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***Abstract*—Fiber optics is the most promising technology for distributed temperature sensing. The paper investigates the characterization of probes based on single or multiplexed fiber Bragg gratings, specifically conceived to evaluate the temperature distribution in applications that imply large temperature gradients, such as in laser induced thermal treatments of solid tumors. A setup for the characterization of fiber Bragg grating sensors in non uniform temperature conditions is described and examples of applications in case that mimic actual working conditions are reported.**

## I. Introduction

Accurate monitoring of the temperature is typically one of the most important requirements to ensure the quality of processes in every field, although the characteristics of the sensors are strongly dependent on the specific application. For instance, in the large majority of cases, thin metallic sensors, such as thermocouples or Pt100, are employed for their ease of use, low cost, simplified interrogation and adequate metrological performance. In some critical applications, however, metallic sensors cannot be used: most notable examples are for uses in corrosive or explosive environments or in many medical applications. In these case optical technologies - in particular fiber optics, whose remarkable advancement in the last decades has been mainly driven by the development of components for telecommunications - provide an excellent alternative for sensing temperatures: indeed, fiber optic sensors (FOSs) are known not only to outperform their metallic counterparts in terms of invasive impact and sensitivity, but also for their intrinsic safety, immunity to electromagnetic interference and possibility operate without degradation in harsh environments [1], [2]. Moreover, some of the working principles exploited in FOSs simplify the realization of so-called distributed or quasi-distributed sensors, which are measurement systems that allow evaluating the entire profile of the quantity of interest (i.e., temperature in the considered case, but also strain) along a certain length [3], [4] [5]. These distributed sensors provide a key advantage in applications where large temperature gradients are involved, like in tumor laser ablation, because in these cases localized sensors can introduce non negligible errors in the reading due to their finite dimension [5].

The most promising techniques for distributed temperature sensing systems are Optical Time Domain Reflectometry (OTDR), Optical Frequency Domain Reflectometry (OFDR) [6], fluorescence thermometry [7] and multiplexed or chirped Fiber Bragg Grating (FBG) sensors [5]. Targeting the application in monitoring the temperature during Laser Induced ThermoTherapy (LITT), also known as Laser Ablation (LA), especially for application to the treatment of liver tumors, OTDR-based instruments cannot be used due to their spatial resolution, which is typically about $40\,\mathrm{cm}$, much larger than the extension of the area under treatment (usually few centimeters). As for OFDR-based instruments, they have very low spatial resolution (about $1\,\mathrm{mm}$), good temperature accuracy ($0.1\,°\mathrm{C}$) and fast acquisition rate (up to $100\,\mathrm{Hz}$), but they are quite expensive and require additional reference fibers [8]. Sensors based on the fluorescence of rare earth dopants are very promising but surface monitoring only [9], [10], [11], and, of course, this makes them unsuitable for application to the ablation of deep-laying organs, such as liver. FBGs currently represent the most cost-effective and well-mastered solution to measure the temperature during tumor treatments based on thermo-therapies: using FBGs, a distributed or quasi-distributed temperature measurement system can be developed using chirped FBGs [5] or multiplexed FBGs.

This paper focuses on the study of the latter approach and in particular on the characterization of a probe that is specifically conceived to evaluate the temperature distribution profile during LA treatment of liver tumors. This represents a particularly critical application for distributed temperature measurement systems the high temperature gradient, about $10\,°\mathrm{C/cm}$. LA is similar to other minimally invasive alternatives to surgical resection, such as Radio-Frequency Ablation (RFA) or MicroWave Ablation (MWA), but exploits the absorption of laser light from tissue to locally increase the temperature above cytotoxic levels ($60\,°\mathrm{C}$). This approach has become one of the elective treatments for small (less than $2\,\mathrm{cm}$) solid tumors [12]; however, despite its increasing adoption, the outcomes could be further improved with the adoption of proper real-time temperature measurement systems, given the difficulty in predicting a priori the size of the area where cytotoxic temperature levels are reached without causing carbonizations [13]. The developed probe could help overcoming these limitations. In order to understand its behavior during LITT in known conditions, but reproducing the same temperature distributions and gradients, a specific setup has been developed, as described in the following.

## II. FBG Principles

FBGs are a fabricated by inducing a periodic refractive index perturbation in the core of a single mode optical fiber. This produces a strong coupling between forward and backward propagating waves around a specific wavelength, $\lambda_{\mathrm{B}}$, known as the Bragg wavelength, given by:

$$\lambda_{\mathrm{B}} = 2n_{\mathrm{eff}}\Lambda \tag{1}$$

where $n_{\mathrm{eff}}$ is the modal effective refractive index and $\Lambda$ the period of the grating. If a broadband light is launched into a FBG, the grating assisted coupling between forward and backward propagating waves produces a peak in the reflected spectrum centered at $\lambda_{\mathrm{B}}$, which shifts as the temperature and strain change according to:

$$\Delta\lambda_{\mathrm{B}} = K_{\mathrm{T}}\Delta T + K_{\varepsilon}\varepsilon \tag{2}$$

where $K_{\mathrm{T}}$ is the sensitivity to the temperature and $K_{\varepsilon}$ to the strain applied to the fiber. Following the approach outlined in Ref. [14], the response of a uniform grating can be modeled as:

$$R(\lambda) = \frac{\sinh^2\left(L\sqrt{k^2-\sigma^2}\right)}{\cosh^2\left(L\sqrt{k^2-\sigma^2}\right) - \frac{\sigma^2}{k^2}} \tag{3}$$

where $R(\lambda)$ is the reflectivity of the grating computed at the wavelength $\lambda$, $L$ is the grating length, and $kL$ is a parameter defining the grating strength. The parameter $\sigma$ can be expressed as:

$$\sigma = \frac{\pi}{\lambda}\delta n_{\mathrm{eff}} + 2\pi n_{\mathrm{eff}}\left(\frac{1}{\lambda} - \frac{1}{\lambda_{\mathrm{B}}}\right) \tag{4}$$

where $\lambda_{\mathrm{B}}$ is related to the variation of the temperature $\Delta T$ as:

$$\lambda_{\mathrm{B}} = \lambda_{\mathrm{B0}} + \xi\Delta T \tag{5}$$

These relations allow computing the behavior also in the case of temperature gradients, as shown in Fig. 1, which compares the grating sensor response to a uniform temperature of $0\,^{\circ}\mathrm{C}$ (red line) and $10\,^{\circ}\mathrm{C}$ (blue line) with that in which there is a linear gradient ranging from $0\,^{\circ}\mathrm{C}$ to $10\,^{\circ}\mathrm{C}$ (green line).

The typical Bragg wavelength shift with temperature for gratings inscribed in single mode silica fibers is about $10\,\mathrm{pm}/^{\circ}\mathrm{C}$. It should be pointed out that, strictly speaking, this relation can be used only when the whole grating is subjected to the same temperature; as evident from Fig. 1, in case of temperature gradients this simple relation provides a rough underestimation of the actual temperature along the grating length.This is particularly limiting in LITT since large temperature gradients due to the localized absorption of the laser beam or the presence of blood vessels could originate local underestimations, with subsequent risk of unpredicted carbonizations [15], [16].

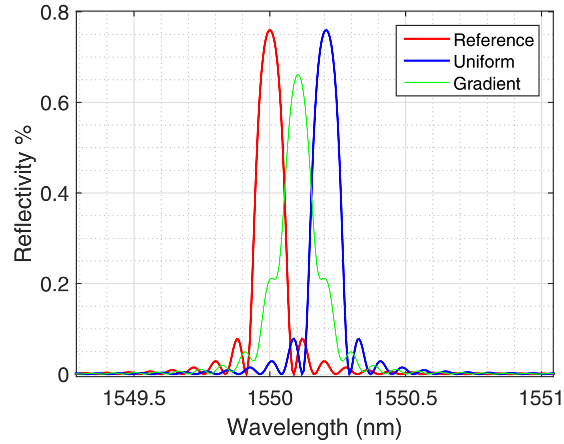


Fig. 1. Shift of the FBG response in presence of a uniform or linear gradient temperature with respect to the condition taken as reference.

## III. Experimental setup

FBGs metrological characterization is typically performed by means of climatic chambers or thermostatic baths able to set different temperature values with the required accuracy. As already pointed out, these approaches allow the accurate characterization of sensors to be employed in situations where the temperature can be considered uniform along the sensor, so thermal gradients are negligible. However, the application described in this paper concerns the monitoring of the surrounding area close to the heat generation source and thus the effects of temperature gradients cannot be neglected. Owing to the lack of characterization setups devised for this particular application, the authors have developed a system able to produce a know thermal gradient along an aluminum bar. The setup has been employed the validate the grating model of Eqn. 3 for non uniform temperature profiles along the grating length. The setup here described is able to produce linear temperature gradients but a similar extended version to produce parabolic or more complex profiles is currently being arranged.

### A. Development

The setup has been designed to characterize FBG sensors having a length of up to $2\,\mathrm{cm}$ that are supposed to be employed when linear temperature gradients are present. Starting from the Fourier equation describing the heat transmission in stationary condition, for mono-dimensional cases the temperature distribution satisfies:

$$\frac{\delta^2 T}{\delta x^2} = 0 \tag{6}$$

where it is easy to obtain a solution for a bar having length $L$ and delimited by two temperatures $\mathrm{T}_1$ and $\mathrm{T}_2$:

$$T = T_1 - \frac{T_1 - T_2}{L}x \tag{7}$$

Any combination of lengths and temperatures satisfying Eqn. 7 would generate the desired temperature gradient;

however, to minimize the power consumption and concentrate the temperature variation along the grating position, a bar with reduced width in the central region has been realized, as depicted in Fig. 2 where the bar shape is reported along with the thermal simulation obtained with a FEM model.

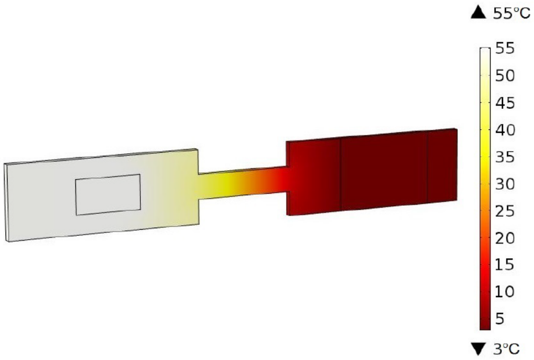


Fig. 2. FEM simulation of the temperature gradient on an aluminum bar with reduced-width in correspondence of the grating position.

### B. Characterization

After having confirmed through FEM simulations the capability of the proposed setup to produce a linear gradient, a real setup has been arranged. An aluminum bar having dimensions of about $20\,\mathrm{cm}$ by $3\,\mathrm{cm}$ by $3\,\mathrm{mm}$ has been cut as in Fig. 2 to enhance the effects in the central part. The two different temperatures at the bar ends have been obtained using a high power resistor to heat and a Peltier cell to cool down,respectively (Fig. 3).

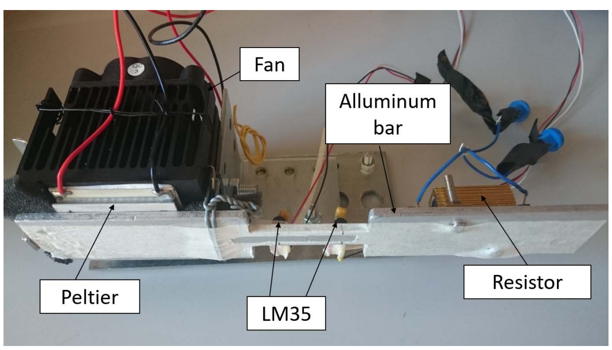


Fig. 3. The experimental setup. The picture also shows the position of the reference temperature sensors.

Two conventional temperature sensors have been fixed at the edges of the reduced width section to allow evaluating the temperature gradient. These sensors were previously characterized by comparison with a calibrated Pt100 temperature sensor. Furthermore, a thermographic camera has been employed to assess the linearity of the temperature distribution. Fig. 4 shows a thermal image taken during working conditions and Fig. 5 reports the temperature measured with the camera along the bar main axis and the corresponding linear fitting. The maximum deviation from the linearity is of about $0.34\,°\mathrm{C}$, mainly due to the camera.

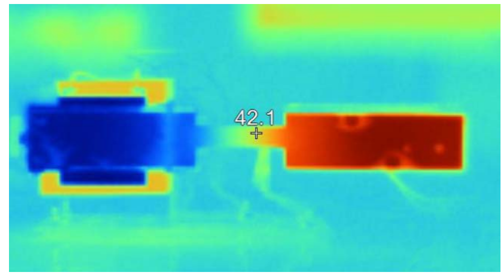


Fig. 4. Picture of a thermographic camera image taken during one of the tests.

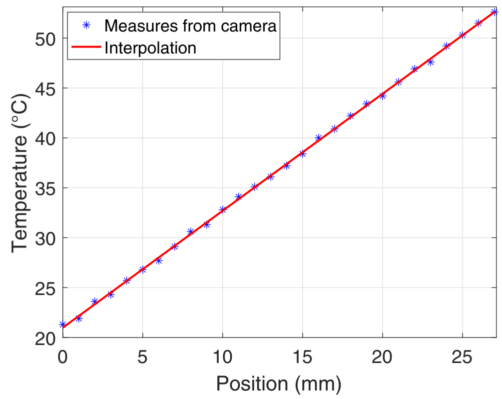


Fig. 5. Temperature measurements obtained from the thermographic camera on the aluminum bar during a test and respective linear interpolation.

## IV. Experimental tests

The setup for sensor characterization has been used with two different sensors: a) "conventional" $1.5\,\mathrm{cm}$ long FBG; b) multiplexed sensor made by three short gratings (lenght about $1\,\mathrm{mm}$) inscribed along the same fiber at a very short distance one from the other ($3\,\mathrm{mm}$). All the sensors were preliminary characterized in a climatic chamber in uniform temperature conditions.

### A. Tests of a single FBG

The first test has concerned a single uniform FBG. The sensor has been positioned in close contact with the bar approximately half-way between the reference temperature sensors (Fig. 6).

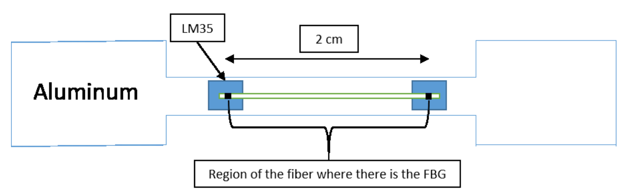


Fig. 6. Measurement set up for the single FBG.

The grating has been interrogated using a home-made instrument that uses a broadband SLED source and a spectrometer. A specific signal processing software has been implemented [4] to improve the performance provided by spectrometer: with a suitable gaussian fitting and signal filtering the wavelength resolution of spectrometer of $100\,\mathrm{pm}$, which corresponds to about $10\,°\mathrm{C}$, is improved to allow having a final resolution of about $0.1\,°\mathrm{C}$.

As an example of the obtained results, Fig. 7) shows the temperature measured by the two reference sensors, the average temperature and the temperature measured using the FBG. At the end of the thermal transient the temperature gradient has been about $7\,°\mathrm{C}/\mathrm{cm}$.

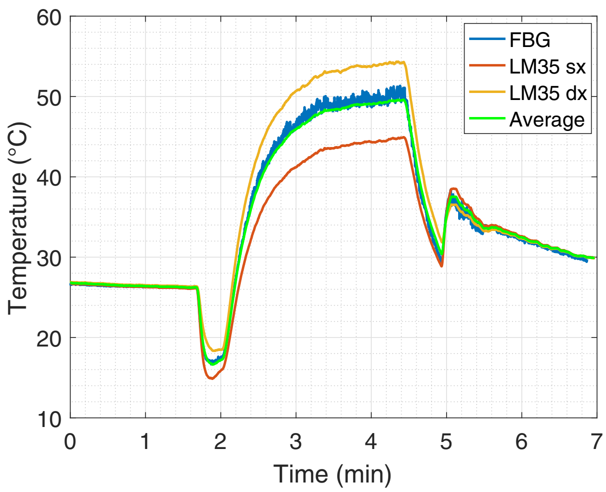


Fig. 7. Temperature measured during the test carried out with a single FBG.

The test shows that the FBG is subjected to a strong temperature difference and its Bragg wavelength is strongly related with the sensor average temperature, thus confirming the under-estimation as predicted by the simulations and other experimental results [17].

### B. Multiplexed FBGs

The second result reported in this papers has been obtained using a multiplexed sensor composed of an array of very short gratings. The three grating wavelengths are separated by about $6\,\mathrm{nm}$ thus preventing any overlap of their backreflected signals during even severe temperature changes.

Since the grating length is short with respect to the thermal gradient, the array can be assumed as a set of punctual sensors able to perform spot measurements. The characterization setup is here useful to assess the array capability to spatially resolve temperature differences at a very short distance.

An example of the result obtained with thermal gradients is reported in Fig. 10. The temperature measured using the three gratings highlights that the temperature is not uniform and at the end of the thermal transient, again with a gradient of about $7\,°\mathrm{C}$; the difference between FBG1 and FBG2, as well as that between FBG2 and FBG3 is of about $3\,°\mathrm{C}$. The test also shows the relevant noise that affects the temperature measurement, which is due to the low signal intensity for certain wavelengths caused both by the reflectivity of each

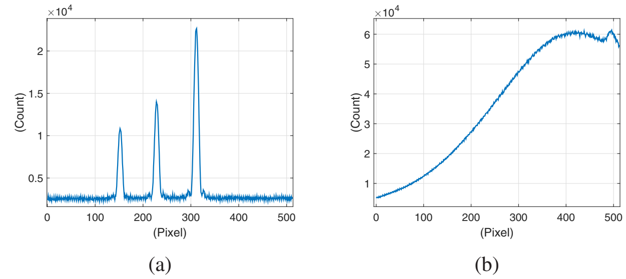


Fig. 8. Reflected spectrum from the three FBGs inscribed on the same fiber (a). The amplitudes are different because of the non uniform spectrum of SLED source in the considered wavelength range and of slight differences in the grating reflectivities (b).

grating and the spectral power spectrum of the used SLED. Improvements will be possible by reducing the wavelength separation of the gratings and by using a wider bandwidth SLED source.

To summarize, with current techological implementation, the single FBG, due to its length, shows a poor spatial resolution and good temperature accuracy, whereas the "multiplexed" grating presents an opposite behavior, thus highlighting a trade-off between spatial resolution and accuracy.

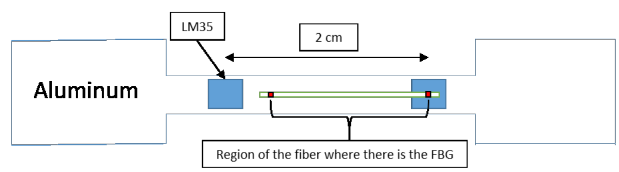


Fig. 9. Measurement setup for the multiplexed probe.

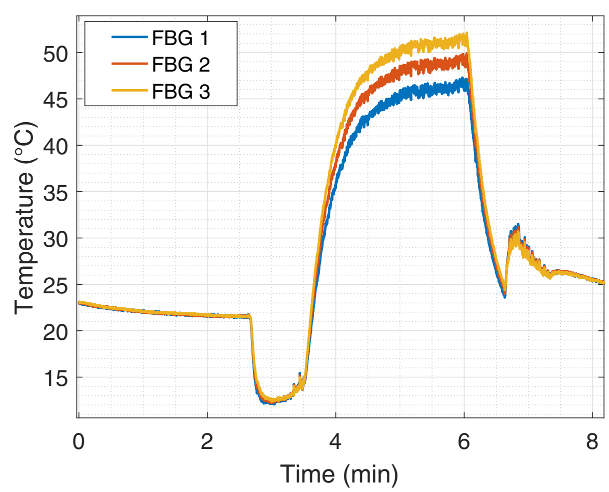


Fig. 10. Temperature measured by the FBG array during a thermal test .

## V. Conclusion

In this paper Fiber Bragg Grating inscribed in optic fibers have been considered to measure the temperature during LITT applications. Their behavior is already well known, but only when used to measure temperatures that can be considered constant over their length; therefore here a setup able to reproduce know linear temperature gradient has been investigated and realized by mean of simulations and comparisons with a thermographic camera. Two different kinds of FBG configurations have been tested: the first has been a single uniform grating, quite long with respect to the temperature changing rate, while the second an array of shorter gratings to sample the temperature profile in different positions. The obtained measured have been compared in order to establish the better solution to be used in LITT. Preliminary results show that, as predicted from theoretical simulations, a long uniform grating, in presence of linear gradient, measures the average temperature between its extremities if the decoding method is based on the peak position tracking. The multiple grating inscribed in the same fiber show instead more flexible results because of their low error due to the gradient along them and because can measure different temperature profiles.

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