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Attosecond quantum uncertainty dynamics and ultrafast squeezed light for quantum communication

Mohamed Sennary¹, Javier Rivera-Dean², Mohamed ElKabbash³, Vladimir Pervak⁴, Maciej Lewenstein^{2,5} and Mohammed Th. Hassan^{1,3}✉

Abstract

Advancements in quantum optics and squeezed light generation have revolutionized various fields of quantum science over the past three decades, with notable applications such as gravitational wave detection. Here, we extend the use of squeezed light to the realm of ultrafast quantum science. We demonstrate the generation of the shortest ultrafast synthesized quantum light pulses spanning 0.33 to 0.73 PHz by a degenerate four-wave mixing nonlinear process. Experimental metrology results confirm that these pulses exhibit amplitude squeezing, which is consistent with theoretical predictions. Moreover, we observe the temporal dynamics of amplitude uncertainty of the squeezed light, demonstrating that quantum uncertainty of light is controllable and tunable in real time. Additionally, we demonstrate control over the quantum state of light by switching between amplitude and phase squeezing. Our ability to generate and manipulate ultrafast, squeezed, synthesized light waveforms with attosecond resolution unlocks exciting possibilities for quantum technologies, including petahertz-scale secure quantum communication, quantum computing, and ultrafast spectroscopy. As an example, we introduce an attosecond quantum encryption protocol leveraging squeezed synthesized light for secure digital communication at unprecedented speeds. This work paves the way for exploring quantum uncertainty dynamics and establishes the foundation for the emerging ultrafast and attosecond quantum science fields.

Introduction

Over the past few decades, significant advances in quantum optics, particularly the generation of quantum light^{1–8}, have played a pivotal role in enhancing the sensitivity of gravitational wave measurements by the Laser Interferometer Gravitational-Wave Observatory (LIGO)^{9,10}. Concurrently, the evolution of ultrafast science, attosecond physics, and the development of cutting-edge tools—such as femtosecond high-power lasers and XUV pulses—have spurred new frontiers in both fundamental research and technological applications. These breakthroughs, acknowledged by the Nobel

Prizes in Physics in 2018 and 2023, have enabled detailed investigations into light-matter interactions at the classical level, thereby providing profound insights into molecular, atomic, and electron dynamics¹¹. For instance, attosecond science has leveraged the high-harmonic generation (HHG) to probe electron motion on timescales as short as attoseconds^{12–17}. Recent experimental and theoretical studies have explored the impact and generation of squeezed light¹⁸ on the HHG process, revealing that the underlying physics of HHG with squeezed light deviates significantly from classical descriptions^{19–28}. Theoretical models predict shifts in both the electronic trajectories driven by the field and the emitted photon energy compared to those observed under coherent laser fields^{29,30}. Experimental demonstrations of HHG^{28,31} in solid-state materials using squeezed light have also shown promising results,

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yielding higher photon fluxes^{19,32}. Additionally, the control of electron and XUV photon statistics through different quantum light modes has been reported, suggesting the potential for tailored quantum control in ultrafast processes^{28,33}. These findings raise critical questions: How do light-matter interactions and ultrafast phenomena evolve when triggered by squeezed light? How do the physics of ultrafast nonlinear optics differ when using quantum light? Addressing these questions calls for new novel tools—specifically, ultrafast quantum light pulses—that can offer a new window into ultrafast science through the lens of quantum physics.

In this work, we present a novel approach for generating ultrafast quantum-synthesized few-cycle pulses produced via a degenerate nonlinear four-wave mixing process. The resulting quantum light pulse exhibits intensity squeezing at the cost of phase uncertainty, as confirmed by both experimental and theoretical analyses. With a pulse duration of 5.3 fs, these pulses represent a promising tool for a range of advanced applications, including ultrafast quantum optics and spectroscopy aimed at exploring light-matter interactions at the quantum level. Moreover, the amplitude squeezing inherent in these pulses enhances the signal-to-noise ratio, surpassing the performance of classical light sources³², with promising applications in ultrafast quantum spectroscopic studies of biological samples.

Furthermore, our approach allows us to control the temporal and spectral properties of the squeezed light, enabling us to probe its real-time dynamics with attosecond resolution. Our experimental results reveal that the uncertainty in amplitude-squeezed light is dynamic, varying with the system's state and its interactions. This ability to manipulate and observe the change of uncertainty in real time opens new avenues for exploring the fundamental nature of quantum mechanics and its implications for quantum control-based technologies.

Moreover, as an initial demonstration of the potential significance of the demonstrated quantum-synthesized light pulses, we present a secure ultrafast quantum communication scheme, leveraging the digital encoding on ultrafast waveforms. Beyond the inherent security of squeezed light in quantum communication, our synthesized quantum pulses introduce an additional layer of digital encryption where the data are carried on the squeezed ultrafast light waveform in the binary format of (0 & 1). This approach establishes a foundational framework for advancing ultrafast quantum science with transformative potential across diverse scientific and technological domains. The demonstrated capabilities of ultrafast quantum applications also pave the way for developing next-generation petahertz quantum electronics³⁴ and communication protocols.

Results

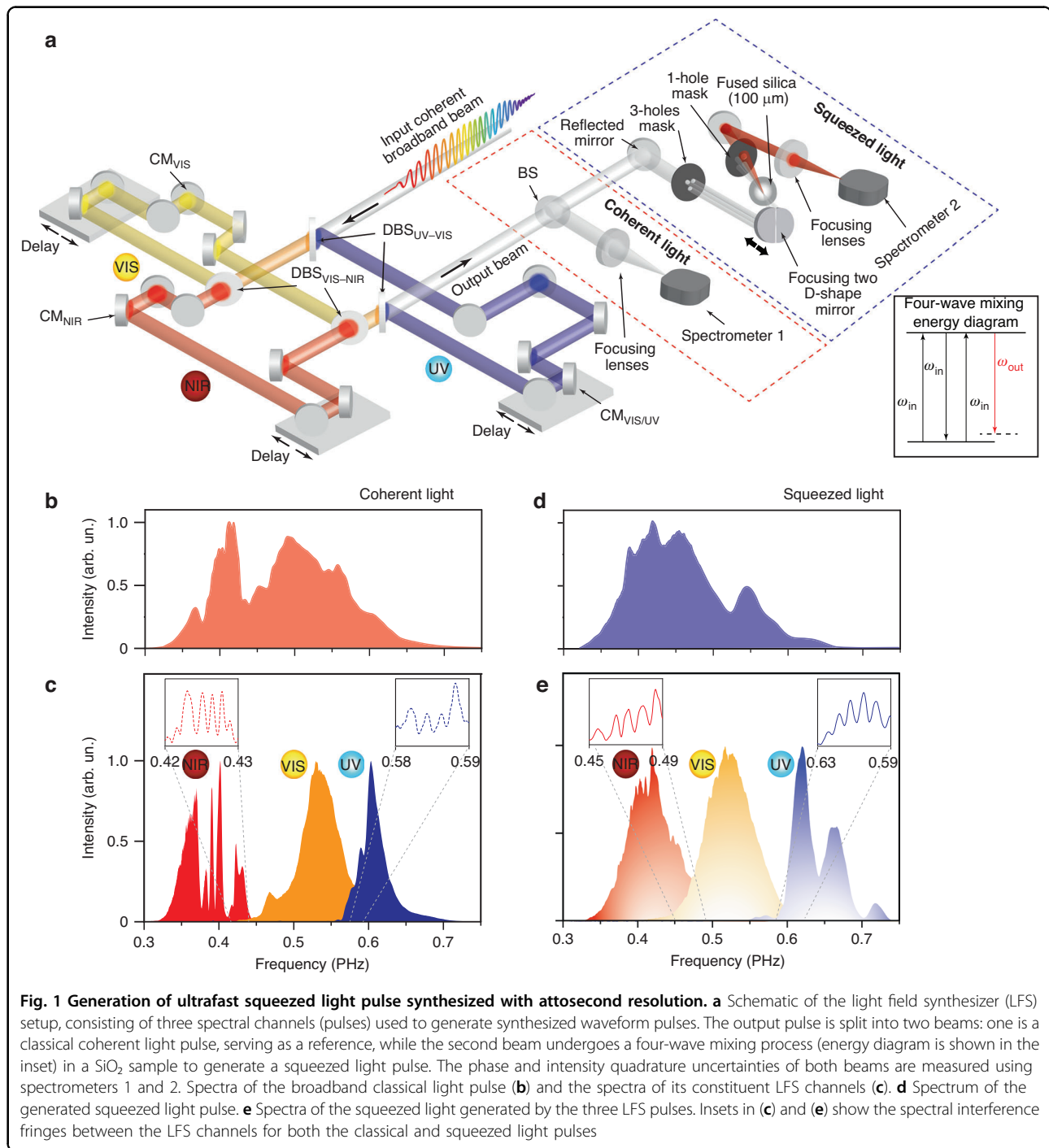
Generation and metrology of ultrafast squeezed light in visible and flanking spectral regions

Harnessing the quantum properties of light for ultrafast applications requires the generation of squeezed light pulses with precise temporal and spectral control. In this study, we generate for the first time, to the best of our knowledge, few-cycle squeezed light pulses in the ultraviolet, visible, and NIR spectral ranges. Our approach is based on a degenerate four-wave mixing (FWM) process in a nonlinear crystal using a light field squeezer setup shown in (Fig. 1a). In this setup, the input beam is divided by a three-hole mask and obtains three identical beams propagate colinearly. These three beams are focused by two D-shaped focusing mirrors (one of them is controlled by a highly precise piezoelectric delay stage) onto a 100 μm -thick SiO_2 target, where the FWM signal is generated. Our setup arrangement maximizes the phase matching between the three input beams, which can be controlled by changing the incident angle by rotating the SiO_2 substrate. This advance allowed us to generate FWM signal from few-cycle laser pulses spanning three different spectral regions: near-infrared (NIR, 1000–690 nm), visible (VIS, 715–500 nm), and ultraviolet (UV, 515–350 nm) obtained from our previously developed light field synthesizer (LFS)^{35–39}, as explained in the Method section. The generated FWM signal is isolated through a spatial filter, and the conversion efficiency is estimated to be on the order of 0.1%, depending on the nonlinear material, thickness, and input beam intensity. These generated pulses exhibit a squeezing in the amplitude or phase quadratures, which can be controlled easily in our setup light squeezer setup by changing the phase matching condition (by changing the tiling angle of the nonlinear medium).

To verify the quantum squeezing characteristics of the generated pulses, we employ a new metrology approach that differs from the conventional approach used for continuous wave (CW) lasers. Our metrology technique involves measuring the spectral interference between temporally delayed pulses (NIR–VIS and VIS–UV) to extract the phase uncertainty ($\Delta\phi$). Additionally, the intensity uncertainty (ΔI) is determined by evaluating the variance in the overall spectral intensity of the squeezed light pulses, which is then compared to that of coherent light.

Hence, the input beam before entering the light field squeezer is divided by a beam splitter into two beams. The reflected beam is opted as our coherent reference beam, which focused and measured by spectrometer #1. The measured spectra of the three different color inputs (UV, VIS, and NIR) coherent light pulses are shown in Fig. 1b. The transmitted beam enter the light field squeezer to generate the squeezed light pulses, and the output is

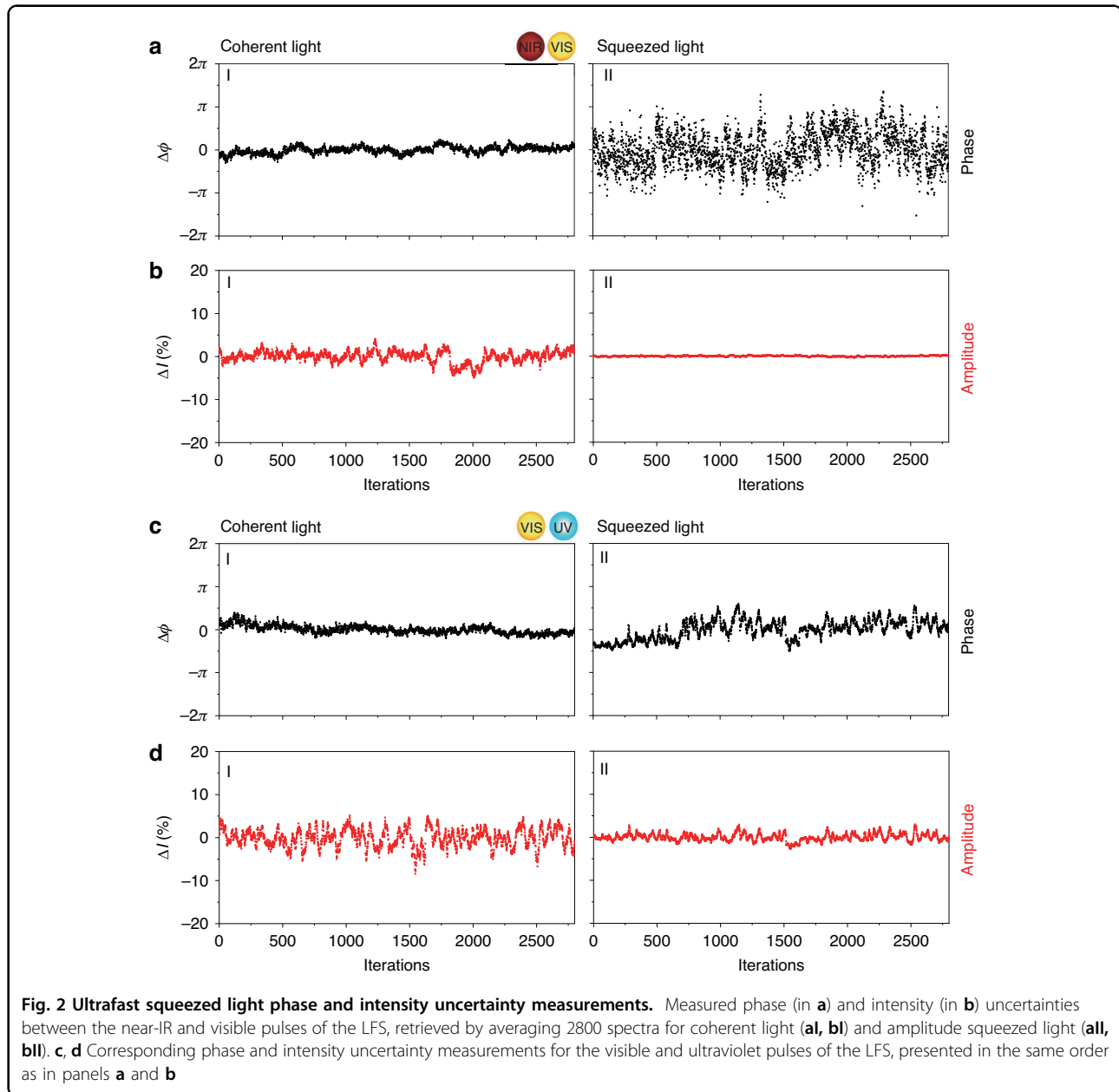




characterized by spectrometer #2. The spectra of the three squeezed pulses are shown in Fig. 1c. Consequently, by analyzing the interference fringes within the spectral overlap region (insets in Fig. 1b and c) between the three pulses, we extract the phase uncertainty ($\Delta\Phi$) for the coherent and squeezed lights. The intensity uncertainty (ΔI) is obtained by measuring the variance in the overall pulse intensity. Amplitude squeezing is confirmed when

the intensity fluctuations of the squeezed light (ΔI_s) are smaller than those of the coherent light (ΔI_c), while the phase jittering of the squeezed light ($\Delta \Phi_s$) exceeds that of the coherent light ($\Delta \Phi_c$).

Our metrology measurements, shown in Fig. 2, demonstrate that the generated light confirms the amplitude squeezing. The phase uncertainty is higher in the squeezed light (Fig. 2aII and cII) compared to the



coherent light (Fig. 2aI and cI), while the amplitude of the squeezed light (Fig. 2bII and dII) is more stable than that of the coherent light. These results confirm that the degenerate FWM process in our light squeezer generates amplitude-squeezed light at the expense of increased phase uncertainty. To assess amplitude stability for individual pulse components, we spectrally filtered the constituent pulses and retrieved their intensity stability. The results shown in Fig. S1 indicate that the amplitude stability difference between the squeezed and coherent light of the different color pulses is roughly comparable. We also perform a shot noise measurement for both classic

and squeezed light by measuring the standard deviation of I (σI) as a function of the beam power and show it in Fig. S2. This result is another proof of the obtained amplitude squeezing of ultrafast light.

Next, we performed theoretical modeling to investigate the nature of the measured phase and amplitude uncertainties and compare it with those of a squeezed state. Then, we calculated the Wigner function as a visual representation of these generated states. The Wigner function is a quasi-probability distribution that provides a visual representation of the quantum state in phase space. Our analysis reveals that the squeezed states correspond

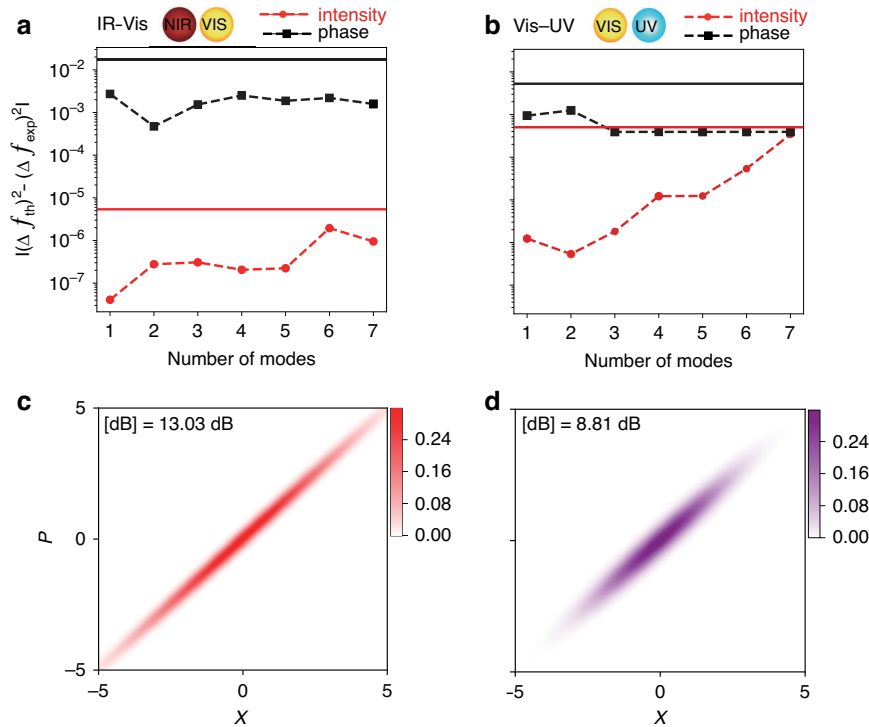


Fig. 3 Wigner functions of the ultrafast squeezed light pulses. **a, b** The optimization results for the IR-VIS and UV-VIS datasets as a function of the number of modes. The dashed curves indicate the absolute error between the theoretical and experimental variances for intensity (in red) and phase (in black). For reference, the experimental variances are represented by solid lines in corresponding colors. **c, d** The Wigner functions of the resulting squeezed states for the IR-VIS and UV-VIS measurements (for $N = 1$), respectively. In these plots, x and p represent the optical quadrature, and for representational purposes, the distributions have been rotated by 45° relative to the p -axis

to a Gaussian distribution that has been squeezed along one optical quadrature and expanded along the conjugate quadrature (Fig. 3, see SI text).

From a theoretical point of view, the four-wave mixing process under co-linear phase matching conditions and within the parametric approximation⁴⁰ produces squeezed coherent states of the form $\otimes_{i=1}^N \hat{S}(r_i)|\alpha_i\rangle$. In this expression, N denotes the number of modes, $\hat{S}(r) = \exp[ra^2 - r^*a^{\dagger 2}]$ is the squeezing operator, and $|\alpha\rangle$ represents a coherent state of light. To determine the compatibility of the experimental results with these theoretical squeezed states, we compared the variances in phase and intensity obtained experimentally, $\Delta\Phi_{\text{exp}}^2$ and ΔI_{exp}^2 , with the theoretical predictions, $\Delta\Phi_{\text{th}}^2(\mathbf{x})$ and $\Delta I_{\text{th}}^2(\mathbf{x})$, (see Ref.⁴¹ and the supplementary information (SI) for detailed calculations), the latter parametrized by $\mathbf{x} = \{(r_i, \alpha_i)\}_{i=1}^N$. Specifically, we defined the following function

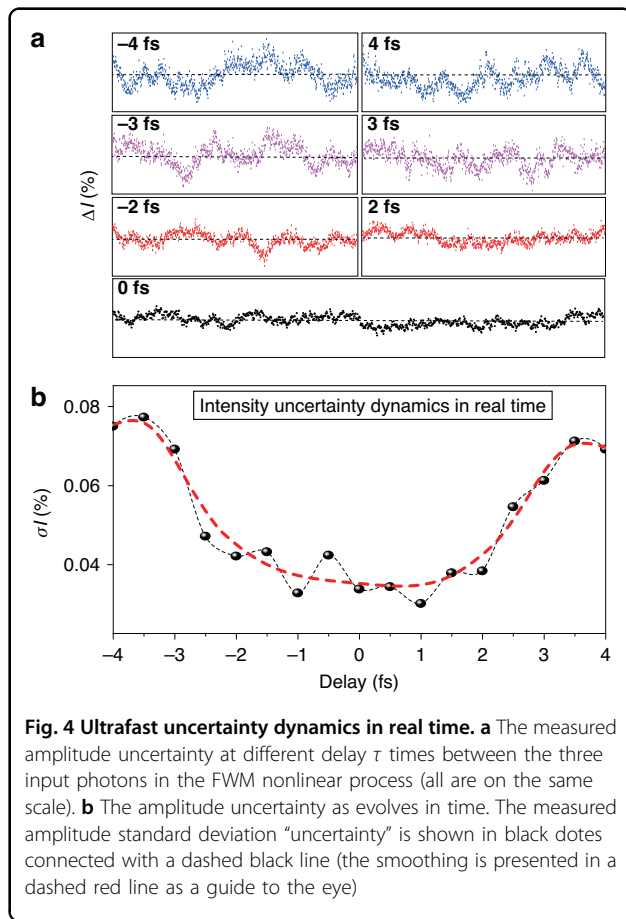
$$C(\mathbf{x}) = A[\Delta I_{\text{th}}^2(\mathbf{x}) - \Delta I_{\text{exp}}^2]^2 + B[\Delta\Phi_{\text{th}}^2(\mathbf{x}) - \Delta\Phi_{\text{exp}}^2]^2 \quad (1)$$

which serves as a measure of the distance between the experimental observations and the theoretical

expectations, where a value of $C(\mathbf{x}) = 0$ would represent a perfect match between the two. Consequently, the comparison involves finding an optimal set of parameters $\mathbf{x}^*$ that minimizes Eq. (1) as much as possible. To achieve this, the parameters A and B have to be chosen carefully to ensure simultaneous minimization of both terms within the function. In practice, the optimization was performed across a range of values for A and B , and the best result was retained (see SI for more details). Furthermore, given that the experimental data suggests the presence of amplitude-squeezing, we restricted our search space to real values of r_i and α_i when solving this optimization problem, as to reduce the number of variables over which to optimize.

The results from this optimization are shown in Fig. 3a and Fig. 3b as a function of the number of modes N , where Fig. 3a represents the IR-VIS dataset and Fig. 3b the UV-VIS dataset. The dashed curves show the absolute difference between the experimental and theoretical variances after optimization, while the solid horizontal lines represent the experimental variance values. In all cases, we observe that the dashed curves lie below their respective solid horizontal lines—indicated in matching colors—demonstrating a good agreement between theory





and experiment, as the absolute error remains around one and two orders of magnitude below the experimental values. Notably, this trend persists across all values of N considered in our study, suggesting that the experimental data are compatible with the presence of squeezed states along multiple modes. However, for both the IR-Vis and UV-VIS datasets, an increase in the number of modes generally corresponds to reduced accuracy in the absolute error, particularly pronounced in the intensity variance. Overall, we observe that the best results are achieved in the $N = 1$ case, yielding a total estimated squeezing of 13.03 dB for the IR-Vis dataset and 8.81 dB for the UV-VIS dataset. The difference in the squeezing level may be attributed to the alignment optimization in the two measurements to achieve the optimized FWM output signal. The Wigner function⁴² of the resulting squeezed states is shown in Fig. 3c and d, respectively, where χ and p represent the optical quadratures. The functions have been rotated by 45° relative to the p -axis for representational purposes. They correspond to a Gaussian distribution that has been squeezed along one optical quadrature and expanded along the conjugate quadrature.

Attosecond control of the quantum light uncertainty dynamics

Having established the generation of ultrafast squeezed light pulses, we now turn our attention to the central question of this study: How does amplitude uncertainty change in real-time? To address this, we directly measure σI , which presents the amplitude uncertainty of the squeezed light as a function of time. We exploit the temporal control between the three input beams in the FWM process to introduce a variable delay (τ) between one photon and the other two photons using the D-shape mirrors (see the setup in Fig. 1a). By measuring σI for different values of τ , we can track the evolution of amplitude uncertainty as the system interacts and evolves in time. The measurements at different delay τ times are shown in Fig. 4a. Our results, presented in Fig. 4b (black circles connected by the black dashed line, and the red dashed line as a guide to the eye), show that the σI has higher values at the positive and negative delays in time. The minimum σI is achieved when all three input photons overlap in time. These results demonstrate that σI is not static but varies in real-time, influenced by the system's state and its interactions.

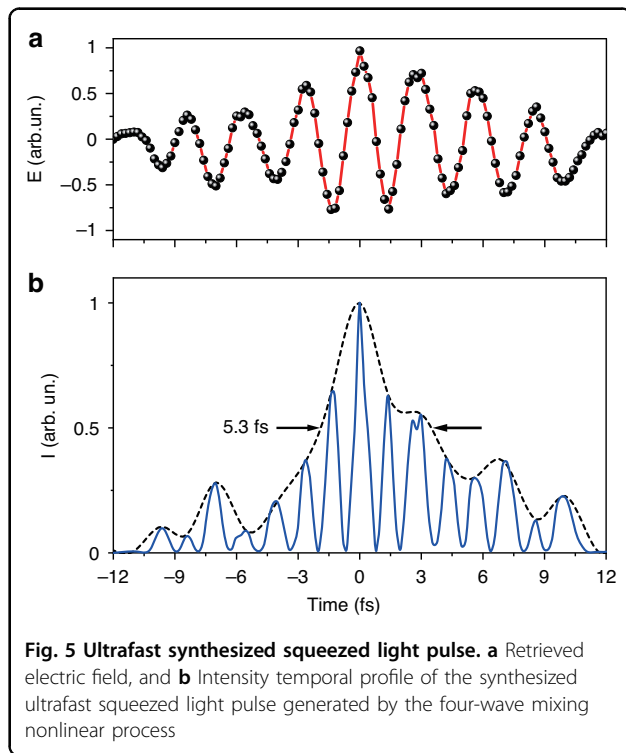
This dynamical uncertainty of the amplitude can be explained as follows: the amplitude squeezing is achieved by utilizing the quantum correlations arising from the nonlinear four-wave mixing interaction among three input photons. In our case, the incident angle of these beams is kept very small ($<5^\circ$). So, the good phase matching, which can be optimized by tilting the nonlinear medium, occurs and ensures constructive interference when the three pulses arrive simultaneously in time. Consequently, the nonlinear signal generation window is temporally confined to the pulses' overlap time ($\tau = -1.5$ to 1.5 fs, from Fig. 4b), reducing the uncertainty in the number and amplitude of generated photons. Conversely, if one of the input pulses arrives with a certain delay (τ) relative to the other two, the nonlinear signal generation window widens, increasing randomness and, in turn, intensity uncertainty.

To further confirm this interpretation, we repeat the measurements with a squeezed phase light, obtained by altering the tilting angle of the nonlinear medium. In this case, the behavior of σI as a function of time, shown in Fig. S3c (black circles connected by a black dashed line, blue dashed line is a guide to the eye), is opposite to the case of amplitude squeezing (Fig. 4b), confirming the dynamic behavior of uncertainty.

Application of synthesized quantum light in petahertz digital data encoding and quantum communication

Remarkably, by the spatiotemporal overlap of the UV, VIS, and NIR pulses, we can obtain nearly the shortest squeezed light pulse in the order of 5.3 fs duration (Fig. 5).





Moreover, by controlling the delay and the amplitude of the UV, VIS, and NIR pulses, we can synthesize the broadband squeezed light waveforms with attosecond resolution^{36–38}. The ability to generate and control ultrafast squeezed light pulses unlocks exciting new possibilities for quantum technologies. One particularly promising application is ultra-secured quantum communication.

Traditional continuous-variable quantum key distribution (CV-QKD) relies on encoding information into the quadratures of quantum states, such as amplitude (ΔI) and phase ($\Delta\Phi$), using a squeezed or coherent light source. The receiver measures one of these quadratures using a local oscillator (LO) to project the quantum state onto the desired quadrature, chosen at random. The security of CV-QKD arises from the inability of an eavesdropper (Eve) to intercept the quantum state without introducing detectable noise, owing to the Heisenberg uncertainty principle.

In our petahertz communication scheme, we leverage the ultrafast nature of the squeezed light pulses to encode quantum-encrypted digital data at unprecedented speeds. As illustrated in Fig. 6, Alice synthesizes and encodes digital data onto amplitude-squeezed light waveforms using the LFS, as we demonstrated earlier^{35,36,43,44}. The measured exemplary waveforms shown in Fig. 6aI–III are the average of three scans, and despite the phase uncertainty of these waveforms, they maintain their shapes. Alice sets a predefined intensity threshold (30%) for the

modulation, encrypting digital data within the squeezed waveforms. She then sends the encoded squeezed light beam to Bob (Fig. 6b), sharing the squeezing degree and the threshold information.

As in conventional CV-QKD, any eavesdropping attempt by Eve (Fig. 6c) to intercept and decode the squeezed light waveform would alter its squeezing degree, thereby revealing the intrusion to both Alice and Bob. Bob can check the signal's squeezing degree by measuring its intensity stability between different pulses (as we did in our experiment and shown in Fig. 2) to confirm the communication's security.

To further enhance security, we propose using one of the three pulses—specifically, the NIR pulse—as a quantum-correlated local oscillator⁴⁵. This eliminates the need for an external classical LO and simplifies synchronization. At the receiver station, after sampling the waveform and decoding the digital data, Bob introduces a controllable relative time delay between the NIR reference pulse and the other pulses. This delay adjusts the interference conditions at specific wavelengths, allowing Bob to effectively select quadrature projections by inducing constructive or destructive interference. By varying the delay, Bob dynamically selects which quadrature component (amplitude or phase) to measure at a given wavelength. He then measures the noise at specific wavelengths within the spectral overlap region, where spectral interference exists between the different channels. Depending on the interference condition at that wavelength, Bob measures a specific quadrature and obtains the squeezing level of the selected quadrature projection. This protocol enhances security by making it difficult for an eavesdropper to predict Bob's quadrature choices or replicate the quantum-correlated states without introducing detectable noise. This approach avoids challenges associated with classical LOs, enables dynamic quadrature selection, and leverages quantum correlations to strengthen the security and efficiency of CV-QKD. Remarkably, our protocol introduces additional layers of security, in analogy to the typical CV-QKD protocol, protecting the communication from potential tampering. Specifically, our approach provides multiple safeguards against Eve's interference: (i) Eve would need the decoding key to correctly interpret the transferred information, (ii) Eve cannot accurately decode the data without knowing the predefined intensity threshold (30%), and (iii) even if Eve knows the threshold, her measurement of the squeezed light waveform using a beamsplitter will inevitably disturb the squeezing, introducing errors in the decoded data due to the altered squeezing degree. This disturbance increases the tolerance error of the predefined threshold and amplifies the likelihood of faulty decoding, as shown in Fig. 6cI–III. Consequently, our approach not only secures the communication channel



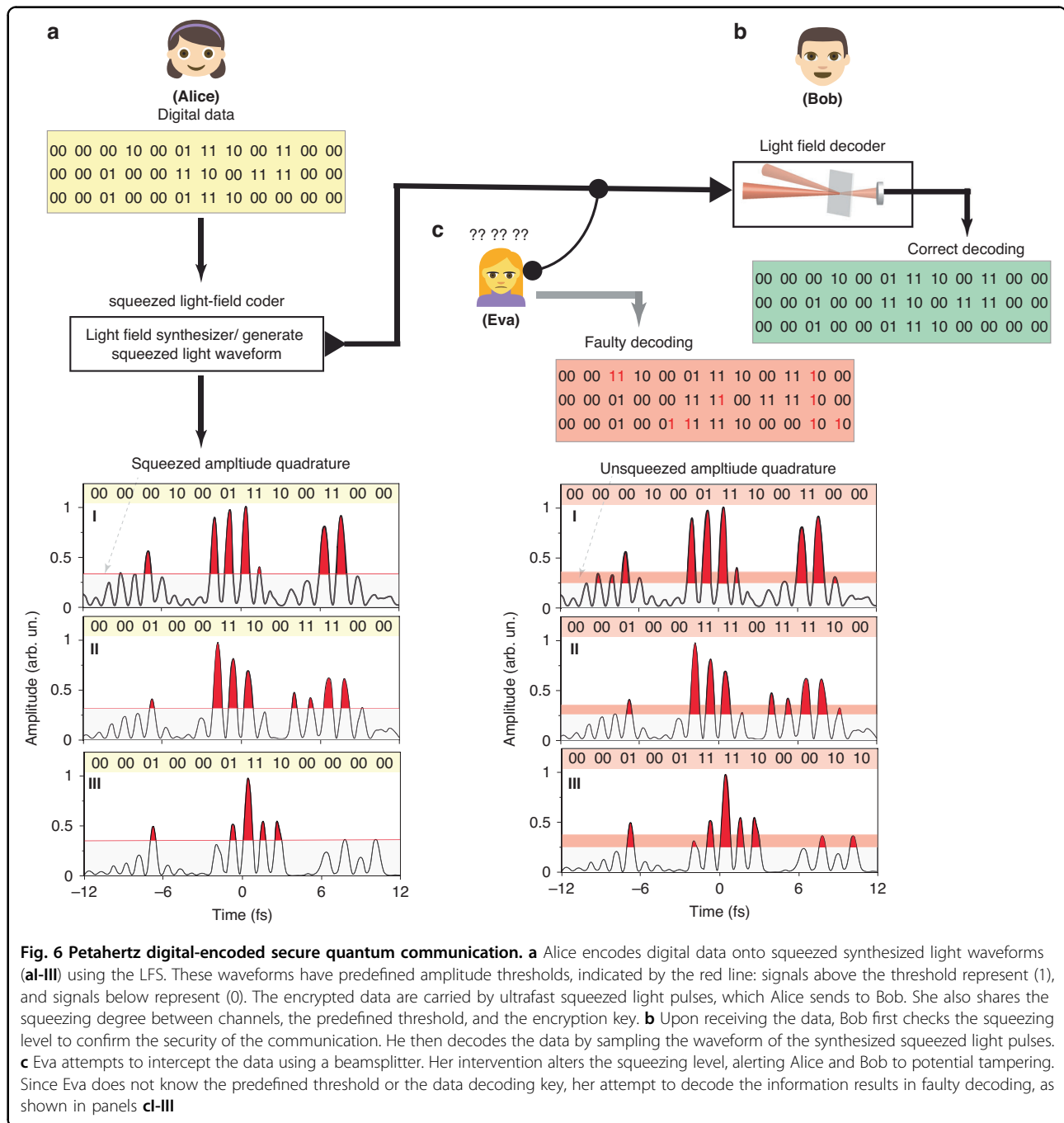


Fig. 6 Petahertz digital-encoded secure quantum communication. **a** Alice encodes digital data onto squeezed synthesized light waveforms (aI–III) using the LFS. These waveforms have predefined amplitude thresholds, indicated by the red line: signals above the threshold represent (1), and signals below represent (0). The encrypted data are carried by ultrafast squeezed light pulses, which Alice sends to Bob. She also shares the squeezing degree between channels, the predefined threshold, and the encryption key. **b** Upon receiving the data, Bob first checks the squeezing level to confirm the security of the communication. He then decodes the data by sampling the waveform of the synthesized squeezed light pulses. **c** Eva attempts to intercept the data using a beamsplitter. Her intervention alters the squeezing level, alerting Alice and Bob to potential tampering. Since Eva does not know the predefined threshold or the data decoding key, her attempt to decode the information results in faulty decoding, as shown in panels cI–III

but also protects the transferred data from unauthorized retrieval.

Discussion

This work introduces a groundbreaking approach to ultrafast quantum optics by demonstrating the generation of broadband squeezed light pulses with attosecond precision. By leveraging these ultrafast quantum light waveforms, we have shown how they can be used for secure quantum communication, marking a significant step

toward the realization of high-speed, encrypted communication networks. Our results not only open new avenues for exploring quantum light-matter interactions in real-time but also lay the foundation for future advancements in ultrafast quantum optoelectronics and quantum computing.

As quantum communication systems evolve, the ability to operate at petahertz-scale data transmission speeds will be critical, and our findings contribute to the development of technologies that can meet these challenges while



ensuring security and robustness. The potential of ultrafast squeezed light in secure communication represents a promising frontier for both fundamental research and practical applications in the quantum technology landscape. Moreover, the dynamic nature of quantum uncertainty observed in our experiments suggests a more fluid picture of quantum reality. This has profound implications for understanding the fundamental nature of time and measurement in the quantum world. The ability to generate and control ultrafast squeezed light also opens exciting new possibilities for ultrafast spectroscopy and quantum computing. In ultrafast spectroscopy, this technology could be used to probe the dynamics of chemical reactions or biological processes on the attosecond timescale, providing unprecedented insights into the fundamental building blocks of matter. In quantum computing, ultrafast squeezed light could be used to manipulate qubits or perform quantum logic operations at unprecedented speeds, paving the way for the development of faster and more powerful quantum computers.

The introduced ultrafast quantum communication protocol operates offering the potential for ultra-secure, high-speed communication networks. Although our petahertz quantum communication protocol offers a higher level of security due to the intrinsic sensitivity of squeezed light to any eavesdropping attempt, there are practical challenges, such as maintaining low-loss transmission or pulse dispersion distortion of squeezed pulses over long distances in dispersive media/optical fibers. However, this can be precompensated by controlling the relative delay between the synthesizer pulses. Moreover, this approach would be promising for space-space quantum communication, where the pulse is not affected by dispersion as it propagates in vacuum. Furthermore, scaling up the LFS and the input coherent laser pulse power to generate a high-power squeezing synthesized pulse would overcome the transmission loss problem and support robust ultrafast quantum communication. Furthermore, achieving quantum communication at petahertz frequency speeds is currently limited only by the laser repetition rate and the delay stage speed in the synthesizer. However, with ongoing advancements in laser technologies, this digital data speed is potentially on the horizon.

In summary, this work introduces a groundbreaking approach to ultrafast quantum optics by demonstrating the generation and metrology of broadband squeezed light pulses with attosecond precision. By leveraging these ultrafast quantum light pulses, we have shown how they can be used for secure quantum communication, marking a significant step toward the realization of high-speed, encrypted communication networks. The demonstrated approach can be potentially extended to the light-matter coupled in QED cavity⁴⁶ and to quantum spin

squeezing⁴⁷. Our results not only open new avenues for exploring quantum light-matter interactions in real-time but also lay the foundation for future advancements in ultrafast quantum optoelectronics and quantum computing^{34,43,48}.

Materials and methods

In our experimental setup, few-cycle laser pulses centered at 750 nm (passively stabilized carrier-envelope phase) are generated by an Optical Parametric Chirped-Pulse Amplification (OPCPA)-based laser system with a repetition rate of 20 kHz. These pulses propagate nonlinearly through a hollow-core fiber filled with neon gas (at 3.5 bar), generating a supercontinuum that spans from the ultraviolet to the near-infrared spectral range. The broadband spectrum is directed into a light field synthesizer (LFS) device^{36–39} where it is split into three spectral channels using dichroic beam splitters: Ultraviolet (UV, 515–350 nm), Visible (VIS, 715–500 nm), and Near-Infrared (NIR, 1000–690 nm). Each of these channels is compressed using six pairs of chirped mirrors to approach their Fourier limits. The temporal profiles of the pulses in each channel are shown in Fig. S4. The full-width at half maximum (FWHM) pulse durations are 10, 9, and 8.5 fs for the UV, VIS, and NIR pulses, respectively. The pulses are recombined using similar dichroic beam splitters and coherently superimposed at the output of the synthesizer, forming a two-cycle laser pulse. This pulse waveform is finely controlled by adjusting the relative delay between the three LFS pulses with a high-resolution piezoelectric linear stage in the UV and NIR beam paths. Neutral density filters are used to control the relative intensities of the constituent pulses. The total power of the output beam from the LFS is one watt.

The beam is first split using a beamsplitter, with the reflected beam (8% of the total power) representing the classic coherent synthesized pulse. This reflected beam is focused into spectrometer #1 (Ocean Optics HR 4000, which has an estimated typical quantum efficiency of 50–70%) with a 5-cm focal length lens (the intensity loss through the optics and optical fiber is estimated to be about <5%). We measure 2800 spectra to assess the average intensity stability. First, we integrated each spectrum to get the total intensity (I_n), where n is the number of iterations. Then, ΔI was calculated by normalizing each spectrum to the average intensity of all the spectra and then calculating the percentage stability. The intensity standard deviation (σI) percentage is calculated from the average and standard deviation of the n intensities for n iterations. On the other hand, the interference fringes between the spectral channels (inset of Fig. 1b and c) are analyzed, and their corresponding Fourier transforms are computed to extract phase jittering ($\Delta\phi$) between the individual pulses.



The transmitted beam, after passing through the beamsplitter, is directed through a 3-hole mask. The three emerging beams, which are identical in power (162.5 mW), are focused using two D-shaped focusing mirrors onto a fused silica sample (beam diameter $\sim 50\ \mu\text{m}$). One of these D-shaped mirrors is mounted on the piezo stage to control the relative delay between one of the input beams with respect to the other two beams. Then, a four-wave mixing process occurs, and a non-linear light signal is generated, which is amplitude-squeezed ($153\ \mu\text{W}$). A 1-hole mask filters out this squeezed light, which is then focused into spectrometer #2 (Ocean Optics HR 4000CG) for characterization of its intensity, phase stability, and jitter. The LFS constituent pulses are delayed, generating better interference fringes at the spectral boundary of each pulse (see in set Fig. 1c and e). Dark noise from the spectrometers (Fig. S5) was negligible, being two orders of magnitude lower than the observed amplitude fluctuations.

For the time-resolved intensity uncertainty measurements, we acquired 1000 spectra at each time delay (τ) between one of the input beams with respect to the other two beams, which interact with the SiO_2 to generate the nonlinear signal. We obtained σ_I at each time delay τ and plotted it in Fig. 4. Next, the relative delay between the LFS channels is also adjusted to synthesize the squeezed light waveform. The waveform is sampled using an all-optical light field sampling technique, reported previously^{35,36,43,44}. This method involves focusing the squeezed light onto the SiO_2 sample ($200\ \mu\text{m}$) alongside a probe beam. By measuring the modulation of the probe beam's transmission induced by the squeezed light, we extract the waveform by analyzing the recorded spectrum intensity as a function of the delay between the squeezed light and the probe pulse.

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Author contributions

M.S. conducted the experiments and analyzed the data. J.R.D. and M.L. carried out the simulations and calculations. M.E. and M.Th.H. developed the ultrafast

CV-QKD approach. M.E. suggested the shot noise experiment. V.P. designed and measured the optics used in the setup. M.Th.H. conceived, supervised, and directed the study. All authors discussed the results and their interpretations and wrote the manuscript.

Data availability

The datasets supporting the findings of this study are available in the Figshare repository at 10.6084/m9.figshare.30120670. Additional data are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare no competing interests.

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