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Invited Papers

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

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A B S T R A C T

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 a 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 thermo-therapies [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

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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 $\psi = 0.77$ nm/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.

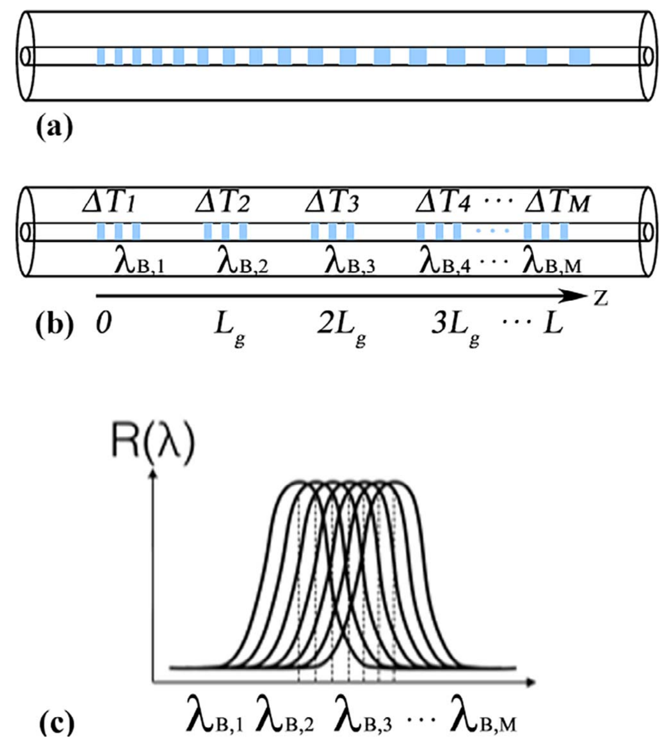

Fig. 1. Principle of CFBG modelling. (a) CFBG: grating period is increasing with distance. (b) CFBG model using M number of uniform FBGs, located at distance $(i-1)\cdot L_g$ and exposed to temperature ΔT_i and related Bragg wavelengths $\lambda_{B,i}$ to form a cascade of filters. (c) Spectrum consisting from M number of uniform FBG spectra.

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 grating, 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 coherency 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 coherency length ≈ 4 nm, while M is chosen such that $L_g \geq 0.03$ 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 $\lambda_{B,i,0}$, depends on the period of the grating Λ and the effective refractive index n_{eff} [14]:

$$\lambda_{B,0} = 2n_{eff}\cdot\Lambda \qquad (1)$$

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