Fiber-optic dual EFPI/FBG for radiofrequency ablation monitoring in liver: *ex-vivo* experiments

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ABSTRACT

We present a miniature and biocompatible fiber-optic sensing system, for specific application in monitoring of the radiofrequency thermal ablation (RFA) process. The sensing system is based on combination of Extrinsic Fabry-Perot Interferometry (EFPI) sensor for pressure detection, and Fiber Bragg Grating (FBG) for temperature measurement. The dual pressure/temperature measurement shows an extremely low cross-sensitivity. Measurements have been performed *ex-vivo* on porcine liver, recording several RFA procedures in different location. Maximum values of 164°C and 162 kPa have been recorded on the ablation point.

Keywords: Fiber optic sensor, Fabry-Perot, Extrinsic Fabry-Perot interferometry (EFPI), Fiber Bragg Grating (FBG), Medical optics instrumentation, pressure measurement, radiofrequency ablation (RFA), *ex-vivo* experiment.

1. INTRODUCTION

Radiofrequency thermal ablation (RFA) is a common therapy for treating tumors up to 3-5 cm in size [1-3]. Its main approach is the ablation of a tumor (diagnosed through ultrasound, MRI, CAT scan) by selectively heating the tumor area. In RFA, an electromagnetic field is generated within the patient by means of an active electrode positioned in contact with the tumor. The electrode has the shape of a thin (1 mm) needle, which can embed secondary arms, positioned at the focal point of the tumor; a second electrode is placed in a neutral point, on patient's spine. Then, a radiofrequency (RF) generator, with 350-500 kHz emission frequency, induces a strong temperature rise near the active electrode, and the tissues are heated by conduction. At >60°C, the mortality of tumor cells is guaranteed. RFA is gaining popularity in tumor treatment as it is an outpatient procedure.

Nowadays, RFA is an acquaintance for treatment of liver tumors [4-5], which represent the third cause of death by cancer. However, specific problems arise when treating large tumors in the liver. The main constituent of liver tissue is water, which when exposed to temperature higher than 100°C changes its phase to vapor. Since vapor is a good dielectric, it progressively insulates the active electrode leading to the interruption of the RFA procedure.

The research carried out by the authors, in connection with San Matteo Hospital in Pavia, Italy, aims at measuring the evolution of physical parameters (temperature and pressure) during the RFA procedure, making it possible to extend this procedure to large tumors. This specific application sets challenging requirements for the sensing platform: 1) the sensing probe must embed temperature and pressure detection in a miniature area, and with a tiny active region; 2) the extremely steep temperature and pressure gradient requires an almost-zero cross-sensitivity; 3) the sensor has to be biocompatible; 4) the probe has to be minimally invasive, in order not to alter the heating pattern, but resistant enough to sustain the insertion; 5) electromagnetic immunity has to be guaranteed, and metal packaging has to be avoided. Fiber optics is the best candidate for this application [6], whereas standard electromechanical sensors fail in this environment.

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In this paper, we present a fiber-optic sensing system, specifically designed for RFA monitoring application, based on the combination of Extrinsic Fabry-Perot Interferometry (EFPI) and Fiber Bragg Grating (FBG) [7-8], embedded on a fiber tip. Experimental results have been obtained, ex-vivo, on porcine liver: this is the phantom of human liver that provides the best reproduction of the biological and electrical properties. Several RFA procedures have been performed, using the typical equipment of medical RFA (RF generator, ablation needles), and positioning the fiber sensor in different positions to monitor the physical phenomena in different locations. In the following, the main highlights are reported.

2. SENSING SYSTEM

The fabrication of the EFPI/FBG probe involves three steps. In first place, an FBG is inscribed on a single-mode fiber operating in the third optical window (10/125 μm size), using a standard phase-mask technique. The second step involves the formation of a Fabry-Perot cavity in proximity of the FBG tail [7]: the single-mode fiber is first spliced to a capillary (inner/outer diameter: 130/200 μm), used to enclose the Fabry-Perot air cavity, and then the resulting structure is spliced to a glass diaphragm, which consists of a multi-mode fiber (130/200 μm size). The final step functionalizes the optical structure to pressure sensing: the diaphragm is etched in hydrofluoric acid until ~2.5 μm thickness is achieved. The probe has maximum thickness of 200 μm and is entirely biocompatible.

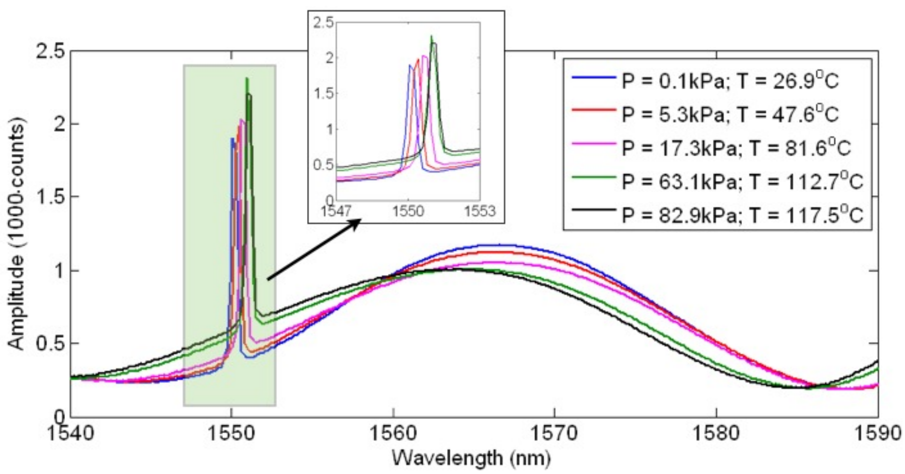

Figure 1. EFPI/FBG reflection spectrum for different values of pressure and temperature. The inset highlights the FBG.

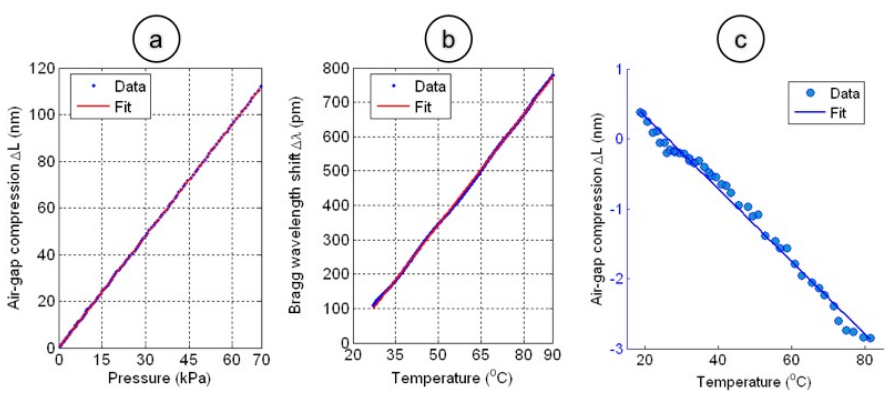

Figure 2. Sensitivity of the EFPI/FBG sensor to pressure and temperature. (a) EFPI sensitivity to pressure (1.60 nm/kPa); (b) FBG sensitivity to temperature (10.7 pm/°C); (c) EFPI sensitivity to temperature (-51.9 pm/°C).

Fig. 1 reports the spectrum of the combined EFPI/FBG. It is possible to show that the reflection spectrum has a neat separation of the FBG (peak wavelength 1550.45 nm and bandwidth ~0.3 nm), while the EFPI exhibits a much broader spectrum due to its low finesse. The reflectivity of the EFPI is close to the nominal 4% value for glass/air interface, while the FBG has a reflectivity of 9%, reduced from the original 95% due to the fusion process during splicing.

Fig. 2 reports the pressure and temperature sensitivity of the probe. The EFPI has a sensitivity of 1.60 nm/kPa, as in Fig. 2(a); this value is in agreement with [7-8]. The FBG has a standard sensitivity of 10.7 pm/°C, while its pressure sensitivity is negligible [8]. Due to its steep gradient, the RFA application requires a minimum cross-sensitivity: Fig. 2(c) shows that the EFPI thermal sensitivity is -0.0519 nm/°C, 32 times smaller than [7] and 304 times smaller than [8]. Thermal compensation is achieved by jointly measuring the air-gap compression ΔL and the FBG wavelength shift $\Delta\lambda$:

$$\begin{bmatrix} \Delta P \\ \Delta T \end{bmatrix} = \begin{bmatrix} 1.60 nm/kPa & -0.0519 nm/°C \\ 0 & 10.7 pm/°C \end{bmatrix}^{-1} \begin{bmatrix} \Delta L \\ \Delta\lambda \end{bmatrix} \quad (1)$$

whereas ΔP and ΔT are the pressure and temperature variations. The detuning coefficient is 32.4 Pa/°C.

The measurement setup for the *ex-vivo* experiments of RFA procedure is shown in Fig. 3. The sample used for ablation is a porcine liver, the natural phantom of human liver. The liver lays on a metallic plate, serving as electrode, while an RFA needle (1 mm diameter) is used to perform the ablation. A radiofrequency generator applies 5-50W at 480 kHz, and embeds an impedance meter that automatically disconnects the circuit when the target impedance falls below 0.1Ω (from the initial ~90Ω). The EFPI/FBG probe, located in proximity of the ablation needle, is interrogated through a white light setup, consisting of a broadband source (Optolink ASE C+L bandwidth), a spectrometer (Ibsen I-Mon) and a 50/50 coupler. Data acquisition is performed through a custom LabVIEW software, that returns pressure and temperature.

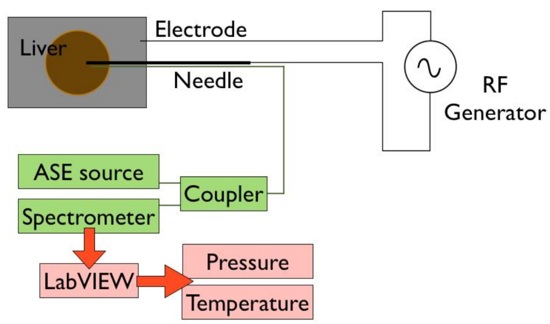

Figure 3. Schematic of the measurement setup used in radiofrequency ablation.

3. EXPERIMENTAL RESULTS

A set of preliminary results is presented in Fig. 4. The main picture shows the porcine liver, hosted in a chamber set to allow insertion of needles. The picture, post-RFA, shows the trace of the ablation around the needle tip, in a brighter color. The fiber-optic probe is inserted on the side, through a protection tube, at several distances from the RFA needle tip; a red laser is used to illuminate the tip of the fiber, which appears slightly misaligned from needle tip.

Two measurements are reported in Fig. 4(a) and Fig. (b). In the first case, the EFPI/FBG probe is located at approximately 1 mm distance from the ablation point. The chart shows a steady temperature rise up to 75°C, followed by a rapid increase up to 164°C peak. On the other side, the pressure trace shows fluctuations due to the alterations of the outer refractive index. After an initial pressure average rise, with peak around 48 kPa, we observe a rise in proximity of the ablation peak. In Fig. 4(b), the distance between the EFPI/FBG and the needle tip is 5 mm. In this case, peak values are inferior to the previous case (33 kPa, 46°C), showing a steep gradient in the RFA procedure

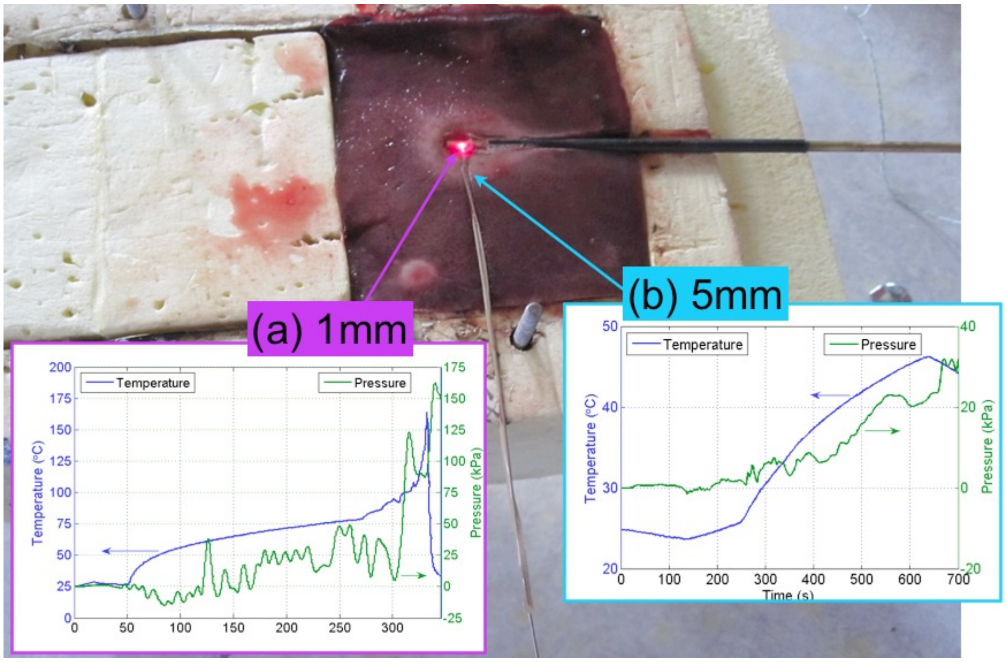

Figure 4. Experimental results of *ex-vivo* RFA procedure on porcine liver. The main picture shows the needle, hosted in a chamber, after the RFA. Insets show pressure and temperature traces at (a) 1 mm and (b) 5 mm distance from needle tip.

4. CONCLUSION

A dual EFPI/FBG sensing system for joint pressure and temperature detection is presented. The probe is miniature, biocompatible, and exhibits a low cross-sensitivity. The application of the fiber-optic probe for radiofrequency ablation of liver tumors is presented. Ex-vivo experiments show peak temperature of 164°C and 162 kPa pressure at 1 mm distance from needle tip, while smaller values are recorded at 5 mm distance. These results represent a preliminary step in the realization of a fiber-optic sensor network for the online monitoring of the RFA procedure.

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