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High coherence photon pair source for quantum communication

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Abstract. This paper reports a novel single mode source of narrow-band entangled photon pairs at telecom wavelengths under continuous wave (CW) excitation, based on parametric down conversion. For only 7 mW of pump power it has a created spectral radiance of 0.08 pairs per coherence length and a bandwidth of 10 pm (1.2 GHz). The effectively emitted spectral brightness reaches 3.9×10^5 pairs s^{-1} pm⁻¹. Furthermore, when combined with low jitter single photon detectors, such sources allow for the implementation of quantum communication protocols without any active synchronization or path length stabilization. A Hong–Ou–Mandel (HOM)-dip with photons from two autonomous CW sources has been realized demonstrating the setup's stability and performance.

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1. Introduction

In quantum communication, flying qubits are encoded either on single photons, or pairs of entangled photons. The latter are key elements for remote communication protocols like teleportation or quantum repeaters. Such protocols are based on a local joint measurement of two photons (e.g. Bell state measurement, BSM) originating from separated sources and rely on the fact that the photons to be measured are indistinguishable. To provide temporal indistinguishability of independent photons, their timing precision has to be better than their coherence time. For photons originating from different remote sources, this can be achieved by pulsed emission times, synchronized by an external clock [1, 2]. Major drawbacks are the need for accurate synchronization of the lasers as well as precise matching and stabilization of the optical path lengths.

Alternatively, timing can be obtained by postselecting appropriate photon pairs by detection [3]. To allow for precise timing, the coherence time of the photons has to be longer than the temporal resolution of the detectors. As an advantage, the sources do not require any synchronization and hence allow the use of relatively simple continuous wave (CW) excitation. In addition due to the long coherence length, the set-up is less sensitive to path length fluctuations which is a limiting factor for joint measurements under pulsed excitation.

Entangled photon pairs are essential for the aforementioned protocols and may, for example, be produced by bi-exciton cascade emission of quantum dots [4, 5] or intracavity atomic ensembles [6], but due to their relatively early development stage, these techniques are still not practical for quantum communication. Alternatively nonlinear effects like spontaneous four-wave mixing [7]–[10] or spontaneous parametric down conversion (SPDC) in nonlinear crystals [1], [11]–[14] can be used. These systems appear to be more practical, but have the disadvantage of a broad emission spectrum (from one to tens of nanometres), providing an insufficient coherence length to tolerate length fluctuations in optical fibres ($4 \times 10^{-6} \text{ K}^{-1}$) of several kilometres.

A narrow-bandwidth emission spectrum can be obtained by counter propagating SPDC [14] or SPDC in photonic crystals [15], but these systems are still under development and

efficiencies are extremely low. Another approach to achieving a long coherence time consists of either inserting the nonlinear crystal in a cavity [16] or using very narrow bandpass filters [17]. The first technique generally provides a smaller bandwidth whereas the latter has the advantage of easy maintenance, advantageous e.g. for field experiments.

In the first part of this paper, we present a CW source of entangled photon pairs with long coherence times. This is achieved by combining the high conversion efficiency of SPDC in a nonlinear periodically poled lithium niobate (PPLN) waveguide with narrow bandwidth filtering via a phase shifted fibre Bragg grating (PSFBG). In the second part, we describe the realization and implementation of different detection techniques. The presented results show that this source in combination with an appropriate, time resolving detection scheme is a useful tool for quantum communication protocols based on entangled photon pairs as e.g. required for teleportation experiments or quantum repeaters. Due to the fact that no synchronization of remote sources is required anymore, a compact and simple CW diode laser can be used, which makes the set-up low-cost and easy to use.

Fibre optical networks provide an existing resource for long distance communication. To take advantage of this and in order to minimize propagation losses, light at telecommunication wavelengths has to be used. At this wavelength—1560 nm in our case—single photons are usually detected by InGaAs avalanche photo detectors (APDs), which provide timing resolution of up to 100 ps and quantum efficiencies of up to 30%, but generally, only in gated mode [18]. This makes them unsuitable for combination with CW-sources due to the lack of synchronization signals. In order to meet the strict conditions on the detectors for high timing resolution and free running operation, we focus on two new generation detectors which have been developed recently. We implemented mid-infrared single photon detection by up-conversion combined with Si-APDs [19, 20] as well as superconducting detectors provided by SCONTEL [21].

To demonstrate the performance of the sources in combination with high resolution detectors, we present a HOM dip in the last part of the paper. The results are discussed in the conclusion.

2. The photon pair source

2.1. Entanglement by parametric down conversion

In the following, the different components of our source are described in detail. Figure 1 shows a schematic set-up of our narrow band CW source. Pairs of energy-time entangled photons are created by SPDC in a nonlinear crystal pumped at $\lambda_p = 780$ nm. The crystal is a 50 mm-long PPLN waveguide (HC Photonics). Phase matching is such that SPDC produces degenerate pairs of signal and idler photons at 1560 nm; with a spectral distribution of $\Delta\lambda_0 = 80$ nm. The crystal's temperature can be tuned and the nonlinear conversion efficiency was measured to be 10^{-5} . Through energy conservation, signal and idler photons satisfy the relationship $\lambda_p^{-1} = \lambda_s^{-1} + \lambda_i^{-1}$, hence detecting the signal photon at λ_s projects the corresponding idler photon on to λ_i . The created photons have the same polarization and exit the PPLN waveguide collinearly. They are coupled into a standard optical single mode fibre with an efficiency of 30%. A bulk high-pass silicon filter (Si) is placed just before coupling into the fibre in order to block the remaining pump light while transmitting ($T = 90\%$) the created photons.

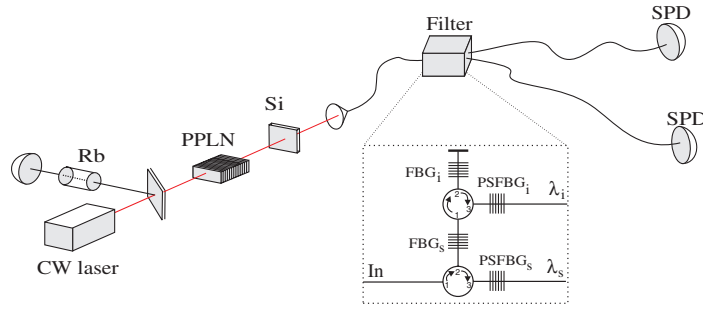


Figure 1. Set-up of the source. A continuous laser (CW), stabilized on the D_2 -transition line of rubidium (Rb), pumps a nonlinear PPLN crystal. Pairs of entangled signal and idler photons are created and emitted collinearly by SPDC. The remaining pump light is filtered by a silicon filter (Si). The photons are coupled into single mode optical fibres. They are then separated and narrowly filtered (Filter, see text) before being detected by low-jitter single photon detectors (SPD).

2.2. Long coherence time by narrow filtering

The spectral distribution of the downconverted light corresponds to a coherence time of only $\tau_c = 43$ fs. In order to increase this value, the photons have to be narrowly filtered. Such narrow band filters are obtained by cascading two different types of fibre Bragg gratings FBGs (see insert, figure 1). The first one is a standard FBG_s with a bandwidth of ~ 1 nm and a high rejection rate (>45 dB) over the entire SPDC spectrum. This FBG reflects the desired wavelength, requiring the use of a circulator. The second one is a PSFBG_s , featuring a 10 pm-wide transmission spectrum and a rejection window of only a few nanometres. The downconverted light with a broad spectrum is sent into port 1 of the circulator. In port 2, the FBG_i reflects light at λ_s over ~ 1 nm and transmits all the remaining wavelengths. The reflected light then exits the circulator via port 3 and is further filtered by a PSFBG_i (λ_s , $\Delta\lambda_s = 10$ pm). The remaining light, transmitted by the FBG, is sent into another similar filter module centered at λ_i .

The overall insertion loss of these filters (AOS GmbH) is 2–3 dB. The filters enable us to reduce the initial broad SPDC spectrum down to a bandwidth of 10 pm (1.2 GHz), corresponding to 7 cm of coherence length in optical fibres, with a rejection of >45 dB over the whole SPDC spectrum. The filters are temperature tuned and stabilized, allowing for a wavelength precision of the order of 1 pm over several weeks. Signal and idler filters are placed at 1558 and 1562 nm, respectively, and independently tunable over 400 pm, allowing for fine adjustment⁴.

2.3. Source characteristics and applications

This type of photon-pair source, combining a nonlinear crystal and narrow-band filters, can be pumped by either a CW or pulsed laser. Here, the source is pumped by a CW diode laser with external cavity (Toptica DL 100) at $\lambda_p = 780$ nm. The laser is stabilized against the D_2 transition line of Rb 87 allowing for long term wavelength stability of less than 0.5 pm.

⁴ In principle the idler-filter is not necessary, but serves to improve the signal to noise ratio by selecting the corresponding photon out of a broad spectrum of non-correlated photons.

Table 1. Comparison of different approaches to entangled photon pair sources by the mean number of photons $\langle n \rangle$ created per coherence time τ_c , bandwidth $\Delta\lambda$ in pm, optical transmission T including coupling efficiency into optical fibres in percentage, their effectively emitted spectral brightness E_λ per s and pm, and the required pump power P .

Process		$\langle n \rangle (\tau_c^{-1})$	$\Delta\lambda$ (pm)	T (%)	E_λ ($s^{-1} \text{ pm}^{-1}$)	P (mW)
Filtered SPDC		0.08	10	13	3.9×10^5	7
Four-wave-mixing ^a	[8]	0.5	200	14	4×10^5	8
Cavity SPDC	[16]	0.012	0.02	14	7.6×10^4	1.7
Atomic ensemble ^b	[6]	0.02	0.01	35	2.3×10^6	N.A.
Quantum dots ^{b,c}	[5]	N.A.	620	8	<1	<0.1

^aNote that [8] works in pulsed mode, such that $\langle n \rangle$ is given in pairs per pulse and P in average power, and hence are different from CW sources.

^bFor quantum dots and atomic ensembles, filtering induces additional losses due to lack of energy correlation between the two photons of a pair and hence their bandwidth is fixed.

^cCoupling efficiency for quantum dots is taken from another experiment [30].

An important parameter to characterize a light emitting source is the spectral radiance $L_\lambda = hc^2 \langle n \rangle / \lambda^5$, with h the Planck quantum, c the speed of light, λ the photons wavelength and $\langle n \rangle$ the average number of created photons per mode [22]. Let us consider a single mode source, so that $\langle n \rangle$ represents the average number of photons per coherence time. If now, the bandwidth of the created spectrum ($\Delta\lambda_0$) is filtered to $\Delta\lambda_f$, on one hand the number N of photons created per second is reduced by a factor $r = \Delta\lambda_f / \Delta\lambda_0$ and on the other hand the coherence time $\tau_c = 0.44 \lambda^2 / (c \times \Delta\lambda)$ is increased by r at the same time. This means that the number of temporal modes per second $M = \tau_c^{-1} \times s$ also diminishes by r . Hence, $\langle n \rangle = N/M$ (and consequently L_λ) remains constant for any given source and is independent of the spectral filtering (for details see [22, 23]).

In order to avoid errors due to multiple photon emission, one is limited to $\langle n \rangle \leq 1$ and in the case of a probabilistic photon distribution [24], this limit is on the order of 0.1 [25]. Our single mode source achieves a $\langle n \rangle$ of 0.08 pairs per coherence length with only 7 mW of pump power injected into the waveguide. This radiance is one order of magnitude larger than any comparable photon pair source based on SPDC. Taking into account the losses due to absorption in the crystal, fibre coupling and insertion losses in filters, an overall optical transmission of $T = 13\%$ per photon is obtained. This leads to an effectively emitted spectral brightness E_λ into the single mode fibre of 3.9×10^5 pairs $\text{pm}^{-1} \text{s}^{-1}$.

This source can be adapted to match various applications [26]–[28] which require either maximal emission rates or long coherence length or any tradeoff in between, simply by choosing a filter of suitable bandwidth. If, for example, employed in conjunction with quantum memories, a bandwidth on the order of up to 300 MHz is required.

In principle, this is possible for any other source as well, but in our case it is also practical since only a few milliwatt of pump power suffices to maintain the maximum $\langle n \rangle$. Furthermore, due to the narrow bandwidth, chromatic dispersion as well as polarization mode dispersion are negligible [29]. In table 1, different approaches to entangled photon pair sources are compared.

From another point of view, our set-up represents a heralded single photon source at 1560 nm with long coherence length and a $P_1 = 0.13$. Up to now, most heralded single photon sources [6], [31]–[33] have focused only on single photon and multiphoton probabilities without taking into account the bandwidth of the heralded photons. This figure is important since chromatic dispersion in optical fibres will strongly reduce the maximal communication distances [28].

Given a Gaussian filter with a width of 10 pm, the photons have a corresponding coherence time of 350 ps. This value is seven times greater than the resolution of state-of-the-art detectors, which are described in the next section.

3. Time resolution by detection

In order to realize a complete asynchronous quantum communication system we have implemented two free-running detectors based on either nonlinear sum frequency generation (SFG) and Si-detectors, or superconducting detectors. Si-APD detectors [34, 35] offer both high quantum efficiencies (of 50%) and temporal resolution better than 50 ps, for wavelengths below 1 μm . In order to detect light at 1560 nm, photons can be frequency converted to e.g. 600 nm by SFG: a signal photon at 1560 nm is combined with a high power (>200 mW) CW pump laser at 980 nm and then sent into a nonlinear PPLN WG crystal, phase matched for up-conversion. Photons at 600 nm are created and detected with an overall efficiency greater than 10%, including coupling, losses and APD detection efficiency. The dark count rate of such a set-up can reach several hundred kilohertz due to pump-dependent nonlinear noise [19, 20]. However, one can reduce this noise level to a more practical level (which in turn reduces the upconversion efficiency), while maintaining the advantages of high temporal resolution and passive detection. In this instance, we chose to operate these detectors with 3% detection efficiency and 30 kHz noise.

3.1. Superconducting detectors

Alternatively, single photons can be detected by a superconducting single photon detector (SSPD), based on the so-called hotspot process [36]. A superconducting nanowire, made out of ultrathin (3–5 nm) niobium nitride (NbN) stripes of 100 nm width, is biased slightly below the critical current I_c . The meander shaped nanowire (on a typical surface of 10 $\mu\text{m} \times 10 \mu\text{m}$) is locally heated by the energy of an absorbed photon. Subsequently, a normal hotspot is created. The nanowire section available for the superconducting current is thus reduced and the critical current density is locally exceeded. Hence, the entire stripe section becomes normal and an easily measurable voltage pulse (mV) is generated before the NbN superconductivity is restored [21].

The hotspot mechanism is a fast process with intrinsic response times as low as 30 ps [37], but practical devices are limited by the kinetic inductance of the meander which is typically hundreds of microns long [38]. Hence, voltage pulses are usually longer than 1 ns and practical counting rates are below 100 MHz. The SSPD overall detection efficiency is mainly limited by the poor absorption in the thin NbN layer in the near infrared region, typically 20% for 3–5 nm thick films.

In our set-up, the free running SSPD system (containing two detectors) is cooled down to 1.7 K by pumping a liquid helium bath to 3 mbar. Both detectors are voltage biased and operated

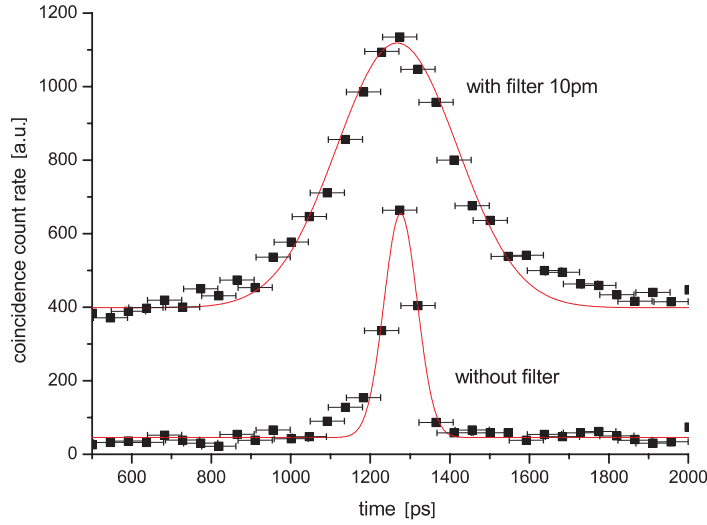


Figure 2. Coincidence measurement of both signal and idler photons by a combination of up-conversion and Si-detectors. If no filters are used (lower graph), the width of the curve corresponds to the timing jitter of the detectors. For the case of narrowly filtered photon pairs (upper graph), a broadening of the response signal clearly shows the photons' coherence length exceeding the detector's temporal resolution.

at a superconducting current of $20 \mu\text{A}$ corresponding to 90% of the critical current. The overall quantum efficiency at 1560 nm was measured to be 5 and 5.5% with dark count rates of 100 Hz and 1 kHz for the two different devices. The timing jitter of the detection module including detector, electronics and signal discrimination, has been established to be of the order of 70 ps using a coincidence measurement with photon pairs of 40 fs coherence time.

4. Experimental results

4.1. Detection of high coherence photons

The coherence length of filtered photon pairs can be measured with a coincidence set-up (figure 1). Detecting the signal photon (λ_s) at time t_0 projects the idler photon (λ_i) into the same temporal mode $t_0 \pm \tau_c$ with an uncertainty given by the photon's coherence time τ_c . In our experiment, the detection signals are sent to a time to amplitude converter (TAC) with a nominal temporal resolution of 45.5 ps. For the coincidence measurement of signal and idler photons, the histogram of the time differences between the two electronic signals is plotted in figure 2. Without filtering, the SPDC photons coherence time is 40 fs. The coincidence peak (lower graph) with a measured FWHM of 80 ps, is the convolution of the two detectors' signals and gives a precise calibration of the set-up resolution.

The second curve (upper graph) is obtained with the 10 pm filters inserted in the photon's path. In this case, τ_c is larger than the detectors' resolution and the coincidence measurement shows a temporal distribution governed by the photon's coherence time. We observe a significant widening of the coincidence peak (400 ps), corresponding to a deconvolved width of 285 ps for each photon. The measured value is less than the theoretical 350 ps due to the filters'

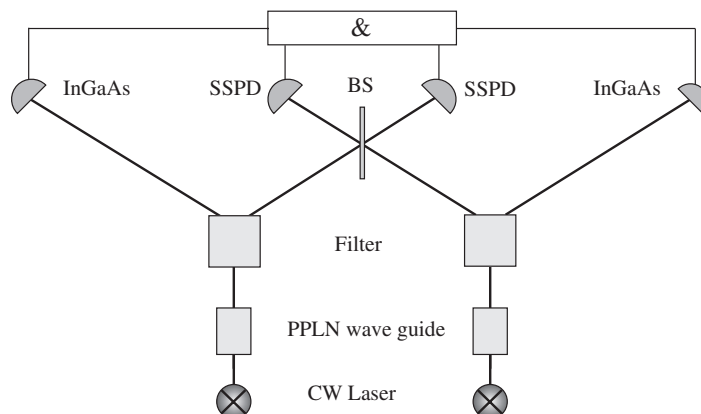


Figure 3. Experimental set-up for a CW HOM-dip experiment. Pairs of photons are independently created by autonomous unsynchronized CW sources. The photons are filtered to 10 pm (Filter) in order to increase their coherence time to 300 ps. One photon from each source is sent onto a 50/50 BS and coincidence count rates between the two high resolution superconducting detectors (SSPD) at the output ports are recorded. Further coincidence detections (&) by the two InGaAs APD ensure that we only observe events with photon pairs from different sources.

non-gaussian spectrum and slightly larger bandwidth than specified. This measurement proves that we have, on one hand, created a photon pair source based on SPDC with highly coherent photons, and on the other hand, demonstrated that recent photon detectors with high temporal resolution are capable of resolving the photons arrival time with sub-coherence time precision. While time resolved detection has already been demonstrated for single photon sources [39], this is, to our knowledge, the first time it has been shown for entangled photon pairs.

4.2. A HOM experiment

In order to demonstrate the performance of our system, we conduct a HOM experiment. In such an experiment, two indistinguishable photons superposed on a 50/50 beamsplitter (BS) bunch together into the same output mode due to their bosonic nature [40]. Indistinguishability requires, besides identical polarization, spectral and spatial modes, that the photons enter the BS simultaneously. This is normally obtained by using photons originating from the same pair [40] or synchronized pulsed emission from different independent sources leading to two-photon interferences [1, 8].

In the case of independent sources with CW excitation, due to the lack of any synchronization, one has to postselect photon pairs arriving at the same time at the BS by detection [41]. This requires detectors with a temporal resolution superior to the coherence time of the photons. The two output modes are each connected to a SSPD as shown in figure 3, and for the case where both SSPDs click, the arrival time difference τ of the photons is recorded by a time to digital converter (TDC), connected to a computer.

If this is repeated continuously and the coincidence count rate R of the two detectors is plotted as a function of the photons' relative time delay τ (figure 4), a decrease in R is observed for $\tau = 0$, due to photon bunching, giving rise to a 'dip'. In order to ensure that the two signal

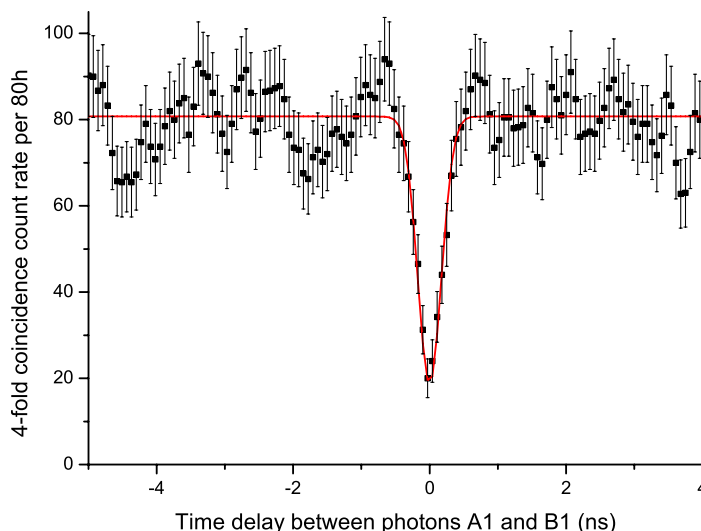


Figure 4. Coincidence count rate between the two SSPD as a function of the measured temporal delay τ of two identical photons impinging on a BS and originating from independent sources. For $\tau = 0$ a HOM-dip with a visibility of $77 \pm 3\%$ is observed. The fit is based on a Gaussian distribution and error bars are standard deviation.

photons originate from different sources, the related idler photons of each pair must also be detected, as illustrated in figure 3. For a Gaussian shaped fit of the experimental data, a raw dip visibility—defined as $(V_{\max} - V_{\min})/(V_{\max})$ —of $77 \pm 3\%$ is observed. This proves the ability to temporally resolve the photons' arrival times at the BS. We measure approximately one 4-fold coincidence per time slot of the TDC (45.5 ps) for each hour of measurement. The incongruity between the experimental data and the fitted Gauss function outside the dip is due to the fact that the transmission spectrum of the filters as well as the detectors' electronic response are not perfectly Gaussian, leading to the observed oscillations. However, a Gaussian fit allows for good estimation of the observed visibility.

Note that we detect all possible arrival-time differences in parallel and each of the time differences is given by the arbitrary emission times of the CW sources. (This corresponds to a 4-fold coincidence count rate of 400 events per hour for a temporal range of ± 10 ns). This value is limited by the probability of two photons, being emitted independently and arbitrarily, arriving at a given time at BS. The final 4-fold coincidence count rate is further affected by losses in fibre coupling, absorption in the filters and low detector efficiencies. For a detailed discussion of the reduction in the observed visibility, we refer to [41].

The detectors' temporal resolution is sufficient to resolve the photons' coherence length. The limited visibility is predominantly due to multi photon creation. Thus the visibility could be further increased by reducing the pump power, with the consequence of longer measurement times.

5. Conclusion

In conclusion, we have realized a set-up of two autonomous CW photon pair sources with long coherence times in combination with new-generation high resolution detectors. A spectral

radiance L_λ corresponding to 0.08 photons per coherence length and an emitted spectral brightness E_λ of 3.9×10^5 pairs $\text{s}^{-1} \text{pm}^{-1}$ are achieved. Such sources can be used in various quantum communication protocols without any need for pulse synchronization as in field experiments for long distance quantum communication. Furthermore, their bandwidth is compatible with quantum memories. Even though some efforts have still to be made by both sides, source and memory bandwidths are within the same order of magnitude and hence make asynchronous quantum repeaters [42] more feasible.

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References

- [1] Kaltenbaek R, Blauensteiner B, Zukowski M, Aspelmeyer M and Zeilinger A 2006 Experimental interference of independent photons *Phys. Rev. Lett.* **96** 240502
- [2] Yang T, Zhang Q, Chen T-Y, Lu S, Yin J, Pan J-W, Wei Z-Y, Tian J-R and Zhang J 2006 Experimental synchronization of independent entangled photon sources *Phys. Rev. Lett.* **96** 110501
- [3] Zukowski M, Zeilinger A, Horne M A and Ekert A K 1993 Event-ready-detectors Bell experiment via entanglement swapping *Phys. Rev. Lett.* **71** 4287–90
- [4] Benson O, Santori C, Pelton M and Yamamoto Y 2000 Regulated and entangled photons from a single quantum dot *Phys. Rev. Lett.* **84** 2513
- [5] Stevenson R M, Young R J, Atkinson P, Cooper K, Ritchie D A and Shields A J 2006 A semiconductor source of triggered entangled photon pairs *Nature* **439** 179–82
- [6] Thompson J K, Simon J, Loh H and Vuletic V 2006 A high-brightness source of narrowband, identical-photon pairs *Science* **313** 74–7
- [7] Liang C, Lee K F, Medic M, Kumar P, Hadfield R H and Nam S W 2007 Characterization of fiber-generated entangled photon pairs with superconducting single-photon detectors *Opt. Express* **15** 1322–7
- [8] Fulconis J, Alibart O, Wadsworth W J and Rarity J G 2007 Quantum interference with photon pairs using two micro-structured fibres *New J. Phys.* **9** 276
- [9] Fan J and Migdall A 2007 A broadband high spectral brightness fiberbased two-photon source *Opt. Express* **15** 2915–20
- [10] Takesue H and Inoue K 2005 Generation of 1.5- μm band time-bin entanglement using spontaneous fiber four-wave mixing and planar light-wave circuit interferometers *Phys. Rev. A* **72** 041804
- [11] Sauge S, Swillo M, Albert-Seifried S, Xavier G B, Waldebeck J, Tengner M, Ljunggren D and Karlsson A 2007 Narrowband polarization-entangled photon pairs distributed over a wdm link for qubit networks *Opt. Express* **15** 6926–33
- [12] Tanzilli S, De Riedmatten H, Tittel W, Zbinden H, Baldi P, De Micheli M, Ostrowsky D B and Gisin N 2001 Highly efficient photon-pair source using periodically poled lithium niobate waveguide *Electron Lett.* **37** 26–8
- [13] Konig F, Mason E J, Wong F N C and Albota M A 2005 Efficient and spectrally bright source of polarization-entangled photons *Phys. Rev. A* **71** 033805
- [14] Lanco L, Ducci S, Likforman J-P, Marcadet X, van Houwelingen J A W, Zbinden H, Leo G and Berger V 2006 Semiconductor waveguide source of counterpropagating twin photons *Phys. Rev. Lett.* **97** 173901
- [15] Irvine W T M, de Dood M J A and Bouwmeester D 2005 Bloch theory of entangled photon generation in nonlinear photonic crystals *Phys. Rev. A* **72** 043815

- [16] Neergaard-Nielsen J S, Nielsen B M, Takahashi H, Vistnes A I and Polzik E S 2007 High purity bright single photon source *Opt. Express* **15** 7940–9
- [17] Halder M, Tanzilli S, de Riedmatten H, Beveratos A, Zbinden H and Gisin N 2005 Photon-bunching measurement after two 25-km-long optical fibers *Phys. Rev. A* **71** 042335
- [18] Ribordy G, Gautier J-D, Zbinden H and Gisin N 1998 Performance of InGaAs InP avalanche photodiodes as gated-mode photon counters *Appl. Opt.* **37** 2272–7
- [19] Thew R T, Tanzilli S, Krainer L, Zeller S C, Rochas A, Rech I, Cova S, Zbinden H and Gisin N 2006 Low jitter up-conversion detectors for telecom wavelength GHz QKD *New J. Phys.* **8** 32
- [20] Langrock C, Diamanti E, Roussev R V, Takesue H, Yamamoto Y and Fejer M M 2005 Highly efficient single-photon detection at communication wavelengths by use of upconversion in reverse-proton-exchanged periodically poled LiNbO₃ waveguides *Opt. Lett.* **30** 1725–7
- [21] Milostnaya I *et al* 2006 Superconducting single-photon detectors designed for operation at 1.55- μ m telecommunication wavelength *J. Phys. Conf. Ser.* **43** 1334
- [22] Migdall A, Datla R, Sergienko A, Orszak J S and Shih Y H 1998 Measuring absolute infrared spectral radiance with correlated visible photons: technique verification and measurement uncertainty *Appl. Opt.* **37** 3455–63
- [23] Klyshko D N 1988 *Photons and Nonlinear Optics* (New York: Gordon and Breach)
- [24] Tapster P R and Rarity J G 1998 Photon statistics of pulsed parametric light *J. Mod. Opt.* **45** 595–604
- [25] Scarani V, de Riedmatten H, Marcikic I, Zbinden H and Gisin N 2005 Four-photon correction in two-photon Bell experiments *Eur. Phys. J. D* **32** 129
- [26] Jacobs B C, Pittman T B and Franson J D 2002 Quantum relays and noise suppression using linear optics *Phys. Rev. A* **66** 052307
- [27] Briegel H-J, Dür W, Cirac J I and Zoller P 1998 Quantum repeaters: the role of imperfect local operations in quantum communication *Phys. Rev. Lett.* **81** 5932
- [28] Fasel S, Alibert O, Tanzilli S, Baldi P, Beveratos A, Gisin N and Zbinden H 2004 High-quality asynchronous heralded single-photon source at telecom wavelength *New J. Phys.* **6** 163
- [29] Fasel S, Gisin N, Ribordy G and Zbinden H 2004 Quantum key distribution over 30 km of standard fiber using energy-time entangled photon pairs: a comparison of two chromatic dispersion reduction methods *Eur. Phys. J. D* **30** 143–8
- [30] Pelton M, Santori C, Vuckovic J, Zhang B, Solomon G S, Plant J and Yamamoto Y 2002 Efficient source of single photons: a single quantum dot in a micropost microcavity *Phys. Rev. Lett.* **89** 233602
- [31] Horikiri T and Kobayashi T 2006 Decoy state quantum key distribution with a photon number resolved heralded single photon source *Phys. Rev. A* **73** 032331
- [32] Soujaeff A, Takeuchi S, Sasaki K, Hasegawa T and Matsui M 2007 Heralded single photon source at 1550 nm from pulsed parametric down conversion *J. Mod. Opt.* **54** 467–71
- [33] Alibert O, Ostrowsky D B, Baldi P and Tanzilli S 2005 High-performance guided-wave asynchronous heralded single-photon source *Opt. Lett.* **30** 1539–41
- [34] Cova S, Lacaita A, Ghioni M, Ripamonti G and Louis T A 1989 20-ps timing resolution with single-photon avalanche diodes *Rev. Sci. Instrum.* **60** 1104–10
- [35] Rochas A, Gani M, Furrer B, Ribordy G, Besse P A, Gisin N and Popovic R S 2003 Single photon detector fabricated in a complementary metal-oxide-semiconductor high-voltage technology *Rev. Sci. Instrum.* **74** 3263
- [36] Gol'tsman G N, Okunev O, Chulkova A, Lipatov G, Semenov A, Smirnov K, Voronov B, Dzardanov A, Williams C and Sobolewski R 2001 Picosecond superconducting single-photon optical detector *Appl. Phys. Lett.* **79** 705–7
- [37] Il'in K S, Lindgren M, Currie M, Semenov A D, Gol'tsman G N, Sobolewski R, Cherednichenko S I and Gershenzon E M 2000 Picosecond hot-electron energy relaxation in NbN superconducting photodetectors *Appl. Phys. Lett.* **76** 2752–4

- [38] Kerman A J, Dauler E A, Keicher W E, Yang J K W, Berggren K K, Gol'tsman G and Voronov B 2006 Kinetic-inductance-limited reset time of superconducting nanowire photon counters *Appl. Phys. Lett.* **88** 111116
- [39] Legero T, Wilk T, Hennrich M, Rempe G and Kuhn A 2004 Quantum beat of two single photons *Phys. Rev. Lett.* **93** 070503
- [40] Hong C K, Ou Z Y and Mandel L 1987 Measurement of subpicosecond time intervals between two photons by interference *Phys. Rev. Lett.* **59** 2044–6
- [41] Halder M, Beveratos A, Gisin N, Scarani V, Simon C and Zbinden H 2007 Entangling independent photons by time measurement *Nat. Phys.* **3** 692–5
- [42] Simon C, de Riedmatten H, Afzelius M, Sangouard N, Zbinden H and Gisin N 2007 Quantum repeaters with photon pair sources and multimode memories *Phys. Rev. Lett.* **98** 190503