Integrated Optofluidics: Optical Control of Particles and Droplets in Fluidic Environments

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Abstract— Being a key enabling technology, optofluidics allows precise light-based manipulation of liquids and solid particles on micrometer scales in fluidic environments and covers high potential to fabricate efficient integrated lab-on-a-chip devices. In many of these devices, the ability to control and to manipulate particles by light is of utmost importance. This comprises an all-optical treatment of particles, viable cells, or droplets to be moved or trapped for analytical purposes. Such an all-optical control can be realized either by direct exposure in optical tweezers or indirectly by activating electric, thermal or mechanical properties by nonlinear light-matter interaction. Beneath particle manipulation, we demonstrate control of cells by holographic optical tweezers as well as droplet manipulation based on dielectrophoretic optical tweezers.

In the past years, optical control of particles by laser light has matured in order to tackle cutting-edge questions of control of particles in technical and biomedical fluidic environment as well as developing techniques to control droplets as entities for smallest reaction containers in lab-on-a-chip applications.

For a direct optical control of particles by light, light-matter interaction is the starting point. Thus, one has to distinguish whether the considered particle is transparent or is absorbing light [1]. In both cases, light-based forces act on the particle and allow direct manipulation or control.

By employing a Gaussian shaped beam on a transparent particle, a combination of gradient and scattering forces drags it into the region of highest intensity, i.e., the center of the beam cross section. This is well-known as optical tweezers [1] and has been developed in the past ten years into versatile holographic optical tweezers [2, 3] or complex optical landscape tweezers based on sculpting and shaping light [4] and has advanced cell investigations in biomedicine considerably [5–8].

In contrast, absorbing particles will be repelled from regions of high intensity. They can be trapped in void-like complex transverse beam structures by the effect of photophoresis. Discovered already in the 19th century [9, 10] and based on a temperature induced gradient that causes a momentum transfer from heated molecules tot the illuminated side of the absorbing particle, it allows trapping particles. Thus, advanced beam shaping methods resulting in so-called bottle-beams are the key for trapping absorbing particles [11, 12]. Among the most promising approaches are diffractive optical elements to generate hollow light landscapes or conical refraction [13]. These light cages can be efficiently used to confine absorbing matter in liquid or solid states [14, 15] and will be presented in our contribution.

We will also demonstrate a direct light to fluidic manipulation based on nonlinear light-matter interaction paving the way to nonlinear optofluidics. We exploit optically induced dielectrophoresis where a nonlinear material is illuminated by a desired light pattern to create virtual electrodes, being the origin of non-uniform electric, often photovoltaic fields which in turn induce a dipole moment in polarizable objects [16]. In contrast to classical dielectrophoresis, virtual electrodes can be easily reconfigured and thus new electrode pattern can be rapidly realized [17]. The flexibility of the nonlinear optofluidic approach is demonstrated by different, complex particle arrangements on the surface of the nonlinear material and by guiding droplets on light-induced circuits [18]. Such integrated droplet labs-on-a-chip are extremely versatile devices allowing, i.e., sorting, deflecting, trapping and separating droplets and pave the way for future droplet-based technological sensor and biomedical diagnostic devices.

REFERENCES

1. Ashkin, A., *Science*, Vol. 210, 1081–1088, 1980.
2. Reicherter, M., et al., *Opt. Lett.*, Vol. 24, 608–610, 1999.
3. Dufresne, E. R., et al., *Rev. Sci. Instrum.*, Vol. 72, 1810–1816, 2001.
4. Woerdemann, M., C. Alpmann, M. Esseling, and C. Denz, *Laser Photonics Rev.*, Vol. 7, 839–854, 2013.
5. Ashkin, A., J. Dziedzic, and T. Yamane, *Nature*, Vol. 330, 769, 1987.

6. Stevenson, D., F. Gunn-Moore, and K. Dholakia, *J. Biomed. Opt.*, Vol. 15, 41503, 2010.
7. Kemper, B., Á. Barroso, et al., *J. Biophoton.*, Vol. 3, 260–266, 2013.
8. Meissner, R., et al., *Lab & More*, Vol. 3, 20–24, 2015.
9. Lebedev, P. N., *Annalen der Physik*, Vol. 6, 433–458, 1901.
10. Arlt, J. and M. Padgett, *Opt. Lett.*, Vol. 25, 191–193, 2000.
11. Alpmann, C., et al., *Appl. Phys. Lett.*, Vol. 100, 111101, 2012.
12. Lloyd, H., *Philos. Mag.*, Vol. 1, 112–120, 1833.
13. Poggendorff, J. C., *Pogg. Ann.*, Vol. 48, 461–462, 1839.
14. Sokolovskiy, G. S., D. J. Carnegie, T. K. Kalkandjiev, and E. U. Rafailov, *Opt. Express*, Vol. 21, 11125–11131, 2013.
15. Turpin, A., et al., *Opt. Express*, Vol. 21, 26335–6340, 2013.
16. Villarroel, J., et al., *Opt. Express*, Vol. 19, 24320–24330, 2011.
17. Glaesener, S., M. Esseling, and C. Denz, *Opt. Lett.*, Vol. 37, 3744–3746, 2012.
18. Esseling, M., et al., *Las. Photon. Reviews*, Vol. 9, 98–104, 2015.