Characterization of Tumour Laser Ablation Probes with Temperature Measuring Capabilities

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***Abstract*— The paper reports on the development and characterization of an innovative all-optical laser delivery fibre probe for cancer cell ablation with simultaneous temperature sensing capabilities. The probe integrates a grating-based temperature sensor and a laser delivery fibre whose tip surface is micro-structured for adapting the beam diffusion to the tumour geometry. Different temperature sensor configurations are analysed; then the most promising is characterized in a simulated laser ablation process using a specific phantom to emulate real liver tissue.**

Keywords*— *Laser tumour ablation, FBG, all-fibre probe.

I. INTRODUCTION

Thermal ablation (TA) is an increasingly popular therapy for treatment of small and mid-size tumours [1]. It is based on miniature percutaneous or endoscopic applicators that heat the surrounding tissue with a high degree of selectivity, damaging cells in a well-confined portion of tissue around the tumour under treatment. Cells death is a function of both temperature and duration of heating, and over 60°C the mortality is nearly instantaneous [2].

Several sources can be used in minimally invasive TA: radiofrequency [3-5], microwave [6-7], and laser [8-10] are the most popular for high-temperature treatments. Laser ablation (LA), in particular, provides a negligible invasiveness, as the applicator is a miniature optical fibre, hence smaller than RF and microwave ablators. In most applications, LA makes use of a solid-state continuous-wave laser, emitting in the near infrared, and coupled into a delivery fibre that serves as applicator [10].

The measurement of temperature is the main benchmark of all TA procedures [11-12]. In current clinical procedures, thermocouples (TCs) are used as temperature probes, either as standalone instruments or directly applied to RF ablation probes [13-14]. From the applicative point of view, however, TCs have critical drawbacks [15], the most relevant being the interaction with the heat source (radio waves and laser beams) that alters the ablation pattern and introduces artefacts. Then, when TCs are directly installed within hollow applicators, as in [14], the applicator itself acts as a heat sink, causing an overestimation of the thermal variations.

Fibre optic temperature sensors are known to be a valid alternative to TCs. Despite their use in TA is still limited, they provide significant advantages, such as: MRI-immunity, miniature footprint, and no alteration of the ablation pattern. In addition, by using wavelength division multiplexing (WDM) techniques or distributed sensors [16], it is possible to obtain a plurality of sensing points along a single fibre, with sub-millimetre spatial resolution. Fibre Bragg gratings (FBGs) in particular represent a good candidate for measurement of temperature in LA [17-20]. Indeed, FBGs allow implementing flexible and noise-robust coding and demodulation techniques based on the use of broadband sources and spectrometers [18]; moreover, FBG arrays are quite a cheap technology, compatible with the costs of typical applicators, especially when directly fabricated during fibre drawing [21]. The application of FBGs to hyperthermia dates back to 2000 [20] when Webb *et al.* demonstrated their first application, but the advent of LA in cancer care pushes forward the requirements. Thermal measurement is indeed the main indicator of cancer cells mortality rate [2], and such metric defines the success of the procedure as well as post-treatment operations. However, European FP7 project IMPPACT [22] demonstrated that the temperature gradient measurement has key impact also on the prediction of ablation outcome, particularly for hepatocellular carcinoma (HCC) and other tumours confined in hepatic tissue [1-8].

In this work, we discuss the development and characterization of FBG-based optical probes to records temperature during LA procedure. In order to allow the correct comparison between different probe configurations, the ablation tests have been performed using a highly reproducible phantom based on agar jelly functionalized to reproduce the absorption characteristics of liver tissue. Experiments have been performed with a fibre pigtailed laser emitting at about 900 nm and using the various homemade FBG probes to evaluate the effect of packaging on the sensitivity and the response time.

II. TEMPERATURE PROBE DEVELOPMENT

FBGs are the most widespread fibre-based sensors. As well known, their spectral transmission response exhibits a notch-like behaviour centred at the so-called Bragg wavelength λ_B, which for small variations exhibits a linear dependency on the applied strain and temperature as:

$$\lambda_B = \lambda_{B0} + k_\varepsilon * \varepsilon + k_T * (T - T_0) \qquad (1)$$

where λ_{B0} is the Bragg wavelength of the grating in the initial strain and temperature conditions (and related the grating period and fibre fundamental mode effective index), k_ε is the sensitivity to the longitudinal strain ε (typical value is 1 pm/με), k_T is the sensitivity to the temperature T of the grating (typical value is 10 pm/°C), and T_0 is the initial temperature. As evident from Eq. 1, there is a cross sensitivity between temperature and strain, and thus different techniques to reduce the impact of the strain have been investigated in the literature to optimize the use of FBGs as temperature sensors. In the considered case it has to be taken into account that during LA the main source of parasitic strain comes from patient respiration that bends the optical fibre. This can be avoided if the sensitive part is placed inside a rigid tube. This solution can also improve the temperature sensitivity by exploiting the tube thermal expansion, but it has to be pointed out that no metals can be used to encapsulate the grating, not to have the same problems described for the thermocouples.

Based on the previous considerations, two preliminary solutions were proposed, both using glass capillary tubes.

The first probe is made by a FBG (wavelength 1555.5±0.3 nm, bandwidth@3dB 0.3±0.1 nm, reflectivity >90%, fibre outer diameter 125 μm) packaged inside a glass capillary filled with epoxy (Figure 1 - left), whereas the second probe is made by a similar FBG glued on the outside of the glass capillary to be directly exposed to the temperature to be measured (Figure 1 - right).

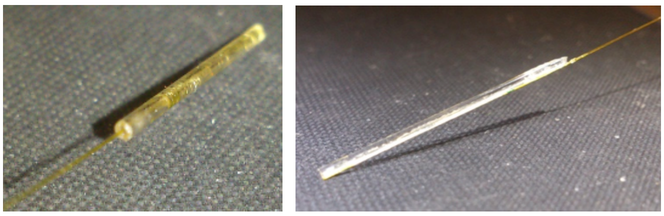

Figure 1. Photograph of developed temperature probes: the version with the FBG inside the glass capillary (left) and that with the FBG on the outside of the capillary (right).

The two probes were first characterized by means of a climatic chamber to evaluate the wavelength dependency with temperature; then the thermal response was measured by forcing a fast transient in temperature, as may occur during LA. Since both probes showed a response adequate for LA applications [23], preliminary tests were carried out using a thermal phantom representative of a real LA situation. Aiming at an application in liver tumours, an agar gel phantom of suitable composition was fabricated [24 - 25]; then the two developed probes were immersed into the agar gel together with four T-type thermocouples for comparison purpose (Figure 2). The phantom was then heated up by means of a resistor to avoid the artefacts in the reading of the thermocouples due to the laser beam, and thus to obtain well-defined and reproducible working conditions. The experiment was repeated many times and for different temperatures; it turned out that the repeatability of the grating reading was very poor (whereas the thermocouples showed excellent agreement between the different measurements), and further investigations evidenced that this behaviour was due to the interactions between the epoxy resin and the FBG through induced uncontrolled strains.

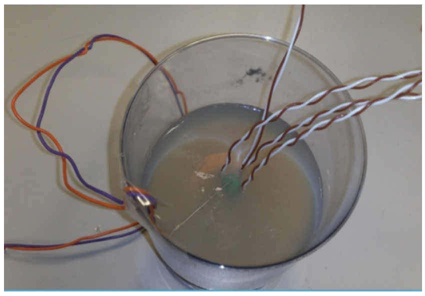

Figure 2. Liver phantom with resistor and thermocouples

To overcome this problem, a different probe was investigated and fabricated. The new configuration is made by a grating (similar characteristics of the previous ones) packaged inside the glass capillary, but with the fixing resin in the pigtail region only, so without epoxy along the grating.
This solution solved the repeatability issue, but slightly worsened the transient thermal response. Figure 3 reports this response evaluated by applying a step of temperature from environmental temperature to hot water (≈45 °C). The rise time in this case is about 0.7 ms, a value well within the requirements for allowing the real-time control of LA by the physicians [26].

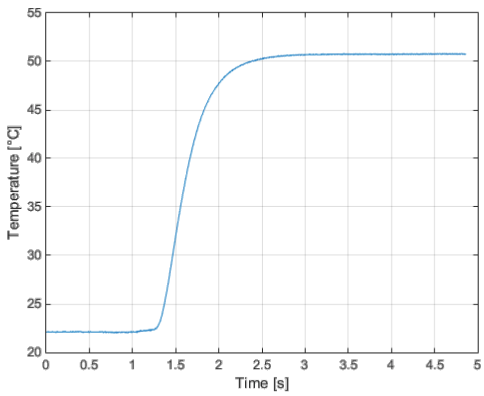

Figure 3. Rise time of the probe made by packaging the FBG inside the glass capillary but with resin only in the fibre pigtail region.

III. TEMPERATURE MEASUREMENT AND DELIVERY PROBE

Following the previously described characterization results, the temperature sensing FBG was integrated with the laser delivery fibre, which is a large diameter fibre with the end-tip surface modified to obtain the most suitable radiation pattern for the specific LA application. Figure 4 shows an example of two different radiation patterns in the liver agar phantom, which was modified adding black Indian ink to better emulate the liver optical absorption [27 - 28].

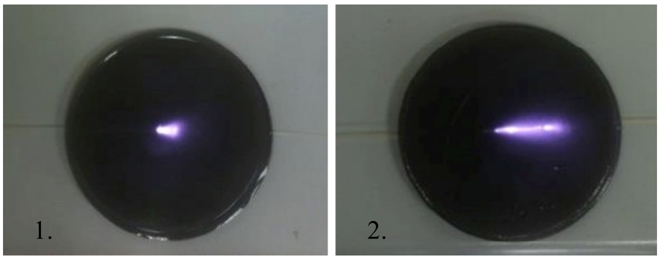

Figure 4. Example of two delivery fibres with different radiation pattern: a normal (left) versus a surface modified fibre (right). In bth cases the fibres are inserted into an agar phantom with the temperature sensing FBG fibre in close proximity.

Figure 5 reports a comparison between the reading from the FBG temperature sensor realized as described in the previous section and a thermo-camera during a simulated LA in the agar phantom. The probe was sandwiched between to agar slices to allow heating the phantom through laser absorption, then the laser was switched off and the upper slice quickly removed to have the FBG and thermo-camera read in the same conditions.

a.

b.

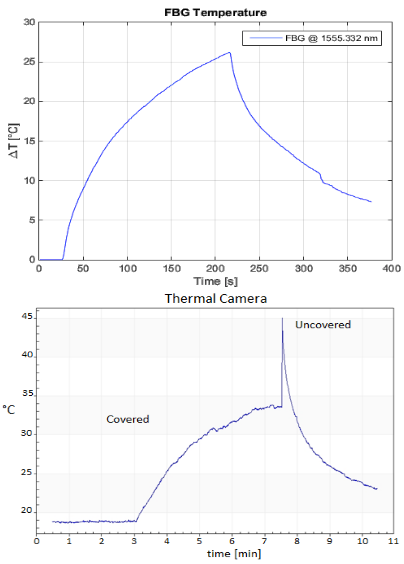

Figure 5. Comparison of the temperature measurement obtained by an FBG positioned in the middle of the ablation zone (a, above) and by thermo-camera reading in the same point (b, below).

During the laser on phase (i.e. when the FBG is covered by the upper slice to ensure a uniform absorption of the laser beam) the reading from the thermo-camera is very similar to that of the grating, but scaled for the presence of the upper agar slice. Then, once the laser is turned off and the upper slice removed, the two measurements are in excellent agreement, with a maximum difference registered during the experiments of 1.5 °C (note that the grating measures the difference with respect to the initial temperature, which is about 20 °C).

IV. Conclusions

In this paper, preliminary results about the development and characterization of an all-optical probe for laser ablation with simultaneous temperature measurement capabilities have been presented.

The proposed probe is made by a laser delivery fibre with suitable modified radiation pattern packaged together with the FBG sensor inside a glass capillary tube, which, besides for protecting the two fibres, allows reducing the cross-sensitivity to strain of the temperature sensor. Different designs for the temperature sensor have been devised and analysed. Then the best configuration has been tested against a thermo-camera in a simulated laser ablation using an agar phantom, obtaining results that differ by less than 2°C, values that are well acceptable for practical LA applications.

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