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A Spectroscopic Technique for Local Temperature Measurement in a Micro-Optofluidic System

Manoj K. Sharma, Arjan J.H. Frijns, Rajesh Mandamparambil, David M.J. Smeulders

Abstract— We present a spectroscopy technique to measure temperature locally in a polydimethylsiloxane (PDMS) micro-optofluidic chip with integrated optical fibers and minimal optical components. The device was fabricated in one step with fiber coupler grooves followed by manual integration of the optical fibers. The experimental setup consists of a micro-optofluidic chip with a pair of optical fibers for excitation and fluorescence collection, a laser module and a spectrometer. The laser module is coupled to one of the optical fibers to guide the light into the microchannel. The fluorescence signal is collected by a second integrated optical fiber placed orthogonally. A spectroscopy technique is used to measure the local temperature in a microchannel (500 μm wide and 125 μm in height) using Rhodamine B as a temperature indicator. It is shown that for a flow rate between 200 and 400 μL/min, the local temperature can be determined.

Index Terms— Microfluidics, optical fibers, fluorescence, sensor systems

I. INTRODUCTION

Fluorescence spectroscopy/microscopy is the most sought after technique in chemical and biochemical analysis. The advantages include real time detection, reliability, possibility of single molecule detection and high sensitivity. To this, there has been continuous effort to integrate optical and electrical components for Lab-on-a-chip systems. The design and fabrication of such systems have been broadly researched and reported [1]–[3]. In an integrated system, the optical detection can be implemented by using either optical fibers [4], [5] or planar waveguides [6], [7]. Though the fabrication of a polymeric waveguide is relatively easy, the fiber alignment of the waveguide to the light source and detector components is crucial. Optical fibers integration overcomes this problem due to the availability of commercial products like laser coupled fibers and LEDs. Also, the extensive availability of fiber optic devices (couplers, power splitter, and multiplexers) adds to the flexibility and functionality of the optical detection unit.

Regulating temperature is an important parameter in microfluidic systems involving physical, chemical or biological applications [8], [9]. Conventionally, the temperature measurement in a microfluidic system is implemented using laser induced fluorescence or confocal microscopy [10]–[13]. Even though such systems demonstrate good spatial and temporal resolution, it requires bulk optical components like lenses, filters and microscope objectives. The use of such bulk optics makes the whole system unportable. Our objective is to use a simple and reliable method to measure temperature locally with minimal optical components. Therefore, in this article, we present a technique to measure local temperature in a micro-optofluidic device using a simple spectroscopic technique. The device has been fabricated in polydimethylsiloxane (PDMS) using soft lithography approach [14]. It consists of a microchannel (500 μm wide and 125 μm in height) and optical fiber coupler grooves (125 μm wide and 125 μm in height).

Similar techniques of embedding optical fibers have been researched and described in literature. Hartmann et al. [15] fabricated planar interconnect channels and inserted capillaries, optical fibers and wires into these channels. UV light was then guided into the optical fibers/capillaries followed by wicking of a UV curable glue up the sides of the capillaries or the fibers. The glue was cured by the UV light to form a dam at the end of the capillary/fiber. Kennedy et al. [16], [17] fabricated a hydrodynamic flow cell with fiber insertion guides. This technique required a contact aligner to bond two patterned pieces of PDMS. Ashok et al. [18] designed fiber insertion channels to embed optical fibers into the device by placing pieces of fibers on the mold (silicon substrate) and fixing them with UV curable adhesive and Xu et al. [19] designed a fiber insertion channel to integrate optical fibers into their device. They used a drop of degassed PDMS to seal the fiber in the insertion channel which also acts like a cladding layer.

Even though the technique described in present paper is similar to the above mentioned work, it differs in that the microchannel and fiber coupler grooves were fabricated in one step instead of multiple production steps and the excitation and fluorescence collection fibers are in direct contact with the fluid. Also, we use a spectroscopy technique to measure the temperature locally in a microchannel with minimal optical components: no additional lenses or filters are needed. The minimal detection assembly unit makes it an ideal setup for temperature measurement in applications like PCR amplification, but can also be used for other applications using fluorescent dyes or markers. Rhodamine B (RhB) with water as a working fluid is an extensively used temperature-sensitive dye. The change in emission intensity is due to the temperature dependence of the RhB quantum yield [10], [13]. Therefore, for the characterization of the fabricated micro-optofluidic device, we also use Rhodamine B (Sigma Aldrich) as a temperature indicator in our experiments.

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II. Device Fabrication

The fabrication process was completed in two parts: (i) the microchannel fabrication with fiber coupler grooves and (ii) the optical fibers integration and sealing them at the end with an optical adhesive (NOA81). In brief, an epoxy based negative photoresist (SU8-2050) was spin coated (layer thickness $H = 125 \mu m$) on a standard 4 inch silicon wafer to fabricate a master mold for the microfluidic channels and optical fiber coupler grooves. The master mold was patterned using the standard photolithography process. Once the master mold was fabricated, PDMS prepolymer (Sylgard 184) in the ratio of 10:1 (base polymer: curing agent) was prepared, degassed in a desiccator connected to a vacuum pump and poured over the master mold. It was then cured in an oven at 65 °C for two hours. Afterwards, the microfluidic channel system was peeled carefully from the master. Fluid inlet and outlet were made using a circular metal punch of 1.2 mm diameter. The device was then sealed to another thin layer (2 mm) of cured PDMS using oxygen plasma based procedure [20]. Commercially available silica clad glass fibers (Thorlabs) of 50 µm and 105 µm core diameters (125 µm including cladding layer and 250 µm including coating layer) were used. Before insertion their protective coating was stripped off and they were cleaned with wipes. Then, the fibers were inserted inside the coupler grooves. The fibers were aligned to the microchannel through these coupler grooves manually under a microscope. Few drops of an optically curable adhesive (NOA 81) were put at the end of the grooves and to be drawn inside by capillary forces. Once the adhesive reached the end of the grooves, the system was illuminated with a handheld UV light source (Thorlabs) to seal the optical fibers. The stability of the fiber inserted inside the coupler grooves was tested by pulling the fiber. Once it was sealed, the fiber was stable and no further alignment was needed.

The optical fiber for fluorescence recording was placed orthogonally at a distance of 200 µm from the illumination fiber so that the incoming laser light was not directly transmitted into the recorder fiber. Figure 1(a) shows the geometry of the fluidic system and fiber coupler grooves for excitation and fluorescence collection and Fig. 1(b) shows a fabricated device with integrated optical fibers.

Fig. 1. (a) Fluidic system of the device with fiber coupler grooves and (b) fabricated device with inserted optical fibers. The channel height is 125 µm.

III. Experimental Setup

A diode pumped solid state laser (DPSS) module (Thorlabs) operating at a wavelength of 532 nm with a maximum output power of 4.5 mW was used as an excitation source. The optical fiber for illumination was coupled to the laser source through a SMA connector. A conventional spectrometer (Ocean Optics) was used to record the fluorescence signal and a syringe pump (Harvard, PHD2000) to pump the RhB dye solution. The inlet tubing, coming from the syringe, was coiled into a petri dish, placed on a hot plate and filled with water. In this way the RhB solution was heated before entering the microchannel. Two thermocouples, one at inlet and another at outlet were employed to measure the incoming and outgoing temperatures. A schematic of the entire setup is shown in Fig. 2.

As mentioned by others [16], [19] and also seen in this experimental setup, this orthogonal fiber arrangement eradicates the need of an optical positioner for fiber alignment. Also, the fiber is in direct contact with the fluid medium eliminating the losses due to optical distortions. An aqueous solution of RhB (0.1 mM) prepared using deionized water from a Millipore MilliQ system serves as a fluorescence sample. All measurements were performed at room temperature.

IV. Results

Our aim is to measure locally the temperature in real time in a flowing medium. Therefore, the fluorescence detection system was tested for varying flow rates. The emission intensity at a flow rate of zero (no-flow), 50µL/min, 100µL/min, 200µL/min, 300µL/min and 400µL/min were recorded. Three independent measurements were conducted and the emission intensity was normalized by its value at zero flow. In Fig. 3, the normalized fluorescence emission intensity is plotted against flow rate. It is observed that the fluorescence intensity increases with increasing flow rates. The increase is about 14% between zero and 200µL/min, while the increase between 200µL/min and 400µL/min is only 4%.

Fig. 2. Schematic of the experimental setup showing the optical components and micro-optofluidic device.

Fig. 3. Normalized fluorescence intensity response as function of the flow rate in the micro-optofluidic chip. The error bars indicate the standard error.
The response of fluorescence intensity on flow speed has been reported previously using different dyes. Haidekker et al. [21] explained the change in emission intensity via shear stress using a fluorescent molecular rotor. Wang et al. [22] argued that the change in fluorescence emission intensity was due to so-called photobleaching. We investigated the effect of photobleaching in our device configuration. For a no-flow condition, the microchannel was filled with the dye solution and the laser was turned on for 10 minutes continuously. The recorded fluorescence intensity is plotted in Fig. 4 (lower line). No signal normalization is applied. A small photobleaching (around 6%) occurs over 10 minutes in a no-flow situation. Next, the flow rate was increased from 50µl/min to 400µl/min. For each measurement, the dye solution was first flushed and then the laser was turned on for 10 minutes continuously.

Next, the laser was turned off and a new batch of solution was introduced into the channel before turning on the laser again. The recorded fluorescence intensity is plotted against time in Fig. 4. For the flowing conditions, a small increase in fluorescence intensity with increasing flow rates is seen. But, at a given flow rate the emission intensity does hardly change over time. This indicates that in the flowing medium, photobleaching does not play a large role in this optical detection configuration. This is also supported by the fact that the residence time in the area of observation is in the range of milliseconds and it decreases with increasing flow rate.

Since the change in fluorescence emission is minimum between 200µL/min and 400µL/min, we chose to perform our temperature measurements at mid value of 300µL/min. The RhB dye solution was carefully filled into a syringe avoiding any air bubbles. The starting temperature (27°C) was chosen to be slightly above room temperature. The temperature was increased gradually to 50°C and the corresponding emission intensity was recorded in real time. The maximum temperature difference noted by the thermocouples placed at the inlet and the outlet of the device was 2°C. The average temperature between the two thermocouples was used. Above 50°C, air bubbles started appearing which resulted in signal fluctuations and therefore these results are not shown here. The emission intensity was normalized by the intensity at 27°C. Figure 5 shows the normalized emission intensity of two independent experiments. The solid line is an exponential fit through the data points of both experiments and is described by:

\[ I(T) = a \exp(bT), \]

where \( I \) is the normalized intensity, \( T \) the prescribed fluid temperature and \( a \) and \( b \) are coefficients with 95% confidence bounds \((a=3.331 \text{ and } b=0.04438^\circ C^{-1})\).

As expected, the measured fluorescence intensity is dependent on temperature. In order to check the effect of RhB adsorption on the temperature measurement, fresh water was flushed through the device after each measurement and the emission intensity was recorded. No emission intensity was observed when only pure water was flowing in the channel. Therefore, it can be concluded that the adsorption did not influence the temperature measurement in this experimental setup and device configuration. Hence, it is possible to monitor temperature in a microfluidic device using simple optical components.

![Fig. 4. Photobleaching of an aqueous solution of Rhodamine B (0.1 mM) measured at room temperature for varying flow rates.](image1)

![Fig. 5. Temperature dependence of the fluorescence emission of Rhodamine B. The solid line is an exponential fit. The circles and triangles represent the measured data for two independent experiments.](image2)

V. CONCLUSION

To conclude, we have reported a micro-optofluidic device with embedded fibers for local temperature measurement in a microchannel. The spectroscopic system is capable of measuring on-chip fluorescence locally in real time using simple optical components. The results for local temperature measurements with a Rhodamine B solution demonstrate the sensitivity of this device for flow rates and temperature dependence fluorescence respectively. We anticipate that the optical detection system demonstrated in this paper can also be used for other applications using fluorescence, like cell counting, particle detection, and on-chip temperature measurement.
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REFERENCES


