# Optical Multiple-Particle Manipulation With a Rectangular-Shaped VCSEL

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*Optical manipulation of cells and particles is an efficient non-destructive technique for isolation and sorting in the field of biophotonics. For several years, vertical-cavity surface-emitting lasers (VCSELs) have been investigated as light sources for particle manipulation inside microfluidic channels, where their small dimension and low power consumption enable direct integration with the channels. In such an integrated module, however, the simultaneous manipulation of multiple particles requires the use of densely packed VCSEL arrays with very small device pitch, making the fabrication process more expensive and complicated. We show efficient single as well as multiple polystyrene particle trapping and sorting inside polydimethylsiloxane (PDMS) microfluidic channels using one rectangular-shaped top-emitting AlGaAs–GaAs VCSEL with an active aperture area of about* $100 \times 14\,\mu m^2$*. The VCSEL emission wavelength is around 850 nm, which is suitable for usage in biophotonics, as biological materials present little absorption in the near-infrared spectral range. Furthermore, the oblong-shaped VCSELs can potentially be integrated with PDMS microfluidic channels to form miniaturized optofluidic chips for ultra-compact particle handling and manipulation.*

## 1. Introduction

The first transverse two-dimensional optical trap was demonstrated in 1970 by Arthur Ashkin [1]. Later he extended this concept to a three-dimensional trap [2]. The working principle is based on the momentum transfer from an incident laser beam to a transparent particle. The particle is pushed forward by light radiation pressure, an effect commonly known as scattering force. For a laser beam with a transverse intensity gradient, the resulting net force pulls the particle towards the maximum of light intensity, creating a two-dimensional optical trap. In the three-dimensional trap, also known as optical tweezers, the forward scattering force is compensated by a longitudinal gradient force when the laser beam is tightly focused. For transparent particles in water, some milliwatts of optical power are sufficient to exert trapping forces in the piconewton regime [3].

Optical tweezers offer the possibility to manipulate microparticles and cells without any mechanical contact, greatly reducing the risk of contamination and mechanical damage [4]. This unique advantage has made them very attractive in the field of biophotonics. Using infrared-emitting lasers greatly reduces the risk of thermal damage, because biological materials show minor absorption in the near-infrared spectral region [3, 4]. The handling of biological samples in microfluidic channel structures with widths below 100 µm enables the drastic reduction of the used sample volume, parallel cycling, and exact timing [5, 6]. Combining microfluidics and optical trapping in an integrated module is the ultimate tool to efficient manipulation of particles and cells without the usage of extensive equipment [7, 8].

In recent years, VCSELs have proven to be excellent light sources for optical trapping, especially due to their small dimension, low price, ease of fabrication, and high-quality output beam [8–13]. Furthermore, due to their vertical emission, VCSELs can be arranged in two-dimensional arrays, which can be employed for simultaneous optical trapping and movement of several cells [10, 12], as well as stacking of polystyrene particles [11]. In all experiments, the optical VCSEL traps were created by focusing the laser beam with a high numerical aperture objective.

Commercial VCSEL arrays used in optical communication typically have a large device pitch of 250 µm. For miniaturized optical trapping without external optics, however, these arrays need to be densely packed, with a center-to-center distance in the range of 25 µm [14]. This makes their fabrication process more expensive as well as complicated. In this article, a different type of VCSEL has been used to demonstrate simultaneous optical trapping of several particles, namely a rectangular top-emitting 850 nm AlGaAs–GaAs VCSEL having an active aperture area of around $100 \times 14\,\mu m^2$. A brief description and characterization of the VCSEL is presented. The results of single as well as multiple trapping and sorting of polystyrene particles inside PDMS microfluidic channels are demonstrated.

## 2. Rectangular-Shaped VCSEL – Device Description

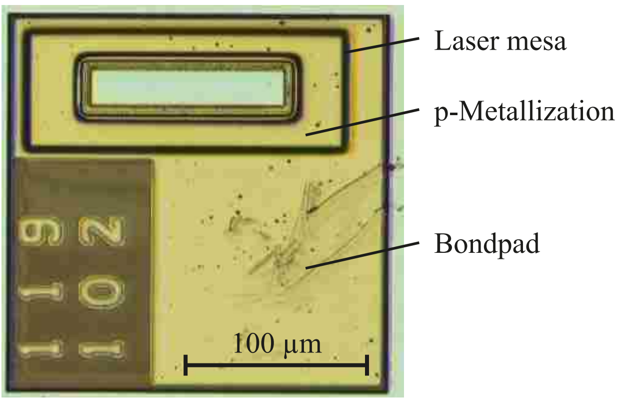


**Fig. 1:** Top view of a fully processed rectangular-shaped VCSEL. The oxide aperture is around $100 \times 14\,\mu m^2$. The rectangular laser mesa as well as the bondpad are clearly visible.

Rectangular top-emitting VCSELs have been provided by Philips Technologie GmbH U-L-M Photonics (www.ulm-photonics.com). The electrically pumped, oxide-confined VCSELs consist of 37 Si-doped AlGaAs n-type distributed Bragg reflector (DBR) pairs, a cavity with 3 GaAs quantum wells and an oxide aperture for current confinement, and 21 C-doped AlGaAs p-DBR pairs. The wafer is designed for laser emission at around

850 nm. Figure 1 shows the top view of a fully processed rectangular-shaped VCSEL with an active area of $100 \times 14\,\mu m^2$. The operation characteristics of the VCSEL used in this work are depicted in Fig. 2. All measurements were done at room temperature. As visible in Fig. 2 (left), the VCSEL has a threshold current of about 20 mA and a roll-over current of about 90 mA, at which a maximum output power of about 39 mW is achieved. The optical spectra displayed in Fig. 2 (right) were measured at three different currents between threshold and roll-over. The red-shift in wavelength is due to increased internal temperature with increasing current. Near threshold, only a few modes oscillate, whereas far above threshold the laser is strongly multimode.

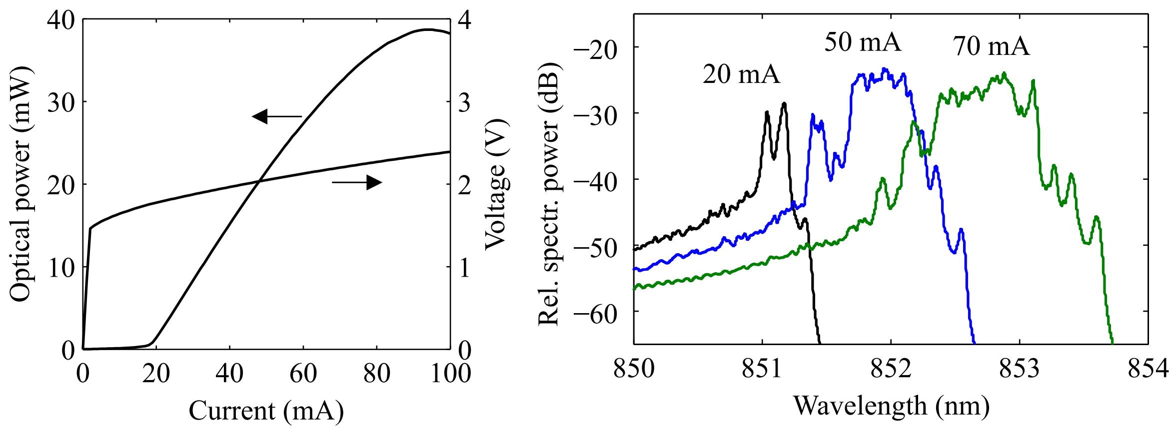


**Fig. 2:** Light–current–voltage characteristics (left) and optical spectra (right) of the rectangular VCSEL used for optical manipulation. The spectra are measured at three different currents between threshold and roll-over.

The near- and far-field profiles of the VCSEL are depicted in Fig. 3. The near-field intensity was measured at an operating current of 85 mA or an output power of 35 mW. It is stronger at the border of the laser but exhibits a relatively homogeneous distribution along the surface. The far-field was measured parallel to the long axis of the VCSEL at three operating currents and is dominated by two peaks with angles between about ±10° with respect to the optical axis. A theoretical analysis of the modal properties of similar rectangular VCSELs is presented in [15].

## 3. Particle Manipulation Experiments

The microfluidic channels are made of polydimethylsiloxane, a transparent and inert polymer. It is often used for prototyping due to straightforward fabrication based on a molding technique [5]. In the so-called soft lithography technique, the material is poured over a master wafer containing the inverse channel structure. Afterwards, the PDMS is cured and peeled off the master wafer.

In the experimental setup [16], the VCSEL is placed on a copper mount and electrically connected to a current source. The VCSEL output beam is collimated and then tightly focused into the sample stage by two objectives. To achieve a strong intensity gradient, an objective with a high numerical aperture of 1.25 is used. Thus, an optical trap is generated

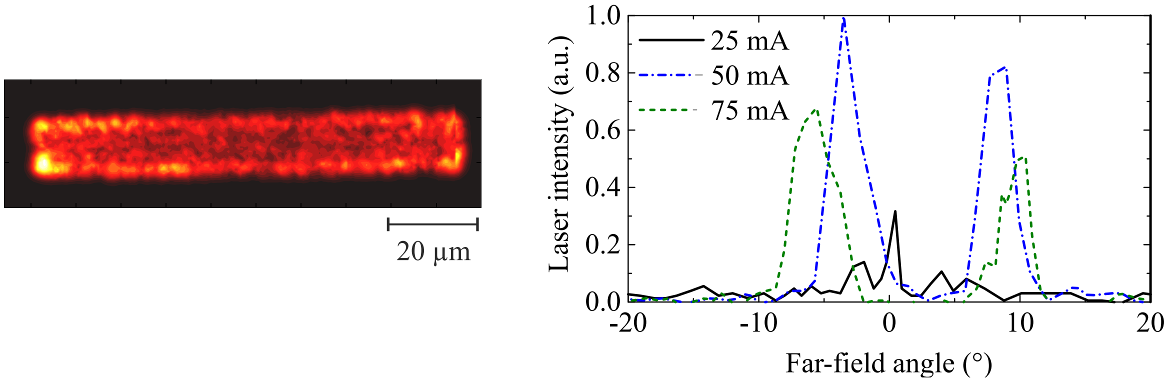


**Fig. 3:** Near-field (left) and long-axis far-field (right) of the rectangular VCSEL used for optical manipulation. The near-field was measured at 85 mA and the far-field at three different currents between threshold and roll-over.

inside the microfluidic channel, which is placed on a computer-controlled positioning system and filled with polystyrene particles in water solution. With the positioning system, a precise relative movement between channel and laser can be realized.

Using this setup, successful trapping of single and multiple polystyrene particles inside PDMS microfluidic channels with widths of 60 and 75 µm was achieved. After trapping with the rectangular VCSEL, the particle can be moved to any desired position in the channel. The tested particles have sizes between 1 and 10 µm. Figure 4 shows a 10 µm particle flowing down a 75 µm wide microchannel. The laser is positioned in the flow track of the particle (1). The particle is trapped by the laser (2), which is then moved from the lower to the upper part of the channel (3,4). Afterwards, the particle is released and the flow track was successfully manipulated (5). As another approach, the particle can be fixed by the laser and thus separated from the other particles while they are flowing by. Another experiment for potential particle sorting is depicted in Fig. 5. Here, there was no flow in the 60 µm wide channel. It is shown how the laser traps two 10 µm particles in the upper part of the channel (1) and moves them to the lower branch of the Y-junction (2–4). With this technique, two types of particles can be separated from each other for sorting applications.

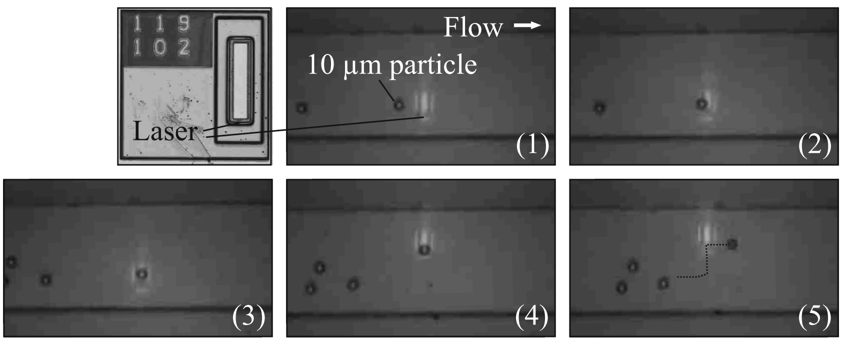


**Fig. 4:** Optical manipulation of a single 10 µm polystyrene particle under flow inside a 75 µm microfluidic channel. In this experiment, the flow track of the particle is manipulated.

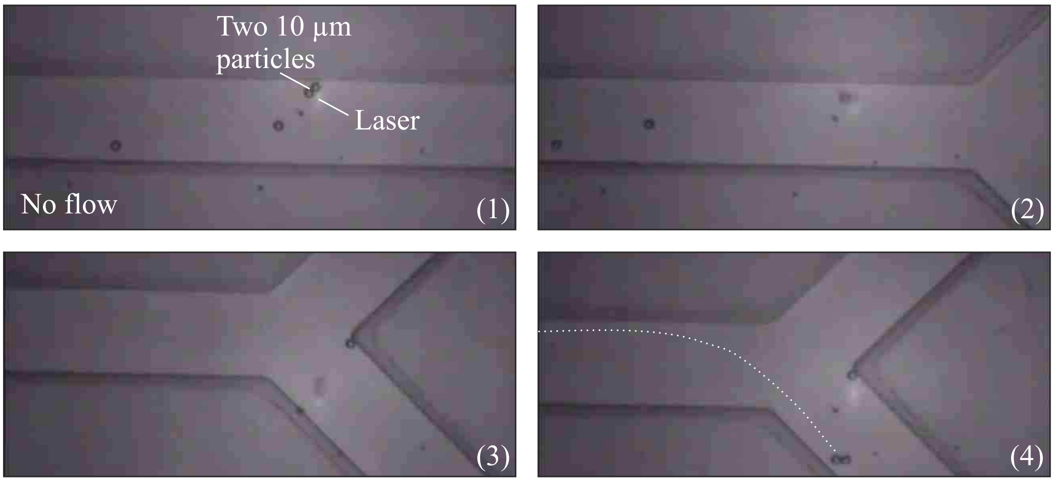


**Fig. 5:** Simultaneous optical trapping of two 10 µm polystyrene particles without flow inside a 60 µm microfluidic channel. In this experiment, particle sorting is achieved by placing them in the desired branch of the Y-junction.

## 4. Conclusion

In this paper, successful optical particle manipulation using a rectangular-shaped VCSEL was demonstrated. Unlike circular VCSELs, this laser has a rectangular $100 \times 14\,\mu\mathrm{m}^2$ active aperture area and shows rather homogeneous lasing over the entire large aperture. The device dimensions can easily be adapted to the specific application. Being oblong, this VCSEL can replace the linear arrangement of circular VCSELs which is typically used to simultaneously trap more than one particle, and it has the advantages of being cheaper and easier to fabricate. The results show the excellent multi-particle trapping ability of this VCSEL. Moreover, this VCSEL, like its VCSEL array predecessors [14], can be integrated directly underneath the microfluidic channel without the need of external optics. Therefore, portable and inexpensive microfluidic chips for biological particle manipulation can potentially be designed.

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