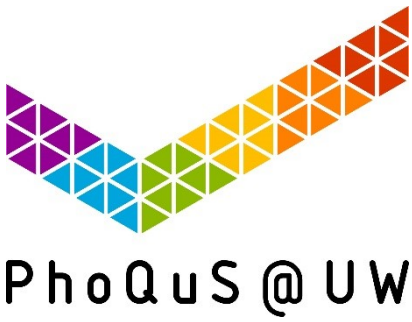

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 316244.

PROJECT FINAL REPORT

Grant Agreement number: 316244

Project acronym: PhoQuS@UW

Project title: Fostering Excellence in Photonics and Quantum Science

Funding Scheme: Coordination and support action - REGPOT

Period covered: **from** 01 November 2012 **to** 31 October 2016

Name, title and organisation : Prof. Konrad Banaszek,
Uniwersytet Warszawski, Wydział Fizyki
ul. Pasteura 5
02-093 Warszawa

Tel: +48-22-5532923, +48-22-5532638

Fax: +48-22-5532999

E-mail: phoqus@fuw.edu.pl

Project website address: http://phoqus.fuw.edu.pl

Table of contents

PUBLISHABLE SUMMARY

1. EXECUTIVE SUMMARY

The overall objective of the PhoQuS@UW project was to enhance the Faculty of Physics, University of Warsaw (FPUW) research potential with a focus on the area of photonics and quantum science, allowing it to reach the European elite level. This supported the ultimate goal to establish FPUW as a world class multidisciplinary scientific centre in the Innovation Union and a noteworthy contributor to the European excellence in this technology driving research domain. This overarching goal was achieved through the following specific objectives:

- to better integrate FPUW in the European Research Area via strengthened and expanded networking and twinning with top level scientists at leading European research institutions in the area of Photonics and Quantum Science;
- to foster scientific excellence at FPUW by raising its research quality and capacity to reach internationally competitive levels through recruitment and retention of experienced researchers with a special focus on those returning from abroad ("brain gain"), acquisitions and upgrades of modern scientific equipment, hiring skilled engineering and innovation management and project management staff;
- to trigger greater contribution to the regional high-tech economy and sustainable regional socioeconomic development through closer cooperation with the industry while engaging decision makers and other stakeholder groups in supporting and fostering innovative research at FPUW;
- to build up ERC-calibre human potential matched with professional support assuring higher success rates of grant applications in international research cooperation programmes, in particular in the EU Horizon 2020, while stimulating innovation-driven research for greater output relevant to this industry sector;
- to draft a Research and Development (R&D) strategy for FPUW that would assure full and efficient use of research facilities and the infrastructure created using European Regional Development Fund (ERDF) for conducting cutting-edge research in Photonics and Quantum Science (R) along with innovation (D) for greater benefit of the European economy and society.

2. SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

Photonics and Quantum Science are transforming the 21st century science and technology. Their impact extends from fundamental physics, such as detection of gravitational waves using highly precise interferometers operating at the quantum limit, through life and environmental sciences, including new approaches to optical imaging and ultrasensitive pollution detection, to widely spread technologies, with the prominent example of fibre optic communication the advances of which rely increasingly on efficient, compact and robust semiconductor laser light sources and all-optical signal processing. The Faculty of Physics at the University of Warsaw (FPUW) is in a unique position to establish itself as a European Centre of Excellence in the area

of Photonics and Quantum Science with a broad impact on Polish and regional environment through a combination of several factors:

- traditional excellence in theoretical and experimental physics documented by publications in leading international scientific journals and numerous collaborations;
- leadership of the national consortium "Laboratory of Photonics and Quantum Technologies" that was selected as one of the 13 projects for the Polish National Roadmap of Research Infrastructures;
- new generation of entrepreneurial academic staff that will sustain the systemic changes induced by the implementation of the proposed project;
- recent major infrastructure upgrades co-financed from European Regional Development Fund (ERDF);
- ability to attract the brightest young scientists from all over the country who continue their professional career in research and technology development thus ensuring broad and sustainable growth.

Overall, the primary objective of the PhoQuS@UW project, which draws on the major strengths of FPUW, was to further enhance FPUW research potential with a focus on the area of photonics and quantum science, allowing it to reach the European elite level. Ultimately, this should establish FPUW as a world class multidisciplinary scientific centre in the Innovation Union and a noteworthy contributor to the European excellence in this technology driving research domain. This overarching goal was achieved through the following specific objectives:

- to better integrate FPUW in the European Research Area via strengthened and expanded networking and twinning with top level scientists at leading European research institutions in the area of Photonics and Quantum Science;
- to foster scientific excellence at FPUW by raising its research quality and capacity to reach internationally competitive levels through recruitment and retention of experienced researchers with a special focus on those returning from abroad ("brain gain"), acquisitions and upgrades of modern scientific equipment, hiring skilled engineering and innovation management and project management staff;
- to trigger greater contribution to the regional high-tech economy and sustainable regional socioeconomic development through closer cooperation with the industry while engaging decision makers and other stakeholder groups in supporting and fostering innovative research at FPUW;
- to build up ERC-calibre human potential matched with professional support assuring higher success rates of grant applications in international research cooperation programmes, in particular in the EU Horizon 2020, while stimulating innovation-driven research for greater output relevant to this industry sector;
- to eliminate artificial boundaries of traditional institutional divisions at FPUW by creating inter-institute Centre of Excellence in PhoQuS;
- to draft a Research and Development (R&D) strategy for FPUW that will assure full and efficient use of research facilities and the infrastructure created using European Regional Development Fund (ERDF) for conducting cutting-edge research in Photonics and Quantum Science (R) along with innovation (D) for greater benefit of the European economy and society.

Objectives of the project were realized in six Work Packages:

- WP1: Networking through exchange of know-how and experience
- WP2: Building human capital through recruitment of experienced researchers
- WP3: Research equipment upgrades
- WP4: Dissemination, Exploitation and Innovation Capacity Building
- WP5: Project management
- WP6: Ex-post Evaluation

Within **WP1** we aimed:

- to build FPUW intellectual capacity and to promote increased scientific dialogue and twinning between the Institutes from FPUW and fourteen groups from thirteen top research centres via secondments of experienced scientific staff to transfer knowledge, new research methodologies and techniques, discuss research progress, share experimental data, work on joint research proposals and publications in top scientific journals to create a forum for exchange of scientific ideas, techniques, and approaches and to share the results of recent research activities through organisation of workshops and conferences.

In **WP2** we built FPUW human capital by recruiting experienced researchers with international experience in the strategically defined areas of photonics:

- recruitment of one group leader and two post-doctoral level researchers to establish an independent group developing innovative optical solutions for biomedical optics;
- recruitment of two ERC calibre experienced researchers in the early stages of their careers, to strengthen two most competitive research pillars of PhoQuS@UW – Atto Science and Quantum Optics
- recruitment of four post-doctoral level candidates with experience in other two application areas – environmental optics and quantum metrology.

In **WP3** we built the capacity of the UWAW research base by acquisition and installation of the following equipment items:

- a set of three research grade cameras,
- a laser pulsed source with octave-spanning spectrum,
- a tuneable source of femtosecond laser pulses,
- an integrated femtosecond laser system,
- a Scanning Electron Microscope,
- start-up equipment for the new group in Biomedical Optics chosen by the group leader (hired by the project),

as well as monitoring of the equipment operation, hiring and supervision of engineers/technicians.

The main objective of **WP4** was to facilitate a shift from curiosity-driven basic research to innovation driven research at the FPUW. This objective was achieved through the following operating actions:

- recruitment of a professional innovation manager,
- transfer of best practice and know-how in innovation management and technology transfer through focused,
- workshops and case studies and site visits at Partnering Institutions,
- implementing an IPR management policy and regulation assuring its effective protection.

The second objective of this work package was to disseminate, exploit and promote among a broader research community, local and regional stakeholders and the general public the results of this project and research achievements of the Faculty of Physics and its scientific collaborators.

The main objectives of **WP5** were to assure efficient and professional management of PhoQuS@UW and to integrate the research community and services supporting management and administration of projects.
The operating actions were:

- to employ a professional and experienced project manager to support the Coordinator and research staff of the Faculty,
- to assure flexible coordination of individual WPs,
- to optimise the interaction between the FPUW, the partnering institutions and EC,
- to follow EC guidelines on financial and administrative procedures.

The main objectives of **WP6** were to evaluate the impact, which the project has had on facilitation and execution of research at the FPUW in terms of:

- the overall quality of research (publications, research grants, etc.),
- improvement in capability of research support facilities and infrastructure,
- new techniques and approaches implemented at FPUW,
- quality and efficiency of management and support services,

and to provide recommendations for short-term and long-term strategic activities aimed at fostering excellence at FPUW in its key competence areas European research community and regional development.

3. DESCRIPTION OF MAIN RESULTS/FOREGROUND

WP1 was realized through five tasks:

- TASK 1.1 Exchange of know-how and experience via secondments with thirteen international top level research groups via incoming and outgoing secondments;
- TASK 1.2 Organization of 4 conferences;
- TASK 1.3 Organization of Special Sessions and Symposia at Conferences;
- TASK 1.4 Organization of Workshops;
- TASK 1.5 Participation of staff of Institutes of FPUW in international conferences.

The outgoing and incoming secondments (Task 1.1) of experienced scientific staff of the Faculty of Physics UW and the twinning European partners have heretofore led to the transfer of knowledge and new research methodologies and techniques, extended scientific discussions of research progress, sharing of experimental data, and work on joint research proposals and publications in top scientific journals. 35 outgoing and 54 incoming visits, to and from partnering institutions, were organized within the project. These visits contributed to strengthening the collaboration with top research centres, resulting in building FPUW intellectual capacity. As an example, one of the results of secondments between top level research groups from FPUW's partners institutions are the following publications:

- *Introducing single Mn2+ ions into spontaneously coupled quantum dot pairs*. M. Koperski, M. Goryca, T. Kazimierczuk, T. Smoleński, A. Golnik, P. Wojnar, P. Kossacki. Phys. Rev. B 89, 075311 (2014). Open Access: arXiv:1310.3383

- *Designing quantum dots for solotronics.* J. Kobak, T. Smoleński, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki and W. Pacuski. Nature Communications 5, 3191 (2014).
- *Strong-field Breit-Wheeler pair production in short laser pulses: Relevance of spin effects.* M. J. A. Jansen, J. Z. Kamiński, K. Krajewska and C. Mueller. Phys. Rev. D 93(5), 013010 (2016). Open Access: arXiv: 1605.03476v1 [hep-ph]
- *Bandwidth manipulation of quantum light by an electro-optic time lens*. M. Karpiński, M. Jachura, L. J. Wright, and B. J. Smith, Nature Photonics (2016), available online at doi:10.1038/nphoton.2016.228

Secondments along with organization of conferences, sessions and workshops resulted in establishing and deepening cooperations and performing research in new, prospective areas with high impact both on science and everyday life. These research and their importance is described in chapter 4 ((Potential impact and the main dissemination activities and exploitation of results).

Within Task 1.2 four conferences were successfully organized:

- QUANTUM OPTICS VIII, 26.05.2013-1.06.2013, Jachranka, Poland,
- THE 3RD POLISH OPTICAL CONFERENCE, 30.06.2013-4.07.2013, Sandomierz, Poland,
- THE 4TH POLISH OPTICAL CONFERENCE, 28.06.2015-02.07.2015, Legnica, Poland,
- 22nd CENTRAL EUROPEAN WORKSHOPS ON QUANTUM OPTICS (CEWQO), 06-10.07.2015, Warsaw, Poland

"Quantum Optics VIII" international conference was organized by The Faculty of Physics UW jointly with the Centre of Theoretical Physics, Polish Academy of Sciences, and the Institute of Physics, Polish Academy of Sciences. It took place in Jachranka, starting on May 26, 2013 and lasted until June 1, 2013. The conference was the eighth one in the series that have been organized every four years since the 1980's. The main topics of the conference included: quantum communication, quantum metrology, nonclassical radiation, optical frequency standards, quantum degenerate Bose and Fermi gases, optical lattices, ultracold molecules, as well as disordered and designed potentials. Its aim was to bring together researchers from various sub-fields of quantum optics to offer a broad overview of current developments in this exciting domain. Naturally, this has fostered the communication and exchange of scientific ideas and the latest discoveries between Polish researchers and the international research community. More than 110 international participants (including 20 researchers of FPUW) took a part in the conference, which included representatives of FPUW as speakers. Note that in accordance with the decision of the Programme Committee two invited lectures were delivered by the scientists from FPUW (J. Chwedeńczuk and Z. Idziaszek). The conference hosted a special session "The Bright Side of Light" which was open to the public. In addition, the conference offered an opportunity to strengthen collaborations of the FPUW scientific staff with the European twinning partners, whose representatives were present at the conference.

In addition to promoting their scientific results in international settings, the researchers from FPUW have actively participated in Polish scientific conferences such as the **"3rd Polish Optical Conference"** and "**The 4th Polish Optical Conference"**. These conferences were organized by the Technical University of Szczecin (traditionally the main organizer) jointly with FPUW. The former conference was held in Sandomierz from June 30, 2013, until July 4, 2013, the latter conference was held in Legnica from 28th June till 2nd July 2015. Its main purpose was to create a forum for the exchange of scientific and technological ideas, solutions, and approaches, including those related to optics teaching and methodology. Other topics included: quantum optics; nonlinear optics; lasers and other sources of coherent radiation; optoelectronics; fiber optics and optical integrated systems; medical optics; instrumental optics; optical spectroscopy and metrology; novel optical materials; applications of optics. The goal of the Polish Optical Conference was to integrate the Polish optical community, enable a forum for presenting the most recent research results and establishing contacts leading to future cooperation. Polish Optical Conference is expected also to gather researchers from engineering and industry as well. It has always been the intention of the organizers to attract participants from as many branches of optical sciences as possible, starting from basic research and ending with the applications of photonics in different fields of technology and industry. In 2013 the program of the Polish Optical Conference consisted of 12 invited talks covering various aspects of optical sciences. In addition, over 30 contributed talks were given, mainly by young scientists, and approximately 50 posters were presented. In 2015, the program of the Polish Optical Conference comprised 15 invited talks covering various aspects of optical sciences. In addition, 28 talks were contributed mainly by young scientists, and 42 posters were presented. This large number of contributions from many research institutions in Poland indicates the steady progress of the conference, which is likely to become the key forum for exchanging research results and ideas between Polish scientists involved in optical research. We believe that this format of the Polish Optical Conference stimulates an exchange of ideas between researchers working on various aspects of optical science. It is noteworthy that a researcher from FPUW, Piotr Fita, was invited to deliver a lecture Femtosecond dynamics of double proton transfer, which was met with great interest.

The conference **Central European Workshop on Quantum Optics** took place in Warsaw, in July 6-10, 2015. There were delivered almost 30 invited talks, presented by well-known specialists in quantum optics, quantum theory of information and other aspects of laser field-matter interactions. On top of that, the public lecture dedicated to a broad audience, entitled Quantum Teleportation, Entanglement, and Einstein's Question "What is Light"? was presented by Prof. Anton Zeilinger (Vienna, Austria). Invitation of internationally renowned scientists was possible only thanks to the support from the PhoQuS@UW project. Let us emphasize that the Conference was attended by a large group of both experienced and young researchers from many European Research Centers, who delivered lectures and presented posters. The Conference was attended by roughly 200 scientists, among which there were 45 from FPUW. The success of the Conference also creates hope that similar large meetings of top scientists from all over the world will be more frequently organized in Warsaw, increasing the visibility of FPUW. For the complete programme and abstracts of the conference please visit: http://cewqo2015.fuw.edu.pl/.

All the organized conferences fostered twinning between the Institutes from FPUW and top research centres from all over the world, stimulated the discussion over the research progress,

sharing experimental data and created a forum for exchange of scientific ideas, techniques, and approaches.

Within Task 1.3, three events were organized: the Session on "Plasmon enhanced diffractive elements" at the "Sub-wavelength photonic devices" Symposium at the International Conference on Transparent Optical Networks - ICTON 2013, Cartagena, Spain, 23-27 June 2013, the Session on "Microstructured optical Fibres" at the XIV National Conference on Optical Fibres and Applications, January 2014, Białowieża, Poland and the Session on “Metasurfaces and sub-wavelength plasmonic DOE” at the SPIE Optics and Electronics Congress on Metamaterials X, in Prague, Czech Republic, 13-16 April 2015.

15th International Conference on Transparent Optical Networks (ICTON 2013) was organized by the National Institute of Telecommunications, Department of Transmission and Optical Technologies in Warsaw, the Department of Information Technologies and Communications of the Universidad Politécnica de Cartagena, and the IEEE Photonics Society Poland Chapter. It took place in Cartagena, Spain, June 23-27, 2013. The REGPOT Session Th.B5 on "Plasmon enhanced diffractive elements" at the "Sub-wavelength photonic devices" Symposium was organized by Dr hab. Rafał Kotyński (FPUW), Prof. Concita Sibilia (Partnering Institution University of Rome "La Sapienza"), and Prof. Tomasz Szoplik (FPUW). The special session on "Plasmon enhanced diffractive elements" during ICTON 2013 was chaired by Prof. Marian Marciniak and Prof. Tomasz Szoplik (FPUW). During the session, the organizers distributed information and promotion materials. The session consisted of 4 invited talks and 2 contributed presentations. ICTON 2013 was attended by nearly 400 international participants, while the REGPOT Session was attended by 40 researchers, mostly from Europe. Two invited presentations of researchers involved in the PhoQuS@UW project were delivered at the Session "Nanophotonics and smart optical nanostructures" of the "Sub-wavelength photonic devices" Symposium.

Conference on "Optical Fibers and Their Applications" is a well-established event with a long tradition, dating back to 1976, when it was organized for the first time. The purpose of the conference series is to summarize the developments in the field of optical fiber technology and its applications in this geographical region and worldwide. The 2014 conference particularly focused on the following directions and applications: optical fiber technology, materials for optoelectronics and photonics, Rare Earth doped and luminescence materials, photonic and optoelectronic components and circuits, metrology of optical fibers, components and optoelectronic circuits, applications of optical fibers, waveguides and optical fibre sensors, lighting technology. The 15th Conference on "Optical Fibers and Their Applications" was organized in Białystok – Lipowy Most, starting from January 29 till February 1, 2014. The conference consisted of eight lecture sessions and one poster session. There were 45 lecture presentations given and 41 posters presented. Over 130 scientists took part in this event. The special session on “Photonic Fibers I” organized by PhoQuS@UW was held on January 30, 2014, at 9.15-10.45. The session consisted of three invited presentations given by top scientists from three top European research groups working in the domain of photonic crystal fibers. This session was chaired by R. Buczyński, University of Warsaw. The costs of participation in the conference of three invited speakers and the FPUW researchers were supported by the PhoQuS@UW.

During the SPIE Optics and Optoelectronics Congress on Metamaterials X in Prague, two following conferences were chaired by PhoQuS@UW members: Conf. 9502. Metamaterials (Chairs: Kuzmiak, Markos, Szoplik- PhoQuS@UW WP4 Leader) and Conf. 9505. Quantum Optics and Quantum Information Transfer and Processing (Chairs: Banaszek- PhoQuS@UW Coordinator, Silberhorn). The Session 7 on "Metasurfaces and Sub-wavelength Plasmonic DOE" was organized and chaired by Rafal Kotyński, FPUW, with the support of the PhoQuS@UW project. The session consisted of 6 contributed talks and was attended by 35 researches mostly from Europe. Three talks, including invited talk, were presented during the conference: "Enhancement of light absorption in polyazomethines due to plasmon excitation on randomly distributed metal nanoparticles" (P. Wróbel, T. J. Antosiewicz, T. Stefaniuk, A. Ciesielski, Univ. of Warsaw (Poland); A. Iwan, Institute of Electrical Engineering (Poland); A. A. Wronkowska, A. Wronkowski, Univ. of Technology and Life Sciences in Bydgoszcz (Poland); T. Szoplik, Univ. of Warsaw (Poland)); "Perfectly matched layer based multilayer absorbers" (M. Stolarek, P. Wróbel, T. Stefaniuk, T. J. Antosiewicz, B. Wieciech, R. Kotynski, Univ. of Warsaw (Poland); "Reduction of plasmon losses in thin Ag silver films" – invited talk (T. Stefaniuk, Univ. of Warsaw (Poland).

Within Task 1.4, four events were organized: Hands-on Advanced Workshop on "Molecular beam epitaxy", Hands-on Advanced Workshop on "Scanning near-field microscopy", the Hands-on Advanced Workshop on "Molecular beam epitaxy" and workshop on "Femtochemistry". Additionally, given recent advances in specific areas of photonics and quantum science, we organized three additional Focused Workshops approved by the Project Officer. The subjects of the Workshops were: "Quantum Limits of Optical Communication", "Recent Advances in Quantum Metrology" and "Spectral and Spatial Engineering of Quantum Light".

The hands-on advanced workshop on "Molecular beam epitaxy" was organized by PhoQuS@UW at the Faculty of Physics UW, starting from September 16 to October 15, 2013. Two lecturers - trainers were hosted: Dr Carsten Kruse from partnering organization University of Bremen (Germany) and Prof. Marek Potemski from Grenoble High Magnetic Field Laboratory (France), which is also partnering organization. Dr Carsten Kruse realized practical exercises on substrate preparation for epitaxy, growth of photonic structures, and growth of low-dimensional structures based on II-VI semiconductor compounds. Several clean-room and growth procedures instituted by Dr Carsten Kruse were performed at FPUW for the first time. Learning these new research methodologies and techniques has already proven to be important for the research activity of scientists participating in the PhoQuS@UW project. With the support of PhoQuS@UW project they have grown several microcavities and structures containing quantum dots using ultra-pure materials prepared for the workshop. The workshop, following Dr Wojciech Pacuski visit to University of Bremen (27.01.2013-02.02.2013), resulted in one joint publication:

- W. Pacuski, T. Jakubczyk, C. Kruse, J. Kobak, T. Kazimierczuk, M. Goryca, A. Golnik, P. Kossacki, M. Wiater, P. Wojnar, G. Karczewski, T. Wojtowicz, and D. Hommel, "Micropillar cavity containing a CdTe quantum dot with a single manganese ion", Crystal Growth & Design 14, 988 (2014).

Skills mastered during the workshop were also crucial in the preparation of a recent publication in Nature Communications:

- J. Kobak, T. Smoleński, M. Goryca, M. Papaj, K. Gietka, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, E. Janik, M. Nawrocki, A. Golnik, P. Kossacki, and W. Pacuski, "Designing quantum dots for solotronics", Nature Communications 5, 3191 (2014)].

One day of Dr Carsten Kruse's visit was devoted to lectures, seminars and discussions on epitaxial methods. Practical exercises planed by Dr Kruse were intensively continued during the workshop. The practical activities were coordinated by Dr Wojciech Pacuski. The second lecturer, Prof. Marek Potemski, realized the more theoretical part of the workshop, with many discussions, seminars and one main lecture. Prof. Potemski and the FPUW researchers discussed their research progress and shared experimental data. The seminars and discussions, identifying the most promising directions for scientific exploration, were chaired by Prof. Andrzej Golnik. The new ideas were immediately tested and new growth processes were performed.

The workshop on scanning near-field optical microscopy was organized in the framework of PhoQuS@UW at the FPUW in January 19-20, 2015. Altogether, over 20 researchers from the FPUW participated in the Workshop. The workshop was organised at the beginning of 2015. The detailed programme of the Workshop included three lectures, and laboratory work with physical vapour deposition (PVD), with scanning electron microscopy and with scanning near-field microscopy. The event was organized by Rafał Kotyński. Lectures included the introductory talk on scanning near-field optical microscopy given by Tomasz Szoplik, the talk on superresolving imaging with metal-dielectric structures and on electromagnetic absorbers given by Anna Pastuszczak, and the talk on nanostructured plasmonic elements and on the PVD evaporation technology with an electron beam given by Piotr Wróbel. The experimental part of the Workshop began in the PVD laboratory with sample preparation – this part of the workshop was also guided by Piotr Wróbel. Prior to the Workshop, several samples were prepared, including Au, NiCr, BaF2 and LiF structures deposited on silica substrates. The second day of the Workshop was entirely devoted to experimental work on scanning electron microscopy with X-ray microanalysis, followed by scanning near-field optical microscopy – this part of the Workshop was guided by Tomasz Stefaniuk.

The workshop on “Molecular beam epitaxy” (17.11.2015-16.12.2015) was organized at FPUW. During the workshop we hosted at FPUW researchers from: Grenoble High Magnetic Field Laboratory (France), Karol Nogajewski, Tomasz Jakubczyk and Marek Potemski and University of Bremen (Germany), Detlef Hommel. The main activity and training was related to implementation of new 3 inch wafers used as substrates in the molecular beam epitaxy (MBE). During workshop, foreign experts trained participants how to recalibrate growth parameters for new kind of substrates. Several growth processes performed in close collaboration with trainers helped us to pass quickly several technological steps and to master the skill of fabrication of big wafers containing Bragg reflectors. The practical activities were coordinated by Wojciech Pacuski. In addition, Detlef Hommel advised how to choose the configuration of effusion cells for the new arrangement of the MBE machine. Using the new 3 inch substrates prepared for the workshop, we have grown several microcavities and structures containing coupled microcavities and Bragg reflectors. During his talk, Karol Nogajewski shared valuable experience on microwave experiments which will be implemented in the measurements on heterostructures containing solitary magnetic ions. The new experiments will be conducted at University of Warsaw on structures fabricated in our MBE machine. The second topic of the workshop was devoted to the future plans of new epitaxial activities in

Warsaw. Marek Potemski and Karol Nogajewski realized more theoretical part of the workshop, with many discussions and seminars. The seminars and discussions were chaired by Andrzej Golnik.

The workshop on ultrafast spectroscopy and femtochemistry organized within the framework of the PhoQuS@UW project at FPUW took place on 29-30 September 2015. The goal of the workshop was to design experiments, test new ideas and plan the new research carried out in the laboratories of the Division of Optics at FPUW. During the workshop, we hosted at FPUW four world renowned specialists in the field: Philipp Kukura, Marcus Motzkus, Arnulf Rosspeintner and Eric Vauthey. Under the supervision of the specialists, we learned various schemes of ultrafast time-resolved spectroscopy such as frequency up-conversion fluorescence spectroscopy, stimulated Raman spectroscopy, micro-spectroscopy with shaped laser pulses and infrared transient absorption spectroscopy. We also designed several schemes of coherent control experiments, which can be used to control the double hydrogen transfer process in organic molecules belonging to the family of porphycenes currently studied in the Division of Optics at FPUW. In addition to being involved in planning the research and designing the new experimental setups in the laboratories, the specialists gave lectures during which they presented the most recent developments in femtosecond spectroscopy, micro-spectroscopy and quantum control. They also took part in two panel discussions devoted to expectations, challenges and perspectives of the field.

The Workshop “Quantum Limits of Optical Communication” organized on 24-26 February 2016 at the University of Warsaw, with the support of the PhoQuS@UW project, focused on some particular aspects of the quantum communication. Standard optical communication systems operate with efficiencies lower than the limits defined by quantum physics. In recent years, significant progress has been made in identifying ultimate capacities of optical channels, developing and implementing sub-shot noise receivers, and understanding non-classical effects such as superadditivity of accessible information through collective readout. The purpose of this workshop was to review these advances and to identify further steps towards practical exploitation of quantum enhancement in optical communication. Main topics of the workshop included: sub-shot noise receivers, collective detection, ultimate capacity of optical channels, quantum-limited optical signal discrimination, mode multiplexing and demultiplexing, noise in optical communication links. More than 80 experienced and young researchers and special invited speakers participated in workshop which included 48 scientists from the Faculty of Physics UW.

The Workshop “Recent Advances in Quantum Metrology” organized on 02-04 March 2016, at University of Warsaw, focused on recent fascinating developments in quantum metrology in order to understand various ways in which one can benefit from intrinsic quantum features of matter and light in practical metrological protocols and get a better feeling of the present development and future prospects of the field. Topics of the workshop included: entanglement enhanced atomic clocks, atomic interferometry, optical interferometry utilizing non-classical states of light, quantum-enhanced imaging, impact of decoherence on quantum metrological protocols and new theoretical methods of quantum estimation theory. 20 Internationally renowned world experts in Quantum metrology delivering invited talks. Almost 100 participants attended in workshop in which included 60 FPUW employees. This Workshop gathered key researchers from the field of quantum metrology boosting significantly the

visibility of the FPUW as a center of world-class quantum metrology research. The employees of the FPUW interested in the field gained a unique opportunity to get first-hand information on the latest developments in the field as well as make their own results recognized by the leaders of the world quantum-metrology community.

The Workshop "Spectral and Spatial Engineering of Quantum Light" organized on 30 March – 1 April 2016, at the University of Warsaw focused on recent fascinating developments in experimental techniques to control and manipulate the pulsed-mode structure of quantum light in order to build tools for large scale photonic quantum information processing and future prospects of the field. The topics covered during the workshop included: spectral-temporal quantum information encoding, spatial encoding of quantum information, mode conversion, frequency conversion, multidimensional quantum information processing, multidimensional quantum key distribution, generation of quantum states of light, nonlinear interaction between light and matter. 16 experts from internationally renowned research groups in quantum optics, including 11 group leaders, delivering invited talks. As a special guests 9 scientists from partnering institutions accept invitation to deliver talk during their visit in FPUW. Almost 60 participants attended in workshop in which included 35 FPUW employees. The SSEQL'16 Workshop brought together representatives of key research groups in the field of multidimensional optical quantum information processing. It significantly boosted the visibility of the FPUW as an important research centre in experimental and theoretical quantum optics. It offered a fantastic opportunity for FPUW experienced and young researchers to directly learn about the most recent results in the field as well as to directly interact with the international researcher cohort. Additionally it enabled the research done at the FPUW to be directly presented to a well-targeted audience of experts in the field. The results of the workshop will be mostly visible in the longer term in the form of new collaborations, research directions, enhanced opportunities for the FPUW to join international research consortia, yet first signs of these developments are already appearing, both via email contacts as well as through increased citations to FPUW research visible in publications posted on preprint servers.

Within Task 1.5, crucial for building intellectual capacity of the Faculty of Physics, University of Warsaw (FPUW) through creating the FPUW researchers a possibility to attend international meetings, conferences and workshops, as participation in such events assures worldwide confrontation with the newest scientific achievements and discoveries. The Committee for the assessment of applications for financing participation in international conferences considered applications to support participation in international conferences taking into account character of the presentation, participation as a chairperson/programme committee member and the resulting visibility for the University of Warsaw. Other benefits include strengthening co-operation of FPUW scientists with the current European partners as well as establishing new international research contacts. During the project duration 41 employees of FPUW were granted financial means to cover their expenses at conferences and workshops. It is indisputable that in order to increase the resulting visibility of the University of Warsaw it is necessary to promote the research achievements of PhoQuS@UW members and FPUW researchers. We are convinced that intensifying networking and sharing of know-how and expertise, created a favourable environment for discoveries, higher impact publications and collaborative innovation.

Implementation of objectives of **WP2** complied with the recruitment procedures of UW. They were applied comprehensively for all three tasks, which are:

- TASK 2.1 Recruitment of a new group leader in biomedical optics and subsequent recruitment of two post-doctoral candidates for his group to build a competitive programme in biomedical optics;
- TASK 2.2 Recruitment of top-level scientists in Atto Science and Quantum Optics areas;
- TASK 2.3 Recruitment of four research fellows.

The recruitment procedures concerning hiring research staff in the PhoQuS@UW complied with the Statute of the University (http://www.uw.edu.pl/en/strony/about_uw/Statut_UW_ANG2006.pdf) which, in turn is consistent with the Polish law regulating universities. In addition, the procedures complied with the European Commission Recommendation of 11 March 2005 on the European Charter for Researcher and on Code of Conduct for the Recruitment of Researchers. University of Warsaw is an Equal Opportunity employer. The open competitions for positions were announced through highly visible international channels, for example the EURAXESS portal in addition to the web page of the Polish Ministry of Science and Higher Education, the FPUW and relevant scientific societies' websites and newsgroups. The announcements were also directly mailed to collaborating scientific centres worldwide. All the candidates for the advertised positions were expected to: (1) hold a PhD degree (or equivalent) in physics or a related subject and have received adequate postdoctoral training, (2) have extensive experience in photonics and/or quantum science, (3) have outstanding publication record and (4) be highly motivated (demonstrated via joint publications, references of the candidate's thesis tutor, previous post-doctoral positions different from the PhD awarding institutions). Additional requirements were applied to the new group leader and the two ERC-project candidates. In every contest the applicants were initially formally screened and later evaluated by the Selection Committee. The Selection Committee has been established on January 21, 2013 by the Faculty Council of the Faculty of Physics, University of Warsaw. The committee includes the following faculty members: Katarzyna Chałasińska-Macukow, Rafał Kotyński, Katarzyna Krajewska, Wojciech Pacuski, Czesław Radzewicz (chairman) and Piotr Szymczak.
On January 16th, 2013 the first competition was announced. Four positions were advertised: top-level scientist - **leader for the atto-science group, leader for bio-photonics (biomedical optics) group**, **two experienced researchers in nano-photonics/plasmonics**. The Selection Committee recommended the following employments:

- Dr hab. Yuriy Stepanenko to employed as an assistant professor (in Poland: adiunkt) and a leader of the atto-science group till 31.10.2015,
- Dr Tomasz Stefaniuk to employed as an assistant professor and an experienced researcher in nano-photonics/plasmonics for the period of 02.04.2013 – 31.03.2014,
- Dr Piotr Wróbel to employed as an assistant professor and an experienced researcher
- in nano-photonics/plasmonics for the period of 02.04.2013 – 31.03.2014.

Dr Andrzej Kaźmierczak has been selected to fill the position of the **bio-photonics group leader** pending his successful interview with the Committee. The Selection Committee has decided to recommend Dr Andrzej Kaźmierczak to be employed as an assistant professor and a leader of the bio-photonics group for the period of 01.05.2013-31.10.2015. During his employment in the PhoQuS@UW Dr. Kaźmierczak was awarded in "Mentoring" programme

within the frame of Skills Programe and Impuls Programme both funded by Foundation for Polish Science.
On March 14th, 2013 a contest for the **experienced researcher in the atto-science group** has been announced. Before the deadline set for March 27th, 2013 only one candidate applied: Paweł Wnuk. The Committee recommended Dr Paweł Wnuk for the position of assistant professor and an experienced researcher in the atto-science group starting on May 1st, 2013 and ending on October 31, 2015. Dr Paweł Wnuk has been employed at the position of assistant professor for the period 01.05.2013 – 31.10.2015. On March 25th, 2013 a contest for **2 positions in the field of quantum science** has been announced. 18 candidates have submitted their applications complied with formal requirements imposed in the competition. After negotiations with the candidates Dr Marcin Zwierz has been employed as an experienced researcher in quantum metrology and at the position of assistant professor for a period of 01.11.2013 – 31.10.2015. On November 7th, 2013 a contest for **2 positions in the bio-photonics group** has been announced. On November 20th, 2013 a contest with a deadline set for November 29th for **one position in the field of quantum science** was announced. There were 8 applications from the candidates. On December 10th, 2013 the Selection Committee met to evaluate the candidates from both contests. As for the quantum science position, the Committee recommended employment of Dr Zahra Shadman at the position of assistant professor and the top-level scientist in the field of quantum science. Dr Zahra Shadman was employed as the leader for quantum optics group for the period of 1.03.2014 – 31.10.2015. The Committee has decided to interview one candidate for bio-photonics group: Dr Adrian Knyziak. The Committee decided to recommend Dr Adrian Knyziak to be employed at the position of assistant professor in the bio-photonics group for the period 1.02.2014 – 31.10.2015. On February 24th 2014 a contest for two positions in the **field of optics and quantum science** was announced. Total of 11 eligible candidates submitted their applications. Afterwards on March 7th 2014 a contest for the **position in the field of bio-photonics** was announced. Total of 5 eligible candidates submitted their applications. The Committee recommended employment as for the field of optics and quantum science position of M.Sc. Bardhan (PhD pending summer 2014) and Dr. Rusakov. If the employment of one or both of them does not take place, the Committee recommends employment of the following candidates in following order: Dr Ziaul Hoque and Dr Nellu Ciobanu. As for the field of bio-photonics position, the Committee recommended employment of Dr Simeonika Rangełowa-Jankowska. As Dr Roy Bardhan could not start his employment at the University of Warsaw on 1st July it was decided that Dr Konstantin Rusakov and Dr Ziaul Hoque will be offered the positions. They accepted the offers and were employed starting 1st July 2014. Also, on 1st July 2014 Dr Simeonika Rangełowa-Jankowska was employed and started her work in the biophotonics group. On 17th November 2014 a contest for an adjunct professor (adiunkt naukowy in Polish) was announced to fill the position to be vacated by the end of 2014 by Dr Adrian Knyziak. Dr Adrian Knyziak decided to quit the job on 31st December 2014 under mutual agreement. The position was advertised for an experienced researcher in the field of photonics in life sciences. There were 3 candidates: Dr Ekrem Cicek, Dr Adnan Nazir and Dr Anna Pastuszczak. The members of the Selection Committee were asked to discuss the applicants' qualifications and vote on selection of one of them via internet. Five Selection Committee members voted pointing unanimously to Dr Anna Pastuszczak. As a result of this vote the Committee recommended employment of Dr Anna Pastuszczak. She was employed starting on 1st January 2015. After approving by EC the request for extending the project duration by half a year, on 28th May 2015 the Selection Committee met to discuss professional plans of employed experienced researchers hired for the

project. The Committee evaluated the performance of the researchers. Before the meeting, the Committee members were provided with individual reports prepared by the researchers who worked for the project in May 2015: Dr Ziaul Hoque, Dr Andrzej Kaźmierczak, Dr Anna Pastuszczak, Dr Simeonika Rangełowa-Jankowska, Dr Konstantin Rusakov, Dr Zahra Shadman, Dr Yuriy Stepanenko, and Dr Marcin Zwierz. First, the Committee agreed on the major evaluation criteria: building excellence and strengthening research potential of the FPUW in photonics and quantum science. The specific criteria included, in particular: research results, establishing new research groups, creating new research laboratories and other activities aimed at improving research capabilities of the FPUW. The Committee recommended extension of the employment for the following experienced researchers: Dr Ziaul Hoque, Dr Anna Pastuszczak, Dr Simeonika Rangełowa-Jankowska, Dr Konstantin Rusakov, Dr Yuriy Stepanenko, and Dr Marcin Zwierz. The researchers from the list above had their employment extended by 6 months starting on 1st November 2015. In August 2015 a contest for 3 positions: one in quantum optics, one in atto science and one in biomedical optics was announced. A total of 5 eligible candidates applied: Dr Dardo Goyeneche, Dr Dawid Jankowski, Dr Tomasz Kardaś, Dr David Pastor and Dr Dragos Trinca. The following discussion and vote were carried out via internet during the period 10-14 September 2015. The Committee recommended that the following candidates: Dr Dardo Goyeneche (quantum optics), Dr Tomasz Kardaś (atto science), Dr David Pastor (biomedical optics) should be employed starting 1 November 2015. They were employed as postulated by the Selection Committee. During the period 4-8 November 2015 the Selection Committee voted (electronically) on appointment of new group leaders. Since the employments of Dr Andrzej Kaźmierczak (former leader of the biomedical optics group) and Dr Zahra Shadman (former leader of the quantum optics group) at University of Warsaw were terminated by the end of October 2015 new leaders had to be appointed. After a consideration of the potential candidates' qualifications and a discussion the Selection Committee recommended Dr Marcin Zwierz for the position of the group leader in quantum optics and Dr David Pastor for the position of the group leader in biomedical optics group.

A key objective of this work package was to augment the research capabilities of FPUW in a few selected fields of optics and quantum science by hiring experienced researchers. As was stated in the application the goal was to strengthen our prior expertise in the fields of quantum optics and ultrafast science as well as to foster new research direction - bio-photonics. A more balanced approach towards basic vs applied research was also expected to be achieved.

- A substantial increase in the quality of basic research has been achieved in the field of quantum science both experimental and theoretical. This increase is, probably, best illustrated by the number and quality of research papers published by our faculty members including several publications in the Nature journals.
- New research directions have been created. (1) In collaboration with the Nencki Institute for Experimental Biology of Polish Academy of Sciences, we have started experimental research in opto-genetics. The goal of this research was to study and influence social behaviour of mice by activating or deactivating certain processes in their brains with light pulses. In the Faculty of Physics we have developed a novel and easy to fabricate light source small enough to be implanted in the brain of a free-moving animal. (2) A novel method for numerical recovery of an incomplete signal based on the assumption that the signal has a sparse representation in a certain domain called compressive sensing has been developed. It is believed that the method will be widely applied in life sciences and

medicine in the future. Both numerical modelling and first experiments have been performed and initial results achieved.

- With an exclusive expertise of the researchers hired for the project we have developed unique experimental capabilities in atto-science. A new atto-laboratory has been designed and built from the scratch to the demanding requirements of conducting research in high harmonic laser pulse generation and attosecond pulse generation. The laboratory is equipped with a state-of-the-art laser system and other necessary equipment. It has already drawn attention of researchers from outside – one of them has applied for the POLONEZ grant (funding scheme offered by the National Science Centre) to conduct experimental research in this laboratory.
- In parallel with the development of atto-science capabilities research in ultrafast (femtosecond) optics was carried out. It has resulted in development of novel sources of femtosecond pulses, saturable absorption mirrors for femtosecond oscillators and applications of femtosecond pulses in molecular spectroscopy. Yet another successful application of ultrafast lasers was optical frequency comb technology that has been applied to construction of optical atomic clocks by the consortium consisting of Jagiellonian University, University of Warsaw (as a leader) and Nicolaus Copernicus University.

WP3 was realized through seven tasks:
TASK 3.1: Purchase of a set of three research grade cameras;
TASK 3.2: Purchase of a laser pulsed source with octave-spanning spectrum;
TASK 3.3: Purchase of a tunable source of femtosecond laser pulses;
TASK 3.4: Purchase of a femtosecond laser system;
TASK 3.5: Purchase of a Scanning Electron Microscope with a resolution of 3.0nm or better;
TASK 3.6: Equipment start-up funding for the new group in Biomedical Optics;
TASK 3.7: Recruitment and supervision of engineers.

Within Task 3.1 the set of three research grade cameras, consisting of iXon Ultra camera with EMCCD detector, X-ray detector consisting of a two-stage microchannel amplifier and very fast sCMOS camera was purchased through an open, state-advertised (commensurate with the estimated cost) tender procedure. The set of three research grade cameras has been used in a number of successful experiments with characterization of spatially multimode quantum light. In these experiments the microchannel intensifier is relayed onto a fast sCMOS camera with a suitable lens. Record breaking readout speed of the camera enables gathering enough statistics to sense the subtlest of single photon properties for the first time.
The results were published in a number of high-profile papers:

- M. Jachura, R. Chrapkiewicz, "Shot-by-shot imaging of Hong–Ou–Mandel interference with an intensified sCMOS camera", Optics Letters 40, 1540-1543 (2015).
- M. Jachura, R. Chrapkiewicz, R. Demkowicz-Dobrzański, W. Wasilewski, K. Banaszek, "Mode engineering for realistic quantum-enhanced interferometry", Nature Communications **7**, 11411 (2016).
- R. Chrapkiewicz, M. Jachura, W. Wasilewski, K. Banaszek, "Hologram of a single photon", Nature Photonics **10**, 576–579 (2016).
- M. Dąbrowski, R. Chrapkiewicz, and W. Wasilewski, Magnetically tuned, robust and efficient filtering system for spatially multimode quantum memory in warm atomic vapors,

DOI:10.1080/09500340.2015.1106016, Journal of Modern Optics, Special Issue: Quantum Memory

Within Task 3.2 The purchase a laser pulsed source with octave-spanning spectrum was made through an open European tender according to public purchase regulations. The apparatus had to be specially customized to suit aforementioned demands. During the production phase, the representative of the purchaser was invited to Coherent headquarters (Santa Clara, USA) for a factory acceptance. Together with Coherent's engineers they were able to tune and tweak the setup to exactly meet elevated requirements. In the process stability was improved by 50%, virtually creating a new standard. The purchase of this source as well as of the other equipment from PhoQuS@UW project upgrades the FPUW research infrastructure. The source is meant to seed a regenerative amplifier. The amplified pulses will exhibit unique combination of parameters: pulse duration of 25 fs, world best carrier envelop stability for commercially available regenerative amplifiers (<200 mrad) and very high stability energy stability (<0.5% RMS). The source has been installed in its final location. It has been integrated with other parts of the setup in a dedicated attosecond laboratory. The source is equipped with carrier envelope stabilization electronics required for generation of attosecond pulses. We also integrated the octave spanning laser into the existing Ti:Sapph amplification chain. In order to conduct high harmonics/attoseconds generation experiments we designed and ordered a custom made vacuum chamber. The chamber was successfully installed in a newly built attosecond laboratory. Most of the experiments in attosecond field involve two laser pulses acting as pump and probe beams. Optimal spatiotemporal overlap the pulses requires interferometric stability of the laser system and optical elements in the beam path. Much attention was paid to lower vibrations of the optical table installed inside the vacuum chamber. We designed and built special vacuum decoupled leg mounts in order to separate the vacuum producing equipment from octave spanning laser source. This allowed us to install turbomolecular vacuum pumps with much higher performance without compromising the optical stability of the system. It is now routinely used to characterize the entire setup and run test measurements. The octave spanning spectrum source has been integrated with the amplifier chain and a hollow core fiber setup is responsible for generation of single cycle pulses around 800 nm. After careful alignment and optimization of the octave spanning laser source we were able to stabilize the carrier envelope phase of the amplified pulse to less than 180 mrad.

The tunable source of femtosecond laser pulses was delivered in December 2013 within Task 3.3. The source has been installed in its final location. It has been integrated with other parts of the setup in a dedicated attosecond laboratory. Together with laser source mentioned in Task 3.2 and equipment bought from other sources it enabled construction of a setup for generation of attosecond pulses of light. Moreover, tunability of the source opens new ways in the atomic spectroscopy on attosecond scale. It allows us to selectively excite different atomic and molecular transitions and probing the electrons movements on the attosecond timescale. This ability increases the quality of the scientific research conducted in the FPUW.

The femtosecond laser system has been purchased within Task 3.4 as a key component for the spectral-temporal manipulation of quantum light project which is carried out in the Quantum Photonics Laboratory. After a detailed analysis of technical, theoretical and experimental aspects of the planned activities technical requirements for the system have been determined. The analysis was done with Dr Karpiński, who moved from UK to Warsaw and coordinated the purchase process. Thanks to his partaking in the process, the system is equipped optimally

for the tasks given the resources available and will enable top notch science. The system is required to provide capability to both generate quantum light at telecommunication wavelengths and provide its diagnostics in terms of both spectral and photon number statistics. It comprises a highly stable dual wavelength (1560 nm and 780 nm) pulsed femtosecond oscillator, for pumping sources of photon telecommunication band photon pairs with the 780 nm, with the 1560 nm beams serving as a phase-locked local oscillator and alignment beam. Adjustable repetition rate is required to allow synchronization with other laser or electronic systems, as well as potential future expansion to a frequency comb system. For photon counting diagnostics the key characteristics are high quantum efficiency (>70%), low noise (< 300 Hz) and timing characteristics. For the foreseen research the latter characteristic is especially important, with the value of timing jitter below 50 ps required. A low noise, high resolution optical spectrum analyser completes the system, providing spectral characterization capabilities. The system was delivered following an open European tender according to public purchase regulations. The system has been installed and tested in the Quantum Photonics Laboratory. The purchase of the system creates a basis for state-of-the-art research in the field of spectral engineering of quantum light to be carried out at FPUW. Therefore it forms a key upgrade of the FPUW research infrastructure. The equipment has been demonstrated to visiting researchers, Dr Bentivegna, Dr Brecht and Dr Lavoie and to participants of SSEQL'16 workshop. Current as well as possible future experiments have been discussed. In particular Dr Bentivegna used his experience in photon counting detectors to assist in first measurements using the single photon counting detectors. Dr Brecht assisted in optimizing a pulse shaping device for the femtosecond laser system. Dr Lavoie assisted in performing data acquisition with the newly acquired single photon counting detectors. The equipment have already been used in successful experiments. The potential to carry out original research using the purchased equipment is illustrated by the article M. Karpiński, M. Jachura, L. J. Wright, B. J. Smith, "Bandwidth manipulation of quantum light by an electro-optic time lens", Nature Photonics (2016), DOI: 10.1038/nphoton.2016.228. Subsequent manuscripts are currently being written: "Second harmonic generation in femtosecond-written waveguides in KDP" in collaboration with Dr Salter from Oxford, "GHz-bandwidth heralded single photon source for broadband quantum memories" in collaboration with Dr Nunn from Oxford, "Spectral shearing of quantum light pulses by electro-optic phase modulation" and "Pulsed visible single-photon spectrograph by frequency-to-time mapping using chirped fiber Bragg gratings" with Dr B. J. Smith from Oxford.

Within Task 3.5 the Scanning Electron Microscope (SEM) suitable for fabrication and characterization of nanooptical and plasmonic structures was purchased through an open European tender. A system of field emission type equipped with secondary electron detector, ring, sectorial detector of backscattered electrons and Everhart-Thornley Detector was specified for this purpose. Starting from the beginning of April 2014 the microscope is used in research with the aim to design and fabrication of a nontransparent cathode for thin film solar cell. The cathode is fabricated on glass substrate covered with photoresist where sets of angularly oriented gratings are recorded. During the project duration the electron microscope Zeiss Sigma was used in studies of optical properties of silver nanolayers. E-beam evaporated thin films have a tendency to form clusters rather than smooth layers. The uniformity, the smoothness and the surface resistivity of e-beam evaporated silver films depend on applied wetting interlayers and proper choice of deposition temperature and rate. Different wetting layers such as Ge, Ni, Ti allow to control scattering and ohmic losses in Ag films. Germanium, which reduces

scattering losses the best, segregates to Ag film and increases ohmic losses. Germanium atoms segregate to such defects in evaporated Ag films as free surfaces, grain boundaries, and interfaces between different phases or dislocations. In a recent research performed together with the PhoQuS@UW partners from the University La Sapienza in Rome we demonstrated that due to segregation of germanium atoms to silver grain boundaries, a smooth silver layer might become a metamaterial itself. This system exhibits such effects as localised plasmon resonances on encapsulated grains and extraordinary second harmonic generation.

Within Task 3.6, after employment of Dr Andrzej Kaźmierczak, leader of newly established biomedical optics research group, planning and execution of equipment purchases for a group has begun in parallel. According to Annex I the equipment was to be chosen by the group leader recruited after the start of the project. Leaders of WP2 and WP3 considered the provisional plans put forth by Dr Kaźmierczak to be justified. This is in accordance with the description of Task 3.6 in Annex I, which makes the specifications dependent on the planned research programme. Within this task following equipment was bought:

- NIR Camera Bobcat 640-GigE with thermoelectrically cooled InGaAs detector designed for shortwave infrared.
- Tunable laser system working in 1300 nm band and 1550 nm band – manufactured by Yenista Optics, composed of a mainframe (type OSICS) and two external cavity tunable laser modules with accessories.
- NIR detection system with optical zoom and set of microscopic objectives and accessories.

All the above acquisitions enabled construction of an experimental setup for characterization of multichannel integrated photonic structures (being the backbone of photonic multichannel Lab-on-a-Chip sensors – a key scientific area of interest of the group).

NIR Camera Bobcat 640-GigE with thermoelectrically cooled InGaAs detector designed for shortwave infrared has been integrated with a monochromator and enabled construction of near-infrared spectrofluorometer for characterization of longwave fluorescence of custom designed and synthesized chemicals. The measurements made with this setup were instrumental in a number of experiments. The results were published in a number of high-profile papers:

- P. Ciąćka, P. Fita, A. Listkowski, C. Radzewicz, J. Waluk, Evidence for dominant role of tunneling in condensed phases and at high temperatures: Double hydrogen transfer in porphycenes, J. Phys. Chem. Lett.7, 283-288 (2016)
- P.Ciąćka, P.Fita, A.Listkowski, M.Kijak, S.Nonell, D.Kuzuhara, H.Yamada, C.Radzewicz, J.Waluk, Tautomerism in porphycenes: Analysis of rate-affecting factors, J. Chem. Phys. B 119, 2292-2301 (2015)

Further pieces of equipment necessary for the research as light sources and detectors were purchased according to the needs of the planned research. These pieces of equipment consisted of two complementary sets: tunable laser system working in 1300 nm band and 1550 nm band and NIR detection system.

Tunable laser system working in 1300 nm band and 1550 nm band – manufactured by Yenista Optics, composed of a mainframe (type OSICS) and two external cavity tunable laser modules with accessories. The laser system of this type together with suitable detection system (see below) is a workhorse enabling characterization of modern photonic microstructures, biophotonical in particular. However, the system is modular and has to be equipped with right accessories for particular tasks. The funding albeit generous did not allow to buy optical interfaces, optomechanics, etc. of every available type. Therefore it was decided to start with a basic system and as the research progresses to carefully identify the missing pieces and acquire

them. This way an optimal system is finally constructed as its operation is indeed successfully achieved. The tunable 1550nm laser system was used to characterize ring resonators, key ingredient of Lab-on-a-Chip sensors. Resonators together with surrounding photonicals namely coupling prisms and waveguide were manufactured using 3d 2-photon laser lithography. The investigation led to positive verification of the function of all components. The above research was complemented by a construction of ultraprecise femtosecond-pulse based subtractive manufacturing device. It has been assembled from universal components and will enable post processing of Lab-on-a-Chip sensors. The laser system is complemented by the NIR detection system with optical zoom and set of microscopic objectives and accessories.

In addition, examination of biooptical chips as examples of feasible integrated optics structures have led FPUW researchers, Konrad Banaszek and Michał Jachura, with active participation Michał Karpiński, then a guest Researcher of the PhoQuS@UW project, to conceive a novel scheme for on-chip generation and verification of quantum entanglement. This interesting idea was further elaborated in a successful collaboration with the leading fibre-optic specialist who has an extensive experience with modelling such structures. This unique cooperation enabled incorporating the idea electro-optic modulation, an effect which has leading role in such applications as ultrabroadband communication which in conjunction with biooptics may enable real time diagnostics. The results were published in Optics Express 23, 33087 (2015), doi: 10.1364/OE.23.033087.

New experimental infrastructure obtained thanks to FPUW project stimulated also research into new modes of highly efficient optical communication, especially in the regime of low average power. In such a regime, for standard keying schemes there is a scaling gap between individual and collective detection of incoming symbols. To benefit from the latter, it is necessary to design entire sequences for efficient encoding of classical information. Examination of a prominent example of such a scheme in the presence of phase noise demonstrated robustness of the nonlinear scaling with the mean photon number. The theoretical results have been published in Optics Express 24, 1693-1698 (2016), doi: 10.1364/OE.24.001693.

The newly acquired parts were enabled experimental trials with possible biochip-based receivers and mode engineering enabled by the use of biochip structures. The trials led by Konrad Banaszek, Michał Jachura and Wojciech Wasilewski were crucial for certifying validity of particularly involved theoretical approaches. The approaches in question are at the very forefront of science where biology meets with fundamental quantum optics (e.g. in biosensing) and may jointly produce future original results. In the peer review process the FPUW team of scientists was asked to reinforce their claims with additional experimental observations. Thanks to recent acquisitions made possible by the PhoQuS@UW the team was well prepared to address this challenge. With rebuild source and detection system we were able to fully answer the reviewer’s comments. This effort enabled acceptance of two articles and providing answers to complicated questions in the case of two more manuscripts which are at the moment back with the editor. The crucial steps involved experimental verification of properties of tiny biochip structures observable only with newly purchased equipment. One article has been published in Nature Communications (available online at doi:10.1038/ncomms11411) the other one in Journal of Modern Optics (preprint version available at arXiv:1512.06561). The other two manuscripts are considered by the editors of Physical Review A (arXiv:1512.00385) and Nature Photonics (arXiv:1509.02890). Finally the new equipment also enabled verification of

purely quantum statistical nature of multimode quantum memories. The experiments were performed in Wojciech Wasilewski laboratory entirely relying on newly acquired parts. The results are available as an open access preprint (arXiv:1604.06049).

One of the activities of WP3 was to hire professional engineers (Task 3.7). Due to the vast subject area of experimental research in FPUW a large diversification of specialties requirements for candidates was necessary. Open competitions were organized. Information about the open position was published on the webpages of the University of Warsaw and of the PhoQuS@UW project as well as on Euraxess portal. Two candidates, Dr. Eng. Paweł Kopyt and Dr. Eng. Marcin Piasecki answered the announcement. The engineer - Dr Eng. Marcin Piasecki was hired half-time as a senior scientific-technical specialist in the Division of Optics of the Institute of Experimental Physics. The engineer - Dr Eng. Paweł Kopyt was hired half-time as a senior scientific-technical specialist in the Division of Optics of the Institute of Experimental Physics. However, Dr Eng. Paweł Kopyt decided to quit the job on March 31, 2014 under mutual agreement. At the same time Dr Eng. Marcin Piasecki agreed to work full-time. Due to the extension of the project the employment of Dr Eng. Marcin Piasecki has been prolonged. However M.Sc. Piotr Skibiński decided to move abroad. Therefore on the 27.07.2015 another competition for the still vacant second engineer position was announced. M.Sc. Radosław Chrapkiewicz was hired full time in the Division of Optics of the Institute of Experimental Physics at FPUW as a senior technical specialist, starting from 02/11/2015 for the duration of the Project. On the 17.06.2013 another competition for the still vacant second engineer position was announced and M.Sc. Piotr Skibiński was hired full time in the Division of Optics of the Institute of Experimental Physics as a senior technical specialist. Engineers started to work on systems extending the capabilities of the lasers and cameras purchased tailored to the typical experiments that are to be performed. Dr Eng. P. Kopyt and Dr Eng. M. Piasecki focused on developing of very fast, reconfigurable digital signal processing platform centered around FPGA. The system was defined modular and so engineered that various peripheral ADCs, DACs, DDS and other devices can be connected directly on their evaluation boards. The central FPGA was equipped with very fast USB3.0 interface. The primary and most demanding application of the platform is multi-MHz bandwidth feedback loops which defined the bandwidth of various interconnects. However with little reconfiguration this hardware can be applied to experiment control, including fast arbitrary waveform generation, data acquisition, sophisticated real time feedback or reconfiguration and others. In addition it will offer a very attractive learning platform for scientist, including computer science specialists who take part in our projects in increasing numbers. The platform has been integrated with systems purchased in Task 3.1—3.4. Dr Eng. Marcin Piasecki was also working on: design and prototyping of ultrafast photodiode with microwave amplifier for electro-optical synchronization and prototype improved interface for DDS synthesizers. A prototype system with USB3.0 interface capable of controlling multiple standard submodules was build. The project M.Sc. P. Skibiński focuses on aims at developing an interconnect allowing for integration of arbitrary pieces of equipment, including but not limited to, photodiodes, ADCs, beam-stabilization devices, delay generators, into one apparatus with arbitrarily defined interdependencies. This system is based on CAN standard and various interconnects, such as USB-CAN converter, are being developed. The resulting devices has been integrated with systems purchased in Task 3.1—3.4. In addition M.Sc. P. Skibiński offered his camera expertise during the installation and use of research cameras bought in Task 3.1. M.Sc. Piotr Skibiński worked also on extending the research potential of the purchased laser sources. The devices constructed by him led to streamlining of

the research in the entire laboratory. The following devices were constructed: devices for continuous monitoring of the laser microclimate conditions, custom remote controlled high voltage power supply and delay generators for the Pockels cells, very low noise power supplies optimised for photodetectors. In addition the software for optimal integration of the above devices was developed. M.Sc. Radosław Chrapkiewicz worked on fast sCMOS camera. He developed suitable software and hardware enabling use of camera in advanced quantum experiments. He also developed optomechanical elements for those experiments. In particular he made a number of elements necessary for development of cold-atoms setup which is now being assembled and will soon replace warm atomic cells in quantum memories laboratory.

WP4 was realized through three tasks:
TASK 4.1: Hiring a professional innovation manager, building innovation capacity, and promoting collaboration between science and industry
TASK 4.2: Preparation, design and maintenance PhoQuS@UW webpage; preparation and publication of the PhoQuS@UW Newsletter
TASK 4.3: Raising the public awareness of the science and encouraging science careers

Task 4.1 of the PhoQuS@UW Project aimed at establishing close cooperation with high-tech small or medium enterprises (SMEs) and industrial companies operating in the Mazovian Region. The ultimate goal is economy growth and sustainable regional socio-economic development. Several events organized at the FPUW the project created an interest in innovation driven research. This evolutionary thinking was supported by contacts with such innovation oriented institutions as: OPTOKLASTER - Mazovian Photonic Technology Cluster, the BioTechMed Cluster and BTM Mazowsze - a non-profit company supporting commercialization of research results.

The Innovation Managers, Dr Radosława Bach and Dr. Cezary Samojłowicz were employed in the Division of Optics of the Institute of Experimental Physics, Faculty of Physics, University of Warsaw (FPUW) as a chief specialists. Dr. Cezary Samojłowicz, implemented at FPUW IPR protection and management guidelines. Dr Samojłowicz performed very well as a “technology broker” – a link between the FPUW research staff and University Technology Transfer Centre (UOTT) and Centre of New Technologies (CeNT). He was very active in stimulating patent applications etc. by the researchers from the FPUW. Noteworthy is that he also won participation in the very prestigious and competitive programme “Top 500 Innovators” run by the Polish Ministry of Science and Higher Education. As one of results of activities of Innovation Managers the booklet “Patenting in science – a practical guide” (Patentowanie w naukach matematyczno-przyrodniczych – praktyczny przewodnik) was published. On an approximately one hundred of pages a short overview is given of the intellectual property law, patenting procedures, followed by several patent examples. The publication has been distributed among researchers of the Faculty of Physics.

Within Task 4.1 several meetings and workshops were organized: 3 meetings of Innovation Committee, 2 workshops for Mazovian industry, 1 workshop on patenting of inventions in natural sciences and mathematics, 5 Open days for industry and 3 on-site meetings.

The meetings of Innovation Committee, apart from permanent IC members, were attended by the representatives of industry (Marek Daszkiewicz - OPTOKLASTER Mazovian Photonic Technology Cluster, Dariusz Kołoda – CEO of the spin-off company Innovation Hub) and

alumni of Top 500 Innovators program (Piotr Nyga from Military University of Technology (MUT) and Dariusz Kołoda), as well as by the Jakub Włodarczyk - one of authors of the Polish National Road Map for Research Infrastructures in Biomedical Imaging, who also is a partner in Euro-BioImaging – a large-scale pan-European research infrastructure project on the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap.

The first workshop for Mazovian industry was focused on targeting at bringing the business partners and scientists together. The workshop attended about 40 persons, a number of presentations were held as well as discussion, both in public and in a more informal atmosphere. The second workshop for the Mazovian industry was focused on presenting research and technologies developed at FPUW to the industry partners. Four presentations on recent results of research were followed by informal meeting during coffee breaks and lunch. Presentation of Anna Pastuszczak resulted in business talks with a company Kubara Lamina during the 5th Open Day for industry (see below). Talk by Paweł Wnuk has attracted attention of representatives of Astri Polska Ltd. (see below).

The workshop on patenting of inventions in natural sciences, mathematics was organized on 17 June 2013. The workshop, entitled "Patents in natural sciences" was conducted by an experienced patent attorney, Dr Jakub Sielewiesiuk (AOMB Polska, Intellectual Property Consultants). Two patents and five patent applications were developed under PhoQuS@UW project. The patent application owner is the University of Warsaw.

"Open Days" were organized five times. Representatives of Płock Industrial and Technological Park, Astri Polska Ltd. (joint venture of Airbus Defense & Space and the Space Research Centre, Polish Academy of Sciences, established by the Airbus Group), SAULE Technologies Ltd., InPhoTech Ltd. and Kubara Lamina S.A. The representatives of Astri Polska and FP UW have exchanged information on projects founded by European Space Agency (ESA) that were of interest for Iwona S. Stachlewska (FPUW), coordinator on the national level of H2020 project entitled "Development of a European high-spectral-resolution lidar airborne facility" of duration 2014-2017. The representative of SAULE Technologies Ltd., involved in research on photovoltaic cells on perovskites, was physicist Olga Malinkiewicz. n research contacts participated Piotr Piątkowski from the Faculty of Chemistry UW. The visitors form InPhoTech Ltd., Tomasz Nasiłowski and Marek Napierała, were interested in photonic fiber technologies developed at the FPUW and in particular in research on waveguides for telecommunication spectral ranges. Yuriy Stepanenko has accepted a proposal of collaboration. Representatives of Kubara Lamina S.A., Mariusz Błażejewicz and Dariusz Baczewski, were interested in collaboration on design and fabrication of innovative multilayer absorbers of microwaves in the range 1-10 GHz that may replace imported ceramic absorbers. Invitation was initiated by Mr Błażejewicz who attended the Symposium of Young Researchers organized at FPUW on May 20th 2015 had a possibility to hear the talk of Bartosz Wieciech, student at the Information Optics Laboratory FPUW, on modelling and optimization of electromagnetic absorbers.

Two on-site meetings were organized for PhoQuS@UW partners from the Department of Basic and Applied Sciences for Engineering at Sapienza University of Rome. During the first visit Tomasz Stefaniuk and Tomasz Szoplik together with guests planned innovative high-tech project connected with design and fabrication of plasmonic Ag-Ge metasurfaces for second harmonic generation. The program of the third on-site consisted of four presentations. Lecture

entitled “Research management at the University of Oxford” was delivered by Dr Michał Karpiński. Michał Karpiński. Another talk by Dr Karpiński on “Research management at the University of Oxford” was followed by an informal discussion with workshop participants on administrative support of innovations at Oxford University, Oxford’s policy on research management and commercialization of results, and management of research data. Local point of view was presented by Dariusz Smoleń gave a talk titled “From an idea to market – how to commercialize results of a scientific project.” Dariusz Smoleń is an entrepreneur and business development manager at the Bio-Tech-Med Cluster Mazovia (www.btm-mazovia.pl). Three his collaborators gave short presentations on their cooperation with recently organized three spin-offs. The hands-on workshop attended by representatives of Mazovian industry and business was completed with two presentations on recent research at the FPUW. Radosław Chrapkiewicz gave a talk on constructing “Camera with image amplifier for imaging in nearly complete darkness.” Anna Pastuszczak – assistant professor at Biomedical Optics Group of PhoQuS@UW project talked on “Applications of compressive sensing.”

Within Task 4.2 the webpage was created by Dr. hab. Rafał Demkowicz-Dobrzański – Task 4.2 leader. The webpage has been launched to disseminate and promote the achievements in photonics and quantum science at the UW within the European Research Area community. There are two versions of the webpage: in Polish http://phoqus.fuw.edu.pl/ and in English http://phoqus.fuw.edu.pl/en/. Polish version of the webpage was addressed to Polish optics, photonics and quantum optics communities and aimed at dissemination and promotion the achievements of the project. English translation of the webpage was distributed among the European Research Area optics communities. The webpage is composed of six navigation links: project, research, partners, events, innovation and jobs/staff. In the research part there is information on Groups involved in the project and their recent important publications. The other website tabs contain information on everyday activities of the project, added regularly.: seminars, workshops, lectures, conferences, trainings courses etc. The webpage contained two intranet parts used for the purposes of project management. One of them was public and available for all faculty staff while the second part available only for registered projects leaders contained project’s forms and documents. At the beginning of 2016 graphic design of the webpage was adjusted to the new, obligatory visual identity of University of Warsaw, introduced in autumn of 2015.

During the project realisation six issues the PhoQuS@UW Newsletter have been published. The major objective of the newsletter is to provide staff of other scientific institutions with the information about PhoQuS@UW project and on other research projects realized at the Faculty of Physics. The first newsletter was distributed via e-mail among 240 European physicists. Among the recipients are researchers from the Partner institutions, physics departments of Polish universities and other research partners of the groups involved in the project.

In the scope of Task 4.3 Faculty of Physics UW with close cooperation with mass media popularised and promoted research in physical sciences and increased the visibility of the physics community the public. A variety of high quality and well recognized promotional materials - posters and banners - were distributed among the participants of several events organized within the scope of the project activities. Main dissemination activities are described in chapter 4 (Potential impact and the main dissemination activities and exploitation of results).

After so many occurrences, promotional posters and banners of the PhoQuS@UW project became popular, approved and attracting attendees who were interested in all branches of modern optics. To enhance the project visibility a lot of promotional materials was distributed among participants of events. These were well-designed folders, ball pens, optics kits, pencils, touch pens, lanyards, bags, key-rings and pendrives. At the beginning of 2016 the project promotional materials were adjusted, to the new, obligatory visual identity of University of Warsaw introduced in autumn of 2015.

A large number of scientific journals offer Open Access option, which means that published articles can be accessed by the public without subscription. Thanks to Open Access option, these articles are freely accessible to science journalists and general public interested in science, thus increasing the popular impact of research activities at FPUW. The PhoQuS@UW project covered the cost of the Open Access option for articles published by FPUW researchers in the area of photonics and quantum science. They were:

- Scheme for on-chip verification of transverse mode entanglement using the electro-optic effect; D. Bharadwaj, K. Thyagarajan, M. Jachura, M. Karpiński, K. Banaszek; Optics Express Vol. 23, Issue 26, pp. 33087-33098 (2015) doi: 10.1364/OE.23.033087
- Magneto-optical polarization rotation in a ladder-type atomic system for tunable offset locking; M.Parniak, A. Leszczynski, and W. Wasilewski; APPLIED PHYSICS LETTERS 108, 161103 (2016); http://dx.doi.org/10.1364/OE.24.001693
- Magnetically tuned, robust and efficient filtering system for spatially multimode quantum memory in warm atomic vapors; M. Dąbrowski, R. Chrapkiewicz, W. Wasilewski; Journal of Modern Optics; ISSN: 0950-0340 (Print) 1362-3044 (Online) Journal of Modern Optics: http://dx.doi.org/10.1080/09500340.2015.1106016
- Quantum memory receiver for superadditive communication using binary coherent states; A. Klimek, M. Jachura, W. Wasilewski, K.Banaszek; ISSN: 0950-0340 (Print) 1362-3044 (Online) Journal of Modern Optics: DOI: 10.1080/09500340.2016.1173731
- Mode engineering for realistic quantum-enhanced interferometry; M. Jachura, R. Chrapkiewicz, R. Demkowicz-Dobrzański, W. Wasilewski, K. Banaszek; NATURE COMMUNICATIONS 7:11411 (2016); DOI: 10.1038/ncomms11411 www.nature.com/naturecommunications
- Phase noise in collective binary phase shift keying with Hadamard words; M. Jarzyna, V. Lipińska, A. Klimek, K. Banaszek, M.G. A. Paris; Optics Express, Vol. 24, Issue 2, pp. 1693-1698 (2016) doi: 10.1364/OE.24.001693

In **Work Package 5** a Professional Project Manager was recruited for the duration of the project to assist the Project Coordinator (PC) with running PhoQuS@UW. Lidia Tańska was employed in the Institute of Theoretical Physics, Faculty of Physics UW, as a chief specialist, starting from 1st Dec. 2012. The recruited Project Manager (PM) provided support not only for the PC but also for the research staff of FPUW, too, in assuring flexible coordination of individual WPs, optimising the interaction between the FPUW, the partnering institutions and EC. The Project Manager was responsible for administrative and financial (with the assistance of the Faculty of Physics and University of Warsaw support services) execution of the project. Additionally Dr Lidia Tańska was responsible for organization of the financial audits.

Moreover one of the tasks of PM was to seek out new opportunities, more effective application for research projects under the 7th and Horizon 2020 Framework Programmes within the Cooperation and pillars. Fulfilling these aims Dr Lidia Tańska actively participated as an

associate member of Krajowa Rada Koordynatorów Projektów Badawczych UE - KRAB in symposia, participated in Information Days, conferences organised by the Ministry of Science and Higher Education, in 2014, workshops organized by National Contact Point and Ministry of Economy and European Commission. Another opportunity to exchange know-how and experience in project management were the visits other research institutions where the project similar REGPOT projects has been carried out. Acquired best practices were implemented in managing procedures in FPUW. Good opportunity for Project Manager to share management practices, know-how and experience in project management was participation in the Symposium "Experience of the REGPOT-PL projects in improving competence in the future EC projects' management" which took place at Warsaw University of Life Sciences on March 2014. The attendance in workshop was a good opportunity to start co-operation with other REGPOT projects, which is effected by exchange of experiences.

The Project Manager was aided by a part-time management assistant. The scope of assistant's work included: collecting materials for the periodic reports and to the financial statements, preparation of regular statements of project costs, allocation of project costs into thematic groups, analysis of the cost of travel of FPUW employees and researchers from partnering institutions, organization of travel of the International Advisory Board members and the Experts appointed by the European Commission, support of organization of projects meetings and scientific events, i.e. conferences and workshops, etc. It is worth noting that all events were supervised by the PM who reported to the PC.

The PhoQuS@UW project management structure was designed to maximise the prospects of meeting the projects overall goal and its operational objectives. Project management tasks were aimed at reaching the optimum performance of project deliverables and expected outcomes to resources consumed. In this case, the resources involve human power (person-months) and financial means in order to achieve efficient execution of the project and expected impacts.

The Coordinator with constant assistance from the Project Manager and the support services at FPUW and UWAW monitored the progress of project execution. As the University and Faculty leaders assured the administrative and technical personnel of the University and Faculty as well as other resources being under the Faculty's management were sufficiently engaged in the Project's execution. FPUW and the Project Coordination Committee ensured means for efficient information exchange with collaborative partners and the European Commission.

The Project Manager prepared all project meetings, starting from a kick-off meeting. During the kick-off meeting the overall strategy and implementation of Action Plan were presented to a broader FPUW community with the detailed supporting actions planned. The first IAB meeting took place during the kick-off meeting. The meeting was opened by Prof. Marcin Pałys, the Rector of the University of Warsaw. During the kick-off meeting the overall strategy and implementation of Action Plan of PhoQuS@UW project were presented. The kick-off meeting allowed also detecting possible bottlenecks in the execution of the project. The second meeting of the International Advisory Board took place in Warsaw on 29th July 2014. It was attended by the members of IAB and the staff of the Faculty of Physics involved in the project. During this meeting the international committee of leading scientists reviewed the overall progress towards fulfilling the project objectives and provided guidance as to their most effective implementation especially in terms of attracting, developing and retaining top scientists at the FPUW. They also provided feedback to the Faculty leaders on strategy and suggestions for

developments in the area of PhoQuS research and technologies. The final project meeting took place on 12th-13th October 2016 in the University of Warsaw. The first day of the meeting was devoted to the presentation and discussion of the evaluation report and the meeting of PC, PM, WP6 Leader with external experts and IAB. During the second day evaluation results were presented to broader group of stakeholders along with the discussion on the future perspectives of Photonics and Quantum Science.

To assure efficient and professional management of PhoQuS@UW and to integrate the research community and services supporting management and administration of projects were monitored the progress of respective Work package by communicating and holding meetings. The daily supervision, monthly meetings with WP leaders and verification of achieving milestones and deliverables, made the Coordinator and Project Manager swiftly aware of any potential disruptions in project implementation. The day-to-day project management runs at two levels: Work Package and the general management of the Project. The Project Coordination Team, comprising of all WP Leaders, Task Leaders, the Innovation Manager and the Coordinator and Project Manager meet quarterly or more frequently while preparing progress, deliverable or periodic reports to the commission. Additionally the day-to-day project management run by exchange of information via e-mails, intranet portal or daily direct meetings with WP Leaders, Task Leaders and the other employees involved in the project.

The one of day-to–day meetings was arranged during the Mini-symposium and workshop: "Experience of the REGPOT-PL projects in improving competence in the future EC projects' management" in March 2014, which provided an opportunity for a meeting with Project Officer. The visit on the premises of the Faculty of Physics, University of Warsaw and discussion the progress of the ongoing REGPOT project PhoQuS@UW were especially important due to the end of the first reporting period in April 2014.

To fulfil goals of WP5 and to raise visibility of the project as a whole was required to create, select and made public the sign recognizable of the project which be used in information and knowledge management, dissemination of results in all aspects of PhoQuS@UW project and to prepare templates of projects documents and reports. A contest for the Project logo was published in the end of December 2012. On January 24 result of the contest on logo was published.

The Coordinator provides European Commission with periodic reports to guarantee efficient communication and easy monitoring of the project progress by the European Commission. Periodic Reports and the relevant financial reports were submitted to the European Commission as planned in Annex I.

Work Package 6 has been commenced in accordance with the Annex 1 in May 2014 (Month 19). The experts were selected by the European Commission at the beginning of 2015. The Experts accordingly to the Annex 1 were obliged to visit FPUW three times during the duration of the project. Taking into account extension of the project and the Annex 1 schedule the first ex-post Evaluation Panel Meeting took place at the FPUW on 15th and 16th of July 2015 (Month 33), the 2nd Ex-post Evaluation Panel took place on 14th – 15th April 2016 (Month 42 = 36 plus 6 months-prolongation of the project). The experts nominated by the European Commission were: Prof. Vladimír Bužek (Slovak Academy of Sciences), Prof. Nikolay Vitanov (Sofia University), and Dr. Argiris Laskarakis (University of Ioannina).

The first evaluation meeting was attended by representatives of the authorities of the University and the Faculty, as well as the personnel involved in the project. At the beginning Konrad Banaszek made a short introduction into the general context of PhoQuS@UW project which plays an important role in integrating efforts carried out at the Faculty of Physics in the area of Photonics and Quantum Physics into the European research landscape. During the meeting the representatives of the authorities presented to the experts state of development of research, employment, infrastructure, etc. It was discussed in detail the status of the project, especially in relation to general development plans at the University of Warsaw. Afterwards the leaders of individual work packages presented progress in the implementation of the project. The second day of meeting was dedicated to research achievements made possible thanks to the support of the project.

The 2nd Ex-post Evaluation Panel took place on 14th – 15th April 2016 (Month 42 = 36 plus 6 months-prolongation of the project. The meeting was attended by the experts nominated by the European Commission and the FPUW personnel involved in the project. At the beginning Konrad Banaszek made a short introduction into the PhoQuS@UW project status update and evaluation schedule. During the meeting the presentations on topics : *The overview of project innovation activities* were delivered by Cezary Samojłowicz, Piotr Wasylczyk, Yuriy Stepanenko and Radosław Chrapkiewicz. The status of the innovation activities which thanks to project appeared in FPUW has been reviewed. The second part of the meeting was dedicated to new research directions initiated during the project. The final part of the meeting was dedicated to topics: *Overview of current funding initiatives. How to preserve institution's excellence and ensure its contribution to regional/European sustainable development?; Discussion on national and regional strategies. Preparations for the final ex-post evaluation visit and involvement of broader groups of stakeholders*. The meeting closed laboratory tour at FPUW premises where new research systems created with the support of the project were presented.

The third Ex-post Evaluation Panel took place on 12^{th} – 13^{th} October 2016, during the third reporting period (Month 48 = 42 plus 6 months-prolongation of the project). It was organized along with the presentation of the evaluation report to a broader group of stakeholders. The first day of the meeting was devoted to the presentation and discussion of the evaluation report and the meeting of the project coordinator, the project manager, and the WP6 Leader with external experts and International Advisory Board (IAB). During the second day evaluation results were presented to a broader group of stakeholders including the IAB members along with the discussion on the future perspectives of Photonics and Quantum Science in the entire region. The speakers underlined the rapid growth of photonics industry and importance of close cooperation with companies, as well as the enormous potential of Quantum Science and Technology. The meeting was attended by approximately 50 persons from various research units all over Poland, as well as the representatives from the Ministry of Science and Higher Education and National Science Centre and representative of Innovate UK and resulted in fruitful discussion with the focus on strengthening the regional collaboration and links with the industry. Such broad audience enabled valuable discussion on the project's outcome, current possibilities and constraints and future perspectives for Photonics and Quantum Sciences.

4. POTENTIAL IMPACT AND THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION OF RESULTS

Since Photonics and Quantum Science are playing transformative role in 21st century science and technology, development of knowledge and implementing new technologies in this area may have significant impact on industry and society. Although the PhoQuS@UW project did not cover costs associated directly with research activities, but assisted activities supporting science, creating the technical and human resources platform for new research directions has important consequences at both institutional, regional, and national levels.

Secondments along with organization of conferences, sessions and workshops resulted in establishing and deepening cooperations and performing research in new, prospective areas with high impact both on science and everyday life. The main research activities toward development of scientific directions are described below.

The most important characteristics of electromagnetic pulses generated by lasers are their intensity and time-duration. The ultrashort laser pulses enable one to study very fast events such as the nuclear motion inside molecules. This has resulted in developing a new branch of science which is now called the femtochemistry. In order to create such short pulses, the coherent bunches of photons of energies of the order of kiloelectronovolts have to be generated. Laser pulses consisting of photons of such energies cannot be generated using conventional resonator techniques. Therefore, to achieve this goal, new methods have to be developed. In principle, there are two possibilities to create pulses of radiation shorter than femtoseconds (based on the free-electron-laser (FEL) and the high-order harmonic generation (HHG) scheme). Both methods have been successfully developed in laboratories worldwide. Here, an obvious question arises: Can we go even further and generate zeptosecond (or even shorter) pulses of coherent radiation? For this purpose, the merger of two well-developed branches of modern physics is required, that have been developed in the past independently of each other. These are the accelerator physics and the laser physics of relativistic intensities. The process that involves the two and leads to the generation of photons in the domain of few megaelectronovolts is the so-called nonlinear laser-induced Compton scattering, with its classical analogue called the Thomson scattering. What possible applications of zeptosecond pulses would be? Since photons in such pulses have enormous energies, they could be applied to probe nuclear reactions in nuclear physics, as it has been accomplished using attosecond pulses for molecular reactions in femtochemistry. Hence, zeptosecond pulses could be applied, for instance, to remotely characterize nuclear materials and radioactive waste, which is of a significant importance for our everyday life. Not surprisingly, large laser facilities are developed in the European Union, among which the Extreme Light Infrastructure (ELI) project is the most prominent example. ELI is a research project conducted as a part of the European Strategy Forum on Research Infrastructures Roadmap. The ELI scientific consortium is focused on research into the interactions between light and matter under the conditions of the most powerful photon beams and at a wide range of wavelengths and time scales measured in attoseconds. In FPUW, there are groups of scientists the research of whom is related to this large European project. In particular, different theoretical aspects of the Strong-Field Quantum Electrodynamics are developed by K. Krajewska and J. Z. Kamiński from the Institute of Theoretical Physics at FPUW, in collaboration with the partnering institutions, mostly the MPI in Heidelberg and the

University of Düsseldorf. Let us also mention the experimental work of Dr. Chiara Mazzocchi from the Institute of Experimental Physics, who collaborates with the Romanian pillar of ELI.

While the ELI project is dedicated to the extreme case of intense and ultrashort aspects of laser-matter interactions, equally important for applications are coherent properties of radiation generated by lasers. In this domain of laser-matter interactions, investigations related to different aspects of the quantum information theory are of great importance. There are also vividly studied at the FPUW, both experimentally and theoretically. Particularly noteworthy is the impact of the PhoQuS@UW project on the scientific development of young researchers from FPUW. Researcher from FPUW, Michał Jachura, spent several weeks at the University of Oxford, UK, learning the most recent theoretical and experimental methods in the field of quantum optics and quantum information. As the result of the experience he gained there, Michał Jachura's work is already appreciated in a wide scientific community. In particular, the article by Michał Jachura and Radosław Chrapkiewicz entitled "Shot-by-shot imaging of Hong-Ou-Mandel interference with an intensified sCMOS camera" [Optics Letters 40, issue 7, pp. 1540-1543 (2015)] was highlighted in the December 2015 special edition of the magazine of the Optical Society of America. The work was also honored in the series "Spotlight on Optics", which is the selection of articles of the highest scientific quality in optics. These two young scientists are members of groups led by K. Banaszek and W. Wasilewski. Another joint project of these groups resulted in the publication that appeared in the prestigious scientific journal Nature Communications 7, 11411 (2016). Note that these achievements were possible not only due to the close collaboration with our partnering institutions but also due to the organization of conferences and workshops at FPUW, that boosted the collaboration of our employees with other scientific centers (mostly in Europe) working on similar topics.

Investigations related to quantum information theory were conducted at FPUW not only in Quantum Optics groups but also in Solid State Physics groups, and are led by P. Kossacki and W. Pacuski. A very fruitful collaboration of these groups is continued with the Laboratory in Grenoble, France, and with the University of Bremen, Germany. The researchers focus on solotronics or semiconductor structures with built-in high-spin elements. Let us mention, for instance, that solotronic structures of a new type, including the world's first quantum dots with individual ions of cobalt, were prepared and tested at FPUW. Moreover, physical systems that are based on individual atoms seem to be a natural consequence of the progress made in the miniaturization. The behavior of individual atoms can be controlled today by placing them in special semiconductor structures, such as quantum dots with individual magnetic ions. Physicists from the Institute of Experimental Physics, FPUW, managed to manufacture and test two new types of such structures. Materials and elements used in their investigations suggest that in the near future the solotronic elements can find practical applications. Moreover, objects with high spin that are built into the semiconductor structures can be used to perform complex tasks related to the processing and storage of quantum information. This is the first step towards using such ions as multi-qubits for storing information. This type of research has been boosted not only by exchange visits to and from the partnering institutions, but also by the workshop organized in FPUW, the hands-on advanced workshop on "Molecular beam epitaxy".

For moderate laser field intensities, we encounter other vast domains of scientific activities, also present in FPUW. We should mention here the femtochemistry, represented by the group leaders Cz. Radzewicz and P. Fita, from the Division of Optics at FPUW. Their collaboration

with partnering institutions have led to significant achievements and deepened our understanding of laser-matter interaction in chemical and biological systems. Czesław Radzewicz also conducted intense research on atomic clocks, closely related to the frequency combs invented in one of our partnering institution in Munich, Germany.

Let us also mention our activity in photonics (groups of T. Szoplik, R.Kotyński and R. Buczyński from the Institute of Geophysics at FPUW). All these examples prove that the researchers of FPUW tried to develop multiple aspects of laser-matter interaction, for which a broad collaboration with other scientific centers is indispensable. In particular, the scientific contacts with the partnering institutions played a significant role in building a stronger intellectual capacity of the FPUW and in increasing its visibility worldwide.

Note that the year 2015 was declared the International Year of Light and Light-based Technologies. This is due to an enormous influence of classical and quantum optics on the development of modern scientific ideas in particular, and on our everyday lives in general. The scientific world awaited for many years for the experimental confirmation of the existence of gravitational waves. It seems that only the development of modern optics has led to the realization of this dream, which was shared by several generations of physicists and astronomers. News about the detection of gravitational waves in the LIGO project appeared at first through unofficial channels in the Internet, but then they were confirmed by scientific publications with the employees of FPUW as co-authors. Still, the challenge is to increase the resolution of detection of the gravitational waves. In order to do so, one has to develop quantum methods that will allow us to reduce the noise of measurements. The most promising methodology to do that is based on the modern theory of quantum information. A researcher from FPUW, Rafał Demkowicz-Dobrzański, was actively involved in this type of research.

For the first time, quantum dots with single cobalt ions were manufactured by Polish researchers from the Faculty of Physics. Materials and chemical compounds used at the Faculty of Physics indicate further directions of development of a new emerging field for research and technology, called solotronics. Solotronics - electronics and spintronics of the future - reaches the ultimate limit of miniaturization as it operates with individual atoms. The results of these pioneering studies have been published in the top scientific journal: NATURE COMMUNICATIONS 5, 3191 (2014) (DOI: 10.1038/ncomms4191), which clearly indicates that the Faculty of Physics UW has already contributed to the European excellence in technology driving research domains. The PhoQuS@UW project has also revitalized scientific networking with the partnering institution -the University of Oxford, UK. The project has resulted in extending and broadening the previous collaboration with the University of Oxford. This has led to a publication in the highly ranked scientific journal NATURE PHOTONICS (2016) (DOI: 10.1038/ nphoton.2016.228). The aforementioned article on efficient temporal photon manipulation for quantum information processing is another example that researchers from Faculty of Physics, thanks to constant interaction with world-renowned experts on photonics and quantum physics, are capable of carrying out internationally competitive research projects. Another results of secondments between top level research groups from FPUW's partners institutions is for example the publication: Introducing single Mn2+ ions into spontaneously coupled quantum dot pairs; M. Koperski, M. Goryca, T. Kazimierczuk, T. Smoleński, A. Golnik, P. Wojnar, P. Kossacki, PHYS. REV. B 89, 075311 (2014).

Hiring talented researchers, purchase of new, modern equipment and deepening the collaboration with top research centres resulted in submitting project proposals in national and European calls. 16 projects were submitted by the researchers hired within the WP2 and FPUW staff involved in the project, of which 8 were granted funding. It is expected, that experience and collaborations gathered during the project realization will contribute to further increase of FPUW research potential and development of photonics and quantum science.

Members of the Faculty of Physics UW organized, co-organized or attended events as an opportunity for dissemination and promotion actions raising public awareness of the PhoQuS@UW research and scientific achievements of FPUW and its partnering institutions via series of promotional events and media. Some of these events were organized periodically, such as:

- "Physicist's Day" (Dzień Fizyka), organized four times, in 2013, 2014, 2015 and 2016;
- The Open Days are organised at the Faculty of Physics of University of Warsaw organized four times, in 2013, 2014, 2015 and 2016;
- University of Warsaw contributed to the nationwide action "Girls as Scientists" encouraging girls to embark on scientific careers, especially in natural and computer sciences. This events twice were held separately and twice in conjunction with Open Days at the Faculty of Physics UW;
- The Science Picnic (Piknik Naukowy) of Polish Radio and the Copernicus Science Centre – PhoQuS@UW supported FPUW participation in this event three times (17th, 18th and 19th edition). The Science Picnic is probably the largest open-air European science disseminating event addressed to the general public;
- The Science Festival (Festiwal Nauki) – PhoQuS@UW supported FPUW participation in this event three times (17th, 18th and 19th edition). The aim is to create a need to participate in development of a strong knowledge-based economy;
- Summer School of Physics as a part of "Summer in the City" action co-organized by Warsaw City Hall, Polish Physical Society and FPUW. It aims at promoting science careers among young generation. It is addressed to pupils of lower-secondary schools (junior high school) and secondary schools. PhoQuS@UW supported FPUW participation in this event three times (2013, 2014, 2015);
- International Fair for Optoelectronics and Photonics OPTONExpo organized at Warsaw International Expocentre EXPO XXI. PhoQuS@UW supported FPUW participation in this event twice (2014, 2015). On the second day of the Fair in 2014 was held Career Forum addressed to candidates to studying optics-related fields of science at Polish universities. In 2015 Dr. Cezary Samojłowicz – the innovation manager at PhoQuS@UW project, discussed possible fields of collaboration with Polish and foreign optics companies: Solaris Laser S.A., SEDI-ATI Fibres Optiques, VIGO System S.A., PCO S.A., and Scitec Instruments Polska.
- PERSPEKTYWY Poland International Education Fair. Probably the biggest and best-known educational fair in Poland serves as an information exchange forum for higher education in Poland and abroad. PhoQuS@UW supported FPUW participation in this event twice (2014, 2015).

Beside these regularly organized events PhoQuS@UW members organized meetings to promote physics and optics and photonics, in particular among high school students (Nowa Słupia 2013, Białystok 2014, FPUW 2014) and lower-secondary pupils (Dębe Wielkie 2013). On March 11-15, 2013 in Warsaw, the National Children's Fund (Krajowy Fundusz na Rzecz Dzieci) organised a workshop where members of the project team carried out outreach activities

for exceptionally gifted secondary school pupils in the field of experimental optics and quantum metrology. PhoQuS@UW supported also Final competition of the nationwide contest in physics “Search for talents” organized at FPUW. Authors of 65 best reports from lower-secondary and secondary schools together with their teachers were invited to compete in front of a jury composed of the Faculty of Physics members. All finalists were accepted for studies in the FPUW without usual qualification procedure.

Close cooperation with mass media, such as radio, television, internet and press popularised and promoted research in physical sciences and increased the visibility of the physics community to the public. This means of communication have large audience: 1st Program of Polish Radio has the listenership around 2,5 millions, TVP Warszawa has the viewership around 65 thousand and the weekly magazine “Tygodnik Powszechny”, in which article "Breaking the (light) waves" by Piotr Wasylczyk was published, has circulation of 18 thousand copies. Interviews, broadcasts, videos and articles in media mentioned above helps in popularization of science and provides significant impact in aim to build the society based on knowledge.

5. ADDRESS OF THE PROJECT PUBLIC WEBSITE AND CONTACT DETAILS

Project public website address: http://phoqus.fuw.edu.pl

Contact details :

Prof. Konrad Banaszek,
Uniwersytet Warszawski, Wydział Fizyki
ul. Pasteura 5
02-093 Warszawa

Tel: +48-22-5532923, +48-22-5532638
Fax: +48-22-5532999

E-mail: phoqus@fuw.edu.pl