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SUMMARY

In this paper we present a new method for integrating optical waveguides and flow handling microstructures. The integrated waveguides are easily added to existing flow structures to improve functionality. The fabricated systems include hermetically closed flow-channels combined with several optical waveguides arranged perpendicular to these. Simple systems for absorption measurements and fluorescence measurements have been demonstrated. Preliminary results promise high sensitivity and increased signal-to-noise ratio.

Keywords: *Integrated optics, waveguide, µTAS, flow-channel, cell sorting, micro-fluidics, micro-systems.*

INTRODUCTION

The downscaling of structures in bio/chemical measurement systems has demonstrated numerous advantages, e.g. lower consumption of reagents and faster measurements. However, many bio/chemical sensors using light, as detection scheme (absorption or fluorescent) still depend on bulk-optical set-ups. The light is usually focused or transmitted unguided through thick layers of glass before interacting with the flow, and collected in a similar way.

Having optical waveguides integrated in the system enables low-loss light transmission and guidance to and from the sample light interaction-zone. This technique allows on-chip light manipulation using splitters, bends, and tapers as well as gratings for wavelength separation or Mach-Zehnder interferometer based detection [1].

The technological foundations of the presented system have been described in detail previously [2]. We will therefore provide an overview over the fabrication process, mentioning various applications and present some recent fluorescence measurements.

DESIGN AND FABRICATION

Our micro-fluidic structures are fabricated using traditional procedures. Flow channels are etched in silicon and sealed by anodic bonding to Pyrex.

The objective is to develop an add-on process that is compatible with the fabrication techniques of micro-fluidic structures that are currently in use. Therefore, the integration of optical waveguides should only introduce minor changes to the existing processes used for etching flow channels.

Depending on the flow channel geometry two fabrication sequences can be used: Deposition of waveguides on the etched channels or deposition of waveguides first and etching of channels afterwards. Experiments with both methods have been performed, where the last method has proven to yield better reproducibility and higher coupling efficiencies across the channel. Structures presented in this paper were consequently produced using the second method.

Optical waveguides

Two different waveguide formation techniques are useful: lithography defined and direct UV-written [3]. Plasma-Enhanced Chemical Vapour Deposition (PECVD) is used in both techniques to deposit eight micron thick SiO_2 buffer-layers, four micron thick germanium doped SiO_2 core-layers and eight micron thick SiO_2 cladding-layers. For lithography-defined waveguides core-layers are selectively etched by Reactive Ion Etching (RIE) before deposition of the cladding-layer. Direct UV-written waveguides are written after deposition of the cladding-layer.

All waveguides included in the design are multimode waveguides; they are 4 µm high and 6, 12, 18 or 24 µm wide, the core cladding index step is 10^{-2}.

Flow-channels

Flow-channels are first etched through the glass-layers using RIE with a 6 µm thick layer of amorphous silicon as mask-material and subsequently etched in the silicon using the glass layers as mask. Changing the etching time provides a simple way to adapt the channel depth. The systems presented in this paper have a channel width of 500 µm and a depth of 50 µm.

Pyrex cover glass

A hermetically sealed flow-channel is obtained by applying Pyrex glass as the top lid. The sometimes cumbersome glass to glass bonding [4] is avoided using a thin (1000 Å) layer of poly-silicon deposited on the silica top cladding.

This is done in a Low Pressure Chemical Vapour Deposition (LPCVD) tube at 580°C. The poly-silicon layer provides the necessary electrical connection to perform the anodic bonding between the Pyrex glass wafer and the silica-silicon wafer.

Interconnection

The liquid interconnections to the flow-channel are produced by drilling holes from the backside with a diamond drill and gluing small pieces of stainless steel tubing onto the system.

Light coupled to the waveguides through fiber butt-coupling is improved by mirror-polishing the waveguide end-face.

Figure 1 shows a schematically view of the system.

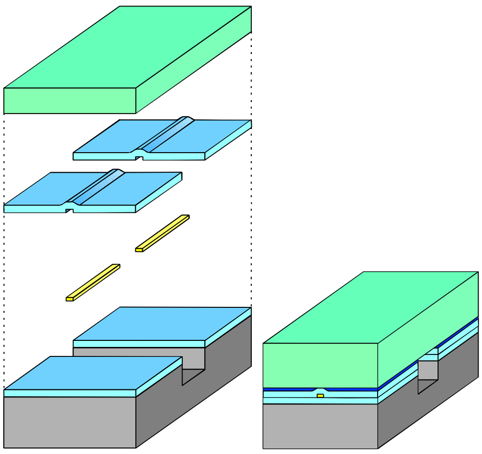

Fig. 1: This figure shows the microsystem with the silicon part, the three layers of glass and the Pyrex part in exploded and normal view.

RESULTS

An important factor in microsystems with integrated optics is the coupling efficiency across the flow-channel. In absorption measurements for instance, a high coupling efficiency increases the dynamic range. Simple theoretical calculations based on geometrical optics show 20 dB loss across a 500 µm wide channel, using two 24 µm wide waveguides. Experimental results show a loss of 14 dB, which corresponds well with the theoretical predictions, if it is assumed that only the fundamental mode of the waveguide is excited.

The propagation loss in the waveguides used in this design are in the order of 0.3 dB/cm for the 24 µm and 18 µm wide waveguides and somewhat higher for the 12 µm (0.4 dB/cm) and 6 µm wide (0.9 dB/cm). Although lower loss has been reported this is an acceptable loss as the waveguides are rather short and the overall loss is dominated by the coupling loss across the channel.

For further examination of the coupling properties, waveguides with different tapers have been fabricated and tested. As expected, wide tapered waveguides are more efficient, as the numerical aperture or acceptance angle is smaller for a wide waveguide. Carefully designed tapering of the waveguides improves the coupling efficiency by 2-3 dB.

APPLICATIONS

To show the flexibility and utility of the integrated optics for bio/chemical microsystems we present three applications where the integration of optical waveguides introduces new possibilities regarding signal-to-noise ratio and selectivity.

Absorption measurements

An important factor when measuring absorption is the interaction length between the light and the liquid (Figure 2). Longer interaction length improves sensitivity. In this system however, a wide channel reduces the coupling efficiency from waveguide to waveguide, which will decrease the dynamic range. Therefore, the optimal channel width is a trade-off between high sensitivity and large dynamic range.

For simple tests, we have measured a linear response between absorbance and concentration of fluorescein down to 20 µM, see Figure 3. An argon laser (λ=488 nm) is coupled into a singlemode fiber which is butt-coupled to the waveguide. The light transmitted through the channel is focused via a microscope objective (x10) on a calibrated photodiode (HP Lightwave multimeter). The well-known Beer-Lamberts law gives the relation between the transmitted intensity and the concentration:

$$\text{Log}\ (I_0/I) = \varepsilon \cdot C \cdot d$$

where I_0 is the incident intensity, I is the transmitted intensity, ε is the molar absorptivity, C is the concentration and d is the interaction length.

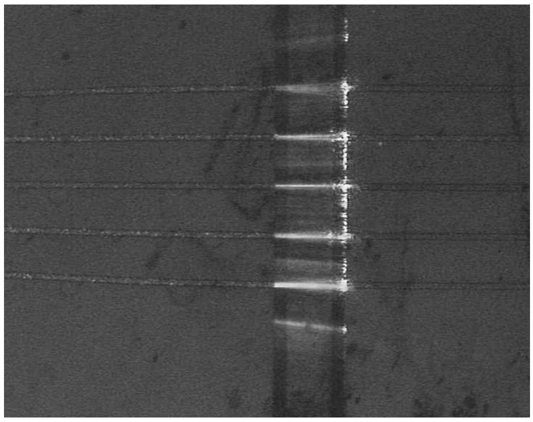

Fig. 2: Five waveguides spanning a 500 µm wide flow channel. Light from an argon-ion laser is coupled into the channel and excites the fluoresceine solution in the channel.

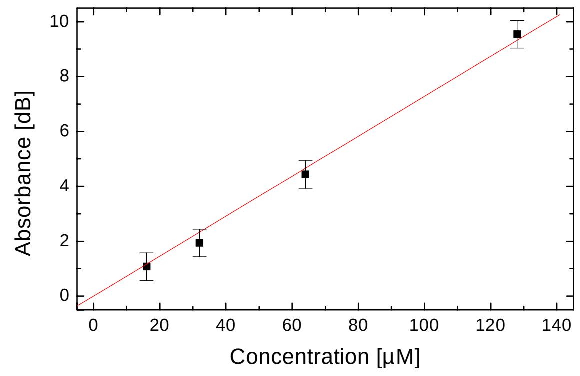

Fig. 3: Absorbance versus different concentrations of Fluorescein. Measuring wavelength is 488 nm

Fluorescence measurements

In order to obtain a good sensitivity when measuring fluorescent signals, it is important to avoid the intense excitation light to reach the detector. The system presented here shows excellent signal-to-noise level when the excitation light axis is arranged perpendicular to the fluorescent light detection axis. This is ensured by coupling the excitation light through the glass lid by means of a singlemode fiber and collecting and guiding the fluorescent light through the integrated waveguide to an output fiber.

To test the system we conducted fluorescence measurements on different concentrations of Rhodamine fluorescent dye. Rhodamine dye is excited at 488 nm using an argon laser and emitted light at 520 nm is detected through an interference filter using a photomulitiplier tube. The result is shown in Figure 4, where a clear linear relation is seen.

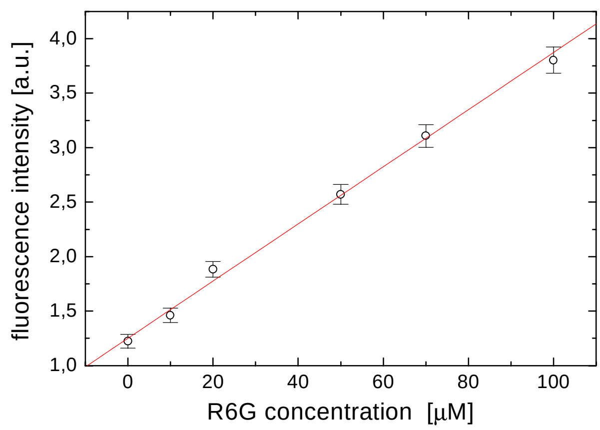

Fig. 4: This graph shows the measured intensity from different concentrations of Rhodamine fluorescent dye excited at a wavelength of 488 nm.

Cell / particle sorting

Experiments with an existing flow-switch device with added integrated optical waveguides have been performed. The flow-switch used for cell/particle sorting has three inlets (for laminating a cell or particle sample between two buffer-streams) and two outlets (one for collecting the cells of interest and one for waste). As the cells are pumped through the system and excited by a laser, the fluorescent-labelled cells are sorted by controlling the two buffer-streams [5]. Traditionally, we have performed excitation and detection in a confocal set-up, resulting in high background noise due to reflections. Integrated optics provide an elegant solution to this problem since the excitation is now perpendicular to the light collecting optics utilising the planar optical waveguides. Preliminary results show a significantly improved sensitivity with this set-up. An increase in selectivity is also expected because of the reduced illuminated volume compared to excitations through the Pyrex glass lid.

CONCLUSIONS

The use of integrated optics increases functionality of bio/chemical microsystem. The optical waveguide circuitry is easily added to existing systems and no re-designing of the flow structures is necessary.

The fabricated waveguides show low losses, but the coupling efficiency across the channel, still leaves room for improvement.

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