UC Irvine

UC Irvine Previously Published Works

Title

Imaging and quantifying of microflow by phase-resolved optical Doppler tomography

Permalink

<https://escholarship.org/uc/item/2p19n057>

Journal

Optics Communications, 232(1-6)

ISSN

0030-4018

Authors

Wang, L
Xu, W
Bachman, M
et al.

Publication Date

2004-03-01

DOI

10.1016/j.optcom.2003.12.060

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Imaging and quantifying of microflow by phase-resolved optical Doppler tomography

Lei Wang^{a,c,*}, Wei Xu^{a,c}, Mark Bachman^{a,b,c},
G.P. Li^{a,b,c}, Zhongping Chen^{a,b,c,d,*}

^a Department of Electrical Engineering and Computer Science, University of California,
1002 Health Science Road, Irvine, CA 92612, USA

^b Department of Biomedical Engineering, Irvine, CA 92612, USA

^c UCI Integrated Nanosystems Research Facility, Irvine, CA 92612, USA

^d Beckman Laser Institute, University of California, Irvine, CA 92612, USA

Received 3 November 2003; received in revised form 5 December 2003; accepted 11 December 2003

Abstract

Phase-resolved optical Doppler tomography (ODT), an imaging technique based on low coherence interferometry, is presented as a new tool to determine electroosmotic flow (EOF) in microfluidic channel. This is a non-contact technique that not only can image cross-sectional EOF profile but also can determine electroosmotic mobility. The electroosmotic coefficient measured by ODT was verified by conventional current monitor method. Since phase-resolved ODT provides cross-sectional imaging of flow velocity, complicated flow dynamics caused by microscale effects such as electrokinetic effects, can be investigated and quantified using this tool, particularly for turbid media such as biofluids, which cannot be readily investigated using other techniques.

© 2003 Published by Elsevier B.V.

PACS: 42.25.Fx; 42.25.Hz; 42.30.Wb; 42.62.Eh; 47.80.+v

Keywords: Interference; Optical Doppler tomography; Microfluidics; Flowmetry

Recently, much interest has been generated in the field of microfluidics. The technology behind the so-called “lab-on-a-chip” is quickly advancing as many research groups focus their efforts to-

wards developing key components for fluidics chips and industry begins to develop them for commercial applications. These devices have potential applications in biotechnology, medicine, pharmaceuticals, environmental science and other fields since they can achieve high sensitive analysis and be multifunctional and mass-produced [1–3]. Furthermore, they require small quantities of reagents for performing analysis and are disposable [4]. In construction of microfluidic devices,

* Corresponding authors. Tel.: +1-9498243576; fax: +1-9498248413.

E-mail addresses: lwang3@uci.edu (L. Wang),
zchen@laser.bli.uci.edu (Z. Chen).

polymers are widely used because they are low cost, inert and available with a variety of material properties. In addition, complicated structures and sophisticated surface modification techniques have been used to improve their fluidic performance [5]. However, these approaches face new issues of optimal fluid control, minimization of dead volumes and unexpected microscale effects such as dynamic coating. In order to understand the resulting flow behavior, several different approaches have been developed to image flow through microchannels. In particle imaging velocimetry (PIV), a fluid is seeded with particle tracers and a flow pattern produced by imaging the tracers over time is used to deduce flow rate [6,7]. This technique can produce velocity field maps over a large region for the flow within the focal plane of the imaging system. A similar approach that does not require particle tracers is to use fluorescent dye tracers instead of scattering particles [8]. However, these techniques provide on-face image instead of cross-sectional image. Nuclear magnetic resonance (NMR) microscopy has also been used to image flow, capable of giving a cross-sectional velocity profile [9]. However, only special particles can be used.

In this paper, we present a flow metrology system based on phase-resolved optical Doppler tomography (ODT) that can produce a cross-sectional velocity image of turbid fluid flow through a microchannel with a spatial resolution of several microns and a velocity sensitivity of 10 $\mu\text{m/s}$ [10,11]. By collecting scattered light from different depths within a sample with its coherent gate, it is capable of projecting and quantifying

cross-sectional velocity profiles of microflow through microchannels, even semi-opaque medium. This technique can complement conventional flow metrology methods and may be particularly useful for studying microflow under complex condition, such as biological fluids and newly developed microchannel materials.

Phase-resolved ODT is based on a Michelson interferometer and employs a broad band light source to provide a coherence gate, which selects back-scattered light from different depths within a sample. A schematic of ODT system is shown in Fig. 1. Light from a super luminescent diode (SLD) is launched into a 2×2 fiber coupler and split into two beams, a reference beam and a sample beam. The reference beam is reflected by a rapid scanning optical delay line (RSOD) [12], and routed back to a detector. The sample beam is directed into a microchannel with moving fluid at an angle with respect to the direction of the flow. This angle is named Doppler angle. The back-scattered light is collected by an objective lens and routed back to the same detector. By the superposition of the reference beam and sample beam an interference pattern is produced, at the point where the optical path-length difference matches the coherence length of the light source. This in turn determines the axial resolution of a phase-resolved ODT system. When the RSOD scans, the coherence length selects different back-scattered light from different depths of the moving fluid. The intensity of the signal is used to construct the structure image of a sample, which is called optical coherence tomographic (OCT) image. The Doppler frequency shift caused by moving fluid is

Fig. 1. Schematic of ODT experiment setup. The insert shows a cross sectional view of microchannels.

extracted by calculating the phase change of two sequential scanning signals at a same location within a scanning period [10,11]. The direction of a flow is determined by the sign of the phase change.

The SLD light source used in the following experiments has a center wavelength of 830 nm and an FWHM of 45 nm, corresponding to a coherence length of 7 μm in air and approximately 5 μm in water. The total power incident on the sample is about 500 μW . An electrical-optical modulator (EOM) was used to introduce a carrier frequency of 500 kHz in order to reduce low frequency noise and get stable phases. A microscope objective lens ($\times 10$) was used to focus light on the sample and collect back-scattered light. In the experiment described here, the interval between two sequential scans was 2 ms, which provided a velocity range about ± 1 mm/s at a Doppler angle of 83.6°C ($\pm$ denotes two opposite flow directions).

The ODT system was used to measure electro-osmotic flow (EOF) seeded with polystyrene beads in polydimethylsiloxane-glass (PDMS-glass) microchannels. The insert in Fig. 1 shows a sectional view of the PDMS-glass microchannel. The microchannel devices were built using standard microfabrication methods [13]. A microchannel (250 μm wide and 30 mm long) was defined lithographically on a silicon wafer substrate. The silicon was etched to 50 μm deep using inductively coupled plasma deep reactive ion etch. This was

used as a mold for casting channels into a soft elastomer material, PDMS. Degassed PDMS mixture was poured over the mold and allowed to cure. The resulting imprinted elastomer was lifted from the mold, access holes are punched at the inlet and outlet of the channel and then the elastomer was pressed against a clean glass slide (PDMS-glass microchannel). Finally, the PDMS device sealed reversibly against the flat surface. No surface treatments such as oxygen plasma or UV grafting were performed.

A mixed solution containing 20 mM phosphate buffer and polystyrene beads with a diameter of 2 μm was prepared for the measurements. Phosphate buffers (20 mM phosphate, pH 7.0) were made from potassium dihydrogenphosphate and adjusted to pH 7.0 with NaOH. The concentration of the polystyrene beads was adjusted to 2%. The resulting solution has large scattering thus turbid.

An EOF measurement was used to demonstrate the capability of phase-resolved ODT system for quantifying microflow dynamics in a $50\text{ }\mu\text{m} \times 250\text{ }\mu\text{m} \times 30\text{ mm}$ (depth $\times$ width $\times$ length) microchannel. Fig. 2 illustrates the structure image of the fluid within microchannel and the EOF cross-sectional velocity profiles of mixed solution in the PDMS-glass microchannel. Panel A shows the structure image of the fluid within the microchannel. The distribution of the fluid can be obtained from this image, assuming that the particle

Fig. 2. Structure image of the fluid and EOF velocity cross-section profiles measured by phase-resolved ODT. External field is 200 V/cm. (a) structure image, (b) phase-resolved ODT image, (c) velocity profile at the center of the channel.

is distributed uniformly in the fluid. Panel B shows the cross-sectional EOF velocity distribution image within the microchannel. In panel B, the velocity direction is color coded (red and blue represents two opposite directions). Positive flow implies that movement is towards the cathode. The driving electrical field was 200 V/cm. In panel B, there are two “dead” corners inside the microchannel, where the EOF velocity may be very small. This may be caused by defects of the microchannel. Panel C shows the velocity profile along the depth at the center of microchannel. This non-parabolic profile corresponds to the plug flow, as expected for EOF. Because, phase-resolved ODT provides cross-sectional velocity information, not only flow rate but also microchannel properties can be measured. This may help optimize and monitor the fabrication of microchannel devices.

In order to confirm the measurement results by phase-resolved ODT system, we compared them with conventional standard measurement technique, i.e. current monitor method. This is done by measuring the EOF at different external electrical fields. Fig. 3 shows the measured average velocity as a function of external electrical field. The same dimension microchannel and electrolyte solution were used. The average velocity was calculated as the sum of the velocity divided by the number of pixels within the microchannel. The electrical fields

Fig. 3. Measured average velocity vs. external electrical field. Corresponding electroosmotic mobility of 20 mM phosphate is $0.9773 \text{ cm}^2/\text{V s}$.

ranged from 33 to 200 V/cm. In Fig. 3, the measured average flow velocity increased linearly with the electrical field, as shown by the linear fit of measured data. By determining the slope from the data, an electroosmotic mobility of the electrolyte is calculated to be $0.9773 \text{ cm}^2/\text{V s}$, which is comparable to the value measured by conventional current monitor method [13]. This confirms that the flow measurement by phase-resolved ODT is as accurate as the conventional method.

In summary, a phase-resolved ODT system has been successfully demonstrated as a flow metrology tool to image cross-sectional flow velocity distribution and quantify flow dynamics within microchannels. Our results indicate that phase-resolved ODT will be a non-contact metrology tool for imaging and performing detailed analysis of biological fluidic flow dynamics in microchannels.

Acknowledgements

The authors wish to thank Dr. Xueqin Ren, Mr. Ruisheng Chang, Dr. Shuwen Hu and the staff of UCI's Integrated Nanosystems Research Facility for helpful discussion and technical assistance. We acknowledge the support of DARPA Bioflips (N66001-01-C8014), National Science Foundation (BES-86924), National Institutes of Health (EB-00293, NCI-91717, EB-00255, and RR-01192), institute support from the Air Force Office of Scientific Research (F49620-00-1-0371) and the Beckman Laser Institute Endowment.

References

- [1] R.L. Chien, J.W. Parce, *J. Anal. Chem.* 371 (2001) 106.
- [2] L.J. Bousse, *SPIE – Microfluidic Devices Syst.* II 3877 (1999) 2.
- [3] R.D. Rocklin, R.S. Ramsey, J.M. Ramsey, *Anal. Chem.* 72 (2000) 5244.
- [4] D.R. Meldrum, M.R. Holl, *Science* 297 (2002) 1197.
- [5] J.I. Molho, A.E. Herr, B.P. Mosier, J.G. Santiago, T.W. Kenny, R.A. Brennen, G.B. Gordon, B. Mohammadi, *Anal. Chem.* 73 (2001) 1350.
- [6] C.D. Meinhart, S.T. Wereley, J.G. Santiago, *Exp. Fluids* 27 (1999) 414.
- [7] P.H. Paul, M.G. Garguilo, D.J. Rakestraw, *Anal. Chem.* 70 (1998) 2459.

- [8] J.A. Taylor, E.S. Yeung, *Anal. Chem.* 65 (1993) 2928.
- [9] B. Manz, P. Stilbs, B. Joensson, O. Soederman, P.T. Callaghan, *J. Phys. Chem.* 99 (1995) 11297.
- [10] Y. Zhao, Z. Chen, C. Saxer, S. Xiang, J.F.de. Boer, J.S. Nelson, *Opt. Lett.* 25 (2000) 114.
- [11] Y. Zhao, Z. Chen, C. Saxer, Q. Shen, S. Xiang, J.F.de. Boer, J.S. Nelson, *Opt. Lett.* 25 (2000) 1358.
- [12] K.F. Kwong, D. Yankelevich, K.C. Chu, J.P. Heritage, A. Dienes, *Opt. Lett.* 18 (1993) 558.
- [13] X.Q. Ren, M. Bachman, C. Sims, G.P. Li, N. Allbritton, *J. Chromatogr. B* 762 (2001) 117.