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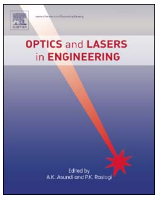

# Two-laser optical tweezers with a blinking beam

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## ABSTRACT

We report on a two-laser holographic optical tweezers setup and present its two major advantages over single-laser one. First, the trap stiffness of a weak trapping beam can be measured with a considerable accuracy. Second, a novel method of examining local viscosity of fluid is proposed. Both measurements are performed based on forcing the oscillations of a microscopic polystyrene bead placed between two optical traps. The two beams are generated by separate laser sources and therefore their trapping power can vary. Moreover, a stronger trap 'blinks', modulated by an electronic shutter. The blinking frequency can be precisely adjusted to the experimental conditions, which results in high accuracy of the measurements.

## 1. Introduction

Optical tweezers are being more and more widely used for examination and precise manipulation of micro- and nano-sized objects. Once the object is trapped in the tightly focused laser beam, it can be displaced or rotated by the use of optical forces. The holographic optical tweezers (HOT) [1–3] use computer generated holograms (CGH) in order to form and steer trapping beams. The holograms are generated by the use of spatial light modulators (SLM) [4,5]. The dynamic holography provides a very flexible way of forming and driving tens of various optical traps simultaneously. Optical tweezers have become useful in biotechnology and chemistry as they allow studying piconewton forces acting on a specimen. Such research often requires examining fluid properties in a narrow sample region, i.e. in the range of tens of micrometers. Several reports on measuring local viscosity with optical tweezers can be found [6–10].

The HOT development goes into various directions. The most important is overcoming the limitations imposed on trap quality due to SLM. Although the manufactures improve the performance of the SLM, the HOT is still of lower quality comparing to more classical solutions (for example galvanic mirror optical tweezers). The main problems are the trap optical quality, low switching frequency (typically 60 Hz), laser power losses (especially at infrared range), diffraction artefacts (like zero order beam). There are many ways to solve the above problems. All of them are of limited value and can be applied to a specific measurement problem. The two-laser HOT opens a new possibility for experiments and allows avoiding some problems specific for the single-laser system. In this paper we present our two-laser HOT and report on two kinds of experiments performed with it.

## 2. Preliminary observations

We have noted several intriguing phenomena while studying the microbead motion affected by the proximity of two optical traps. In our first experiment the single-laser HOT (solid line, Fig. 1) was used. A Nd:YAG laser beam is collimated and illuminates a SLM matrix. SLM (Spatial Light Modulator, Holoeye-Pluto) enables multiple traps generation, both light and dark. Dark traps carry non-zero angular momentum (vortex beams [11,12]). Such vortex traps (also known as doughnut traps) have an annular intensity distribution with a dark region in the trap center. Particles tend to be either trapped inside a bright ring or circulate along it as a result of angular momentum transfer from the beam to the particle. A dimensionless quantity describing an optical vortex and closely related to the ring diameter is called topological charge (m) [13]. The higher the charge, the wider the focused vortex beam.

The beam reflected from the SLM surface is tightly focused by the oil-immersion microscope objective (1.3NA, 100x, Olympus UPlanFL N). An adjustable z-position (along the beam axis) of this objective combined with a x-y positioning microscope stage allows examining the entire sample area. Additionally, a heating stage keeps the constant temperature of a sample. Polystyrene microbeads of two sizes (4.5 and 10 µm in diameter) were used in our experiments. A 20 µl volume of beads in aqueous solution was put into the chamber between a microscope slide and a cover slip. The chamber was approximately 0.8 mm deep and the focal point of the trapping beam was located at

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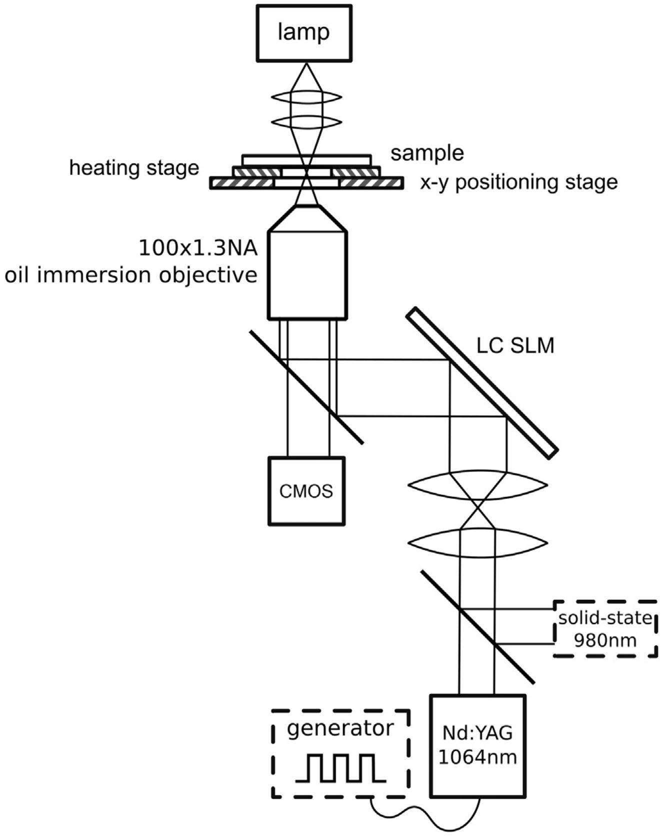

**Fig. 1.** The scheme of standard (solid line only) and two-laser (solid + dashed line) holographic optical tweezers.

least 100 μm away from the surface. Therefore, the influence of the glass-water interfaces can be neglected. The image of the sample was recorded with a high-precision fast video camera (5000 fps). In viscosity measurements (Section 5.2) the frame rate was reduced to 500fps due to thermal effects.

### 2.1. Experiment

In the first experiment two traps were used - a zero-order diffraction (ZOD) beam and a holographically generated conventional Gaussian trap. The traps were separated by the distance of 4–5 μm and a 10 μm bead was placed between them. Since the bead experienced a peculiar tremor, a fast video camera was used to observe bead trajectory. Fig. 2 presents a trajectory of bead center in a x-y plane within 1 s. The bead tends to go back and forth along the line connecting the traps. The oscillations are strictly periodic, with a period of about 0.0082 s (giving a frequency of ~120 Hz).

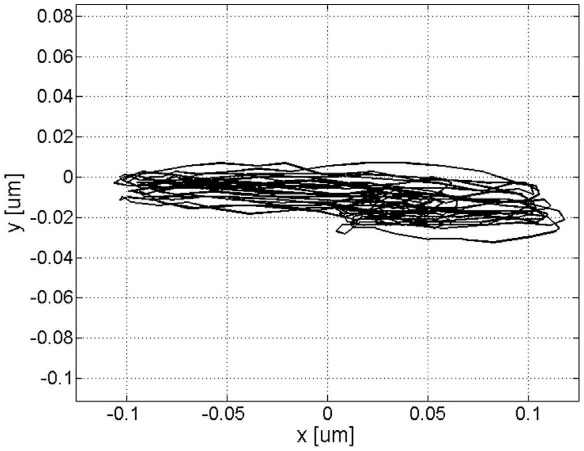

**Fig. 2.** Bead center position in x-y plane within 1 s. The bead was moving between ZOD and conventional trap.

In the second experiment, the Gaussian trap was replaced with a vortex beam (m = 30) and thereby the ZOD trap was encircled with a bright ring (Fig. 3a). The bead situated in the inner dark region was set into rotations as a result of an angular momentum transfer from the optical vortex. A retraced trajectory reveals, however, the existence of an additional radial component of this movement. The angular frequency of the revolution depends on the dark beam intensity. In contrast, the angular frequency of minor oscillations does not. A cycle performed by the bead (in 0.125 s) can be seen in Fig. 3b. Approx. 15 radial oscillations occurred within a full rotation, resulting in the angular frequency of ~120 Hz. Indeed, a 120 Hz frequency peak was present in a Fourier spectrum of bead's movement.

To sum up, certain periodic driving force (f = 120 Hz) was present in our system. A fast-cam recording in the sample plane was performed. As expected, the beams pulsate ('blink') as a result of SLM refresh rate (f = 60 Hz). More surprisingly, the zero-order diffraction trap and the first-order one are in antiphase, hence the doubled frequency. Indeed, it is a result of the SLM design. During the transition between two subsequent patterns displayed on SLM matrix, pixels take random values. For this short time, ZOD beam increases in intensity while another one decreases significantly. More detailed analysis of this phenomenon can be found in [14]. The bead is attracted to the light ring of the dark trap when the dark trap's intensity increases. When the intensity decreases, the bead moves towards ZOD center. This is the reason for minor oscillations observed in our system.

In order to verify the above assumptions, a subtle change to the trap configuration was introduced. The ZOD beam was no longer used. It was substituted by a standard non-vortex trap placed in the center of a doughnut trap. The intensity distribution in the sample plane did not change (as in Fig. 3a). It appears that circulation of the particle may now be treated as purely azimuthal (Fig. 4). Switching trap intensities still occurs, although both first-order diffraction beams blink in a synchronized way.

Concluding, the relative pulsation of traps acts as a driving force. A bead would get trapped in a stable position between two beams but their periodical changes in intensity made the particle oscillate. In our work, we expand this idea and propose a novel realization of microscopic harmonic oscillator. To better investigate the behavior of the bead between the two traps, the two-laser HOT is necessary. Its main advantage is avoiding the interference phenomenon between two closely located optical traps. The second is that the trap intensity modulation with a well-controlled frequency is possible.

## 3. Two-laser tweezers

The modified experimental setup is presented in Fig. 1 (including dashed line). Two major modifications to our standard optical tweezers were applied: (1) a laser of a different wavelength was introduced and (2) the first laser was connected to a waveform generator.

As stated before, the two traps need to be separated by about a bead's radius distance. When they are closer, an interference pattern affects the bead's motion. The bead is either stuck within the central fringe or moves in an irregular way. However, the second laser of different wavelength abolishes the proximity limitation.

A 1064 nm cw Nd:YAG laser (Laser Quantum Ventus, 4 W) is now driven by the electronic waveform generator. A signal of a desired shape and frequency is applied. In our experiment, a square-wave function of 50% duty cycle was chosen in order to achieve a 'blinking' character of the trap. Hence, the generator acts as an electronic shutter.

The other cw solid-state laser diode (980 nm, 0.5 W) is introduced in the system to provide an additional constant (i.e. unmodulated) trap. With both beams on, the bead is held stably by the stronger trap.