# Fiber optic sensing for temperature control during laser ablation of cancer tissues

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## ABSTRACT

Laser Ablation (LA) is a minimally invasive tumor treatment, particularly valuable when conventional methods are unsuitable. LA utilizes laser energy delivered using an optical fiber, offering advantages like electromagnetic immunity and flexibility of the applicator. Challenges in achieving complete tumor destruction and minimizing collateral damage prompt the need for improved monitoring and LA control. Fiber optic sensors offer advantages over conventional methods, such as small size, electromagnetic immunity and biocompatibility. This study employs fiber Bragg grating array sensors for precise temperature monitoring and implements closed-loop temperature control based on these measurements. Preliminary findings show effective control of temperature, indicating the potential of fiber sensors use in LA as a promising technique to enhance the efficacy of cancer treatment.

**Keywords:** Cancer treatment, laser ablation, laser ablation control, fiber optic sensing, fiber Bragg gratings

## 1. INTRODUCTION

Laser ablation (LA) is a minimally invasive cancer thermal treatment method, particularly beneficial when conventional approaches like surgical resection, chemotherapy, or radiotherapy are unsuitable [1]. The fundamental concept of LA involves delivering laser energy through a fiber optic cable to induce local coagulation, necrosis, and apoptosis in cancer cells. The key advantages of LA arise from the material of the laser fiber (usually silica or plastic): immunity to electromagnetic interference, small size (laser fiber diameter < 1mm), and flexibility. This allows access to deep-lying organs and LA application during magnetic-resonance and computed tomography imaging.

Despite these advantages, challenges persist in ensuring complete tumor destruction and preventing collateral damage to healthy tissues around the tumor. The limitations stem from the lack of precise monitoring techniques and the use of an open-loop approach where laser parameters are set before the procedure and remain constant during the treatment [2]. This study addresses these challenges by employing fiber optic sensors, in particular fiber Bragg grating (FBG) arrays, for temperature monitoring in organs undergoing LA and developing laser-energy control based on temperature measurements.

## 2. METHODS

### Experimental set-up

The experimental set-up consists of the laser diode, the laser guiding fiber, the optical interrogator, the FBG array, and ex vivo porcine liver. The liver was obtained from a local butchery at the day of the experiments and was at a room temperature before the start of the experiments. For the experiments, each liver specimen was sectioned by half, the FBG array and the laser fiber were placed parallel to each other on one half of the specimen. After, the other section of the liver was laid on top of the fibers, effectively sandwiching the fibers between the liver sections. Such configuration allows a simple and accurate positioning of the fibers in the laboratory setting and have smaller probability of the fiber damage than using interstitial insertion method with the medical needles in the previous work of the group [3].

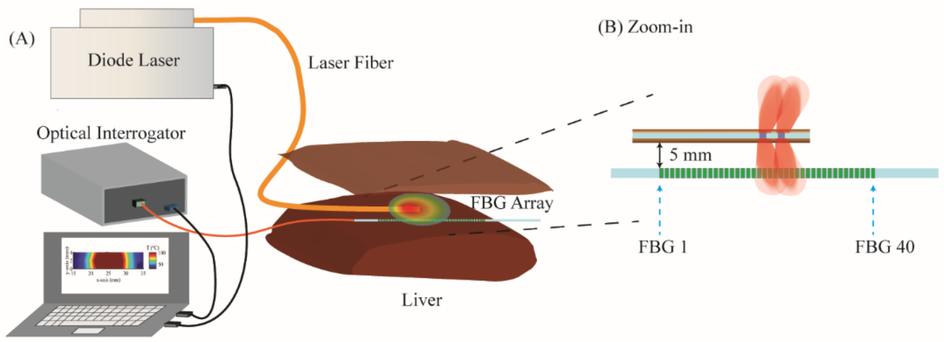


Figure 1. Schematics of experimental set-up: (A) FBG array and laser fiber positioned between two slices of ex vivo porcine liver parallel to each other; (B) zoom-in of FBG array and laser fiber with ELVeS® Radial® double ring tip.

**Fiber Bragg grating array sensors**

FBG is a periodic variation in the refractive index in the core of optical fiber along the length of typically a few millimeters to a centimeter [4]. When a broadband light is guided to the optical fiber, such periodic structure acts as a a wavelength-dependent reflector, that reflects the specific wavelength, called Bragg wavelength $\lambda_B$, and passes all other wavelengths. The Bragg wavelength depends on the effective refractive index, $n_{eff}$, and periodicity of the modulation, Λ:

$$\lambda_B = 2\eta_{eff}\,\Lambda \tag{1}$$

FBG sensing principle relies on the fact that external perturbations (strain Δε and temperature ΔT) cause the change of $n_{eff}$ and Λ, and, as a result, the change of the Bragg wavelength:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1+p_e)\,\Delta\varepsilon + (\alpha+\zeta)\Delta T \tag{2}$$

where $p_e$ is a photoelastic constant (variation of index of refraction with axial tension), and α a coefficient of thermal expansion of the fiber, and $\xi$ is a thermo-optic coefficient (variation of the refractive index with temperature). Therefore, FBG sensor is sensitive to both strain and temperature alterations, the cross-sensitivity of FBG should be considered during the experimental setup preparation.

It is possible to inscribe a chain of FBGs (each having different periodicity Λ, and, as a result, different Bragg wavelength $\lambda_{B_i}$) at different segments along the optical fiber. As a result, such FBG chain, also called FBG array, provides a quasi-distributed temperature measurement, where each FBG acts as a sensing point.

The FBG arrays used in this work were fabricated with femtosecond point-by-point writing technology. The FBG array has 40 gratings uniformly distributed in the spectral range of 1460-1620 nm, grating length is 1.15 mm, and an edge-to-edge distance is 0.05 mm - the resulting sensing length of the FBG array is 48 mm. Each FBG has a polyimide coating (diameter 145±5 µm), which has high thermal resistance (>300 °C). that makes polyimide-coated fiber more preferable option for laser ablation than conventional acrylate-coated fibers, that can withstand only 80 °C. More information about the fabrication of the FBG arrays is available in the previous works of the group [5], [6]. Hyperion si255 optical interrogator was utilized for real-time FBG spectra measurements. The interrogator has 1460 nm – 1620 nm wavelength range, 1 pm wavelength accuracy.

**Laser ablation equipment**

*Ex vivo* laser ablation of healthy porcine liver tissue was performed using a diode laser. The continuous-wave laser at wavelength 808 nm was guided from the laser to the ablated tissue via flexible quartz optical fiber with core diameter of 500 µm, that has double ring tip. The laser diode driver allows to control output laser power via electric current modulation. The power range chosen for PI controlled ablation was 0.1 W – 4.3 W.

**LabVIEW program for laser ablation control**

In order to have laser diode power regulation in real-time based on FBG array temperature measurements, the diode laser and the interrogator were connected to the laptop via USB and LAN connection correspondingly. The LabVIEW program

has been developed using Hyperion si255 LabVIEW libraries and controlling commands of the laser.
The input parameters of the program are: set temperature $T_{set}$, proportional, integral and derivative gains, steady-state time $t_{ss}$.
After the start of the program, temperature is measured and plotted on LabVIEW GUI in real-time, PI control logic is used to maintain the temperature at $T_{set}$. After steady-state time ($t_{ss}$), the laser is switched off and temperature is monitored for 60 s. Then, the program saves temperature, time and laser power values used in text files. MATLAB software was used for post-processing analysis of the results.

## 3. RESULTS AND DISCUSSION

In order to evaluate the efficacy of the developed LA control, three types of the experiments were performed: uncontrolled ablation, temperature-control with $T_{set}$ = 30 °C, and temperature-control with $T_{set}$ = 50 °C. Fig. 2 reports temperature profile evolution in time (distance along the array vs. time) and related temperature profiles measured by the FBG array for uncontrolled ablation, that had a constant power of 4.3 W. As can be seen, a 300 s irradiation leads to temperature increases by 47.1 °C. The, the laser was switched off and temperature started to decrease.

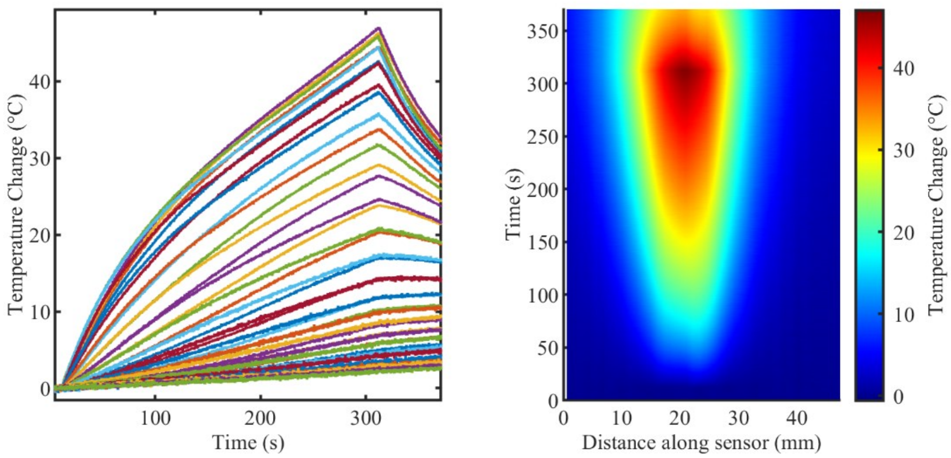


Figure 2. Measured temperature during uncontrolled laser ablation (constant power of 4.3 W) of *ex vivo* liver tissue: (left) temperature profiles measured by each FBG of the array; (right) temperature profile evolution in time (distance along the array vs. time).

Fig. 3 and 4 show laser power evolution and temperature profiles measured during the temperature-controlled ablation experiment with set temperature $T_{set}$ = 30 °C and $T_{set}$ = 50 °C correspondingly. Indeed, the maximum temperature reaches the steady state after around 85 s and maintain the stable temperature for a steady state time of 300 s.

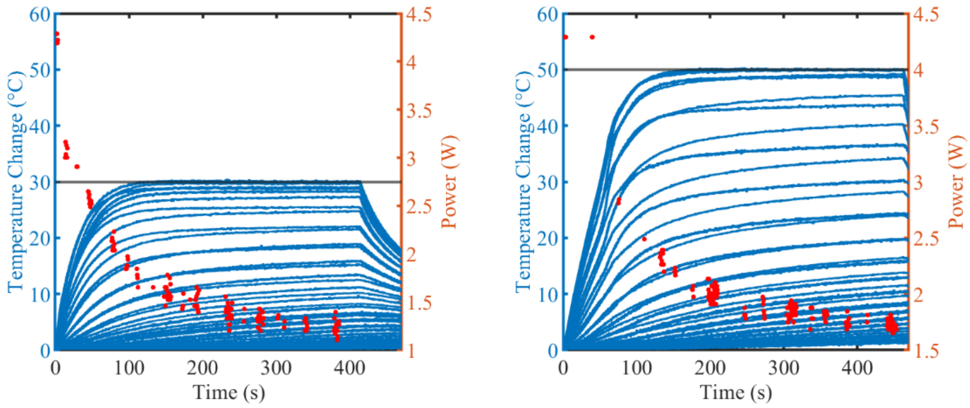


Figure 3. Temperature and power during controlled laser ablation of *ex vivo* liver tissue at (left) set temperature = 30 °C; (right) set temperature = 50 °C.

For closed-loop laser control experiments, 3 trials were performed for each set temperature and mean maximum temperature and its standard deviations are calculated, which is, in average, maintained below 15% during the heating and colling phases, whereas it is <2% during the steady-state phases.

## 4. CONCLUSION

The approach here proposed is an innovative feature for the specific application of LA for tumor treatment, where usually no closed-loop control is performed, but the procedure relies only on the experience of the doctor or the predefined laser treatment parameters. In this work we propose to use closed-loop control of LA based on temperature measured by FBG arrays. The highly-dense FBG arrays were customized in order to have high thermal resistance thanks to polyimide coating, and high spatial resolution (~1.2 mm). The results show that LA control can be a promising technique to improve the efficacy of cancer treatment. Indeed, preliminary findings of this study indicate effective control of temperature, thus, the methods can allow more accurate treatment of the region of interest and can significantly reduce collateral damage to surrounding healthy tissues.

## ACKNOWLEDGEMENTS

This work was supported by the European Research Council (ERC) through European Union's Horizon 2020 Research and Innovation Program under Grant 759159 and through Horizon Europe Framework Programme for Research and Innovation under Grant 101069181.

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