Miniaturized Particle Manipulation With an Integrated Optical Trap Module

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The combination of microfluidics and optical manipulation offers new possibilities for particle handling in the field of biophotonics. VCSELs with small dimensions and low power consumption allow such a combination at potentially low cost. The circular laser output beam is shaped by an etched surface relief and an integrated photoresist microlens. Thus the output beam is weakly focused with a beam waist of some micrometers in the microfluidic channel. The microfluidic chips are based on polydimethylsiloxane (PDMS). With this configuration we were able to demonstrate particle deflection with a linear VCSEL array integrated with a microfluidic chip.

1. Introduction

Optical tweezers open up the possibility of handling single particles with sizes in the nanometer to micrometer range while avoiding any mechanical contact [1]. The working principle is based on the momentum conservation of photons incident on a transparent particle [2]. Reflection and refraction lead to a scattering force pushing the particle forward, and also to a gradient force pulling the particle to the maximum of intensity, that is to say toward the optical axis. With these two forces a two-dimensional optical trap is generated. By using for example a tightly focused laser beam, a three-dimensional trap can be achieved [3], also called optical tweezers.

Another important research topic in recent years is the utilization of lab-on-a-chip systems for the biological and chemical analysis of samples. With such a system smallest particles can be isolated and investigated, combining several analysis steps, e. g., mixing, heating, and detection. The microfluidic channels used in these systems have widths of some ten micrometers.

For the selective manipulation of particles in microfluidic channels, the combination of microfluidics and optical manipulation has gained increasing interest. The use of vertical-cavity surface-emitting lasers (VCSELs) provides several advantages [4]. They have small dimensions with typical active diameters of less than ten micrometers, are inexpensive, and their symmetric structure supports a circular high-quality output beam. Their surface emission allows the comparatively easy fabrication of arbitrary-shaped two-dimensional arrays of optical tweezers, rendering techniques unnecessary like beam steering or holography. The dimensions can be additionally decreased by directly integrating microlenses on the laser surfaces. Avoiding any external optics allows the connection of laser source and microfluidic chip, resulting in a small and light weight portable system.

2. Integration of Laser Array and Microfluidic Channel

The operation of an integrated optical trap demands a minimized distance between the laser surface and the microfluidic chip to prevent strong beam expansion. At the same time, electrical contacts to the p-metalization at the top side of the laser chip must be realized. These requirements can be met by flip-chip bonding the laser chip to the microfluidic chip. Figure 1 shows a schematic of the module. The VCSEL array is located directly under a thin glass slide which seals the microfluidic channel. Indium solder bumps connect the p-contact pad to a metalization layer on the glass, which extends to the edges of the microfluidic chip. With this fan-out, the p-side of the lasers can be easily contacted, while the n-side is accessible by the common back side metalization.

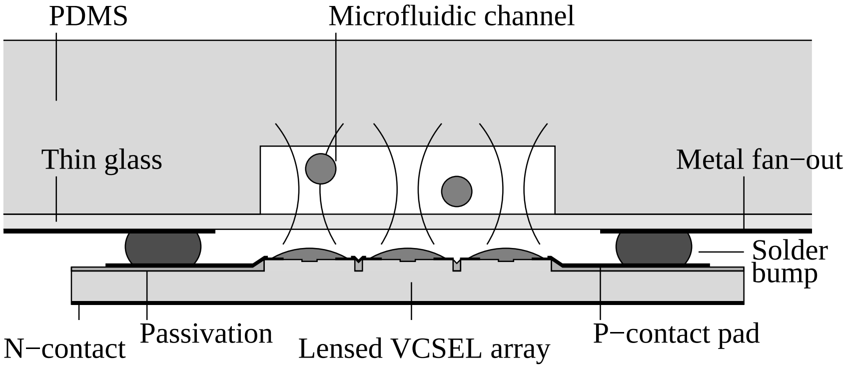

Fig. 1: Schematic of the integrated trap array module. The laser chip is directly connected to the microfluidic chip by indium solder bumps, which serve both as mechanical and electrical contact. The Gaussian-like output beams are shaped by integrated microlenses, thus generating weakly focused laser beams for particle manipulation at the sample stage [5].

Instead of using external optics, we have proposed the laser output beam to be shaped by a photoresist microlens, which is integrated directly on the laser output facet, as described above.

To fabricate this structure, lithography, metalization, and lift-off processes must be performed on the glass side of the microfluidic chip. After completion, the glass contains the metal fan-out as well as small islands of indium, by which a good alignment of the fan-out structure to the channel can be attained. For soldering, the laser chip is flipped and placed on the metalized glass side. When heated, the indium melts and alloys with the p-contact pad on the laser chip. After cool-down, a stable electrical and mechanical contact is formed.

Figure 2 shows a photograph of a complete module. It has a size of about $3.5 \times 3\,\mathrm{cm}^2$. The fan-out on the $30\,\mu\mathrm{m}$ thick glass and the VCSEL array chip soldered to its center are clearly visible. Directly below the laser chip with integrated microlenses, the PDMS layer contains a microfluidic T-junction, which ends in reservoirs for the generation of hydrostatic pressure.

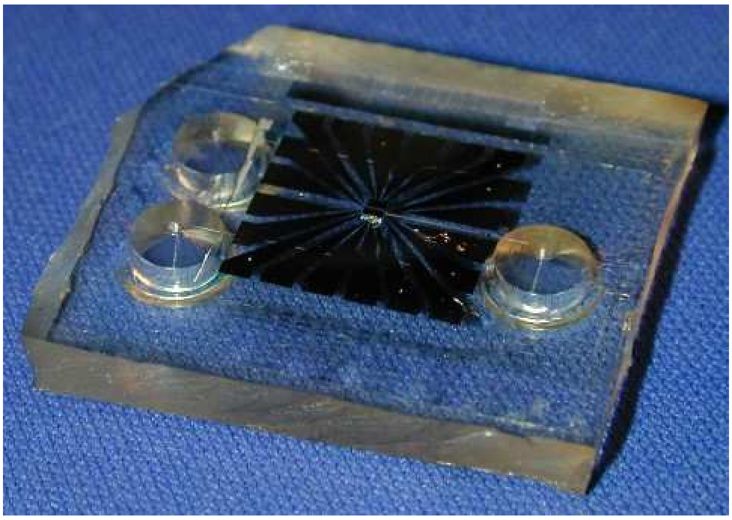

Fig. 2: Photograph of an integrated trap module (placed upside down) with a metal fan-out on the glass slide and a flip-chip-mounted VCSEL array chip in the center. The fluid reservoirs according to Fig. 7 can be seen in the PDMS layer.

3. Components of an Integrated Trap Module

3.1 Microlensed surface relief VCSELs

For the integrated optical trap module, a Gaussian-like beam profile is essential and can be attained with the inverted surface relief technique. In this process an additional $\lambda/4$-antiphase layer increases the threshold gain of the structure. By removing the layer selectively in the center of the laser output facet the transverse fundamental mode is being preferred.

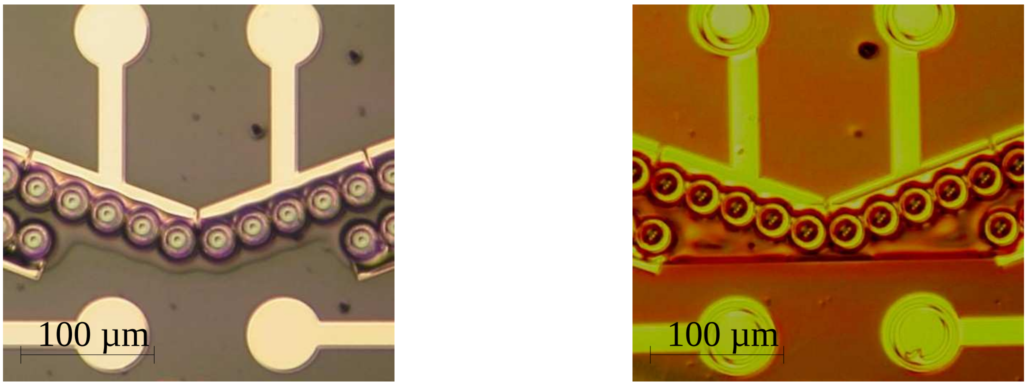

Fig. 3: Microscope images of laser arrays with five lasers connected in parallel. The laser facets are shown before (left) and after (right) the fabrication of microlenses.

The first step towards the miniaturization of the trap setup is the fabrication of integrated microlenses on the laser surfaces (Fig. 3). Figure 4 shows the fabrication of these lenses. In the first step, islands of PMGI photoresist are structured by optical lithography. In a thermal reflow process the cylindrical islands assume spherical shapes. A variation of the radius of curvature can be achieved by changing the photoresist thickness.

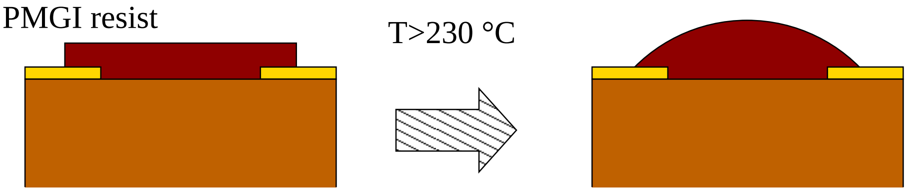

Fig. 4: Fabrication of a PMGI microlens on a laser surface. First a cylindrical island is lithographically structured (left). In a thermal reflow step this island assumes a spherical shape (right).

Figure 5 depicts the beam diameter with increasing distance from the laser surface. Whereas the standard VCSEL shows strong divergence, the device with surface relief and microlens features delayed divergence up to about 25 µm distance to the laser surface.

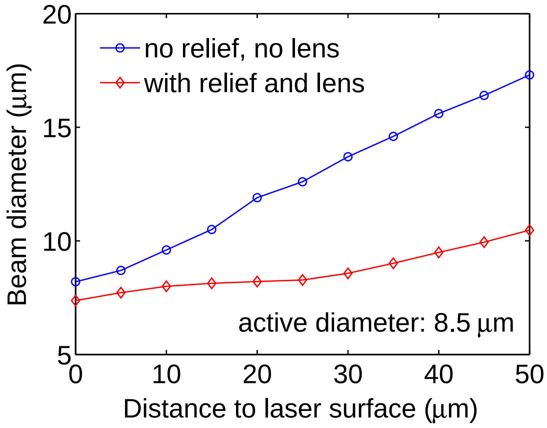

Fig. 5: Beam diameter versus the distance to the laser surface for both the standard and the relief VCSEL, the latter with an integrated microlens. The diameters of the oxide aperture and the relief are 8.5 and 4 µm, respectively.

The laser characteristics before and after the fabrication of the microlenses are compared in Fig. 6. The microlensed devices have lower threshold currents and increased maximum output powers. The polymer material of the lenses effectively reduces the phase detuning between relief and unetched region of the output facet, such that the laser characteristics tend to approach that of a standard VCSEL.

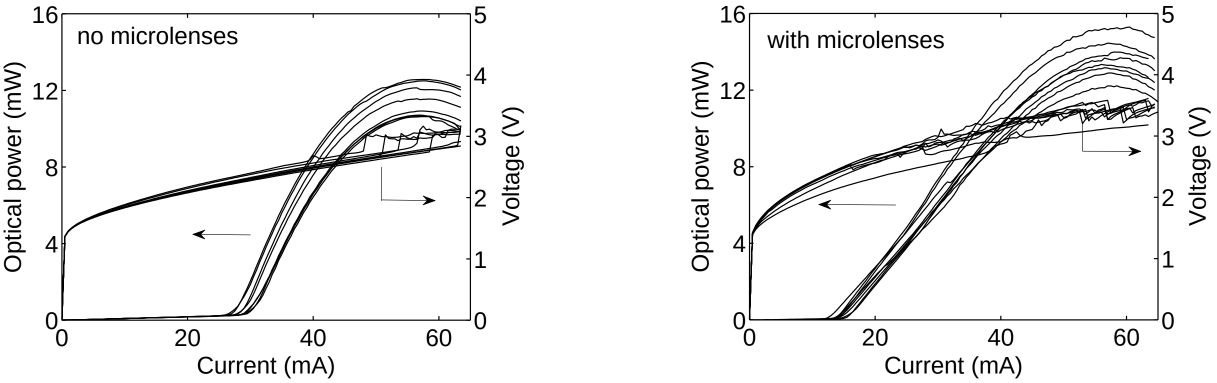

Fig. 6: Operation characteristics of eight VCSEL arrays according to Fig. 3 on a given sample, each array having five lasers driven in parallel. Measurements are done before (left) and after (right) the fabrication of microlenses. The VCSEL dimensions are as in Fig. 5.

3.2 Microfluidic chip

The microfluidic channels are made of polydimethylsiloxane (PDMS), a transparent and inert polymer. It is often used for prototyping due to straightforward fabrication based on a molding technique [6], as illustrated in Figure 7. At first, thick and stable SU8 resist is structured via lithography on a silicon wafer. It contains the negative image of the channel structure and serves as a master. The viscous PDMS is then poured over this mold and cured at 65 °C for one hour. Afterwards, the elastic PDMS can be peeled from the master wafer without damage. To close the channels, the PDMS is sealed with a cover glass. A prior treatment of both surfaces with oxygen plasma renders this connection irreversible. The fabricated microchannels contain T- and Y-junctions and have widths of 30 to 150 µm and a height of 50 µm. Inlet and outlets of the channels are connected to reservoirs containing polystyrene particles solved in water. The fluid levels can be adjusted, and the resulting difference in hydrostatic pressure leads to a controllable fluid flow inside the channels. The particle velocity can be varied from only a few µm/s to more than 100 µm/s.

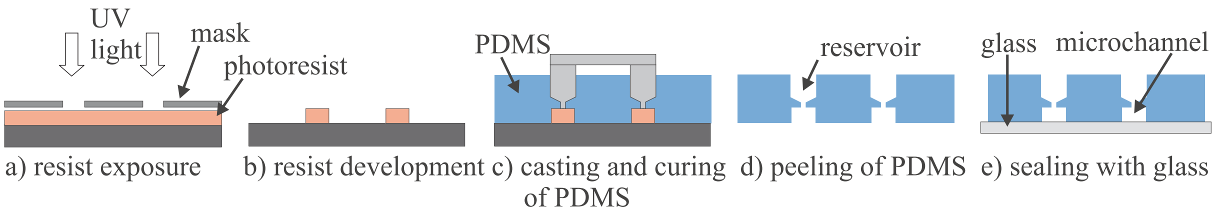

Fig. 7: Fabrication of microfluidic channels by a PDMS molding technique. With a custom-made metal tool, fluid reservoirs are incorporated during the casting step (c).

4. Deflection Experiments With the Integrated Trap

In this section we show continuous microparticle deflection and trapping with the integrated module from Fig. 2, in which the VCSEL array is tilted with respect to the flow direction of the microfluidic channel.

Figure 8 illustrates sequences of a deflection experiment with 15 µm diameter polystyrene particles at an optical power of about 5 mW. Besides the 100 µm wide microfluidic channel, also two linear VCSEL arrays are visible, where only the one at the upper half of the channel is operated. It is tilted by an angle of about 20°. The particles are moving from right to left with velocities of about 10 µm/s, depending on their position in the channel. In Fig. 8a, one 15 µm particle approaches the optical lattice and is attracted by the laser beams. The particle is deflected by the tilted optical lattice (Figs. 8b to h) and deviated from its initial path. While being laterally deflected, orthogonal to its flow direction, the particle is simultaneously lifted by the scattering force when moving from one trap to the next. This is indicated by a blurring of the particle image in the experiment. As seen in Fig. 8, the particle movement is rather slow and the deflection is not complete. These present shortcomings will be resolved in future with higher-power VCSEL sources.

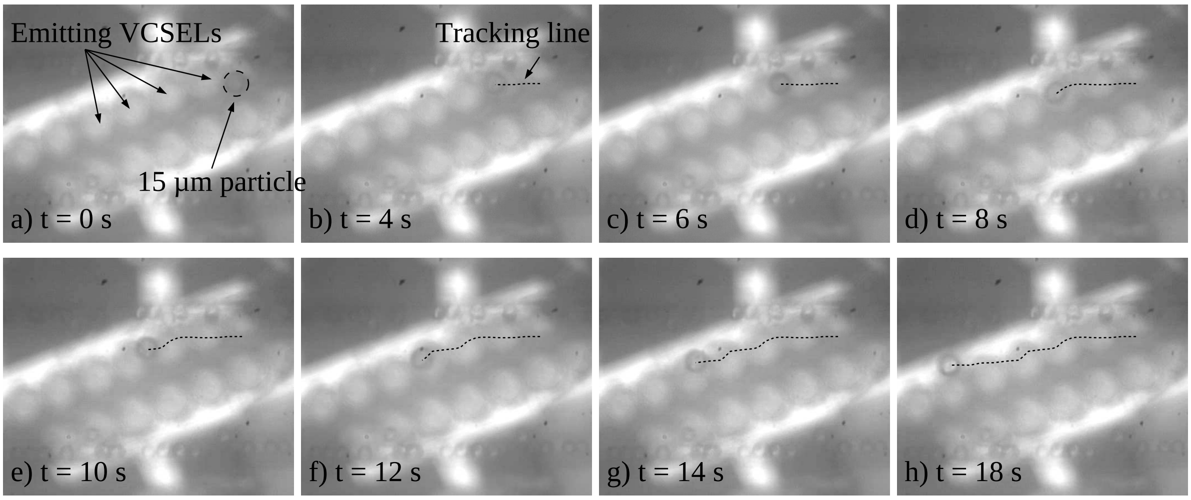

Fig. 8: Snapshots of a continuous deflection experiment with an optical power of 5 mW. A 15 µm polystyrene particle is redirected to the lower part of the channel while passing the optical lattice.

Particle trapping instead of deflection is achieved either with a reduced flow velocity or with an increased optical power. With the former method, the traps in Fig. 9 have been successively filled with 10 µm diameter polystyrene particles. Since the particles are lifted by the scattering force as described before, even multiple trapping can occur. Figure 9 shows four laser traps being occupied by up to three particles.

By increasing the size of the tilted VCSEL arrays, efficient optical particle separation in microfluidics should be achievable without external intervention. With similar schemes, where the optical lattice was generated with a single-beam source by interference or beam

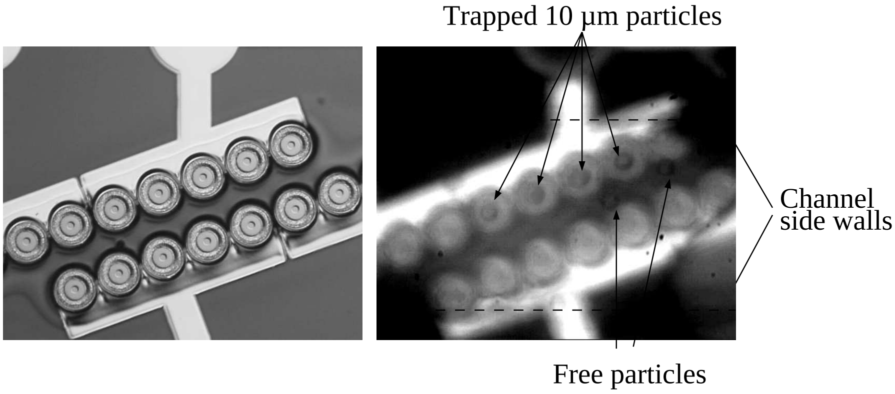

Fig. 9: Tilted VCSEL array with four laser traps occupied by up to three 10 µm particles. The optical output power in the trapping experiment was 5 mW. The photo on the left shows the surface relief VCSELs before the formation of microlenses.

splitting, also particle sorting was demonstrated by other groups. The sorting functionality relies on the fact that the interaction of particle and optical lattice is dependent on the material and geometrical properties of the particles [7]– [9]. In our approach, since the position of the optical lattice is fixed and no moving parts are necessary, the array can be connected to the chip, making this scheme attractive for direct integration.

5. Conclusion

We have shown our recent progress on VCSEL-based optical trapping combined with microfluidics. This work aims to demonstrate novel ultra-compact modules suited for microparticle analysis. It underlines the suitability of VCSELs as laser sources in optical manipulation systems. The small dimensions of VCSELs allow a drastic miniaturization by means of integrating the laser directly underneath the microfluidic channel. Microlenses are corporated on the laser output facets.

With a tilted linear VCSEL array in combination with a microfluidic chip, continuous particle deflection was demonstrated. In future work VCSEL output characteristics must be further improved by epitaxial design and heat sinking. Particle and finally biological cell sorting should then be possible in an efficient way.

References

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