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Optofluidic analysis system for ethanol solutions

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Abstract

We present a versatile optofluidic analysis system for non-invasive, flow-through examination of alcoholic solutions. The underlying principle is based on partial total internal reflection at the solid-liquid interface. Using an on-chip air micro-prism the laser beam is diverged, resulting in a unique reflected/transmitted light pattern depending on the solution being examined. Ethanol containing samples were passed through devices having different working ranges. Measurements between 0 and 90% ethanol were successfully conducted. Fabricated by means of rapid-prototyping techniques, the design can be customized in terms of working range as well as resolution in a cost-effective and fast manner.

Keywords: Optofluidics; refractive index; ethanol

1. Introduction

In the last two decades microfluidics has emerged to a key building block for various sensor applications. Especially for biological and chemical lab-on-a-chip devices different advantages of microfluidics can be exploited to improve their performances. One property which often is used for liquid sample characterization is the refractive index [1]. Many molecules have a significant impact on the refractive index of a buffer solution. In the case of ethanol and de-ionized (DI) water the refractive index increases proportionally with increasing ethanol content. This characteristic can be used for an accurate, non-invasive, and label-free determination of the composition of an analyte based on an optical analysis method.

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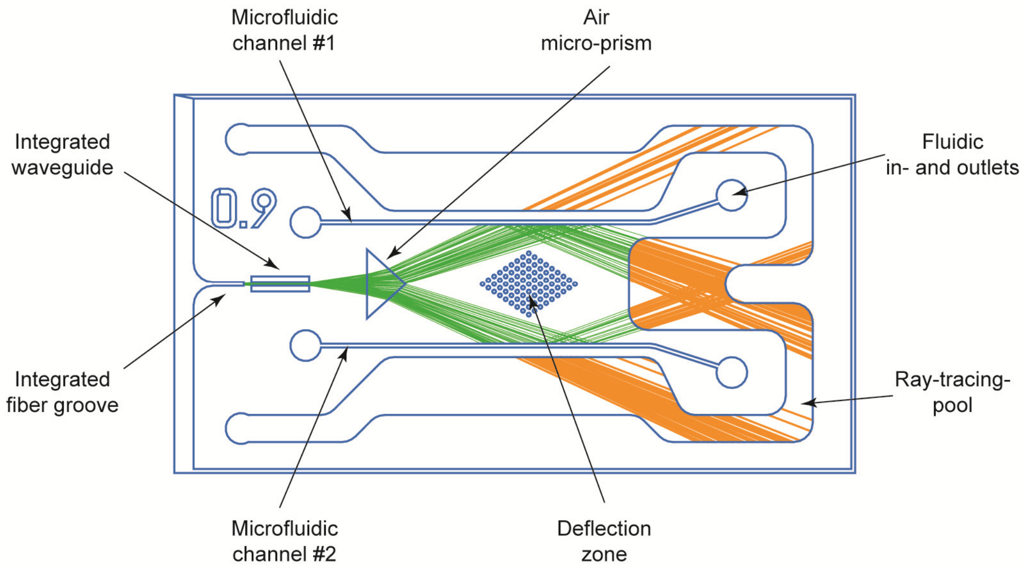

Figure 1: Schematic of working principle. Laser light (green) is expanded by air micro-prism. Depending on the analytes light is partly transmitted through and partly reflected by the microfluidic channels. Ray-tracing pool is used for visualization of exiting light rays (orange).

The presented device exploits this change in the refractive index to determine the alcohol content in liquid samples. Fig. 1 illustrates the working principle. Using a glass fiber clamped into an integrated fiber groove light is guided from an external light source (531 nm, approx. 15 mW) onto the chip. An integrated waveguide ensures defined light conditions (light alignment and divergence) on-chip. The most essential parts of the device are the air micro-prism and the two microfluidic channels. Defined by the shape of the prism the two microfluidic channels are hit by light rays with different incident angles. Depending on the refractive indices of the analytes in the channels, and hence on their ethanol contents, at these solid-liquid interfaces incident light rays above the critical angle experience total internal reflection while the rest is partially transmitted. Both, the reflected as well as the transmitted light rays are visualized in a ray-tracing-pool (filled with a fluorophore). Digital image processing is then applied to calculate a ratio of reflected and transmitted light at the microfluidic channel #1, giving a measure for the ethanol content. The microfluidic channel #2 filled with DI water provides a reference value to minimize any errors in the measurements caused by, e.g., variations in laser light intensity.

2. Device Fabrication

The devices were fabricated in polydimethylsiloxane (PDMS) using standard soft lithography procedures. For the fabrication of the master devices a new rapid prototyping technique [2] was utilized following the protocol described by Weber *et al.* [3]. This technique based on dry-film lamination was chosen to allow for a rapid and cost-effective manufacturing. Although not reaching the resolution of other methods, the tremendously shortened production time and the fact that no clean room setting is necessary justifies this technique for proof-of-concept studies. Additionally, the achievable aspect ratio of almost two satisfies the requirements of the presented device. SEM images of one master device are given in Fig. 2.

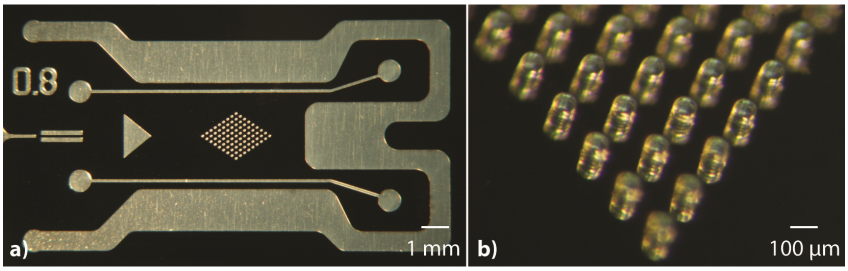

Figure 2: a) Picture of one master device for PDMS replica fabricated in dry resist. b) Close up view of achieved structure dimensions (aspect ratio approaching 2).

The fabrication process is divided into four main steps. First, multiple layers of dry resist are laminated on the substrate (e.g., silicon wafer). After lamination, UV-exposure for 24 s is performed. To increase the adhesion of the dry resist a post-exposure bake (1 - 5 min) is necessary. The development is conducted under ultrasonic agitation for 60 - 120 s. Following this protocol, master devices for PDMS replica can be manufactured within less than one hour.

3. Results and Discussion

For the determination of the reflected and the transmitted light signals the excited fluorescence in the ray-tracing-pool was detected by use of an optical long-pass filter and a CCD camera. The captured images were segmented into 4 x 6 elements (Fig. 3). After gray-scale converting, segments 2/2 and 2/3 were integrated to obtain a value representing the transmitted light signal of microfluidic channel #1. For the reflected light signal segments 3/3 and 3/4 were integrated. At the microfluidic channel #2 an analogous procedure was applied.

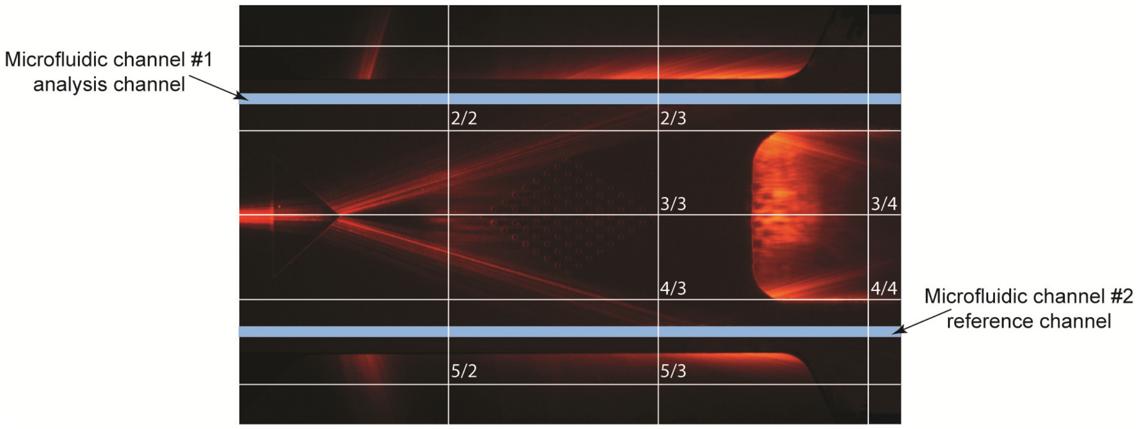

Figure 3: Fluorescence image taken during the analysis. Raster segments 2/2 and 2/3 are integrated for transmitted signal of channel #1. Segments 3/3 and 3/4 represent reflected signal of channel #1. Segments 5/2 and 5/3 as well as 4/3 and 4/4 are integrated in the same manner for channel #2. Blue lines in the figure illustrate the two microfluidic channels.

The results of ray tracing simulations and experimentally obtained values are illustrated in Fig. 4a and Fig. 4b, respectively. An increase in the ratio of reflected and transmitted light signal with decreasing ethanol concentration is evident in both diagrams.

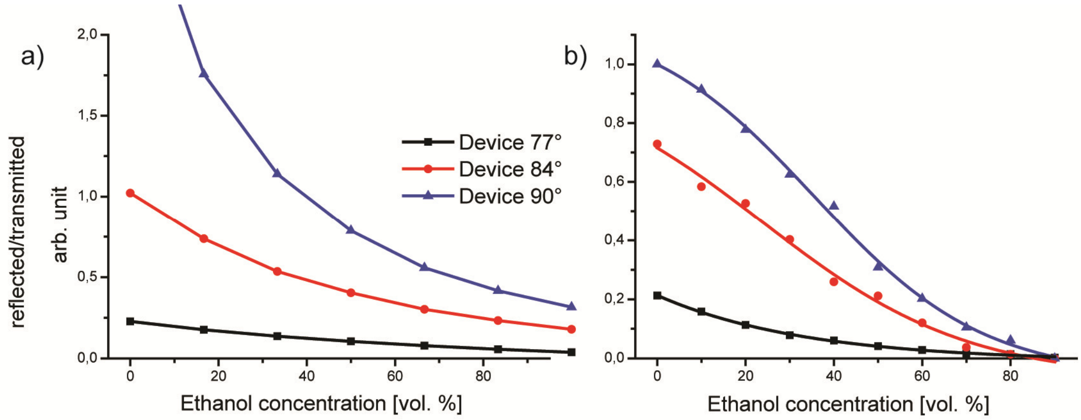

Figure 4: a) Simulation results (ZEMAX, USA) for different ethanol concentrations. Ratio of reflected and transmitted light signals increase with decreasing alcohol content. Changing the angle of the incident light (by adapting the air micro-prism) results in different characteristics. Working ranges: Device 77° below 10%; Device 84° between 10 and 50%; Device 90° between 40 and 80%. b) Experimentally obtained ratios of reflected and transmitted light signals measured on three different devices. Working ranges agree with those of simulations.

In contrast to the experiments, the simulation results exponentially increase towards very high values for lower concentrations. This trend is suppressed in reality by an offset of the transmitted light signal. The working range can be defined by adapting the air micro-prism. In Fig. 4b the transitional phase of the fitted sigmoid curve (Device 84° and 90°) defines the lower end of the working range. At these points the transmitted signals converge to the offset value and no significant change occurs anymore.

4. Conclusions

A simple method for high-throughput, non-invasive, and label-free determination of alcohol contents in liquid samples from 0 up to 90% has been elaborated. Using the proposed principle a precision constantly better than ±3% absolute ethanol concentration could be achieved. The stability of the analysis was significantly increased by the implemented reference channel. Advantages like the robustness in execution, the ease in fabrication, and the possibility of optimizing the design parameters make this system a promising approach for microfluidic analyses in various areas.

Acknowledgements

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