On-Chip Optical Tweezers Based on Micro-Reflectors

Jinsheng Lu[1,3], Shaoliang Yu[2]*, Vincent Ginis[1,4], Simon Kheifets[1], Soon Wei Daniel Lim[1], Min Qiu[5], Tian Gu[2], Juejun Hu[2,6], and Federico Capasso[1]

[1]*Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*
[2]*Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[3]*State Key Laboratory of Modern Optical Instrumentation, College of Optical Science and Engineering, Zhejiang University, 310027 Hangzhou, China*
[4]*Data Lab/Applied Physics, Vrije Universiteit Brussel, 1050 Brussels, Belgium*
[5]*Key Laboratory of 3D Micro/Nano Fabrication and Characterization of Zhejiang Province, School of Engineering, Westlake University, Hangzhou 310024, China*
[6]*Materials Research Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
**yusl@mit.edu*

Abstract: We introduce a new class of on-chip optical tweezers with high trapping efficiency, compact footprint, and broadband operation by integrating free-form micro-reflectors to the facets of waveguides.

1. Introduction

Optical tweezers have advanced significantly in a plethora of research landscapes [1] including atom optics, chemistry, and biology since Arthur Ashkin pioneered the research field of optical trapping in the early 1970s, nearly half a century ago [2]. Traditional optical tweezers use a high numerical aperture (NA) objective to focus light into a tight spot and generate a strong intensity gradient for trapping, which require a bulky and costly benchtop system [3]. Miniaturized planar on-chip optical tweezers based on photonic waveguides or plasmonic structures have been proposed [4-6] to overcome these shortcomings. However, they use the gradient of the evanescent field for trapping. The trapping happens very close to the device - less than one wavelength away - due to the near field behavior of the evanescent fields. On-chip optical tweezers with high NA that can trap and levitate particles is of great significance in many research fields but has not yet been demonstrated. Here, we show that by integrating free-form micro-reflectors to the facets of on-chip waveguides for wavefront shaping, a three-dimensional optical field gradient can be generated for stable optical trapping with high trapping efficiency, compact footprint, and broadband operation.

2. Design

The design of our on-chip optical tweezers based on a pair of elliptical reflectors is shown in Fig. 1(a). The free-form focusing reflectors are 3D printed onto the facet of the waveguides through two-photon lithography. The 1550-nm wavelength single-mode waveguides are made of polymer with a cross-sectional size of 2.5 µm × 2.5 µm on a silicon substrate. The core and cladding materials of the waveguides are EpoCore and OrmoCore, with indexes of 1.575 and 1.537, respectively. One of the two foci of the elliptical reflector is placed at the waveguide facet. The other is set at the pre-defined crossing point of the two reflected beams, which is positioned z = 12 µm above the upper surface of the chip. Each of the two counter-propagating beams diverges upon exiting the waveguides before being total-internally reflected and focused by the elliptical reflectors. The two focused beams intersect at a specific angle and together generate a 3D gradient field, which can be used for particle trapping.

3. Results

Simulations are carried out to investigate the trapping performances under different crossing angles (θ) of the two beams. The FDTD simulated light intensity distributions of the two crossed beams are shown in Fig. 1(b) and 1(c) when the crossing angle is set to be 30° and 60°, respectively. The light in both waveguides is TE polarized and in phase. A larger angle results in a higher intensity gradient in the z-direction but produces a larger beam size in the horizontal x-direction with more interference fringes. When a microparticle with a diameter of 4.5 µm is placed into the focal spot region, it is subject to both the optical scattering force F_{SCAT} and gradient force F_{GRAD}. Since the scattering forces in the x-direction from the two counter-propagating beams cancel out, the total optical force in the x-direction is only due to the gradient force, which produces a potential well for particle trapping, shown in Fig. 1(d) and (e). When the crossing angle is smaller than 56°, the trapping potential depth is larger than 500 k_BT/mW, corresponding to a trapping power of at least 20 µW for the 10 k_BT stable trapping threshold. In the z-direction, the scattering forces from the beams do not cancel and tend to push the particle away from the trapping well. To achieve trapping in the z-direction, the minimum total force $F_z^{min} = \min\,(F_{SCAT} + F_{GRAD})$ should be negative. There is an optimum angle of around 65° when the minimum total force reaches -0.5 pN/mW, as displayed in Fig. 1(e) and (g). However, the crossing angle is constrained from below by the total internal reflection condition. In the experiment, the crossing angle was set to be 50°. The measured light intensity distribution of the crossed beams is shown in Fig. 1(h). The optical microscope image in Fig. 1(i) shows a microparticle stably trapped by the on-chip optical tweezer.

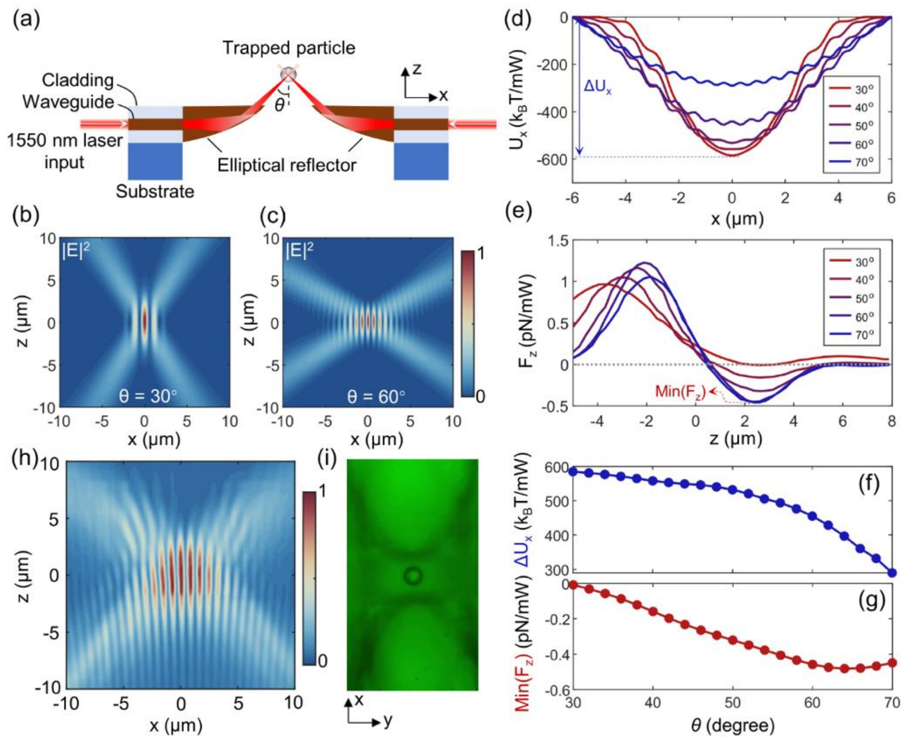

Fig. 1. On-chip optical tweezers. (a) Schematic of the on-chip optical tweezers. (b-c) Simulated light intensity distributions of the two crossed beams at two incidence angles. (d-e) Calculated (d) trapping potential in the x-direction and (e) optical force in the z-direction when the two beams are crossed with different angles. (f-g) Calculated (f) trapping potential depth and (g) minimum optical force versus crossing angle of the two beams. (h) Measured light intensity distributions of the two crossed beams above the chip. (i) An optical microscope image showing a particle with a diameter of 4.5 μm trapped by the chip.

In summary, a new class of on-chip optical tweezers based on free-form micro-optics is proposed and experimentally validated. The free-form micro-optics can be used to shape wavefronts on-demand in a chip-level platform. Here we use them to generate a 3D gradient light field for trapping suspended particles. The potential applications include atom/ion trapping and cooling, cell analysis and assembly, micro-fluidic sensing, among others.

References

[1] D. Gao, W. Ding, M. Nieto-Vesperinas, X. Ding, M. Rahman, T. Zhang, C. Lim, and C.W. Qiu, "Optical manipulation from the microscale to the nanoscale: fundamentals, advances and prospects," Light Sci. Appl. **6**, e17039-e17039 (2017).
[2] A. Ashkin, "Acceleration and trapping of particles by radiation pressure," Phys. Rev. Lett. 24, 156-159 (1970).
[3] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm and S. Chu, "Observation of a single-beam gradient force optical trap for dielectric particles," Opt. Lett. **11**, 288–290 (1986).
[4] S. Kawata and T. Tani, "Optically driven Mie particles in an evanescent field along a channeled waveguide," Opt. Lett. **21**, 1768 (1996).
[5] M. L. Juan, M. Righini, and R. Quidant, "Plasmon nano-optical tweezers," Nat. Photonics **5**, 349–356 (2011).
[6] S. Lin, E. Schonbrun, and K. Crozier, "Optical manipulation with planar silicon microring resonators," Nano Lett. **10**, 2408–2411 (2010).