A fiber optic probe for thermal therapy

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***Abstract*—We demonstrate a novel fiber optic device for controlled generation of photothermal effects. The fiber probe is pumped by a laser diode and incorporates polymer composites allowing to generate highly localized heat and obtain temperature measurements simultaneously. We analyze the temperature field in the vicinity of the device through computer simulations and these are validated with experimental measurements.**

Keywords—Optical fiber devices, optical fiber sensors, photoactive polymers, thermal therapy.

I. Introduction

Thermal therapies have shown good potential for reducing the collateral effects observed in traditional cancer treatments. Since heat can induce different physiological effects leading to cellular death, a tumor may be reduced in size (or even destroyed) through heat exposure [1, 2]. Laser light has shown excellent performance for achieving highly localized heating and induce cellular death [2, 3]. This so-called photothermal therapy (PTT), may also be carried out with optical fibers to perform interstitial thermotherapy. With this approach, light can be delivered to intricated locations within the body, allowing for treating inoperable or deep-seated tumors (e.g., brain tumors) [4]. PTT is based on light absorption by the tissue, and for some cases, high laser powers (> 1 W) and long exposure times (several minutes) are required to circumvent the low absorption of some types of tissues. Alternatively, exogenous absorbers such as gold nanoparticles or carbon nanotubes have been used as "nano-heaters" owing to their enhanced optical absorption [5]. These nanomaterials allow for using low power lasers and short exposure times (a few seconds) to trigger cell death [5, 6]. However, high-power lasers may produce undesirable collateral effects, and the use of nanoparticles in biological systems is still under debate owing to their potential toxicity. In this work, we present advances in the development of a laser diode-pumped, fiber-optic photothermal (FO-PTT) probe incorporating polymeric materials for heat generation and temperature sensing. The device is intended for thermal therapy and uses a silica multimode optical fiber tip to allocate two different polymer composites: one based on carbon nanopowder (CNP) for heat generation and one with rare-earth powders for fluorescence temperature measurements. Since the CNP is contained within the polymer matrix, the photothermal composite avoids the dissemination of carbon nanostructures within heating zone. As demonstrated with experiments and numerical simulations, the proposed FO-PTT probe allows for highly localized heat generation and further provides temperature readings simultaneously.

II. Probe Fabrication

Fig. 1 shows the FO-PTT probe; it uses an optical fiber tip formed upon fusing the claddings of two standard multimode fibers (62.5 μm core diameter). The dual fiber optic tip is then inserted and glued in a standard 21G needle to provide mechanical strength to the fibers. This reinforced fiber tip is then inserted into a glass capillary for allocating the polymer composites as described below. Since the cores of the fibers are not fused, one of them serves for pumping the composites and the other for collecting the fluorescence from the temperature sensitive polymer (see Fig. 1).

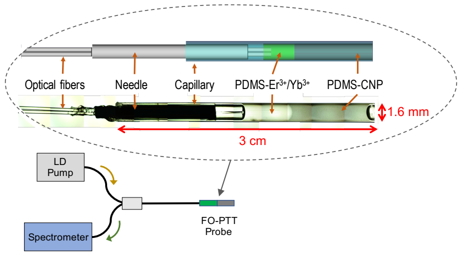

Fig. 1. Schematic representation (above) and actual image (below) of the fiber-optic photothermal (FO-PTT) probe. The probe includes a photothermal polymer composite for heat generation (PDMS-CNP) and a fluorescent compound for temperature measurements (PDMS-Er^{3+}/Yb^{3+}).

The photothermal polymer composite used for the probe is obtained upon mixing carbon nanopowder (CNP, Sigma Aldrich, 633100) with polydimethylsiloxane (PDMS, Dow Corning, Sylgard 184). The mixing procedure has been previously reported for fabricating PDMS membranes showing photothermal effects [7]. These composites show a linear increase in temperature as a function of the laser power. The same mixing method is also used to obtain the temperature sensitive composite but replacing the CNPS with sodium yttrium fluoride powder doped with Yb^{+3} and Er^{+3} (Sigma Aldrich 756555). This Er^{+3}/Yb^{+3} composite shows efficient up-conversion (UC) emission pumped by infrared (IR) light and has been previously demonstrated as a suitable material for fiber optic fluorescent thermometry [8]. The concentrations for the CNP and the fluorescent powder used for the composites were respectively 0.05% and 1% in weight. After mixing, both composites are blended with the PDMS curing agent in a 1:10 ratio and poured into the glass capillary. As depicted in Fig. 1, the Er^{+3}/Yb^{+3} composite is poured first followed by the photothermal polymer. The device is finally placed in an oven and cured at 90 °C during 2 hours, resulting in a FO-PTT probe with suitable dimensions (see Fig. 1) for insertion into a 13G catheter.

III. Probe Characterization and Results

Pumping and interrogation of the FO-PTT probe is performed with a laser diode (975 nm, Thorlabs) and a solid-state spectrometer (Ocean Optics, USB4000), respectively. The pump signal first reaches the Er^{+3}/Yb^{+3} composite producing UC emission; the residual pump is then absorbed by the photothermal composite and heat is generated through optical absorption by the CNP. The temperature of the probe is obtained using the fluorescence intensity ratio (FIR) technique, which is based on taking the ratio of two spectral bands of the fluorescence signal [8]. The FIR varies linearly with temperature, providing a simple means for monitoring this parameter as a function of the pump power.

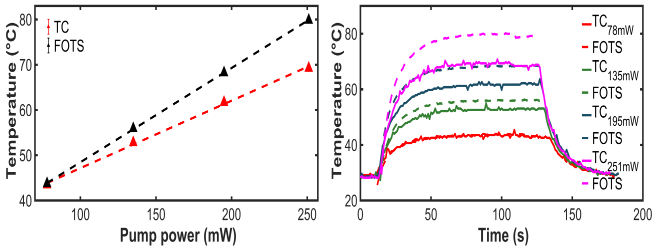

Fig. 2. Left: Temperature of the FO-PTT probe as a function of pump power obtained with the fluorescence reading (FOTS) and with an external thermocouple (TC). Right: time response of the FOTS compared to the TC reading.

The photothermal features of the FO-PTT probe were evaluated by measuring the temperature as a function of the pump power. For comparison purposes, an external thermocouple (TC) was placed in contact with the glass capillary of the device. Fig. 2 shows the temperature reading obtained from the fluorescence signal and with the TC. Clearly, the temperature increases linearly with pump power reaching up to 80 °C for a pump power of ~ 250 mW. As the pump power increases, the reading from the TC differs from the fluorescence temperature measurements, suggesting that the temperature drops sharply away from the center of the probe. The time response was also evaluated and as shown in Fig. 2, the temperature reading obtained with the fluorescence signal tracks very closely the TC reading. For these measurements, the temperature readings from both devices (TC and fluorescence) showed some differences as well.

In order to obtain the full temperature field, T, in the vicinity of the FO-PTT probe, we solved numerically the steady energy equation containing a heat generation term (Q_{gen}), which includes photothermal conversion parameters. Simulations were run in axisymmetric coordinates (r, z) using a ray optics representation of the light beam coming out from the optical fiber (I_0 distribution) and using Snell's law to calculate the optical path as the light beam crosses media interfaces with different refractive indices (n_i). We therefore solved the steady energy equation:

$$\nabla \cdot (-k\nabla T) = Q_{gen} \quad (1)$$

having a heat generation term of the form:

$$Q_{gen} = \eta_{eff}\kappa_2 I_0 \mathrm{e}^{[-\kappa_2(z-z_0)-r^2/A]} \quad (2)$$

where: $A = w^2/2$, $I_0 = P_0\mathrm{e}^{-\kappa_1 z_0}/(A\pi)$. These equations describe an irradiation zone with an intensity profile coming out from the fiber at z_0 and having a divergence radius of $w = w_0 + z\tan(\theta)$, considering the numerical aperture of the optical fiber $NA = n_i \sin(\theta)$. P_0 is the optical power from the laser diode, which is first absorbed by the Er^{+3}/Yb^{+3} layer (extinction coefficient κ_1) without the photothermal effect. The residual pump then enters the active PDMS-CNP layer having an extinction coefficient κ_2 and inducing heat generation with a specified photothermal conversion efficiency η_{eff}. Heat is then dissipated in the surrounding media applying proper boundary (Robin) conditions.

As shown in Fig. 3, the temperature drops sharply away from the device. We further found that the increase in temperature inside the probe is larger when the surrounding medium is air compared to the results obtained using water. This is due to the fact that water has a higher thermal conductivity than air, limiting the accumulation of heat inside the device. The temperature fields were also obtained experimentally using laser induced fluorescence thermometry (LIFT) [9]. As seen in the images included in Fig. 3, the temperature profiles in the vicinity of the probe closely resemble those obtained with the numerical model.

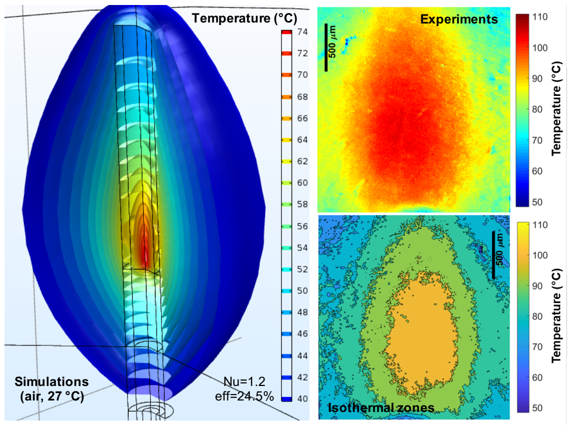

Fig. 3. Temperature profiles in the vicinity of the FO-PTT probe obtained through computer simulations (left) and experimental results obtained with laser-induced fluorescent thermometry (right).

IV. Conclusions

We have demonstrated a novel FO-PTT probe which may find applications in thermal therapies. The increase in temperature can be controlled with the laser pump power and temperature readings can be obtained simultaneously. This "heat source" in a fiber can provide a novel means to perform interstitial therapy.

Acknowledgments

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