Doctoral Dissertation
Doctoral Program in Metrology (XXXVII cycle)

Fibre Optic Sensors for Tumour Therapy Monitoring

Applications of Optical Fibre Sensing Technologies to Thermal and Radiotherapy Treatments of Neoplasms

By

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Abstract

The most widely adopted treatments for tumours in internal organs are surgical resection, chemotherapy, and radiotherapy. In recent years, minimally invasive thermal therapies have attracted increasing attention among surgical approaches, owing to their reduced patient discomfort, shorter recovery times, and lower complication rates compared to traditional resections.

The present thesis focuses on the development of optical fibre sensor technologies for the real-time monitoring of thermal and radiation-based oncological treatments. Optical fibres are particularly well-suited for medical applications due to their biocompatibility, electrical safety, and immunity to electromagnetic interference.

The core of the research has been dedicated to the development of a tool to enable the accurate temperature monitoring in different types of thermal therapies, from low-temperature hyperthermia to high-temperature ablation. To this end, fibre Bragg grating (FBG)-based temperature sensors have been designed, fabricated, and characterized. These sensors were created by femtosecond laser inscription of FBGs into single-mode fibres and subsequent encapsulation in glass capillaries, leading to devices with an accuracy of one tenth of Celsius degree. These sensors were employed to validate a microwave hyperthermia system and to track temperature distribution during laser ablation experiments on ex-vivo liver tissue, including cases involving nanoparticle-mediated enhancement. To further reduce invasiveness, for the first time in the biomedical field, a thermal model based on the heat pulse method was developed, allowing the prediction of temperature in regions where direct sensing is not feasible. Such predictive capabilities are essential for optimizing ablation parameters, ensuring selective heating of the tumour while preserving surrounding healthy tissue.

As for radiotherapy, a key challenge lies in the real-time evaluation of both radiation dose and spatial dose distribution during in-vivo treatments. Conventional dosimetry methods evaluate one of the two parameters only; moreover, they are not suited for

real-time in-vivo applications. To overcome these limitations, optical fibre-based dosimeters were developed using specially doped silica fibres to improve sensitivity to ionizing radiation. Multiple sensor architectures were explored, including both distributed and quasi-distributed configurations. Distributed sensors, while capable of mapping spatial dose profiles, are constrained by the limited acquisition speed of optical frequency-domain reflectometry (OFDR). In contrast, quasi-distributed sensors, based on arrays of FBGs or single-mode–multimode–single-mode (SMS) structures, offer higher temporal resolution and achieve sensitivities of up to $0.2\,\mathrm{pm/Gy}$, albeit with very limited spatial resolution.