α). Both these coefficients are temperature-dependent [9,10] and can be summed as $\beta(T)$, the thermal sensitivity of the waveguide material. This implies that the latter is independent on the studied resonance's wavelength, and could be generalized to any spectral shift in the wavelength or frequency range of interest. To rule on this hypothesis, the thermal sensitivity $\beta(T)$ was calculated for 21 resonances along the spectral bandwidth. Considering $\beta(T)$ as a polynomial function, we show that its integral can be determined by integrating Eq. 2 along the temperature range of interest (between T_0 and T_1) as shown in Eq. 3. One can hence determine the polynomial function describing the sensitivity of each HO-FBG resonance peak.

$$\int_{T_0}^{T_1} \left(\frac{1}{\lambda_B} \frac{d\lambda_B}{dT} \right) dT = \ln \left(\frac{\lambda_B(T_1)}{\lambda_B(T_0)} \right) = \int_{T_0}^{T_1} \beta(T) dT \quad (3)$$

Fig. 4a presents the thermal sensitivity values calculated at each temperature step for each of the 21 resonances, as a function their initial wavelength at RT. One can note that no significant dependence on the latter can be observed. Hence, we extract the generalized sensitivity law as a function of temperature as presented in Fig. 4b.

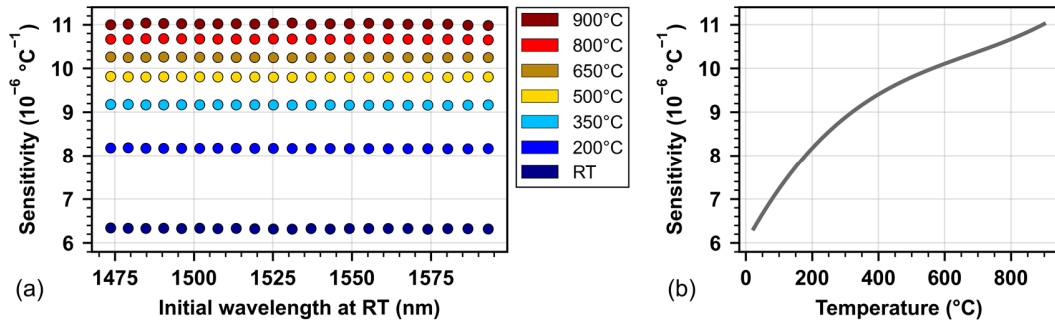


Fig. 4. (a) Thermal sensitivity values calculated at each temperature step for each resonance of the HO-FBG as a function of their initial wavelength at RT. (b) Sensitivity law extracted between RT and 900°C.

The calibration law obtained from the HO-FBG can subsequently be used, knowing a reference point ($T_0, \lambda_B(T_0)$), to determine temperature values from raw wavelength measurements for a given resonance. To quantify measurement uncertainty obtained with this approach, we determined the temperature error ($T_{\text{FBG}} - T_{\text{ref}}$) obtained by applying the sensitivity law to two wavelength-multiplexed second-order FBGs ($m_{\text{invc}} = 2$) submitted to three thermal cycles between RT and 900°C. The reference temperature T_0 was taken at the beginning of the first cycle. These second-order FBGs are representative of deployable transducers for multi-point temperature sensing. The results are presented in Fig. 5, where the residual errors obtained with our model are compared to the uncertainty of the reference

thermocouple (TC) (dark grey envelope) as well as the IEC 60584-1 [11] standard for type N class 1 TCs (light grey envelope). The obtained measurement error for the FBGs is lesser than 2.5°C over the whole temperature range, and compliant with the applicable standard. This shows that the described method allows reaching satisfactory temperature measurement performances, and is applicable to wavelength-multiplexed FBGs for high temperature sensing.

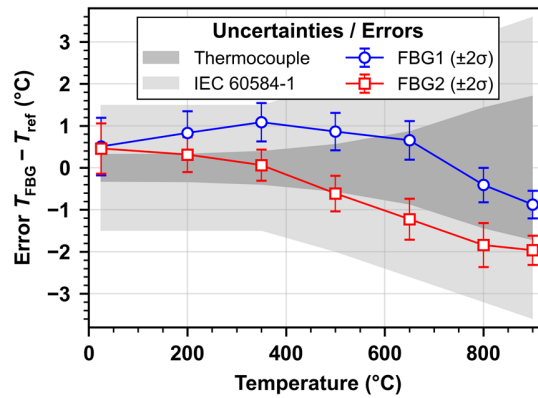


Fig. 5. Temperature errors obtained with second-order FBGs using the proposed sensitivity model on three thermal cycles up to 900°C .

4. Conclusions

This work illustrates one of many applications of high order fiber Bragg gratings recently developed in our group. As presented here, this in-fiber component allows us to easily determine a generalized thermal sensitivity function that is characteristic of the waveguide material, and can successfully be applied to any wavelength-multiplexed FBG deployed in the field of operation in the same waveguide material. This approach suppresses the need for transducer-specific calibration, which from an operational standpoint represents a significant workload reduction, without compromising measurement accuracy.

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