Supplemental Document

Biomedical Optics EXPRESS

Single-cell all-optical coherence elastography with optical tweezers: supplement

Maxim A. Sirotin,[1] Maria N. Romodina,[1] Evgeny V. Lyubin,[1] Irina V. Soboleva,[1,2] and Andrey A. Fedyanin[1,*]

[1] *Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia*
[2] *Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow 119071, Russia*
[*] *fedyanin@nanolab.phys.msu.ru*

Supplement DOI: https://doi.org/10.6084/m9.figshare.17082188

Parent Article DOI: https://doi.org/10.1364/BOE.444813

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To test a developed single-cell all-optical coherence elastography (SCAOCE) method, a series of experiments with test objects was carried out. Polymer microprisms served as a test sample for imaging using the optical coherence microscopy (OCM) module of the SCAOCE and comparing them with optical microscopy data and a priori values. An experiment with Brownian microparticles was carried out to assess the range of effective optical trapping forces in optical tweezers (OT); the obtained values of the forces are then used for elastography of the phantom sample. An agar gel in three concentrations, in which polymer microparticles were suspended, was chosen as a phantom sample for elastography with the SCAOCE.

1. TEST OBJECT IMAGING WITH THE SCAOCE

Microobject imaging performed by the SCAOCE technique is demonstrated using sample of a triangular polymer microprism printed by two-photon laser lithography [1]. The sample has a near-triangular shape with a length and width of about 5 μm, with the height of about 200 nm and with a refractive index of 1.58. The characteristics of the structure are set by the choice of the material and the parameters of the lithography process.

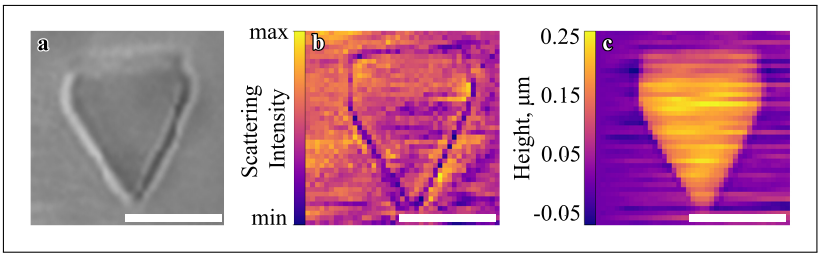

Fig. S1. Microscope image of a polymer microprism (a), its scattering intensity map (b) and shape visualization with phase scan (c). Scale bars are 5 μm.

Figure S1 shows comparison between images of a polymer microprism obtained using an optical microscope (Fig. S1(a)) and using the OCM module of the SCAOCE method (Fig. S1(b-c)). For OCM scans, scattering intensity map and phase scan $\Delta\varphi$ are shown. Microprism scans are consistent with the image in an optical microscope. Using the specified value of the refractive index n and formula $h = \lambda\Delta\varphi/(4\pi n)$ [2] with the help of the SCAOCE OCM module, it is possible to restore the height h of the object, which is 190 nm for a given sample and is in good agreement with the expected one.

2. TRAPPING FORCE ESTIMATION AND PHANTOM SAMPLE ELASTOGRAPHY

To determine the stiffness of the optical trap, a method based on the equipartition theorem [3] is used. Two experiments are carried out with suspensions with two diameters of polystyrene microparticles: 10 μm and 5 μm (Kisker Biotech PPS-10.0, 25 mg/mL and Kisker Biotech PPS-3.0, 50 mg/mL). For a 10 μm-particles sample, the suspension is diluted in distilled water in a ratio of 1:5, which provides a concentration of $1*10^{-5}$ μm^{-3} and an average interparticle distance of 80 μm. For a sample of 3 μm beads, the suspension is diluted in distilled water in a ratio of 1:100, which provides a concentration of $3*10^{-5}$ μm^{-3} and an average interparticle distance of 50 μm. Then 40 μL of the prepared suspension is added to a sealed cell between two cover slips.

A single microbead is captured in an optical trap. For each OT power, the SCAOCE signal is recorded for 150 seconds. In each experiment (with a certain particle diameter) for each power, the signal is sequentially recorded from 3 particles. Then the signal is transformed to the z-position of the microbead, the position variance of the microbead is calculated, and the data are averaged.

The experiment is carried out first for samples of 10 μm particles (Fig. S2 (a)), then for samples of 3 μm particles (Fig. S2 (b)).

The position variance of the trapped particle in the z direction $\langle z^2 \rangle$ is related to optical trap stiffness k_z by the formula $k_z \langle z^2 \rangle = K_B T$ [3], where K_B is the Boltzmann constant and T is the absolute temperature. The maximum trapping force in this case can be estimated by the formula $F_z^{max} \approx k_z r$ [4, 5], where r is the radius of the particle. The stiffness and maximum trapping force from power are presented in Fig. S2 (a-b).

Thus, the characteristic trapping forces at a power of 5-30 mW are 1-10 pN. The proportionality coefficient between maximum trapping force and power is determined from the linear fit and is 0.1 pN/mW for 10-μm particles and is 0.3 pN/mW for 3-μm particles. The values obtained are consistent with the forces in optical tweezers in other works [4].

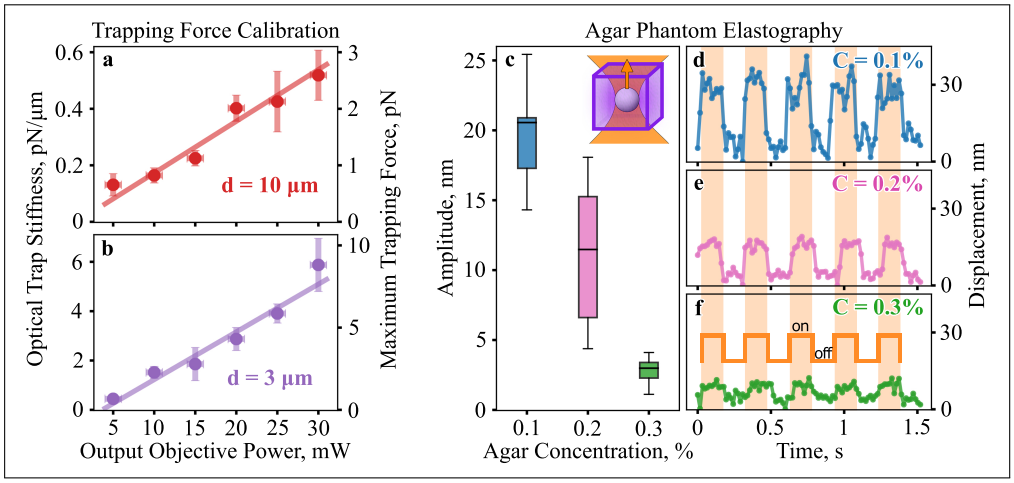

Fig. S2. The stiffness of the optical trap and maximum trapping force depending on the power for microbeads with diameters of 10 μm (a) and 3 μm (b). The points are experimental data, the straight lines are the linear fit. The oscillation amplitude of microbeads with a diameter of 3 μm, fixed in the agar gel, depending on the concentration of agar (c). Maximum trapping force and frequency are fixed and equal to 10 pN and 3 Hz, respectively. The inset illustrates the experimental design. Typical microbead trajectories under the OT excitation for each agar concentration (d-f). Blue, pink and green curves depict microbead oscillations in agar gel of 0.1%, 0.2% and 0.3% (w/w) concentrations, respectively. The periods of turning on and off the OT beam are indicated by orange vertical strips and meander in (f).

In the next series of experiments, the elasticity of phantom samples of agar gels of different concentrations is determined. To prepare the samples, agar powder (0.1 g, 0.2 g, and 0.3 g) is mixed with 100 ml of distilled water (to obtain concentrations of 0.1%, 0.2%, and 0.3% (w/w), respectively) and is boiled. The mixture is added with 50 μL of a suspension of 3-μm microparticles (Kisker Biotech PPS-3.0, 50 mg/mL), as a result of which the concentration of particles is $2{*}10^{-6}$ μm^{-3}, the average interparticle distance is 140 μm. Then 40 μL of the prepared solution is placed in a sealed cell between two cover slips, the sample is left for 30 minutes until it hardened completely.

The SCAOCE method is used to measure the response of particles suspended in a gel to the OT impact with a fixed trapping force of 10 pN and a fixed frequency of 3 Hz. For each concentration of agar, the response is sequentially recorded from 5 microbeads, 100 seconds from each. Further, the data are processed and averaged. The amplitude of the response on concentration is shown in Fig. S2 (c), the characteristic trajectories of particles under the action of an optical trap are shown in Fig. S2 (d-f).

From the measured amplitude A, the values of the shear modulus $|G|$ of agar gels are estimated with the formula $|G| = F(6\pi r A)^{-1}$ [6, 7], where F — trapping force acting on microparticle with radius r in agar gel. For concentrations of 0.1%, 0.2%, and 0.3% (w/w), the estimated shear modulus is 0.02, 0.04, and 0.12 kPa, respectively. The values are in order consistent with experimental data obtained in other works [6, 8]. Deviations can be associated both with the peculiarities of the composition of the agar powder and with the method of sample preparation.

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