Invited Papers

Detection of thermal gradients through fiber-optic Chirped Fiber Bragg Grating (CFBG): Medical thermal ablation scenario

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ABSTRACT

In this paper, we describe a novel method for spatially distributed temperature measurement with Chirped Fiber Bragg Grating (CFBG) fiber-optic sensors. The proposed method determines the thermal profile in the CFBG region from demodulation of the CFBG optical spectrum. The method is based on an iterative optimization that aims at minimizing the mismatch between the measured CFBG spectrum and the CFBG model based on coupled-mode theory (CMT), perturbed by a temperature gradient. In the demodulation part, we simulate different temperature distribution patterns with Monte-Carlo approach on simulated CFBG spectra. Afterwards, we obtain cost function that minimizes difference between measured and simulated spectra, and results in final temperature profile. Experiments and simulations have been carried out first with a linear gradient, demonstrating a correct operation (error 2.9 °C); then, a setup has been arranged to measure the temperature pattern on a 5-cm long section exposed to medical laser thermal ablation. Overall, the proposed method can operate as a real-time detection technique for thermal gradients over 1.5–5 cm regions, and turns as a key asset for the estimation of thermal gradients at the micro-scale in biomedical applications.

1. Introduction

The detection of thermal gradients at the micro-scale is an emerging challenge in several fields, particularly in biomedical engineering relatively to minimally invasive thermal ablation (TA) and thermotherapies [1, 2]: in TA, typical thermal gradients can exceed 5 °C/mm and 1 °C/s [3], and the amount of ablated tissue is highly dependent upon the temperature achieved in each point of the tissue. In other applications, such as laser angioplasty, almost linear temperature gradients are observed over the millimeter scale [4].

Overall, there is a strong need for a sensing technology capable of resolving temperature patterns and estimate temperature gradients at the sub millimeter scale, with a minimally invasive form factor and biocompatible [5]. Optical fiber sensors are an excellent candidate for this task, as they allow distributed and/or multiplexed sensing [5] on a single optical fiber, and operate with miniature and biocompatible glass optical fibers. Fiber Bragg gratings (FBGs) have been used for multiplexed temperature sensors, in array format, since the 00s [6–8]. The latest FBG sensing units, operated with a white-light setup or a scanning-wavelength laser source, have a straightforward principle of operation based on wavelength-division multiplexing (WDM) [5], which allows separating the contribution of each FBG sensor in the spectral domain. The main limitation of FBG arrays is the poor capability to achieve a dense spatial sensing: depending on the FBG inscription
setup, each FBG has a minimum length of 1–5 mm, and the minimum distance between each FBG (center-to-center) is 2–5 mm [9,5]. Thus, FBGs are not successful in measuring sub-mm thermal gradients.

On the other side, distributed sensors operated with optical frequency domain reflectometry (OFDR) [10] can resolve spatial gradients with resolution of approximately 0.1 mm; the principle of operation is the Fourier analysis of the backscattered light in a standard optical fiber, due to Rayleigh scattering at the micro-scale [11]. In a previous work, Macchi et al. [12] demonstrated the use of an OFDR-based sensor to detect thermal gradients in thermal ablation. OFDR systems, however, suffer from several limitations: they are extremely bulky and expensive (making it hard to convert them to ruggedized portable devices), achieve sub-millimeter sensing only in off-line mode (not in real time), and are sensitive to fiber bending; most importantly, since they operate with weak Rayleigh scattering, they are vulnerable to the reflectivity occurring on the fiber tip, which poses a high barrier towards in vivo application.

Chirped FBGs (CFBGs), particularly in case of a linear chirp, can be a solution to this scenario, as somehow anticipated in [13]. The CFBG acts as a broadband FBG, and its reflection spectrum is dependent on the temperature (or strain) profile experienced along the whole grating length [14,15]. To some extent, the CFBG acts as what we can define as a semi-distributed sensor, lying within multi-point sensors and distributed sensors: they have an active region in which the sensing mechanism takes effect (like FBGs) but the CFBG spectrum has an interpretable dependence on the whole temperature pattern in each part of the active area (like distributed units) [16].

CFBG-based sensors have been used mainly in mechanical engineering for strain and crack detection [17,18], and very recently the fabrication of a CFBG on a plastic fiber was demonstrated by Marques et al. [19]. The first use of CFBG sensors for temperature measurements (linear profile) is described in [20]. However, it uses small bandwidth (3 nm) that limits sensing length and chirp rate equal to \( \omega = 0.77 \text{ nm/} \text{cm} \). The first work in which high bandwidth (> 40 nm) CFBG sensors have been applied to thermal gradient detection, in radio-frequency thermal ablation, has been proposed by Tosi et al. [21]: this work however is limited to the detection of monotonic temperature gradients (i.e. gradients measured between a cold-spot to a hot-spot), while the best proposition to measure temperature in biomedical engineering is to estimate Gaussian or Gaussian-like gradients, which are typically observed in thermal ablation (and particularly laser ablation), as stated in [22].

In this work, we introduce a new methodology for the detection of thermal gradients within 1.5 cm and 5 cm length [23], having linear or Gaussian-like shaped as typically experienced in thermal ablation and thermo-therapies [24]. A white-light setup as in [21] is used to interrogate the CFBG, using the same setup of standard FBGs; the reflection spectrum of the CFBG is subsequently analyzed through an optimization algorithm, that estimates the temperature gradient from the CFBG spectrum readout. CFBG demodulation is founded on a model based on coupled-mode theory (CMT) proposed in [14]: the measured spectrum is compared to the CMT-based CFBG model, with an applied temperature perturbation, which is modified until the model and the measured spectra provide the best match. The optimization algorithm is based on an a priori assumed temperature pattern, and can take into account CFBG spectral ripples, spectral equalizations, and other features that increase the performance. The method is successfully tested on both simulations and on experiments carried out with a commercially available CFBG. Overall, the proposed method is an excellent tool to analyze the shape and amplitude of thermal gradients occurring during minimally invasive thermo-therapies, opening a new avenue for the detection of thermal patterns at the micro-scale [23, 24].

The rest of the paper is organized as follows. Section II presents the model of the CFBG sensor obtained through discretized CMT. The decoding algorithm is illustrated in Section III. Section IV validates the proposed method through simulation of CFBG sensor exposed to thermal patterns. Section V demonstrates experiments and results, applying both a linear gradient in a thermally calibrated setup, and a Gaussian-shaped gradient obtained in a fiber laser ablation setup. Finally, Section VI draws conclusions.

2. CFBG model

The principle of operation of the CFBG model, which is used to simulate the sensor behavior but also to demodulate the CFBG spectrum, is to discretize the chirped grating having length \( L \) into \( M \) uniform gratings, each having length \( L_g = L/M \), each of the \( M \) discretized grating is treated as a uniform standard grating, with its Bragg wavelength determined by the chirp coefficient [24], and simulated using the CMT [14]. The underlying assumption is that the white-light setup used to detect the CFBG spectrum is incoherent, and the coherence length of the optical broadband source is much shorter than \( L_g \); this occurs in experiments presented in Section V of this paper, for which the optical source has coherence length \( 4 \text{ nm} \), while \( M \) is chosen such that \( L_g < 0.03 \text{ mm} \).

The principle of operation of the CFBG model is shown in Fig. 1. All variables used for CFBG modelling and spectrum decoding algorithm are described in Table 1. Based on the CFBG discretization model, each uniform FBG having length \( L_g \) has a wavelength-selective behavior, when one wavelength is reflected and other wavelengths are transmitted through the grating. The peak of reflected wavelength, the Bragg wavelength \( \lambda_{B,0} \), depends on the period of the grating \( \Lambda \) and the effective refractive index \( n_{eff} \) [14]:

\[
\lambda_{B,0} = 2n_{eff}\Lambda
\]  

(1)

where the subscript \( i = 1, \ldots, M \) denotes the \( i \)-th grating of the discretization. This reference Bragg wavelength \( \lambda_{B,0} \) is found for the reference temperature. As from [24], the peak wavelength depends from applied temperature and can be found from (2):

![Fig. 1. Principle of CFBG modelling. (a) CFBG: grating period is increasing with distance. (b) CFBG model using \( M \) number of uniform FBGs, located at distance \( i \cdot L_g \) and exposed to temperature \( \Delta T_i \) and related Bragg wavelengths \( \lambda_{B,i} \), to form a cascade of filters. (c) Spectrum consisting from \( M \) number of uniform FBG spectra.](image-url)
where we assume a strain-free configuration. In this work, we use fiber material that has the value of thermal sensitivity coefficient $\xi$ equal to 10.2 pm/°C. According to Erdogan’s CMT [14], the reflected spectrum for all wavelengths for each discretized uniform grating can be determined using the following expression:

$$\lambda_{fl}(\lambda) = \lambda_{g,0} + \xi \cdot \Delta T_i$$

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$$\lambda_{fl}(\lambda) = \lambda_{g,0} + \xi \cdot \Delta T_i$$

where $\Delta T_i$ is the temperature change at the $i$-th position of the CFBG. To this model, we apply a spatial temperature variation which is able to estimate a temperature distribution within the sensing region of the grating.

The principle of operation of the demodulation algorithm is the following: together with the CFBG measured spectrum, which is acquired following: with the white-light interrogator, and chosen the appropriate discretization step, it is possible to obtain the correct $kLg$ value to be used in the simulations.

3. CFBG demodulation

The approach makes use of the CFBG as a semi-distributed sensor, which is able to estimate a temperature distribution within the sensing region of the grating.

This method can be used for different types of temperature profiles. We focus on polynomial gradients (linear, or quadratic [27]) and Gaussian, or super-Gaussian gradients typical of thermal ablation [24]. The principle of operation of the demodulation algorithm is the following: together with the CFBG measured spectrum, which is acquired in real time by the interrogation system, we generate a CMT-based model of the CFBG based on Eq. (1)–(5) such that the model matches the real CFBG. To this model, we apply a spatial temperature variation $\Delta T(z)$, which is exerted on every discrete FBG according to Eq. (2), until the spectrum of the measured CFBG and the simulated CFBG overlap. Fig. 3 provides main steps of decoding algorithm. In the following, this algorithm is outlined.

3.1. Initialization $\lambda_{g,0,M}$

The initialization part is performed with no $\Delta T$ gradient along the...
CFBG, i.e. in reference condition. The goal is to obtain the model of the CFBG as in Eq. (1)–(5) based on CMT, and therefore to populate all the grating parameters outlined in Table 1. From the manufacturer, we can obtain the grating length (L) as well as the optical parameters (Δn_eff, n_eff, ξ, L, λ_{B,0,1}). In detail, the initial and final wavelengths, i.e. λ_{B,0,1} and are obtained through spectral observation to obtain an initial guess, and running an optimization based on the CMT theory until there is the best match between the CFBG spectra on the left and right side. The thermooptic coefficient, on the other hand, is set to 10.2 pm/°C as the sensor is calibrated as in [25].

The discretization factor $M$ is chosen according to the selection of the reflectivity shape. In other words, large value of the discretization factor leads to rounding of the reflectivity figure, which leads to the difference from the actual reflectivity spectrum.

An essential part of the algorithm is an equalizer $H(λ)$, which is applied to the simulated CFBG in order to equalize its spectrum. This is necessary as the CMT returns an absolute value for the reflectivity of the CFBG, while the measured CFBG has an amplitude that depends on the gain and exposure time of the detector, and is quantized. In addition, the CFBG spectrum may have spectral ripples which are not accounted in the CMT-model. Thus, after the CFBG model is generated and the spectrum is simulated, we multiply the CFBG spectrum by the equalizer.

The grating strength $kL_g$ determines the overall CFBG reflectivity, which needs to match the measured peak reflectivity. Fig. 2 serves as a calibration for the CMT-based CFBG model based on the discrete set of gratings. Calibration is done only with the first spectrum (at the beginning of the measurement process) to define $M$ and $kL_g$.

Some values of our CFBG model parameters (number of modeled FBGs $M$, and their grating strength $kL_g$) can be obtained from developed code, illustrated in Fig. 2, that defines relation between $M$, $kL_g$ and maximum reflectivity of simulated CFBG. Thus, maximum value of spectrum measured by spectrometer provides possible $M$ and $kL$ values for our CFBG model. Then, as it was mentioned about the optimization of wavelength range, we modulate CFBG spectrum using Eq. (1)–(4) and CFBG parameters with approximate wavelength range, defined from first spectrum measurement. After, modulated CFBG wavelength range margins are optimized by iteration method to minimize difference between measured and modulated CFBG spectra.

3.2. Reconstruction of temperature profile

The next part of the decoding involves the reconstruction of temperature pattern from measured reflectivity spectrum. The process is performed under the assumption that the $ΔT(z)$ function has a known pattern. In this work, we focus on two types of hypothesis. In the first case, we assume that the gradient is a $P$-th order polynomial, i.e.

$$ΔT(z) = \sum_{n=0}^{P} a_n z^n$$

where $a_n$ are main distribution parameters: central position, variance and amplitude respectively. The Gaussian gradient is a very good render of thermal gradients introduced in thermal ablation. This hypothesis is shown in Fig. 4: the temperature distribution for laser ablation, simulated as in [22] in Comsol Multiphysics at exposure time of 10 s and 300 s is compared with a Gaussian function as in Eq. (8). It is possible to see that there is a sufficiently good agreement between the theoretical LA pattern and a Gaussian fit to justify the assumption.

The process starts with assumption of the range of probable values of the fitting function $ΔT(z)$: amplitude, central position and variance for the Gaussian function, or the $a_n$ coefficients for the polynomial function. For each parameter set, we generate the $ΔT(z)$ corresponding function; then, we use this temperature pattern to perturb each of the $M$ discrete gratings composing the cascade of filters, and obtain the CFBG simulated spectrum as in Eq. (6). Then, we obtain the final calculated spectrum $R_{meas}$ by multiplying the simulated spectrum for the equalization function obtained in the initialization, in order to match the spectral shape with the measured spectrum $R_{meas}$.

We use a Monte-Carlo method [29] to create all possible combinations of parameter values in given range. Each produced combination provides distinct temperature profile and modeled CFBG spectrum, that compared with measured spectrum. As a cost function, we use the root mean square error (RMS).

![Diagram of the decoding algorithm](image-url)
mean square error between the simulated spectrum, processed through filtering, and the measured spectrum until the best temperature pattern that minimizes the cost function (CF) is found with Eq. (9).

\[
CF = \sum_{\lambda = \lambda_1}^{\lambda_M} \left( \frac{1}{M} (R(\lambda)_{\text{calc}} - R(\lambda)_{\text{meas}})^2 \right)^{1/2}
\]

(9)

where \( R(\lambda)_{\text{calc}} \) and \( R(\lambda)_{\text{meas}} \) are simulated and measured reflectivity for corresponding \( \lambda \) wavelength, and \( M \) is the total amount of gratings. At the end of demodulation, the decoding algorithm implements obtained variables to construct final temperature profile from the estimated parameter set. The estimated parameters are also used as the initial guess for the next measurement, speeding up the convergence of the algorithm.

4. Simulation

The algorithm described in this section has been implemented in MATLAB and LabVIEW. A proof of principle to validate the algorithm has been performed, to verify whether the CFBG demodulation can operate in ideal conditions.

Initially, a CFBG sensor with 50 mm length, and 1520–1580 wavelength bandwidth has been modeled with Eq. (1)–(5). Used parameters of the model: \( M = 300 \), \( k_L = 0.2 \), \( \delta n_{\text{eff}} = 10^{-5} \), \( n_{\text{eff}} = 1.5 \); choice of these parameters is done using Fig. 2 to fit the experimental reflectivity with \( \text{Peak } R_{\text{CFBG}} \approx 0.75 \).

Fig. 5 demonstrates effect of temperature profile, shown in Fig. 6 (blue), on spectrum in our CFBG model and compares it with reference spectrum without applied temperature profile. Fig. 5b illustrates zoom on the inner region, that clearly shows reflection change due to Gaussian temperature distribution centered at the middle of the sensor.

Important aspect of proposed method is noise, that can affect accuracy of temperature reconstruction. Fig. 6 shows a set of the theoretical results obtained: when we simulate Gaussian temperature profile, similar to simulated in Fig. 5, and model this temperature profile effect on CFBG spectrum with additive white Gaussian noise (AWGN) with SNR = 30 dB, consequent demodulation of this spectrum provides reconstructed temperature with resulted mean square error equal to 1.35 °C.

Moreover, effect of theoretical AWGN noise added to modulated CFBG spectrum on proposed method is illustrated in Fig. 7. It can be seen, that accuracy does not decrease significantly comparing with low SNR value of spectrum measurements, maximum mean square error is equal to 1.9 °C. CFBG for SNR ≥ 44 dB provides mean square error less.
than 1 °C. Overall, noise has not significant effect on the proposed method.

5. Experiments

5.1. Setup

The software for CFBG temperature measurement, theoretically proved in previous section, has been tested on a batch of measurements performed during the experimental stages with linear and Gaussian temperature profiles. Figs. 8 and 9 show the schematic and the photograph, respectively, of developed system: a superluminescent LED (SLED, Exalos EKS, 1520–1600 nm, 10 mW), mounted on its control board that stabilizes the driving current and operative temperature, delivers the light to the CFBG sensor, through a 50/50 coupler. The same coupler routes light reflected from CFBG to a spectrometer (Ibsen Photonics, I-MON-512-USB, 1520–1600 nm, 512 pixels), connected to a PC for detection and spectrum decoding to obtain temperature profile. The whole system has been packaged into a portable format. A LabVIEW software has been developed to perform data acquisition, processing, and storage.

We measured CFBG spectrum once in reference conditions (before any variation is applied) and in each instant when a temperature variation is applied.

5.2. Linear temperature profile

The developed software and hardware have been tested on a measurement sample with the reference of Peltier cell, that used to obtain a linear temperature pattern. Fig. 10 shows the setup, which has been implemented by heating or cooling the two sides of a CFBG with a Peltier cell (left side, corresponding to the shorter wavelengths) and an electrical resistor (right side, corresponding to the longer wavelengths); two LM35 temperature chip sensors (accuracy 0.5 °C for 25 °C) have been used as reference to compare the results. In this setup, by controlling the Peltier cell and the resistor we can generate quasi linear thermal gradients having arbitrary slope and have a reference on the two sides of the grating. In this measurement, we used a CFBG with 15 mm length and 40 nm bandwidth.

We show in Fig. 11 the result of the decoding algorithm, comparing the results obtained on the grating side with the CFBG decoding method and by the LM35 reference sensors. It is possible to see that the measurement provides a good agreement with a maximum error of 2.9 °C. In the setup, we performed a cycle of temperature maintenance, followed by a cooling (2–4 min) and heating (4–8 min), a further cooling, and a second heating stage in which the polarity of the gradient has been reversed (after 11 min resistor starts 2-min heating). The CFBG outcome provides a good agreement with the measured data.

The discrepancy between the measured and reference data can be explained by several factors: at first, the LM35 sensor has a relatively large size compared to the size of each discrete grating; not controlled heat leakage due to natural convection since the sensor is exposed to free air and related not perfectly-linear temperature gradient; also, there...
temperature profile shown in Fig. 13, where temperature amplitude is increased in one point and after variance is increasing with heat propagation along sensor; when the laser is turned off, the heat keeps expanding, that explains peak decrease and variance increase after some time. It is clearly seen in Fig. 14, that shows temperature profile for specific spectrum measurements and distances along sensor. Fig. 14a illustrates increase of variance with heat propagation with time, while Fig. 14b shows that the most abrupt temperature changes can be observed near ablation point (40 mm along sensor) and gradual temperature changes at edges of ablation.

As a result, measured temperature profile effectively shows area with temperature less than threshold value needed to guarantee necrosis of tumor cells.

6. Conclusion

Effective real-time, in vivo temperature sensing can significantly increase efficacy of thermo-therapies in biomedical applications; the measurement of thermal gradients on a millimeter-scale spatial resolution with minimally invasive sensors is a key asset. We developed a methodology for the measurement of linear and Gaussian-shaped thermal patterns, based on optical Chirped Fiber Bragg Grating (CFBG) sensor that achieves sub-mm resolution for distributed temperature sensing and maintains the advantageous properties of fiber-optic sensors. The developed methodology approximates the CFBG as a set of standard FBGs, each perturbed by a temperature change; an optimization routine allows reconstructing the thermal gradient. The system has been validated first on a simulation benchmark, whereas the measured CFBG spectrum is replaced by a model counterpart. Then, two experimental setups have been prepared to mimic linear gradients over 15 mm length with a reference system, and a laser ablation induced gradient recorded with a 15 mm CFBG. Experimental results show a good match with the reference system and with the theory (for LA setup), demonstrating that this methodology is a promising asset for thermal sensing in biomedical applications.

References


