On-Chip Optics for Manipulating Light in Polymer Chips

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Abstract
We report the development of two methods of incorporating optical systems into typical polymer-replica microfluidic lab-on-a-chip devices, focusing on devices for flow cytometry.

Introduction
Lab-on-a-Chip (LoC) devices offer great promise both for recreating biomedical devices and research tools on a mass-producible, highly integrated platform [1] and also for enabling new devices with novel functionality to aid the exploration of emerging fields such as stem cell research [2] and flow cytometry [3]. The ability to create portable, lower cost, mass-produced cytometry chips could help cytometry capabilities to be available on-site at every hospital and clinic. Microfluidic control could enable a myriad of on-chip functions for more precise and repeatable sample handling while opening the door to truly single-cell studies. For LoC devices to be practical, the results obtained by LoC methods must be at least comparable to those obtained by traditional methods. Biological assays often use light as a readout medium; in the case of cytometry, the use of both fluorescent probes and light scattering measurements in flow cytometry. Device performance relies heavily on the performance of the optical system, yet the miniaturization of the optical portion of such devices has received significantly less attention than the miniaturization of the fluidic portions. The optical components of the device could significantly benefit from integration into the chip, given the greatly reduced optical path lengths, proximity to the sample, and the possibility of creating a lower cost device that is more compact and robust.

We present two key advancements in on-chip optics that enable more efficient and effective light manipulation in LoC style devices while maintaining compatibility with the often-used PDMS replica molding techniques for device fabrication. These advancements are (i) two-dimensional slab-waveguided optics for light paths intersecting the path of a fluidic channel, and (ii) liquid core waveguides for light paths collinear to the microfluidic channel.

Optical-Quality 2D Slab-Waveguided Lenses
Two-dimensional lenses are fabricated within a slab waveguide to recreate the functionality of typical optical systems, such as those used in in the flow cytometer. In the cytometer, optics are used to illuminate a biological sample and/or to detect light from the sample as it flows in a fluid jet through the light path. When miniaturizing such devices using LoC platforms, simply replacing optical systems with simple optical fiber or waveguide systems often results in a significant loss of performance. Lenses are needed to shape sample illumination beams, to allow light collection over a specific angular range (for scattering measurements), and to collect light almost exclusively from the sample (reducing background noise at the detectors, especially important in fluorescence measurements). In addition, low-quality interfaces in miniaturized devices (waveguide facets, flow channel walls, etc) are often a source of light scattering and loss. Typical mold making processes for replicated microfluidic devices, such as standard RIE etching or mold creating by photoresist, create features with rough sidewalls not suitable for quality optics.

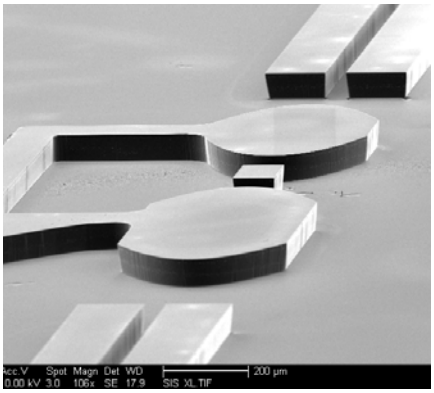

Figure 1. SEM image of a silicon mold master used to create a simple two lens relay system between two fibers (here outlined by their cladding channels). In this device, a beam stop was placed between the two lenses. Cryogenically etched silicon mold masters can exhibit highly vertical sidewalls and low sidewall roughness (~30 nm rms).

We have developed a process for creating two dimensional lenses with optically smooth facets inside of a slab waveguide (controlling light loss perpendicular to the device plane) using a process fully compatible with typical PDMS processing techniques for LoC devices.

Mold masters (~70 μm deep) are etched at cryogenic temperatures (<-115°C) using ICP-assisted reactive ion etching (ICP RIE; Plasmalab 100, Oxford Instruments). Careful balance of substrate cooling, gas flow rates,

chamber pressure, and RIE and ICP powers ensure highly vertical etch profiles with smooth faces [4]. Mold masters (shown in Fig. 1) are then replicated in polydimethylsiloxane (PDMS). The lenses are replicated into the slab waveguide, a high-index layer of PDMS (Nusil LS-6946) only as tall as the lenses and channel features (~70 um). This layer is cladded above and below by a lower-index PDMS material (Gelest OE41). The slab waveguide architecture [3] confines light in the direction perpendicular to the plane of the device, while lenses manipulate light in the plane of the device. The lenses are filled with a high-index fluid or polymer (Nusil LS-5257, Nusil LS-6257, n~1.57) to act as an immersed lens relative to the lower-index polymer body. Current measurements show sidewall roughness as low as 30 nm (rms) can be achieved using this method [5]. Work is underway to characterize the performance of PDMS-based lenses and waveguides created from these optical-quality mold masters.

Liquid-Core Waveguides in Cell Sorter

Liquid core waveguides are created to allow for light paths collinear to the flow of fluid in a microfluidic channel. This enables continual sample illumination, multi-location sample interrogation, and the ability for the light path to follow the fluidic path even through turns and forks. In LoC devices, the fluid is surrounded by a high index medium (the device body) rather than a low index medium precluding TIR confinement. By identifying a suitable low-index channel coating material (Teflon AF 601S, DuPont Inc.) and a suitable coating process, we have demonstrated a fluid-core waveguide compatible with PDMS processing techniques that does not require a dual-fluid system to create the index contrast needed for TIR [6]. The thin coating of Teflon AF over the channel walls creates a low index (n=1.31) cladding layer compatible with any standard liquid core (typically n>1.33). Incident light is confined and guided by Teflon AF coated waveguide along the fluid flow enhancing the fluorescence/scattering detection sensitivity. A spatial filter, (Fig. 2 (a)) consisting of transparent detection and verification slits on a printed black transparency mask, is placed at the image plane of the microfluidic channel in front of the optical long pass filter and the detector (PMT) [7]. As fluorescent beads (Bangs Lab. Inc.) pass the detection slits, a signal of three peaks is detected triggering the integrated PZT actuator such that the targeted sample is directed to one of the collection channels in Fig. 2(b). Beads are continuously excited, thus fluorescence can simultaneously be detected from beads in any channel at multiple points. Light continues to be guided after the microfluidic channel is split at the junction, thus a second signal can be detected after sorting to verify the successful sorting event as shown in Fig. 2 (c).

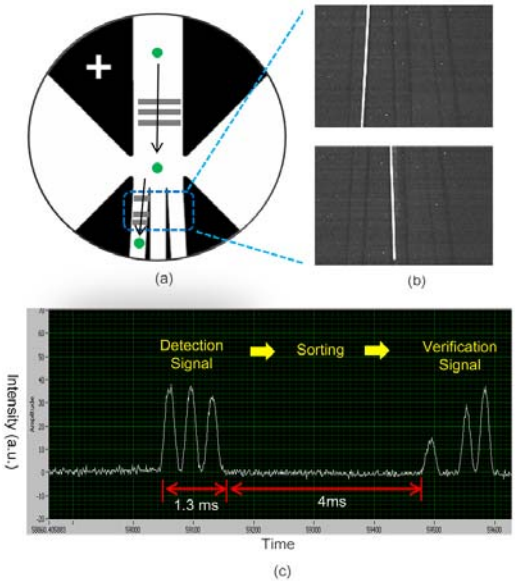

Figure 2. (a) Schematic of the sorting junction with the spatially encoded filter overlapped and aligned at the image plane. The spatial filter blocks all light other than the spatially modulated light passing through transparent slits. (b) Light introduced from above the main channel by the optical fiber excites fluorescent beads even after the main channel is split into three sorting channels. (c) A successful sorting event is confirmed by the verification signal that follows the detection signal.

Conclusions

We present the development of two practical, efficient methods of incorporating optics in LoC devices that are compatible with typical methods of creating microfluidic devices (i.e. polymer replica molding). These easily fabricated tools will enable researchers to readily incorporate highly-tailored optical setups directly onto the chips, without the need to modify the external setup for each new chip. The technologies will help enable more efficient light interactions by reducing losses and more effectively manipulating the light path, helping to create more integrated and sophisticated biophotonic devices with superior performances.

References

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