Measurement 124 (2018) 15–19

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Issues and characterization of fiber Bragg grating based temperature sensors in the presence of thermal gradients

Riccardo Gassino, Jennifer Pogliano, Guido Perrone, Alberto Vallan*

Department of Electronics and Telecommunications, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Torino 10129, Italy

ARTICLE INFO

Keywords:
Quasi-distributed temperature measurement
Fiber optic sensors
FBG
Tumor laser ablation monitoring

ABSTRACT

This paper reviews the main issues arising from the use of fiber Bragg gratings as temperature sensors in the presence of significant thermal gradients. These conditions occur for example during laser thermal ablation of tumors. In particular, the paper focuses on the identification of the grating position along the fiber, which represents one of the main uncertainty contributions. A novel experimental setup for the grating center localization is proposed and the corresponding characterization procedure has been devised. The setup is built in such a way as to generate reproducible linear temperature distributions. Tests carried out using a sensor prototype have shown that the grating position can be found with a standard uncertainty of 0.3 mm.

1. Introduction

Fiber Bragg Gratings (FBG) inscribed in silica glass fibers are widely employed as temperature sensors both in industrial and biomedical applications because they combine the advantages typical of fiber optic sensors, with robust, technologically mature, and quite easy to use interrogation systems. In particular, FBGs are the elective temperature sensor in laser-based processes since in these cases common metallic sensors (e.g., thermocouples or thermistors) cannot be used as they partially absorb the laser light and thus perturb the temperature distribution. However, since commercially available FBGs are usually a few centimeters long, they only provide reliable readings when the temperature distribution is uniform along their length. An example of an application that makes use of FBG-based temperature sensors because it involves laser radiation, but is very critical because of the large temperature gradients, is temperature monitoring during Laser Ablation (LA) of tumors. This cancer treatment, which is an alternative to surgical resection, employs laser radiation to locally increase the tumor mass temperature above cytotoxic levels, causing cell death [1]. For deep-laying organs, such as in the cases of liver or pancreas tumors, fiber optic applicators are used to deliver the laser radiation into the target area. Despite these kind of probes have already been employed in the medical field (for example in the treatment of cardiac diseases [2] and in cancer therapy [3]), their diffusion is still limited; and one reason is the lack of suitable sensors for real-time monitoring of the tissue temperature during the medical procedure [4]. Indeed, the effectiveness of LA requires a suitable combination of temperature and exposition time, being the two quantities inversely related. Usually, ablation treatments last from 2 min to 10 min and require reaching temperatures in the 60–100 °C range [5]. In in vivo applications, however, it is practically impossible to estimate a priori the treatment duration necessary to obtain the targeted temperature from the laser power because of the large tissue variability and the blood perfusion. A solution has been to bundle [6] or inscribe into the laser delivery probe [7] one or more FBGs to measure the actual temperature increase. On the other hand, the use of FBGs poses some critical issues from the metrological point of view. For instance, the calibration of FBG sensors is routinely performed with respect to reference temperature sensors using climatic chambers or other controlled environments [8–10] in which the temperature is maintained constant at predefined values. Unfortunately, this is far from the operative conditions in LA, where gradients as large as 10 °C/cm occur due to low thermal conductivity of the organs. Therefore, as common FBGs present a length that spans from a millimeter to a couple of centimeters, the presence of a non-uniform temperature distribution can introduce unacceptable errors. Moreover, bare FBGs, which are often used to minimize the invasive impact [11] and the thermal inertia, can be affected by influence quantities, such as the bending introduced by patient breathing.

This paper investigates the most relevant aspects related to the qualification of FBGs as temperature sensors in non-uniform conditions, targeting in particular LA of liver tumors. Section 2 briefly recalls the FBG working principle and then introduces the main uncertainty contributions. Particular attention is given to the knowledge of the sensor position, which has not been considered so far in literature, but has to be known in order to significantly reduce temperature measurement errors. The solution proposed in the paper takes advantage of an

---

* Corresponding author.
E-mail address: alberto.vallan@polito.it (A. Vallan).

https://doi.org/10.1016/j.measurement.2018.03.049
Received 30 January 2018; Received in revised form 15 March 2018; Accepted 20 March 2018
Available online 28 March 2018
0263-2241/ © 2018 Elsevier Ltd. All rights reserved.

experimental setup described in Section 3, and able to generate reproducible temperature gradients. Finally, Section 4 presents the experimental characterization results obtained with the help of the previously mentioned setup, whereas Section 5 draws the conclusions.

2. FBG working principle and measurement related issues

2.1. Working principle

FBG are manufactured by inducing a periodical modulation of the core refractive index of a single mode optical fiber. This results in the reflection of a specific group of wavelengths that depends on the grating period and on the modal effective index. Since these two quantities are related to the temperature and to the axial strain applied to the grating, the spectrum of the reflected light presents a narrow peak having a central position λ_B that can be computed with the following linear model:

$$\Delta\lambda_B = k_\epsilon \cdot \epsilon + k_T \cdot \Delta T \tag{1}$$

where the sensitivity coefficients relating the wavelength shift respectively to the strain and to the temperature are approximately k_ϵ= 1 pm/ϵ and k_T 10 pm/°C for gratings having λ_B around 1500 nm. It is evident that the FBG acts as a temperature sensor provided that the strain is known or is kept constant. The temperature evolution can then be retrieved by tracking the Bragg wavelength using different standard interrogation techniques, such as that based on a broad-band source (typically a super-luminescent LED, SLED) and a spectrometer or on a tunable laser and a power meter.

The following sections focus on the most significant issues arising when using the FBGs as temperature sensors, especially in the presence of non-negligible thermal gradients.

2.2. Strain cross-sensitivity

The cross-sensitivity of FBGs to both strain and temperature, clearly evident in Eq. (1), raises a series of problems in the practical use of the sensor, for example during a LA procedure. In this case the optical fiber containing the grating is inserted into the patient percutaneously through a suitable needle and this may induce axial strain and bending, which are then read by the FBG as temperature variations. Moreover, even if a perfect insertion is performed, the motion due to the patient breathing introduces artifacts. This problem can be mitigated by designing a suitable embodiment that encapsulates the FBG and prevents unwanted strain or bending from affecting the fiber. For LA applications the FBG sensors can be either inscribed in standard telecom single mode fibers (10/125 μm) bundled with the laser delivery fiber or inscribed in the same laser delivery fiber [7]. In both scenarios, to reduce the sensitivity to bending, the fiber portion containing the FBG (usually positioned towards the probe end) can be encapsulated in a glass capillary (Fig. 1).

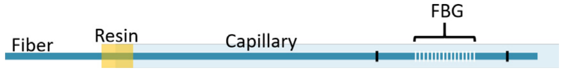

Fig. 1. A schematic representation of the fiber with the FBG, inserted in a glass capillary and fixed on one side with epoxy resin.

With this solution, the capillary withstands the external stresses, although it affects the thermal properties of the probe since both the thermal capacity and the sensor time constant increase. Extensive tests in view of application to LA were previously carried out both with bare FBGs and with FBGs protected by different types of glass capillaries [12]. The results had shown that, at least for the considered capillaries, the time constant remains below about 0.2 s, a value that can be considered negligible for the intended application. However, the capillary not only affects the sensor dynamic response, but it can also absorb part of the laser radiation and this modifies the temperature distribution in the surrounding medium. In applications like LA, where the temperature presents a large gradient due to the high thermal resistance of the tissue, the sensor thermal properties (i.e., its thermal resistance and capacity) can be significantly different from those of the surrounding material and thus the presence of the capillary may significantly affect the temperature measurement. Of course, the closer is the capillary to the delivery fiber, the more evident is the effect of the absorption; therefore particular attention should be paid to probes that combine the laser delivery and the sensing fiber inside the same capillary. This introduces a systematic error than is almost impossible to model if the surrounding material properties are not well known. Again, LA represents a critical case since the tissue properties are subjected to a large variability, even within the same organ. A possible solution is to minimize the error by reducing the probe dimensions and by using materials having tissue-matching thermal properties. However, the actual error can only be assessed though an experimental approach. Therefore, to quantify this perturbation tests were carried out by placing the laser in front of the encapsulated sensor and recording the temperature increase in free space, which represents the worst case condition for the almost null thermal conductivity. The results showed a temperature increase up to 0.5 °C/W for capillaries with external diameter of 1 mm and even higher values for thicker capillaries.

2.3. FBG length

The linear relation between Bragg wavelength and temperature in Eq. (1) is found considering a constant temperature distribution along the grating. This does not represent a limitation in applications in which thermal gradients are small (for example in structural health monitoring), but introduces large errors when a significant thermal gradient is present along the grating axis, like in LA: as commercial sensors can be as long as 2 cm, the sensor surface is exposed to a temperature difference that can be as large as 20 °C. FBG response in the presence of non-uniform conditions was addressed in a theoretical way for strain measurements [13] and the results showed a dependency of the Bragg wavelength with the gradient shape. This means that the sensor cannot be used to successfully recover the temperature value if the thermal distribution is unknown. Nevertheless, if the temperature distribution is linear, it is possible to demonstrate that the Bragg wavelength is proportional to the grating average temperature through the same sensitivity constant found for a uniform temperature distribution (Eq. (1)). Short FBGs can partially solve this issue; however, they are not off-the-shelf products and present a large spectral response that could prevent an accurate estimation of the Bragg wavelength.

2.4. FBG position

The accurate knowledge of the sensor position with respect to the region whose temperature is under measurement is of great importance when large gradients are present. For commercial FBGs this problem is particularly significant since their location along the fiber axis is provided with an error of the order of a few millimeters, and this may introduce unacceptable temperature errors even for moderate gradients.

The error due to the sensor position is experimentally addressed in the next sections of the paper. The proposed approach takes advantage of the grating sensitivity to the average temperature in the presence of linear gradients. Consequently, when the grating is exposed to a linear temperature distribution, it provides the value of the average temperature, corresponding to the temperature at the center of the grating. In this way it is thus possible to relate the grating measurement to the grating position.

3. Setup for linear temperature distributions

The impact of non uniform temperature distributions on the actual

Download English Version:

https://daneshyari.com/en/article/7120679

Download Persian Version:

https://daneshyari.com/article/7120679

Daneshyari.com