Bandwidth manipulation of quantum light by an electro-optic time lens

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The ability to manipulate the spectral-temporal waveform of optical pulses has enabled a wide range of applications from ultrafast spectroscopy to high-speed communications. Extending these concepts to quantum light has the potential to enable breakthroughs in optical quantum science and technology. However, filtering and amplifying often employed in classical pulse shaping techniques are incompatible with non-classical light. Controlling the pulsed mode structure of quantum light requires efficient means to achieve deterministic, unitary manipulation that preserves fragile quantum coherences. Here, we demonstrate an electro-optic method for modifying the spectrum of non-classical light by employing a time lens. In particular, we show highly efficient, wavelength-preserving, sixfold compression of single-photon spectral intensity bandwidth, enabling over a twofold increase of single-photon flux into a spectrally narrowband absorber. These results pave the way towards spectral-temporal photonic quantum information processing and facilitate interfacing of different physical platforms where quantum information can be stored or manipulated.

The time–frequency (TF) degree of freedom of non-classical light has come to the fore as a promising candidate for multidimensional quantum information science, due in part to its compatibility with integrated photonic platforms and fibre networks. Recent research efforts have diversified from generation of single-photon wavepackets with controlled TF properties and their characterization to active filtering and amplifying often employed in classical pulse shaping. The deterministic nature of the electro-optic effect, in which a phase factor quadratic in transverse position, introduces 9.9 ps group delay dispersion followed by passing through a lithium niobate waveguide, provides a realistic path to overall unitary operation. This allows us to demonstrate a twofold increase of photon flux into a spectrally narrowband absorber, confirming practical value of the scheme for the development of quantum networks, where losses can be tolerated in a repeat-until-success approach.

Electro-optic bandwidth compression can be explained by referring to the fundamental space–time duality between paraxial propagation of an optical beam and dispersive propagation of an optical pulse. Compression of spatial bandwidth of a Gaussian beam can be accomplished by collimating it using a lens placed one focal length from its waist. This corresponds to multiplication of the transverse field profile by a phase factor quadratic in transverse momentum, acquired during free-space propagation towards the lens, followed by a phase factor quadratic in transverse position, introduced by the lens. In the time–space duality, free-space propagation corresponds to pulse propagation in a second-order dispersive medium imposing a quadratic spectral phase, which can be realized either via nonlinear interaction with an intense auxiliary pulse or electro-optic phase modulation, which is used in our experiment. In the TF domain, dispersive propagation distributes spectral components of the wavepacket in time, whereas the TL introduces appropriate time-dependent frequency shears that move spectral components towards the central frequency leading to bandwidth compression, as conceptually depicted in Fig. 1. Thus dispersive propagation followed by a TL achieves spectral bandwidth compression of a Gaussian wavepacket, provided the collimation condition is satisfied.

To demonstrate this approach to bandwidth manipulation for quantum pulses, we generated fibre-coupled spectrally pure single-photon wavepackets of 3-nm full-width at half-maximum (FWHM) spectral bandwidth and 830-nm central wavelength by heralding from a pulsed spontaneous parametric down-conversion (SPDC) single-photon source (see Methods). The electro-optic bandwidth compressor (EOBC) is realized by propagating the heralded photon through 256 m of standard single-mode fibre introducing 9.9 ps group delay dispersion followed by passing through a lithium niobate waveguide, travelling-wave, electro-optic phase modulator (EOM) (Fig. 2b). The TL is realized by driving the modulator with a 10 GHz, 33 dBm sinusoidal radio-frequency (RF) signal, yielding temporal phase modulation of the form $\theta_{TL}(t) = A\sin(2\pi f_{RF} t)$, where $A = 25.7$ rad (Supplementary Information). The RF signal is produced by amplifying the output of a dielectric resonator oscillator.
Figure 1 | Conceptual scheme of electro-optic bandwidth compression. An optical wavepacket propagates through a second-order dispersive medium imposing quadratic spectral phase, known as group delay dispersion (GDD). This extends the temporal duration of the single-photon wavepacket $\psi(t)$ by shifting different frequency components in time by a value proportional to the derivative of the spectral phase imprint $\phi(\omega)$. In the next step, a quadratic time-dependent phase profile $\theta(t)$, known as a time lens (TL), is applied to the wavepacket in a synchronous manner shifting the frequency components by a value proportional to its derivative towards the central value $\omega_0$, thus compressing the spectral bandwidth of the wavepacket. The amount of GDD is precisely adjusted to fulfill the bandwidth compression condition (see main text for details).

Figure 2 | Experimental set-up. a, Pulses from a Ti:sapphire laser, frequency-doubled in a beta barium borate (BBO) crystal, pump spontaneous parametric down-conversion (SPDC) in a potassium dihydrogen phosphate (KDP) crystal to generate spectrally pure single-photon wavepackets in the signal mode, which are heralded by detection of a photon in the idler mode at an avalanche photodiode (APD). b, The signal photons, after separating from the idler photons at a polarizing beam-splitter (PBS) and passing through a bandpass interference filter (IF), are directed towards the electro-optic bandwidth compressor (EOBC) consisting of a polarization controller (PC), single-mode fibre (SMF) and electro-optic phase modulator (EOM). The EOM is driven by a 10 GHz sinusoidal RF field temporally locked to the single-photon pulse train, which is derived from a photodiode (PD) monitoring the laser pulse train. Synchronizing the parabolic region of the RF modulation with the single-photon pulse implements a time lens. The initial and final spectra of the heralded single-photon wavepackets are measured by means of a time-of-flight spectrometer comprising a circulator, chirped fibre Bragg grating (CFBG), low-timing-jitter APD and time-to-digital converter (TDC) working in the start–stop mode. c, To verify the efficiency of the device we compared the total flux of photons through a narrowband spectral filter based on a grating monochromator with and without the use of the EOBC.
phase-locked to a high harmonic of an 80-MHz sinusoidal reference signal derived from the pulsed SPDC pump beam \(^5\). The relative temporal position of the optical pulse and RF signal was adjusted by an RF phase shifter. As the duration of the optical pulse is shorter than the modulation period, the TL is approximated by the parabolic region of sinusoidal phase modulation, known as the TL aperture\(^6\), giving a chirping factor of \(K = 4\pi f_R A^2\) (Fig. 2). To just fill the TL aperture after propagation through the dispersive medium the bandwidth of heralded photons was reduced to 0.9 nm FWHM using an interference filter (IF). The GDD value was chosen to match the TL chirping factor (Supplementary Information).

To directly verify this approach to bandwidth manipulation, the spectrum of heralded single-photon wavepackets was measured before and after the compression procedure using an efficient 0.07-nm-resolution spectrometer\(^26\) (Fig. 2b and Methods). The spectrum of heralded photons entering the EOBC was acquired at the EOM output with no RF signal applied. Subsequently, the RF signal was switched on and the phase set to implement a focusing TL, followed by heralded single-photon spectrum acquisition. To further illustrate the space–time duality between electro-optic bandwidth compression and Gaussian beam collimation, the heralded single-photon spectrum for a diverging TL was obtained. Measured spectra for the three aforementioned cases (initial, focusing TL and diverging TL), yielding FWHM bandwidths of 0.92 ± 0.06 nm (401 ± 26 GHz), 0.15 ± 0.01 nm (65 ± 4 GHz) and 1.45 ± 0.17 nm (631 ± 74 GHz), respectively, are presented in Fig. 3a (see Methods). We quantify the device performance using a compression factor given by the input and output spectral bandwidth ratio. Owing to finite spectral resolution the 6.1 ± 0.6 ratio extracted from raw measured data presents a lower bound on the EOBC performance. The experimentally determined spectrometer instrument response function yields a FWHM resolution of 0.07 nm (Fig. 3b).

By modifying the TL chirping rate and aperture as well as the GDD, the EOBC can be tuned to a different bandwidth regime. In the Supplementary Information we show spectral compression results of 2-nm bandwidth pulses by means of a 40-GHz electro-optic TL.

We directly show that the EOBC can be used to enhance the rates at which bandwidth-incompatible photons can be successfully interfaced despite its non-unit overall transmission of 27 ± 1% (see Supplementary Information for discussion of device efficiency). To this end, we emulated a spectrally narrowband absorber, such as a quantum memory, by a narrowband spectral filter (Methods). We measured the total flux of photons transmitted through a filter with transmission bandwidth comparable to the compressed photon bandwidth in two different experimental configurations: photons are (1) manipulated by the EOBC and then sent through the filter and (2) sent directly through the filter without passing through the EOBC, as presented in Fig. 2c. The numbers of coincidence counts registered in these two cases within an acquisition time of 150 s are presented in Fig. 4a. In Fig. 4b, ratios of coincidence counts measured in the two aforementioned scenarios are presented for a range of central wavelengths of the input photons (see Methods for details on source tuning and measurement procedure). The ratios significantly exceed unity across the entire 820–860-nm spectral range, demonstrating the high efficiency and broad spectral acceptance of this approach to quantum pulse control. Indeed, this clearly demonstrates that our approach exceeds the performance of even unit efficiency spectral filtering. With these characteristics our technique can be readily applied in a sequence of spectral and temporal phases to achieve an arbitrary pulse-mode unitary transformation\(^27\), and holds promise for enabling efficient interfacing of hybrid quantum network nodes. The EOBC approach may also find application in spectral manipulation of general field-quadrature states of optical modes, such as squeezed states. Currently, losses from the device introduce a significant admixture of vacuum noise to the quadrature state. However, it is feasible to address the technical sources of loss (see Supplementary Information for discussion of losses), thus improving the EOBC transmission to levels necessary for preservation of non-classical features of such states\(^21\).

A key characteristic of a quantum pulse manipulation device is its performance in terms of the introduced photon noise, quantified by the conditional degree of second-order coherence, \(g^{(2)}(0)\) (ref. 19). We experimentally determined \(g^{(2)}(0)\) of heralded single photons with the EOBC switched on and off (Methods). The conditional degree of second-order coherence values without, \(g^{(2)}(0) = 0.0209 ± 0.0024\), and with, \(g^{(2)}(0) = 0.0158 ± 0.0031\), the EOBC switched on confirm preservation of the non-classical character of the heralded single-photon pulses, \(g^{(2)}(0) < 1\). The use of RF fields to implement spectral control of optical pulses means that our device is intrinsically free from optical photon noise, which contrasts methods based on nonlinear optics, where care is needed to minimize contamination of the single-photon pulse with unwanted light originating from bright auxiliary optical pump beams.

In conclusion, we applied the technique of electro-optic temporal lensing to quantum light, experimentally demonstrating an all-fibre, single-photon bandwidth compressor. We directly show that our device significantly increases the single-photon absorption rate into a spectrally narrowband absorber while preserving the non-classical character of single-photon wavepackets. The high-efficiency, broad spectral acceptance, reconfigurability of the applied phase and central-wavelength preservation show the potential of electro-optic bandwidth manipulation for the development of quantum networks. To date, electro-optic phase modulation methods have only been used

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**Figure 3 | Spectral manipulation of single-photon wavepackets.**

**a.** Raw spectrometer data presenting the initial (orange), compressed (green) and broadened (blue) spectra of heralded single-photon wavepackets corresponding to no time lens, focusing and diverging TL configurations, respectively. **b.** Instrument profile of the spectrometer employed in the experiment, which results in distortion of the measured spectral intensities.
to modify spectral-temporal properties of continuous-wave quantum light\textsuperscript{28,29}. Our work highlights the versatility of electro-optic manipulation as an efficient, low-noise platform enabling spectral control of both quantum and classical pulsed light sources over a broad range of central wavelengths. By utilizing both temporal and spectral phase operations, this approach holds promise to advance TF-encoded quantum communication and simulation protocols\textsuperscript{32,33}, enabling tailored multimode TF unitary operations\textsuperscript{27} by taking advantage of technology-driven developments in RF waveform generation\textsuperscript{30} and fibre Bragg gratings.

Methods

Methods and any associated references are available in the online version of the paper.

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Figure 4 | Performance of the bandwidth compressor. a, To verify the practicality of the EOBC, we emulated spectrally narrow single-photon absorption by measuring transmission through a narrowband spectral filter. Initially, we directed the 3-nm FWHM bandwidth heralded single-photon wavepackets onto a filter with 0.13–0.16 nm FWHM spectral bandwidth, and detected the number of heralded photons transmitted through the filter in 150 s (crosses). Alternatively, we sent the heralded single-photon wavepackets through the EOBC before directing them through the filter and registering coincidence detection events (filled squares). To demonstrate the versatility of this approach, measurements were performed for a range of single-photon central wavelengths, with the filter tuned accordingly (see Methods for a detailed description of the experimental procedure).

b, The ratio of counts registered in these two configurations remains above unity across the entire spectral range investigated, clearly confirming a net gain in photon flux into the narrowband absorber enabled by the spectral compression. Error bars combine contributions from Poisson count statistics and ±5% relative count uncertainty originating from the non-repetitive transmission of fibre connectors used to switch between the two experimental configurations. This results in small discrepancies between the ratios obtained in two subsequent measurement series (orange and blue).
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Author contributions
M.K. and B.J.S. conceived the project. M.K. and M.J. designed and performed the experiment. M.J. analysed the data with input from M.K. L.J.W. developed the RF phase-locking system and contributed to the early stages of the experiment. M.K., M.J. and B.J.S. wrote the manuscript. M.J. prepared the figures.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.J.

Competing financial interests
The authors declare no competing financial interests.
Methods

Single-photon source. Pulses originating from a Ti:sapphire oscillator (80 MHz repetition rate; Spectra-Physics Tsunami) with 200 fs duration, 830 nm central wavelength are frequency doubled in a beta barium borate (BBO) crystal yielding a second-harmonic beam with 415 nm central wavelength and average power of 300 mW. A small pick-off from the Ti:sapphire beam is directed onto a fast photodiode (PD) to provide a synchronizing signal for the electro-optic TL (25).

The 415 nm beam is focused in a 8-mm-long bulk potassium dihydrogen phosphate crystal to probabilistically produce degenerate (830 nm central wavelength), spectrally uncorrelated pairs of orthogonally polarized photons, signal and idler, with spectral bandwidths of 3 nm and 8 nm, respectively. Generated photons are separated using a polarizing beam-splitter (PBS) and coupled into single-mode fibres (Corning HI-780). By detecting the idler photon using a avalanche photodiode (APD) single-photon counting module we herald the presence of the signal photon employed in the experiments. A field-programmable gate array (FPGA) is used to register coincidences between detection events with a coincidence window of 8 ns for $g^{(2)}(0)$ and efficiency measurements, while a time-to-digital converter (TDC; Picoquant PicoHarp 300) is used to register coincidences for the heralded single-photon spectrum measurements.

Single-photon spectrometer. The pulsed nature of photons used in the experiment enables us to employ a time-of-flight spectrometer based on the dispersive Fourier transform principle. A chirped fibre Bragg grating (CFBG) maps the spectral profile of a single-photon wavepacket onto its temporal distribution, which is measured with respect to the idler photon detection (26, 31).

The temporal distribution is determined with resolution better than 50 ps using a pair of free-running, low-timing-jitter single-photon counting modules (Micro Photon Devices, SPD-050-CTB-FC) followed by a TDC working in start–stop mode (Fig. 2b). After appropriate spectrometer calibration, the time-of-arrival distribution can be directly translated into the heralded photon spectrum. This approach results in high spectral resolution of 0.07 nm with a spectral range of approximately 10 nm, leading to a maximum temporal window of 10 ns, which is compatible with the 80 MHz pulse train. Finite spectrometer resolution results from timing jitter of the single-photon counting modules monitoring the signal and idler arms. A more detailed description of the device and its calibration can be found in ref. 26.

Spectral measurement uncertainty. To estimate the uncertainties in spectral measurements we assumed Poisson statistics for the experimentally collected photon counts in each spectral bin of width 0.034 nm, with variance equal to the number of counts registered within this bin. Then we performed a Monte Carlo simulation by generating $10^6$ auxiliary spectra drawing the number of counts in each bin from the corresponding Poisson distribution, each time retrieving the FWHM bandwidth of generated spectra. This procedure produced $10^6$ estimates of the FWHM bandwidth related to one experimental spectrum and we took the standard deviation of this FWHM set as our measurement uncertainty.

Spectrally narrowband absorber. The narrowband absorber was realized as a bandpass spectral filter implemented using a 300 nm focal length monochromator (Andor Shamrock 303i) with a 1,200 lines per mm diffraction grating. In place of the output slit at the focal plane of the monochromator we placed multimode fibre connected to an APD single-photon counting module (Perkin Elmer SPCM-AQ4C) instead. The grating was mounted on a motorized turret, which allowed us to precisely tune the wavelength transmitted by the filter. The filter transmission profile was measured using an optical spectrum analyser (ANDO AQ6317), yielding spectral bandwidths of 0.13–0.16 nm FWHM, depending on the selected central wavelength.

Determination of photon flux ratios. Experimental points in Fig. 4a were determined according to the following procedure. We started by selecting the desired central wavelength of signal photons by modifying the potassium dihydrogen phosphate crystal tilt angle. Afterwards, we sent photons directly into the narrowband absorber described in the previous paragraph and maximized the registered coincidence counts rate by rotating the monochromator grating. We collected the total coincidence counts registered within 150 s and present the obtained result in Fig. 4a (crosses). In the next step, we inserted the EORC between the single-photon source and the narrowband absorber using two FC/PC-type fibre connectors. Using the manual phase-shifter of the RF signal, we adjusted the relative phase of the sinusoidal RF signal with respect to the incoming photon wavepackets so that the coincidence count rate was maximized. We compensated a small polarization rotation introduced by bending the single-mode fibre during set-up reconfiguration by manipulating a polarization controller to maximize the coincidence count rate. We collected the total coincidence counts registered within five series, 30 s each, monitoring the coincidence count rates and manually compensating for RF signal phase drift if needed. The number of counts registered in this configuration is presented in Fig. 4a (filled squares).

Measurement of the second-order correlation function. The $g^{(2)}(0)$ measurement of heralded single photons was obtained by placing a polarization-maintaining fibre coupler with a splitting ratio of approximately 50:50 in the signal arm with each output port monitored by an APD (Perkin Elmer SPCM-AQ4C), which we denote D2 and D3. Signals from D2, D3 and the heralding detector, denoted D1, were directed to the FPGA coincidence logic, where D1 and D2, D1 and D3, and D1, D2 and D3 coincidence events as well as single-count events at D3 were recorded within a coincidence window of 8 ns. Counts were acquired in 50 series of 360 s duration. For each series, the second-order correlation function $g^{(2)}(0) = \langle N_1 N_2 \rangle / \langle N_2 \rangle^2$ was calculated, where $N_2$ are counts within 360 s for coincident detection events at a set of detectors labelled by ‘d’. We present the mean value of the calculated correlation functions with measurement uncertainty accounting for 5% Ti:sapphire laser power instability over the measurement time.

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