Summary of Professional Accomplishments

1. *Name*

   Michał Karpiński

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*

- Magister (MSc equivalent) degree in physics (with distinction), Faculty of Physics, University of Warsaw, 2006.
- Doktor (PhD) degree in physics (with distinction), title of PhD dissertation: „Engineering of quantum correlations in optical systems", Faculty of Physics, University of Warsaw, 2012.

3. Information on employment in research institutes or faculties/departments or school of arts.

2012 – 2013	research-technical specialist, University of Warsaw, Faculty of Physics.
2013 – 2016	post-doctoral research associate, University of Oxford, Department of Physics, United Kingdom.
from Oct 2015	adiunkt (assistant professor), University of Warsaw, Faculty of Physics.

4. *Description of the achievements, set out in art. 219 para 1 point 2 of the Act*

   The description should be a substantive depiction of the achievements in question, as well as precisely define the individual contribution to their creation, in the case where a given achievement is a jointly authored work, taking into account the possibility of indicating achievements from the period of the entire professional career.

4.1 *Title of the scientific achievement*

Shaping single-photon light pulses using temporal optics methods

4.2 List of publications forming the basis of the scientific achievement

H1. F. Sośnicki, M. Mikołajczyk, A. Golestani, M. Karpiński, *Interface between picosecond and nanosecond quantum light pulses*, Nature Photonics **17**, 761 (2023), 22 citations.

H2. A. Golestani, A. O. C. Davis, F. Sośnicki, M. Mikołajczyk, N. Treps, M. Karpiński, *Electro-optic Fourier transform chronometry of pulsed quantum light*, Physical Review Letters **129**, 123605 (2022). 6 citations.

H3. M. Karpiński, A. O. C. Davis, F. Sośnicki, V. Thiel, B. J. Smith, *Control and measurement of quantum light pulses for quantum information science and technology*, Advanced Quantum Technologies **4**, 2000150 (2021). 28 citations.

H4. F. Sośnicki, M. Mikołajczyk, A. Golestani, M. Karpiński, *Aperiodic electro-optic time *lens for spectral manipulation of single-photon pulses,* Applied Physics Letters **116**, 234003 (2020). 12 citations.

H5. F. Sośnicki, M. Karpiński, *Large-scale spectral bandwidth compression by complex electro-optic temporal phase modulation*, Optics Express **26**, 31307 (2018). 19 citations.

H6. M. Karpiński, M. Jachura (equal contribution), L. J. Wright, B. J. Smith, *Bandwidth manipulation of quantum light by an electro-optic time lens,* Nature Photonics **11**, 53 (2017). 116 citations.

H7. L. J. Wright, M. Karpiński, C. Söller, B. J. Smith, *Spectral shearing of quantum light pulses by electro-optic phase modulation*, Physical Review Letters **118**, 023601 (2017). 59 citations.

The number of citations according to Web of Science: 585 (without autocitations).

Copies of the above publications are included as appendix no. 5.

Appendix no. 6 contains the statements of the co-authors of the publications, apart from Michał Jachura, whose contribution is listed in the publication no. H6.

4.3 Description of the scientific achievement

4.3.1 Introduction

The concept of energy quanta of the electromagnetic field, later called photons, was put forward more than 120 years ago by Planck in order to explain the spectrum of black body radiation. Initially, photons seemed to be only an auxiliary concept, allowing to reconcile experimental results and theoretical predictions. However, the development of the theory of quantum electrodynamics as well as pioneering experiments concerning, among others, antibunching of photons, finally confirmed the existence of photons as energy quanta of the electromagnetic field, independently of the emitting or absorbing medium [Kimble77, Mandel95]. In particular, they allowed to formulate the concept of the photon wave function [Białynicki94, Smith07].

A photon is most often described as a single excitation of an electromagnetic wave with a well-defined frequency. It would then have a precisely defined energy, equal to the product of the frequency and the Planck's constant. However, it is physically impossible for photons to exist with a precisely defined energy. This results from the Fourier transform: a signal with a precisely known frequency must be infinite in time – and the photon must have been emitted at a finitely distant time. A more complete description of a photon is a single excitation of a certain wave packet, which is a superposition of excitations with well-defined energies [Fedorov05, H3]. This allows for a description of a situation in which the photon energy is not uniformly distributed in time. In particular, if we limit ourselves to time scales much longer than the period of the considered oscillations of the electromagnetic field, which can be formalized as the so-called slowly varying envelope approximation [Fedorov05], we can talk about single-photon pulses of light: wave packets of effectively finite duration and a frequency spectrum of non-zero width. Here we will consider single-photon pulses with frequencies in the optical range, however the concepts discussed here can also be applied to other frequency ranges of electromagnetic radiation, both higher (X-rays, gamma rays) and lower (terahertz and microwave photons) [Rosenfeld20, Adams24].

Of course, we must remember that a single-photon pulse contains a single quantum of energy. Hence, when measuring the detection time of a photon in the form of a wave packet with a duration of, for example, 50 ps, we will obtain a random value of the detection time in the range of about 50 ps (depending on the specific shape of the temporal envelope of the wave packet). Similarly, a single measurement of the frequency will result in a certain value in the range of at least approximately 9 GHz (this results from the Fourier transform of a pulse with a time width of 50 ps). Only multiple preparation of single-photon pulses (in the same way) and multiple measurements allow recording histograms of photon detection times and of measured photon frequencies (energies).

In recent years, studies of single-photon light pulses have concerned, on the one hand, their fundamental properties, and on the other hand, their applications. They include, among others, methods of generating and measuring single-photon pulses [Cooper13, P17, Ding25], time measurement issues in quantum mechanics [Maccone20], issues concerning correlations between photons in time and energy, including entanglement of photons in the time-spectral degree of freedom [Davis20]. From the application side, research is underway on the use of single-photon pulses as carriers of quantum information [Hayat12, Humphreys13, Brecht15, Reimer16, H3], enabling its efficient transmission over long distances, efficient transfer of the transmitted quantum information to material objects (such as quantum memories or quantum processors) [Awschalom21, Uppu21], obtaining information on parameters of interest in an optimal way (quantum metrology) [Donohue18, Mukamel20], as well as on the processing of quantum information (including quantum computations) using photon-only approach [Madsen22, PsiQ25].

A significant challenge concerning the above-mentioned research topics (and more) is the possibility of modifying single-photon light pulses, for example by changing their duration, central wavelength, spectral width, or spectral-temporal profile of the wave packet [Kimble08, Wallquist09]. The research results published until the period of formulating the idea of this habilitation project in 2013–2015 focused on the development of single-photon sources with specific spectral-temporal properties [Mosley08, Takeuchi14] and on single-photon frequency conversion (quantum frequency conversion) [Huang92, Zaske12]. Within this habilitation project I focused on the study and development of methods for modifying single-photon wave packets after their generation, independent of their source.

Previous studies in this area were very limited: they included, on the one hand, experimental works using experimentally complicated methods based on nonlinear optics [Lavoie13, Donohue14], on the other hand, isolated works on electro-optic modification of the spectrum of single photons [Rakher11, Olislager12], in particular by means of amplitude modulation [Kolchin08]. I have identified a set of methods, which until then were developed and employed experimentally exclusively in the context of classical optics, which allows a systematic approach to experimental shaping of single-photon pulses: the approach using temporal optics methods [Torrres11, H3]. Moreover, it allows improving the temporal and spectral resolution of measurements of the spectrum and temporal profile of single-photon light pulses.

The challenge is illustrated by the example of a 50-ps-long pulse given earlier: it is only slightly longer than the temporal resolution of the best efficient single-photon detectors (ca. 10 ps), while its spectral bandwidth of 9 GHz is comparable to the resolution of the best optical spectrometers capable of multichannel detection (2–10 GHz, depending on the spectral range). Collecting at least 10 experimental points in time and frequency by direct measurement is an experimental challenge. The methods of temporal optics, such as time-to-frequency mapping or temporal imaging can help overcome these limitations [Torres11, Salem13, H3].

Before describing the series of publications, I will briefly present the basics of temporal optics. Temporal optics is based on the analogy between the mathematical description of the diffractive propagation of light in space and the dispersive propagation of short optical pulses in dispersive dielectric media [Kolner94]. I will begin by presenting the analogy between a spatial lens and a temporal lens.

A temporal lens is a time-frequency analogue of a traditional optical lens, which we will call a "spatial lens" from now on. From the point of view of Fourier optics [Goodman], imaging with a thin spatial lens (in the paraxial approximation) is achieved by subjecting the wave emitted by the object to appropriate phase changes in complementary degrees of freedom. The wave emitted by an object undergoes diffractive propagation according to the Fresnel-Kirchhoff equation. As a result of this diffractive propagation towards the lens, it acquires a phase that depends quadratically on the transverse component of the wave vector k_T (for simplicity we limit ourselves here to one transverse dimension). Upon propagation through the lens, the wave experiences a phase shift that depends quadratically on the transverse position. Finally, during diffractive propagation towards the image plane, the wave again acquires a phase that depends quadratically on k_T. When the values of these three quadratically varying phases correspond to the fulfillment of the imaging condition, we obtain a scaled image of the object in the image plane, where the image magnification is determined by the ratio of the phase quadratically dependent on k_T accumulated by the wave during diffractive propagation in front of and behind the lens (or in other words, the ratio of the distances between the image and object planes and the lens).

The mathematical form of the Helmholtz equation describing the spatial propagation of an optical wave in the paraxial approximation and the equation describing the propagation of a light pulse in dispersive media in the slowly varying pulse envelope approximation are the same:

$$\frac{\partial A_{\mathrm{s}}(x,z)}{\partial z} = -\frac{i}{2k}\frac{\partial^2 A_{\mathrm{s}}(x,z)}{\partial x^2}, \qquad \frac{\partial A_{\mathrm{t}}(\tau,z)}{\partial z} = \frac{i\beta_2}{2}\frac{\partial^2 A_{\mathrm{t}}(\tau,z)}{\partial \tau^2},$$

where A_s is the position-dependent amplitude of the field undergoing diffraction, z is the position along the direction of propagation, x is the transverse position, k is the length of the wave vector, A_t – time-dependent amplitude of the field, β_2 – group velocity dispersion, and τ is the time (in the reference frame of the pulse).

W związku z tym, możliwe jest zastąpienie w powyższym wywodzie poprzecznej składowej położenia przez zmienną czasową, a składowej poprzecznej wektora falowego (będącej transformatą Fouriera składowej porzecznej położenia), przez częstotliwość fali optycznej.

Consequently, it is possible to replace the transverse position in the above reasoning by the time variable, and the transverse component of the wave vector (which is the Fourier transform of the transverse position) by the frequency of the optical wave.

In full analogy to the spatial lens, it is possible to realize imaging of the temporal profile of a light pulse using a temporal lens, by subjecting it to a phase that is quadratically dependent on frequency, quadratically dependent on time and again quadratically dependent on frequency. With the appropriate selection of the proportions of these quadratically variable phases, a magnified or demagnified "image" of the temporal profile of the pulse can be obtained [Kolner89, Foster11].

The medium that allows subjecting the pulse to a phase that is quadratically dependent on frequency is a regular dispersive medium – the desired phase is obtained as a result of the group velocity dispersion of the medium. A more difficult issue is the implementation of the temporal lens itself, i.e., of a device that subjects the pulse to a phase that is quadratically dependent on time. In the case of temporal lenses for high-intensity light pulses, nonlinear optical interactions with a strong pump pulse with a linearly time-varying frequency (i.e. chirped pulses) are used for this purpose [Foster11]. However, the use of methods using strong pump beams in quantum optics is significantly hampered by the difficulty of simultaneously achieving a high probability of nonlinear interaction in the case of single-photon signals and eliminating the photon noise originating from the strong pump beam.

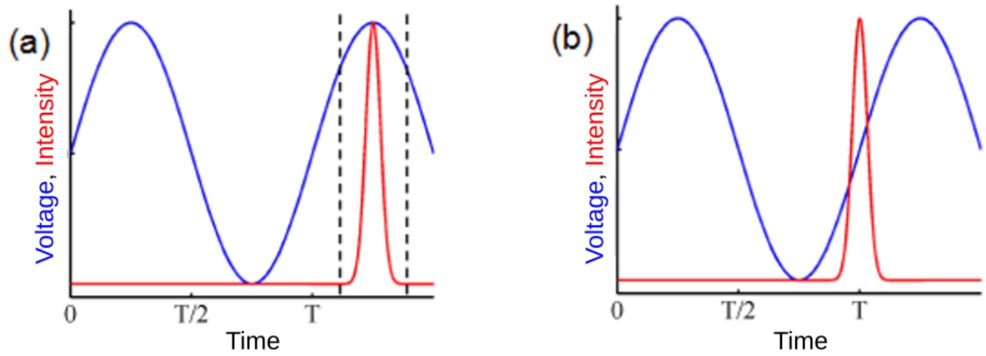

Fig. 1. Intensity of a short pulse of light (red, arbitrary units) against a background of a sinusoidally varying voltage (blue, arbitrary units) inducing a change of the refractive index of an electro-optic medium that is proportional to the voltage. (a) The pulse experiences a phase that varies quadratically in time. (b) The pulse experiences a phase that varies linearly in time. The synchronization between the pulse and the voltages signal as in (a) corresponds to the implementation of a temporal lens; the arrangement as in (b) implements a "temporal prism." The dashed lines indicate the aperture of the temporal lens: the range of phase variation that can be approximated by a parabola.

The electro-optic effect (Pockels effect) can be used to realize a temporal lens without using strong pumping beams, i.e., without using optical nonlinearities. As a result of applying a voltage to a material with electro-optic properties. In the case of a time-varying voltage, a time-varying phase is obtained by a light pulse propagating through the medium. This effect can be used to obtain a phase quadratically dependent on time, i.e. a temporal lens, as shown in Fig. 1 [Kolner89, Zhang13]. In this case, the implementation of the temporal lens is deterministic and takes place without the use of strong optical fields, which makes it extremely attractive from the point of view of applications in quantum optics.

The presented series of publications entitled "Shaping single-photon light pulses using temporal optics methods" includes conceptual and experimental studies aimed at verifying the possibilities of using temporal optics methods to realize transformations of single-photon light pulses and verifying their potential in the context of applications in the field of optical quantum technologies. At the time of starting work on this series of publications, only a few works on the use of temporal optics methods, such as temporal prisms or temporal lenses, to study issues related to quantum optics had been published. In [Lavoie13, Donohue13, Donohue14] the nonlinear-optical time lens using optical frequency mixing with a chirping pump beam was applied to single-photon pulses. It should be noted that the results presented in the works [Lavoie13, Donohue13] were not presented in the context of temporal optics, despite their use [Salem13]. Similarly, [Agha14] proposed to change the spectral width of single photons by three-wave-mixing with a chirp pump, i.e. by means of a nonlinear temporal lens, without referencing the extensive temporal optics literature. [Matsuda16] presented experimental results of modifying the spectrum of single photons using temporal phase modulation by means of the nonlinear optical Kerr effect. Before 2014, the only references to the use of temporal optics methods in quantum optics, according to my knowledge, were in the following works: [Zhu13] contains a theoretical discussion of spectral shaping of single-photon light pulses by means of two nonlinear temporal lenses, together with an experimental implementation using low-intensity classical light with single-photon detection. In addition, in [Nunn13] a theoretical concept of using the improvement of photon detection resolution in time using a time-frequency converter based on electro-optical parabolic phase modulation is presented in a new quantum cryptographic key distribution protocol based on multidimensional encoding in time and frequency. In [Tsang06] the concept of modifying the quantum state of pairs of photons entangled in time using time imaging with electro-optical time lenses is presented. These results are included in the review paper [Torres11].

To sum up, at the time of starting the work on the cycle of publications, there were sevaral published works on the modification of the spectral width of single photons using nonlinear optical methods and single theoretical works proposing the use of temporal optics methods based on electro-optic modulation for the spectral-temporal shaping of optical pulses in the context of quantum optics.

4.3.2 Cycle of thematically related scientific articles

The series of publications includes works on the electro-optic spectral shift of single-photon optical pulses (papers H7 and H2) and on the modification of the spectral width of single photons (papers H6, H5, H4 and H1). Paper H3 presents a review and analysis of the applications of temporal optics methods in the context of quantum optics and photonics. The experimental studies included in publications H6 and H7 were carried out in the laboratories of the Department of Physics at the University of Oxford in the research group of Prof. Brian J. Smith. They concerned photons with a central wavelength in the near-infrared range, around 830 nm wavelength. The remaining publications concern photons from the telecommunications wavelength range (around 1560 nm). The experimental work that is the basis for the H1, H2, and H4 papers was performed in the research group that I created and led, at the Quantum Photonics Laboratory, within the Faculty of Physics, University of Warsaw. It should be emphasized that, although the theoretical foundations of these two groups of papers are similar, their experimental implementation is significantly different, due to different light detection techniques and significantly different availability of optical fibre components in these two spectral ranges. In section 4.2 the publications forming the cycle are arranged chronologically, starting with the newest one. Here, I will present the publications in the order resulting from the connections between them, starting with the oldest one. In several cases, this order is not chronological.

Electro-optic spectra shifting of photons – the time prism

(2 publications)

[H7] L. J. Wright, M. Karpiński, C. Söller, B. J. Smith, *Spectral shearing of quantum light pulses by electro-optic phase modulation*, Physical Review Lette **118**, 023601 (2017).

The paper presents an experimental realization of deterministic and continuously tunable single photon spectrum shift. Single-photon ultrashort light pulses were generated using the heralded single photon technique, by detecting one photon from a pair of photons generated in a nonlinear process of spontaneous parametric frequency division. By using a photon pair source providing an appropriately symmetrical joint photon spectrum, the announced photons had the form of a coherent wave packet with a duration of about 1 ps (they were in a pure state) [Mosley08]. The photons were transmitted by an electro-optical phase modulator controlled by a sinusoidal microwave electrical signal synchronized with optical pulses with a frequency of 40 GHz and power above 2 W, which corresponds to an amplitude of ±15 V for an impedance of 50 Ω.

Through the electro-optical Pockels effect combined with the modulator operating in the phase-matched traveling wave mode (i.e., with synchronized propagation of the optical pulse and the microwave signals along the modulator), the electric field applied to the modulator electrodes resulted in a change in the effective refractive index that was proportional to the applied voltage.

Synchronization of single-photon pulses with the, respectively, rising or falling edge of the sinusoidal electric signal resulted in a shift of the spectrum of single-photon wave packets. This effect is a realization of the simplest scheme of temporal optics: the temporal prism. It is an analogy of the spatial prism: the spatial prism introduces an optical path that linearly increases with the position in the direction transverse to the direction of propagation of the light beam. The effect is a change in the direction of propagation, i.e. a shift of the spatial spectrum by a constant value (dependent on the prism angle and the prism material). In the spectral-temporal case, a linearly varying phase in time results in a spectral shift of the signal. This effect can also be understood purely in the context of the Fourier transform properties: if a signal $\psi(t)$ has a Fourier transform (spectral amplitude) of $\tilde{\psi}(\omega)$, then the when we multiply the signal by the linearly varying phase: $\psi(t)e^{i\Omega t}$, the resulting Fourier transform will yield $\tilde{\psi}(\omega-\Omega)$: a spectrally shifted signal.

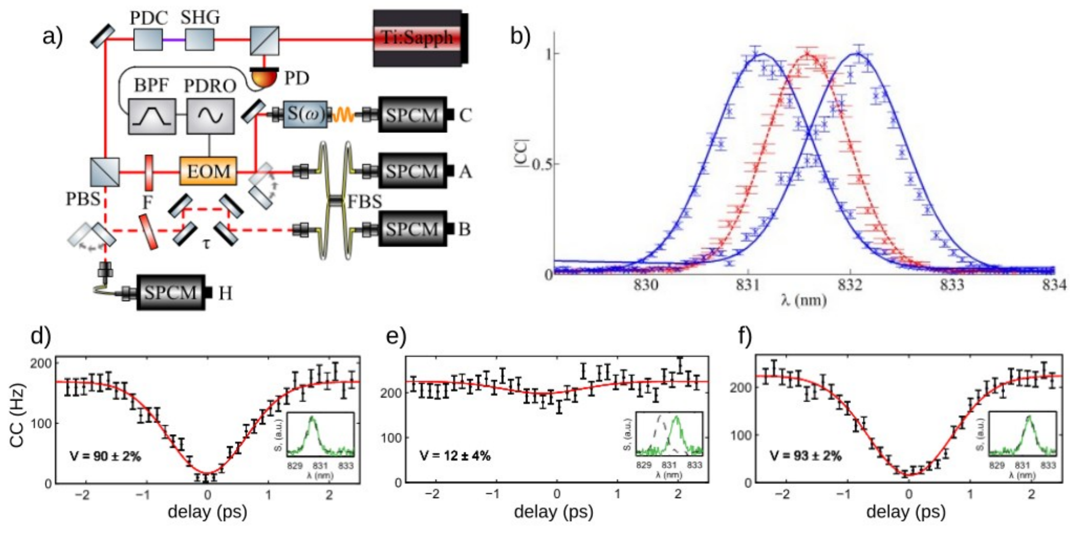

Fig. 2. a) Schematic diagram of the experimental setup used in the H7 paper. Femtosecond pulses with a central wavelength of 830 nm and a repetition rate of 80 MHz generated by a titanium-sapphire (Ti:Sapph) oscillator are directed to a second harmonic crystal (SHG). The second harmonic beam (415 nm) pumps the spontaneous parametric down conversion process in the KDP crystal (PDC). The frequency-degenerate pairs of perpendicularly polarized photons created in the crystal are separated on a polarizing beam splitter (PBS). The spectrum of one of the resulting photons is wider than the spectrum of the second photon. In the case of a spectral shift of herladed photons, one of the photons of

the pair is directed to a single photon detector (SPCM H), while the other, after passing through a spectral filter (to remove the pump beam), is directed by an optical fiber to an electro-optic phase modulator (EOM, usable bandwidth: 40 GHz). The modulator is driven by an amplified 40 GHz sinusoidal electrical signal, generated by a voltage-controlled oscillator phase-locked to a reference signal from a photodiode (PD) monitoring pulses from the Ti:Sapph laser beam, filtered by a narrowband microwave filter (BPF). By adjusting the phase of the microwave signal, an overlap in time of single-photon pulses with the linear part of the sinusoidal microwave signal is achieved, as in Fig. 1(b). The monochromator $S(\omega)$ together with the single-photon detector (SPCM C) enable the measurement of the spectrum, in coincidence with the detection of a photon on the SPCM H detector. The spectra measured in coincidence mode (CC) are shown in panel (b). Red: phase modulation off; blue: phase modulation on, synchronization as in Fig. 1(b) and shifted by half the microwave signal period. Positive and negative spectral shifts are visible. In panels (d), (e), (f) the results of Hong-Ou-Mandel interference measurements of photons passing through the modulator and reference photons are presented. Spectra of interfered photons are presented in the insets (photons passing through the modulator – black; reference photons – green). In order to perform Hong-Ou-Mandel interference measurements, the second photon after the PBS was directed through a tunable spectral filter F and a delay line τ to a fibre optic beam splitter (FBS). Photons passing through the modulator were directed to the second input of the FBS. The FBS outputs were connected to two single-photon detectors, SPCM A, B; coincidences from two photon counters were recorded. In panel (d) the coincidence counts are presented as a function of delay for the case of switched off electro-optic modulation and for the matched reference photon spectrum. Panel (e) shows the measurement results after switching on the electro-optic modulation: the spectrum of the signal photons is shifted, which causes the interference visibility to decrease. After tuning the reference photon spectrum by rotating the spectral filter F, high interference visibility is restored.

The spectra of photons shifted towards shorter and longer wavelengths were measured by scanning the output of a grating spectrometer with a single photon detector operating in coincidence with the heralding detector. The histograms of photon counts for individual transverse positions of the detector, corresponding to different wavelengths, allowed the measurement of the spectrum of single photons. A clear spectral shift of about 0.5 nm was observed in each direction.

Furthermore, the non-classicality and coherence of the single-photon pulses spectrally shifted by the electro-optic time prism were verified. Two-photon Hong-Ou-Mandel interference measurements were performed between reference photons (not subjected to the action of the time prism) and photons subjected to electro-optic phase modulation (i.e., under the action of the time prism). It was shown that the spectral shift enabled the visibility of two-photon interference to be increased from about 10% (for mismatched central wavelengths) to 90% (by matching the central wavelength of the modulated photon to the central wavelength of the reference). This experiment confirmed that the time prism preserves the coherence of the spectrally shifted wave packets and that it does not introduce amplitude noise, which enables non-classical interference of photons subjected to the time prism. The time prism effect can be used to tune the central wavelength of single-photon wave packets, for example those emitted from quantum dots [P30].

The initial concept of this work was not formulated in the context of temporal optics. During the work towards this publication, I identified for the first time the possibility of using the temporal optics description, among others through the concept of a time prism. The initial research conducted by me within this work became one of the main impulses for formulating the goal of this series of publications.

Applicant's contribution: *I rebuilt and improved the elements of the experimental system: the source of photon pairs, measurement of the photon spectrum. Together with a PhD student, I started and tested the operation of the synchronized electro-optical modulation system. I proposed to perform the part of the experiment concerning two-photon interference and developed a method of its implementation within the available experimental parameters. I supervised the collection of final experimental data. I contributed to writing the text of the publication and to preparing figures and graphs.*

[H2] A. Golestani, A. O. C. Davis, F. Sośnicki, M. Mikołajczyk, N. Treps, M. Karpiński, *Electro-optic Fourier transform chronometry of pulsed quantum light*, Physical Review Letters **129**, 123605 (2022).

The paper presents and experimentally implements a new method for characterizing the temporal envelope of short light pulses, with a duration shorter than the time resolution of available detectors. The method is presented for classical light and for heralded single photons.

The Fourier chronometry method is based on a principle analogous to Fourier transform spectroscopy, but with the role of time and frequency reversed. In Fourier transform spectroscopy, the light intensity at the output of an interferometer is recorded with respect to the time delay between the interferometer arms. The Fourier transform of this signal allows determining the spectrum, thanks to the use of the Wiener-Khinchine theorem. In Fourier chronometry, the intensity (or number of photons) at the output of the interferometer is also measured, but this time the spectral shift between the interferometer arms is varied. This allows recording the intensity at the output as a function of the spectral shift. The inverse Fourier transform allows recovering the temporal profile of the pulse. In the experiment, the tunable spectral shift was realized using an electro-optic time prism – analogous to the H7 work, but at a different wavelength of about 1560 nm in this case. The increase in the pulse duration during propagation in a medium with group velocity dispersion was successfully measured using the technique. The technique can find applications for the characterization of short light pulses in situations where the measurement of the spectrum (which is necessary for standard short pulse characterization techniques, such as FROG or SPIDER) is impossible due to an unusual spectral range or low signal level.

Applicant's contribution: *I made a leading contribution to the experimental part of the work and to writing the publication. I identified the range of experimental parameters allowing for the implementation of the experiment, designed the experimental setup based on the theoretical proposal of foreign partners. I supervised the execution of the experiment and the analysis of experimental data. I wrote a significant part of the text of the publication.*

Single-photon spectral bandwidth modification using time lenses

(4 publications)

[H6] M. Karpiński, M. Jachura (equal contribution), L. J. Wright, B. J. Smith, *Bandwidth manipulation of quantum light by an electro-optic time lens,* Nature Photonics **11**, 53 (2017).

Here, a system using a temporal lens was experimentally implemented. The system is analogous to a spatial system collimating a Gaussian beam. A Gaussian beam with a small waist diameter (i.e., large divergence, and therefore broad spatial spectrum) can be collimated by propagating over a distance d and using a lens with an appropriate focal length (with a value close to d). This corresponds to the imprint of a quadratic phase in the spatial spectrum (propagation) and a quadratic phase in the transverse position (lens). The effect of the system is a transverse broadening of the beam combined with a narrowing (compression) of its spatial spectrum (corresponding to a reduced divergence angle). The spectral-temporal analogue of this system is a system combining propagation in a medium with group velocity dispersion (equivalent to diffractive propagation in space) and a time lens introducing a quadratically varying phase in time, cf. Fig. 1(a). The effect of the system's action on a short pulse of light with a broad spectrum is its stretching in time (due to propagation in a dispersive medium) and narrowing of the spectrum (due to the action of a temporal lens, the action of which can be understood as introducing a time-dependent spectral shift).

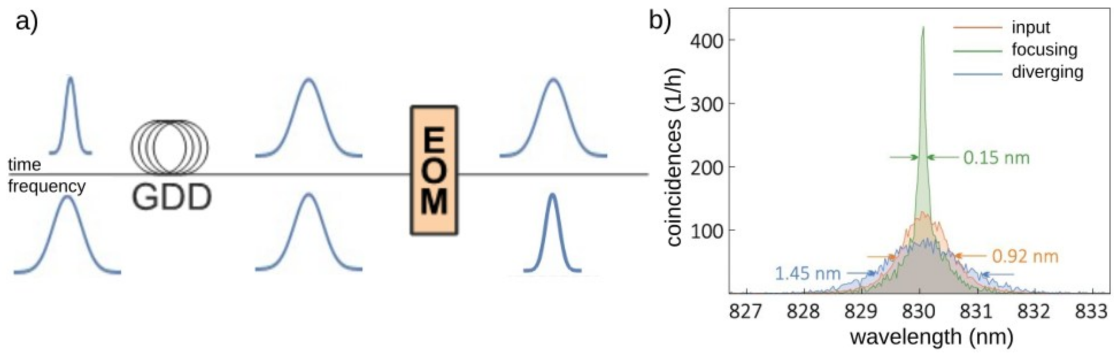

Fig. 3. (a) The concept of spectral bandwidth compression: a short pulse with a wide spectrum is broadened in time by propagation in a medium with group delay dispersion (GDD), while becoming chirped at the same time. Then, as a result of the action of an electro-optic temporal lens, realized by synchronizing the optical pulse with parabolic phase modulation by means of an electro-optic phase modulator (EOM), cf. Fig. 1(a), the pulse spectrum is narrowed. The temporal envelope remains unchanged at this stage. (b) Measured spectra of heralded single photons: spectrum without electro-optic modulation (orange), for a converging time lens – spectral compression (green), for a dispersing time lens – spectral broadening (blue). The full widths at half maximum are provided.

The experimental setup used the source of heralded photons described in H7. Single-photon wave packets were introduced into a single-mode optical fibre of about 250 m in length, in which the pulses were stretched in time and chirped. The time lens was realized electro-optically, by synchronizing the optical pulses with the maximum or minimum of sinusoidal phase modulation: in the extreme of the sinusoid, the phase profile in time is approximately parabolic. By matching selecting the fibre length to the temporal amplitude of the phase modulation (the so-called collimation condition), it was possible to realize the narrowing of the spectrum of the optical signal together with the extension of the pulse duration. Spectrally-resolved heralded photon detection resolution was realized by means of the dispersive Fourier transform technique, using chirped fiber Bragg gratings as the necessary dispersive medium. A detailed description of the technique is available in [P13]. The experimental challenge was to ensure the appropriate time stability of the synchronization of single-photon optical signals and the sinusoidal voltage signal.

The requirements for time stability and electrical signal power led to the decision to implement the time lens using an electrical signal with a frequency of 10 GHz. Experimental data were collected confirming the narrowing of the spectrum by shifting the outlying spectral components towards the central frequencies, see Fig. 3. In addition, a filter test was performed: the photon flux from the source passing through a narrow spectral filter (implemented using a monochromator) without using the temporal collimator system was compared with the photon flux passing through a spectral compressor and an identically set spectral filter. A more than two-fold increase in the photon flux was demonstrated in the second case, which confirmed the potential practical usefulness of the system for efficient modification of spectral widths, in particular in the context of hybrid quantum networks. At the time of publication, this was the first implementation of a spectral bandwidth reduction system that was more efficient than the use of passive spectral filtering.

Applicant's contribution*: I made a leading contribution to the work at every stage of its development: I proposed the use of temporal optics techniques to address the spectral bandwidth modification problem and I proposed the use of the filter test to directly verify the method's performance. I designed the experimental setup, in particular I recognized the need to reduce the frequency of the electrical signal to 10 GHz. I gathered all the necessary components to implement the experimental setup. I calibrated the setup, collected experimental data and analyzed them together with M. Jachura. I wrote most of the text of the publication and made a significant contribution to the difficult editorial and peer-review process.*

Moreover, I conceived the idea of using chirped fibre Bragg gratings to perform the dispersive Fourier transform at a wavelength of 830 nm in the single-photon counting regime, which was used in the H6 paper and is described in detail in the [P13] paper.

[H4] F. Sośnicki, M. Mikołajczyk, A. Golestani, **M. Karpiński**, *Aperiodic electro-optic time lens for spectral manipulation of single-photon pulses,* Applied Physics Letters **116**, 234003 (2020).

The paper presents an experimental implementation of an electro-optic time lens operating in aperiodic mode. The parabolic phase modulation described in paper H6 is realized by approximating it at the maximum or minimum of the sinusoidal electric signal driving the modulator. This limits the possibility of using the time lens only to a series of pulses that are synchronized with the maxima or minima of the control signal. In paper H4 I proposed a scheme in which the electro-optic time lens is approximated by the maximum of the impulse response of a fast photodiode. In this system, the electro-optic modulator is controlled by an amplified electric signal from a photodiode, to which ultrashort (sub-picosecond) light pulses are directed. This allows to eliminate the limitation on the time interval between optical pulses subjected to the action of the time lens resulting from the periodic nature of sinusoidal electric signals. In addition, this system is characterized by very good time stability, since it allows to avoid the difficult task of synchronizing the electric generator to the pulse train of the pulsed laser. In the H4 paper, the electrical signal is generated directly from laser pulses. This allowed obtaining long-term stability without the need for active synchronization. In the aperiodic temporal lens system preceded by a dispersive medium (1.2 km of SMF-28 fibre), spectral compression of classical optical pulses and heralded single photons was realized. The paper was published in Applied Physics Letters and was highlighted as the featured paper within the journal issue.

Applicant's contribution: *My contribution to the work includes the idea, design of the experimental setup (including the photon pair source), supervision over the construction of the experimental setup, experiment execution and data analysis, and leading participation in writing the publication.*

[H5] F. Sośnicki, **M. Karpiński**, *Large-scale spectral bandwidth compression by complex electro-optic temporal phase modulation*, Opt. Express **26**, 31307 (2018).

The parabolic electro-optic time lens enables the realization of spectral bandwidth modification only in a limited range – by a factor of 10 to a maximum of 20. This results from the limited achievable amplitude of the parabolic phase modulation: the parabolic signal grows, by definition, quadratically in time, quickly encountering a limitation in the form of the maximum electric field, and thus the maximum voltage that can be applied to the modulator. This limitation results, among others, from the breakdown (ionization) voltage of the modulator materials. A way to avoid the maximum modulation amplitude limitatio is to use the fact that the phase is significant up to one period of oscillation: 2π, or its integer multiple, cf. Fig. 4. In the spatial case, this concept is used by the well-known Fresnel lens.

Fig. 4. The concept of a Fresnel time lens: a par abolic phase in time that reaches excessive values (left side of the figure) can be replaced by a „wrapped" phase once the value of 2π is reached (right side of the figure).

In the H5 paper, the possibility of realizing transformations of spectral bandwidths and durations of single photons by several orders of magnitude was investigated using numerical simulations. In particular, the possibility of conversion between the spectral bandwidths characteristic of pulses carrying information in optical fibre telecommunications, i.e. about 100 GHz, and spectral widths of the order of 100 MHz, close to the widths of absorption lines of systems using atoms or ions to process quantum information using an approach involving the Fresnel time lens was investigated. After performing preliminary analytical calculations, a numerical simulation was performed. The key was to ensure appropriate sampling, providing time resolution at the level of tens of femtoseconds and spectral resolution at the level of tens of megahertz: this required covering more than 7 orders of magnitude within the simulation and realizing numerical Fourier transforms on 10^7 points. For this purpose, graphics card programming (CUDA) was used. The temporal distortions and noises, amplitude distortions and noises, and phase-wrap modulations at 2π, 4π, 6π, and 8π were also modelled. The results of numerical simulations indicated the possibility of experimentally realizing efficient spectral bandwidth conversion between short telecommunication photons with a spectral bandwidth of the order of 100 GHz and long, nanosecond photons with a spectral bandwidth below 1 GHz.

Applicant's contribution: *formulation of a hypothesis regarding the possibility of realizing a spectral width converter using a temporal Fresnel lens. I performed preliminary calculations, identified challenges related to the required resolution of numerical simulations and the need to use CUDA. I supervised the implementation of numerical calculations, verification of their correctness and interpretation of their results. I had a leading contribution to writing the text of the publication.*

[H1] F. Sośnicki, M. Mikołajczyk, A. Golestani, **M. Karpiński**, *Interface between picosecond and nanosecond quantum light pulses*, Nature Photonics 17, 761 (2023).

The paper presents an experimental implementation of a single-photon spectral bandwidth converter using a Fresnel time lens. The implementation of a large-scale pulse stretching in time and spectral narrowing requires (1) the use of a medium with a very large group delay dispersion, (2) the implementation of a complicated temporal profile of the Fresnel time lens, and (3) measurement of the spectrum of single-photon signals with a spectral bandwidth of the order of 500 MHz.

Telecommunication dispersion compensation modules based on a chirped fibre Bragg grating (dispersion coefficient of 5 ns/nm and 10 ns/nm, which gives 15 ns/nm when used together) were used as the dispersive medium. The heralded photons from the photon pair source used in [H4] were directed to a spectral shaping system based on a spatial phase modulator to match their spectrum to the parameters of the Fresnel time lens system. Subsequently they were directed to the dispersion module and then to the electro-optic phase modulator. The key to the realization of the Fresnel time lens signal was to generate a complex voltage signal, amplify it and include in the initial signal the compensation of distortions resulting from the complex transmission coefficients of the elements in the electrical signal path: coaxial cables, microwave amplifier, and the complex electro-optic coefficient.

It is worth noting the extremely wideband nature of the Fresnel lens voltage signal – the centre of the signal is slowly varying, corresponding to a frequency of ca. 100 MHz, while the outlying parts of the signal have frequencies above 30 GHz. Therefore, the key to the implementation of the experiment was the use of an arbitrary waveform generator (AWG) with a bandwidth above 35 GHz (Keysight M8196A) and a high-power microwave amplifier (over 2 W) with an ultra-wide radio-frequency bandwidth, from 100 MHz to 35 GHz (RF Lambda). The characterization of the complex transmission coefficients of microwave elements was possible thanks to the loan of an oscilloscope with a bandwidth of up to 64 GHz (Keysight). The electro-optic response was characterized by measurements of the sidebands in the modulation of a continuous-wave optical signal. The effects of the complex transmission coefficients were included in the numerical model and compensated by assigning an appropriate profile of the input voltage signal generated by the AWG.

The initial characterization of the system operation was performed using classical light: using appropriately spectrally filtered pulses from a femtosecond erbium oscillator. The measurement of the narrowed spectrum was performed using a heterodyne optical spectrum analyser (Apex, resolution up to 5 MHz). Spectral bandwidths below 150 MHz were obtained. The time profile of the narrowed pulses, with a width of more than 5 ns, was measured using a very fast photodiode (with a bandwidth of more than 12 GHz).

Due to the small spectral bandwidth of the narrowed single-photon pulses, it was not possible to use the dispersive Fourier transform (the resolution of which is limited to about 4 GHz) to measure their spectrum. A voltage-tunable Fabry-Perot resonator with a resonance bandwidth of about 400 MHz was used to measure the spectrum of the spectrally compressed photons. As a result of the tuning, an increase in the photon flux by a factor of 50 was measured in the photon counting mode in coincidence with the heralding photons, as compared to the case without electro-optic modulation. A spectral width of 500 MHz was measured, with the Fabry-Perot resonator width (420 MHz) having a significant contribution to the measured width. The width of the photon spectrum at the input to the system was above 70 GHz.

The obtained results constitute the first efficient interface connecting the temporal and spectral scale of quantum optics of short light pulses (of the order of 1 ps) with the quantum optics of long light pulses (of the order of ns), where photons can efficiently interact with material media and quantum information processing objects, such as trapped ions or quantum memories.

This work was published in the Nature Photonics journal and was highlighted within the journal issue by publishing an accompanying “News&Views” article [Donohue23].

Applicant’s contribution: *idea, design of the experimental setup, identification of key experimental challenges, ongoing supervision of the experimental implementation and consultation of the obtained experimental results, supervision of data analysis, key participation in writing the publication.*

[H3] M. Karpiński, A. O. C. Davis, F. Sośnicki, V. Thiel, B. J. Smith, *Control and measurement of quantum light pulses for quantum information science and technology*, Advanced Quantum Technologies 4, 2000150 (2021).

This is a review paper, but it contains an original study and new conclusions in the form of presenting the temporal optics techniques (time lenses, dispersive Fourier transform, temporal imaging) in the context of their new applications in quantum optics and quantum information processing. The lack of the possibility of amplifying single-photon signals and the need to focus on avoiding losses imposes different requirements and conditions for the applications of temporal optics methods than those presented in the previously available literature on classical applications of temporal optics. In addition, the paper presents the theory of so-called temporal (or pulse) modes of quantum light and the application of light pulse shaping methods based on temporal optics to the characterization of quantum states of light in time and frequency, photon shaping in the context of quantum networks and quantum metrology of time and frequency.

Applicant's contribution**:** *I made key contributions to the paper by identifying new requirements and constraints on the applications of temporal optics methods to quantum optics and by writing more than 6 of the 19 pages of text (excluding references), including most of Chapter 3 describing temporal optics methods in the context of quantum optics..*

In summary, the presented series of thematically related publications includes studies verifying the possibility of using temporal optics methods in quantum optics and presenting several possible applications of these effects. It includes the first electro-optic experiments using temporal-optics methods in quantum optics, such as electro-optic spectral shift [H7] and modification of single-photon spectral bandwidth [H6, H4], a broad analysis of the possibilities of using temporal-optics methods in optical quantum technologies [H3], and their applications: as the interface between narrowband and wideband platforms for quantum information processing [H5, H1] and in the framework of a new method for characterizing short optical pulses [H2].

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

University of Warsaw, Faculty of Physics, 2012–2013

After defending my doctoral thesis on the generation of photon pairs in multimode nonlinear waveguides at the Faculty of Physics, University of Warsaw in June 2012, I continued working on this topic. In particular, I collaborated with MSc student Michał Jachura on measurements of two-photon interference of photons generated in multimode nonlinear waveguides [P8].

[P8] M. Jachura, M. Karpiński, C. Radzewicz, K. Banaszek, *High-visibility nonclassical interference of photon pairs generated in a multimode nonlinear waveguide*, Opt. Express **22**, 8624 (2014).

In addition, I performed measurements illustrating the problem of linking the visibility of interference with information on the choice of the path in the interferometer by a quantum particle with internal degrees of freedom. The experiment used the polarization degree of freedom of single photons. The results of this work became part of the publication [P9]:

[P9] K. Banaszek, P. Horodecki, M. Karpiński, and C. Radzewicz, *Quantum mechanical which-way experiment with internal degrees of freedom*, Nature Commun. **4**, 2594 (2013).

I also worked on theoretical analyses of the generation of entangled photon pairs in transverse spatial modes in nonlinear waveguides in collaboration with the group of Prof. Krishna Thyagarajan from the Indian Institute of Technology in Delhi [P10, P11, P12]

[P10] D. Bharadwaj, K. Thyagarajan, M. Karpiński, K. Banaszek, *Generation of higher-dimensional modal entanglement using a three-waveguide directional coupler*, Phys. Rev. A **91**, 033824 (2015).

[P11] D. Bharadwaj, K. Thyagarajan, M. Jachura, M. Karpiński, K. Banaszek, *Scheme for on-chip verification of transverse mode entanglement using the electro-optic effect*, Opt. Express **23**, 33087 (2015).

[P12] M. Jachura, M. Karpiński, K. Banaszek, D. Bharadwaj, J. Lugani, K. Thyagarajan, *Generation and characterization of discrete spatial entanglement in multimode nonlinear waveguides*, Phys. Rev. A **95**, 032322 (2017).

University of Oxford, Department of Physics, United Kingdom, 2013–2016

At the University of Oxford, I worked in the Optical Quantum Technologies research group under the supervision of Professor Brian Smith from January 2013 to January 2016, initially as a Marie Curie Individual Fellow and then as part of the UK National Quantum Technologies Program. While working at the University of Oxford, the concept and first papers for the series of publications [H6, H7] were developed. In addition, during this period I worked on the following topics.

First of all, I will mention the study of the possibility of realizing high-resolution measurements of the spectrum of single photons using the dispersive Fourier transform, also known as frequency-time mapping. I was the originator of the idea of using a chirped fibre Bragg grating with a variable period to obtain high group velocity dispersion, and consequently high resolution with low losses. Thanks to my contacts within the research community, I gained access to hard-to-reach samples of fibre Bragg gratings with appropriate parameters. This project was carried out experimentally by other members of the research group [P13]:

[P13] A. O. C. Davis, P. M. Saulnier, M. Karpiński, B. J. Smith, *Pulsed single-photon spectrometer by frequency-to-time mapping using chirped fiber Bragg gratings*, Opt. Express **25**, 12804 (2017).

I participated in experimental studies on new methods of quantum state tomography of the electromagnetic field in continuous variables, for pulsed modes. Together with collaborators, we demonstrated experimentally, using balanced homodyne detection, a new method of quantum state tomography, which does not require full detector characterization, i.e., data pattern tomography [P14]. Furthermore, using quantum process tomography in continuous variables, we experimentally characterized the probabilistic non-Gaussian Fock state filtering process (for the case of a single-photon filter) [P15]. My main contribution to this work included numerical calculations necessary to simulate the experiment and analyse measurement data using quantum tomography methods. I also participated in the optimization of the experiment, including the single-mode source of heralded single photons and the balanced homodyne detector with a large electronic bandwidth (>100 MHz).

[P14] M. Cooper, M. Karpiński, B. J. Smith, *Local mapping of detector response for reliable quantum state estimation*, Nature Commun. **5**, 4332 (2014).

[P15] M. Cooper, E. Slade, M. Karpiński, B. J. Smith, *Characterization of conditional state-engineering quantum processes by coherent state quantum process tomography*, New J. Phys. **17**, 033041 (2015).

In addition, I participated in work on the implementation of the spontaneous parametric frequency division process in waveguides in the potassium dihydrogen phosphate (KDP) crystal. During my stay at the University of Oxford, in cooperation with a research group from the Department of Engineering of the University of Oxford, a method for fabricating waveguides in KDP crystals using strong femtosecond pulses was developed [P16]. My contribution to the work included a literature study on methods for fabricating waveguides in crystals and the development of assumptions for waveguide fabrication.

[P16] L. Huang, P. Salter, M. Karpiński, B. Smith, F. Payne, M. Booth, *Waveguide fabrication in KDP crystals with femtosecond laser pulses*, Appl. Phys. A **118**, 831–836 (2015).

I also contributed to the work on the measurement of the time-spectral wave function of single-photon pulses using the electro-optic spectral shearing interferometry method [P17, P18]. The spectral shift was realized using an electro-optic time prism developed in the H7 paper. I participated at the conceptual stage and in the initial phase of construction and calibration of the experimental setup.

[P17] A. O. C. Davis, V. Thiel, M. Karpiński, B. J. Smith, *Measuring the single-photon temporal-spectral wave function*, Phys. Rev. Lett. **121**, 083602 (2018).

[P18] A. O. C. Davis, V. Thiel, M. Karpiński, B. J. Smith, *Experimental single-photon pulse characterization by electro-optic shearing interferometry*, Phys. Rev. A **98**, 023840 (2018).

I participated in theoretical work on the study of the possibility of realizing entanglement swapping between two pairs of photons entangled in the time-frequency degree of freedom, conducted in collaboration with the group of Prof. M. Raymer from the University of Oregon (USA) and Prof. Karsten Rottwitt from the Technical University of Denmark (DTU) [P19]:

[P19] D. L. P. Vitullo, M. G. Raymer, B. J. Smith, M. Karpiński, L. Mejling, K. Rottwitt, *Entanglement swapping for generation of heralded time-frequency-entangled photon pairs*, Phys. Rev. A **98**, 023836 (2018).

I was also one of the authors of the idea of using a time prism to implement a source of heralded single photons with multiplexing in the spectral degree of freedom. The idea was experimentally realized in the group of Prof. I. A. Walmsley from the Department of Physics, University of Oxford [P20]:

[P20] T. Hiemstra, T. F. Parker, P. Humphreys, J. Tiedau, M. Beck, M. Karpiński, B. J. Smith, A. Eckstein, W. S. Kolthammer, I. A. Walmsley, *Pure single photons from scalable frequency multiplexing*, Phys. Rev. Applied **14**, 014052 (2019).

In collaboration with the group of Prof. I. A. Walmsley, I also investigated the problem of optimal coupling of heralded single photons to a broadband quantum memory based on hot atomic vapours [P21]. I participated in the development of the assumptions of the numerical simulation of this problem.

[P21] P. S. Michelberger, M. Karpiński, I. A. Walmsley, J. Nunn, *Engineering the spectral and temporal properties of a GHz-bandwidth heralded single-photon source interfaced with an on-demand, broadband quantum memory*, J. Mod. Opt. **65**, 1668 (2018).

In addition, during my time at the University of Oxford, I became a Fellow of one of the constituent Colleges of the University, the St. Hilda's College. In 2013 I won a Non-Stipendiary Junior Research Fellowship at the College. I was a Fellow of St. Hilda's College until 2015. The fellowship significantly broadened my research horizons, due to the highly interdisciplinary nature of the College.

University of Warsaw, Faculty of Physics, 2015–2024

From October 2015 to the present, I have been employed as an assistant professor (pol. *adiunkt*) at the Division of Optics, Institute of Experimental Physics, Faculty of Physics, University of Warsaw (FUW). From October 2015 to January2016 I was simultaneously employed part-time at the University of Oxford.

The main goal of my research conducted in the above-mentioned period within the Quantum Photonics Laboratory (QPL) at FUW was to conduct research leading to five of the seven publications of the publication cycle: H1–H5. This required the creation of a research team, obtaining external funding and acquiring appropriate equipment, and establishing international cooperation. These aspects are described later in this section and in section no. 6.

In addition, I participated in research that was related to the cycle of publications, on the measurement of the time profile of high-frequency electro-optic phase modulation (of the order of 10 GHz) using time-frequency mapping and spectral interference [P22]:

[P22] M. Jachura, J. Szczepanek, W. Wasilewski, <u>M. Karpiński</u>, *Measurement of radio-frequency temporal phase modulation using spectral interferometry*, J. Mod. Opt. **65**, 262 (2018).

I also conceived and supervised numerical and experimental studies on modelling of sinusoidal electro-optic time lenses. The motivation for undertaking the research was the observed discrepancies between the experimental results on modification of single-photon spectral bandwidth and the standard theoretical model. Working under my supervision, PhD student Sanjay Kapoor developed a new analytical model of electro-optic time lenses and performed its numerical and experimental validation. The results were included in the paper [arXiv1] in 2022, in 2024–2025 the paper was supplemented with experimental results and submitted to a peer-reviewed journal in 2025.

[arXiv1] S. Kapoor, F. Sośnicki, <u>M. Karpiński</u>, *Aberration-corrected time aperture of an electro-optic time lens*, arXiv preprint arXiv:2207.07618 (2022).

I also participated in theoretical work on the use of a cavity containing temporal lenses to implement filtering of orthogonal time-frequency modes, in collaboration with the group of Dr. Giuseppe Patera from the University of Lille (France) [P23]:

[P23] B. Dioum, S. Srivastava, <u>M. Karpiński</u>, G. Patera, *Temporal cavities as temporal mode filters for optical information processing*, Phys. Rev. A **111**, 033704 (2025).

Other research, more distantly related to the series of publications, conducted under my supervision within my research team at QPL covers 3 topics: (1) the use of fibre Bragg gratings as sensors of mechanical vibrations and (2) activities related to quantum key distribution and (3) research on the spectral shaping of single photons emitted by quantum dots.

Within the first topic, I participated in works on the study of mechanical wave propagation in sheet metal structures using fibre optic sensors in cooperation with a team from the Institute of Fluid Flow Machinery of the Polish Academy of Sciences in

Gdańsk. The research showed the possibility of locating mechanical damage [P24] using a single fibre Bragg grating and mechanical wave reflections from the edges of the sheet metal structure and confirmed the theoretical model of sensor position optimization [P25]. My contribution included planning the use of optical methods, supervision of the construction and calibration of the optical part of the experimental system and the course of experiments.

[P24] R. Soman, K. Balasubramaniam, A. Golestani, M. Karpiński, P. Malinowski, *A two-step guided waves based damage localization technique using optical fiber sensors*, Sensors **20**, 5804 (2020).

[P25] R. Soman, K. Balasubramaniam, A. Golestani, M. Karpiński, P. Malinowski, W. Ostachowicz, *Actuator placement optimization for guided waves based structural health monitoring using fibre Bragg grating sensors*, Smart Materials and Structures **30**, 125011 (2021).

I also participated in the planning and initial validation of an experiment that investigated the possibility of using fibre Bragg gratings in polarization-maintaining fibres to distinguish signals originating from different mechanical wave modes:

[P26] R. Soman, F. O. Moaf, P. Fiborek, M. Kurpińska, S. Sarbaz, M. Karpiński, T. Wandowski, *Investigating the effect of orientation of polarization maintaining fiber Bragg grating sensor on its sensitivity to fundamental symmetric and antisymmetric guided wave modes*, Measurement **252**, 117307 (2025).

Within the second topic, I conducted experimental studies related to quantum key distribution, together with members of my team and, in the case of [P27], in cooperation with the group of Prof. R. Piramidowicz from the Warsaw University of Technology. In [P27], based on the idea by Adam Widomski, a photonic integrated circuit made of indium phosphide was designed, manufactured and characterized. The design and characterization aimed to show the possibility of using this type of photonic integrated circuit as a transmitter for multidimensional quantum key distribution protocol. My role was to develop the design assumptions of the photonic integrated circuit and supervise the experimental part carried out in QPL.

[P27] A. Widomski, S. Stopiński, K. Anders, R. Piramidowicz, M. Karpiński, *Precise on-chip spectral and temporal control of single-photon-level optical pulses*, J. Lightwave Technol. **41**, 6255 (2023).

Moreover, together with Maciej Ogrodnik and Adam Widomski, I developed the idea of using the so-called temporal Talbot effect to detect single photons in time-bin superpositions. Efficient detection of this type of superpositions is important due to possible applications in receivers in multidimensional quantum key distribution systems. Simulation and experimental verification were carried out under my supervision. The results were published in [P28]:

[P28] A. Widomski, M. Ogrodnik, M. Karpiński, *Efficient detection of multidimensional single-photon time-bin superpositions*, Optica **11**, 926–931 (2024).

Together with my team, I also participated in the work of an international team from Germany, Italy and Poland (within the QuantERA QuICHE project, cf. further and sec. 6.2) on a new security proof of multidimensional quantum key distribution protocols in the absence of precise information on the detection efficiency in two complementary bases. Together with members of the QPL team, we contributed on the possible ranges of experimental parameters for which the proof was verified. The work was published in the Physical Review Applied [P29]:

[P29] F. Grasselli, G. Chesi, N. Walk, H. Kampermann, A. Widomski, M. Ogrodnik, M. Karpiński, C. Macchiavello, D. Bruß, N. Wyderka, *Quantum key distribution with basis-dependent detection probability*, Phys. Rev. Applied **23**, 044011 (2025).

In parallel, under my supervision, in cooperation with partners in the QuICHE project, an experimental verification of the multidimensional QKD protocol (4 dimensions) with time-bin encoding was carried out, both within the Quantum Photonics Laboratory and in the urban fibre optic network of the University of Warsaw. The work was posted in the arXiv repository [arXiv2] and submitted to a refereed journal.

[arXiv2] M. Ogrodnik, A. Widomski, D. Bruß, G. Chesi, F. Grasselli, H. Kampermann, C. Macchiavello, N. Walk, N. Wyderka, M. Karpiński, *High-dimensional quantum key distribution with resource-efficient detection*, preprint arXiv:2412.16782 (2024).

Within the third of the aforementioned research topics, in cooperation with members of the Division of Solid State Physics of the Faculty of Physics, University of Warsaw, an experimental verification of the possibility of changing the central wavelength of single photons emitted by a quantum dot using an electro-optic time prism was carried out under my supervision. The work was published in the Nanophotonics journal [P30]:

[P30] S. Kapoor, A. Rodek, M. Mikołajczyk, J. Szuniewicz, F. Sośnicki, T. Kazimierczuk, P. Kossacki, M. Karpiński, *Electro-optic frequency shift of single photons from a quantum dot*, Nanophotonics, DOI: 10.1515/nanoph-2024-0550 (2025).

During my employment as an assistant professor at the Faculty of Physics, University of Warsaw, I was the head of the following research projects:

- Polish part of the European QuICHE ("Quantum Information and Communication with High-dimensional Encoding") consortium, funded under the European Union (EU)/National Science Center of Poland (NCN) QuantERA program, 1.3 M Polish zloty (for UW), 2019–2024. The QuICHE consortium included, in addition to the research group under my supervision at FUW, research groups from Germany (University of Paderborn, group of Prof. C. Silberhorn and University of Dortmund, group of Prof. D. Bruß), Italy (University of Pavia, group of Prof. C. Macchiavello), France (University of Lille, group of Prof. M. Kolobov) and the United Kingdom (Imperial College London, group of Prof. I. A. Walmsley).
- Foundation for Polish Science First TEAM project, "Phase-only shaping of light pulses for applications in quantum technologies, 2.95 M Polish zloty, 2019–2023,
- Foundation for Polish Science HOMING project, "Manipulating spectral entanglement by complex temporal phase modulation", 0.75 M Polish zloty, 2016–2018,
- National Science Center (Poland) SONATA project, "Coherent spectral manipulation of quantum states of light" 0.67 M Polish zloty, 2015–2019.

Currently I am leading the:

- National Science Center (Poland) SONATA-BIS project, "High-dimensional entanglement in an integrated optical platform", 4.65 M Polish zloty, 2024–2029,
- WEAVE OPUS-LAP international project of National Science Centre (Poland), in collaboration with the University of Innsbruck (Austria), „ Tailoring SIngle-Photon spectra for HYbrid quantum networks (TSI-PHY)", 1.9 M Polish zloty (for UW), 2024–2027,
- The FUW team within the international Horizon Europe project, „Mid-Infrared Quantum Technologies for Sensing (MIRAQLS)", EU–UK–Switzeraland–Canada cooperation, 0,33 M Euro (2023–2025), I joined the project via the Hop-On mechanism.

6. Presentation of teaching and organizational achievements as well as achievements in popularization of science or art

6.1 Teaching achievements

6.1.1 Supervision of students and PhD students

I was the supporting supervisor of two PhD students:

- Dr Filip Sośnicki, his thesis entitled „Spectral shaping of quantum light pulses by electro-optic phase modulation" was defended with distinction at the Faculty of Physics, University of Warsaw on 10May 2023. Prof. Czesław Radzewicz was the supervisor of the thesis.
- Dr Ali Golestani Shishvan, his thesis entitled „Temporal shaping and measurement of pulsed quantum light" was defended at the Faculty of Physics, University of Warsaw on 29 November 2023. Prof. Czesław Radzewicz was the supervisor of the thesis.

Both alumni continue their research carriers, they are currently working as post-doctoral researchers at reputed international research institutions.

Currently I am the supporting supervisor of 5 PhD students: Adam Widomski, Msc, Eng. (who submitted his PhD thesis in May 2025), Michał Mikołajczyk, MSc, Maciej Ogrodnik, MSc. Jerzy Szuniewicz, MSc, and Jan Krzyżanowski, MSc.

I supervised 7 Master's theses at FUW:

- Jan Krzyżanowski, thesis entitled „Enabling two-photon interference by temporal lensing", 2024. The thesis received a distincion in the 33rd Poland-wide Professor Adam Smoliński Competition for the best diploma theses in the field of optoelectronics.
- Dinara Kalkabaeva, thesis entitled „Spatially-multimode waveguided electro-optic phase modulation", 2022.
- Arifah Nurul Amaliah, thesis entitled „Spectral compression using a sinusoidal electro-optic time lens", 2021.

- Adam Widomski, thesis entitled “Generation and detection of QKD symbols encoded in time and frequency”, 2019.
- Michał Mikołajczyk, thesis entitled „Spectral charactarization of single photons”, 2018.
- Maciej Gałka, thesis entitled „Engineering spectral correlations of photon pairs”, 2017.
- Filip Sośnicki, thesis entitled „Electrooptic temporal telescope for nanosecond pulses”, 2016.

As well as 6 Bachelor’s theses:

- Natalia Bednarek, thesis entitled „Measurement of short laser pulses using the SWIFTS method”, 2024.
- Michał Chrzanowski, thesis entitled „ Large group delay dispersion for medium-wavelength infrared optical signals”, 2024.
- Antoni Skoczypiec, thesis entitled „Simulation and design of fibre Bragg gratings”, 2024.
- Ksawery Mielczarek, thesis entitled „To measure a laser pulse a billion times shorter than a blink of an eye – the SPIDER technique”, 2023.
- Jan Krzyżanowski, thesis entitled „Synchronization in quantum key distribution systems”, 2022.
- Dominika Bondar, thesis entitled „ Spatially resolved infrared single photon detection based on space to time mapping”, 2019.

6.1.2 Supervision of the Student Association of Optics and Photonics (pol. *Koło Naukowe Optyki i Fotoniki, KNOF*) of the University of Warsaw. Since 2016, I have been the scientific supervisor of KNOF UW. The Association conducted outreach activities (including demonstrations at Science Festivals and Science Picnics) and organized lectures and trips to scientific events. In 2022, the Association received the Award of the Photonics Society of Poland for outstanding student association activity in 2021.

6.1.3 Organization and conduct of teaching activities

During my employment at the University of Oxford, I focused on my research activities. My involvement in the teaching activities at Oxford included supervising one undergraduate group project (5 students) in collaboration with industry in 2015.

Since October 2015, I have been performing my teaching duties as an assistant professor at the Faculty of Physics, University of Warsaw, in the amount of 210 teaching hours per year (the number of hours was reduced by 50% during the implementation of the Foundation for Polish Science First Team project, from December 2019 to November 2023).

I conducted or am conducting the following classes:

- „Instrumental optics” Master’s level specialist lecture, yearly since 2016/17 (initially in Polish, as „Optyka instrumentalna”)

- Laboratory assistant at the 2nd year undergraduate Physics labs (pol. *Pracownia Technik pomiarowych*), 2016/17, 2023/24 i 2024/25

- 1st year introduction to physics (electricity and magnetism) (pol. *Fizyka II, elektryczność i magnetyzm*), problem solving classes, 2015/16
- Photonics (pol. *Fotonika*), problem solving classes, 2015/16, 2016/17.
- Geometric and instrumental optics laboratory (pol. *Laboratorium optyki geometrycznej i instrumentalnej*), laboratory assistant (2 student groups), 2015/16.
- Introduction to optics and condesed matter physics (pol. *Wstęp do optyki i fizyki materii skondensowanej*), problem solving classes, 2017/18
- Introduction to physics III (optics and elements of contemporary physics) (pol. *Podstawy fizyki III (Optyka i elementy fizyki współczesnej*), problem solving classes, 2018/19, 2019/20.
- Supervision of a student group project, every year since 2020/21
- Preparation of experimental demonstration for the "Thermodynamics with elements of statistical physics" (pol. *Termodynamika z elementami fizyki statystycznej*) lecture, 2015/16.

In addition, I supervised individual research projects as part of the second-cycle studies and for individual students (an average of 2 students per semester). I also acted as a tutor for 8 students of Interdisciplinary Individual Studies in Mathematics and Natural Sciences (MISMaP). I was responsible for preparing the English-language "Instrumental optics" lecture based on the Polish-language "Optyka intrumentalna".

Since 2023/24, I have been coordinating and leading, as part of a 4-person organizing committee, the joint "Optics Seminar" at the Faculty of Physics, University of Warsaw. The seminar takes place every week in the summer and winter semesters. I am also a member of the organizing committee of the "Joint Seminar on Quantum Technologies" (formerly "Seminarium Informacji Kwantowej", since 2018/19).

6.2 Organizational achievements

6.2.1 Quantum Photonics Laboratory

During my employment as an assistant professor at FUW, I transformed and developed the Quantum Photonics Laboratory from a small quantum-optical laboratory for research in the near infrared spectral range (wavelength up to 1000 nm) into a laboratory for quantum-optical research in the near, telecommunications and mid-infrared range (wavelength from 750 nm to 2100 nm), equipped with unique equipment on a global scale, consisting of high-performance devices, optical fibre links to external optical networks and unique devices built under my supervision by members of my team. At the same time, I created a team of ambitious young people, without whose knowledge and commitment the Laboratory could not have been established and operated. My team has gained international recognition and is invited to join international consortia (e.g. an application was submitted to the Marie Skłodowska-Curie Doctoral Training Networks Actions call, to which I was invited with my team, or to European Innovation Council projects – 2 invitations in 2025). More details about my research group are available at www: photon.fuw.edu.pl.

6.2.2 International collaboration

After obtaining my PhD, I developed a wide range of research collaborations. During my employment at the University of Oxford, I established contacts with my then supervisor Prof. Brian Smith, who is now at the University of Oregon (USA), with Prof. Nicolas Treps at the Sorbonne University in Paris (France; joint publication H2), with Prof. Mikhail Kolobov and Dr. Giuseppe Patera at the University of Lille (joint publication [P23], collected material for a subsequent publication), with Dr. Alexander Davis, who is now at the University of Bath (joint publication H2) and with the group of Prof. Peter G. R. Smith at the Optoelectronics Research Centre, University of Southampton (United Kingdom). As part of the collaboration with the University of Southampton, we received commercially unavailable samples of fibre Bragg gratings, which are currently used in experiments at the Quantum Photonics Laboratory in Warsaw.

As a part of the QunatERA QuICHE project, in 2019 I started a collaboration with the group of Chiara Macchiavello from the University of Pavia (Italy) and Prof. Dagmar Bruß from the University of Dortmund (Germany), leading to the works [P29, arXiv2].

In 2024 I started a collaboration with Dr. Robert Keil from the University of Innsbruck (Austria) on shaping single photons emitted by quantum dots, within the WEAVE project.

6.2.3 Organization of summer schools

I was the head of the organizing and program committees of two international scumer schools:

- Siegman International School on Lasers, 25.06–2.07.2022, European Centre of Geological Education of the University of Warsaw in Chęciny, Poland. The School was organized in co-operation with the Optica society, within the prestigious Siegman School series. Over 120 participants from around the world, including lecturers from top research centres worldwide (e.g. ETH Zurich, Switzerland; Cornell University, USA).
- Summer School on Mid-Infrared Quantum Sensing and Technologies, 23-28.06.2024, Faculty of Physics, University of Warsaw, Warsaw, Poland. A summer school within the MIRAQLS project, over 75 participants from around the world, including lecturers from top research centres worldwide (e.g. ETH Zurich and EPFL, Switzerland; Imperial College London, UK).

6.2.4 Organization of conferences

I contributed to the organization of the following conferences:

- I was a member of the organizing committee of the „Masovian

Symposium on Quantum, Optical and Atomic Physics (MaSQOT)", Institute of Physics of the Polish Academy of Sciences, Warsaw, Poland, 10–11.06.2024.

- I was a member of the organizing committee of the international „Quantum Optics X" conference, Toruń, Poland, 5–11.09.2021.
- I was a co-organizer of the „Standing up for Science" workshop, organized in collaboration with the Sense about Science foundation (UK), November 2017, Warszaw, Poland.
- I was the main organizer of the international „Workshop on Spectral and Spatial Engineering of Quantum Light", February 2016, Warszaw, Poland.
- I was a co-organizer of the „Integrated Quantum Photonics Workshop", January 2015, Oxford, UK
- I was a co-organizer of the „Quantum Coherence Workshop", March 2013, Oxford, UK.

6.2.5 Infrastructural project coordination

Within the Innovative Growth Operational Program infrastructural project: "National Laboratory for Photonics and Quantum Technologies – NLPQT", 2019 – 2023:

- I was the project coordinator at the Faculty of Physics (FUW), I was responsible for the coordination of equipment purchases and construction within 6 research groups and for coordination of reporting. The project was successfully completed and reported;
- Additionally, I was the coordinator of the Quantum Technology Laboratories within the NLQP project, I was responsible for coordination between 3 research entities and I contributed to the early stages of the construction of the Warsaw – Poznań quantum key distribution link.

6.3 Research outreach achievements

6.3.1 I conduct open lectures with demonstrations for students (on average 1.5 per year) as part of classes for students organized at the Faculty of Physics, University of Warsaw, by the Polish Physical Society and the Faculty of Physics, University of Warsaw, on the refraction of light and on optical fibres.

6.3.2 I organized 2 visits to the Quantum Photonics Laboratory as part of the Warsaw Science Festival (pol. *Festiwal Nauki*, in 2017, 2018) including experimental demonstrations. I also organized a visit of primary school and secondary school students to the Laboratory in 2024.

6.3.3 I am one of the founders of the Candela Foundation and the chairman of the Foundation Council (2021 – now). The Candela Foundation, candela.org.pl, popularizes optics and photonics and supports young scientists in Poland. In particular, the Foundation runs a national program of paid summer internships in research laboratories for talented students called "Resonators" and publishes a monthly “Polish Newsletter on Optics and Photonics” in Polish and English.

6.3.4 I am a co-founder and vice-chair of the Polish branch of the Marie Curie Alumni Association, supporting participants and graduates of the Marie Skłodowska Curie EU programs (2017 – present).

6.3.5 I prepare press releases on the most important scientific results obtained by me and my team.

6.3.6 I have participated three times in research outreach radio broadcasts (including Radio TOK FM, Radio dla Ciebie), where I talked about the research conducted by me and my collaborators and team members.

Podpisany elektronicznie przez
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