Doctoral Dissertation Review Report

PhD Candidate: Michał Lipka
Thesis title: Ultrafast Quantum Optics with Spectral Resolution
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This report is a review of the doctoral dissertation by Michał Lipka. He has published 24 articles, of which he is first author of 11. These articles are published in high quality journals: 1 in Nature Communications (14.7 impact factor), 1 in Applied Physics B (2.0 impact factor), 3 in Optics Express (2.0 impact factor),1 in Applied Physics Letters (3.5 impact factor), 3 in Optics Letters (3.1 impact factor), 4 in Physical Review Letters (8.1 impact factor), 2 in Physical Review A (2.6 impact factor), 1 in npj Quantum Information (6.6 impact factor), 2 in Physical Review Applied (3.8 impact factor), 1 in Optica (8.4 impact factor), 1 in IEEE Journal on Selected Areas in Communications (13.1 impact factor), 1 in Quantum (2.0 impact factor), 1 in New Journal of Physics (2.8 impact factor), and 1 in Communications Physics (5.4 impact factor). These articles have been well-received by the scientific community as evidenced by the number of citations that they have received since publication (over 400 citations according to Google Scholar). This is a good sign for Michał's long-term professional success.

The thesis is based upon work in five of the publications including one preprint. The dissertation presents research related to characterization and manipulation of ultrashort optical pulses including entangled photon pairs generated from the nonlinear optical process of spontaneous parametric down conversion (SPDC). Overall, the dissertation is well written and organized. The introductory chapter (Chapter 0) presents the general theoretical foundations of quantum optics with ultrashort pulses, particularly defining wave-packet creation and annihilation operators photon-number (Fock) states, including single-photon states occupying ultrashort pulses, and coherent states that are often used to represent the state of the field generated by a laser.

Chapter 1 presents experimental results associated with a novel image intensified camera system capable of measuring single-photon-level fields at a high data rate. This camera is used throughout the thesis as a tool for characterizing quantum light fields. The key innovation is combining a gated image intensifier, constructed with custom gating electronics for fast switching, with a fast Complementary Metal-Oxide-Semiconductor (CMOS) charge-coupled device (CCD) array that harnesses custom readout electronics and data analysis. The system is shown to allow measurement of single-photon-level fields as well as perform photon correlation measurements, including the second-order intensity correlation. This demonstrates that the camera is capable of characterizing entangled photon pairs, which is the topic of Chapter 2.

Chapter 2 presents measurements of spatial-spectral correlations between photon pairs generated in SPDC utilizing the camera described in Chapter 1. The necessary theory of SPDC, in which a pair of photons can be

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probabilistically generated, is described within Chapter 2. In the process, a strong optical field, known as the pump, is incident on a material with a nonlinear optical response. As the pump propagates through the material, a pair of photons, traditionally called signal and idler, can be produced through the nonlinear optical interaction, in which a pump photon is annihilated in the process. Correlations between the signal and idler photons can arise in this process in the polarization, transverse-spatial and spectral-temporal degrees of freedom, which can be viewed as entanglement between photon pairs. These correlations, which arise due to energy and momentum conservation, can be controlled by choice of pump field spatial and temporal mode shape as well as properties of the second-order nonlinear medium. In the experiments presented in Chapter 2, measurements of correlations between spatial and spectral degrees of freedom of photon pairs are shown, demonstrating the camera can indeed be used to characterize the spatial-spectral state of photon pairs.

Chapter 3 presents another application of the photon-counting camera. Here a pair of spectrally broad bandwidth photon pairs is generated through the SPDC process. One of the photons, the probe, is passed through a highly-dispersive sample, in this case an atomic vapor, while the other photon, the reference, remains unaltered. The photon pairs are then interfered on a balanced beam splitter, followed by frequency-resolved coincidence measurements performed using the photon-counting camera with a grating-based spectrometer. The spectrally-resolved two-photon interference pattern provides redundant information about the spectral phase imposed on the probe photon, which enables phase extraction using quantum light. The measurement technique may find applications in time-dependent spectroscopy utilizing weak probe fields rather than the strong fields typically encountered in such experiments.

Chapter 4 presents an interferometric method to characterize ultrashort optical pulses at the single-photon level. The technique involves sending the pulse to a Mach-Zehnder interferometer comprised of two beam splitters. One path of the interferometer introduces a known time delay and the other path introduces a known frequency shift, or spectral shear. The two paths are interfered on the second beam splitter, as is common in spectral shearing interferometry for direct electric field reconstruction (SPIDER). Here, instead of performing frequency-resolved measurements for a single setting of delay and spectral shear at the output of the interferometer, intensity correlation measurements are made at the output of the interferometer as a function of the time delay and spectral shear. This second-order intensity correlation measurement allows one to extract the first-order coherence properties of the field, which for a single-temporal mode field is equivalent to determining the wave packet spectral amplitude and phase, as assumed in SPIDER. The spectral shear is implemented here using fast, electro-optic phase modulation that is synchronized with the optical pulse, an experimental setup that was developed by Michał Lipka. As acknowledged in the thesis, the majority of the experimental work described in this chapter was carried out by two bachelors students, with guidance from two faculty members. Michał supervised the day-to-day work including construction of parts of the setup; writing parts, and supporting the development of the experiment control and measurement software and data analysis; and writing substantial parts of the manuscript.

Chapter 5 demonstrates the use of the fast electro-optic phase modulation methods developed by Michał Lipka to realize a fractional Fourier transform on temporal modes at the single-photon level and classical field regime.

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The theory of the fractional Fourier transform is reviewed and its implementation via sequential application of quadratic spectral phase, quadratic temporal phase and a second quadratic spectral phase. Then experimental results are presented that demonstrate the ability to perform the fractional Fourier transform on temporal modes. A major innovation that enabled Michał to realize this mode transformation is the precise quadratic temporal phase that can be achieved using electro-optic phase modulation driven by a radio-frequency (RF) signal derived from the optical signal to be modulated. This approach allows the RF signal and optical pulse to be synchronized to high accuracy, while providing a large overall phase modulation amplitude. This technique demonstrates the necessary building blocks for more complicated temporal mode processors.

Chapter 6 presents a quantum sensing application of the quadratic spectral and temporal phase modulation techniques described in Chapters 4 and 5 to perform an experiment aimed at distinguishing two spectrally shifted pulses that have no phase coherence between them. This is analogous to spatially resolving two incoherent objects with overlapping point-spread functions arising from the imaging system. The theory of the resolving power of the measurement is presented in terms of Fisher information and it is shown that by using a coherent measurement, one can achieve better resolution than using intensity measurements, which is a well-known result for the spatial analog. To implement a measurement that provides spectral resolution beyond what can be achieved using direct detection an interferometric approach is realized. The signal to be measured is split in two paths. In one path the temporal-mode Fourier transform is performed, and in the other path the temporal-mode inverse-Fourier transform is performed. The temporal-mode (inverse-)Fourier transform is realized experimentally using a sequence of quadratic spectral phase, quadratic temporal phase (with opposite sign) and quadratic spectral phase. These paths are interfered on a second beam splitter and the intensity at the each output is monitored. The relative intensities at the outputs of the interferometer are used to provide an estimate for the spectral separation of the incoherent input sources. The experimental results show that using this interferometer comprised of two phase modulators, one in each arm of the interferometer, one can effectively perform coherent temporal mode sorting, a central task in many quantum applications in which the quantum information of interest is encoded in the temporal mode shape of light. Thus, it is likely that the methods presented will find application beyond the quantum sensing application.

The dissertation clearly presents the candidate's general theoretical knowledge in ultrafast quantum optics and quantum information science as noted above. Most of the experiments described within the thesis were performed by the candidate with only supervisory input from the thesis advisors (Chapter 4 being the exception where the contributions are clearly articulated). Furthermore, the overall subject of the doctoral dissertation, which is focused on the control and characterization of ultrafast quantum states of light, is at the cutting edge of research in quantum optics and quantum information science. The dissertation presents key technological innovations – specifically a novel single-photon counting camera and fast electro-optic phase modulation techniques – along with nice applications of these for quantum information science (e.g. quantum spectroscopy, temporal mode sorting and temporal mode manipulation).

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In conclusion, I find the presented material meets all requirements for the PhD dissertation. The author has published several high-quality papers and continues to be scientifically active. His contribution to the field is highlighted by high-profile publications.

Sincerely,

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