Optical tweezers for measuring selected physical quantities in microscale

(Summary of professional accomplishments)

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Wrocław, June 2018

Table of contents

1. Curriculum vitae

Personal information	**Contact information**
First and last name: Sławomir Drobczyński Date of birth: 15 February 1978 Place of birth: Lwówek Śląski Marital status: married, two children	Wrocław University of Science and Technology Faculty of Fundamental Problems of Technology Department of Optics and Photonics Wybrzeże Wyspiańskiego 27 50-370 Wrocław e-mail: slawomir.drobczynski@pwr.edu.pl phone no.: 71 320 43 31 fax: 71 328 36 96

Education

- **Wrocław University of Science and Technology** (10.2006)**,** Doctor of Physical Sciences
  Title of dissertation ”Imaging polarimetry with carrier frequency and its application in biomedicine”, dissertation supervisor Prof. Henryk Kasprzak.
- **Wrocław University of Science and Technology** (2002–2006), doctoral studies: Faculty of Fundamental Problems of Technology, Institute of Physics
- **Wrocław University of Science and Technology** (1997–2002), full-time studies Faculty of Fundamental Problems of Technology, Field of Technical Physics, Specialization Biomedical Engineering.
  Master's thesis on the subject of "Construction and implementation of a speckle interferometry system using a laser diode with a pulse-triggered beam".
- **General secondary school in Lwówek Śląski**, Matura exam in 1997, Biology and Chemistry Class.

Work experience

- 2016, short-term science internship program: Department of Electrical & Computer Engineering, Colorado State University, USA;
- since 2014, Assistant Professor at the Department of Optics and Photonics;
- 2008-2014, Assistant Professor at the Institute of Physics at Wrocław University of Science and Technology;
- 2006-2008, research and teaching assistant at the Institute of Physics at Wrocław University of Science and Technology;
- February 2007 – October 2008, postdoctoral fellowship at the University of Strasbourg, France;
- 2006, 2-month internship at the University of Strasbourg, France;
- 2005, 3-month internship at the University of Murcia, Spain.

2. Description of scientific work

2.1. Scientific work before receiving the doctor degree

I am a graduate of the Faculty of Fundamental Problems of Technology at the Wrocław University of Science and Technology. In 2002, with a very good grade, I graduated from in the field of Technical Physics - specialization in Biomedical Engineering - Electromedical Equipment.

In my master's thesis entitled *"Construction and implementation of a speckle interferometry system using a laser diode with a pulse-triggered beam"*, I combined all my interests and experiences gained during my studies in the field of experimental physics, construction of microprocessor controllers, and programming in the field of image analysis. During my studies, I took an active part in the work of the Physiological Optics Group headed by Professor Henryk Kasprzak. After completing my Master's studies, I began doctoral studies in this team.

The work conducted as part of my doctoral thesis was to be a continuation of research on the birefringent properties of ocular tissues (mainly corneas) carried out in the Physiological Optics Group. Due to the specifics of the research object, which is the eye, a very fast method of measuring the properties of birefringent anisotropic media had to be developed. I devoted the first part of my work to studies in the field of optics of anisotropic media and measurement methods. The result of my work was a significant development of the imaging polarimetry method with carrier frequency[1]. The method I developed allows the measurement of the properties of nondichroic linear birefringent, dichroic linear birefringent and nondichroic elliptically birefringent media. I have also built a measuring system consisting of an optical system, an electronic circuit and computer software. The operation of the system has been confirmed through measurements of a static, homogeneous birefringent object, as well as inhomogeneous elasto-optic samples and eye tissues. In 2005, I completed a three-month internship at the University of Murcia in Spain[2], in a world-renowned research team in the field of physiological optics headed by Professor Pablo Artal.

In 2006, before I defended my PhD, I went on a two-month internship in the team of Professor Jean-Pierre Munch at the University of Strasbourg. During my stay in France, I came across the technique of optical trapping for the first time. After completing my internship, I received a postdoc position proposal at the Strasbourg Institute of Physics and Chemistry of Materials.

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[1] **Drobczynski S.**, Kasprzak H., Appl. Opt. 44, 3160-3166, 2005.

[2] **Drobczynski S.**, Bueno J., Artal P., Kasprzak H., Appl. Opt., 45, 5489-5496, 2006.

2.2. Scientific work after receiving the doctor degree.

In 2006, I obtained the title of Doctor of Physical Sciences and I was employed as a research and teaching assistant at the Institute of Physics of the Wrocław University of Science and Technology. In connection with my interests in research of the properties of optically anisotropic media, I started cooperation with dr hab. Piotr Kurzynowski. We have worked together to develop measurement techniques for birefringent mediums[3][4][5][6][7]. I also participated in the work of the team of prof. Ryszard Poprawski on the construction of the system for the dynamic measurement of spontaneous birefringence of ferroics using a polarization microscope.

In February 2007, I went on a two-year postdoctoral fellowship at the Strasbourg Institute of Physics and Chemistry of Materials. During the internship, I learned the technique of optical trapping and its use in molecular biology measurements. As part of the studies on interactions of specific proteins with DNA strands, I developed a method for stabilizing the measurement system based on real-time image analysis. While still in France, I became interested in holographic methods of generation and control of optical traps.

After returning to Poland, I undertook activities aimed at the construction of the optical manipulator system at the Institute of Physics of the Wrocław University of Science and Technology. Due to my interest in diffraction optics, I started working in a scientific group of dr hab. Jan Masajada. At the beginning, I took up numerical modeling of computer-generated diffraction structures.

In 2010, I have received the first project entitled "The use of low-power laser diodes for the generation of holographic optical traps" funded by the Ministry of Science and Higher Education. The result of the project was the creation of a working holographic optical manipulator system, which made it possible to look for scientific cooperation in the field of biology and medicine. At the same time, I developed methods of generating synthetic holograms, and using video cameras and image analysis to track the trajectory and dynamics of trapped objects.

As part of the next project entitled "Optical Tweezer in biomedical applications" awarded by NCRD (National Centre for Research and Development), in which I was a contractor, I built a second, improved holographic optical manipulator system working with a high-power laser. The project enabled the development of the equipment base and establishment of cooperation in the field of biological research. In 2011, degree candidate MSc Eng. Marcin Bacia began interdisciplinary doctoral studies. His doctoral dissertation, of which I was an auxiliary supervisor, concerned the use of holographic optical tweezers to measure selected properties of biological preparations and colloids.

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[3] Kurzynowski P., Wozniak W. A., **Drobczynski S.**, Opt. Comm. 267, 44-49, 2006.

[4] **Drobczynski S.**, Kurzynowski P., Opt. Eng. 47, 023603-1 - 023603-4 , 2008.

[5] Kurzynowski P., **Drobczynski S.**, Wozniak W.A., Opt. Express 17, 10144-10154, 2009.

[6] Wozniak W.A.,Kurzynowski P.,**Drobczynski S.**, Appl. Opt. 50, 203-212, 2011.

[7] Pretka M., Wozniak W.A., Kurzynowski P., **Drobczynski S.**, Appl. Opt. 55, 868-872,2016.

My cooperation in the field of cell research required the use of optical traps characterized by a much greater trap force in relation to those obtained by the holographic method. For this reason, I equipped the manipulator with a high-power laser beam control system. For this purpose, I used a pair of electrically controlled scanning mirrors. The natural consequence of the use of high-power lasers was the local temperature measurement in microscale. In cooperation with prof. A. Bednarkiewicz from the Institute of Low Temperatures and Structure Research of the Polish Academy of Sciences in Wroclaw, I have developed a method of temperature measurement using nanoluminophores doped with lanthanide ions. Working with optical thermometers, and later with "micro-heaters" built of porous silicon, forced further modifications of the optical manipulator system. Micro-heaters and thermometers are activated by light of different wavelengths, hence the need for simultaneous and concurrent control of laser beams of different wavelengths. In the temperature measurements using nanoluminophores, the luminescence spectrum is monitored, which requires a track for spectral measurements.

The multifunctional optical manipulator, unique on a national level, that I developed, enabled advanced biological and medical research in microscale. I am the initiator of a scientific consortium, which includes the Wroclaw University of Science and Technology, Institute of Low Temperatures and Structure Research of the Polish Academy of Sciences and the Medical University of Wroclaw, appointed to apply for an NCN (National Science Centre) grant for joint research using the manipulator I built. Application for a grant "The development of multifunctional optical tweezers and microrobots to investigate the effect of localized hyperthermia on cancer cells and spheroids obtained from primary cultures" proved effective, and the agreement with NCN for the implementation of the joint grant, of which I am the supervisor, is in the process of signing.

My international cooperation includes the University of Eastern Finland and Colorado State University in the USA.

The optical manipulator I built enabled carrying out a lot of scientific research in the field of biology and medicine, as well as doctoral and diploma theses. My scientific activity regarding the development of the optical trapping technique and its metrological applications is the basis of this habilitation application.

3. Description of scientific work constituting the foundation of the habilitation application

Pursuant to Art. 16 para 2 of the Act of 14 March 2003 on university degrees and university title in arts (Journal of Laws no. 65, item 595, as amended), I indicate a series of papers on the subject. *"Optical tweezers for measuring selected physical quantities in microscale".*

3.1. Publication list

List of a series of publications in the scope of optics and experimental physics concerning development of an optical tweezer system and its use for measuring physical quantities in microscale. A series of 10 publication constituting the habilitation dissertation together with information on IF coefficient and ministerial score from 2017.

No.		IF*	M**
H1	**Drobczynski S.**, Hebraud P., Munch J.P., Harlepp S., Design and realization of a high stability optical tweezer, Opt. Eng. 48, 113601-1 - 113601-5,2009.	1.082	20
	I was the originator and creator of the method of stabilizing the optical tweezers system based on image analysis, I participated in the measurement and analysis of data and the preparation of the manuscript. *I estimate my percentage contribution at 50%*		
H2	**Drobczyński S.**, Duś-Szachniewicz K., Symonowicz K., Głogocka D., Spectral analysis by a video camera in a holographic optical tweezers setup, Opt. Applicata 43, 739-746, 2013.	0.637	15
	I was the originator of the topics proposed in this publication. My contribution to the creation of this work consisted in the execution of the entire measuring station and in conducting all measurements in the optical manipulator system. I participated in the analysis of the obtained results. I prepared the publication manuscript. *I estimate my percentage contribution at 60%*		
H3	Masajada J., Bacia M., and **Drobczyński S.**, Cluster formation in ferrofluids induced by holographic optical tweezers, Opt. Lett. 38, 3910-3913, 2013.	3.416	45
	My contribution to the creation of this work consisted in the execution of an optical manipulator system and software for holographic control of optical traps, and the operation of a fast camera for observing phenomena in a paramagnetic liquid. *I estimate my percentage contribution at 30%*		
H4	**Drobczyński S.**, Masajada J., Woźniak M. and Ziółkowski P., Laser diodes in holographic optical tweezers, Photonics Lett. of Poland 6, 35-37, 2014.		10
	I was the originator of the topics proposed in this publication. My contribution to the creation of this work consisted in the execution of the entire measuring station, conducting all measurements and data analysis in the optical manipulator system. I prepared the publication manuscript. *I estimate my percentage contribution at 60%*		

H5	Ślęzak J., **Drobczyński S.**, Weron K. and Masajada J., Moving average process underlying the holographic-optical–tweezers experiments, Appl. Opt. 53, B254-B258, 2014.	1.650	30
	My contribution to the creation of this work consisted in the execution of the entire measurement system and in conducting all measurements in the optical manipulator system. I participated in the analysis of the obtained results and the preparation of the manuscript. *I estimate my percentage contribution at 40%*		
H6	**Drobczynski S.**, Ślęzak J., Time-series methods in analysis of the optical tweezers recordings, Appl. Opt. 54, 7106-7114 ,2015.	1.650	30
	My contribution to the creation of this work consisted in the execution of the entire measurement system and in conducting all measurements in the optical manipulator system. I participated in the analysis of the obtained results and the preparation of the manuscript. *I estimate my percentage contribution at 60%*		
H7	**Drobczyński S.,** Duś-Szachniewicz K., Real time force measurement in double wavelength optical tweezers, JOSA B 34, 38-43, 2017.	1.843	35
	I was the originator of the topics proposed in this publication. My contribution to the creation of this work consisted in the execution of the entire measuring station, conducting all measurements and data analysis in the optical manipulator system. I prepared the publication manuscript. *I estimate my percentage contribution at 80%*		
H8	**Drobczyński S.**, Prorok K., Tamarov K., Duś-Szachniewicz K., Lehto V-P., Bednarkiewicz A., Towards controlled photothermal treatment of single cell: Optically induced heating and remote temperature monitoring in-vitro through double wavelength optical tweezers, ACS Photonics 4, 1993-2002, 2017.	6.756	40
	My contribution to the creation of this work consisted in the development of the research concept, the execution of the entire measuring station, the performance of experiments in the optical manipulator system, the analysis of measurement data and participation in the preparation of the manuscript. *I estimate my percentage contribution at 45%*		
H9	Lamperska W., Masajada J., **Drobczyński S.**, Gusin P., Two-laser optical tweezers with a blinking beam, Opt. and Lasers in Eng. 94, 82–89, 2017.	2.431	30
	My contribution to the creation of this work consisted in the development of an optical manipulator system, software for holographic control of optical traps and the operation of a fast camera with image analysis enabling the measurement of the trajectory of entrapped objects. I proposed and made electronic modulation of the laser beam. *I estimate my percentage contribution at 20%*		

H10	Fraczkowska K., Bacia M., Przybyło M., Drabik D., Kaczorowska A., Rybka J., Stefanko E., Drobczynski S., Masajada J., Podbielska H., Wrobel T., Kopaczynska M., Alterations of biomechanics in cancer and normal cells induced by doxorubicin, Biomedicine & Pharmacotherapy 97, 1195–1203, 2018.	2.759	25
	My contribution to the creation of this work consisted in the development of an optical manipulator system, holographic software for optical traps and image analysis enabling the measurement of forces. I participated in the measurement of biomechanical properties using an optical manipulator and in the analysis of the results. *I estimate my percentage contribution at 10%*		

IF* - Impact factor, M** - list of Ministry of Science and Higher Education

3.2. Description of the scientific achievement

The scientific achievement, which is the habilitation achievement, concerns the subject of optical trapping. My publications on this subject are divided into three threads: holographic generation of optical traps, methods of measuring the trajectory of trapped objects and the use of optical tweezers for measuring physical parameters in microscale.

3.2.1. Introduction

In 1873, James Clerk Maxwell in his work “A Treatise on Electricity and Magnetism” introduced the pressure of light theory[8], which indicates that light might exert optical strength. This fact was confirmed experimentally in 1900 by the Russian physicist Piotr Lebedev. A significant breakthrough in the study of optical forces occurred only after the appearance of lasers. Laser beams with powers of hundreds of milliwatts are capable of exerting forces of piconewton orders (pN). A pioneer of experiments with a highly focused laser beam acting on dielectric specimens was Arthur Ashkin. In 1986, he published his work[9], in which he described the first successful attempt of optical trapping using a single laser beam.

For particles much smaller than the wavelength, we explain the trapping effect based on Rayleigh's theory of light scattering. There are two forces acting on a dielectric sphere placed in a focused Gaussian beam. The first one is a consequence of the transfer of momentum by scattered photons. It is proportional to the intensity of light and works along the propagation direction of the light beam. The second force results from the interaction of the electric component of the light beam and the induced electric dipole that arises in the object as a result of interaction with the light beam. The force is proportional to the square of the electric field intensity and acts in the direction of the gradient of light intensity. The condition of stable trapping is the domination of force from the electric field gradient over the scattering force resulting from the transfer of momentum by photons.

For particles larger than the wavelength of the light, the optical trapping effect can be explained on the basis of geometric optics. The light rays falling on a transparent particle with a resultant refractive index higher than the coefficient of the medium in which it is located are

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[8] Andrzej Kajetan Wróblewski, *Historia fizyki*, PWN Warszawa 2007

[9] Ashkin A., Dziedzic J. M., Bjorkholm J. E., Chu S., Opt. Lett. 11,288-290, 1986.

subject to double refraction. The change in the direction of the rays is accompanied by the change of the momentum carried by the light wave. In accordance with the principle of conservation of momentum, part of the momentum is transferred to the particle, resulting in a resultant reaction force acting on the particle. The sum of all the rays passing through it creates an unbalanced force that moves the particle towards the brightest area of the light beam. This force is called the gradient force. Stable trapping is achieved when the gradient force in areas outside the focus area is large enough to overcome the scattering force, which in turn pushes the object outside the trap toward the optical axis. Such conditions occur in practice only in light beams with a high intensity gradient, which are obtained by means of microscopic lenses with a large numerical aperture.

Optical traps made with this technique cannot capture atoms at room temperature but can be used to trap and move larger particles in the range of a few nanometers to several dozen micrometers. This makes this optical trapping technique applicable in many fields of science. Within a few years from the publication of the work by Ashkin, many laboratories around the world have begun many interesting studies. Optical tweezers can be used to manipulate non-living and living matter. Proper selection of the wavelength allows minimizing the destructive effects of high-energy laser beam on biological samples. The considerable advantage of the optical trapping technique is the sterile grip on biological structures. The obtained forces of the pN order are sufficient to move the cells of their organelles, to stretch and modify individual macromolecules, for example of DNA.

Professor Maximillian Pluta in his book wrote that[10]: "*The laser micromanipulator is a device used to perform various treatments on micro-objects by "point" irradiation with laser radiation and at the same time enabling observation or photographic registration of the effects of these treatments*". Today we already know that the optical micromanipulator has gained in its functionality and, according to its name, it is able to move micro-objects.

In this summary of scientific accomplishments, I point to my contribution to the development of optical micromanipulation technique and its use for measurements of selected physical quantities in microscale. On the basis of the scientific literature, it can be concluded that we use the term optical tweezers for a system that generates an optical trap, with the proviso that the position of the trap in the preparation area is variable and should be associated with a change in its position with respect to the preparation, and not with the change of the position of the preparation relative to the trap. In the following part, I will use the term optical tweezers and optical manipulator interchangeably.

3.2.2. Holographic generation of optical traps

To create an optical trap, i.e. a beam of light characterized by a large intensity gradient, fundamentally two conditions have to be met. First, in a microscope system, using a microscope lens with a large numerical aperture ($NA \geq 1$), the laser beam should be strongly focused in mode TEM_{00}. Secondly, the effective diameter of the laser beam should be widened so that it fits the lens aperture as much as possible. In practice, for this purpose, we use a properly designed Kepler telescope system.

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[10] Maksymilian Pluta, *Mikroskopia Optyczna*, PWN Warszawa 1982

An important function of optical tweezers is to create a system of several independent traps and control their position within the microscope preparation. This way, we obtain the possibility of multipoint grip or impact on microscopic objects.

Historically, the first sets of optical tweezers were equipped with one immobile trap and a microscope table ensuring the movement of the preparation in relation to the optical trap. To ensure high resolution of the motion of the preparation against the trap, piezo-shifters operating with the accuracy of individual nanometers were used.

The next step in the evolution of the optical manipulator system was to generate several traps with independent control of their position within the microscope preparation. For this purpose, a laser beam scanning system, similar to that used in confocal scanning microscopy, was used. The position of the laser beam is cyclically changed between several points that correspond to the locations of the optical traps. If the time of position change is shorter than the time when the laser beam remains stationary at a given point, then we will effectively observe the arrangement of several optical traps. In English-language literature, this method is known as time-sharing.

In practice, the most common scanning system is implemented using galvanometric mirrors or acousto-optic modulators. The number of stable traps obtained by this method is related to the maximum beam scanning frequency and the inertia of the entrapped object. Usually the number of traps does not exceed ten.

Approximately since 2000, works on the use of DOE diffractive optical elements to generate optical traps have been appearing. The development of liquid crystal technology of spatial light modulators in the LCoS (Liquid Crystal on Silicon) reflective configuration gave rise to a holographic generation of optical traps. The attractiveness of this method lies in the ability to create several or even several dozen stable traps, positioning each of them not only in the plane of the preparation, but also along the axis of light propagation. It also allows shaping the intensity distribution of the beam, thanks to which it is possible to generate traps not only with Gaussian, but also Laguerre-Gauss or Bessel distribution of light intensity.

Figure 1 is a schematic of the holographic layout of the optical manipulator. The telescope system built of L1 and L2 lenses is used for spatial lighting of an SLM with a plane wave. At the basis of the holographic generation of optical traps lies the diffraction theory of mapping.

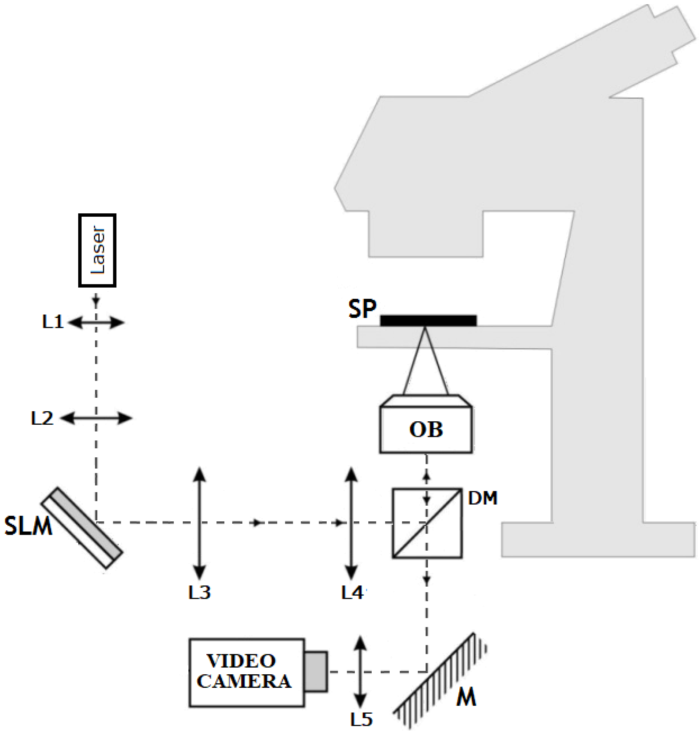


Figure 1. A schematic of the holographic optical manipulator system.

In the focal plane of the pictorial space of the microscopic lens (OB) with a large numerical aperture, the distribution of the amplitude of the light wave is described by the Fourier transform of the diffraction pattern reflected on the SLM. The spatial light modulator is a matrix of controlled liquid crystal cells where in each of them we can obtain a change in the refractive index. A computer-generated hologram, CGH, is a bitmap, wherein the brightness level of each pixel corresponds to the phase shift introduced by the liquid crystal cells. Optical traps are obtained by strong focusing of beams deflected on the structure of computer-generated phase holograms displayed on the SLM. The telescope, built of L3 and L4 lenses working in the "4f" system, extends the modulated plane wave so that the central part of it fills the OB lens aperture. The dichroic mirror DM is selected so that it has a high reflectivity for the laser beam, most often in the IR range, and a high transmission coefficient for visible light for the microscopic sample observation track.

Research described in the works H2-H10 was carried out in a system, the basic configuration of which is shown in Figure 1. The implementation of specialized tasks of the optical manipulator required modification of this measurement system. It was equally important to develop algorithms for generating phase structures to guide and shape the laser beam. The challenge was also to develop fast methods for calculating phase structures, in particular for increased diffraction efficiency. The proposed solutions allowed for the development of specialized software, which became an integral part of the optical manipulator I built. It allows CGH calculation, SLM control and video camera support. The diffraction structure displayed on the SLM is calculated in such a way that the optical trap appears in the place indicated by the cursor in the video image of the microscope preparation. Using a monitor with a touch panel, I developed an interactive way of directing optical traps, giving the impression of touching the microscopic structures during their movement.

The process of preparing the synthetic diffraction structure displayed on the SLM proceeded according to the following scheme. The phase hologram $\phi_k(r)$ generating *k*-th optical trap can be obtained in one of two ways: by using a two-dimensional diffraction grating with discrete levels of the phase (blazed grating) that deflects the laser beam to a given point of the preparation or by calculating the Fourier transform of the given light intensity distribution representing the optical trap in the focal image plane of the microscopic lens. The resultant phase distribution $\phi_T(r)$ generating a given optical traps system is determined according to the following formula:

$$\phi_T(r) = \arg\{\sum_k T_k(r)\} = \arg\{\sum_k A_k e^{i\phi_k(r)}\} . \quad (1)$$

The values of the A_k coefficient have been normalized so that $0 \leq A_k \leq 1$. By changing the value of the *k*-th coefficient, we obtain the regulation of the energy distribution in individual traps. Adding the modulo 2π to the resultant phase distribution of phase Fresnel lens's $\phi_L(r)$ structure causes the movement of the trap system along the light propagation axis.

$$\phi_{SLM}(r) = \{\phi_T(r) + \phi_L(r)\}\mathrm{mod}2\pi . \quad (2)$$

To change the depth of each trap in the preparation, the function $T_k(r)$ generating the trap must consider the structure $\phi_{Lk}(r)$ of the phase Fresnel lens:

$$T_k(r) = A_k e^{i(\phi_k(r) + \phi_{Lk}(r))} . \quad (3)$$

The spiral distribution of the $\phi_V(r)$ phase can be added to $T_k(r)$, what will result in the creation of the trap with the Laguerre-Gaussian intensity distribution.
The last stage is obtaining the bitmap $B(r)$ reprezenting the distribution function of the phase $\phi_{SLM}(r)$:

$$B(r) = G\{\phi_{SLM}(r)\} . \quad (4)$$

Due to the dispersion of the liquid crystal modulator, it is important to limit the number of gray levels. For example, for Hamamatsu's modulator X10468-07, for waves with a length from 1064nm the 2π modulation is obtained for the gray level value of 216, and for the wave with the length of 980 nm for value of 196.

Lack of continuity of the phase profile is the cause of the unwanted effect of ghost traps. The appearance of higher diffraction orders spoils the energy balance in the system.

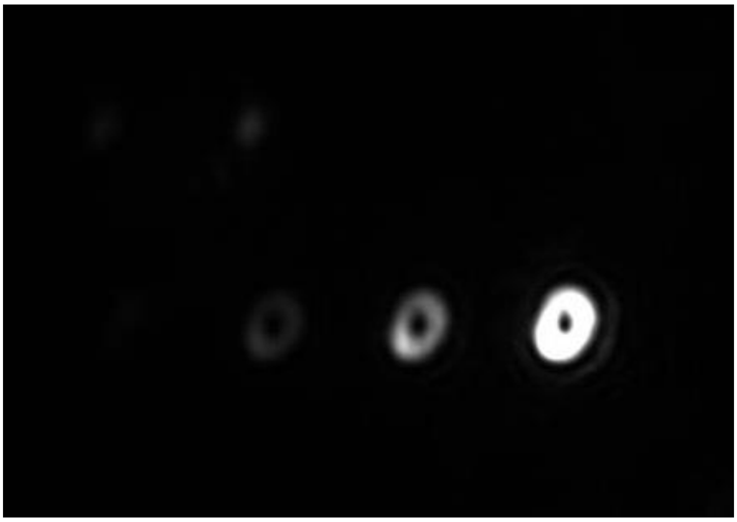


Figure 2. Ghost traps during the hologram reconstruction.

I implemented the basic vector calculations using optimized mathematical libraries of Intel® Integrated Performance Primitives for Intel® Architecture. The developed software automatically detects the type of processor and selects the optimal use of MMX (Matrix Math eXtensions) technology. The use of this technology allows for quick calculation of phase diffraction structures. In combination with the display of a video image of a microscopic specimen at 60 frames per second, it provides smooth motion when moving trapped objects. The described algorithms for generation of holographic optical traps together with appropriate modifications were used to carry out the research presented in works H2-H10.

In work H3, two properties of the holographic generation of optical traps were used. The first is the ability to simultaneously generate several stable traps, which is unachievable in the method of laser beam scanning. The second is to create traps with different light intensity distributions. Up to now, the observation of the behavior of the paramagnetic liquid, popularly known as ferrofluid, was carried out only in the presence of a single Gaussian beam. There are still scientific discussions on the explanation of the physical mechanisms governing the behavior of ferrofluid illuminated by a focused laser beam. The literature mainly describes three effects: optical trapping, thermal effects and intermolecular interactions. Research described in work H3, obtained in the system of a holographic optical manipulator, enrich the set of observed phenomena. This refers mainly to the dynamics and interaction between ferrofluid clusters in the presence of three optical traps. During measurements using optical vortex beams, it was found that the flatness correction of the liquid crystal modulator was a significant factor. As a result of the technological process, the active surface of the modulator is not flat. The reflection of a plane wave from the modulator, even for the displayed homogeneous structure, causes deformation of the wavefront. This effect was particularly evident during the generation of optical vortex traps, and it was more and more visible with increasing topological charge of the vortex.

In the phase structure calculation procedure (equation 2), the phase map $\phi_C(r)$ of flatness modulation of the SLM should be considered. Equation 2 then takes the form:

$$\phi_{SLM}(r) = \{\phi_T(r) + \phi_L(r) + \phi_C(r)\}\mathrm{mod}2\pi\ . \tag{5}$$

Figure 3 shows the effect of applying a corrective phase map $\phi_C(r)$ to the generation of the optical vortex beam with a topological charge 6. The distribution of phase $\phi_C(r)$ (Figure 3c) is obtained on the basis of the measurement results of wavefront deformation reflected from the SLM surface in the Mach-Zehnder interferometer system.

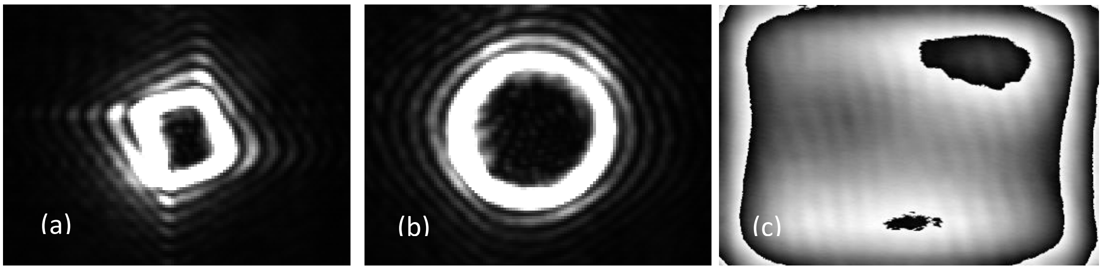
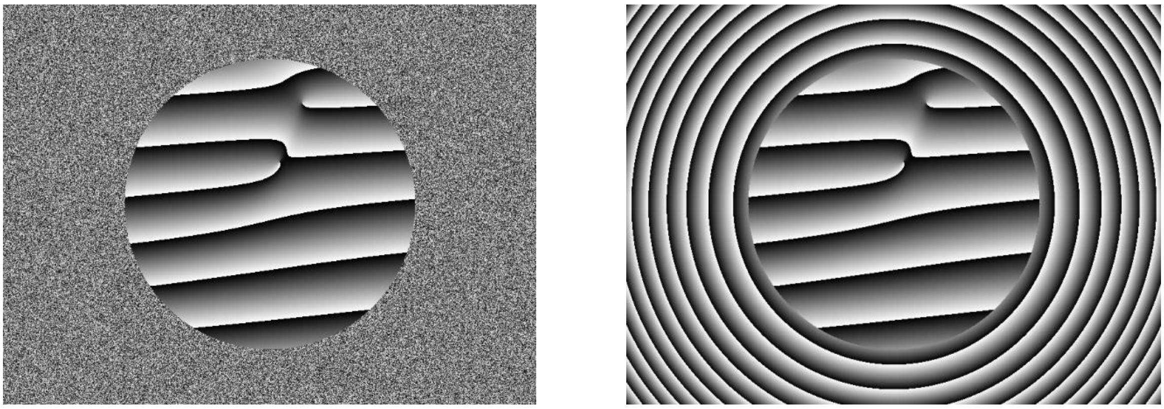


Figure 3. Distributions of intensity for the Laguerre-Gauss type trap and topological charge 5 (a) before and (b) after correction of the SLM modulator. (c) Phase correction structure.

Subsequent modifications of the procedure for calculating the diffraction structure were related to the use of a laser diode as the source of the trapping beam. Due to the wide spectrum of light emission, laser diodes have become attractive in biological applications. The selection of the appropriate spectrum of emitted light is associated with the limitation of the absorption of electromagnetic radiation and, consequently, the avoidance of damage to biological tissue structures. In comparison with other light sources used in optical trapping, laser diodes are characterized by a significantly lower price, ease of use and smaller dimensions. Their basic disadvantages include low power and worse quality of the beam. Due to the specificity of laser diodes, the calculated diffraction structures should be characterized by high diffraction efficiency and the ability to correct the shape of the beam.

Work H4 presents the results of research on the use of laser diodes in a holographic optical manipulator. Research on the beam forming system in the laser illuminator showed that the shape of the diode emitter is the key parameter. Laser diodes from three groups were tested: multimode, single-mode and single-mode coupled with optical fiber.

Two approaches were used to correct the shape of a focused laser beam. The first consisting in the generation of a diffraction structure by the Fourier transform method using the iterative algorithm of Gerchberg-Saxton to increase the diffraction efficiency. The second is the aperture restriction on the generated phase map (Figure 4).



(a) (b)

Figure 4. The aperture restriction of the phase map. (a) with a random phase distribution (b) with a Fresnel lens.

By reducing the aperture, we improve the symmetry of the beam (convolution with the diffraction image of the Airy disc), but we reduce the intensity gradient which can lead to the loss of the ability to trap. The outside of the structure, except for the specific circular aperture, is used to suppress the zero-diffraction order. It creates in the preparation another stationary optical trap. If we create a random phase structure (Figure 4a), then the beam from the zero-diffraction order will be dispersed. If on the outside we generate the Fresnel lens structure (Figure 4b), then the trap from the zero-diffraction order can be shifted to a different depth than the working traps.

The obtained diffraction structures, despite the lower power of the laser diode, allowed generating optical traps with sufficient electric field density for biomedical applications.

3.2.3. Measurement of trajectories of trapped objects

In addition to the obvious function of optical tweezers, which is the capture and movement of micro-objects, an equally important function is the ability to measure their physical properties. In particular, these are mechanical properties. The force that restores the tilted object from the center of the optical trap is proportional to its deflection. Thus, the mechanical equivalent of the optical trap is the Hooke spring. Knowing the trap stiffness of the k_h trap and measuring the deflection of the trapped object from the equilibrium position, we can determine the force that caused this deflection.

To determine the stiffness of the optical trap, the equation of motion of the enclosed object must be written. According to Langevin theory of Brownian motion, the movement of a trapped particle in harmonic potential is described by the Langevin equation[11]:

$$m\frac{d^2x(t)}{dt^2} + \beta\frac{dx(t)}{dt} + k_h x(t) = \sqrt{k_B T\beta}\frac{dB}{dt}, \tag{6}$$

where:

$x(t)$ – trajectory of the trapped particle with mass m,

$\beta\frac{dx(t)}{dt}$ – Stokes force acting on a spherical particle with a radius r in liquid with viscosity η,

$\beta = 6\pi\eta r$,

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[11] R. Kubo, M. Toda, and N. Hashitsume, *Statistical Physics*, Springer, Heidelberg, 1985, Vol. 2.

$\sqrt{k_B T \beta}\frac{dB}{dt}$ – random force component, created as a result of the collision of the trapped particle with liquid molecules, we assume that it has the form of white noise, that is, it is a derivative of Brownian motion B.

For appropriately big time scale $t \gg \tau_p$ ($\tau_p = \frac{m}{\beta}$) equation (6) can also change its form. When using in the experiment polystyrene beads with diameters of 1÷5 µm, the ratio of inertia of the particle to the viscosity force is small, therefore in the equation (6) we omit the inertial element and write it in the following form

$$dX = -\lambda X dt + \sqrt{D} dB \,, \tag{7}$$

where:

$\lambda = \frac{k_h}{\beta}, D = \frac{k_B T}{\beta}$.

It is a stochastic differential equation which is solved by the Ornstein-Uhlenbeck process:

$$X(t) = \sqrt{D} \int_{-\infty}^{t} dB(s) e^{-(t-s)\lambda} \tag{8}$$

The key to determine the stiffness of the k_h optical trap is the measurement of the trajectory of the trapped object $x(t)$. In laboratory practice, in systems with a single stationary trap, a quadrant photodiode (QPD) is used to detect the motion of the trapped object. The image of the object in the laser beam is mirrored on the surface of the QPD diode. The motion of the particle in the optical trap causes appropriate covering of the photodetector quarters. U_x and U_y voltages, which are proportional to the deflection of the particle from the equilibrium position in the X and Y directions, respectively, are usually recorded at a frequency of 10-20 kHz.

A commonly used method for determining k_h is the Fourier method. The power spectral density of the object's trajectory is described by Lorentzian:

$$PSD(f) = \frac{k_B T}{\pi^2 \beta (f_c^2 + f^2)} \tag{9}$$

where f_c denotes corner frequency and is:

$$f_c = \frac{k_h}{2\pi\beta} \tag{10}$$

In the optical tweezers system, in which several optical traps are generated, the use of a photodiode is difficult. In particular, if we want to measure the deflection of the object from the center of the trap or the stiffness of the optical trap in various places of the preparation. We often encounter this in practice e.g. when measuring the mechanical properties of cells.

In work H2, the possibilities of using standard cameras to measure the stiffness of an optical trap in a holographic optical manipulator system were analyzed. As standard cameras, we can recognize those that capture images at full resolution at a rate not exceeding 60 frames per second. If the image registration is limited to a part of an imaging sensor, it is possible to measure the k_h parameter for small laser powers. According to equation (10), the stiffness of the optical trap is proportional to the frequency f_c.

Tracking the trajectory of a trapped object involves analyzing the image of subsequent frames of a recorded video sequence. The most commonly used method is to calculate the position of the center of mass of the image of an object. In work H2, another method was proposed, consisting in entering a circle into the image of a trapped polystyrene sphere. To get closer to the detection capabilities of the QPD photodiode in the optical tweezers system, a fast camera was used. Registration from a limited area of the sensor allows achieving speed up to 10,000 frames per second.

In work **H5,** the statistical properties of the trajectory signal of the trapped object registered with the fast camera were analyzed. The analysis of time series has shown that the commonly used Ornstein-Uhlenbeck model, which is equivalent to the first-order autoregressive AR(1) model, is insufficient to describe the experimental data. In the AR(1) process, the current value is a linear combination of the previous value and external noise value:

$$X_n = aX_{n-1} + \xi_n \, , \tag{11}$$

where $a = e^{-\lambda \Delta t}$ is a constant.

The recording of images at high frequency results in the appearance of an additional section in which the current value depends linearly on the previous noise sample. Therefore, the observed process should be supplemented with the first-order moving average MA(1) and finally we obtain the ARMA model (1,1). The detected memory effect is related to the operation of the imaging sensor, on which residual charges from the previous registration remain.

In **H6** work, the time series methods were used to analyze the recorded trajectories of motion. Treating optical tweezers as a discrete line filter allows for a clear distinction in the experimental data of the properties of the original physical process represented by part of the AR and disturbances caused by the experiment appearing in MA part. It was proposed to use the PACF (partial autocorrelation function) to evaluate experimental data. The function checks at the same time whether the data is free of interference and whether they provide an estimate of the stiffness of the k_h trap. The developed statistical tools were used to analyze the actual measurement data. This allowed determining the impact of camera parameters on experimental data.

For systems with a stationary trap, the basic characteristic is to determine the dependence of the stiffness trap on the laser power. For a Gaussian beam, this is a linear relationship. In the case of optical tweezers with a moving trap, it is necessary to determine the distribution of the variability of the k_h parameter within the microscope preparation. The inhomogeneity of the stiffness coefficient distribution results from the aberration of the optical system, and also depends on the accuracy of the optical path adjustment. In the case of a holographic generation of optical traps, the change of the stiffness coefficient of the trap is associated with a decrease in diffraction efficiency for increasing angles of beam deflection.

In **H7** work, the method of measuring the distribution of the stiffness coefficient k_h in the working area of the optical manipulator is presented. The method is based on the use of a fast camera to measure the dynamics of motion of a trapped polystyrene sphere moving in a medium over concentric circles. For discrete changes in the position of the optical trap on a circular path $\delta r_n = r_{n+1} - r_n$ (Figure 5a), the sphere trajectories are recorded (Figure 5b).

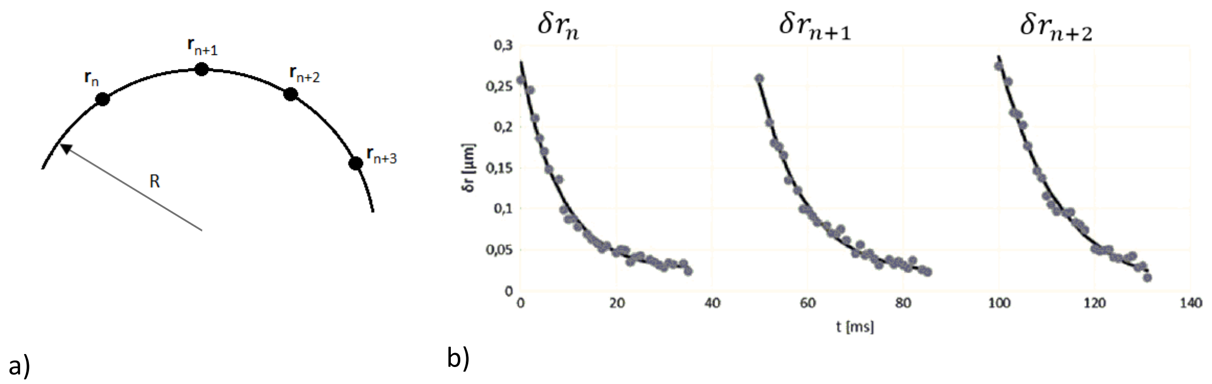

Figure 5. (a) discreet movement of the sphere on the circle, (b) movement trajectories.

On the basis of the movement formula:

$$\beta\frac{dr}{dt} + k_h r = 0 \ , \tag{12}$$

the stiffness coefficient k_h is calculated.

$$k_h = -\frac{\beta}{t}\ln\left(\frac{r(t)}{r_0}\right) . \tag{13}$$

An important element of the proposed measurement method is the calibration of optical tweezers. It consists in determining the relationship between the camera coordinate system by means of which the preparation is observed and the function generating a hologram or setting the inclination of the scanning mirrors. The developed multi-point calibration method using image analysis algorithms allows precise positioning of the trap and accurate measurement of its coordinates. The developed procedure is used to calibrate the manipulator with the holographic generation of optical traps, as well as for the scanning system using galvanometric mirrors used to direct the high-power laser beam.

The developed image analysis procedures have been implemented in the software for controlling the optical manipulator. As in the hologram generation procedures, the IPP®. libraries were used. They allow processing of a limited image area at 2000 frames per second.

3.2.4. Measurements of selected physical quantities in microscale

The most popular use of optical tweezers results from their principle of operation. Measurement of force and displacement on a micrometer scale and sterile measurement conditions have made the optical manipulator widely used in biological research. An example is the measurement of mechanical properties of living cells or DNA strands. My first works with the use of optical trapping were concerned with investigations of elastic properties of DNA.

In **H1** work, the method of stabilization of optical tweezers with a single stationary trap is presented. The change of position and, consequently, manipulation of the captured object were obtained by the movement of the microscope table. In addition, placing the microscope preparation on the piezo-shifter enabled it to be moved with an accuracy of 1 nm. The piezo-shifter was also used to position the microscopic lens. Owing to that fact, the optical trap could move along the axis of the laser beam propagation. Working on the enlargement of the microscope system above 100x, mechanical and thermal fluctuations of the microscope table elements became noticeable. The motion of the microscopic preparation was identified based on the analysis of the image of the polystyrene sphere fixed to the surface of the coverslip. The position correction in the X, Y plane was made on the basis of the center of mass measurement. The autofocus algorithm was used to stabilize the position in the Z axis. The use of image analysis and piezo-shifting algorithms allowed for three-dimensional stabilization of the trap position relative to the microscope preparation. The developed method of stabilization made it possible to carry out subtle measurements of mechanical properties of stretched DNA strands under the influence of various chemical factors.

I carried out further tests of mechanical properties of DNA in the holographic optical manipulator I built. The H10 paper presents the results of measurements of biomechanical properties of DNA strands and stem cells of acute myeloid leukemia in the presence of doxorubicin used in chemotherapy.

Performing such measurements required a sufficiently high stiffness of the optical trap. Increasing the power of the laser beam illuminating the SLM can cause permanent damage to the liquid crystal. I proposed active cooling of the liquid crystal matrix using the Peltier element. The increase in the intensity of laser light causes an increasingly stronger manifestation of higher diffraction orders responsible for the formation of ghost traps (Figure 2). The power of a stationary trap from the zero-diffraction order is also significantly increased, which is the stronger the smaller the fill factor of the modulator.

To extend the functionality of optical tweezers I have built a hybrid system. The holographic optical manipulator has been additionally equipped with a high-power laser beam guidance path using galvanometric mirrors. In work H7, the use of such a system for measuring intercellular adhesion force is presented.

The optical manipulator can be used to measure the viscosity of the liquid in which trapped objects are located. In H2 work, a viscosity measurement method based on equation (10) is described. As an example, viscosity measurements of glycerol solutions of various concentrations were carried out.

In H9, another way of measuring the viscosity of a liquid in a holographic optical manipulator system is presented. The viscosity coefficient is determined on the basis of observation of the trajectory of movement of the trapped object by means of fast video recording. The movement of the trapped object was determined in two ways. The first was based on the object's jumps between two correspondingly similar Gaussian traps. Second was based on the object's jump between Gaussian trap and beam with optical vortex. The developed numerical algorithms allowed generating a beam with optical vortex with a topological charge equal to 30, maintaining a high symmetry of the beam. Due to the sensitivity of the measuring system to mechanical vibrations, none of the known methods of mechanical laser beam modulation (e.g. optical chopper, optical shutter) was unacceptable. That's why I proposed electronic modulation of the laser beam.

Entirely new measuring possibilities appear when using micro- and nano-tools captured by the optical trap. All kinds of micro tools can be produced with two-photon photolithography. Highly developed material engineering allows the preparation of such elements whose physical properties will depend on the wavelength of the trapping laser light. The hybrid optical manipulator system described in the **H7** work allows for the generation of several independent optical traps, for different wavelengths and different powers.

The **H8** paper presents the use of nanotools in the hybrid optical manipulator system. Optical traps captured and activated specialized structures. Optical thermometers made of nanoluminophores based on lanthanides and porous silicon were used for local heating of the medium. The temperature measurement consists in comparing the intensity of the luminescence of two specific Erbium ion bands in up-energy conversion (i.e., excitation 980 nm, emission 520-540 nm). Their mutual relationship depends on the temperature the nanoparticle is in. An optical trap at 980 nm captured the thermometer (phosphor) particle and activated its work at the same time. Porous silicon was stimulated by a trap generated by a 1064 nm laser, for which it showed strong absorption. Another optical trap held the cell near which the heater and thermometer were placed. Owing to that fact, the process of single cell hyperthermia was observed. It is a new technique that allows testing of biological processes in living cells.

3.2.5. Conclusions

The presented series of publications entitled "Optical tweezers for measuring selected physical quantities in microscale" shows my contribution to the development of scientific research using optical tweezers. One of the goals of my work was to involve various scientific communities in research using optical tweezers. Providing the device to a wider group of users required adapting the system to perform specific functions. It became necessary to characterize its parameters in detail, describe the possibilities and limitations of the applicability of the constructed system.

The usefulness of the holographic generation of optical traps required the development of adequately fast computational algorithms ensuring high diffraction efficiency and symmetry of the generated traps.

The measurement of displacements and forces acting on trapped objects required an accurate position measurement. In multi-trap systems, specialized photodiodes for video cameras had to be abandoned. Theoretical considerations indicated the minimum requirements for video recording parameters. It has been shown that the use of a fast camera has a significant impact on the recorded experimental data. The use of the autoregressive–moving-average (ARMA) model to describe the experimental data allowed isolating the physical properties and disturbances of the measurement system.

The optical manipulator system I developed enabled taking measurements of biomechanical properties, viscosity of liquids and observation of colloid properties. The promising direction of research seems to be the use of nanoengineering to produce specialized sensors, such as thermometers or pH sensors.

4. Description of other scientific and research achievements

4.1. Scientific publications

No.		IF	M*
1	Jankowska E., **Drobczynski S.**, Menoni C. S., Analysis of surface deformation in thin-film coatings by carrier frequency interferometry, Appl. Opt. 56, C60-C64, 2017. *I estimate my contribution at 30% (development of numerical methods for the analysis of measurement results and analysis of obtained experimental data)*	1.650	30
2	Sojka B., Podhorodecki A., Banski M., Misiewicz J., **Drobczynski S.**, Dumych T., Lutsyk M. M., Lutsyk A. and Bilyy R., β-NaGdF4:Eu3+ nanocrystal markers for melanoma tumor imaging, RSC Adv. 6, 57854–57862, 2016. *I estimate my contribution at 5% (participation in the development and construction of the fluorescence microscopic system)*	3.108	35
3	Pretka M., Wozniak W.A., Kurzynowski P., **Drobczynski S.**, Evaluation of a linear birefringence measurement method with increased sensitivity, Appl. Opt. 55, 868-872 ,2016. *I estimate my contribution at 10% (development of software for recording high-resolution measurement data)*	1.650	30
4	Bacia M., Lamperska W., Masajada J., **Drobczyński S.**, Marc M., Polygonal micro-whirlpools induced in ferrofluids, Opt. Applicata 45**,** 309- 316, 2015. *I estimate my contribution at 20% (development of the measurement system and software)*	0.637	15
5	Bacia M., **Drobczyński S.**, Masajada J., Kopaczyńska M., Pęseta optyczna jako narzędzie współczesnej bioinżynierii Optical tweezers as a tool of modern bioengineering], Acta Bio-Optica et Informatica Medica 19, 114-122, 2013. *I estimate my contribution at 20% (participation in editing the manuscript)*		12
6	Augustyniak I., Popiołek-Masajada A., Masajada J. and **Drobczyński S.**, New scanning technique for the optical vortex microscope, Appl. Opt. 51, C117-C124, 2012. *I estimate my contribution at 5% (development of software for registration of measurement data)*	1.650	30
7	Wozniak W. A., Kurzynowski P., **Drobczynski S.**, Adjustment method of an imaging Stokes polarimeter based on liquid crystal variable retarders, Appl. Opt. 50, 203-212, 2011. *I estimate my contribution at 30% (development of software for registration and analysis of measurement data and participation in measurements)*	1.650	30

8	Masajada J., Leniec M., **Drobczynski S.**, Thienpont H., Kress B., Micro-step localization using double charge optical vortex interferometer, Opt. Express 17, 16144-16159, 2009. *I estimate my contribution at 5% (development of software for controlling the SLM modulator)*	3.307	45
9	Kurzynowski P., **Drobczynski S.**, Wozniak W.A., Dynamic polarization states and birefringence distributions measurements in spatial elliptical polariscope using Fourier analysis method, Opt. Express 17, 10144-10154, 2009. *I estimate my contribution at 30% (development of software for registration and analysis of measurement data and participation in measurements)*	3.307	45
10	**Drobczynski S.**, Kurzynowski P., Imaging polarimeter for linear birefringence measurements using a liquid crystal modulator, Opt. Eng**.** 47, 023603-1 – 023603-4,2008. *I estimate my contribution at 50% (formulation of the research problem, development of software for registration and analysis of measurement data and participation in the measurement)*	1.082	20
11	Bueno J., **Drobczynski S.**, Automized imaging polarimetry with carrier frequency: influence of the initial phase and diattenuation, Opt. Pura Apl. 40, 57-64, 2007. *I estimate my contribution at 30% (development of numerical methods and analysis of measurement data)*		
12	Kurzynowski P., Wozniak W. A., **Drobczynski S.**, A new phase difference compensation method for elliptically birefringent media, Opt. Comm. 267, 44-49, 2006. *I estimate my contribution at 20% (numerical calculations and simulations of the measurement system properties)*	1.588	25
13	**Drobczynski S.**, Bueno J., Artal P., Kasprzak H., Transmission imaging polarimetry for a linear birefringent medium using a carrier fringe method, Appl. Opt., 45, 5489-5496, 2006. *I estimate my contribution at 40% (formulation of the research problem, development of numerical methods and analysis of measurement data, participation in measurements)*	1.650	30
14	**Drobczynski S.**, Kasprzak H., Application of space periodic variation of light polarization in imaging polarimetry, Appl. Opt. 44, 3160-3166, 2005. *I estimate my contribution at 70% (formulation of the research problem, development of numerical methods and analysis of measurement data, participation in the manuscript editing)*	1.650	30

M* - Points of the Ministry of Science and Higher Education

4.2. Presentations at scientific conferences

No.	**Conference**
1	National Electronics Conference, Darłówko Wschodnie 3-7.06.2018 poster "Application of an optical trap to a random number generator"
2	44 Congress of Polish Physical Society, Wrocław 10-15.09.2017 **paper** "Multifunctional optical manipulator"
3	Polish Optical Conference, Gniezno 2 – 6.07.2017 **paper** "Controlled heating of micro-objects in the optical manipulator system"
4	SPIE Optics + Photonics 2016/ Optical Trapping and Optical Micromanipulation XIII, San Diego 28.08-1.09.2016 poster “Double wavelength optical tweezers for remote temperature sensing”
5	43 Congress of Polish Physical Society, Kielce 6-11.09.2015 **paper** "Holographic optical tweezers"
6	Polish Optical Conference, Legnica 28.06 – 2.07.2015 **paper** "Holographic optical tweezers for spectroscopic studies"
7	Stochastic Modeling of Anomalous Dynamics in Complex Physical and Biological Systems Hugo Steinhaus Center, Wrocław 14-16.05.2015 poster "Time series methods in analysis of the optical tweezers”
8	XIX Polish-Slovak-Czech Optical Conference on Wave and Quantum Aspects of Contemporary Optics, Wojanów 8-12.09. 2014, **paper** "Remote temperature sensing of optical trap by using up-converting particles” **Organizing committee**
9	III Polish Optical Conference, Sandomierz, 30.06-4.07, 2013 **paper** "Application of dynamic holography in optical manipulators"
10	BioMedTech Silesia, Rzeszów 15 -16.03.2013 poster "Optical tweezers”
11	5th International Symposium, Optical Tweezers in life science, Berlin, Germany,18.06.2013 poster “Changing the state of nano-particles in ferrofluid with optical tweezers”
12	18th Czech-Polish-Slovak Optical Conference on Wave and Quantum Aspects of Contemporary Optics, Ostravice, Czech Republic, 3-7.08.2012 poster “Particle position measuring with optical tweezers using video processing”
13	7th International Conference on Photonics, Devices and Systems, Prague, Czech Republic, 24-26.08.2011 poster “Light polarization state analyzer based on two spatial carrier frequency method”
14	17th Slovak-Czech-Polish Optical Conference Wave and Quantum Aspects of Contemporary Optics, Liptovsky Jan,Słowacja,6 – 10.09.2010 poster “Performance analysis of imaging Stokes polarimeter based on liquid crystal modulators”
15	3rd EUROPEAN MEETING IN PHYSIOLOGICAL OPTICS, London, UK, 7-9.09.2006 poster “Polarimetry with carrier frequency and its application in measurement of anisotropy of the eye elements”
16	The 5-th International Workshop on Automatic Processing of Fringe Patterns, Stuttgart, Germany, 12- 14.09.2005 poster “Some remarks on accuracy of imaging polarimetry with carrier frequency”
17	106-th Conference of the DGaO, Wrocław, 17-20.05. 2005 poster “Imaging polarimetry with carrier frequency for the linearly birefringent media”
18	International Conference on Systems of Optical Security, Warszawa, 11-12.12.2003 poster “Modeling of influence of liquid crystal modulator adjustment on reconstruction of birefringence and azimuth angle in imaging polarimetry with carrier frequency”

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ZA PREZENTACJĘ

„Szczypce optyczne"

PRZEDSTAWIONĄ PODCZAS KONFERENCJI **BIOMEDTECH SILESIA 2013 DOKTOR**

ZABRZE, 08.03.2013
MIEJSCE / DATA

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INTERNETOWA PROMOCJA NAUKI - INPRONA

3rd place - Audience Award Institute of Physics, Faculty of Fundamental Problems of Technology Wrocław University of Science and Technology for the presentation “Optical tweezers” presented at the BIOMEDTECH SILESIA 2013 Conference

Conference publications:

No.	
1	**Jankowska E., Drobczynski S., Menoni C. S., Carrier frequency interferometry for wavefront measurements of coated optics, IEEE 17291842, 1-2, 2017.**
2	Bacia M., Masajada J., Drobczynski S., Lamperska W., Kutrowska J., Walczak K., Light induced particle organization in paramagnetic fluids, Proc. SPIE 9441, 1-12,2014.
3	Slezak J., Drobczynski S., Weron K., Masajada J., Moving average process underlying the holographic-optical-tweezers experiments, Proc. SPIE 9066, 2013.
4	Matejek D., Langner M., Drobczynski S., Optical tweezers, ISBN 978-83-63151-03-4, 271-280, 2013.
5	Drobczynski S., Bacia M., Wozniak M., Symonowicz K., Particle position measuring with optical tweezers using video processing, Proc. SPIE 8697, 86970X-1 – 86970X-6,2012.
6	Drobczynski S., Wozniak W.A., Kurzynowski P., Light polarization state analyzer based on two spatial carrier frequency method, Proc. SPIE 8306, 83060R-1 – 83060R-6,2011.
7	Drobczynski S., Kurzynowski P., Wozniak W.A., Performance analysis of imaging Stokes polarimeter based on liquid crystal modulators, Proc. SPIE 7746, 77461F-1 – 77461F-8,2010.
8	Wozniak W.A., Drobczynski S., Kurzynowski P., **Spatial elliptical polariscope for polarization distribution measurements, Proc. SPIE 7390, 739009-1 – 739009-10, 2009.**
9	Drobczynski S., Kasprzak H., Some remarks on accuracy of imaging polarimetry with carrier frequency, in Proceedings of the 5-th International Workshop on Automatic Processing of Fringe Patterns, 204-207, 2005.
10	Drobczynski S., Kasprzak H., Modeling of influence of Liquid Crystal Modulator adjustment on reconstruction of birefringence and azimuth angle in imaging polarimetry with carrier frequency, Proc. SPIE, 5566, 273-277,2003.

4.3. Scientific cooperation

- Wrocław Research Centre EIT +;
- Institute of Low Temperature and Structure Research, Polish Academy of Sciences, Wrocław;
- Department of Pathomorphology, Wrocław Medical University;
- Department and Clinic of Haematology, Blood Neoplasms, and Bone Marrow Transplantation, Wrocław;
- Department of Biomedical Engineering, Wrocław University of Science and Technology;
- Division of Metrology and Measurement Systems, Institute of Mechanical Technology, Poznan University of Technology;
- Institute of Human Genetics, Polish Academy of Sciences, Department of Reproductive Biology and Stem Cells, Poznań;
- Department of Applied Physics, University of Eastern Finland;
- Department of Electrical & Computer Engineering, Colorado State University, USA.

4.4. Science internship programs

- Department of Electrical & Computer Engineering, Colorado State University, USA, 2016 (1 month);
- Universite Louis Pasteur Strasbourg, France, 2007-2008 (20 months);
- CNRS Strasbourg, France, 2006 (2 months);
- Laboratorio De Optica, Universidad De Murcia, Spain, 2005 (3 months).

4.5. Patents

- S. Drobczyński, "Method and system for holographic imaging with stimulated-emission-depletion microscopy", PL 228233 B1;
- S. Drobczyński, "System and method for holographic imaging with stimulated-emission-depletion microscopy", PL 228298 B1;
- P. Kurzynowski ,W.A. Woźniak, S. Drobczyński, "The method of determining the optical properties of the nondichroic birefringent media and the elliptical polariscope system", PL 220901 B1;
- H. Kasprzak, S. Drobczyński, "The method of determining maps of the phase shift distribution of nondichroic elliptically birefringent media and the system for determining the distribution maps of the phase shift of nondichroic elliptically birefringent media", PL 210025 B1.

Patent applications:

- "Method of diagnosing lymphoid tumors", P423266;
- "Compact measuring chamber compatible with optical tweezers at controlled oxygen concentration" P424002.

4.6. Participation in research projects

No.	Project	participation
1	The development of multifunctional optical tweezers and microrobots to investigate the effect of localized hyperthermia on cancer cells and spheroids obtained from primary cultures, 2017/27/B/ST7/01255, National Science Center, OPUS ,36 – months, PLN 1 445 160.	**supervisor**
2	The use of low-power laser diodes for the generation of holographic optical traps, N N518 498839, Ministry of Science and National Education, 36-months, PL 343 325.	**supervisor**
3	Optical Tweezer in biomedical applications, N R13 0023 10, NCRD, 36-months, PLN 1 486 300.	**main contractor**
4	Imaging polarimetry with carrier frequency for the linearly birefringent media, 3 T11E 006 30, Ministry of Science and National Education,10-months, PLN 33 750.	**main contractor**
5	Utilizing innovative optical tweezers technology to develop low-invasive target therapy for lymphomas, LIDER/016/275/L-5/13/NCBR/2014, 36-months, PLN 1 199 996 .	contractor
6	Optical Vortex Scanning Microscope, National Science Center, OPUS, 36-months, PLN 448 624.	contractor
7	Analysis of the tear film quality of tear film. A new window into the etiology of eye diseases associated with tear film, 2011/03/D/ST7/02512, National Science Center, SONATA, 36-months, PLN 399 672.	contractor
8	Compact polarimeter for real-time measurements of the optical properties of birefringent anisotropic centers, N N505 378337, Ministry of Science and National Education,30-months, PLN 219 400.	contractor
9	Utilizing optical vortices to study surface topography on a micro and nano scale, N N505 463438, ,30-months, PLN 266 100.	contractor
10	Task 7.1. NAOMIS – developing modern methods for biodetection and bioimaging of cells with the aid of nanomeasure luminescent markers, NCRD, *EIT+ Wrocław Research Centre, 53-months, 500 000 euro*	contractor

Other projects implemented using the optical manipulator I built:

- "Development of new measurement methods for holographic optical tweezers", Ministry of Science and National Education, Diamond Grant, 42-months, PLN 191 600;
- "Micromechanics of the membrane and its participation in the process of self-segregation of biological membrane components", PRELUDIUM (2016/21/N/NZ1/02767), National Science Center, 24-months, PLN 96 800;
- "Molecular mechanism of action and evaluation of the therapeutic effect of the combination of 5-aza-2'-deoxycytidine and topoisomerase inhibitors in the treatment of colon cancer", National Science Center, OPUS, 36-months, PLN 1 072 520.

4.7. Stipends and awards

- 2018, project LIDER "Utilizing innovative optical tweezers technology to develop low-invasive target therapy for lymphomas", in which I was a co-contractor, received the Polish Intellectual Development Award, under the patronage of the President of the Patent Office of the Republic of Poland;
- 2016, the Rector of the Wrocław University of Science and Technology award for a distinctive contribution to the university's activities;
- 2011, Young Staff stipend;
- 2009, START stipend of the Foundation for Polish Science;
- 2006, the Rector of the Wrocław University of Science and Technology award for the doctoral dissertation;
- 2006, diploma of recognition of the director of the Institute of Physics at the Wrocław University of Science and Technology for the doctoral dissertation.

5. Didactics

My didactic work focuses on specialized laboratory classes such as:

- Interferometry and holography
- Classic and synthetic holography
- Wave optics
- Optical measurements

Since 2012, I have also run a lecture and laboratory "Optoelectronic measuring apparatus" of which I am the author. The course is run for first-cycle students in the field of Quantum Engineering and second-cycle students in the field of Optical Engineering. The aim of the course is to prepare students for work in modern physical laboratories and to familiarize them with currently available and used optoelectronic technologies. During the classes, students learn the practical aspects and principles of operation of the most popular measurement techniques. The course presents methods of obtaining data from measurement sensors, sending them to a computer, analyzing measurement data and controlling the operation of external devices from a computer.

I exercise substantive supervision over the Laboratory of Interferometry and Holography. In the prepared exercises, I present classic interference experiments in combination with modern methods of data acquisition and analysis, e.g. computer image analysis in the Matlab computing environment.

Participation in the implementation of various research projects encourages me to follow current technological solutions and the current state of knowledge. During classes, I mention every new equipment. In working with students, I put a special emphasis on understanding the discussed physical phenomena and drawing appropriate conclusions, in particular in the context of measuring applications.

Diploma theses:

No.	First and last name	Title	Year	Type
1	Marcin Bacia	Application of iterative algorithms to computer generation of holograms	2011	MSc
2	Agata Chochowska	Measurement of selected characteristics of an optical trap	2012	Eng.
3	Piotr Grela	Measurement of focal length of lenses using the autofocus algorithm	2013	Eng.
4	Tomasz Poźniak	The implementation of Fresnel lenses generated on a liquid crystal transmission modulator	2013	Eng.
5	Grzegorz Łupkowski	Measurement of displacements using speckle photography using a digital video camera	2013	Eng.
6	Adrian Adamski	Development of software for the analysis of far-field diffraction images	2015	Eng.
7	Joanna Hołyszko	Application of colloidal phosphors for temperature measurement in an optical manipulator system	2015	MSc
8	Patryk Frankowski	Development of a microscope illuminator with the use of a high-power LED	2017	Eng.
9	Aleksandra Korzeniewska	Development of a system for the reconstruction of the wavefront using the Shack-Hartmann element	2017	Eng.
10	Eliasz Korzeniewski	Computer analysis and visualization of displacement measurements using speckle interference method	2017	Eng.
11	Mateusz Świerad	Measurements of the trajectory of objects in asymmetrical optical traps	2017	Eng.
12	Iwona Biernacka	Adaptation of a student registration system for holograms for cooperation with a digital camera	2018	Eng.
13	Edyta Bobrowska	The use of SLM modulator to generate asymmetrical optical traps	2018	Eng.
14	Aleksandra Korzeniewska	Application of the Shack-Hartmann element in the dynamic wavefront correction system	2018	MSc
15	Eliasz Korzeniewski	The use of up-energy converting nanoluminophores in microscopic imaging	2018	MSc

Auxiliary supervisor of doctoral dissertation of Marcin Bacia on the subject of "Holographic application of optical tweezers for measurements of selected properties of biological preparations and colloids".

In 2011, MSc Eng. Marcin Bacia defended his master's thesis entitled "Application of iterative algorithms to the computer generation of holograms", of which I was a supervisor. As part of interdisciplinary doctoral studies, MSc Eng. Marcin Bacia used the experience gained in the computer technology of the generation of holograms to adapt the holographic system of optical tweezers to specific biological tests. The PhD student demonstrated the ability to combine the needs of specialists in the field of biology and medicine with the technical capabilities of the optical tweezers system. It should be emphasized that the acquired skills and developed procedures for the preparation of biological preparations allowed for conducting many interesting and difficult experiments, e.g. testing the elastic properties of DNA strands. As for the preparation related to colloid research, the PhD student showed great ingenuity and good engineering skills. The results of experiments on the impact of optical traps on ferrofluids have been published in the renowned journal Optics Letters.

Supervision of student projects within student research groups:

- development and construction of a linear camera for measurements of diffraction spectrum;
- development and construction of laser diode controllers;
- development and construction of a high voltage amplifier.

6. Promotion of science

- conducting meetings with youth as part of "Open doors at the Wrocław University of Science and Technology";
- conducting laboratory classes in physics for students of the Salesian Middle School in Wrocław.

7. Reviewing publications in international and national journals

I have reviewed scientific publications several times for the following journals:

- Optics Express
- Optics Letters
- BioMed Research International
- Optica Applicata