Optofluidic Elements for On-Chip Sample Analysis

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The benefits of the integration of novel optofluidic elements, e.g., fluidic lenses and liquid-core / liquid-cladding (L2) waveguides, for on-chip optical sample analysis are discussed. Using properly designed microfluidic channels, pre-calculated flow rate ratios and transparent fluids with different refractive indices but similar viscosity novel fluidic optical elements can be created. In this contribution we present a dynamically reconfigurable fluidic lens which can focus light three-dimensionally and a L2 waveguide concept which can couple the incident laser beam in the analysis channel. The optofluidic system is fabricated on a glass substrate in a photosensitive polymer by fast laser micro-stereolithography.

Introduction

The combination of optics and microfluidics generates a new field of research called optofluidics. By using transparent fluids with different refractive indices in the laminar flow regime of the microchannels novel functionalities of optical elements can be created. Changing the flow condition in the channel by manipulating the flow rates or simply replacing the fluids alters optical properties like shape, focal length and guiding modes which is almost impossible to obtain with the fabricated solid equivalent. When using miscible fluids a smooth interface with a defined refractive index gradient due to diffusive mixing parameters (Reynolds number, diffusion coefficient) is created. Based on these conditions multiple sensor applications with increased optical functionality can be found [1].

Optofluidic systems can be divided into three main categories: Solid/Liquid-Devices – structured solid chip and pressure driven liquid define the optical properties, Liquid/Liquid-Devices – optical functionality is created only by manipulation of certain liquids, Colloidal/Liquid – Dissolved particles in a buffer solution provide the desired optical quality. In this contribution the focus lies on liquid/liquid flow systems generating stable adjustable optofluidic components.

In conventional optical miniaturized sensor systems the required measurement sensitivity is achieved by applying extensive and costly source and detection instruments. Fluidic elements like lenses, mirrors and waveguides can be integrated to decrease costs, simplify the setup and enhance the functionality. As examples electrowetting lenses, liquid crystal displays and oil immersion microscopes should be mentioned.

The integration of fluidic sensor systems, e.g., to measure the fluorescent characteristics of an analyte, often needs the implementation of optical elements (lenses, waveguides) to ensure a well-defined reconfigurable light propagation. In this contribution we present the design, fabrication and measurement results of a novel hydrodynamically adjustable lens chip for 3D light focusing and a liquid-core-cladding waveguide concept fabricated by rapid prototyping.

Device Description

We present two chip designs for the integration of optofluidic components fabricated by single-layer micro-stereolithographic prototyping in a transparent photoresin to improve the optical performance of liquid-based analysis systems in terms of excitation light guiding and focusing. 2D light focusing fluidic lenses have been published [2], [3]. Our novel chip design is illustrated in Fig. 1, left. We show how standard fluid manipulation (altering fluidic inlet flow rates) enables the formation of a fluidic lens with adjustable three-dimensional light focusing ability.

The biconvex fluidic lens shape is generated in two steps. The center of the micro-channel has the highest flow velocity because of the parabolic velocity profile due to the laminar flow regime (Re ≤ 1). By using the centrifugal effect at both 90° bends of the divided channels the interface between lens body and cladding fluid arches from a straight to a convex form [3] (Fig. 1, right). After bringing the two streams together a single biconvex form in the vertical channel direction originates. The following expansion chamber causes a deceleration of the stream developing a biconvex shape of the microfluidic lens in the horizontal direction. In this light focusing area we achieve the formation of a 3D curvature adjustable convex lens by choosing fluids with different refractive indices (lens body fluid = $CaCl_2$ 5mol/l, cladding fluid = DI-water).

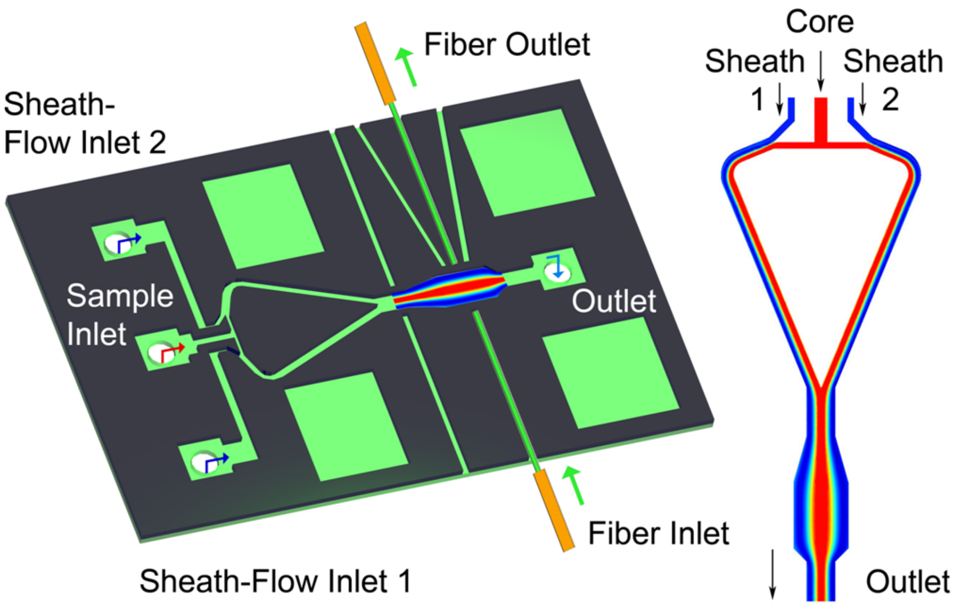

Fig. 1: Left: Schematic design of the optofluidic lens chip with three fluidic inlets and one outlet. For multi-angle light intensity measurements trenches were designed for the insertion of glass fibers. Right: Top view of the computational fluid dynamics (CFD) simulation (COMSOL Multiphysics).

The second design, a liquid-core / liquid-cladding (L2) waveguide chip, is created by using a core fluid with a higher refractive index than the cladding fluid and the microfluidic chip material (PDMS, glass substrate). The core fluid is introduced over a core inlet and bordered by the cladding fluid with the hydrodynamically focusing principle [4]. Under these conditions total internal reflection between the fluids occurs. This is achieved by using Benzothiazole as core fluid and DI-water as cladding fluid. The L2 waveguide allows laser light guidance on the chip for illumination purposes (sample excitation for fluorescence detection or absorption measurements) in a sample analysis channel. Therefore, it is not necessary to fabricate optical smooth microchannel walls in order to reduce manufacturing efforts significantly. With additional fluidic sideports it is also possible to direct the light path continuously by shifting the fluids in the channel. The incident laser light is coupled in the L2 waveguide with an inserted glass fiber.

Device Fabrication

Long production durations and expensive fabrication steps of conventional techniques like silicon micromachining make rapid prototyping schemes attractive for various research areas. To introduce novel functionalities on a chip it is often helpful that each innovation is tested independently to prove the underlying concept and measure specific process parameters uninfluenced. As proposed in [5] the optofluidic chips were fabricated by micro-stereolithographic production (Fig. 2, left) without masking and complex developing steps. Based on a glass substrate the microchannel structure was manufactured in a transparent photoresin (Renshape SL-7570) to obtain low light absorption in the visible range. After this one-layer procedure the fluidic connection holes were drilled through the substrate. The written structure was then capped with a thin layer of PDMS (Polydimethylsiloxan). To simplify the insertion of the glass fibers for measurements the structured photoresin height is 170 µm.

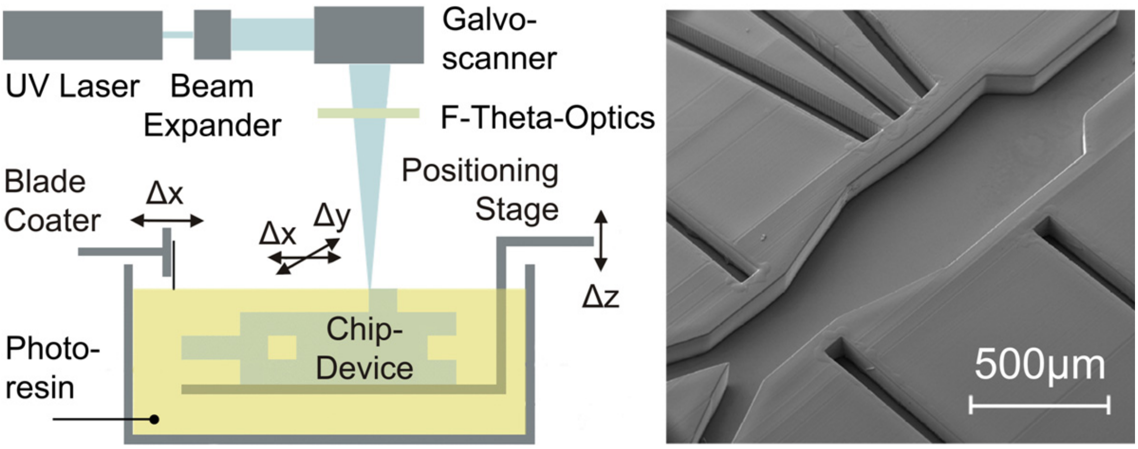

Fig. 2: Left: Functional diagram of the Micro-Stereolithography setup (MIPRO) for the fabrication of 3D fluidic sensor prototypes. The fluidic photoresin is polymerized by a deflected UV laser beam. Right: SEM image of the flow expansion chamber with multiple fiber trenches to measure the performance of the fluidic lens.

Results and Discussion

For reproducible stable fluid conditions (flow rates) the fabricated optical microfluidic devices are attached to a fluidic supply unit (kdScientific syringe pumps). The chips are mounted on a custom made plastic holder with supply tubes. As optical setup we used a free-space solid-state laser (λ = 532 nm, P_{CW} = 5 mW) coupled to a glass fiber (50 / 150 µm). The fiber end was cleaved and inserted into the fiber trench. A fiber-coupled Si-photodiode (FC-PC / pigtailed-ending) was applied to measure the focused light intensity. After calibration of the sensor we have measured the focused light intensity propagating through the optofluidic lens (Fig. 3, left). The results show that we are able to focus light three-dimensionally in the channel and that an adjustment of the flow rates alters the lens shape, which adequately confirms the CFD simulations. The occurring difference between measurement and simulation results arises from a variation of the channel dimensions caused by the prototyping resolution and from the non-continuous flow rates of the syringe pumps used for the measurements. Figure 3, right depicts the design of the waveguide structure for the illumination of the analysis channel. The graph demonstrates the refractive index gradient due to the diffusive mixing over the length of the microchannel. Further research is planned to integrate both designs and advantages into one optofluidic system.

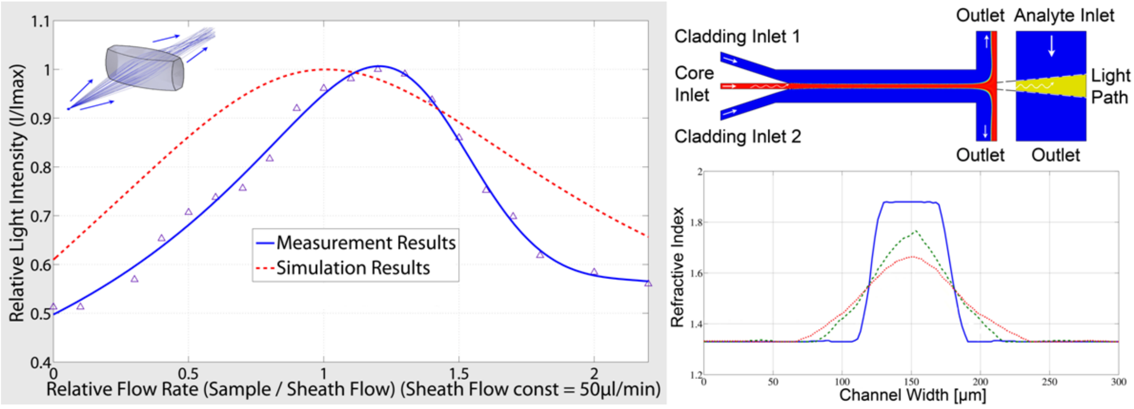

Fig. 3: Left: Normalized light intensity measurements and ray-tracing simulations (ZEMAX EE). A light focusing optimum in transversal direction is reached at the following flow rates; core = 60 µl/min, cladding$_{1,2}$ = 50 µl/min. Right: Schematic design of the waveguide chip directing the coupled light from the core inlet to fluidic analysis channel. The refractive index step decreases due to diffusive mixing as a function of the distance from the inlet.

Conclusion

We have developed two novel microfluidic devices with light focusing and guiding characteristics fabricated by fast high quality micro-stereolithography. The first fluid channel design introduces a three-dimensional microlens, the second a liquid-core-cladding waveguide which both enables new areas of microfluidic optical applications.

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