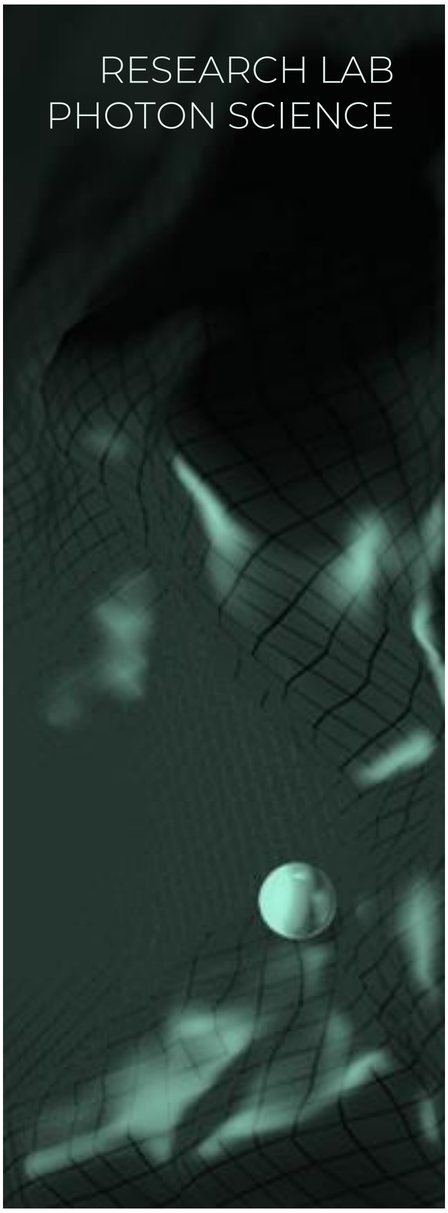

LIGHT TWEEZERS

FROM OPTICAL LEVITATION AND TRACTOR BEAMS TO LIGHT-DRIVEN MICROMACHINES

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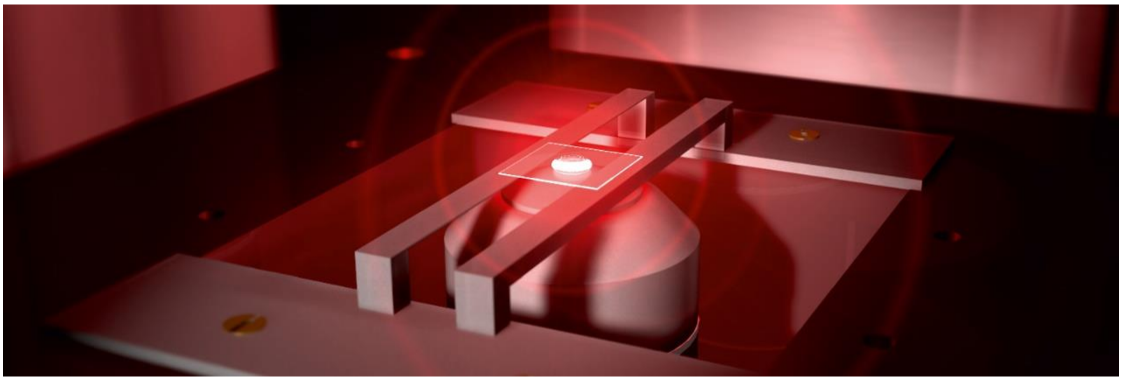
GENERAL THEME

Light Tweezers – From Optical Levitation and Tractor Beams to Light-Driven Micromachines

The interaction of light and matter is at the heart of countless phenomena and applications. While the scattering or modification of light by matter is rather intuitive and part of our day-to-day lives, the precise and controllable mechanical manipulation of matter with light sounds like the brainchild of a science-fiction author rather than a rigorous scientific concept. However, so-called optical tweezers are an established concept in various disciplines in the natural or other sciences, from physics to biology and medicine. The father of optical tweezers, Sir Arthur Ashkin [1,2], was awarded the Nobel Prize in Physics in 2018.

In the framework of the research lab experiments described in this document, you will delve deeply into the fascinating world of light-based manipulation of matter. You will trap, levitate, and move microscopic objects with the help of a laser beam, measure exerted forces, observe, and characterise various physical phenomena. To do so, one of your tasks will be the assembly of an optical setup, which will grow step by step to allow for more advanced measurements. In addition, you will study the theoretical concepts underlying this intriguing field of research. Are you ready to follow in a Nobel Laureate's footsteps?



Please read the entire document very carefully before starting the experiment or before switching on the laser. Don't be discouraged by the length of the document. It contains many details to help you in progressing.

A. PREPARATION FOR THE RESEARCH LAB COURSE

Welcome to this research lab experiment 'Light Tweezers – From Optical Levitation and Tractor Beams to Light-Driven Micromachines'!

In preparation for the experimental and theoretical tasks, please follow the list below <u>prior to the actual experiment</u>.

1. Please read this document carefully.
2. Afterwards, please read the provided literature carefully (Section D; highlighted in **boldface**).
3. **Please discuss the following points with the other members of your group.**
    a. Please familiarize yourself with the concept of linear, elliptical, and circular polarization of light.
    b. (Sketch and) describe how a ray of light behaves if it impinges on an air-dielectric (e.g., glass) interface. Assume an angle of incidence different from 0° or 90°.
    c. (Sketch and) describe how a ray of light behaves if it impinges from air onto a glass sphere (off-centre) rather than onto a planar surface.
    d. Briefly discuss two approaches for describing optical trapping (dipole approach and geometrical optics approach).
    e. (Sketch and) discuss the focusing of a light beam by a strong lens.
    f. Discuss at least 2 applications or devices involving light-matter interactions in general.

These topics will also be discussed with your tutor on the day of the experiment. Please note that in the following description, we indicate different types of tasks by different colours to help you with the organization of the experiment and with the time management.

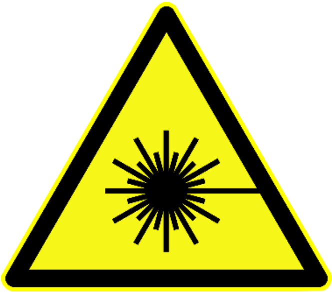
Blue: Discuss with your tutor during the experiment and take notes. The results of this discussion are relevant for the next tasks and should be included in your final report. Also those parts of the experiment are coloured blue that require your tutor to be around.

Red: These tasks are not essential for continuing the experiments. Therefore, they don't have to be completed during the actual experiment and can be tackled at home when preparing the report.

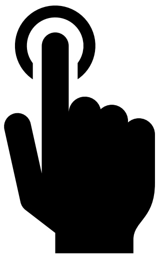
Black: Important steps of the experiment and data analysis to be done during the experiment. **Bold-faced comments are of particular importance!**

B. RESEARCH LAB COURSE TASKS

GETTING STARTED



CAUTION: Working with a laser can be dangerous! The laser used in this experiment is a Class 3B and has a power of more than 40 mW. Do not look directly into the beam or specular/diffuse reflections of it! **Always wear safety googles!** Keep the laser beam below your eye level, switch it off or block it whenever moving elements inside, into or out of the beam. Protect yourself and others. **Before starting the experiment, please follow the laser safety instructions by your tutor.**



CAUTION: Optical components, detectors and light sources are sensitive elements! Handle them with extra care! The quality of your measurements, the time you must spend to fulfil the required tasks, and eventually your level of motivation ultimately depend on the state and condition of the setup's building-blocks. So, please don't touch the optical surfaces. Store the components in a save place if they are not being used. And please handle the electronics with similar care.

1. **General tasks in a nutshell, and what to expect.**
    - The chart below summarizes some of the topics and learning goals to be covered in this research lab course.

Theoretical Understanding of Light-Matter Interactions and Optical Forces

Intuitive Interpretation Models of Light-Induced Forces

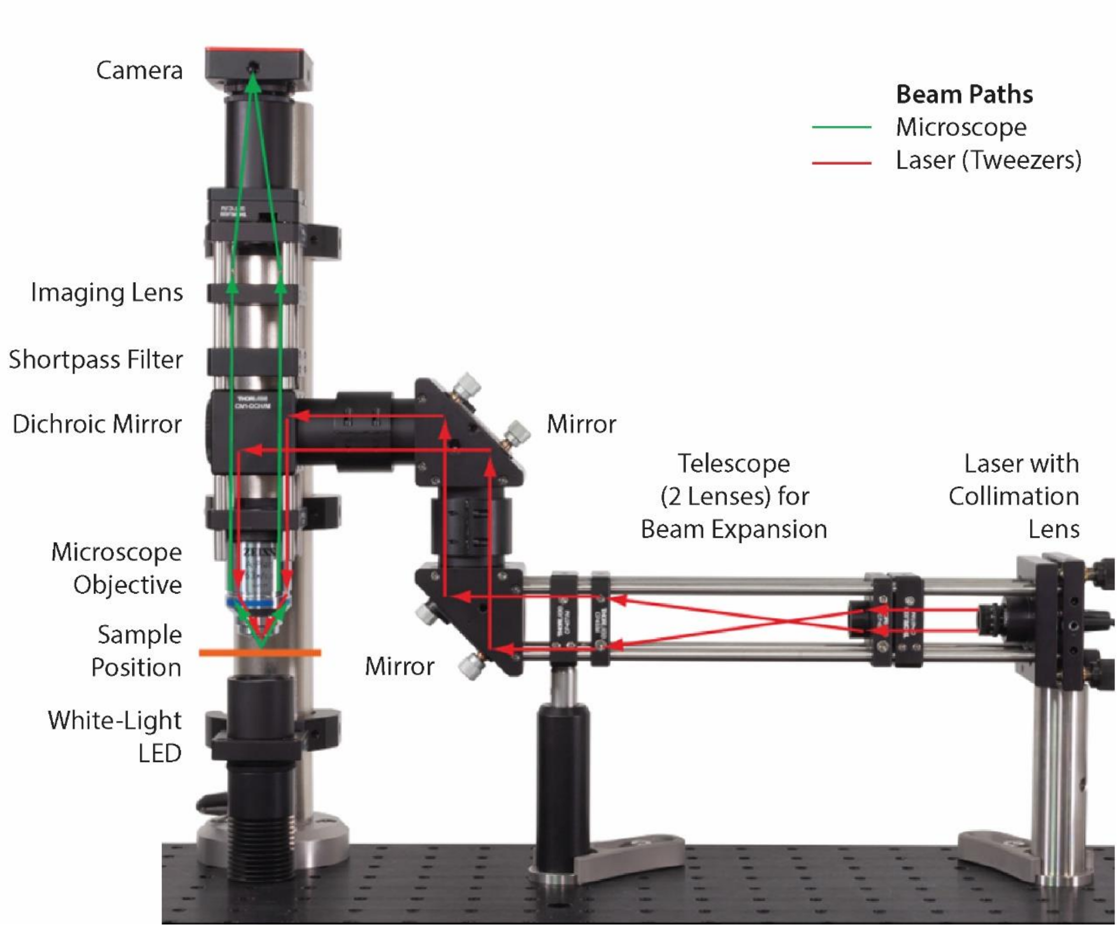
Building, Aligning, and Using Optical Setups

Theoretical and Experimental Quantification of the Observed Forces

Implementation of Advanced Concepts

2. **The different stages of the optical setup(s).**
    - We use a modular cage system for the experiments. In the final stage, the setup will consist of a simple optical bright-field microscope (green beam path in photo below) and an extra beam path (red) for laser light preparation and focusing (the actual tweezers). The same microscope objective is used for white-light imaging and for spatial confinement of the trapping (laser) beam. Many of the electronic components of the setup are not shown in the photo below for better visibility.
    - During this research lab, the setup will grow slowly step-by-step (microscope – sample stage – laser part) to study more involved phenomena.

- Please don't rush and take extra care in handling the optical components of the setup. The better the modules are built and aligned, the better the setups will work.



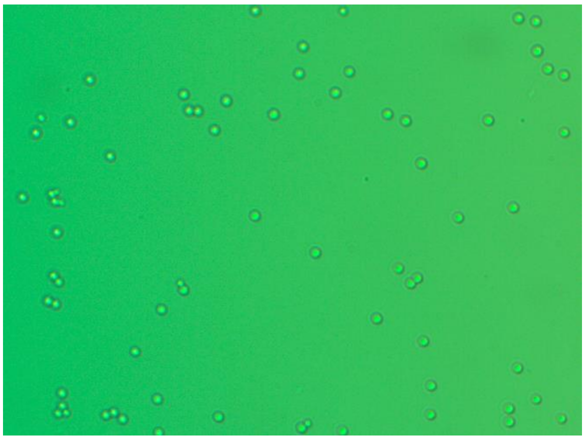
3. **Samples and sample preparation.**
   - The samples mentioned in the descriptions below and to be studied during this lab course first need to be prepared!
   - Discuss with your tutor, how to do so. Please talk to her/him whenever a new sample needs to be prepared.

4. **Discuss with your tutor the basic aspects of light-matter interactions, optical forces, light-based mechanical manipulation, sample preparation, and the main aims of this research lab. Use this opportunity to ask questions regarding the literature, the involved topics, and the research lab course in general.**

And now, it is finally time to start with the actual experiments.
Enjoy!

I. BUILDING A MICROSCOPE AND OBSERVING FORCES ON MICRSOCOPIC PARTICLES WITHOUT LASER ILLUMINATION

5. **Even without a laser beam, microscopic particles in liquids are subject to external forces. In this regard, a very peculiar and surprisingly strong effect is Brownian motion, resulting in a random walk of microscopic matter.**
   - In this introductory part of the experiment, we observe, record, and quantitatively analyse Brownian motion of polystyrene beads. **For the measurement, we first build a simple white-light microscope** (see green beam path in the photo above).
   - With the white-light LED (and the sample stage, see orange line for proper sample positioning) installed but still switched off (the laser should be OFF during this part of the experiment!), first attach the microscope objective and beam-splitter module to the (1.5") vertical post. Afterwards, also place the camera imaging module above and slide its cage rods carefully into the corresponding holes of the other module underneath. Then fasten the screw of the post clamp carefully.
   - Switch on the white-light LED (approx. 50% brightness) and connect the camera to the computer. Open the ThorCam software. **Familiarize yourself with the camera settings!**
   - Place the sample labelled 'SILICA 2.06 µm' containing silica beads with an approximate mean diameter of 2.06 µm very carefully on the stage module.



   - Move the sample upwards in z-direction very slowly until you see a sharp image of one or more particles (see example image on the right; by the way, why is it so green?). Keep in mind that the working distance between objective and sample is rather small (side note: if you crash the objective into the sample, you must do 100 push-ups 😉). If you don't find any particles, use the motor controllers to also move in x- or y-direction (transverse).
   - If you found a position on the sample where multiple particles (not too closely spaced to ease tracking) are visible on the camera image, record a several images at various lateral positions. Afterwards, start recording a video (length: 2 min or more). Look for a second well-suited position on the sample and record yet another video.
   - Use a video analysis tool (e.g., Viana.net [4], Matlab or similar) for tracking the particles' motion in 2D space automatically (analyse the motion of at least 3 individual particles). To get the dimensions right please consider that the imaged area of the sample for the given components (camera chip, etc.) is approximately 130 µm x 98 µm large.
   - Visualize the recorded and retrieved particle motion in xy-plots.

- Calculate the squared displacements along the x- and y-directions for all recorded time steps t_i ($x^2(t_i) = [x(t_i) - x(0)]^2$; similar for y) and all particles you tracked before.
- From the resulting values, calculate the (time-averaged) mean squared displacements in x- and y-direction for all time spans up to the duration of the video ($\langle x^2 \rangle(t_n) = [\Sigma^n_{t=i}\, x^2(t_i)]/n$). Plot and discuss the resulting data.
- Discuss, how the particle motion along the third coordinate axis (z) could be analysed and monitored.

II. LASER 'GUNS' AND LINEAR MOMENUTM TRANSFER – PUSHING WITH LIGHT

6. **If we shine a laser beam on a resting particle, it will be hit by the photons. In the simplest configuration, a photon is retro-reflected, changing the sign of its momentum vector. Momentum conservation tells us that the difference in the photon's momentum (before and after interaction) must be exerted onto the particle – a phenomenon referred to as light or radiation pressure.**
   - **For the measurements, we now extend the setup and attach part of the actual laser tweezers module to the microscope** (see red beam path without the telescope in the photo above; the laser is still switched OFF!). Part of the module might be already preassembled and mounted to the breadboard. You only need to connect it to the beam splitter and, thus, to the microscope.
   - **WEAR THE PROVIDED LASER SAFETY GOGGLES FROM NOW ON!** Switch on the laser controller, turn the key to 'ON' and press the 'ENABLE' button to turn on the laser. You can slowly increase the laser power by turning the wheel. **DON'T LOOK INTO THE LASER BEAM!** You should see a red laser spot appearing on the live camera image (if the power is sufficiently high and the sample is in the focus). Optimize the setup to see the scenario described above; use the same sample. Please keep in mind that imaging and laser focussing are done by the same lens.
   - Discuss with your tutor if the settings are alright before you go ahead.
   - The sample stage can be moved by the hardware controllers directly or with a special software. Open Thorlabs Kinesis on the computer. **Familiarize yourself with the motion control software!** Now, move the sample stage laterally to spatially overlap the focused laser beam with a particle (choose a particle that coincides with the image plane). Repeat this process for other particles. Note down your observations.
   - Discuss and explain the observed effects.
   - What other mechanisms in light-matter interactions could be taken advantage of to induce particle motion?

III. LASER TWEEZERS AND GRADIENT FORCES – OPTICAL TRAPPING IN 3D

7. **To trap a microscopic particle in all three spatial dimensions, we need to make sure that we create a trapping potential that forces the particle into a stable position in 3D space. A key concept for achieving this configuration are <u>optical gradient forces</u>. A particle with certain properties gets soaked into the region of highest intensity, hence, towards the optical axis and into the focal plane.**
    - Discuss with your tutor and explain this counter-intuitive phenomenon based on geometrical optics and momentum conservation.
    - Include a sketch of the working principle in your report.
    - We now extend our setup further and add the telescope for beam expansion to the system. The telescope clips into the rail system right next to the laser.
    - WEAR THE PROVIDED LASER SAFETY GOGGLES! **Start realigning the setup.** With the laser now switched on, try to trap a particle by moving the sample (same sample as before) relative to the laser beam. Play around with the actuator controls, the role of speed and acceleration of the positioning stage with a particle trapped, etc. Familiarize yourself with the trap and its capabilities. Try different laser powers and write down your observations. Take camera photos were necessary.
    - Record a video with one particle trapped in the laser beam (the stage not moving anymore) and other particles still freely moving around.
    - Analyse the video again with the tracking tool used above. What's the difference in motion characteristics comparing a trapped to freely moving particles? For better comparison, calculate again the squared displacements now for the trapped particle.

8. **Trapping multiple particles in a single beam.**
    - Now try to trap more than one particle in your focused laser beam simultaneously. Record a video (also while releasing the particles again by switching off the laser). What is the influence of the laser power on the trapping performance for multiple particles?
    - Explain why more than one particle can be held within a single beam, and which conditions must be fulfilled to do so. Discuss why particles are also stably trapped outside the actual focal volume (at a lateral distance larger than the beam size in the focus).

9. **Studying trap stiffness and maximum holding force.**
    - Discuss with your tutor, which 'traps and pitfalls' you should avoid in this part of the experiment.
    - A particle moving in a liquid experiences a frictional force. We now take advantage of exactly this friction to determine the holding force of the optical tweezers you built.

- To this end, trap a single particle with your laser beam at approx. 50% laser output level. Move the sample with one of the actuators (x or y) at a constant speed and find the maximum velocity at which the particle still stays trapped in the laser beam. Note down the corresponding velocity. Perform this experiment for at least 2 individual particles (ideally of noticeably different sizes) and two significantly different laser output levels per particle.
- To calculate the maximum holding force (related to the trap stiffness), we need the following dependences, laws, and parameters:
  - the frictional force is defined as $F_F = 6\pi\, \eta_{eff}\, R\, v$ (η_{eff}: effective viscosity of liquid; R : particle radius; v : velocity relative to liquid).
  - To calculate the max. frictional force – equalling the maximum holding force – from the measured maximum velocity, we also need to know the effective viscosity.
  - The effective viscosity influenced also the Brownian motion studied earlier. It depends on the mean squared displacement and, thus, also on the linear slope of the corresponding curves you plotted before. The slope is defined by $s = (2\ k_B\ T) / (3\pi\ \eta_{eff}\ R)$ with the (room) temperature T.

10. **Experimentally characterizing the trapping performance in dependence on the chosen particles.**
    - Please move the sample stage downwards until you can safely remove the sample (please place it back in its box). Place the sample labelled 'UNKOWN PARTICLES' on the sample stage and carefully approach it to the microscope objective again until you see particles in the image plane.
    - Try to trap individual particles in this sample and note down your observations (also take camera shots).
    - Discuss and explain your findings. Compare them to the previous experiments.

11. **Trapping 'living' organisms (bacteria) ☺.**
    - We now prepare a new sample which consists of a mixture of water and ACTIMEL. Use a mixing ratio of more than 20 : 1 (water : ACTIMEL) to get an optical transparent emulsion.
    - Now, place the sample in the setup (with the laser switched OFF!) and align it again such that you see particles in the imaging plane.
    - Try to trap individual particles and observe their behaviour.
    - Discuss your findings and compare them to the previous experiments.

IV. READY, SET, GO – SIMPLE LIGHT-DRIVEN MICROMACHINES AND THE ANGULAR MOMENTUM OF LIGHT

12. **If we can transfer light's linear momentum to matter, we should also be able to transfer angular momentum (angular momentum conservation). In this part of the experiment, we thus observe the effects of light's polarization (spin angular momentum) on trapping in general and on the dynamics of trapped particles in particular. We thus get in touch with a method for driving simple 'micromachines' all-optically [5,6].**
    - If the light changes its angular momentum during the interaction, part of this angular momentum must be exerted (partially) on the particle. Which properties a microscopic particle should exhibit for the overall angular momentum of the incoming light to change?
    - For the experiment, please carefully place the sample labelled 'VATERITE' on the sample stage and align the system such that you see some of the particles floating in the liquid with the microscope. Now, **while wearing safety goggles**, switch on the laser and trap one of the larger (3-4 μm) microparticles.
    - Record a video of the procedure and note down your observations.
    - The angular momentum of a conventional linearly polarized Gaussian laser beam is zero. But if we polarize it circularly, it features non-zero angular momentum. To this end, we add the corresponding polarization optics to the setup in the horizontal part of the rail system.
    - Discuss with your group mates and then with your tutor, which elements need to be added, and what to take care of.
    - Now, trap a particle with the circularly polarized light beam, record a video, and discuss what you observe and what should you observe.
    - Also, discuss with your tutor what you should have observed and whether this part of the experiment needs to be repeated.
    - Change the handedness of the circularly polarized light and repeat this experiment.
    - Discuss your observation and explain what you saw.

V. ALL WORK AND NO PLAY… – THE MAZE CHALLENGE

13. **OPTIONAL: Now, we test your acquired skills.**
    - Place the sample with the label 'MAZE' in the setup and on the sample stage.
    - Move it upwards until you see part of the maze (located centrally on the substrate surface) with the camera. Ask your tutor for details.
    - Find a dielectric microparticle nearby, trap it with the laser beam, and transport it to a starting point near the substrate surface (if you find particles still sitting in your way, you can remove them first with the laser beam).
    - Time to play: try to manoeuvre the particle through the maze, from entrance to exit, by moving the latter with the motorized positioning stages. Perform some test runs. Keep in mind that velocity and acceleration play a crucial role. Both parameters can be set for the stages via the Kinesis software or directly with the stage controller.
    - Now, measure the time every group member needs to 'exit' the maze without 'dropping' the particle. Ask one of your teammates or the tutor to start and stop a stopwatch. The team with the shortest successful maze run wins a prize (winners to be announced at the end of the term). Good luck!

14. **Before we conclude this research lab:**
    - Ask your tutor about additional experiments to be performed, discuss with him/her any remaining questions, and help tidying up the setup.

AFTER COMPLETION OF ALL EXPERIMENTS AND TASKS

Please (jointly) prepare a final report summarizing the basics (including Section A), discussing the experimental and theoretical steps, setups, findings, and plots (Section B), and include your answers to the following questions (Section C) at appropriate positions. The report should be submitted via Moodle within approximately 4 weeks after the scheduled date of the experiment.

C. ADDITIONAL TASKS

…to be addressed together with the description and discussion of your setups, measurement procedures, and experimental findings.

1. If we replaced our transparent dielectric particles in the trapping experiments (in a liquid) by absorbing metallic ones, what would change?
2. Which additional aspects would need to be considered if we tried to trap dielectric particles in air rather than in a liquid?
3. Think about and briefly discuss potential strategies for trapping multiple particles at different places in the imaged sample area simultaneously.

D. REFERENCES AND USEFUL LITERATURE

...to be studied before the actual lab course starts.

[1] A. Ashkin, **Acceleration and Trapping of Particles by Radiation Pressure**. Physical Review Letters. 24, 156–159 (1970)

[2] A. Ashkin, **Forces of a single-beam gradient laser trap on a dielectric sphere in the ray optics regime**. Biophys. J. 61, 569-582 (1992)

[3] J. W. Shaevitz, **A practical guide to optical trapping**; http://genomics.princeton.edu/shaevitzlab/OT_Practicle_Guide.pdf

[4] A. Voßkühler, **Viana.net – Videoanalyse für den Physikunterricht**; http://viananet.de/downloads

[5] S. Zhang et al., **Reconfigurable multi-component micromachines driven by optoelectronic tweezers**. Nat. Commun. 12, 5349 (2021)

[6] M. Friese, et al. **Optical alignment and spinning of laser-trapped microscopic particles**. Nature 394, 6691, 348-350 (1998)

[7] G. Volpe et al., **Roadmap on Optical Tweezers**, Journal of Physics: Photonics 5, 2, 022501 (2023)

[8] M. S. Rocha, **Optical tweezers for undergraduates: Theoretical analysis and experiments**, American Journal of Physics 77, 704-712 (2009)

E. VERSION

V1.1, released on February 8, 2024; Peter Banzer (uGraz).