Optical sensor for heat conduction measurement in biological tissue

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Abstract. This paper presents the design of a heat flux sensor using an optical fiber system to measure heat conduction in biological tissues. This optoelectronic device is based on the photothermal beam deflection of a laser beam travelling in an acrylic slab this deflection is measured with a fiber optic angle sensor. We measure heat conduction in biological samples with high repeatability and sensitivity enough to detect differences in tissues from three chicken organs. This technique could provide important information of vital organ function as well as the detect modifications due to degenerative diseases or physical damage caused by medications or therapies.

1. Introduction

Biomedical science and practical medicine demand innovative and cutting edge techniques for early and accurate diagnosis of diseases. Assessing the state of a tissue may be carried out to characterize the heat conduction therein\(^1,2\). The thermal properties can determine the physical characteristics of biological tissues\(^3\) and thus may be associated with morphological and compositional changes caused by various degenerative processes. This work is aimed to demonstrate the feasibility of this technique to be applied in the area of biophotonics for characterizing heat conduction in biological tissue using a device based on the photothermal deflection phenomenon in an optical integrated device offering an alternative technique to characterize tissue properties with respect to actual qualitative microscopic tests performed in clinical ambiances for identifying alterations in tissues.

2. Design and characterization of optical sensor

The proposed device is based on the photothermal deflection of a laser beam propagating in a slab of thermo-optical material, acrylic for instance, in which is applied a temperature gradient that causes the beam to be deflected to the coldest section of the slab. The deflection is a function of the temperature gradient so it is also a function of the heat applied to one of the block sides perpendicular to the axe of propagation. The deflecting angle is measured with an intensity modulated fiber optic angle sensor. This optoelectronic device quantifies the power change of a light beam caused by a decoupling of the modal profile in optical fibers, due to the deflection that arises when it travels through the thermo-optic material exposed to a temperature gradient. In this case the lateral deflection angle \(\theta\) may be approximated as,
\[ \theta = \frac{1}{n} \frac{dn}{dT} \int \nabla T(x,t) \cdot dz , \]  

where \( n \) is the refractive index and \( \frac{dn}{dT} \) is the thermo-optical coefficient of the acrylic block respectively. \( \nabla T \) is the temperature gradient given by:

\[ \nabla T(x,t) = -\rho \frac{\partial Q}{\partial x} - \rho c \frac{\partial T}{\partial t} , \]  

In this expression \( \rho \) is the density and \( c \) is the specific heat capacity of the block material.

The experimental setup of the heat flux sensor is shown in Figure 1. It is composed of a laser source at the wavelength of 1550 nm, an optical fiber for signal transmission at the input and output with a collimator at its butt (two identical collimator lens) to ensure negligible divergence angle along the optical path. Located between the collimating lens pair is a thermo-optic material, specifically a clear acrylic block, selected because of its high thermo-optic coefficient (\( \frac{dn}{dT} \)), easy manufacturing and low cost. The device uses a pair of plates to align the input and output sides of the block to be perpendicular to the beam path in order to achieve normal incidence and avoid light reflection. Light at the output is then collected by the output fiber and measured with a Si photodetector interfaced with a computer.

![Figure 1. Heat flux optical sensor experimental setup.](image)

Initially we characterize the optical sensor response applying a heat pulse of \( Q = 5.03 \text{ [mW/cm}^2\text{]} \) during 410 [s]; for this, the heat source is turned on for 80 [s] and turned off at 490 [s]. Each measurement was registered until 1050 [s] elapsed to register the recovery of the signal during cooling. We consider a time before \( t = 20 \text{ [s]} \) in order to monitor the stability of the system. Then we make a repeatability test with three monitoring of the sensor response under the same conditions, as we show in the Figure 2.
We made a calibration test monitoring the output power response for three different heat values applied as source $Q_s$. In Figure 3, we show the experimental calibration curves of the sensing system, when the medium at the boundary acrylic block is an air gap in between. As in the previous test the heat source is turned on at time $t_{on} = 10$ [s] and turned off at time $t_{off} = 420$ [s] and registered until $1050$ [s] elapsed.

In results shown in Figure 3, at the moment when the white light lamp is turned on, it causes the deflection of the beam as heat flows through the acrylic slab. The optical output power undergoes a progressive decrease even after the heat is turned off at time $t_{off} = 420$ [s], as a result of thermal inertia presented in acrylic material. Then, the beam begins to correct the skew angle and causes the gradual increase of the output power. Using these results to characterize the thermal source, we calculated the power decrease $\Delta P$ in the output signal by the heat flow $Q_s$ applied by the thermal source, measured in the range of $10$ [s] to $250$[s] of curves in Figure 3. We plotted $\Delta P$ values versus $Q_s$ shown in Figure 4:
3. Measurement of heat conduction in biological tissues

To demonstrate the sensitivity of our device to characterize thermal properties of biological tissues, we measure heat conduction in three different commercial chicken tissue (heart, liver, gizzard), applying a heat pulse of $Q=4.221 \text{ [mW/cm}^2]\text{]$ during 420 [s]. A thin tissue layer was placed between the heat source and the acrylic slab. The thickness of the tissue layer was about 1 mm. Results are shown in Figure 5.
One can see in Figure 5 that the three tissues have different thermal conduction behaviour that is expressed as a different slope and power decrease. The chicken heart had the highest heat conduction rate while the liver had a medium rate and the gizzard had the lowest rate. We consider these variations could be caused by their composition and structure, it was also been reported the strong relation of water content with thermal conductivity\(^4\). The heat flux sensor’s has a good sensitivity to detect differences in thermal behaviour that characterizes each type of tissue once it has been exposed to a certain heat flux.

4. Discussion

Heat flow measurement technique proposed in this work operates with high sensitivity and resolution to detect differences in thermal properties in biological tissues through the measurement of heat conduction using an integrated optical beam deflection device. This device could identify structural or compositional changes in tissues due to a degenerative disease or certain medications. The potential of this optical integrated device is to quantify from the heat conduction curves, with the aid of a heat diffusion numerical method thermal properties, as effusivity, diffusivity and thermal conductivity of biological tissues that could be used in clinical studies.

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