Towards Integrated VCSEL Arrays for Optofluidic Sorting Applications

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We present the concept of an ultra-small, potentially low-cost microfluidic sorting unit based on vertical-cavity surface-emitting lasers. The densely packed lasers are integrated with the microfluidic channel and form an optical lattice. We show first results in an experimental setup, followed by tests of the first generation of integrated setups. A promising novel integration approach and future prospects are introduced.

1. Introduction

In 1970, Arthur Ashkin for the first time reported particle movement by laser beams [1]. He found that forces arising from light momentum transfer attract a particle to the center of a focused laser beam. Since then, scientists from different fields of research have spent much effort to render the principle of optical trapping useful for many areas. One of these areas affects the field of biophotonics, e.g., the manipulation of DNA [2] or red blood cells [3]. Micrometer-sized fluidic channels are a popular medium to handle extremely small volumes with a rather high throughput. By merging them with lasers for optical manipulation, analyzing and sorting of particles can be combined in a so-called lab-on-a-chip. In the competition towards increased miniaturization, vertical-cavity surface-emitting lasers (VCSELs) offer particular advantages. Besides the inexpensive fabrication and the circular beam profile they offer the possibility of two-dimensional array formation with almost arbitrary geometries and high device density. Their output powers in the milliwatt range are sufficient for the manipulation of particles. Owing to the low power consumption, integration into handheld, battery-driven devices seems feasible.

2. Optofluidic Sorting Principle

One possibility of performing automated sorting is to combine a sensing unit with a unit for continuous deflection. Figure 1 shows an overview of the optofluidic sorting approach we are going to realize. The sorting takes place in a microfluidic channel with a width of several tens of micrometers. Flow direction of the particle solution is from left to right, where the channel splits into a Y-junction. The sensing unit consists of a VCSEL with extended cavity (VECSEL) and will not be detailed here. Particles passing the cavity will be classified, for example by size or refractive index, and a suitable control signal is induced for the optical lattice responsible for deflection. An optical lattice is a one- or two-dimensional arrangement of optical traps, a promising technique to achieve deflection in microfluidics. It can be generated by interferometric light patterns [4], holographic tweezers [5], or, in our case, arrays of densely packed VCSELs. At each trap of the lattice the particles are attracted and deflected stepwise, provided that the trapping force is in the same range as the fluidic drag force. In the presented sorting approach, the VCSELs are arranged in two linear arrays tilted by a certain angle, which allows particle deflection in two directions.

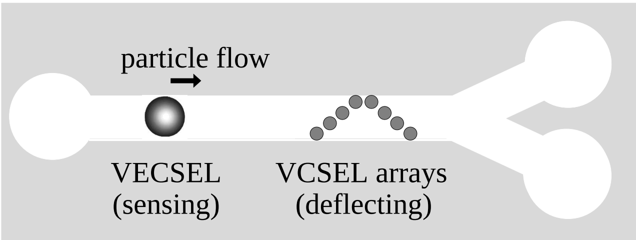

Fig. 1: Schematic of the optofluidic sorting approach. The VECSEL for particle detection is followed by linear VCSEL arrays for particle deflection. The microfluidic channel splits into two channel outlets.

The working principle of the sorting device is depicted in Fig. 2. With a signal "large particle" received from the analysis unit, the lasers of the left array are switched on, resulting in a redirection of the particle into the upper branch, whereas for the analysis signal "small particle", the right laser array is switched on in order to direct the particle into the lower outlet of the microfluidic channel.

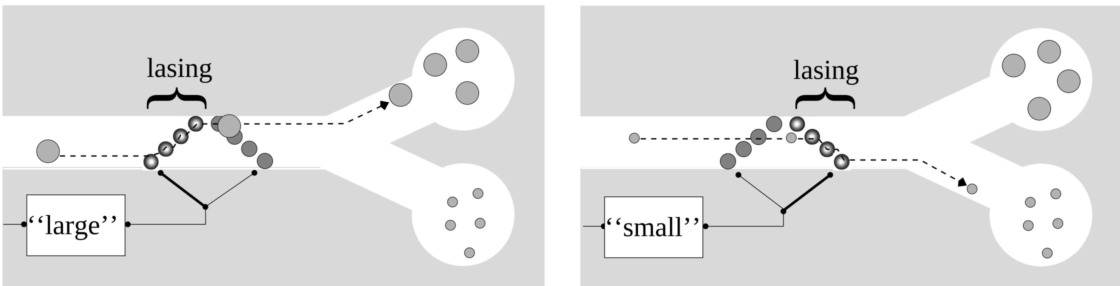

Fig. 2: Working principle of the optofluidic sorting approach. According to the signal received from the analysis unit, larger particles are directed into the upper outlet (left), whereas smaller ones are directed into the lower outlet of the microfluidic channel (right).

3. Continuous Deflection of Particles in Microfluidic Channels

Continuous deflection of particles using external optics for beam steering has already been reported [6]. The left part of Fig. 3 shows snapshots of such a deflection experiment with a 10 µm particle. The particle approaches the tilted linear laser array (1, 2) and is stepwise deflected into the upper branch of a Y-junction (3–5). The experimental setup for this deflection experiment is depicted in the right part of Fig. 3. The VCSEL array with a pitch of about 25 µm and 30° tilt relative to the particle flow direction is electrically contacted on a copper laser mount. The first objective lens collimates the beam, and the second one with high numerical aperture (NA) provides beam focusing inside the microfluidic channel. The 50 µm wide channel was fabricated from polydimethylsiloxane (PDMS) by soft lithography. For observation, the setup is illuminated by a white light

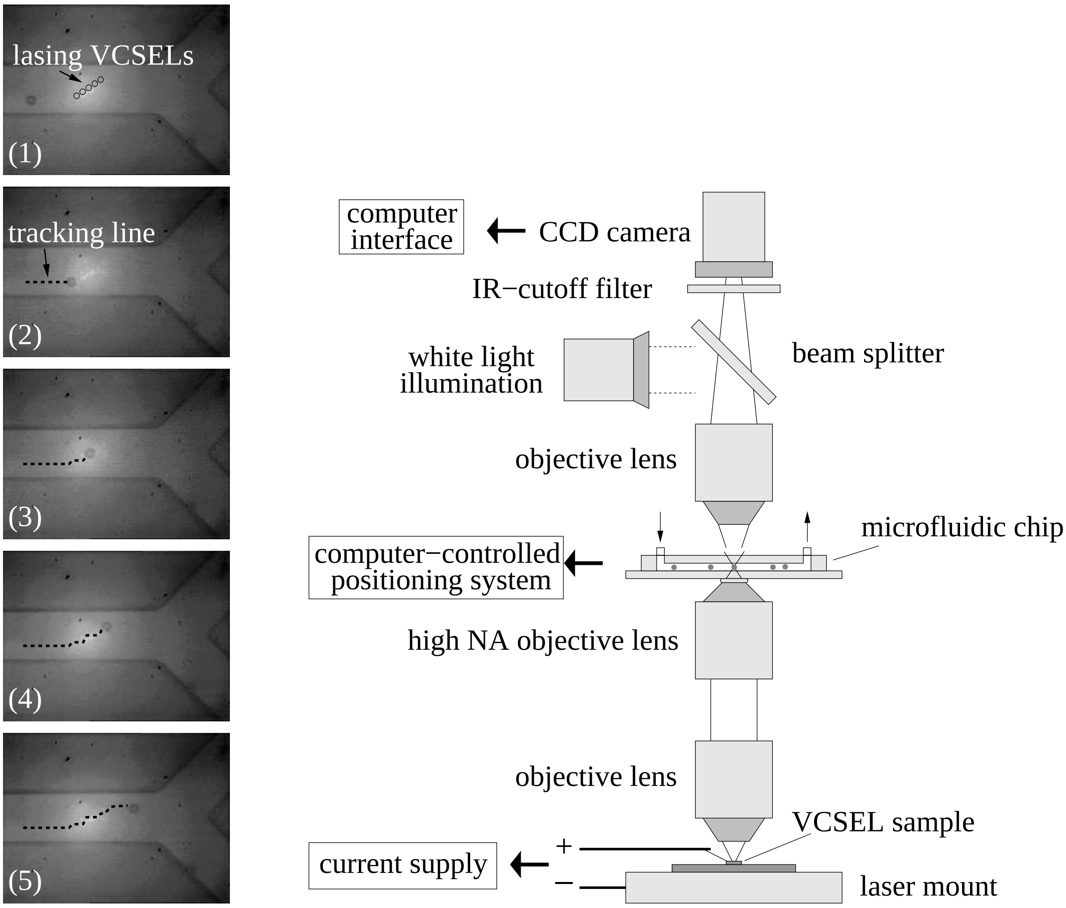

Fig. 3: Left: Snapshots of a deflection experiment in a microfluidic channel with 50 μm width. An arriving 10 μm diameter polystyrene particle approaches the tilted laser array and is stepwise redirected to the upper branch of the Y-junction at the traps of the optical lattice. Right: Optical trapping setup used for the deflection experiment. Beam focusing in the microfluidic channel is achieved by two objective lenses. The observation system basically consists of a light source, a CCD camera, and a computer interface.

source. By means of an objective lens and a CCD camera connected with a computer, the experiment is easily observable.

Extending this setup by an array pointing downwards, it will be possible to direct particles into the outlet of choice, depending on the signal received from the preceding analysis unit. However, it is evident that the used setup is rather bulky, which calls for drastic miniaturization.

4. Integration of Laser Arrays and Microfluidic Channel

Integration is crucial for miniaturized, low-cost optofluidic sorting devices. In an earlier approach we have accomplished the integration of lasers and microfluidics by soldering the laser chip to the lower surface of the microfluidic chip [7]. Figure 4 shows a schematic of this integration concept. Metal fanout tracks are structured on the lower surface of the glass slide sealing the microfluidic channel. The laser chip is attached to the microfluidic chip, and both electrical and mechanical connection are achieved by indium solder bumps. However, it is reasonable to expect a poor heat dissipation in this concept.

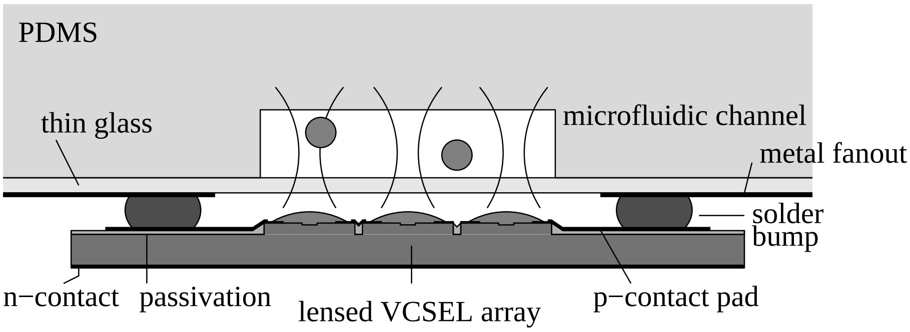

Fig. 4: Earlier approach of the VCSEL chip integrated with the microfluidic channel. Indium solder bumps provide both electrical and mechanical connection.

Figure 5 shows snapshots of a 15 µm particle continuously deflected by such an integrated laser array with a tilt angle of 20°. The PDMS microfluidic channel has a width of 100 µm and is highlighted by horizontal lines for better visualization. An incoming particle approaches the tilted laser array (1, 2). It is stepwise redirected at the traps of the optical lattice and deviated from its initial path (3–5). Unfortunately, the particle movement is rather slow and the deflection is incomplete, due to low laser performance mainly caused by the insufficient heat dissipation. This thermal limitation is supposed to be removed with the new integration approach.

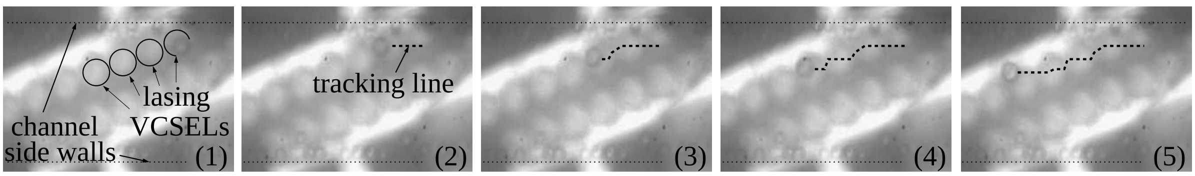

Fig. 5: Snapshots of a deflection experiment with the integrated setup from Fig. 4. The width of the microfluidic channel (highlighted by horizontal lines) is 100 µm. A 15 µm particle approaches the integrated laser array (flow direction from right to left) and is attracted at each trap of the optical lattice and thus stepwise redirected to the lower part of the channel.

The intended way of integration utilizes bottom emission. In this approach, a laser chip with both p- and n-contacts on the upper side is soldered upside down (flip-chipped) onto a structured heat sink. Both the electrical and mechanical connection are achieved via indium solder bumps, structured lithographically on the fanout tracks of the heat sink. After soldering, the substrate is removed from the back side of the laser chip to enable laser emission.

The microfluidic chip consists of a polymer structured by hot embossing and a 30 µm thin glass slide sealing off the channel. For beam shaping, photoresist microlenses are provided on the lower surface of the glass slide. The lenses are fabricated by means of photolithography combined with thermal reflow. After successful fabrication of the two components, laser and microfluidic chip are merged by an adhesive. Figure 6 shows a sketch of the complete device.

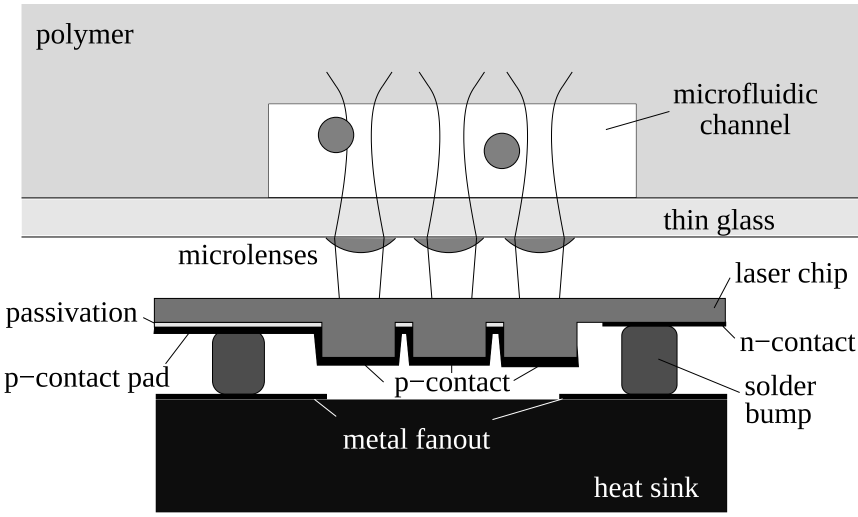

Fig. 6: Schematic of the intended integration concept. The linear laser arrays are soldered upside down onto a heat sink. Indium solder bumps connect both p- and n-contact with the metal fanout on the heat sink. The laser chip is positioned at a very small distance to the microfluidic chip, which has microlenses on the lower surface.

5. Conclusion

We have presented a novel concept of a fully integrated, VCSEL-based optofluidic sorting device, with a main focus on the sorting unit which is controlled by a sensing unit. Laser arrays and microfluidic channels were fabricated and characterized in an experimental setup to verify the sorting principle and the suitability of the lasers. Furthermore, particle deflection has been shown in the first generation of an integrated setup. The next generation will incorporate the VCSEL arrays for deflection into both output channels. The integrated sorting performance is supposed to be enhanced by overcoming the thermal limitations with a flip-chip soldering approach with incorporated heat sink. An additional path of improvement is to further reduce the laser pitch from presently 26 µm to 18 µm.

Acknowledgment

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