Optical Characterization of Thermal Properties of Biological Tissue

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ABSTRACT

In this work we utilize heat conduction measurements trough the photothermal beam deflection technique to characterize thermal properties of biological tissue. We design a heat flux sensor based on the phenomenon of photo-thermal laser beam deflection within a thermo-optic slab (acrylic), where the deflection is quantified by an optical fiber angle sensor. We analytically model the heat flux sensor response based on heat wave propagation theory that well agree with experimental data. We present heat conduction measurements on different tissues applying a heat pulse. Hence we obtain the thermal effusivity coefficient of bovine tendon and chicken liver and heart. It has been shown that thermal conduction depends on the tissue´s chemical composition as well on their structural arrangements, so any modification in tissue will affect on heat conduction rendering this method potentially useful as an auxiliary in biomedical studies. Nowadays there are several thermal effusivity and diffusivity measurement techniques with classic calorimetry (using thermistors) for research and industrial applications. However there are only few integrated optical devices already proposed, turning this optical technique in an innovative and alternative sensing system for thermal properties characterization.
Keywords: Thermal diffusivity, photothermal beam deflection, heat flux, collagen.

1. INTRODUCTION

Heat conduction capacity in any material is related to their composition and the way their molecules are arranged, its means their structure. In biological tissues it is possible to identify a sample characterizing his thermal behavior. This research aims to analyze directional heat conduction in biological tissue, where the biochemical composition is the same but the structure is different, so that require cutting the organic sample in different directions. Results are expected to differ significantly in order to identify each tissue according to their sense of dissection.

Currently there are some studies evaluating thermal properties in materials, some others particularly measure in human or animal tissues. These studies propose different measurement techniques than this project, they present experimental systems based on thermistors and photoacoustic techniques[2,3]. In this paper, we present an experimental system for measuring tissue´s thermal properties based on the phenomenon of thermal beam deflection, in which the mean element is a heat flux sensor implemented in optical fiber setup and assembly by a fiber angle sensor[1] that quantifies the change of light output power caused by the modal profile decoupling in optical fibers, due to the deflection experimented by a laser beam when it travels within a the thermo-optical material exposed to a temperature gradient, varying only in one direction of the coordinate system, thus we refer to this thermal gradient component as the T_x field.

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2. PHOTOTHERMAL BEAM DEFLECTION IN INTEGRATED OPTICS

Measuring the photothermal beam deflection within an acrylic block by effect a temperature gradient is the working principle of the heat flux sensor, and this phenomenon is described in this section.

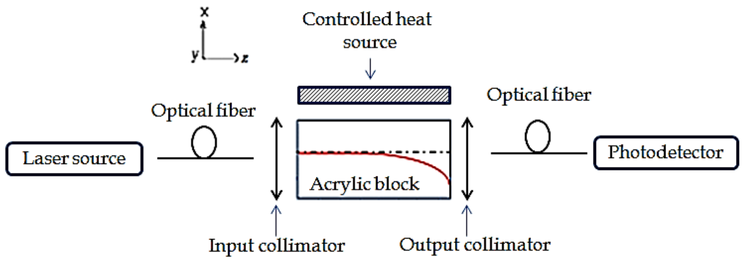

Figure 1. Photothermal beam deflection within an acrylic slab scheme.

In Figure 1 we illustrate the photothermal beam deflection phenomenon within an acrylic slab, in which we apply an uniform heat flux Q with a calibrated thermal source; this generated heat set a temperature difference between the parallel faces of the slab in the propagation axis z, which causes a one-dimensional temperature gradient T_x. Consequently this thermo-optical material undergoes a molecular expansion causing a refractive index gradient $\eta\ (x)$, and given that the laser beam propagates in this medium, it causes an angular deviation on the optical path, therefore the laser beam is deflected to colder and higher refractive index region.

This phenomenon can be quantified using a heat flux sensor in integrated optics, which is assembled by a laser source, optical fiber for signal transmission and collimation system (two identical collimator lens) to ensure negligible divergence angle along the optical path, the acrylic slab is located between the collimating lenses. We selected acrylic because it has a thermo-optical coefficient ($dn\ /\ dT$) higher than glass. The sensing system presents a pair of plates that align and hold the slab, to achieve normal incidence (0 °) between the input slab face an the optical axis , it also provide a greater mechanical stability in the sensing system. Finally the light signal is sent from a photodetector to a computer interface for the acquired data.

3. THERMAL WAVES THEORY

Thermal wave concept is originated for describing the heat transfer behavior as a harmonic heat flow. Let us assume a heat flow producing a temperature gradient ∇T, we only consider the heat flow varying along the X direction (constant in the plane YZ) crossing within the acrylic slab in the half of the face. Given that the photothermal beam deflection phenomenon assumes thermal gradient the existence, the non-zero component in this gradient define the Tx field, which is given by the expression:

$$\nabla T = \frac{\partial T}{\partial x}\hat{a}x + \cancelto{0}{\frac{\partial T}{\partial y}}\hat{a}y + \cancelto{0}{\frac{\partial T}{\partial z}}\hat{a}z \qquad (1)$$

and

$$T_x \equiv \frac{\partial T}{\partial x} \qquad (2)$$

Then a scheme is proposed in Figure 2, in which there are three bounded media, so the thermal wave propagates in the intermediate Medium 1, the heat will be applied on the external Medium 0. The remaining Medium 2 importance is about the thermal impedance established with Medium 1 and will be defined their thermal effusivity ratio. Each medium is characterized by thermal properties inherent in their nature, which define the structure and characteristics that differ with respect to other materials. Such thermal properties mentioned above (efussivity e, diffusivity α, conductivity k), are independently involved in the heat propagation. Other physical attributes which also affect the field T_x are the size of the Medium 1 and the distance in which the laser beam propagates (X axis).

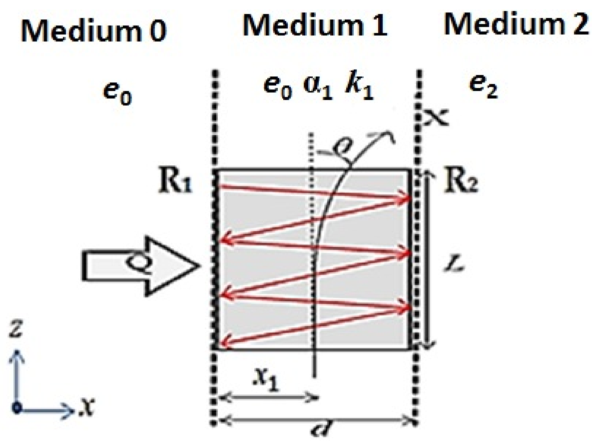

Figure 2. Thermal wave model scheme.

Effusivity intervention is essential on treating the thermal wave model, from this thermal property depend the reflection coefficients R_i that regulate the intensity of heat propagation through the analyzed medium. Eventually the heat wave has an infinite number of reflections in the Medium 1 and thus will establish the T_x field propagation.

The T_x field due to a thermal step in time applied to the surface of the acrylic slab is modeled from a semi-infinite medium that reflect back and forth between the two interfaces within the acrylic block (Medium 1). The expression to define Tx field propagation in the direction x at time t with m reflections is given by[4]:

$$T_x = -\frac{Q}{k_1}\sum_{m=0}^{\infty}\left(R_2R_1\right)^m\left[1-erf\left(\frac{\left(2md+x\right)}{2}\sqrt{\frac{1}{\alpha_1 t}}\right)-R_2\left\{1-erf\left(\frac{\left[2\left(m+1\right)d-x\right]}{2}\sqrt{\frac{1}{\alpha_1 t}}\right)\right\}\right] \qquad (3)$$

where R_1 and R_2 are the reflection coefficients of thermal wave at x = 0 and x = d respectively, and the superscript S is used to indicate that the thermal step in time is considered.

$$R_1 = \frac{1-b_{10}}{1+b_{10}} \qquad (4..1) \qquad\qquad R_2 = \frac{1-b_{12}}{1+b_{12}} \qquad (4.2)$$

which defines the effusivity e is the magnitude which quantifies a material's ability to exchange heat with the environment in an unsteady (transient conditions) is therefore considered as a measure of thermal impedance should be noted that the heat flow is proportional to this property transient conditions in contrast where the steady state is proportional to the thermal conductivity. This property is relevant heat transport in the heating and cooling of the surface of the materials, as well as cooling processes. It is one of the least explored physical quantities and therefore rarely appears in tables reported thermal properties. The expression that describes it is given by:

$$e=\sqrt{\rho c k} \qquad (5)$$

and is included in the coefficients R1 and R2 by the expressions:

$b_{10}= e_0/e_1$ (6.1) $b_{12}= e_2/e_1$ (6.2)

finally ρ corresponds to the material density and c the heat capacity.

In the thermal wave model we consider a heat pulse, that occurs when the heat source is turned on at t=0 [s] and turn it off in t=t_{off}, therefore should be considered a negative amplitude thermal pulse. Then the solution for a heat pulse of finite duration is:

$$T_x(x,t)=T_x^S(x,t)-U(t-t_{off})T_x^S(x,t-t_{off}) \tag{7}$$

4. HEAT CONDUCTION IN BIOLOGICAL TISSUE

Experimentally the measurement procedure of photothermal beam deflection in the acrylic slab involves placing it at a certain distance with respect to the thermal source, then we adjust the position of the slab in order to obtain the maximum transmittance signal. Subsequently we initiate tests to monitor the output power of the transmitted laser beam, where the heat source is activated at 20 [s] (time interval in which to evaluate the stability of the light signal), then we keep it turn on for 410 [s] (heating process) and at this moment the power is turned off (t_{off}). We monitoring the signal up to 1050 [s]. To perform the following measurements is necessary to keep a recovery period in which the light signal returns to baseline.

The first results we report in this paper is the repeatability test, in which we look for ta similar response when we measure heat conduction in bovine tendon under the same experimental conditions. We applied a heat pulse of Q=4.88[mW/cm^2] for 410 seconds, then turn off the heat source and monitor the output signal to 1050[s]. These results are shown in Figure 3.

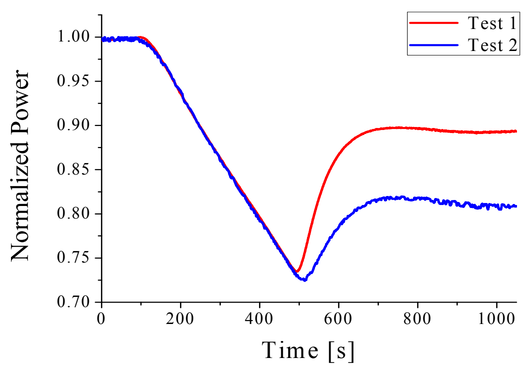

Figure 3. Repeatability test for heat conduction in tissue.

In the results shown in Figure 3 we demonstrate the good repeatability for the experimental system measuring the heat conduction and thus we can proceed with the sensor´s calibration. The heat applied provides an expected a power output decrease (due to modal decoupling explained above), then when the heat source is removed from the system, there is a slight thermal inertia and finally the signal starts to recover to the baseline power slower than in the heating process.

We proposed thermal wave model to calculate the effusivity value of materials therefore experimental calibration scheme assumes the air as Medium 0 and Medium 2, given its known thermal effusivity coefficient and it was extracted from the literature (e_{aire} = 5.5 [Ws$^{1/2}$/m^{2}K]). Medium 1 is the acrylic slab, within it the thermal wave reflections are transmitted for heat propagation, eventually causing the deflection of the laser beam. For acrylic we know k_1 = 0.188 [W / mK], α_1 = 0.11x10^{-6} [m^2/s], e_1=150 [Ws$^{1/2}$/m^{2}K]. Once again we applied a heat pulse Q=4.88[mW/cm^2] for 410 [s] and the signal will be measured up to 1050 [s]. Afterwards the experimental results will be fitted by the theoretical curve.

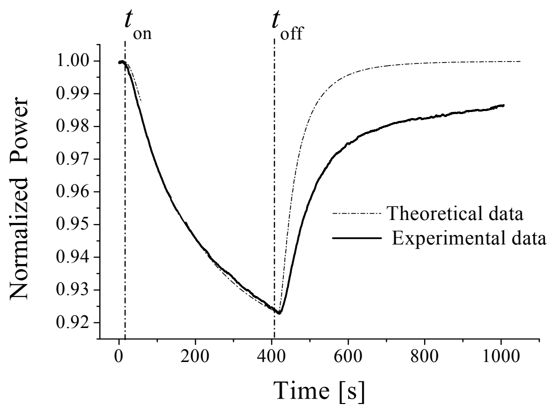

Figure 4. Heat flux sensor´s calibration curve.

The calculated theoretical curves represent an artifice of good accuracy in the experimental results fitting for the time in which the heat source is turn on (heating process), contrary to what happens during the process where the block cooled and the output power begins to return to baseline. In this cooling process, the thermal wave model does not consider enough elements to represent a good accuracy fitting tool, so we calculate effusivity coefficients of biological tissues in the range t = 20-430 [s], lapse in which we have data enough to fit to the experimental curves.

Heat conduction in the biological tissue measurements were made to show the potential of this technique to be applied in the area of photonics. In these experimental tests a tissue slice with thickness of approximately 1 [mm] was placed in contact with the acrylic slab, so new experimental assembly considers the biological sample as Medium 0, and it was heated by the calibrated heat source. Then we apply a heat flux value Q and we monitored the heat conduction in the tissue slice by measuring the decrease of output power due to the beam deflected in the acrylic slab.

So the thermal effusivity coefficient (biological tissue) e_0 is calculated from the fitting theoretical curves to the experimental results. Diffusivity values α_1 and thermal conductivity k_1 remain constant during experimental tests because they are the thermal properties of acrylic (medium 1). The tissue under study in this article is the bovine tendon, in which we will measure directional heat conduction given two senses in the cut. Both tests were made with the same experimental conditions, applying Q=4.88[mW/cm^2]. The results curves are shown in Figures 5 (a) and (b).

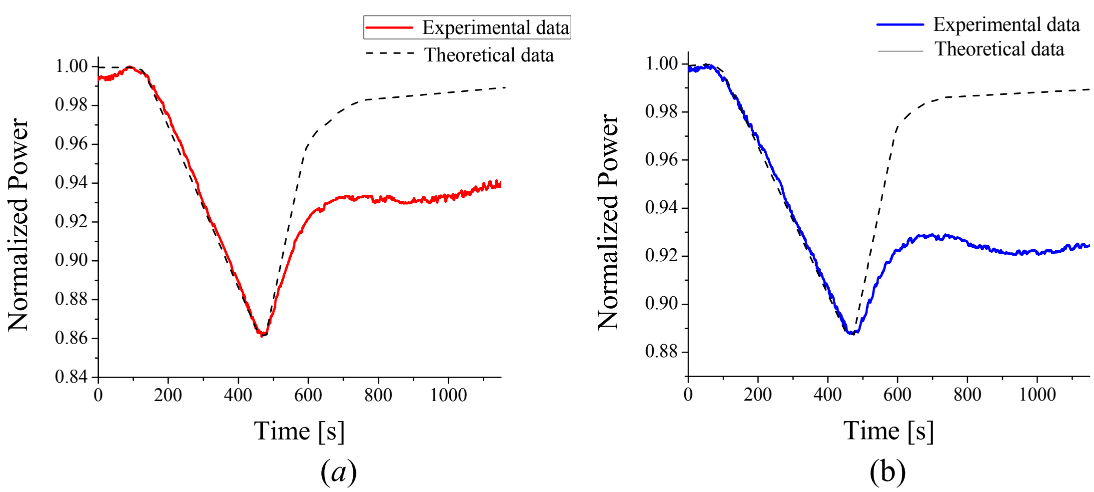

Figure 5. Heat flow measurements in bovine tendon. (a) Sample with vertical sense cut. (b) Sample with horizontal sense cut

The horizontal cut in bovine tendon is one that follows the direction of the fibers, and as a result has a higher heat conduction than the vertical cut which is perpendicular to the fiber direction. Finally the theoretical fitting allowed us calculate effusivity for both samples and the results are shown in Table 1:

Tissue	Effusivity [[$Ws^{1/2}m^{-2}K^{-1}$]
Horizontal slice	18.0
Vertical slice	15.7

Table 1. Effusivity coefficients in bovine tendon for directional heat conduction measurements.

CONCLUSION

We presented an application in the area of biophotonics using the photothermal beam deflection technique in integrated optics, which presents a good sensitivity and repeatability, with suitable parameters for heat flow measurements in biological tissue. The results obtained testing directional heat conduction in bovine tendon allowed to differentiate and identify vertical and horizontal cuts. The effusivity coefficient in the horizontal slice is greater than the vertical one and we assume it is because there is higher heat conduction in a biological tissue when the cut is performed in the direction of the fibers, therefore it increase the ability of thermal exchange with the bounded Medium.

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