Generation of microfluidic flow using an optically assembled and magnetically driven microrotor

J Köhler, R Ghadiri, S I Ksouri, Q Guo, E L Gurevich and A Ostendorf

Applied Laser Technology, Ruhr-Universität Bochum, Universitätsstraße 150, 44801 Bochum, Germany

E-mail: koehler@lat.rub.de and ghadiri@lat.rub.de

Received 9 May 2014, revised 1 October 2014
Accepted for publication 9 October 2014
Published 24 November 2014

Abstract
The key components in microfluidic systems are micropumps, valves and mixers. Depending on the chosen technology, the realization of these microsystems often requires rotational and translational control of subcomponents. The manufacturing of such active components as well as the driving principle are still challenging tasks. A promising all-optical approach could be the combination of laser direct writing and actuation based on optical forces. However, when higher actuation velocities are required, optical driving might be too slow. Hence, a novel approach based on optical assembling of microfluidic structures and subsequent magnetic actuation is proposed. By applying the optical assembly of microspherical building blocks as the manufacturing method and magnetic actuation, a microrotor was successfully fabricated and tested within a microfluidic channel. The resulting fluid flow was characterized by introducing an optically levitated measuring probe particle. Finally, a freely moving tracer particle visualizes the generated flow. The tracer particle analysis shows average velocities of 0.4–0.5 µm s⁻¹ achieved with the presented technology.

Keywords: microfluidics, micropump, optical tweezers, microassembling, optical assembling, microfabrication, magnetic actuation

Online supplementary data available from stacks.iop.org/JPhysD/47/505501

(Some figures may appear in colour only in the online journal)
measurement of the viscosities of fluids, which is important for diagnostics in medicine and biological systems [7, 8].

Recently, all-optical techniques have been reported where the required microstructures have been fabricated using optical microfabrication techniques and the actuation principle has been based on optical forces [2, 9]. Using a laser direct writing technique such as two-photon polymerization [10, 11], the structures can be fabricated with sub-micrometer resolution. Due to the high resolution, the fabricated microstructures can be precisely tailored to match the desired application. Subsequently, those structures can be optically driven by several techniques based on the momentum transfer between light and matter [12]. Sophisticated holographic optical tweezers [13–16] allow the simultaneous manipulation of multiple objects using a single laser source. By optimizing the design of the actuated microstructure according to the characteristics of the optical forces, a higher driving efficiency can be achieved [17].

However, optical actuation exhibits some limitations and drawbacks. First, a laser source and optical components are needed to drive the microfluidic component, resulting in a rather large and costly system. Secondly, in optical actuation the driving velocity is proportional to the applied laser power. Thus, if faster motion is required, the laser power has to be increased but has to remain below the damage threshold of the applied material. Hence, the maximal driving velocity is limited for this method. Furthermore, optical driving of the micro-rotor requires a transparent environment with a refractive index smaller than the refractive index of the component to be driven.

Alternatively, the microstructure can be excited by magnetic forces. Ryu et al [4] presented a magnetic stir-bar with dimensions of approximately 0.5 mm fabricated by spin-coating, lithographic patterning and etching of different thin films. With magnetic actuation of the rotor, pumping and mixing of the fluids is demonstrated. When it comes to smaller dimensions, magnetic microspheres in the range of very few micrometers can be used to form microchains [18, 19]. If an external magnetic field is applied, the microspheres agglomerate to chains and can be controlled by magnetic actuation. Due to a rotating external magnetic field the rotors can be used for mixing applications. Nevertheless, the size of the magnetic chains can hardly be controlled. When it comes to higher rotation speed, the chains can break or microspheres agglomerate to big magnetic clusters. Researchers have experimented with magnetic nanocomposites, a mixture of a photosensitive material and magnetic nanoparticles, to offer the ability to drive the fabricated microstructure magnetically [20]. However, the incorporation of high nanoparticle concentrations into the photosensitive material is challenging, as the particles disturb the laser direct writing process.

To circumvent the described limitations, we propose a method combining optical microfabrication based on a laser assembling technique and magnetic actuation. Using an assembling approach, also presented in [21, 22], spherical particles were coated in advance with high-affinity biomo-olecules serving as a gluing layer. The particles were made to approach each other by optical tweezers and when attached, the structure became stable due to the binding agents. Recently, micro-mechanical systems have been fabricated using the assembling approach while combining optical and mechanical micromanipulation [23]. The assembling method also offers the benefit of fabricating complex microstructures with locally adjusted properties. For example, magnetic microparticles with a high concentration of magnetite can be incorporated into the microstructure at desired locations to increase the magnetic response of the microscopic object. Another benefit of this approach is the potential to combine magnetic and optical forces to achieve higher driving velocities with a magneto-optical driving solution. Furthermore, microassembling also facilitates the integration of larger structures into channels which are tighter than the structure, similar to the case of the ‘ship in a bottle’ problem. The single building blocks can first be transported into the channel and the structure can be built inside the channel.

In this work, we demonstrate the optical assembling of a microrotor and the subsequent magnetic actuation. First, the generated fluid flow in the proximity of the microrotor is analysed by using an optically levitated measuring probe particle. The displacement of the particle due to the fluid flow is acquired and the flow velocities are calculated. Finally, the microrotor is introduced into a microchannel to allow a directed fluid flow. The flow inside the channel is investigated by analysing the motion of a freely moving tracer particle, which follows the provoked current.

### 2. Laser assembling of microstructures

The idea of laser assembling microstructures [21, 22] is to use minute forces induced by laser light to align microparticles into the desired constellation and to join them to a stable structure. The forces acting on these particles arise due to the interaction between photons and matter, when light undergoes a change of propagation direction at the particle surface in the form of refraction, reflection and absorption. Here, the momentum of light is partly transferred to the particle, resulting in a force proportional to the applied laser power P. When the particle radius is much larger than the wavelength of light, this force can be described by [24]

\[
F_{\text{opt}} = \frac{n_0 Q P}{c}
\]

(1)

where \(n_0\) is the refractive index of the surrounding medium, \(c\) the speed of light and \(Q\) the trapping efficiency, which depends on the optical properties of the particle and the incident angle of light.

Using a laser source with a Gaussian shaped energy distribution and transparent particles, the forces acting on a transparent polymer particle are directed to the centre of the laser beam, trapping the particle in this radially stable position. By strongly focusing the laser beam, an additional force along the axial direction is induced, also trapping the particle in the axial direction. Thus, using a focused gaussian laser beam, the particle can be stably trapped in 3D. With a constant laser power, the optical trap can be described by a harmonic potential with the optical restoring force proportional to the displacement of the particle from the stable position

\[
F_{\text{opt}} = -k x
\]

(2)
with $k$ describing the linear relation between the displacement and the force, also called the trap stiffness. It can be calculated or experimentally measured by analysing the motion of the trapped particle [25]. With the known stiffness, the forces acting on a particle can be calculated by measuring the displacement of the particle from the trap centre.

By deflecting the laser light, a single particle can be moved to the desired position. With the same Gaussian shaped laser beam profile, the resulting forces on an absorbing or reflecting particle will be directed in the direction of beam propagation and the particle cannot be trapped stably. As such particles are not trapped by a Gaussian beam but are ‘pushed’ away, transparent particles are generally easier to handle and are preferred in optical trapping applications.

Combining this technique with light modulators and allowing the generation of several controllable laser beams by temporally or spatially modulating the incoming light, several particles can be controlled simultaneously. Given this optical grippers, also called optical tweezers (OT) or holographic optical tweezers (HOT), arbitrary structures can temporally be formed out of single microparticles. In our experiments we use an optical setup similar to the one described in [22], using a cw laser source (Coherent Verdi G6, $\lambda = 532$ nm), a reflective spatial light modulator (Hololoe Pluto) and a high numerical aperture microscope objective (Carl Zeiss, Plan-Apochromat, 100x, NA 1.4). The laser light is focused into a sample chamber, consisting of an aluminum part (although other non-magnetic materials can be used) with a circular hole of 10 mm. The sample chamber can be closed by cover glasses and sealed with silicone gel. All microparticles required for the experiments are inserted into this sample chamber. Once the laser light is switched off, the particles will lose the imposed alignment and will return to an arbitrary motion within the fluid, due to the Brownian motion.

To utilize the formed structure as a microscopic tool, it is necessary to achieve a stable binding between the single particles. For this purpose, the application of particles coated with high-affinity biomolecules has been shown to be appropriate. The biomolecules used in our experiments are Streptavidin (SA) and Biotin (B), exhibiting a high mutual affinity, once they are made to approach each other, which is mainly based on the complimentary structure of the molecules. With this approach, particles with different coatings are approached using OTs to form a specific microstructure. In the following experiments, a simple rotor geometry is applied, generated by the linear arrangement of three spherical microparticles with a diameter of approximately 3 $\mu$m for each particle. The particles for the rotor assembling are transparent B-coated polystyrene (PS) microspheres (Kisker Biotech, PC-B-3.0) and SA-coated PS microspheres, which contain magnetite (Bangs Laboratories, ProMag™ 3 Series). The magnetic particles show a notable absorption and are therefore harder to handle than the transparent particles. Due to the characteristics of the SA-B assembling technique, the particles forming the rotor have to be aligned in an alternating design. Intending to keep the rotor geometry simple by using only three particles, two different rotor structures are feasible: One transparent particle surrounded by two absorbing magnetic particles or one magnetic particle surrounded by two transparent PS particles. The first type is more promising, because in this configuration the rotor can be trapped at the rotational axis, described by the transparent particle in the centre. This allows the stable fixation or motion of the microrotor during the rotation, as will be shown in the following paragraphs.

Figure 1 shows the assembling process of the described microrotor in buffer solution (Bangs Bead Storage Buffer 7.4), as the binding of SA-B molecules is sensitive to changes in the pH value. Still, once the SA-B molecules are bound, the complex is stable to pH changes afterwards. Here, the assembly of the rotor prototype typically takes less than a minute. The slightly darker and smaller particles in the images are the magnetic particles surrounding the transparent PS particles. The rotor is built by gripping the transparent particle and making it approach the first magnetic particle. Afterwards, the joined doublet is moved to the second magnetic particle. For the entire assembling process, one single laser beam acting on the transparent particle is sufficient.

3. Magnetic actuation of microrotor

Due to the incorporated magnetic particles, the optically assembled microstructure can be magnetically actuated by applying an external magnetic field $\vec{B}$. The magnetic forces acting on a paramagnetic particle can be described by

$$\vec{F}_{\text{magn}} = \frac{V_0 \Delta \chi}{\mu_0} (\vec{B} \cdot \nabla) \vec{B}$$

with the difference in magnetic susceptibilities $\Delta \chi$ between the particle and the surrounding medium $V_0$, describing
the volume of the particle and \( \mu_0 \) being the permeability of the vacuum. If the rotation of a magnetic structure is desired, a rotating magnetic field is required. The magnetic torque \( \vec{\tau} \) acting on the particle with the magnetic moment \( \vec{m} \) can be described by

\[
\vec{\tau} = \vec{m} \times \vec{B},
\]

(4)

The magnetic torque will act on the particle until the magnetic moment of the particle is aligned along the magnetic field. To deliver a homogeneous and controllable rotating magnetic field, we apply a set of four electromagnets (ITS-MS 2520, Intertec Components, 4 W max. Power), which are aligned pairwise opposing each other around the sample chamber (figure 2) and act as a 'stepper motor'.

The magnetic field in the chamber is described as a superposition of the fields from each pair of electromagnets. The electromagnets are controlled by a stepper motor driver (TMCM-1110, Trinamic), by adjusting the current at the corresponding magnets to control the direction of the magnetic field and the microrotor. More details about the stepper motor configuration and control can be found in [26, 27]. Figure 3 shows the rotational control of a microrotor by controlling the external magnetic field. Obviously, with a higher rotating speed more fluid can also be displaced and therefore stronger fluid flow can be generated.

To identify the maximum rotating speed at which the microrotor can be stably operated, the microrotor was driven at different rotating speeds and the stability of the motion was examined. It has been observed that the assembled microrotors could be driven at rotating speeds of up to approximately 120 rpm. Up to 120 rpm the evaluated rotors are horizontally aligned and parallel to the cover glass of the sample chamber. With higher rotational speed instabilities occur; the rotors start to raise and rotate perpendicular to the cover glass. We assume that the instability arises due to slight asymmetries of the assembled structure and its imbalance. Also, inhomogeneities of the magnetic field inside the sample chamber can have an influence on the unstable behaviour of the microrotor at higher rotating velocities.

4. Analysis of generated fluid flow using a measuring probe particle

As described above, optical tweezers can be used not only to exert minute forces on microparticles, but also to measure tiny forces exerted on microscopic particles. Following this, the fluid flow velocity can be derived from the measured force on a particle. Therefore, a probe particle (Sigma-Aldrich, 78452 FLUKA, PS, \( \Theta = 2 \mu m \)) is introduced close to the magnetically driven rotor to analyse the effect of the microrotor and to visualize the generated fluid flow. As illustrated in figure 4, one optical trap holds the microrotor by the central transparent particle while another trap is generated close to the rotor, to trap the probe particle.

As the quantity of the flow strongly depends on the distance to the rotor, this distance has to remain constant and is set to 8.5 \( \mu m \) (measured between the particle and rotor centre) in the following experiments. While the microrotor and the probe particle are fixed in this position, the external magnetic field starts to rotate with varying angular velocity. To analyse the effect of the actuated microrotor, the position of the probe particle is tracked by a CMOS camera (Edmund Optics, EO-0413M) at a frame rate of 80 Hz and the data is evaluated using a position detection algorithm implemented in NI Vision Builder. With the camera-based method, sub-pixel accuracy down to 5 nm can be achieved [25]. As described above, the particle displacement expected from the generated fluid flow scales linearly with the applied trapping laser power, which has to match the analysed flow velocity. If these quantities mismatch, two scenarios are possible: the particle will be pushed out of the optical trap or the displacement is not large enough to be detected. Therefore, in our experiment we use three different trapping laser power levels ranging from 5.7 to 10.1 mW. The laser power was measured at the laser source output. The optical components lead to attenuation of the laser power and the resulting power which is available for trapping is approximately 14% of the output power.

Figure 5 shows the results for the particle tracking when a laser power of 5.7 mW is applied and the microrotor is driven at 60, 90 and 120 rpm. The rotation of the magnetic field is set to the corresponding velocities for 8 s. A pause period is introduced between the different rotational velocities to clearly identify the distinct regions.

The trapped probe particle shows a random motion around the equilibrium position, which shifts for each rotational speed. The equilibrium position is determined by the balance of the mechanical force (drag force) induced by the current around the microrotor and the optical forces acting on the probe particle. It can be experimentally determined by measuring the average particle displacement \( \tau_d \) of the trapped probe particle for the different rotational speeds. Each time the magnetic field is switched off, the particle motion returns back to the original equilibrium position. The equilibrium position shifts from approximately 100–180 nm when the rotational velocity of the rotor increases from 60 to 120 rpm.

The average particle displacement for the different laser power levels and rotation velocities are shown in figure 6. The linear relation between the detected average particle displacement and the rotational speed can be observed. With higher laser power, the optical trap stiffness is increased and the particle displacements are reduced, thus higher fluid flow rates can also be analysed with the given system. A lower laser power is preferred for slower flow
rates, as the measurement is more sensitive in this case and also small flow-induced forces can be detected. With the given displacements and a calibrated trap, the fluid flow rates can be quantitatively analysed. Figure 7 shows the calculated fluid flow velocity and force in dependency of the rotation speed.

The optical trap was calibrated with a trapping laser power of 5.7 mW using the equipartition theorem [25]. Here, the particle motion is detected at an increased frame rate of approximately 600 Hz, which is achieved by decreasing the region of interest (ROI) of the camera to the area relevant for tracking the probe particle. The calibration of the optical trap holding the probe particle results in a trap stiffness of $k_x = 0.4 \text{ pN} \cdot \text{m}^{-1}$.

With this trap stiffness and the detected particle displacement, the forces acting on the probe particle can be calculated (equation (2)). Using Stoke’s law for a spherical particle

$$F_d = 6\pi\eta r v c_F$$

with the fluid viscosity $\eta$ (in our case we assume $\eta = 1 \text{ mPas}$, as the utilized buffer solution contains approximately 99% water), the probe particle radius $r$, the correction factor by Faxen $c_F$ to correct the wall effects [28], the fluid flow velocity can be calculated from the balance of the optical and the friction force $F_d$.

In our experiment, a probe particle with a radius of $r = 1 \mu m$ is trapped at a height of $h = 1.5 \mu m$, resulting in a correction factor $c_F = 1.62$ [28].

As the probe particle will remain in the equilibrium position defined by the optical force and the drag force

$$F_{opt} = F_d$$

the fluid velocity can be expressed by

$$v = \frac{k_x x_d}{6\pi\eta r c_F}.$$  

Table 1 summarizes the results of five experiments at three different rotating speeds. It contains the calculated force (equation (2)), which equals the drag force for the equilibrium state acting on the probe particle and the calculated fluid flow velocity in $x$-direction for the different rotating velocities. With higher rotational speed the fluid flow velocities and thus the force increases.

The highest fluid flow velocity achieved in this experiment is $2.1 \mu m \cdot s^{-1}$ at a rotation rate of 120 rpm. Higher fluid flows can be expected if the rotor motion can be controlled more stably at higher rotational rates and by optimizing the microrotor geometry.

### 5. Integration of microrotor into a microchannel

To achieve a directed fluid flow, as is necessary for micropumps and micromixers [4, 29], the described rotor has to be integrated into an appropriate microchannel. The characteristics of the generated flow strongly depend on the geometrical properties of the channel. For the demonstration of an implemented micropump, we choose a channel geometry similar to those described in [26, 29], showing a rectangular cross-section and a semi-circular protrusion. The microchannel width was chosen to be 9.5 $\mu m$ and the channel height 8 $\mu m$. The entire length of the channel was chosen as 60 $\mu m$. By integrating the microrotor inside the protrusion, a fluid flow can be generated depending on the rotating speed and rotating direction of the microrotor (figure 8).

The designed microchannel was fabricated by two-photon polymerization in our laboratories as described in [30] using Femtobond 4B (LZH e.V., Germany) as the photosensitive material. After fabricating the microchannel, the microchannel is inserted into the sample chamber and
the particles necessary for the assembling of the microrotor are added subsequently. Successively, the described rotor is assembled outside the channel and transported into the channel using optical tweezers acting on the transparent particle of the microrotor. The assembling strategy also allows the fabrication of larger structures, which would not fit the channel inlet, by first transporting the single particles into the channel and by successively assembling the structure inside the microchannel.

When the rotor is driven by rotating the external magnetic field, the fluid is unequally conveyed in the upper and lower part of the rotor, resulting in a directed flow. To visualize the fluid flow, a freely moving tracer particle is introduced inside the channel, which will be conveyed by the fluid and detected by the camera system. By evaluating the recorded video sequence, the particle and the fluid flow can be analysed. The same particle that was used in the former paragraph as a probe particle (PS, Ø = 2 µm), is used here as a freely moving tracer particle, without any trapping by the optical tweezer.

In general, a constant rotation of the rotor will lead to a time-dependent flow which shows a strong local dependence.

**Figure 5.** Probe particle position, while the rotating speed is varied from 60 to 120 rpm (laser power $P_L = 5.7$ mW). The average particle displacement increases with increasing rotating speed. The blue regions indicate the periods with a static magnetic field.

**Figure 6.** Average probe particle position for different rotating speeds and varying laser trap strength. By applying a lower laser power the particle will be displaced more easily by the flow, therefore even a weak fluid flow can be clearly visualized.
inside the channel. While usually the fluid flow contains components in x-, y- and z-directions, the main component under the described conditions is the flow in x-direction, which will be evaluated in our experiments. Figure 9 shows the motion of the tracer particle inside the microchannel, while the microrotor is rotated counterclockwise at a rotating rate of 120 rpm.

Here, the blue spots indicate the tracer particle position in time intervals of 4 s. For estimating the average fluid velocity in x-direction the shaded areas have been examined, each one expressing distances of 20.5 µm. By considering the time necessary to pass the corresponding distances, we find average velocities of 430 nm s⁻¹ and 510 nm s⁻¹ in the left shaded area and in the right shaded area of the microchannel, respectively. The fluid flow in the microchannel is dominated by a parabolic flow field and thus the velocity of the tracer particle varies significantly. In the left shaded area, the tracer particle is transported close to the wall of the microchannel and a lower velocity can be observed. The average velocity determined in the right shaded area is higher, as the tracer particle moves rather along the middle of the microchannel. Due to the discrepancy of the measuring method with a tracer particle, the experiment can be seen as a proof of concept. Nevertheless, it shows that the developed micropump generates a directed fluid flow. The central part of the channel was not considered in this observation, as the fluid flow is more inhomogeneous in this region and significantly higher than in the entire channel.

Table 1. Effect of the increased rotating speed on the calculated force acting on the probe particle and the fluid flow velocity.

| Rotating speed ω [rpm] | Force $F_x$ [fN] | Fluid flow velocity $v_x$ [µm s⁻¹] |
|------------------------|------------------|----------------------------------|
| 60                     | 38.3 ± 2.91      | 1.3 ± 0.10                       |
| 90                     | 51.2 ± 3.06      | 1.7 ± 0.10                       |
| 120                    | 65.6 ± 5.75      | 2.1 ± 0.19                       |

Figure 7. Calculated fluid flow velocity and force in dependency of the rotation speed is shown.

Figure 8. Integration of microrotor into a microchannel to generate a directed fluid flow. By alternating the rotation direction of the microrotor, the fluid flow direction can be reversed.

Figure 9. Microrotor assembled, introduced into a microchannel and magnetically driven counterclockwise. The blue spots indicate the tracer particle position in time steps of 4 s (the scale bar is 9 µm). A supplementary video file is available online (stacks.iop.org/JPhysD/47/505501).
6. Conclusion

In this work, a flexible method for assembling a magnetic microrotor with the desired size and shape for the generation of fluid flow was presented. With the implementation into a microchannel, the use as a micropump was demonstrated and a directed fluid flow ensued. Correspondingly, the rotor can be used as a micropump or for mixing applications. After incorporating magnetic particles into the microstructure, the fabricated structure was actuated magnetically by applying an external magnetic field. So far, the limitation for a stable magnetic drive was analysed to be approximately 120 rpm. Certainly, several modifications could lead to higher flow rates, e.g. higher rotational speed of the rotor (e.g. due to a higher outer magnetic field), adaptations and improvement of the microchannel design and a variation of the rotor shape and size. Within the stable conditions, the influence of the rotation speed on the generated fluid flow in an aqueous environment was analysed using an optically trapped measuring probe particle. The displacement of the microparticle, which can be observed when the fluid flow is generated, shows a linear dependence on the rotating velocity. Both the assembling and the analysis of the fluid flow were performed with the same technique of optical tweezers. A proof of principle experiment and a directed fluid flow ensued. Correspondingly, the rotor chamber axis. An increase of the fluid flow can be expected by further optimization of the rotor and channel geometry. Further work will be performed in the future on a dual driving approach combining magnetic and optical actuation to enable more powerful micropumps.

Acknowledgments

We would like to thank the German Research Foundation DFG (Deutsche Forschungsgesellschaft) for their generous support within the R Koselleck project (OS 188/28-1).

References

[1] Terray A, Oakey J and Marr D W M 2002 Appl. Phys. Lett. 9 1555–7
[2] Maruo S and Inoue H 2006 Appl. Phys. Lett. 89 144101
[3] Lu L H, Ryu K S and Liu C 2002 J. Microelectromech. Syst. 5 462–9
[4] Ryu K S, Shaikh K, Goluch E, Fan Z and Liu C 2004 Lab Chip 6 608–13
[5] Arnold D P 2007 IEEE Trans. Magn. 43 3940–51
[6] Wu T, Nieminen T A, Mohanty S, Miotke J, Meyer R L, Rubinsztein-Dunlop H and Berns M W 2011 Nat. Photon. 6 62–7
[7] Bishop A I, Nieminen T A, Heckenberg N R and Rubinsztein-Dunlop H 2004 Phys. Rev. Lett. 92 198104
[8] Knöner G, Parkin S, Heckenberg N R and Rubinsztein-Dunlop H 2005 Phys. Rev. E 72 031507
[9] Maruo S, Takaara A and Saito Y 2009 Opt. express 17 18525–32
[10] Kawata S, Sun H B, Tanaka T and Takada K 2001 Nature 412 697–8
[11] Korte F, Serbin J, Koch J, Egbert A, Fallnich C, Ostendorf A and Chichkov B 2003 Appl. Phys. A 77 229–35
[12] Ashkin A 1970 Phys. Rev. Lett. 24 156–9
[13] Hayasaki Y, Itoh M, Yatagai T and Nishida N 1999 Opt. Rev. 6 24–7
[14] Dufresne E R, Spalding G C, Dearing M T, Sheets S A and Grier D G 2001 Rev. Sci. Instrum. 72 1810–6
[15] Curtis J E, Koss B A and Grier D G 2002 Opt. Commun. 207 169–75
[16] Grier D G and Roichman Y 2006 Appl. Opt. 45 880–7
[17] Lin X F, Hu G Q, Chen Q D, Niu L G, Li Q S, Ostendorf A and Sun H B 2012 Appl. Phys. Lett. 11 113901
[18] Biswal S L and Gast A P 2004 Anal. Chem. 76 6448–55
[19] Eickenberg B, Wittbracht F, Stohmann P, Schubert J-R, Brill C, Weddemann A and Hütten A 2013 Lab Chip 13 920–7
[20] Xia H, Wang J, Tian Y, Chen Q D, Du X B, Zhang Y L, He Y and Sun H B 2010 Adv. Mater. 22 3204–7
[21] Park I Y, Sung S Y, Lee J H and Lee Y G 2007 J. Micromech. Microeng. 17 N82–9
[22] Ghadiri R, Weigel T, Eisen C and Ostendorf A 2012 J. Micromech. Microeng. 22 65016
[23] Kim J D and Lee Y G 2013 J. Micromech. Microeng. 23 065010
[24] Ashkin A 1992 Biophys. J. 61 569–82
[25] Neuman K C and Block S M 2004 Rev. Sci. Instrum. 75 2787–809
[26] Henighan T, Giglio D, Chen A, Vieira G and Sooryakumar R 2011 Appl. Phys. Lett. 98 103505
[27] Sacconi L, Romano G, Ballerini R, Capitanio M, De Pas M, Giuntini M, Dunlap D, Finzi L and Pavone F S 2001 Opt. Lett. 26 1359–61
[28] Svoboda K and Block S M 1994 Cell 77 773–84
[29] Barbic M, Mock J J, Gray A P and Schulz S 2001 Appl. Phys. Lett. 79 1399–401
[30] Ksouri S I, Aumann A, Ghadiri R and Ostendorf A 2012 Opt. Photon. 4 44–7