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List of abstracts (part 2)

Tomography of a Raman Quantum Memory for Temporal Modes of Light

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Practical, scalable, architectures for networked quantum information processing draw upon the strengths of different media: for instance in which one exploits the precision and controllability of quantum states and interactions in material systems and photonic systems which exhibit only weak interaction with their environment (and other photons). The former facilitate information processing, whereas the latter are ideal for the transmission of information between nodes of a quantum network. Temporal modes (TMs) of light are an appealing encoding for photonic quantum information processing [1]. To interface with these, two prerequisites are to be able to firstly prepare – and verify – these states, and secondly to selectively adress, and separate out, a chosen temporal mode. We present the means to address the both of these criteria.

To interface with TMs, the quantum pulse gate (QPG) based upon sum-frequency generation, enables a time non-stationary beam-splitter interaction to be implemented [2]. By appropriately tuning the pump pulse, a chosen temporal mode may be selectively mapped to a different frequency (and temporal mode, determined by the phase matching conditions). However, such devices are also subject to a lower limit of bandwidths of ∼100 GHz, and are not compatible with quantum light sources operating in the MHz-GHz regime.

The Raman memory [3] also constitutes a platform which implements a time non-stationary beam-splitter interaction, whereby a chosen signal may be mapped into (and retrieved from) an atomic excitation, whilst orthogonal modes are transmitted. We demonstrate selective storage of ns duration weak coherent state TMs in a Raman quantum memory in warm caesium vapour. The $6S_{1/2}(F = 3, 4)$ hyperfine levels are used as the ground/storage states, respectively; and the control pulse drives a two-photon Raman transition between these via the $6P_{3/2}$ manifold. Pulses are carved from a continuous wave diode laser using a fibre-integrated Mach-Zehnder electro-optic modulator driven by two AWGs enabling full control of the output amplitude and phase.

At elevated efficiencies, the "broadband beam-splitter" interaction becomes multimode and the Schmidt modes become destorted [4]. To verify the usefulness of a device for interfacing with TMs, we reconstruct the modal structure of the memory interaction by probing the storage efficiency of an ensemble of prepared input signals.

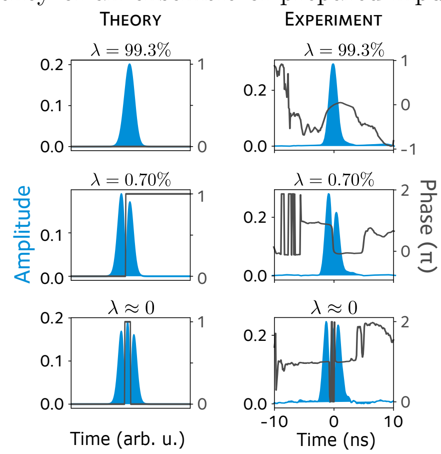

FIG. 1. Eigenmodes of the memory interaction, theory (L.) and extracted from a typical experiment (R.). The singular values indicate a separability of 99%.

With this we are able to establish the eigenmodes and extract the mode-selectivity of the interaction.

Additionally, to verify the states which are sent to the memory, one requires access to the amplitude and phase of the pulses. Existing pulse characterisation techniques [5–7] based upon spectral methods do not have the resolution to access the ns scale pulses used here. We demonstrate a single-shot, self-referenced protocol that operates instead in the temporal domain, *Temporal Amplitude & Phase: Algorithmic Reconstruction via Time-domain Interferometry* (TeAPARTI).

We have demonstrated the TM-selective operation of the Raman memory which provides the basis for using this a device for the manipulation of TMs.

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Temporal-mode selective purification and manipulation of multimode quantum light

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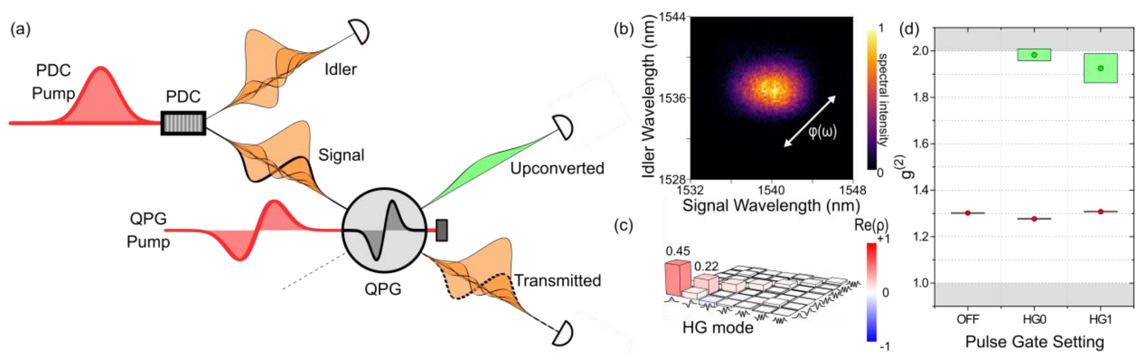
In order to fully exploit the time-frequency degree of freedom for photonic quantum information science, it is necessary to develop and demonstrate techniques which can manipulate the temporal structure of multimode quantum light without introducing excess noise. In this work, we experimentally demonstrate such a technique using shaped ultrafast pulses and dispersion-engineered frequency conversion as a quantum pulse gate. We controllably select broadband field-orthogonal (i.e. intensity overlapping) modes out of a multimode downconverted photon state, converting the specified mode from the infrared to the visible regime while leaving the unselected modes unaffected. Through photon-number correlation measurements, we show that such a technique selects a single mode with high purity (above 95\%) and low noise (SNRs above 70). We also show through the photon-number correlations that our device can be used to both purify and redistribute the coefficients of a multimode photon state.



(a) Experimental concept. We produce photon pairs through parametric downconversion (PDC) spanning many time-frequency modes. By shaping the pump the quantum pulse gate (QPG) and measuring the upconverted light, we project onto a custom temporal mode. (b) Joint spectral intensity of the two-photon state and (c) experimentally reconstructed temporal-mode density matrix of the signal photon for a chirped PDC pump pulse. The multimode structure is hidden from the spectral intensity measurements, but revealed through mode-selective reconstruction. (d) The second-order correlation function ($g^{(2)}$) of the transmitted photons (red) and upconverted photons (green), demonstrating both the purification of the upconverted light ($g^{(2)}\approx 2$) and the manipulation of the structure of the transmitted photons, evidenced by the mode-dependent change in the $g^{(2)}$.

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Mimicking atmospheric turbulence using a spatial light modulator to test hacking a free-space quantum key distribution receiver

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Introduction. In theory, quantum key distribution (QKD) is unconditionally secure; however in practice, a real system is never perfect. An eavesdropper (Eve) could exploit any flaws or vulnerabilities of a system to hack it. Therefore, it is important to study a physical system, and find a solution or countermeasure to any successful attacks. An example of such an attack on a free-space QKD receiver is achieved by changing the spatial mode of the incoming beam to the receiver[1]. However, this attack is dependent on Eve's ability to precisely maintain a particular input angle to the receiver.

An attack could be hindered by beam wander effects caused by atmospheric turbulence in the free-space transmission channel. The assumption of a physical limitation on Eve is not usually included in the security analysis of a QKD system. In practice it is common to have a secure area surrounding the transmitter and receiver to ensure Eve is not present. By mimicking atmospheric turbulence of various strengths, we can explore how beam wander and spatial mode aberrations affect Eve's ability to hack a free-space QKD receiver, as well as determine the required 'safe' perimeter for secure communication.

Turbulence emulator. We emulated turbulence in the lab using a phase-only spatial light modulator (SLM). The advantage of using an SLM as opposed to testing outside is the ability to reproducibly generate turbulence of various strengths without working in an unpredictable environment. We chose to generate the phase holograms that represent turbulence based on the Kolmogorov model[2] using a superposition of Zernike polynomials[3]. Zernike polynomials make a convenient basis choice as they directly relate to known optical aberrations, such as tip/tilt, defocus, astigmatism, etc.

We verified the accuracy and reproducibility of the atmospheric turbulence emulated by our SLM setup using simple equations and devices, such as a CCD camera or wavefront sensor, for independent characterization. It is crucial to know whether the emulated turbulence generated by the SLM setup agrees with the theoretical predictions before testing hacking the receiver. Figure 1 compared the theoretical and experimental far-field intensity distributions that emulates various turbulence strengths. This data illustrates we have excellent agreement between theory and experiment.

Conclusion. We successfully emulated atmospheric turbulence in a lab environment using a phase-only SLM, and demonstrated a spatial mode detection efficiency mismatch attack in a turbulent channel. We then study a spatial mode detection efficiency mismatch attack under a range of atmospheric turbulence strengths to determine the maximum unsafe radius around the receiver. Under the practical assumptions that only the total detection rate and quantum bit error rate are monitored for this particular receiver, Eve could attack a non-decoy state BB84 system from up to ~ 250 m away in typical sea-level conditions ($r_0 = 3.5$ cm for a 20 cm diameter beam at 532 nm). If there is a chance that Eve is inside this secure zone, or has advanced adaptive optics capacities, then extra care regarding these types of attacks may be required.

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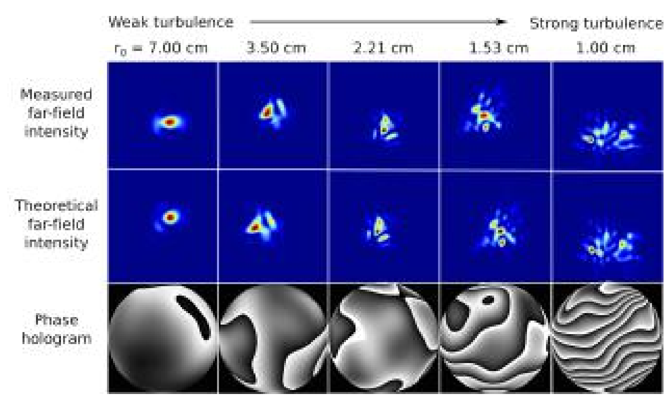

FIG. 1. Comparison between measured and theoretical far-field intensity distributions of a laser beam propagating through a range of turbulence strengths (r_0, atmospheric coherence length), and the corresponding SLM phase hologram ($D = 20$ cm and $\lambda = 532$ nm). The greyscale in the holograms represents a 0 to 2π phase range.

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ORCA – an ultrafast multimode quantum memory

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Quantum networks promise to revolutionise computing, simulation, and communication. Light is the ideal information carrier for quantum networks, as its properties are not degraded by noise in ambient conditions, and it can support large bandwidths enabling fast operations and a large mode, thus information, capacity. Quantum optical memories, i.e. devices that store, manipulate, and release on demand quantum light, have been identified as critical components of such photonic networks, because they facilitate scalability. In order to be compatible with ultrafast multimode quantum light, these memories thus have to be broadband, noise-free and, depending on the particular application, single or multi-mode.

Here we present the Off-Resonant Cascaded Absorption (ORCA) memory protocol, the first memory to combine broadband acceptance with zero noise operation. The operational principle of ORCA is summarised in Fig. 1 (a). A strong off-resonant "control" field mediates the mapping of a "signal" pulse into a collective atomic excitation via cascaded absorption/emission. The storage bandwidth of ORCA is determined by the control pulse, and, unlike in many memory protocols, is not in principle limited by the ground state splitting of the atomic storage medium. The major feature of ORCA however, is that the protocol is fundamentally noise-free as there is no physical process (such as four-wave mixing) present via which the control field could spontaneously populate the signal or storage modes, owing to the cascaded energy level configuration and wavelength difference between the two optical fields.

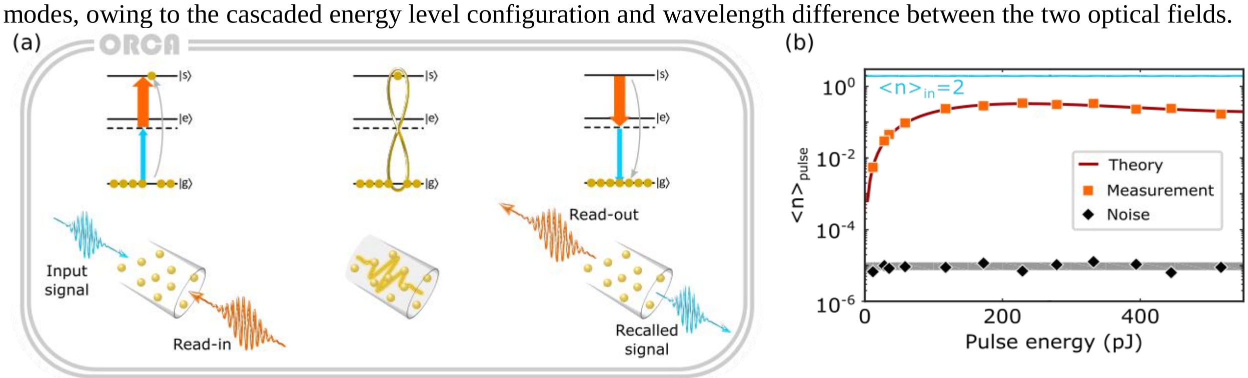

Fig. 1. (a) The ORCA memory protocol. (b) Recall of weak (average input photon number of 2) coherent states for different control pulse energies. The measured noise lies within the dark counts of our detectors (grey band), and our theoretical model accurately describes our data.

In order to verify the noise-free properties of the ORCA protocol, we implement a proof-of-concept demonstration in warm caesium vapour. We store ~1 GHz bandwidth heralded single photons, generated via parametric downconversion (PDC). We measure the heralded auto-correlation function of our input signal to be g(2) =0.020(5), confirming that we herald high-quality single photons which are a very sensitive probe for assessing noise performance. Without the need for time-consuming atomic state preparation in ORCA, we are able to operate the memory at the full 80 MHz repetition rate of our PDC pump. The photons are stored for 3.5 ns with an efficiency of η = 14.6(1.9)% (~5% end-to-end without optimisation of losses). Upon recall, we obtain g(2) = 0.028(9). Within our measurement accuracy we thus observe no change in g(2), which proves that the ORCA memory adds zero noise.

Furthermore, we develop a complete theoretical model of the experiment which accurately describes our data, as shown in Fig. 1(b). Using this model, we theoretically investigate the mode capacity of the ORCA memory and find that it can efficiently support both single and multimode operation, depending on the control pulse duration and memory dimensions. We thus demonstrate the first quantum memory protocol, which operates in ambient conditions and is compatible with ultrafast multimode quantum light.

Kaczmarek, KT et al. *High-speed noise-free optical quantum memory* Phys. Rev. A 97, 042316 (2018).

Measuring dispersion in nonlinear crystals beyond detectors' spectral range

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Single-photon sources are essential for the experimental implementation of various quantum information processing and communication protocols. One of the most popular types of such sources is based on spontaneous parametric down-conversion (SPDC). In this phenomenon, which occurs in a crystal with large effective nonlinearity, some photons, from the so-called pump pulse, are converted into pairs of signal and idler photons. Thanks to this, one may obtain photons, which are correlated in many degrees of freedom. Their wavelengths strongly depend on the crystal's properties, such as poling period, refractive index, temperature, or more generally phase-matching conditions. By carefully chosing the aforementioned parameters it can be possible to generate pairs of photons with significantly different wavelengths (e.g. one belonging to the visible range, and the other one to the IR spectra range).

In this work we show a simple technique for dispersion measurements in a nonlinear crystals by making use of phase matching in the process of parametric down-conversion itself. The method can be applied for various types of crystals, in which spectrally non-degenerated phase-matching conditions are satisfied. It also allows to determine the coefficients of Sellmeier equations with limited detection capabilities, caused by the lack of detectors specified for desired spectral range.

Here we use an exemplary PPKTP crystal, phase matched for 396 nm to 532 nm and 1550 nm in order to demonstrate our method. The phase matching conditions can be tuned by changing the temperature of the crystal and the pump wavelength. We collect a selection of spectra for the pump beam and one of the resulting SPDC photons as a function of the temperature and pump beam wavelength. This allows us to generate respective tuning curves, which we fit the model to. As a result a precise dispersion relations (Sellmeier equations) can be obtained in a very broad wavelength range even outside the detection range of the measurement apparatus.

Multimode adaptive optical decoders for quantum communication

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The production, manipulation, storage and measurement of quantum states of light constitute a key toolbox enabling the development of quantum-information technologies. In particular, photons are the most natural platform for the transmission of information using quantum protocols, which offer enhancements over classical ones in terms of, e.g., transmission rate and security. This research field has attracted much attention in the past, with substantial theoretical work on channel capacities [1], cryptography [2] and repeaters [3], as well as several experimental demonstrations [4, 5].

In this work we study concrete decoder schemes for classical information encoded on quantum-optical states. These can be used for free-space or optical-fiber communication, which is usually modeled by phase-insensitive bosonic Gaussian channels [6]: the incoming signal interacts with the environment, e.g., a thermal state, via a linear optical interaction, e.g., a beam-splitter. It has been shown [7] that the maximum transmission rate, i.e., the capacity, of such channels can be attained by a simple separable encoding: the optimal codewords are sequences of coherent states over several modes of the field. However, the optimal decoding does make use of entangling measurements over several modes of the field [8–11] and of non-linear optical components [12]. Hence, the implementation of such optical decoders, which would trigger a plethora of applications in optical communication and beyond, e.g., in metrology [13], seems a daunting task to carry out with current technology. For this reason, there is still a gap between the ultimate capacity of optical channels and the transmission rates that are currently achievable, see Fig. 1.

Research has then mainly focused on decoding sequences of coherent states with the general class of Adaptive Decoders (AD) depicted in Fig. 2a. The latter combines the available *single-mode* technology, e.g., photodetectors and local transformations, with *multi-mode passive* interferometers and *classical feedforward control*. The rationale behind this choice is that introducing correlations between modes during the decoding procedure may increase the transmission rate of simple separable measurements, getting closer to the ultimate capacity of optical channels.

We present two results related to ADs. First, we introduce a concrete decoder scheme that employs a Hadamard interferometer and single-mode measurements and we show that it can increase the transmission rate of optical channels above that attained by previous proposals [14, 15]. Then, we prove a general benchmark result implying that the best transmission rate attainable by ADs can also be attained with separable decoders [16]. Finally, we discuss how ADs may still be a more favorable choice in energy-starved scenarios typical of long-distance communication.

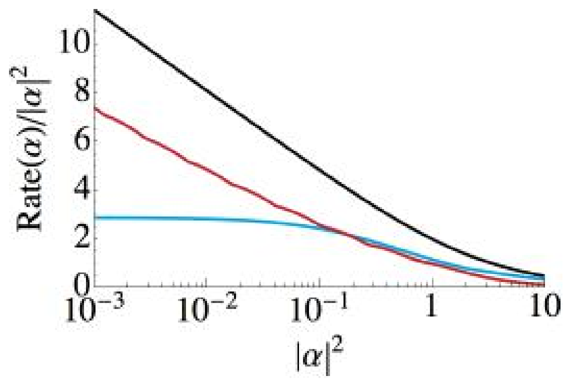

Figure 1. Plot of the transmission rate per unit of signal energy vs. the latter. The black curve corresponds to the capacity of the optical channel. The red curve corresponds to our Hadamard decoder, while the blue curve corresponds to a simple single-mode decoder.

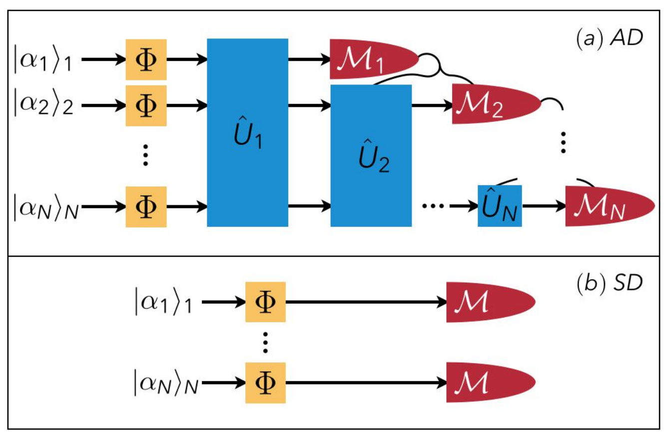

Figure 2. Schematic depiction of the class of (a) Adaptive Decoders (AD) and (b) Separable Decoders (SD) for communication on the optical channel Φ. Coherent-state codewords are known to be optimal. (a) The AD comprises multi-mode passive Gaussian interferometers $\hat{U}_j$ and arbitrary single-mode measurements $\mathcal{M}_j$, adaptively dependent on the measurement results of previous modes. (b) The SD performs the same single-mode measurement $\mathcal{M}$ on each mode without interactions or adaptive procedures.

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Tailoring Non-Gaussian Continuous-Variable Graph States

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Quantum entanglement, one of the key resources for quantum information processing, can be deterministically generated in a scalable manner in continuous variable (CV) systems. However such CV entangled states typically display Gaussian statistics, which limits their use for quantum computing. It is experimentally feasible to overcome this problem by the mode-selective subtraction of photons from multimode Gaussian states, thus rendering them non-Gaussian [1]. Furthermore, photon subtraction is known to enhance the entanglement between a pair of modes.

In multimode setups, however, the theoretical properties of the resulting non-Gaussian states are still surrounded by open questions. In the present contribution we use techniques from quantum statistical mechanics [2] to obtain the multimode *Wigner function* for photon-subtracted states. This directly allows us to uncover a general condition for the negativity of the Wigner function, and to explore the state's entanglement properties.

As a key result, we use correlation functions to derive the general Wigner function of a non-displaced photon-subtracted state:

$$W_-(\beta) = \frac{1}{2}[(\beta, V^{-1}A_gV^{-1}\beta) - \mathrm{tr}(V^{-1}A_g) + 2]W_G(\beta),$$

where $W_G(\beta)$ is the Wigner function of the initial Gaussian state from which the photon was subtracted, and V is its covariance matrix. All non-Gaussian features are introduced by the matrix A_g, that depends on the mode g in which the photon is subtracted, and which can be expressed analytically [3]. From the expression for $W_-(\beta)$ we directly deduce an elegant condition for the negativity of the Wigner function. Moreover, for pure states, we show that coherent subtraction of a photon can enhance entanglement between modes. We prove [4] that this entanglement can persist in *all* mode bases, contrary to the Gaussian case [5].

These methods also allow us to understand more details about specific classes of states. In particular, we will treat the case of photon subtraction from CV *graph states* (see Fig. 1 for an example). Such graph states can be implemented by generating gaussian entanglement between the optical modes of a multimode squeezed vacuum. These states display Gaussian statistics upon measurement of the field quadratures. Moreover, they form the backbone of measurement-based quantum computation, and can be produced in present-day experiments [6]. Photon subtraction can introduce non-Gaussian features in these states, hence making them appropriate for applications in quantum information processing.

In this contribution, we take a first step in exploring the physical properties of such experimentally achievable photon-subtracted CV graph states [7]. By investigating the spread of non-Gaussian features through the graph upon subtraction of a photon in one of its vertices, we pave the way for future experimental developments. This finally imposes the question how these results can be applied in the field of quantum computation.

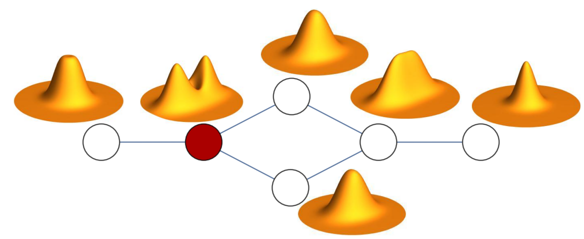

Figure 1: Single-mode Wigner functions for a six-mode graph state with a photon subtracted in the red vertex. In this case, non-Gaussian features spread throughout the whole network. However, we demonstrate that this will generally not be the case, and that vertices at more than two steps from the point of subtraction will remain completely unaffected.

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Complex temporal imaging systems for spectral shaping of quantum light

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The spectral-temporal degree of freedom of light offers a promising platform for integrated photonic quantum information processing and quantum communication An important challenge in experimentally realizing spectral-temporal manipulation of quantum states of light is the need for highly efficient, low-noise tools. In this context the intrinsically deterministic electro-optic methods show great promise for quantum applications.

Particularly important for efficient photonic interlinking of various quantum systems, ranging from single quantum emitters to quantum memories, is the need to match the spectral-temporal profiles of photons to those of the linked systems. Here we focus on modification of the spectral bandwidth of single photon pulses. Coherent modification of spectral bandwidth needs to be realized by means of phase-only operations. By subjecting a single-photon pulse which has been chirped using an appropriate length of single-mode fibre to the action of an electro-optic time lens (providing a quadratic temporal phase imprint), coherent bandwidth compression is achieved, as exemplified in Fig. 1(a)

To date, by using a single electro-optic time lens we demonstrated 6-fold spectral compression of heralded single photon pulses with efficiency that enabled us to significantly increase single photon flux through a narrow bandpass filter [1]. Here we experimentally show a temporal-optical system combining two time lenses with appropriate dispersive propagation that enables achieving up to 20-fold compression of single-photon spectral bandwidth with high efficiency. Directly measured spectral profiles of heralded single-photon pulses are presented in Fig. 1(b).

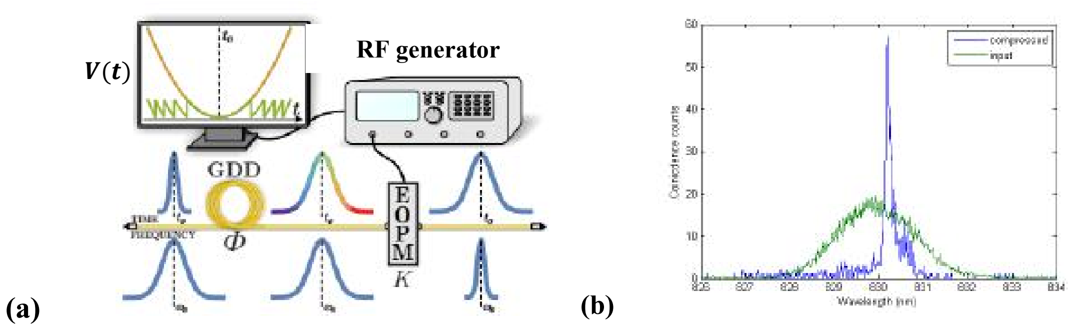

Figure 1 (a) Conceptual schematic of bandwidth compression. **(b)** Spectra of heralded single-photon pulses before (green), and after (blue) spectral compression by a sequence of 2 devices presented in (a). Spectral bandwidth is reduced from 2 nm FWHM (full width at half-maximum) to 0.1 nm FWHM.

Further we discuss the limitations of standard time-lens-based electro-optic bandwidth compressors and show that the use of temporal phase modulation patterns of higher than quadratic complexity [see inset of Fig. 1(a)], may enable very large scale bandwidth compression. We present the results of numerical simulations indicating the feasibility of reaching compression factors of the order of 10^3, enabling interfacing GHz- and MHz-bandwidth quantum systems [2].

Our results demonstrate the experimental feasibility of complex time-lens-based optical systems for manipulation of quantum light. They present an important contribution towards efficient photonic interfacing of different quantum information processing platforms into a quantum network.

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High-resolution single-photon spectrometry

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Spectral-temporal modes of light have gained much interest as a way of dense information encoding and as an intrinsic absorption and emission property of physical systems. Quantum information is one of the fields, that could gain the most by spectral-temporal modes control [1]. Investigation of spectro-temporal modes in the single-photon regime demands a device for frequency distribution measurements [2]. Here we report a high-resolution telecommunication infrared single-photon spectrometer with ability to simultaneously monitor multiple spectral channels.

Presented spectrometer is a fiber-integrated device based on frequency-to-time mapping via chromatic group delay dispersion (GDD) together with a single-photon time-of-arrival measurement. The spectrometer works in telecommunication range allowing seamless integration with existing fiber networks.

We employ a low-loss telecommunication dispersion compensation chirped fiber Bragg grating introducing a 4954 ps-nm of GDD, which transforms spectral modes onto the temporal envelope of a single-photon pulse. Time-of-arrival detection with low time-jitter supercunducting single-photon counting module ensures work in GDD-limited resolution regime. We report a herladed single-photon spectral measurements with resolution below 0.06 nm and wavelength measurement within range from 1554 nm to 1563 nm with almost constant efficiency. Polarization multiplexing allows monitoring 2 spectral channels using a single dispersive media.

A single-photon bandwidth compression by electro-optic temporal phase modulation, a JSI of photon pairs from SPDC source and spectral interference fringes (Fig. 1) created via propagation in polarization maintaining fiber with skewed birefringent axis are measured to present the capabilities of this technique.

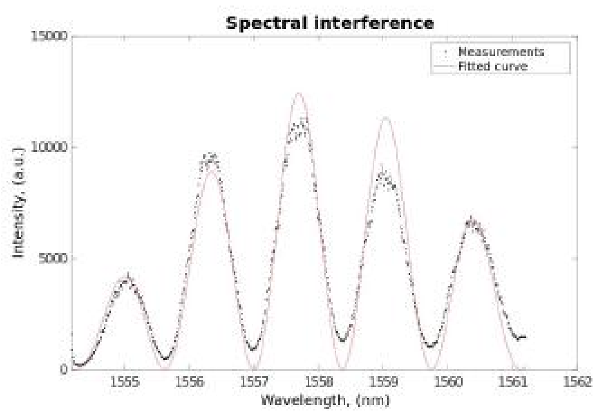

Fig. 1 – Spectrum of herlasded single photons subjected to spectral interference. Experimenteal points with a fitted curve of the form: $f(x) = 12646.1 * \exp(-((x-1558.7)/2.955)^2) * \cos(2*\pi*x/2.750)$.

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Characterization of classical static noise via qubit as probe

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Abstract

The dynamics of quantum Fisher information (QFI) of a single qubit coupled to classical static noise is investigated. The analytical relation for QFI fixes the optimal initial state of the qubit that maximizes it. An approximate limit for the time of coupling that leads to physically useful results is identified. Moreover, using the approach of quantum estimation theory and the analytical relation for QFI, the qubit is used as a probe to precisely estimate the disordered parameter of the environment. Relation for optimal interaction time with the environment is obtained and condition for the optimal measurement of the noise parameter of the environment is given. It is shown that all values, in the mentioned range, of the noise parameter are estimable with equal precision. A comparison of our results with the previous studies in different classical environments is made.

Quantum dark soliton qubit and entanglement generation

We study the possibility of using dark-solitons in quasi one dimensional Bose-Einstein condensates to produce two-level systems (qubits) by exploiting the intrinsic nonlinear and the coherent nature of the matter waves. We calculate the soliton spectrum and the conditions for a qubit to exist. We also compute the coupling between the phonons and the solitons and investigate the emission rate of the qubit in that case. Remarkably, the qubit lifetime is estimated to be of the order of a few seconds, being only limited by the dark-soliton death due to quantum evaporation. Further, we explore the spontaneous creation of entanglement between two dark soliton qubits due to quantum fluctuations, by using the superposition of two maximally entangled states in the dissipative process of spontaneous emission. By driving the qubits with the help of Raman lasers, we observe the formation of long distance steady-state concurrence. Our results suggest that dark-soliton qubits are a good candidates for quantum information protocols based purely on matter-wave photonics.

Composably secure time-frequency quantum key distribution

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(Dated: April 1, 2017)

We present a composable security proof, valid against arbitrary attacks and including finite-size effects, for a high dimensional time-frequency quantum key distribution (TFQKD) protocol based upon spectrally entangled photons. Such schemes combine the impressive loss tolerance of single-photon QKD with the large alphabets of continuous variable (CV) schemes, but finite-size security has previously only been proven under the assumption of collective Gaussian attacks. Here, we derive a composable security proof that predicts key rates on the order of Mbits/s over metropolitan distances (40 km or less) and maximum transmission distances of up to 140 km.

Most photonic QKD implementations fall into one of two regimes. Traditional discrete variable (DV) schemes encode the secret key in a two-dimensional Hilbert space such as the polarisation of a single photon. Such protocols now enjoy general, *composable* security proofs [1] that function with reasonably small finite-size data blocks, and converge to the ideal Devetak-Winter rates [2] in the asymptotic limit. Continuous variable (CV) schemes instead utilise an infinite-dimensional Hilbert space, commonly the quadratures of the optical field. Whilst the finite range and precision of real-life detectors ensures the key is never perfectly continuous, CVQKD nevertheless has the capability to achieve greater than one bit per transmission and hence potentially much higher rates. Furthermore, composable, general, finite-size CVQKD security proofs have also appeared, although the present results either require extremely large block sizes [3], or are very sensitive to losses [4] and fail to converge to the Devetak-Winter rates.

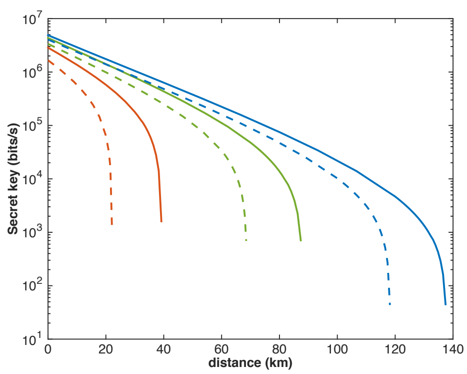

FIG. 1: Secret key rate as a function of transmission distance for protocols where the key is generated from frequency (dashed) or time (solid) variables. Sample sizes are $N = \{10^9, 10^{10}, 10^{11}\}$ in red, green and blue respectively with a security parameter of 10^{-10}.

An alternative approach is to encode the key in the continuous degrees of freedom of single photons, inheriting both the loss tolerance of DVQKD and the larger encoding space of CV protocols [5]. These time-frequency schemes are primarily pursued via the temporal and spectral correlations of single photons emitted during spontaneous parametric down conversion (SPDC) and the security stems from the conjugate nature of frequency and arrival time measurements. Significant progress has been made in security analysis [6], particularly identifying analogies between the time and frequency observables of a single photon and the canonical quadrature observables. However, a general composable security proof is lacking. In this work we present such a proof by combining the entropic uncertainty proofs for CVQKD [4] with efficient, finite-size decoy-state analysis [7] for DVQKD which allows us to rigorously determine the number of single photon events. The resultant proofs allow for high rates key rates over urban and inter-city distances with reasonable block sizes. Detailed proofs, calculations and simulation parameters can be found in [8].

Note added: During the writing up of this work the authors became aware of similar results obtained independently by Niu et al. [9].

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The ultimate miniaturization of Atomic and Molecular scale Boolean Logic Gates using QHC method.

Belonging to the Quantum Hamiltonian Computing (QHC) branch of quantum control [1-2],atomic-scale Boolean logic gates (LGs) with two inputs - one output (OR, NOR, AND, NAND, XOR, NXOR) and - two outputs (half-adder circuit) were designed on a Si(100)-(2×1)–H surface following the experimental realization of a QHC NOR gate [3] and the formal design of an half-adder with 6 quantum states in the calculating block [4]. Recently we have focused also to find an automatization way for designing and miniaturzating of the quantum systems to have for example a functioning Boolean halfadder with minimum number of states.

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High-Dimensional Temporal Mode Manipulation using Quantum Memories

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There are many architectures for quantum information processing, each with their own distinct advantages and drawbacks, and the route towards scalable quantum technologies is likely to involve combining these unique advantages in a hybrid system. Photons are a promising platform for quantum communication and for interfacing different nodes of a quantum network. However, to optimally couple different devices and components of a quantum network we require the capability to engineer and manipulate the spectral-temporal wavepacket of pulsed photons, the so-called temporal mode (TM) [1].

Here we demonstrate a temporal mode manipulation device which can separate and reshape arbitrary temporal wavepackets of light. We show TM manipulation of weak coherent pulses in a Raman quantum memory in warm atomic caesium vapour [2]. The Raman interaction can be described as a time non-stationary light-matter beam splitter that acts on a single temporal mode [3], and therefore the shapes of the stored and retrieved TM are defined by the temporal amplitudes of the strong control pulses used to drive the memory. This enables storage, delay and re-shaping of a user-defined TM in one single device.

The Raman memory operates on pulses in the MHz and GHz regime, and can therefore interface narrowband atomic systems with fast GHz-bandwidth communication networks. We demonstrate bandwidth conversion of ns-duration Gaussian pulses by increasing and decreasing the bandwidth by a factor of 25, as shown in Figure 1(a). We compare the efficiency of this process to that of using a bandwidth filter, and find that the memory can outperform a filter at large compression factors.

Furthermore, TMs have been identified as an appealing basis for quantum information science as they form a high dimensional basis that is compatible with single-mode fibres [1]. By selecting the TM of the storage and retrieval control pulses of the Raman memory, we can fully determine which mode is stored and then retrieved from the memory, allowing us to separate and convert TMs. We demonstrate conversion between different Hermite-Gaussian modes and Figure 1(b) shows that we can fully convert between the first five basis states, and the efficiency of the conversion (storage and retrieval) is around 35% for all state transformations.

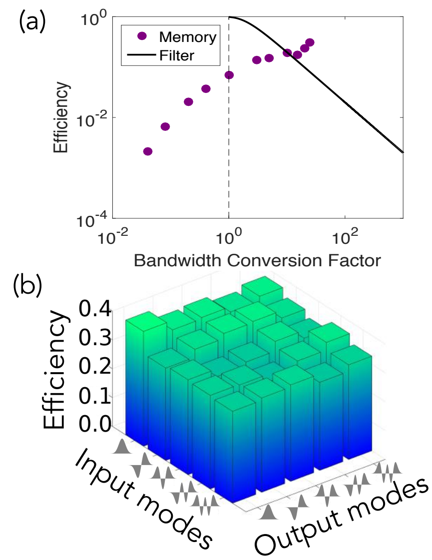

Figure 1: (a) Efficiency of bandwidth conversion using the Raman memory. The solid line shows the equivalent efficiency for a bandwidth filter. (b) The efficiency of conversion between different Hermite-Gaussian temporal modes.

We have shown that the Raman memory is a versatile device for temporal mode manipulation. Its applications include interfacing different solid state systems such as atoms and quantum dots, where you require not only bandwidth conversion but also re-shaping (temporal inversion) of the temporal wavepacket. It also will enable quantum key distribution using temporal modes as a high dimensional encoding alphabet to realise fibre-compatible qudits. This highlights its potential as a key device in future quantum networks.

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Projectors onto time-frequency entangled states

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Abstract: We propose the use of sum-frequency generation with two single photons as the input fields, combined with a pulse-mode selective measurement, to realize a projective measurement onto a time-frequency entangled state. We show how this result can be applied to a versatile time-frequency entanglement swapping scheme.

The Bell-state measurement, consisting of a projective joint measurement of two qubits onto one of the four Bell states, is ubiquitous in the field of quantum information, and is a key step in protocols such as teleportation, superdense coding, and entanglement swapping [1]. In quantum optics, this is typically achieved by interfering two photons at a balanced beamsplitter and measuring in the polarization basis. Here we propose that sum frequency generation (SFG) with two single photons as the input fields, combined with a projective measurement of the output SFG photon [2], could be harnessed to project onto a time-frequency entangled state of arbitrarily high dimension, in analogy with the Bell-state measurement. We show how this framework could be used in an entanglement swapping scheme for time-frequency entangled photon pairs [3], [4].

The Hamiltonian describing the $\chi^{(2)}$ processes of SFG and parametric downconversion can in general be expressed in the Schmidt mode basis for the frequency domain as

$$\hat{H} = \hat{H}_{\text{PDC}} + \hat{H}_{\text{SFG}} = \xi \hat{p} \sum_i \sqrt{\lambda_i} \hat{a}_i^\dagger \hat{b}_i^\dagger + \xi^* \hat{p}^\dagger \sum_i \sqrt{\lambda_i} \hat{a}_i \hat{b}_i, \tag{1}$$

where ξ is a non-linear parameter coupling the fields, $\hat{p}^{(\dagger)}$ is the annihilation (creation) operator for the pump (SFG) photon in a particular time-frequency field mode, and $\hat{a}_i$ ($\hat{b}_i$) is the annihilation operator for a photon in the ith signal (idler) Schmidt mode, with Schmidt coefficient $\sqrt{\lambda_i}$. In particular, we point out that SFG described by the above process with two photons as input acts effectively as a projector onto the state $|\psi\rangle = \sum_i \sqrt{\lambda_i} \hat{a}_i^\dagger \hat{b}_i^\dagger |\text{vac}\rangle$, which is the two-photon state created by the complementary PDC process, provided the SFG photon is projected onto the mode described by $\hat{p}$.

We can directly apply this result to entanglement swapping, where two photons, each from an independent entangled pair, are jointly measured so as to project their remote partner photons onto an entangled state. We analyze the case of entanglement swapping in the frequency domain, where two independent entangled photon pairs are created through PDC, and the interacting photons are jointly measured by undergoing SFG followed by a measurement of the resulting photon [5]. We find that in the case where the PDC and SFG processes are both described by the same Hamiltonian as above, the resulting heralded state will be of the form $|\psi\rangle_{\text{herald}} = \sum_i \sqrt{\lambda_i^3} \hat{a}_i^\dagger \hat{b}_i^\dagger |\text{vac}\rangle$. Finally, we propose a method that exploits this result to swap and herald time-frequency entangled states with versatile user-defined mode structures and degree of entanglement [6], in compatibility with the recently proposed framework for temporal-mode quantum information processing [7].

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Entanglement Detecion via Numerical Approaches

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There is no unique definition of multipartite quantum entanglement. Yet, entanglement always implies the absence of separability of one form or another. It therefore becomes valuable to understand which form of separability is considered. Two prominent definitions of separability are given as the convex combination of pure product states in a fixed partition [1] (partition entanglement) or the convex combination of separable states with respect to different partitions, based on the former definition (K-entanglement) [2].

An entanglement criterion based on Hermitian operators and their so-called separability eigenvalues was recently introduced [3]. The idea behind the criterion is finding the bounds for the expectation value of a Hermitian operator with respect to separable states, which are given by the lowest and highest separability eigenvalues. Should a state violate these bounds, it is entangled.

In the continuous case, an entanglement analysis was performed on a 6-mode Gaussian state [4]. For this test, the analytical minimal separability eigenvalue for Gaussian-type states was determined. For an optimal solution in the sense of experimental uncertainties a genetic algorithm was implemented for finding a suitable operator. This algorithm was used to scan over the space of test operators to find the one operator that is able to witness entanglement with the highest statistical significance; see Fig. 1.

In the discrete-variable case, finding extremal separability eigenvalues is, in general, analytically not possible. We developed an algorithm that uses the algebraic structure of the separability eigenvalue equations for finding the maximal separability eigenvalue [5]. This algorithm is a generalization of the power iteration, which is a simple solver for the standard eigenvalue problem. We proved the convergence and working principle of the algorithm. Furhtermore, bound-entangled states were investigated and their entanglement structure verified by a numerically determined separability eigenvalue, cf. Fig. 2.

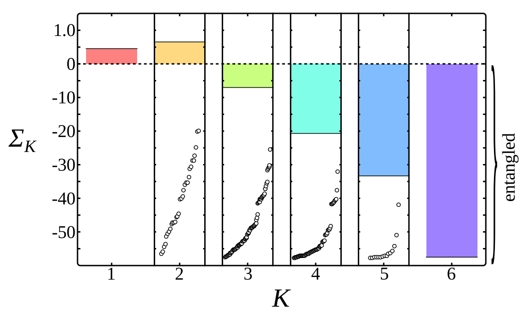

FIG. 1: Results of entanglement test on continuous-variable state. Negative Σ values correspond to the significance of detected entanglement. Bars represent K-partitions, whereas circles represent individual partitions.

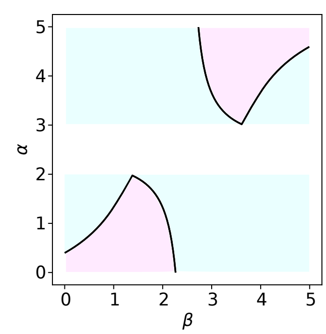

FIG. 2: Results of entanglement test on discrete-variable state parametrized by α. The test operator was parametrized by β. For combinations of α and β in the red area (blue area), entanglement was detected (not detected). The state is separable in the blank area.

Our work shows the advantage of the separabilit, eigenvalue equations in optimally verifying entanglement. These equations can be applied to continuous- as well as discrete-variable states and are able to verify partition entanglement and K-entanglement. The numerical methods highlight the usefullness, in particular, as they allow us to investigate the entanglement structure of a state with a single criterion.

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A Real-Time Source Device Independent Quantum Random Number Generator

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Random numbers are a fundamental tool for many applications, from simulation and modelling (e.g. Monte Carlo) to Cryptography (e.g. AES, QKD). Good random numbers should be statistically independent and uncorrelated with each other. Moreover, for cryptographic application they should also be secure i.e. unpredictable.

Following work in [1], we apply a method to generate high speed unpredictable random numbers by measuring the quadratures of the electromagnetic field. No assumption is made on the source, only the detection device is trusted. By measuring alternatively two orthogonal quadratures, Q and P, of our source using a homodyne detection, we estimate a bound on the minimal entropy of P conditioned on any classical or quantum side information that a malicious eavesdropper may detain [2]. This bound is estimated via the entropic uncertainty principle ([3]):

$$H_{\min}(P_{\delta p}|E) \geq -\log_2 c(\delta q, \delta p) - H_{\max}(Q_{\delta q}) \quad (1)$$

The entropy bound is estimated by measuring Q, and the random numbers we get out of the measurement of P are hashed accordingly (see fig.1).

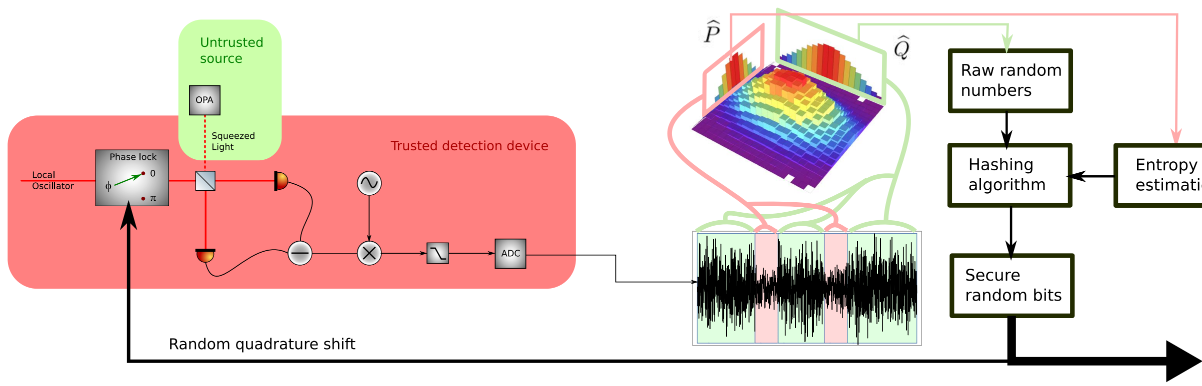

FIG. 1: Protocol for the source independent Quantum Random Number Generator (QRNG)

All this is done live, so we built a real self testing QRNG. We apply this method with two different sources of entropy, a thermal state and a squeezed state of light and demonstrate the advantage of the latter to maximize the extractable randomness. This is the first demonstration of a live, high speed, self-testing Source Device Independent Quantum Random Number Generator (SDI QRNG).

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Eliminating noise from a broadband and single-mode quantum memory

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Single-mode broadband quantum memories provide unique capabilities that can enhance and expand the performance of future quantum networks. On the one hand, they facilitate the temporally multiplexed generation of pure single photons at high clock rates, which dramatically increases photon generation rates [1]. On the other hand, they can serve as special quantum mechanical beam splitters that can operate on novel bases for information encoding. One such basis are temporal modes – complex temporal amplitudes of pulsed single photons – which have been identified as appealing high-dimensional basis states for integrated quantum networks [2].

Our system of choice is a quantum memory in warm atomic Caesium vapour, based on an off-resonant Raman scattering protocol [3], which combines operation at ambient conditions, high storage efficiencies, GHz bandwidth storage, and single-mode operation [4].

Previous implementations of the Raman memory have suffered from four-wave mixing noise (Figure 1a) where the control couples to the populated state to produce a noise photon by Anti-Stokes scattering. This noise contaminates the retrieved fields with thermal noise, destroying the non-classical statistics of stored quantum states. This has been identified as the key limiting factor in reaching quantum level operation [5].

Here we demonstrate a novel technique to suppress the four-wave mixing noise by creating an absorption feature for the noise, thereby preventing that process. This is achieved by arranging the detuning such that it is resonant with an atomic transition (Figure 1a and 1b) [6]. Using this technique we have shown a nearly an order of magnitude reduction in noise photons when using this suppression method (Figure 1c).

With the elimination of this noise pathway, the Raman memory is a technically simple broadband and single mode memory capable of selectively storing an arbitrary and user chosen quantum state. Therefore, with further engineering, the Raman memory is a promising candidate for temporal-mode selection and multiplexed photon generation in future quantum networks.

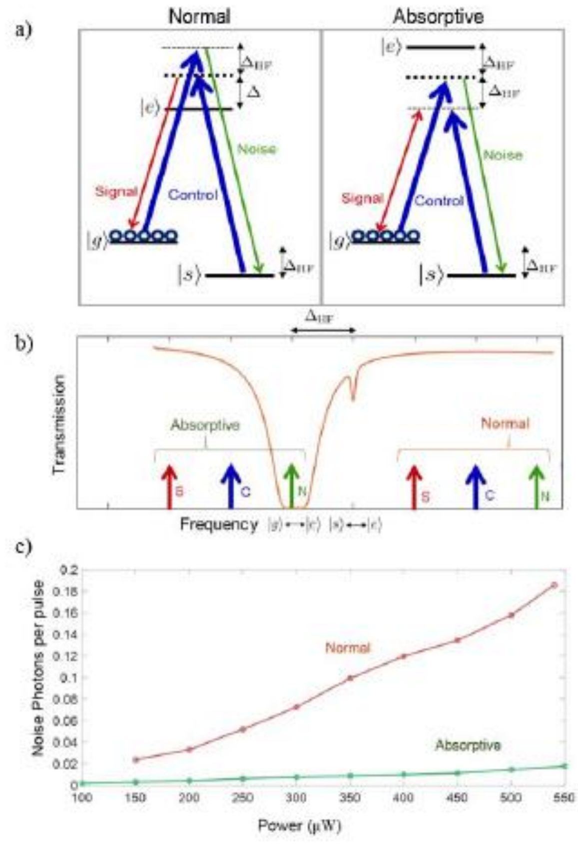

Figure 1
a) Energy level diagram showing the fields involved in the Raman memory, including the four-wave mixing process
b) Transmission spectra of Caesium showing the position of the fields in the normal operation of the Raman memory and when in the absorptive suppression scheme.
c) Noise photons produced per pulse in the two regimes as a function of control field power that is, memory operation strength.

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Spectral Correlations in Frequency Multiplexed Single-Photon Sources

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Single-photon sources are an important resource for a number of applications in quantum optics, including tasks in quantum information processing and communications. One of the most common methods for generating single photons is heralded parametric down conversion (PDC). However, such photon sources are inherently probabilistic, with the probability of delivering a single photon per trial often limited to a few percent in realistic experiments.

Multiplexing, where the outputs of several independent sources are switched into a common output conditioned on a herald event can be used to increase the probability of delivering a single photon in the common output channel. We have demonstrated a frequency-multiplexing scheme (fig 1 a) [1], which uses the spectral degree of freedom of a highly frequency correlated PDC process (fig 1 b). Spectral detection of a herald photon over a continuous frequency domain reveals information about the frequency of the corresponding heralded, or signal photon. This measurement is used to switch the heralded photon into a common output frequency, thereby increasing the single photon delivery probability at that frequency.

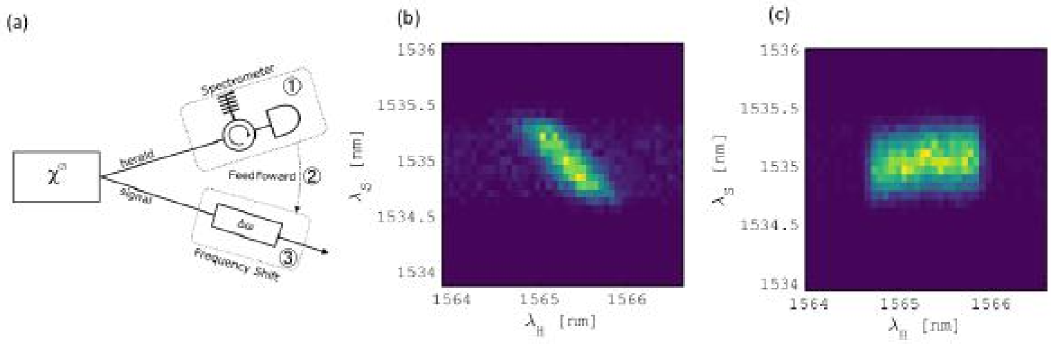

Figure 1. a) Frequency multiplexing scheme. b) Section of a highly correlated joint spectrum generated by a PDC source. c) Frequency correlations after frequency shifting of the signal photon.

Here we compare the performance of multiplexing over a continuous degree of freedom to previous schemes that use discrete frequency-bin or spatial-mode encodings. In our experiment, the number of multiplexed frequency modes is dependent on both the frequency shift range and the bandwidth of the PDC pump. We explore the parameter space of the experiment and investigate how losses, frequency resolution of the herald photon and the number of frequency modes affect the heralded photon spectral purity and photon number statistics. Our current experiment is capable of multiplexing approximately 2.5 frequency modes and has a measured heralded spectral purity of 0.64. We discuss the prospects for competing with other multiplexing schemes [2, 3] and single emitter sources with realistic experimental parameters.

Keywords: Photon-Source; Multiplexing

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Single-pass squeezed states of light for quantum computation

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Abstract

We present an experimental analysis of a parametric down-conversion based source generating broadband squeezed light in multiple temporal/spectral modes.

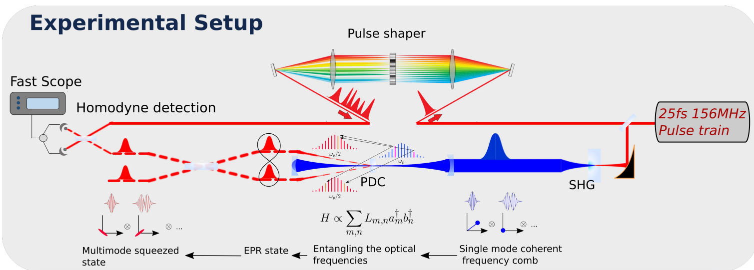

Figure 1: Experimental setup. We use a mode-locked Titanium:Sapphire laser of 40 nm-spectrum (FWHM) centered at 795 nm. The pulses first undergo a second harmonic generation process through a 1.5 mm-long BBO crystal, which produces a pulse train centered at 397.5 nm and of 1.6 nm spectrum. Then, the blue pulses oscillate in an optical cavity and serve as a pump for a type I non-collinear spontaneous parametric down-conversion (SPDC) process in a 2 mm-long BBO crystal placed at the pump waist. Pulsed signal and idler beams are then superimposed on a 50/50 beamsplitter and multimode squeezing is measured using homodyne detection, which local oscillator is shaped in order to measure the different squeezed modes separately.

A multimode squeezed state of light can be used as a quantum resource to perform Measurement Based Quantum Computation (MBQC) in continuous variables [1], [2]. Here we present a new source of multimode squeezed states based on a type I non-collinear spontaneous parametric down-conversion, which is pumped with an optical frequency comb (fig.1). Signal and idler beams are produced in a single-pass configuration and they exhibit multipartite entanglement in continuous variables [3]. Superimposing the beams on a 50/50 beamsplitter produces squeezed light in multiple temporal/spectral modes. To improve squeezing level, we introduce a synchronous cavity for the pump pulses of the SPDC that enhances pump power. The produced states are characterized by homodyne detection where local oscillator is shaped. Simulation shows that the squeezed modes can be mathematically described by Hermite-Gaussian functions. Pulse-shaped homodyne has allowed us to address each squeezed mode independently, and the preliminary results are presented on figure 2.

In a second phase, we aim to produce dual-rail cluster states, which are large-scale quantum networks displaying entanglement in time and in continuous variables [4]. This can be achieved by delaying signal/idler by one inter-pulse delay, and then mixing them on a beamsplitter to induce correlation among successive pulses. If seeded, our source can produce squeezed light with large photon number of appropriate spectral/temporal shape to perform space-time positioning beyond classical limit [5].

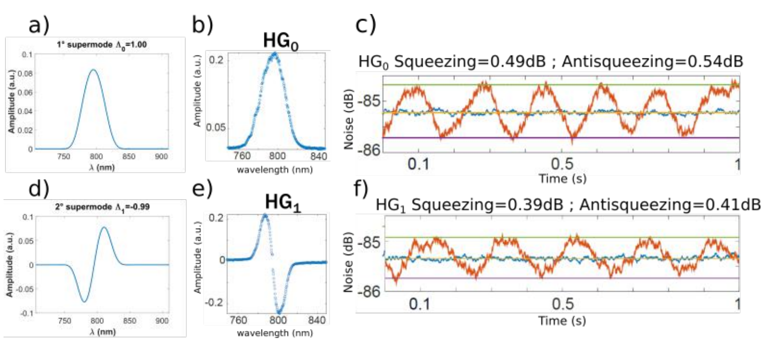

Figure 2: a)-d): theoretical spectral shape of modes HG_0 and HG_1 ; b)-e): spectral shape of the local oscillator (LO) in HG_0 and HG_1 ; c)-f): noise variance of the homodyne photocurrent.

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Bloch-Messiah decomposition and Magnus expansion for parametric down-conversion with monochromatic pump

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(Dated: May 3, 2018)

We discuss the Bloch-Messiah decomposition for the broadband squeezed light generated by type-I parametric down-conversion with monochromatic pump. Using an exact solution for this process, we evaluate the squeezing parameters and the corresponding squeezing eigenmodes. Next, we consider the Magnus expansion of the quantum-mechanical evolution operator for this process and obtain its first three approximation orders. Using these approximated solutions, we evaluate the corresponding approximations for the Bloch-Messiah decomposition. Our results allow us to conclude that the first-order approximation of the Magnus expansion is sufficient for description of the broadband squeezed light for squeezing values below 12.5 dB. For higher degrees of squeezing we show fast convergence of the Magnus series providing a good approximation for the exact solution already in the third order. We propose a quantitative criterion for this ultra-high-gain regime of parametric down-conversion when the higher-orders terms of the Magnus expansion, known in the literature as the operator-ordering effects, become necessary.

Single photon spectral-temporal manipulation: Application to QKD

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Abstract: We discuss the advantages and the challenges of generating and manipulation the spectral-temporal mode-function of single photon states. We utilize novel technologies such as frequency-time conversion and spectral-temporal pulse shaping to carve the single photon resource to our need. We show an application to Quantum Key Distribution in the spectral-temporal domain to generate a large-alphabet secure key.

The ability to characterize quantum states of light is an essential prerequisite for all optical quantum technologies including quantum computing [1,2], quantum key distribution [3], and quantum-enhanced sensing [4]. Development of sources and detectors of quantum optical states requires accurate reconstruction of the field modes with which they interact, and dependable state reconstruction is an important tool for standard quantum process tomography [5]. For quantum states it is important to have a characterization scheme that is sensitive to the nonclassical correlations that can exist between separate subsystems. Quantum correlations between photon pairs can arise in any of the several physical degrees of freedom of light, such as polarization [6], transverse spatial mode [7] or the longitudinal, or time-frequency (TF), state [8]. Recently quantum states of light occupying spectrally broadband pulsed TF modes have attracted interest due to their potentially large information content in the TF basis and compatibility with integrated optical platforms. Technologies to produce such states, such as spontaneous parametric downconversion (SPDC) sources, are comparatively well-developed, and can produce photon pairs in orthogonal modes with high-dimensional entanglement in the TF basis. The two-photon TF wavefunction $|\psi\rangle$ can be completely expressed in terms of the complex-valued joint spectral amplitude function $f(\omega_1,\omega_2)$ [9] such that

$$|\psi\rangle = \int f(\omega_1,\omega_2) a^\dagger_{\omega_1} b^\dagger_{\omega_2} d\omega_1 d\omega_2 |\text{vac}\rangle \tag{1}$$

where $a^\dagger_{\omega_1}$ and $b^\dagger_{\omega_2}$ are operators that act on the vacuum to create a single monochromatic photon in their respective modes with frequency ω_1 and ω_2 respectively. All the spectral-temporal properties of the photon pair, including TF entanglement, can be retrieved from $f(\omega_1,\omega_2)$.

The ability to manipulate and accurately detect f both in the spectral and in the temporal domain is essential, as it has direct implication to quantum information and quantum technologies in general. In this spectral-temporal domain, the amount of available quantum resources can be incredibly large, hence providing a large quantum system within a single beam of light.

We present and discuss the work that has been achieved in the past years with spectrally-broad single photon states. Notably, we show the usefulness of generating single photons that are not spectrally entangled, *i.e.* f is separable. Such source allows us to concentrate on pure single photon states without having to consider the mixedness of the state. We then show how to manipulate these single photon both in the spectral and in the temporal domain through non-linear interaction. Spectral and temporal pulse shaping is achieved by utilizing respectively a spatial light modulator and a fast, high power electro optical phase modulator. These allows to shape both the modefunction of the single photon both in spectrum and in time.

We apply these techniques to Quantum Key Distribution (QKD) in a prepare and measure protocol. We show that these operations allow for rapid heralded detection of both spectral and temporal bands, which consist of conjugated observables. The utilization of high resolution single photon spectrometers (0.04 nm) and time to frequency conversion enables a temporal resolution on the picosecond scale. This finally allows generation of a large alphabet key from a single photon resource.

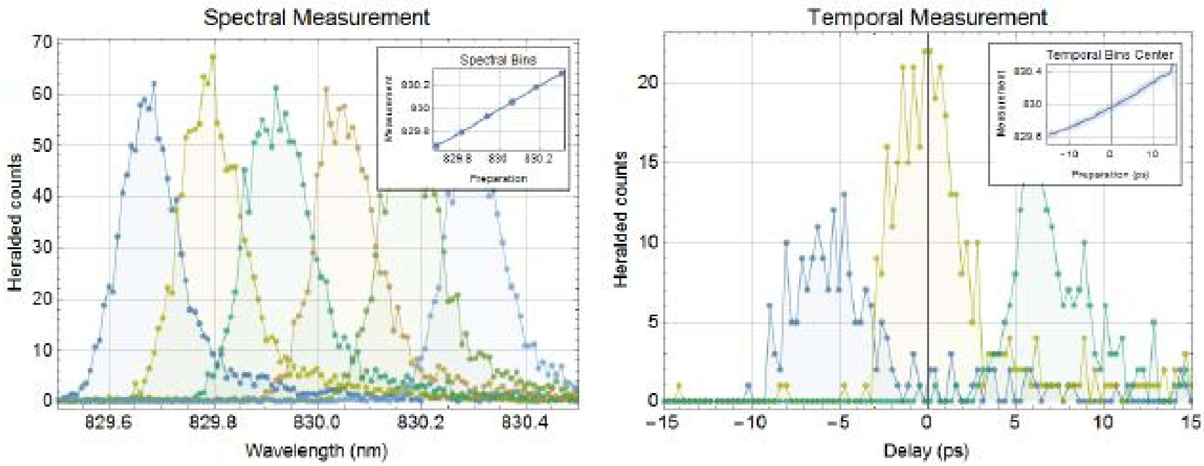

Figure 1: Spectral and temporal measurements from a single photon state. The spectrum is filtered with a pulse shaper in one case, and its temporal modefunction is delayed with a temporal phase in the other.

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Generalised Bloch-Messiah Reduction

A necessary ingredient for using the tools of Gaussian quantum information to model nonlinear quantum optical processes is to choose, from the infinite-dimension spectal-temporal modes of an optical field undergoing a nonlinear process, an appropriate finite-dimensional, discrete basis upon which to use the finite-dimensional tools of Gaussian quantum information. Luckily, the question of the existence of such a modal basis has been answered in the affirmative, with Bloch-Messiah (BM) reduction (also known as Euler decomposition), providing a natural canonical form, whilst establishing the irreducibility of single-mode squeezing, and providing insights into how two mode squeezers can be understood through their Schmidt decomposition. In this setting the book is widely believed to be closed, however a fairly strong assumption has been made regarding the degrees of freedom in the optical modes, i.e. each degree of freedom is treated equally. This assumption is suitable on a single spatial mode, where only the spectral-temporal degrees of freedom are at play, or for a single spectral-temporal mode distributed over many spatial modes. However, where spatial and spectral degrees of freedom are both present, such as in the increasingly complex devices being developed experimentally, different degrees of freedom are, in the practical sense, distinct.

By introducing additional constraints into the Euler decomposition, we demonstrate a new family of canonical forms available for modeling nonlinear processes. We demonstrate that these provide a natural minimal modal basis for applying Gaussian quantum information techniques and recover known results for maximal squeezing in a remarkably straightforward form; we observe that multi-mode squeezing becomes, in some instances, an irreducible resource; we observe how correlations may be distributed across various degrees of freedom and explicate the nature of correlations necessary for post-selecting states for photonic quantum information; finally we discuss how, in realistic settings, experimental imperfections could be well characterized through these methods.

Noise-dependent optimal strategies for quantum metrology

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(Dated: June 3, 2018)

For phase estimation using qubits, we show that for some noise channels, the optimal entanglement-assisted strategy depends on the noise level. We note that there is a non-trivial crossover between the parallel-entangled strategy and the ancilla-assisted strategy - in the former the probes are all entangled, the latter the probes are entangled with a noiseless ancilla but not amongst themselves. The transition can be explained by the fact that, separable states are more robust against noise and therefore are optimal in the high noise limit, but they are in turn outperformed by ancilla-assisted ones.
(Physical Review A 97 (3), 032333)

Quantum metrology describes strategies which allow the estimation precision to surpass the limit of classical approaches [1–3]. When the system is sampled N times, there are different strategies [4] which will allow one to achieve the Heisenberg limit, where the variance of the estimated parameter scales as $1/N^2$. All of these are equivalent when the systems are noiseless. However, in the presence of noise, these strategies are shown to be inequivalent, where entanglement and the use of ancillae are shown to improve the precision of the estimation [5].

In this work, we show that for some noise channels, the best entanglement-assisted strategy depends on the noise parameter. The results obtained are valid for phase estimation using qubits. We note that there is a non-trivial crossover between the parallel-entangled strategy Fig. 1 (a) and the ancilla-assisted strategy Fig. 1 (b), where the individual probes in the latter case may be entangled with an ancilla but not to each other. One would expect the performance of the intermediate strategy (Fig. 1 (c)) to lie in between that of (a) and (b), which we show to be true.

A strategy to reduce the effect of noise is to use an ancillary system that is entangled with the probes but does not participate in the estimation [4]. It has been shown for many channels that the ancilla is useful for all levels of the noise parameter [9, 12]. Since unentangled probes usually perform better than entangled ones in the high noise regime, which is in turn out-performed by ancilla-assisted ones, when comparing the unentangled ancilla-assisted strategy to the parallel-entangled strategy, there must be a crossover in the performance of the strategy depending on the noise parameter: we show there is a large class of noise channels where this transition occurs.

The Pauli $x-y$ noise channel is described by

$$\mathcal{E}[\rho] \to (1-p)\rho + \frac{p}{2}(\sigma_x \rho \sigma_x^\dagger + \sigma_y \rho \sigma_y^\dagger), \tag{1}$$

where the efficiency $(1-p)$ is the probability that the transmission is noiseless.

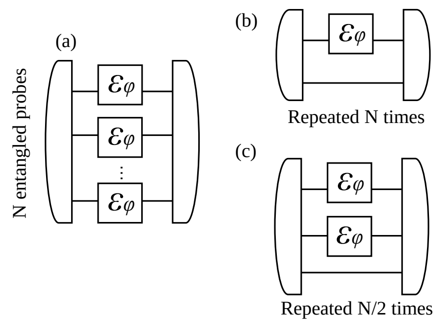

FIG. 1. The quantum metrology strategies whose optimality may depend on the noise level of the channel (a) the parallel entangled strategy: a state of N probes goes through N maps in parallel, this is known to be optimal in the noiseless case. (b) The ancilla-assisted scheme, where N individual probes entangled with a noiseless ancilla go through the map, the probes are not entangled to each other. (c) The intermediate strategy, where two probes are entangled with a noiseless ancilla.

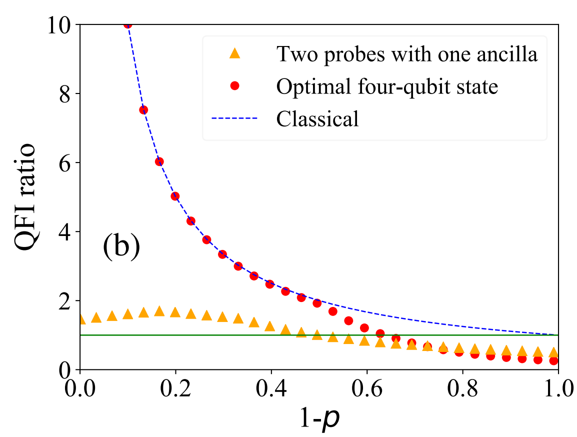

FIG. 2. Pauli x-y noise: the QFI ratio of the ancilla-assisted strategy to the optimal four-qubit state (red circles), the ancilla-assisted strategy to the intermediate strategy (yellow triangles), and the ancilla-assisted strategy to the best classical strategy (blue dashed line). he advantage becomes increasingly as the noise parameter goes to 1.

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