Summary of Professional Accomplishments

1. Name. **Piotr Kolenderski**
2. Diplomas, degrees conferred in specific areas of science or arts, including the name of the institution which conferred the degree, year of degree conferment, title of the PhD dissertation
   a) 2001-2016, **MSc**, Nicolaus Copernicus University in Toruń,
   "Spectral properties of photon pairs generated in parametric down conversion process",
   supervisor: Dr. hab. Konrad Banaszek,
   b) 2006-2010, **PhD**, Nicolaus Copernicus University in Toruń,
   "Photon pairs engineering in nonlinear media",
   supervisor: Dr. hab. Konrad Banaszek, ,
3. Information on employment in research institutes or faculties/departments or school of arts
   a) 2008-2009, Nicolaus Copernicus University in Toruń, assistant;
   b) 1.10.2010 – 30.09.2013, Nicolaus Copernicus University in Toruń, assistant;
   c) 1.10.2010 – 30.09.2013, Institute for Quantum Computing, University of Waterloo, Canada, postdoctoral fellow
   d) 1.10.2013 – 30.09.2021, Nicolaus Copernicus University in Toruń, assistant professor
4. Description of the achievements, set out in art. 219 para 1 point 2 of the Act
   a) title of the achievement:
   Methods of generation, control and detection of single photons and their applications in fundamental and applied research
   b) list of the related articles

H1. S. Kolenderska, **P. Kolenderski**
Intensity correlation OCT is a classical mimic of quantum OCT providing up to twofold resolution improvement,
Sci Rep **11**, 11403 (2021)
IF: 3.998

H2. Artur Czerwinski, Karolina Sedziak-Kacprowicz, **Piotr Kolenderski,**
Phase estimation of time-bin qudits by time-resolved single-photon counting
Phys. Rev. A, **103**, 042402 (2021)
IF: 2.777

H3. S. Kolenderska, F. Vanholsbeeck & **P. Kolenderski**
Quantum-inspired detection for spectral domain optical coherence tomography
Opt. Lett., **45**, 3443 (2020)
IF: 3.714

H4. M. Lasota & **P. Kolenderski**
Optimal photon pairs for quantum communication protocols,

Sci. Rep. **10**, 20810 (2020)
IF: 3.998

H5. S. Kolenderska, F. Vanholsbeeck & **P. Kolenderski**
Fourier domain Quantum Optical CoherenceTomography
Opt. Express., **28**, 29576 (2020)
IF: 3.669

H6. M. Lasota & **P. Kolenderski**
Quantum communication improved by spectral entanglement and supplementary chromatic dispersion
Phys. Rev. A, **98,** 062310 (2018)
IF: 2.777

H7. K. Sedziak, M. Lasota & **P. Kolenderski**
Reducing detection noise of a photon pair in a dispersive medium by controlling its spectral entanglement
Optica, **4**, 84 (2017)
IF: 7.536

H8. **P. Kolenderski**, C. Scarcella, K. D. Johnsen, D. R. Hamel, C. Holloway, L. K. Shalm, S. Tisa, A. Tosi, K. J. Resch & T. Jennewein
Time-resolved double-slit interference pattern measurement with entangled photons
Sci. Rep., **4**, 4685 (2014)
IF: 3.998

c) detailed description of the achievements reported in the papers presented above is given in the last section of this document

5. Presentation of significant scientific or artistic activity carried out at more than one university, scientific or cultural institution, especially at foreign institutions:

My research after obtaining the PhD till recently is focused on the applications of methods of single photon generation, control and detection. During the post-doctoral fellowship at Institute for Quantum Computing, Waterloo, Ontario, Canada I was involved in quantum optical experiments. For three years I co-supervised students and PhD students and I build several experimental setups. The main goal was the construction of photon pair sources useful for further implementations of fundamental tests of quantum mechanics and demonstration of quantum communication protocols. In particular, me and collaborators demonstrated the Aharon-Vaidman quantum game and showed the interference patter buildup by looking at the consecutive defections of single photons. In additions, I simulated and demonstrated a particular source of single photon pairs, which features positive spectral correlation. It is important with respect to extending the range of fiber based quantum communication.

Next, I moved to Nicolaus Copernicus University in Toruń, where I established a group, Single Photon Application Laboratory. The research focuses around two main topics which have single photon sources in common: quantum communication (satellite and fiber based) and interaction of single photons with isolated quantum systems. The detailed description is presented in the last paragraph of this document.

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science or art:
    A) Teaching:
        1. Quantum Information in Applications (lectures and practice, 2013-till recently)
        2. CAD/Inventor (practice, 2 years)
        3. Basics of research data processing (practice)
        4. Physics III – Optics,
        5. Physics II – Electromagnetism
        6. Physics I – Classical Mechanics
    B) Supervision of undergraduate students:
        1. Daniel Gustaw, BSc
        2. Andrzej Gajewski, MSc
        3. Marta Misiaszek (Pałucka), MSc
        4. Patrycja Jabłońska, MSc
        5. Karolina Sędziak (Kacprowicz), MSc
        6. Paulina Stafiej, MSc
        7. Agata Tomela, Eng
        8. Jakub Szlachetka, BSc
        9. Agata Tomela, MSc Eng
        10. Jakub Szlachetka, MSc
    C) Co-Supervision of PhD students:
        1. Andrzej Gajewski
        2. Marta Misiaszek-Schreyner
        3. Karolina Sędziak-Kacprowicz
        4. Maria Gieysztor
        5. Jakub Szlachetka
        6. Anudatha Anarthe

7. Apart from information set out in 1-6 above, the applicant may include other information about his/her professional career, which he/she deems important:

    Single Photon Application Laboratory was established in 2013 by the Applicant at National Laboratory of Atomic Molecular and Optical Physics. The laboratory was equipped almost from the scratch by using the funds attracted by the Applicant. Today (September 2021), a state-of-the-art laser systems, superconducting single photon detectors, photon pairs sources, cryogenic and room temperature confocal microscopy setups are up and running. The Applicant is leading a group of 4 postdocs, 6 PhD students and 2 students covered by Applicant’s grants and funds from commercial contracts with companies.

I. SINGLE PHOTON SOURCES

Spontaneous parametric down conversion (SPDC) is the phenomenon which is the core of all the applications that will be described here. A single photon – when propagating in a nonlinear medium – decays into a photon pair. It is an effect which is similar to optical parametric oscilator (OPO), but it has an important key differing feature – it cannot be explained on the basis of Maxwell equations. Traditionally, the input photon is called pumping and the resulting output photons: signal and idler. **The simplified theoretical description** can be based on a basic hamiltionian, which takes into account single modes for all the interacting photons: pump, signal and idler. In practice, the multimode character of the input and output light must be taken into account. The pumping light can be a continuous-wave (CW) or a pulsed laser, therefore its spectral amplitude can be represented as a Dirac-delta or a Gaussian function, respectively.

For certain applications, quantum communication in particular, the photons generated in the nonlinear crystal must be **coupled to sinlge-mode fibers**. When coupled, the spatial modes are fixed. However, in order to get an efficient coupling, spatial modes of the produced photons must match the spatial mode of single-mode fibers. This is sometimes a demanding task.

SPDC itself is a quantum-mechanical process as it cannot be described by means of classical electrodynamics. The process naturally produces photons which feature nonclassical correlations called **entanglement**. Photons can be entangled in many different ways. Polarization is the most useful degree of freedom which was used for various practical applications such as quantum key distribution, entanglement swapping or Bell inequality violation. The prerequisite for polarization entanglement is the lack of any distinquishing information in any other degree of freedom. Therefore, spectral and spatial characteristics of the photons must be carefully chosen. In particular, coupling to single-mode fibers is important as it fixes the spatial modes of the resulting photons.

Below, three types of application will be described. Those are quantum communication, photon-matter interaction and optical coherence tomography.

II. APPLICATIONS

A. Quantum Communication

Quantum communication (QC) is a term encompassing all sorts of protocols for transferring information or generating a secret sequence of bits between two parties by means of effects originating in quantum mechanics. The most notable protocols are:

- Quantum Key Distribution (QKD), where the aim is to establish a secret sequence of bits between two parties. The information carriers are quantum-mechanical objects, such as photons. The security of the protocols relies on the fundamental theorem of quantum mechanics, no-cloning theorem, which says that there is no universal cloning machine. Therefore, any disturbance of the information carrier by an unauthorized party will not be unnoticed.
- Entanglement swapping. Here, the quantum correlation between a pair of particles can be transferred from one pair to another.

Note that there are two important things for the QC protocols: **randomness** and ability of **detecting any disturbance** during transmission. Polarization entanglement is a resource which provides randomness, whereas single particles as information carriers allow to rely on no-cloning theorem. Both of them **provide security**.

Entanglement is a resource which can be used for QKD. In a typical experimental scenario, a pair of polarization-entangled photons is transmitted over long distances in single-mode fibers. Fibers are useful for this application as no pointing and tracking is required for the optical link. However, this link suffers from attenuation, typically 0.18dB/km for standard telecom fibers, and chromatic dispersion, typically 18 ps/(nm km). Single photon detectors feature not perfect quantum efficiency. It is of the order of 80% at 800nm for silicon Single Photon Avalanche Diodes (Si-SPAD), 25% at 1550nm for InGaAs/InP and $> 90\%$ at 1550 nm for Superconducting Single Photon Detectors (SSPD). Noise, which is quantified as the dark count rate (DCR), is another factor which influences practical implementations of QC protocols. The effects which were listed so far: the fiber attenuation and dispersion together with the detector quantum efficiency and noise define performance of the QC protocols.

The problem which was tackled can be expressed as follows: **How to improve the performance of practical quantum communication protocols based on photon pairs transmitted via a dispersive medium?** The working conjecture is that temporal-spectral correlation can be another resource which can be used for this purpose.

Let us analyze the propagation of a single photon wave-packet in a dispersive medium. This propagation mechanism is mathematically analogical to the wave-packet evolution studied in the first year of Quantum Mechanics course. The starting point is a Gaussian wave-packet and a propagator (hamiltonian) defining the dynamics in a dispersive medium. While the propagation of the Gaussian mode, its shape is preserved. Its width changes and is proportional to the dispersion and there is also a quadratic phase which is acquired.

The same framework can be applied to two photons propagating in a dispersive medium. The spectral state of the pair is assumed to be described by a two-dimensional Gaussian function, which is parameterized by three parameters: widths of the two photons and correlation (mathematically the Pearson correlation coefficient). It is assumed that the total state of the photon pair is a product of spectral, spatial and polarization components. Note that the parity of the total wave function of the two photons always obeys boson properties. Therefore, there is no correlation between different degrees of freedom. What we are interested in is entanglement in spectral and polarization degrees of freedom.

In practice, it can be generated by means of spontaneous parametric down conversion by carefully adjusting the phase matching of the nonlinear medium. It is useful to consider an effective phase matching function introduced in Ref. [1], which takes into account the joint effect of nonlinear medium and characteristics of spatial modes coupled to fibers. This function when multiplied by the spectral amplitude of the pumping laser yields the fiber-coupled photon-pair state.

It was observed theoretically and experimentally in Ref. [2] that in very specific conditions the positively correlated photon pairs can be generated. Physical interpretation is the following: the photon with higher energy is correlated with the counterpart with higher energy. This may sound like violation of energy conservation relation as the energies of the photons generated in SPDC must add up to the energy of the photon of the pump. However, in this specific application the pump must be specially broadband. In another words, the crystal can be considered as a filter which transforms the input, pump, photons into pairs featuring positive spectral correlations.

This specific feature of a BBO (β- barium borate) crystal was first probed using a CW laser [2] as a pump. In this experiment, the magnitude of the effective wave function was measured revealing the potential to generate positive spectral correlations. The setup was composed of three main components, the CW tunable laser, photon-pair generator based on a BBO crystal, and a single-photon-sensitive fiber-based two-photon spectrometer. The last component exploits chromatic dispersion in single-mode fibers and temporal resolution of single photon detectors. When properly calibrated it can be used as a spectrometer [3]. Therefore, by setting the pump wavelength and measuring the spectral correlation, it was possible fo reconstruct the magnitude of effective phase-matching function, which provides information on the type of spectral entanglement that can be generated using this crystal.

In the next step, a pulsed laser was purchased and used to replace the CW light source [4]. The measurements performed in a couple of different pumping scenarios, including differing the spectral bandwidth (pulse duration), proved the usefulness of this technique to generate and control the amount of spectral entanglement. The measurement was limited in its spectral resolution by the timing resolution (timing jitter) of the single photon detectors. The available at that time InGaAs/InP detectors allowed for at most 150 ps of the timing resolution. This is the key technological factor whose importance will be more evident a few paragraphs later.

A single-mode fiber, such as commonly used SMF28e+, is designed in the way to minimize the loss and chromatic dispersion in the spectral range around 1550 nm. It is particularly important in the context of the main application, which is long distance, high-throughput optical communication. The low attenuation is very important when dealing with single photons, especially when the measurements rely on coincidence detection where any loss scales quadratically. In the quantum communication application, when the information is encoded in a single photon, the efficiency cannot be improved simply by increasing the input optical intensity. Any loss decreases the throughput of the link. In practice, single photon detectors feature dark counts, which is the signal generated by a detector even if there was no photon present. The two features, the detector noise and the loss imposed by fibers, limit the maximum range of the quantum communication protocols relying on the single photon transmission. This limit can be defined as the link (fiber) length which provides enough loss to make the number of photon detections equal to the number of the dark counts.

To tackle the problem of the limited range of fiber based QC, detectors should feature the lowest possible dark count rate. In practice, currently available detectors have approximately 100 dark counts per second (cps), but for the state-of-the-art ones it can be as low as 1 cps. Secondly, the transmission loss should be minimized. The attenuation in the fibers is already at its lowest, but coupling to the fibers of the photons generated initially in free space must be carefully taken into account.

Another strategy, which was a core of the research presented here, relies on using temporal quantum correlations (entanglement), time-resolved single photon counting and temporal filtering [5][H7]. The probability of a dark count is proportional to the time when the detector is active. This time is called detection window. To minimize the chance of fake count and maximize the chance of a photon detection, the detection windows should be as long as the temporal width of the wave-packet of a photon to be measured. This is the optimum working point assuring maximum range

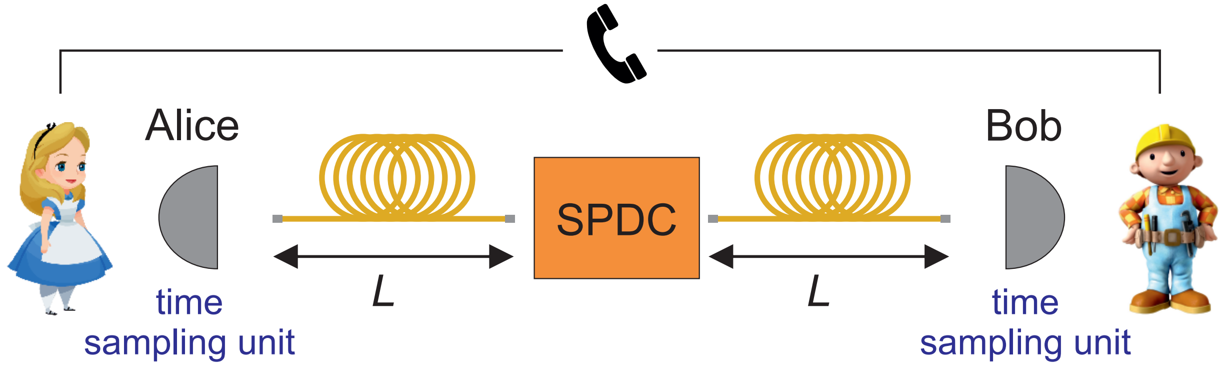

FIG. 1. Generic quantum communication scheme with a symmetric broadcasting [5][H7].

of quantum communication protocols. However, when using spectral entanglement one can get the same amount of detected photons by using narrower detection window. This, in turn, results in lower noise and longer maximum range.

This effect was first introduced in Ref. [5][H7], where by numerical simulation it was shown that when taking into account the parameters of real fibers, detectors and photon sources, the range of fiber based QC can be increased by approximately 20%. The effects of remote temporal wave-packet narrowing was experimentally presented in Ref. [6]. The generic scheme is presented in Fig. 1. The source based on periodically poled KTP crystal was used to generate and control the spectral correlation of photon pairs. In the experiment, it was shown that the temporal mode of the heralded photon can be reduced to approximately 30% of its non-heralded size. In addition to that, settings of the entire photon pair source and the communication channel in general where analyzed. The main effect, which was presumed to allow for the maximum range extension, was positive spectral correlation within a fiber-coupled photon pair. This statement is valid, but surprisingly turned out not to be true with slightly modified assumptions, what will be explained later on.

So far, it was assumed that the source of entangled photon pairs is located in between two parties which perform a quantum communication protocol. The main findings can be encapsulated as follows: polarization entanglement allows for quantum communication protocols whereas spectral entanglement is an extender of the maximum range in a fiber link. In some cases, the source of information carriers can be installed at one and of the communication link and the photons can be sent to the other place. Is is schematically depicted in Fig. 2. Here, the goal is to maximize the

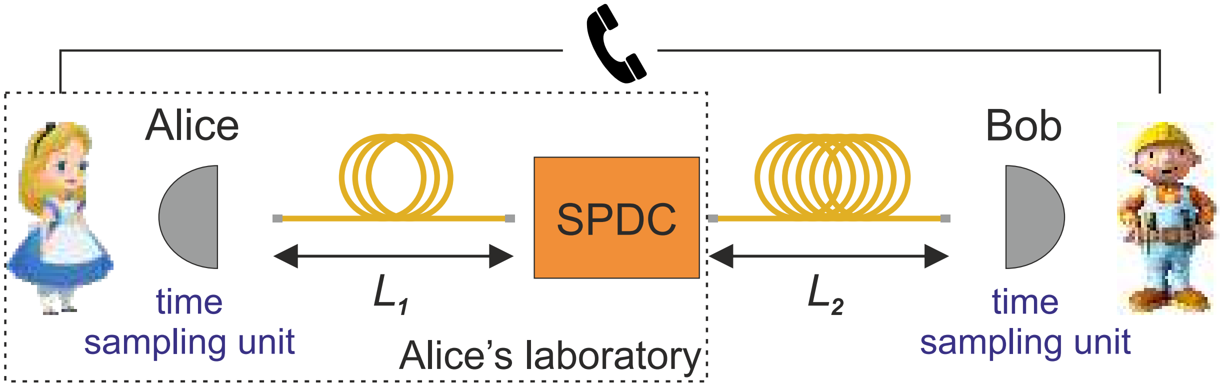

FIG. 2. Generic quantum communication scheme with an asymmetric broadcasting [7][H6].

distance between the two parties, L_2. This analysis resulted in another surprise. Numerical simulation provided an evidence that not only is there an optimal amount of fiber that must be used for optimal performance of the protocol, but also if there is not enough fiber on the transmitter side, the quantum communication is not possible at all. The physical interpretation is the following. If the fiber on the transmitter side is too long, then the loss dominates precluding the protocol. On the other hand, if the fiber is not long enough, the remote wave-packet narrowing effect is not active due to the insufficient spectral resolution provided by the fiber dispersion. Therefore, there is a trade-off between the two allowing for the optimal performance of the protocol. As concluded in Ref. [7][H6], as an example, for the link of the length of 214 km one needs approximately 150 km of fiber on the broadcaster side. Summarizing, the optimal communication distance requires additional chromatic dispersion for an optimal performance. Also, note that the fiber can be replaced with any other medium providing chromatic dispersion, e.g. prism, diffraction grating, dispersion compensating fiber. Each of the alternative sources of dispersion introduces losses, which must be taken into account.

The problem which is being discussed concerns increasing the maximal range of single-photon-based quantum communication protocols. So far, it was shown that when spectra of individual photons are set to typical experimentally available values, for a given communication distance it is beneficial to use spectral entanglement. In the next step, the attempt was made to optimize all parameters of the source which can be controlled for a given communication link. This analysis came with yet another surprising results. The photons, which provide the maximum range of quantum communication link should feature no spectral entanglement [8][H4].

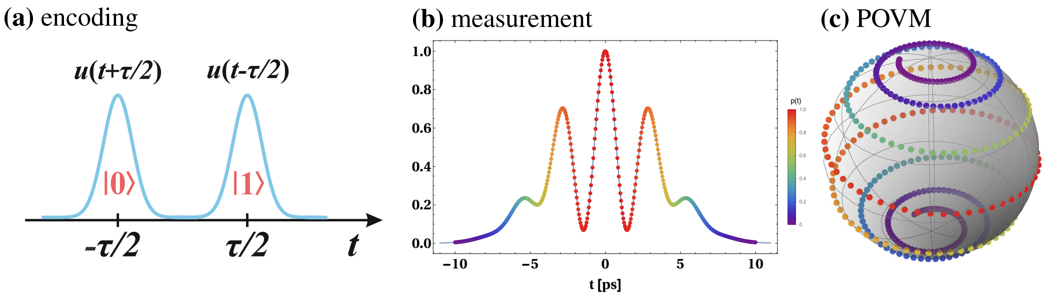

FIG. 3. Time-bin encoding and time-resolved single photon detection scheme [12].

For the protocols discussed so far, the information was encoded in polarization of single photons. The spectral correlation within a photon pair in some circumstances led to the extension of the length of the quantum communication link or increased the link's efficiency. Later, the time-bin encoding scheme was analyzed where a single photon is prepared in two temporal wave-packets, as visualized in Fig. 3. Each wave-packet is associated with a logical bit. This qubit-encoding method was adapted from earlier works by the Geneva group [9–11]. For measurements and analysis, a novel scheme based on time-resolved single photon detection and chromatic dispersion was introduced [12]. Figure 3(a) shows a superposition of two temporal wave-packets of a single photon. When it propagates through a dispersive medium, it follows evolution which is mathematically similar to the propagation of a wave-packet in free space. Such an evolution causes a coherent overlap and therefore, results in interference of the two, what is schematically depicted in Fig. 3 (b). This is a typical time-resolved single-photon measurement statistics. There are two types of interpretation. First, there are two wave-packets propagating in a dispersive medium resulting in an interference pattern measured in the time domain. Second, the two wave-packets are associated with a qubit state which, when evolving in the medium, undergoes a unitary evolution. Then, a photon detection at a given instant is associated with a certain quantum measurement, an element of positive operator valued measurement (POVM). States associated with such a set of measurements are related to the points marked in Fig. 3(b), are presented in Fig. 3(c).

This method can be relatively easily used to generate multidimensional quantum states and also multipartite ones. One can use a generic setup for generating photon pairs by means of SPDC and modifying a pumping pulse by using Mach-Zehnder interferometer to obtain two pulses separated in time by multiple of its temporal widths. It assures that the overlap between them can be neglected. In a typical experimental scenario, the duration of the pulse is of the order of 100 fs and the separation of the order of 1 ps, which is related to a spatial separation in free space of

300 μm. When such a double-pulse enters a nonlinear medium, it can generate a biphoton (photon pair) which inherits the temporal characteristics od the pumping mode. Each of the two photons can be described by a joint temporal amplitude featuring correlation. Therefore, this method can be used to encode and measure entangled qubits in time domain. A feasibility study of quantum state tomography was included in Ref. [13][H2]. The optimal parameters for the generalized measurement implementation were shown. The quality of the tomography was analyzed in the context of realistic, experimentally available parameters. Among a few results, it is noteworthy that for the efficient phase estimation, one needs approximately 5 km of fiber for the currently available single photon detectors with the timing jitter of 20 ps. As a preliminary experimental study, a nonlinear PPKTP crystal was pumped using a double-pulse. The resulting photons were coupled to 10 km-long single-mode fibers. The arrival time of each of the photon was recorded with respect to the laser pulse which entered the Mach–Zehnder interferometer. The data is presented in Fig. 4.

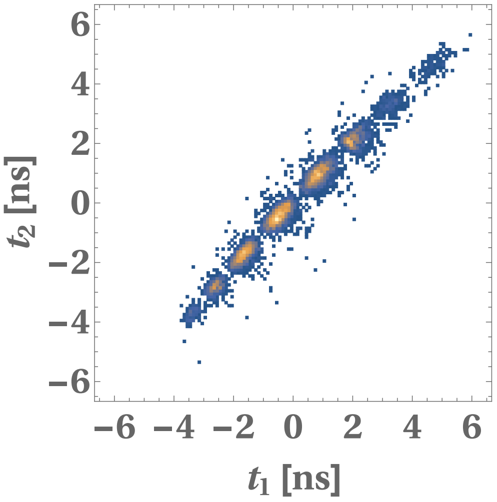

FIG. 4. Statistics of arrival times of photon pairs generated for the framework of temporal encoding. Preliminary data.

Summarizing, the series of papers, which includes H2, H4, H6 and H7, covers the problem of extending the range of quantum communication protocols. Single photons are used as information carriers, polarization entanglement may be used to implement classic QKD protocols, eg. BB84, and spectral entanglement can be used to extend the range [5][H7] [7][H6] [8][H4] when used with time resolved single photon counting. Moreover this framework can be used without polarization entanglement to implement qudits in temporal domain [13][H2]. This idea is still explored and some practical implementations are on the way.

B. Photon Matter Interaction

An interaction of matter and light is one of the biggest topics in contemporary physics. In typical experiments, a gas or a solid state is illuminated with a laser light. Therefore, the interaction is typically modeled by treating the atom as a quantum object, but the light can be assumed to be a classical electromagnetic wave because of the very high optical intensity. Such techniques are very well developed, like spectroscopy or fluorescence microscopy.

More control over the optical illumination can provide additional information about an interrogated sample. As a simple example, let us assume a couple of atoms close to each other. If the atoms are illuminated by a strong laser pulse, one can assume that all of them can be excited and then the atoms will emit the fluorescence photons. By measuring the number of emitted photons one can indirectly measure the number of atoms. However, typical single photon detectors are not photon-number-resolved, which makes this task more difficult. Illumination with a photon state which is well defined could help to overcome some of these limitations.

As another example, let us imagine a single atom (eg. nitrogen vacancy in diamond). If this object is illuminated by a classic laser beam, the standard Abbe diffraction limit applies. However, if a single atom is made to absorb a pair of photons, then the resolution is increased, and the classic diffraction limit is surpassed.

There are many more potential applications and enhancements which can be achieved when the methods of quantum light absorption and detection are applied. I will present two already accomplished phases of the project aiming in observation of interaction of single photon with isolated quantum system.

1. Phase 1: Experimental demonstration of Fock state interacting with matter

The first step towards experimental demonstration of Fock state interacting with matter was demonstration of an interaction of a photon prepared in a Fock state with a group of color centers in diamond. The sample was very dense which improved the ability to observe the absorption and resulting fluorescence emission. The experimental setup as reported in Ref. [14] is presented in Fig. 5. The single photon source was based on SPDC process, where two photons were initially created at their center wavelengths of approximately 532 nm and 1550 nm. The telecom, 1550 nm, photon, when detected by the SSPD, heralds the existence of visible range photon. Next, the heralded photon illuminates the sample, which is placed in the microscopy setup. The microscope objective is used for both: to focus the pumping single photon and collect the fluorescence response of the sample. The fluorescence photon is then measured by a single photon avalanche diode (SPAD).

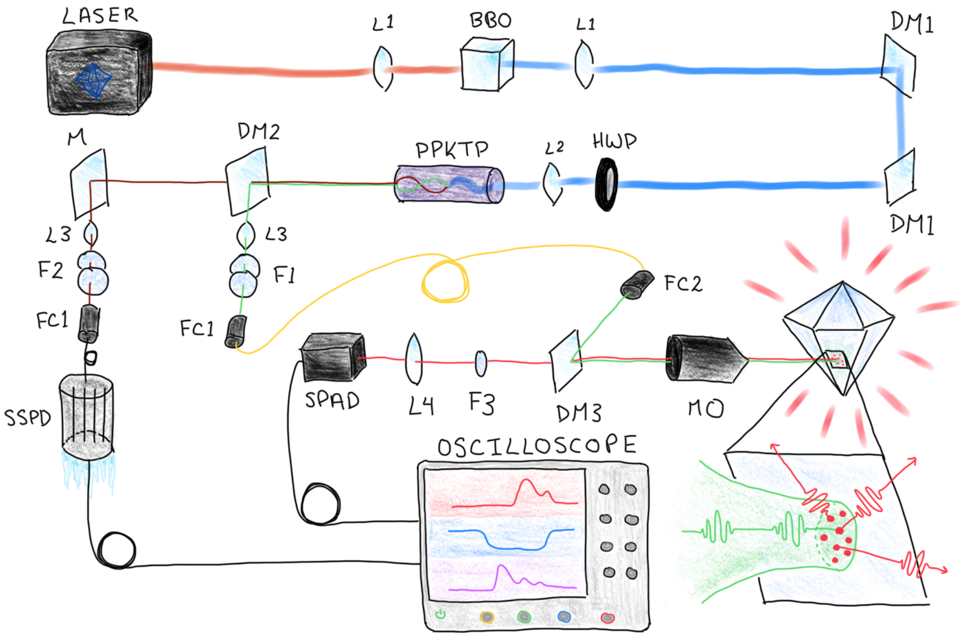

FIG. 5. The schematic of the experimental setup which was used to demonstrate an interaction of a single photon in a Fock state with an ensemble of nitrogen-vacancy color centers in diamond [14].

The resulting photons, the heralding 1550 nm and the fluorescence one (600 - 850 nm), where detected by respective single photon detectors. The electric signals from the detectors were analyzed by an oscilloscope which was set to measure the relative arrival time of the electric pulses from the detectors. The timing jitter of the entire system was approximately 50 ps, which is orders of magnitude smaller as compared to the fluorescence lifetime of the nitrogen vacancy (NV) centers. This allowed to measure the fluorescence decay time. The example measurement is presented in Fig. 6. The very high timing resolution allowed to see not only the decay time, but also the effect of non-radiative transition which preceeds the radiative one. It was estimated that the fluorescence decay time was approximately 8 ns and the non-radiative 100 ps.

A typical fluorescence lifetime measurement can be done by using electro-optic modulators and CW lasers. In this case, the sample is illuminated and suddenly the illumination is turned off by the modulator. As a result, the fluorescence lifetime measurements cannot report on the

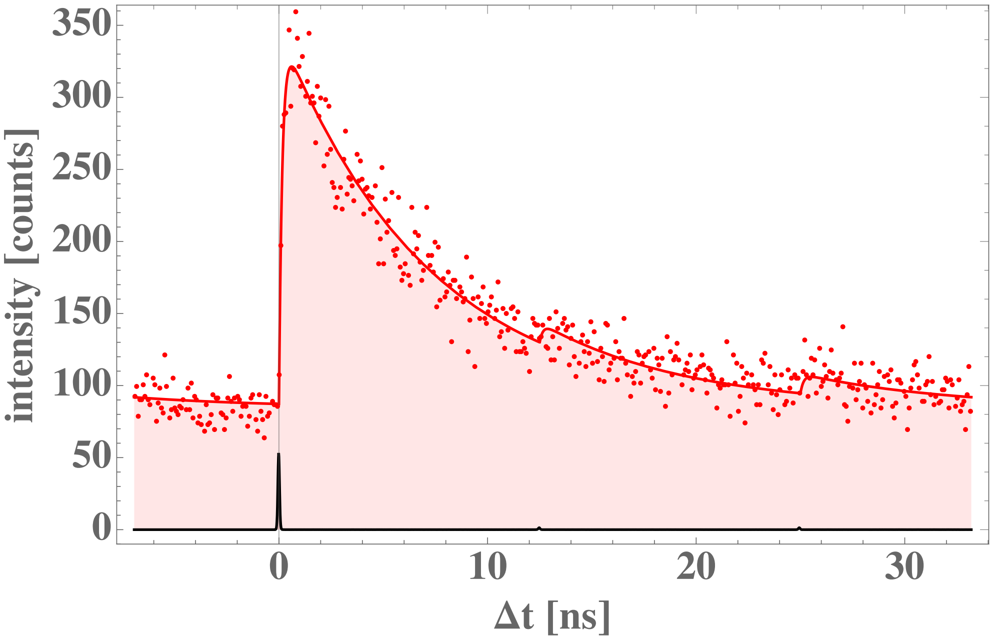

FIG. 6. The histogram of the fluorescence photons arrival time [14]. The fluorescence decay time was approximately 8 ns and the nonradiative one 100 ps.

non-radiative time as this experimental method does not offer sufficient temporal resolution.

Note that the experiment reported in Ref. [14] proved that it is possible to observe effects of a single-photon illumination and photon-matter interaction at a single particle level. Also, the results of the lifetime measurement differ as compared to the pre-existing literature as the experimental conditions at the time before the interrogation by a single photon were profoundly different. Here, the sample was not illuminated.

2. *Phase 2: Single photon fluorescence microscopy*

The imaging resolution is given by the Abbbe limit which depends on the wavelength and numerical aperture of the optics. Multi-photon processes can improve it by the factor which is proportional to the number of photons involved in the interaction. It is a well known observation and experimental rule of the thumb that to get the Abbe limit, the sizes of the spatial mode of the light entering the microscope objective and its entrance aperture must be similar. This results in some loss as not all the light is being transmitted through the microscope objective. When pumping with the laser beam, this is not a problem as the laser power can be increased to compensate for this effect. However, when dealing with single photons, loss is a key factor that determines the usefulness of a method.

In the previous section, it was shown how to reduce the problem of limited distance and efficiency of quantum communication protocols by resorting to features of transmission channel and spectral entanglement within the information carriers. It was also shown elsewhere [15][H8] that quantum correlation can be used to remotely select the spatial mode of a single photon wavepacket. In that experiment, a polarization-entangled photon pair was generated. Then, one of the photons was measured The detection of this photon heralded the existence of the other particle, which propagated in the setup composing of a birefringent crystal, which split its path according to the input polarization. The choice of the quantum state in the polarization analyzer resulted in the specific shape of interference pattern built up by the heralded photons. Interestingly, the resolution and photon efficiency of fluorescence microscopy can also be improved by using the same mechanisms. Mathematically, propagation in the dispersive medium is described by the same equations as propagation in free space. On the other hand, the photon pairs generated in the nonlinear crystal when propagating in free space feature spatial entanglement. This two are the basic building blocks of the idea presented in Ref. [16].

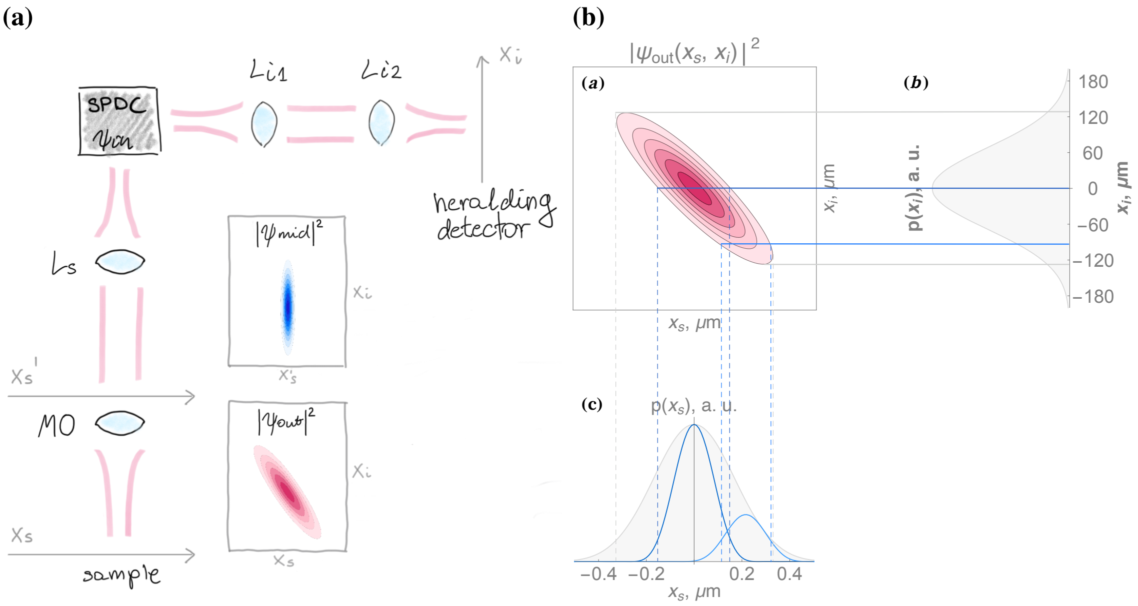

FIG. 7. The schematic shows (a) the concept of the fluorescence microscopy with heralded photons and (b) the basic mechanism of heralded single photon fluorescence microscopy [16].

For the method presented here, a single heralded photon is used for the illumination, therefore standard Abbe limit applies. In the experimental setting, which is analyzed by numerical simulation, it is assumed that the heralding and heralded photons both propagate in the free space.

The heralding photon is measured by spatially resolved single-photon detector. Detection of the heralding photon remotely prepares a heralded photon's state which depends on the optics and position of the heralding detector. The detailed study shows that the spatial mode of the heralded photon at the entrance of the microscope objective can be significantly smaller as compared to the one that is required by the microscopist's rule of thumb. At the same time, it can yield diffraction limit and allows for enhanced transmission.

Typical confocal fluorescence microscopy requires scanning over the area of the sample. This method allows to opt out the scanner to some extent when an array of single photon detectors is used to measure heralding photon. This effect is a direct consequence of intrinsic spatial correlation within a photon pair. The photon detected by each of the detectors at the array heralds another photon at a sample area in a location which is correlated with the heralding detector location.

Summarizing, this part of research is build on the notion of quantum correlations which can be used to remotely narrow one wavepacket after the other one was measured. After the first experimental demonstration of this feature [15][H8] and experimental prove that an interaction of single heralded photon with a group of color centers is possible[14], the detailed feasibility study was pursued [16].

C. Optical Coherence Tomography

So far a clear evidence of advantages of quantum correlation was provided. Spectral entanglement allowed to extend existing fiber-based quantum communication protocols whereas spatial entanglement allowed to alleviate loss and approach diffraction limit in single-photon based fluorescence microscopy setting. There are also applications where entanglement is not a required resource or can even diminish the desired effects. As a simple example, let us consider a case of two photons coupled to single-mode fibers. Their spatial modes are uncorrelated which is imposed by the fibers. Let's assume that there is no correlation in the polarization. If the goal is to herald a spectrally pure state by detecting one of the photons, then the state of the pair most not feature spectral entanglement, which would otherwise led to mixed single photon heralded state. Another example was presented above and described in detail in Ref. [8][H4], where it was shown that the photon pairs featuring no correlation (no entanglement) are optimal for long distance fiber -based quantum communication, when both the source and the link are taken into account.

When applying quantum optical methods to solve practical problems, there must be a clear advantage which does not exist when resorting to classical optics. This is due to the fact that optical setups capable of generating entanglement have limited efficiency and typical application is very prone to photon loss. Note that the loss in two-photon protocols scales quadratically. This motivates a careful analysis of entanglement-based methods applied in the case of optical coherence tomography.

Quantum optical coherence tomography is based on one of the most important quantum optical effect known as Hong-Ou-Mandel interference. It can be observed when two identical photons, typically produced in the process of SPDC, overlap on a 50:50 beam splitter. If the overlap is perfect, meaning there is no distinguishing information, the two photons always leave from the beam splitter the same output port. Therefore, the two detectors monitoring the output ports of the beam splitter never click simultaneously. If the overlap is reduced, for example by delaying one photon with respect to the other, then the coincidences appear. Through scanning of the time delay one gets a coincidence count curve which is traditionally called Hong-Ou-Mandel (HOM) dip. It is a signature of quantum interference of two photons. In the experimental setup which is used to demonstrate the effect, the two photons before mixing on the beam splitter, are reflected from two mirrors. One of them is used to alter the optical path for the overlap modification purpose. The width of the HOM dip is inversely proportional to the spectral width of the photons.

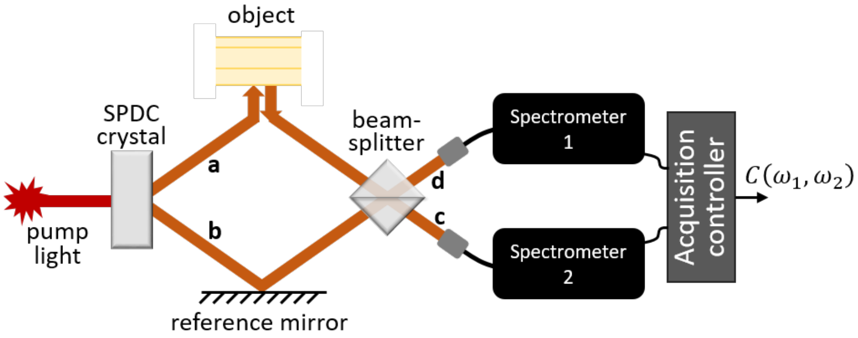

FIG. 8. Quantum optical coherence tomography using two-photon joint spectrum detection [17][H5]. The pumping laser illuminates a nonlinaer SPDC crystal, where a photon pair is produced. Next, it propagates in the optical setup composed of a reference mirror and an object, which is to be characterized. The two photon then are mixed at a beam splitter and coupled to long single-mode fibers, whose output ports are monitored by time-resolved single photon detectors. This allows to measure the joint spectrum signal $C(\omega_1, \omega_2)$.

This effect can be used to characterize the internal structure of the transparent sample. The goal is to measure the thickness of the layers which a sample is composed of. A layer is defined as a uniform material where the refractive index is constant. To show the key underlying mechanism of QOCT, let us consider a generic sample composed of two layers. Here, one of the mirrors in the HOM experimental setup can be substituted by the sample. Naturally, when scanning with the mirror, one gets two HOM dips resulting from interference at the two interfaces in the sample. Also, there is additional signal exactly in between the two interfaces. The widths of HOM dip define the axial resolution of the method. When the photon pairs produced by SPDC are used, the method provides additional feature of being immune to the even order of the chromatic dispression.

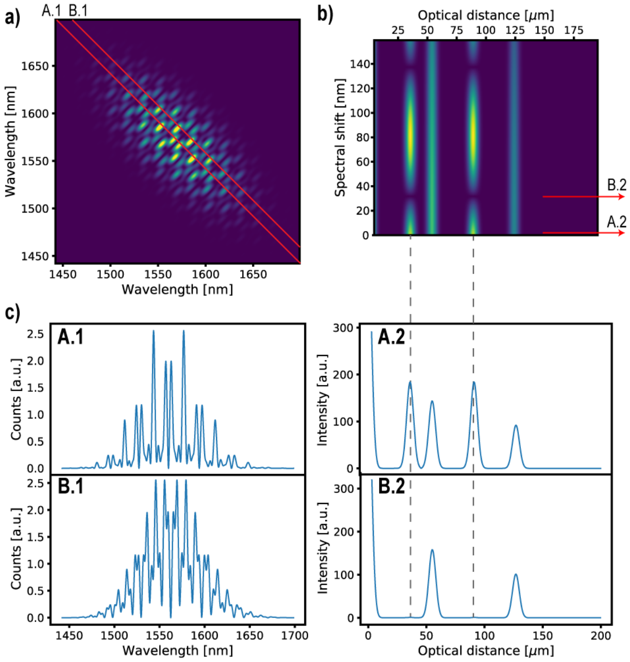

FIG. 9. Example numerical simulation result for the object with two interfaces [17][H5]. (a) Join spectral intensity corresponding to a 50 µm thick quartz. **(b)** Fourier transforms of 200 consecutive off-diagonals of the join spectral intensity show that the height of the artefact peaks goes to 0 for certain spectral shifts. **(c)** The main-diagonal spectrum, A.1, is Fourier transformed to obtain an A-scan, A.2, with two artefact peaks. An off-diagonal spectrum can be found at 31.2 nm spectral shift, B.1, which when Fourier transformed gives an artefact-free A-scan, B.2.

The additional signal originating from the two interfaces, is considered as an artifact, which must be neglected for the proper characterization. The method relaying on a simple coincidence detection and scanning with the reference mirror suffers from the artifacts especially when multi-layer objects are analyzed. An extension of the standard QOCT method was proposed [17][H5].

Here each of the output port of the beam splitter is monitored by single-photon-sensitive time-resolved spectrometers, see Fig. 8. This allows to measure a joint spectral amplitude of photon pairs. Note that for this method to work the delay between the reference mirror and the sample must be fixed.

The measured signal is a product of the joint spectral amplitude, $\left|\phi\left(\omega_1, \omega_2\right)\right|^2$, of a photon pair generated initially in the SPDC source and the transfer (modulation) function of the measurement apparatus, $M\left(\omega_1, \omega_2\right)$:

$$C(\omega_1, \omega_2) = \left|\phi\left(\omega_1, \omega_2\right)\right|^2 M\left(\omega_1, \omega_2\right). \tag{1}$$

The modulation component, $M\left(\omega_1, \omega_2\right)$, incorporates dispersion-free structural information about the object. Fig. 9 presents a numerical simulation result for a thin quartz plate. The panel (a) shows the joint spectral intensity, $C(\omega_1, \omega_2)$ with a visible modulation pattern. The off-diagonal parts of the signal contain artifact free information. It is now the matter of the appropriate algorithm to extract the right detuning form the central diagonal in order to obtain information about the layer structure of the object. It was also observed by the collaborator, but not reported yet, that the artifacts can be used to improve resolution of the method. This is additional information, which originate in interference effect, which improves the measurement.

Photon pairs generated in the SPDC process can feature quantum correlation, which can be used to reduce unwanted effects such as the impact of the chromatic dispersion on the spatial resolution. However, entanglement is not always a necessary condition for enhancements. An experimental setup as depicted in Fig. 10 was used to demonstrate a method based on single photon counting, but with the SPDC photon pair source substituted with faint laser pulses attenuated to the single photon level [18][H3].

An example measurement result is depicted in Fig. 11, where a depth profile of an onion slice is imaged using this method. The detailed analysis shows the resolution of approximately 18μm at the distance of 1.1 mm was possible. It was also showed in another work [19][H1] that the advantage, which was attributed unequally to quantum properties of the light, is also present when classic intensity correlation measurements are performed.

Summarizing, in practice quantum optical coherence tomography is limited by the efficiency (due to the loss of the light in the system and sample) and by the characteristics of fundamental effect, Hong-Ou-Mandel interference, which it is build on. The goal was to show how in practice the artifacts originating form quantum interference can be neglected [17][H5] and to analyze the case where quantum optical methods, such as photon counting, can be useful, but quantum

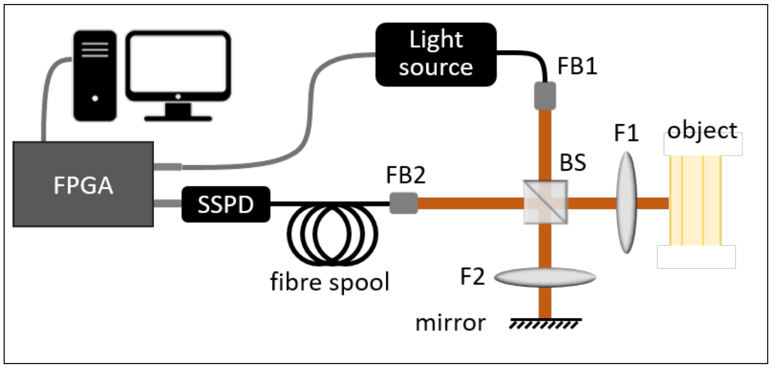

FIG. 10. Quantum-inspired detection for Spectral DomainOptical Coherence Tomography [18][H3]. The light source is a pulsed laser attenuated to a level of single photon per pulse. Pulses are coupled to a fibre (FB1) and propagate in a Linnik-Michelson interferometer. The input wavepacket (pulse) is then split at a beamsplitter (BS) into two arms. In the object arm, one wavepacket interacts with the object and acquires an additional phase; in the reference arm, the other one is reflected from the mirror. They both overlap at the beamsplitter and the output is coupled to a single-mode fibre spool using a fibre coupler FB2. The time-resolving Superconducting Single-Photon Detector (SSPD) together with the long dispersive fibre spool work as a spectrometer. Time reference is provided by a photodiode signal from the light source. The data is collected using an FPGA time-stamping electronics. F1, F2 - lenses.

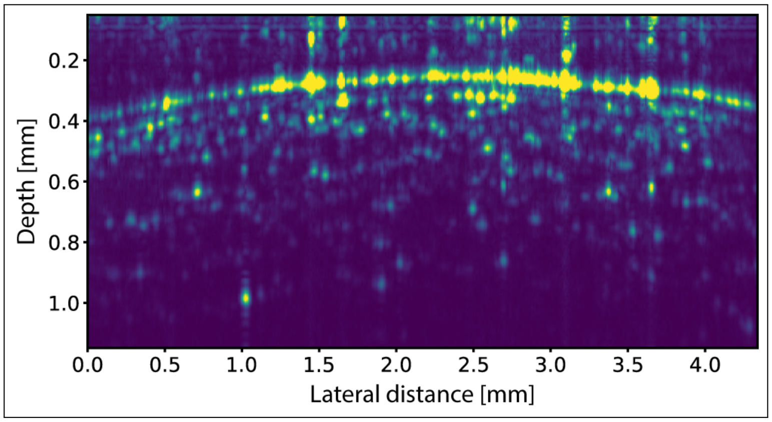

FIG. 11. An image of an onion slice [18][H3]. An average of 10 B-scans acquired at the intensity level of approx. 10 pW.

entanglement is not necessary [18][H3], [19][H1].

III. APPLICANT CONTRIBUTIONS

S. Kolenderska, P. Kolenderski, *Intensity correlation OCT is a classical mimic of quantum OCT providing up to twofold resolution improvement*, Sci Rep **11**, 11403 (2021) – I supervised and supported the experimental and theoretical part of the project which was related to quantum optical effects in optical coherence tomography. I also provided experimental means for the implementation of the experiment, and edited the manuscript.

Artur Czerwinski, Karolina Sedziak-Kacprowicz, Piotr Kolenderski, *Phase estimation of time-bin qudits by time-resolved single-photon counting* Phys. Rev. A, **103**, 042402 (2021) – I initiated the research line on the measurement method of time-bin encoded states, prepared the research plan, acquired funds, supervised the work of the PhD student and the postdoc, and edited the manuscript.

S. Kolenderska, F. Vanholsbeeck, P. Kolenderski, *Quantum-inspired detection for spectral domain optical coherence tomography* Opt. Lett., **45**, 3443 (2020) – I supported the experimental and theoretical part of the project which was related to quantum optical effects in optical coherence tomography. I also provided experimental means for the implementation of the experiment, and edited the manuscript.

M. Lasota, P. Kolenderski, *Optimal photon pairs for quantum communication protocols*, Sci. Rep. **10**, 20810 (2020) – I initiated the project on the optimization of the entire quantum communication setup, supervised the work of the postdoctoral fellow, and acquired funds for this research, and edited the manuscript.

S. Kolenderska, F. Vanholsbeeck, P. Kolenderski, Fourier domain Quantum Optical Coherence Tomography Opt. Express., 28, 29576 (2020) – I supported the experimental and theoretical part of the project which was related to quantum optical effects in optical coherence tomography. I also provided experimental means for the implementation of the experiment, and edited the manuscript.

M. Lasota, P. Kolenderski, *Quantum communication improved by spectral entanglement and supplementary chromatic dispersion*, Phys. Rev. A, **98**, 062310 (2018) – I am the author of the idea, supervised the work of the postdoctoral fellow, and acquired funds for this research, and edited the manuscript.

K. Sedziak, M. Lasota, P. Kolenderski, *Reducing detection noise of a photon pair in a dispersive medium by controlling its spectral entanglement*, Optica, **4**, 84 (2017) –I initiated the project and I am the author of the idea. I prepared the research plan, acquired funds and supervised the work of the PhD student and the postdoc, and edited the manuscript.

P. Kolenderski, C. Scarcella, K. D. Johnsen, D. R. Hamel, C. Holloway, L. K. Shalm, S. Tisa, A. Tosi, K. J. Resch, T. Jennewein, *Time-resolved double-slit interference pattern measurement with entangled photons* Sci. Rep., **4**, 4685 (2014) – I led the project, co-authored the idea, implemented the experiment and edited the manuscript.

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