Performance assessment of FBG temperature sensors for laser ablation of tumors

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***Abstract*—The paper presents the characterization results of temperature sensors designed to be employed during thermal treatments of tumors, such as in the laser ablation of malignant cells. The developed sensors are based on Fiber Bragg Gratings, a sensing element able to measure the temperature in proximity of the laser beam without significantly modifying the radiation pattern or perturb the temperature at the sensor site. Different sensor embodiments are analyzed and compared in term of linearity and dynamic response; then a preliminary test during an emulated ablation using a phantom is also presented.**

I. Introduction

Hepatocellular carcinoma (HCC) is the sixth typology of neoplasm for diffusion in the entire world and the third more important cancer related cause of death [1]. Classic therapies, like chemotherapy and radiotherapy, not always provide satisfactory results, whereas surgical approaches, like orthotopic transplantations and resections, have limitations related to the eligibility of patients to withstand such surgeries and to the lack of donors [2].

Aiming to treat non-candidate to transplantation or to resection patients, different "mini-invasive" techniques to induce the malignant cell necrosis have been developed. These approaches typically take advantage of a localized energy delivery to produce a thermal shock capable of killing the tumor cells, and have proved to be very effective provided that a temperature higher than 60°C is reached and the lesion is not larger than about 3 cm. The latter, however, is representing a less and less relevant limitation thanks to their continuous optimization and to surveillance programs able to highlight prematurely neoplasms, so that these thermal ablation therapies have become the first-line treatment for HCC in the majority of cases [1]. Different methods have been recently investigated to locally induce a temperature increase, such as the use of radio-frequency currents (RadioFrequency Thermal Ablation, RFTA), of micro-waves (Microwave Ablation, MWA) or of lasers (Lases Induced ThermoTherapy, LITT). Thanks to these techniques it is possible to specifically heat up tissues, but the optimal treatment would also require the simultenous measurment of the induced temperature to ensure the proper cytotoxicity while avoiding carbonizations. Heating probes are typically introduced by means of capillary needles having dimensions as small as 1 mm, guided to the right position with the help of ecography, magnetic resonance (MR) or CT (Computed Tomography) facilities.

Measurement requirements are rather demanding since a temperature resolution of about $0.1°$C and accuracy better than 1 °C are typically specified [3]. Spatial resolution better then 1 cm and time response below 1 s are also important to precisely monitoring the temperature at the ablation location during the fast tissue heating.

Nowadays RFTA and MWA devices embeds electrical sensors, usually thermocouple or thermistor because of their small dimensions, whereas devices for LITT are controlled by means of ecography monitoring because of the lack of temperature sensor compatible with the laser radiations [4].

Aim of this work is the characterization of all-fiber temperature sensors suitable to be employed during laser ablation or in other applications where the sensor does not have to interfere with the electromagnetic fields, such as during MR-based thermometry.

II. Sensor working principle and temperature probe development

The considered temperature transducers are based on Fiber Bragg Gratings (FBGs). An FBG is basically a portion of optical fiber whose core has been modified in order to reflect a specific wavelength, the so-called Bragg wavelength λ_0. FBGs are sensitive to both strain and temperature and, for small changes, the Bragg wavelength shifts is function of these effects though a linear relation:

$$\lambda = \lambda_0 + k_\epsilon \cdot \epsilon + k_\mathrm{T} \cdot (T - T_0) \tag{1}$$

where λ_0 is the Bragg wavelength at reference temperature and when the FBG is unstrained, ϵ is the strain and $(T - T_0)$ is the temperature shift. The coefficients k_ϵ and k_T are the strain- and temperature-wavelength shift coefficients, which for standard FBGs are of about 1 pm/$\mu\epsilon$ and 10 pm/°C, respectively.

Bare FBGs (i.e. realized in pieces of fiber with only primary coating) are the simplest way to measure temperature using optical fibers. They present high temperature sensitivity and reduced dimensions, and thus are most suitable to be employed in arranging very low invasive and fast sensors. On the other hand, strain and curvature perturbations are hardly avoidable in real applications for bare fibers, hence large errors

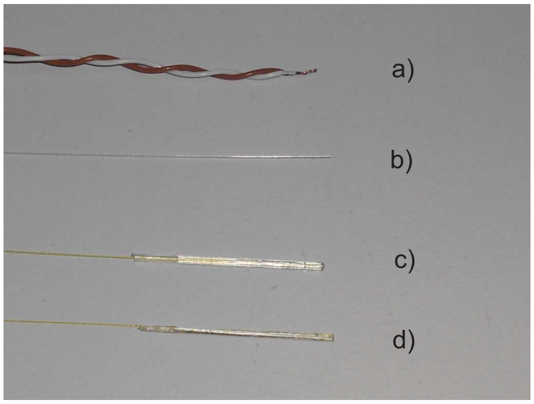

Fig. 1. A miniaturized thermocouple (a) and the FBG sensors employed in the characterization tests: b) bare fiber; c) fiber inside the capillary; d) fiber glued on the external of the capillary.

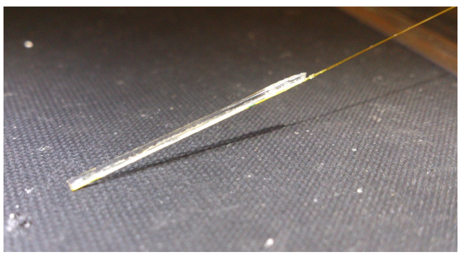

Fig. 2. Detail of the probe arranged fixing the FBG on the capillary external surface with epoxy glue.

can be introduced since strain effects are indistinguishable from temperature effects. To avoid unwanted mechanical effects while still maintaining small the footprint of the sensor, we have thus investigated different sensor embodiments. Many solutions have been already investigated by several authors, for example packaging the bare FBG in a metallic pipe [5], [6], but these approaches can not be employed to monitor laser ablations since the sensor does not have to interfere with the laser beam. The solutions investigated in this paper are based on the use of a small diameter quartz capillary to protect the fiber and increase the mechanical robustness. One sensor prototype has been arranged introducing the fiber inside the capillary tube, then the gap between the fiber and the inner walls of the tube has been filled with epoxy resin, thus obtaining a steady sensor probe almost transparent to the laser radiation. A second probe has been developed gluing the sensing fiber on capillary surface using the same resin. In this probe the capillary only acts as a mechanical support for the fiber that remains exposed to the surrounding environment. This second probe shows a faster thermal response.

A picture of the sensor prototypes is shown in Fig. 1, where the FBG sensor dimensions are compared with a miniaturized thermocouple. Bare FBG (the second from the top) is simply a commercial FBG that works in reflection mode, while the two sensors in the bottom of the picture are the probe arranged introducing the fiber in the capillary and fixing the fiber on the capillary external surface, respectively.

III. EXPERIMENTAL RESULTS

The arranged prototypes have been characterized in order to assess their sensitivity with respect to temperature, their linearity and the their time response in the presence of fast temperature changes. FBG sensors are interrogated using a custom made system build around a broad band SLED source and a commercial FBG analyzer, whose wavelength resolution and measurement rate are 0.1 nm and 1 kS/s, respectively. A three port circulator is used to route the signal from the SLED to the sensing grating and from it to the analyzer. The acquired optical spectra are sent to a PC though a USB interface and there processed in real-time using a LabView program that implements a peak search algorithm and then uses an optimization algorithm to accurately detect the peak wavelength position. In this way, the analyzer resolution has been virtually improved by about two orders of magnitude. The architecture of developed interrogation system and the setup for the sensor calibration is shown in Fig.3.

A. Sensor calibration

The sensors have been calibrated in a controlled environment using a climatic chamber and a reference thermometer having an uncertainty of about 0.5 °C. The thermometer output is an analog signal that has been measured using a general purpose acquisition board (DAQ). In these preliminary tests, the chamber stability and the reference thermometer represent the main contribution to the overall calibration uncertainty, but we plan to arrange a more reliable setup as soon as the best sensor probe configuration will be defined and new sensor prototypes will be assembled. Calibration tests have been carried out in a temperature range from 20°C to about 50°C. During the tests, both the reference thermometer and the FBG response were recorded. Fig. 4 shows the behavior of the FBG peak wavelength versus the sensor temperature. The bare grating has a nominal wavelength of 1545 nm, whereas the gratings supported by the capillary have a nominal wavelength of 1555 nm. The experimental results data have been fitted with linear model thus obtaining a linear relationship between temperature and wavelength whose parameters are reported in Tab.I. The initial peak wavelength positions of the grating are in agreement with the nominal wavelength provided by the manufacturer and the bare grating has a smaller wavelength as expected. The difference between the measured and nominal initial wavelength is due the manufacturer tolerance and unwanted strain that occur during the resin polymerization process. The sensitivities are close the nominal value of 10 pm/°C and the effects both of the resin and of the capillary to the sensitivity do not play a significant role. Anyway, tests carried out with other sensor prototypes have shown that the amount of resin and the bonding procedure can significantly affect the sensor linearity and can introduce non-negligible hysteresis phenomena. The characterization procedure has been thus also useful to assess the quality of the sensor development process.

The linearity of the tested sensors has been obtained as the absolute deviation from the linear model and is always below $\pm$ 1°C, as shown in Fig. 5. It should be noted that these results also account for the sensor stability and the calibration uncertainty, which is here the main uncertainty contribution.

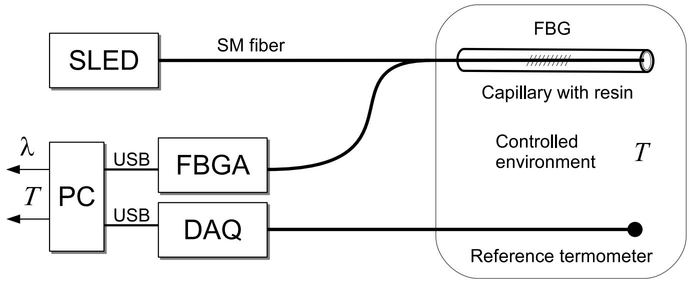

Fig. 3. Characterization setup and interrogation system for the investigated FBG sensors.

TABLE I. SENSITIVITY AND INITIAL BRAGG WAVELENGTH OF DIFFERENT FBG SENSORS.

	λ_0(nm)	k_T (pm/°C)
FBG-bare	1544.465	10.2
FBG-capillary	1555.465	9.1
FBG-external	1555.220	10.1

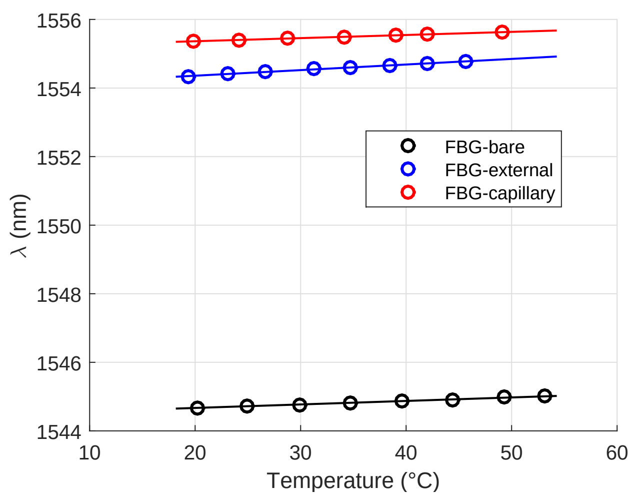

Fig. 4. FBG responses as recorded during the calibration tests.

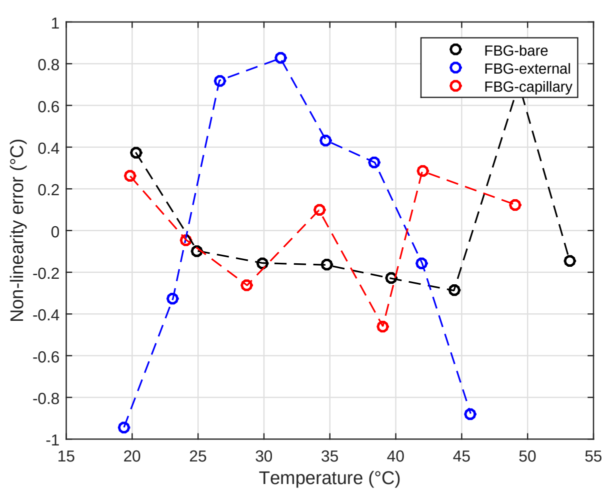

Fig. 5. FBGs deviation from the linear model obtained with the calibration test. The deviation accounts for sensor non-linearity, sensor stability and calibration uncertainty.

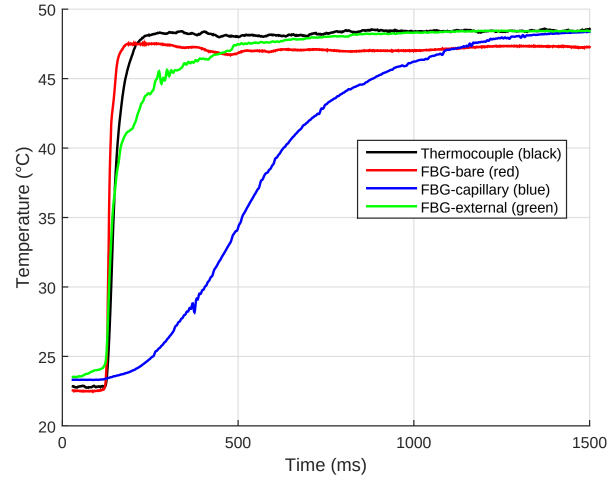

Fig. 6. Thermal transient as recorder by the thermocouple and the FBG sensors.

TABLE II. THE MEASURED TIME CONSTANTS.

	Time constant (ms)
Thermocouple	20
FBG-bare	40
FBG-capillary	500
FBG-external	60

B. *Time constant evaluation*

Sensors for thermal ablation should have a fast response in order to provide a prompt feedback on the actual temperature of the heated area. A temperature too low is not cytotoxic and thus not effective, and a temperature too high might damage healthy tissues. The sensor time constant has been experimentally measured taking advantage of the analyzer fast sampling rate [7] and the real time spectra processing.

A hot water bath has been employed to force a sharp temperature change from ambient temperature, which was about 23 °C, to the bath temperature of about 50 °C. A miniaturized thermocouple similar to the one shown in Fig. 1 has been employed as reference thermometer to monitor the water temperature. The characterization results are shown in Fig. 6, where the thermocouple time response is also shown for comparison purposes. The time constant has been measured as the time required to reach the 68 % of the full temperature step and the results are shown Tab.II. The bare FBG time response is the fastest as expected, whereas that of the FBG inside the capillary is about one order of magnitude larger. The FBG fixed on the capillary surface exhibits a fast response and it thus represents a good compromise between robustness, unwanted strain effects and time response.

C. *Monitoring of a simulated laser ablation*

In order to assess the effectiveness of the proposed sensors, a preliminary thermal test has been carried out using a phantom of human liver made with agar jelly. The agar concentration has been chosen in order to emulate the thermal behavior of a real liver [8], [9], even thought this simplified model can not take into account the effect of vessels and the presence of liver non-uniformity. Since the employed agar jelly is almost transparent, it has been loaded with a dark ink in order to obtain a phantom with light absorption characteristics as close as possible to those of a real liver [10], [11]. This aspect is particularly important since, during the test described in this section, the phantom is heated using a power laser delivered with a multimode optical fibers. The fiber endface has been modified in order to have an optical power distribution with an almost circular shape localized around the fiber laser tip [12]. Prior to actual use in simulated ablation monitoring, the FBG sensor embedded into the capillary has been also tested placing it directly in the laser beam to measure the temperature increase during the heating phase and due to the light absorption from the glue. This way we have verified that the perturbation effect due to the glue absorption is less than 0.5°C, a value that can be considered negligible, at least in these preliminary applications.

Afterwards the fiber for the laser delivery has been introduced inside the phantom together with the FBG probe. Fig. 7 shows the dark phantom during a thermal test. Fiber on the left side of the picture is for the laser delivery and fiber for the temperature measurement is routed from the right side. The probe was placed at a distance of about 1 mm from the delivery fiber.

During the test the laser was turned on for about 5 minutes and it was programmed to deliver a constant optical power of about 1 W in order to heat the central part of the phantom. The temperature distribution at the phantom surface was continuously recorder using a thermal camera. Fig.8 shows an infrared picture taken at the end of the heating phase where it is possible to see the hot spot due to the laser. The acquired pictures were processed in order to measure the temperature behavior at the hot spot position. The behavior is reported in Fig.9, where is possible to see a first order thermal transient dominated by the large heat capacity of the phantom and the reduced thermal resistance with the surrounding environment. At the same time the FBG probe recorded the temperature inside the phantom, depicted in Fig.10, whose behavior is in agreement with the temperature profile measured using the camera. Anyway, despite the phantom thickness was only 1 cm, temperature inside the phantom was significantly higher than the temperature at the phantom surface, and at the end of the heating phase the temperature difference was larger than 10 °C, thus highlighting the importance to measure the temperature as close as possible to the laser beam.

Fig. 7. The liver phantom during the thermal test. The fiber for the laser delivery is on the left side of the phantom and the fiber connected to the FBG probe is routed from the right side. Part of the laser beam is scattered outside the phantom and is detected by the camera.

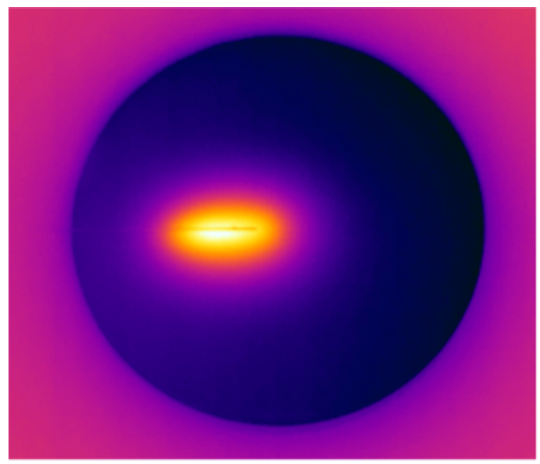

Fig. 8. Infrared picture of the surface phantom during the emulated ablation. Dark color corresponds to about 20 °C. The temperature of the hot spot is of about 38 °C.

IV. Conclusion

Laser ablation is emerging as a promising technology for mini-invasive treatment of tumors. The ablation procedure requires an accurate knowledge of the temperature in order to deliver the proper amount of heat. Traditional electrical temperature sensors, which are currently employed to monitor Radiofrequency Thermal Ablation or electromagnetic thermal ablations, can not be here employed because of the presence of metals and other non-optically compliant materials. Fiber optical sensors based on FBG do not suffer from this limitation but commercially available devices are mainly suited for strain monitoring or are not designed for medical applications. The paper has investigated the performance of different temperature probes based on FBG, in terms of linearity and time constant. A probe composed of an FBG glued inside a glass capillary has been employed to monitor the temperature inside the phantom of human liver during a simulated laser ablation. The results have shown the feasibility of the proposed approach and have demonstrated that the sensor does not perturb significantly the laser ablation procedure and that it could be employed to monitor the temperature in real time.

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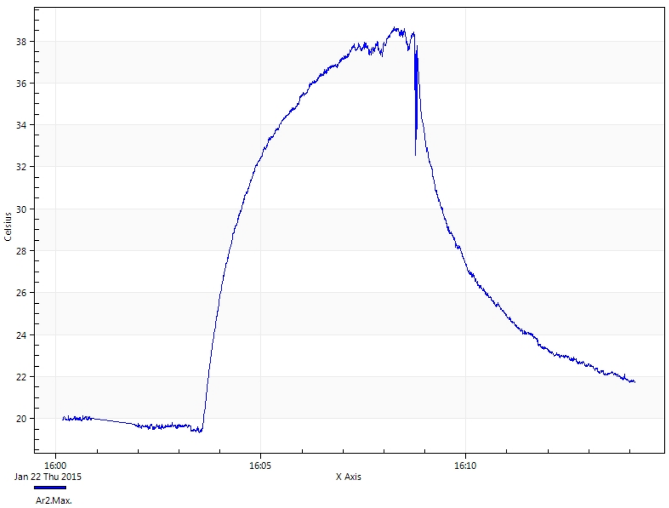

Fig. 9. Temperature behavior at the delivery fiber tip position as recorded by the thermal camera.

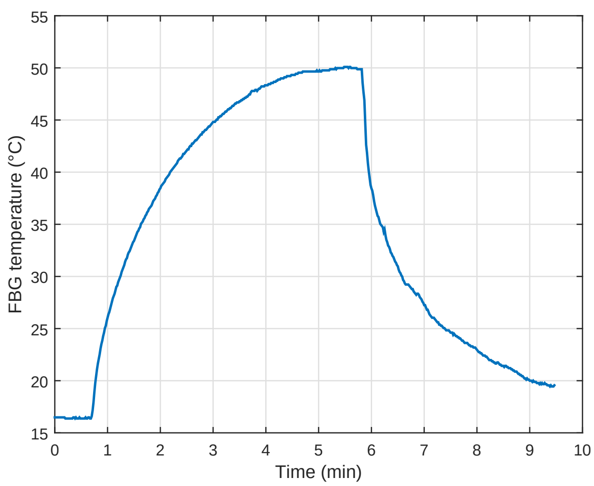

Fig. 10. Temperature behavior as measured by the FBG probe

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