LETTER

A versatile source of polarization entangled photons for quantum network applications

Florian Kaiser, Amandine Issautier, Lutfi A Ngah, Olivier Alibart, Anthony Martin and Sébastien Tanzilli

Laboratoire de Physique de la Matière Condensée, Université Nice—Sophia Antipolis, CNRS UMR 7336, Parc Valrose, F-06108 Nice Cedex 2, France

E-mail: sebastien.tanzilli@unice.fr

Received 24 December 2012
Accepted for publication 26 December 2012
Published 27 February 2013
Online at stacks.iop.org/LPL/10/045202

Abstract

We report a versatile and practical approach for the generation of high-quality polarization entanglement in a fully guided-wave fashion. Our setup relies on a high-brilliance type-0 waveguide generator producing paired photons at a telecom wavelength associated with an advanced energy-time to polarization transcriber. The latter is capable of creating any pure polarization entangled state, and allows manipulation of single-photon bandwidths that can be chosen at will over five orders of magnitude, ranging from tens of MHz to several THz. We achieve excellent entanglement fidelities for particular spectral bandwidths, i.e. 25 MHz, 540 MHz and 80 GHz, proving the relevance of our approach. Our scheme stands as an ideal candidate for a wide range of network applications, ranging from dense division multiplexing quantum key distribution to heralded optical quantum memories and repeaters.

(Some figures may appear in colour only in the online journal)

1. Introduction

Entanglement served historically as an essential resource for testing the foundations of quantum physics, such as non-locality [1] via violation of the Bell inequalities [2–4]. More recently, entanglement has been employed as a key ingredient in extended versions of Bohr’s complementarity notion [5, 6]. Today, quantum information science (QIS) exploits entanglement for enhanced communication and processing protocols [7]. On one hand, quantum key distribution (QKD), already commercialized, provides a unique means to establish private ciphers between distant partners [8]. On the other hand, various entanglement-enabled network tasks, such as quantum relays [9], memories [10] and repeaters [11], are extensively studied in research laboratories. State-of-the-art manipulation of entanglement is achieved using disparate experimental techniques such as atom traps [12], Josephson junctions [13] and quantum integrated photonics [14]. System versatility and compatibility stand now as cornerstones for pushing QIS one step further. In the context of photonic entanglement sources [15–20], we report a remarkably versatile solution, capable of creating any pure polarization entangled state encoded on telecom wavelength photons. Exploiting an advanced energy-time to polarization observable transcriber associated with a wavelength tunable high-brilliance photon-pair generator, we demonstrate excellent entanglement fidelities for spectral bandwidths that can be chosen over five orders of magnitude. Our scheme stands as an ideal candidate for a wide range of network applications, ranging from dense division multiplexing QKD [21] to heralded optical quantum memories [10].
2. Experimental setup and related capabilities

As in classical communication, low-loss optical fibres and high-performance components based on guided-wave technologies enable exploitation of the telecom C-band wavelengths (1530–1565 nm) for generating and distributing photonic entanglement. Among the most widely used observables are time-bin and polarization [7], the latter being undoubtedly the easiest to analyse. Depending on the application, many schemes have been developed to generate photonic polarization entanglement. Usually, the photon pairs are generated using the nonlinear process of spontaneous parametric down-conversion (SPDC) in either bulk [17] or waveguide configurations [20], possibly surrounded by an optical cavity to reduce the generated bandwidth [15, 18]. Among other pertinent generators, we find dispersion-shifted optical cavity to reduce the generated bandwidth [15, 18]. We overcome these problems with the experimental setup of figure 1. It consists of two main stages, namely an advanced fibre optical energy-time-to-polarization transcriber apparatus (a) and a wavelength tunable, high-brilliance, advanced fibre optical energy-time to polarization transcriber source.

![Schematic of the experimental setup.](image)

The fibre optical transcriber apparatus. Sending the diagonally polarized bi-photon state $|D_1 \otimes D_2 \rangle = \frac{1}{\sqrt{2}} (|H_1 \rangle + |V_1 \rangle) \otimes \frac{1}{\sqrt{2}} (|H_2 \rangle + |V_2 \rangle)$ leads to four possible outputs: (i) $|V, l \rangle_1 |V, l \rangle_2$, (ii) $|V, l \rangle_1 |H, e \rangle_2$, (iii) $|H, e \rangle_1 |V, l \rangle_2$ and (iv) $|H, e \rangle_1 |H, e \rangle_2$, where $e$ and $l$ denote ‘early’ and ‘late’ temporal modes, respectively. Temporal post-selection of cases (i) and (iv) generates the desired polarization entangled state $|\Phi(\phi)\rangle$. (b) The high-efficiency photon-pair generator. A 780 nm laser pumps a PPLN/W to generate paired photons at a degenerate wavelength of 1560 nm. After passing through a polarization controller (PC), the photons are conveniently filtered to bandwidths ranging from 25 MHz to 80 GHz, using standard telecom techniques. (c) Standard polarization state analysers. Alice and Bob each comprise a half-wave plate (HWP), a polarizing beam-splitter (PBS) and a single-photon detector (SPD). The ‘&’ represents an AND-gate that connects the two SPDs for recording coincidence counts between the two users. PZT: piezoelectric transducer fibre stretcher.

3. The integrated optics waveguide generator and related characterization

We now connect the transcriber to a 4.5 cm long PPLN/W photon-pair generator exploiting the so-called type-0 SPDC process. As shown in figure 1(b), the crystal is pumped by a vertically polarized 780 nm continuous wave laser to create vertically polarized paired photons $|V_1 \rangle |V_2 \rangle$ at an average flux as high as $\sim 10^{14}$ photons per second and per mW of pump power. Due to the spontaneous character of the down-conversion process, the coherence time of the pairs corresponds to that of the laser. To fulfil the transcriber requirement $t_{\text{pair}} \gg \Delta t$,
the laser is frequency stabilized against a hyperfine transition in the D\textsubscript{2} line of rubidium, giving a pair coherence time $\tau^{\text{pair}} = 3$ $\mu$s. As shown in figure 2, wavelength degeneracy, i.e. 1560 nm, is obtained at a temperature of 387 K, and the associated spectral bandwidth is about 4 THz ($\leftrightarrow$ 32 nm), covering the full telecom C-band of wavelengths.

In addition, the emission wavelength can be tuned over more than 100 nm with respect to the SPDC energy conservation by adapting the phase-matching condition via temperature control. After the PPLN/W, the pairs are collected using a single-mode fibre and sent to the filtering stage. In this realization, we use three exemplary filters: a standard 80 GHz dense wavelength division multiplexer (DWDM) adapted to standard telecom networks [21], a 540 MHz phase-shifted fibre Bragg grating (PS-FBG) compatible with broadband spectral acceptance quantum memories [28, 29] and continuous wave quantum relays [16], and a 25 MHz PS-FBG matching much narrower spectral acceptance quantum memories [30, 31]. This results in a source bandwidth versatility covering more than five orders of magnitude by simple filter adaptation. More details on the PS-FBG filters are given in section A.3. After the filter, polarization entanglement is created by the transcriber, in front of which a polarization controller (PC\textsubscript{2}) is used to rotate the photons’ polarization to the diagonal state $|\psi\rangle_{\text{in}} = |D_{1}1\rangle|D_{2}2\rangle$, as described above. This condition is necessary for generation of the maximally entangled state $|\Phi(\phi)\rangle$, and therefore violation of the Bell inequalities [2, 3] with optimal visibilities [32].

4. Coincidence histogram for three different bandwidths

To characterize the suitability of the transcriber for handling narrowband photons, we first measure the time-dependent two-photon correlation function for the three filters mentioned above. A 50/50 fibre beam-splitter (BS) is used to separate and distribute the photons to Alice and Bob, each employing a single-photon detector (SPD) connected to a coincidence measurement apparatus (\&). More details on these detectors are provided in section A.4. As shown in figure 3, three well separated coincidence peaks are obtained for each filter.

The two outer peaks at $\delta t = \pm 76$ ns correspond to cross polarization contributions which have been split up temporally by the transcriber, while the central peak contains the $|H\rangle_{1}|H\rangle_{2}$ and $|V\rangle_{1}|V\rangle_{2}$ contributions to the desired entangled state. At this stage, the central-to-side peak ratio of 2 indicates that all the contributions have the same probability amplitudes and that maximally entangled states can be post-selected out of the central peak. For the 80 GHz bandwidth, an $\sim 5.5$ ps photon coherence time is expected, such that the 230 ps peak width is mainly given by the convolution of the detectors’ timing jitters. With the two narrowband filters in place, the single photons’ coherence time is increased. This leads to peak broadenings of $800 \pm 20$ ps and $15.6 \pm 0.7$ ns, which are in good agreement with the specified bandwidths of the 540 and 25 MHz filters, respectively.

5. Entanglement quality for three different bandwidths

We now examine the quality of the produced entanglement at the output of the full setup of figure 1. For state analysis (c), we use a standard Bell inequality type setup, where Alice and Bob each employ a half-wave plate (HWP), a polarizing beam-splitter (PBS) and an SPD. We also consider only photon-pair events within the full-width at half-maximum region of the central coincidence peaks of figure 3 for post-selecting the maximally entangled state $|\Phi(\phi)\rangle$. Violation of the Bell inequalities requires maintenance of the coherence of the state, i.e. in our case stabilization of the phase $\phi$, over the full measurement time [32]. We also stress that, for our extremely long temporal mode separation, the transcriber is
required to be an advanced system, meaning that a high-speed (>1 kHz) and high-resolution (Δφ < \frac{π}{1007}) phase stabilization scheme is employed. This is detailed and demonstrated to be remarkably suitable for that purpose in section A.2.

In the following, we analyse the state \(|\Phi^−\rangle\), obtained when φ is set to π in the transcriber. In this case, the coincidence rate is measured for four standard and consecutive analysis settings on Alice’s side, i.e. \(|H\rangle, |V\rangle, |D\rangle, \) and \(|A\rangle\), while Bob's HWP is continuously rotated. As an exemplary result, we consider the 25 MHz filter and take advantage, for this particular measurement, of two super-conducting SPDs to reduce accidental coincidence events (for more details, see section A.4). As shown in figure 4, excellent raw visibilities, of 99 ± 3%, are obtained for all four orientations at Alice. The corresponding Bell parameter is calculated to be S_{raw} = 2.82 ± 0.02, which leads to a violation of the Bell inequalities by more than 40 standard deviations [2, 3]. For the two other spectral bandwidths, i.e. 80 GHz and 540 MHz, similar high visibilities have been measured. All the obtained entanglement measurement results and other pertinent figures of merit are summarized in table 1.

6. Conclusion
We have implemented a remarkably versatile experiment for the production of polarization entangled photons. The versatility concerns both the created state and the spectral properties of the photons. In other words, taking advantage of an advanced fibre optical transcriber connected to a highly efficient waveguide generator, we can create any pure polarization entangled state. Depending on the application, by adapting the phase-matching condition and the filter, the single-photon wavelength can be tuned over more than 100 nm and the associated spectral bandwidth chosen over more than five orders of magnitude. We have also achieved remarkable normalized source brightnesses which stand among the highest ever reported for narrowband entangled photon pairs [15–20]. Analysing the maximally entangled state \(|\Phi^−\rangle\), the Bell inequalities have been violated by more than 40 standard deviations for three exemplary filters, i.e. 80 GHz, 540 MHz and 25 MHz.

Table 1. Summary of the entanglement measurements carried out with the source setup of figure 1. The main results are given as a function of the considered spectral bandwidth, and without any correction for noise contributions (raw); V_{raw}: the two-photon interference pattern visibility obtained in a standard Bell inequality test setup; \(\chi^2\) (\%) \(\chi^2\) : the fidelity to the closest maximally entangled state \(|\Phi^−\rangle\); S_{raw}: the corresponding Bell parameter [2], calculated as introduced by Clauser et al [3]. Note that the brightness (B) unit corresponds to the number of pairs of photons coupled in a single-mode fibre, normalized per second, mW of pump power and MHz of spectral bandwidth.

| Bandwidth (MHz) | 80 × 10^3 \(\alpha\) | 540\(\beta\) | 25\(\delta\) |
|-----------------|-----------------|-----------------|-----------------|
| τ_{phot} (ns)   | 5.5 × 10^{-3}   | 0.8             | 15.6            |
| Pump power\(d\) (mW) | 0.02           | 0.4             | 7               |
| \(\chi^2\) (\%)\(b\) | 5 × 10^{-5}   | 2 × 10^{-3}        | 2 × 10^{-2}        |
| Detected pair rate (s^{-1}) | 2000         | 50              | 6               |
| B ((s mW MHz)^{-1}) | 960           | 300             | 380             |
| V_{raw} (%)      | 99.6 ± 1.3     | 97.1 ± 0.9      | 99 ± 3          |
| S_{raw}          | 2.82 ± 0.01    | 2.80 ± 0.02     | 2.82 ± 0.02     |

\(\alpha, \beta, \delta\): For these two configurations, two indium–gallium–arsenide free-running avalanche photodiodes have been employed as single-photon detectors (SPDs) [33].
\(d\): For this configuration, two super-conducting SPDs have been employed to reduce accidental coincidence events [33].
\(b\): τ_{phot}: single-photon coherence time.
\(\delta\): The pump powers are measured in front of the waveguide generator.
\(\beta\): \(\chi^2\) = \(\frac{2}{\eta^2}\) : mean number of pairs per coherence time.

We believe that such a versatile and high-performance realization represents an ideal candidate for the implementation of fundamental quantum optics experiments, as shown in [6], as well as various quantum network scenarios, ranging from dense division multiplexing QKD (80 GHz–1 THz) to heralded optical quantum memories (10 MHz–1 GHz) [10]. In the latter framework, our source is already suitable for connection with future ion or atom based quantum storage devices operating directly at telecom wavelengths. With current quantum storage devices operating below 900 nm, a coherent wavelength adaptation, in and out of the memories, can be addressed by means of nonlinear optical frequency conversion [34, 35, 25].

Acknowledgments
The authors thank V D’Auria, A Kastberg, L Labonté, M P De Micheli and D B Ostrowsky for their help, as well as ID Quantique, Scontel, AOS GmbH, Teraxion and OLI (Topica Photonics) for technical support. Financial support from the CNRS, the ANR ‘e-QUANET’ project (grant ANR-09-BLAN-0333-01), the European ICT-2009.8.0 FET open project ‘QUANTIP’ (grant 244026), the Ministère de l’Enseignement Supérieur et de la Recherche (MESR), the Délégation Générale pour l’Armement (DGA), the Conseil Régional PACA and the Majlis Amanah Rakyat (MARA) is acknowledged.
Appendix

A.1. Fibre optical transcriber for the production of maximally and non-maximally entangled states

First consider, at the transcriber input, the diagonally polarized bi-photon state $|\psi\rangle_{in} = |D\rangle_1 \otimes |D\rangle_2 = \frac{1}{\sqrt{2}} (|H\rangle_1 + |V\rangle_1) \otimes \frac{1}{\sqrt{2}} (|H\rangle_2 + |V\rangle_2)$, where $|D\rangle_i$ represents the diagonal polarization state and the subscripts $[1,2]$. Two photons that can differ in wavelength and/or in emission time. After the transcriber, the state reads $|\psi\rangle_{out} = \frac{1}{\sqrt{2}} (|H\rangle_1 + e^{i\phi_1} |V\rangle_1) \otimes \frac{1}{\sqrt{2}} (|H\rangle_2 + e^{i\phi_2} |V\rangle_2)$, where $e$ and $l$ denote early and late temporal modes, respectively, separated by $\delta t$ with a relative phase difference $\phi_i, i \in [1,2]$. From the experimental side, separating the paired photons at a beam-splitter and recording coincidence counts between two detectors leads to the histogram of figure 3. The operation principle of the transcriber is similar to that of energy-time entanglement [7]. On one hand, $\delta t$ is required to be much greater than the coherence time of the single photons ($\tau_{coh}$) to prevent temporal overlap between pairs projected onto parallel ($|H\rangle_1 + |e^{i\phi_1} |V\rangle_1$) and ($|V\rangle_1 |H\rangle_2 + |V\rangle_1 |H\rangle_2$) and orthogonal ($|H\rangle_1 |H\rangle_2$ and $|V\rangle_1 |H\rangle_2$) states. On the other hand, the coherence time of the incident pairs ($\tau_{coh}$) has to be substantially greater than $\delta t$ to allow interference between early and late two-photon contributions in the central peak of figure 3. Post-selecting these central peak events reduces $|\psi\rangle_{out}$ to the maximally entangled state $|\Phi(\phi)\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1 |H\rangle_2 + e^{i\phi} |V\rangle_1 |V\rangle_2)$, where $\phi = \phi_1 + \phi_2$.

This scheme can be generalized when considering, at the transcriber input, a two-qubit product state of the form $|\psi\rangle_{in} = (a_1 |H\rangle_1 + b_1 |V\rangle_1) \otimes (a_2 |H\rangle_2 + b_2 |V\rangle_2)$, where $|a_i|^2 + |b_i|^2 = 1$. In this case, appropriate post-selection projects the state onto $|\psi\rangle_{out} = \alpha (|H\rangle_1 |H\rangle_2 + b e^{i\phi} |V\rangle_1 |V\rangle_2)$, where $\alpha = \frac{\sqrt{|a_1|^2 + |b_1|^2}}{\sqrt{|b_2|^2 + |b_2|^2}}$ and $\beta = \sqrt{|a_2|^2 + |b_2|^2}$. Consequently, this scheme permits the creation of any pure bi-photon polarization entangled state, expressed as superpositions of $|\Phi^+\rangle$ and $|\Phi^-\rangle$ Bell states. Note that in our case, the three parameters $\alpha, \beta$ and $\phi$ are accessible experimentally, namely by controlling the input state and fine tuning of the phase set in the transcriber. Furthermore, rotating the polarization of one photon by $\pi/2$ (using an additional half-wave plate) after the transcriber, and suitably choosing $\phi$ between 0 and $\pi$, allows the creation of superpositions of $|\Psi^+\rangle$ and $|\Psi^-\rangle$ Bell states.

A.2. Phase stabilization of the transcriber and manipulation of the entangled state

Violation of the Bell inequalities requires the coherence, i.e., the phase relation $\phi$ between the two contributions to the entangled state, to be stable during the full measurement [32]. Phase fluctuations mainly come from temperature fluctuations in the long arm of the transcriber. For 18 m path length difference, we have $\Delta \phi / \Delta T \approx 10^5$ rad K$^{-1}$. Stabilizing the phase via temperature control only would require sub-mK temperature stability, which is technically challenging, especially for long-term measurements. In contrast to former transcriber-like realizations [26, 27] that have relied, at most, on temperature stabilization, we actively stabilize the optical length of the retardation line using a 50 kHz feedback loop system. It comprises a piezoelectric transducer (PZT) fibre stretcher in the long arm to compensate for drifts, and a telecom reference laser to constantly monitor the phase. The laser is actively frequency stabilized with respect to the frequency of the pump laser using a frequency doubling stage followed by a transfer cavity locking scheme. A fraction of this laser light is sent to the transcriber in the backward direction compared to that of the paired photons. With such a stabilization system, the phase in the transcriber can be set on demand to any desired value, and further reconfigured in a very fast (>1 kHz) and accurate ($\Delta \phi < \frac{\pi}{100}$) manner.

To demonstrate our capability to both control and accurately tune the phase $\phi$ set in the transcriber, Alice and Bob fix their respective half-wave plates (HWPs, see figure 1) at 22.5$^\circ$ to project the entangled state in the phase sensitive diagonal basis $|D,A\rangle$. For this particular measurement, indium–gallium–arsenide (InGaAs) single-photon detectors are employed. Tuning of $\phi$ is achieved by changing the optical path length of the long arm of the transcriber using the PZT. As shown in figure A.1, we obtain, as a function of $\phi$, interference patterns in the net coincidence rates for the three filters employed. Here, ‘net’ indicates that accidental coincidence events associated with the dark-counts in the InGaAs detectors have been subtracted.

The related visibilities are 99.9 ± 1.2, 99.4 ± 1.5 and 97 ± 2% for 80 GHz, 540 MHz and 25 MHz, respectively. The corresponding raw visibilities are 99.9 ± 1.2, 97.1 ± 1.2 and 88 ± 2%. Note that the latter raw values are only limited by the noise in the InGaAs detectors employed (see section A.4). These pertinent results underline the high phase stability ($\Delta \phi < \frac{\pi}{100}$) achieved with the transcriber apparatus, even for long-term measurements.

Furthermore, as outlined in section A.1, the accurate phase control achieved enables switching from the $|\Phi^+\rangle (\phi = 0)$ to the $|\Phi^-\rangle (\phi = \pi)$ Bell state (see figure A.1), or
the creation of any superposition of these two states, with switching speeds of more than 1 kHz.

Finally, note that such a high stability would permit increase of the PM fibre length from 18 m to \( \sim 90 \) m and, therefore, manipulation of single photons down to \( \sim 5 \) MHz of spectral bandwidth while maintaining high-quality entanglement.

A.3. Phase-shifted fibre Bragg grating filters

Phase-shifted fibre Bragg gratings (PS-FBGs) are fibre equivalents to bulk optical cavities. Usually, they are fabricated by inserting a \( \pi \) phase-shift defect in the middle of a fibre Bragg mirror. Compared to bulk optical cavities, PS-FBG filters are easy to implement since both frequency stability (\( \lesssim 1 \) MHz) and accurate tunability (\( \Delta v / \Delta T \approx 200 \text{ MHz K}^{-1} \)) are achieved using basic temperature control. However, narrowband PS-FBGs cannot be applied directly to polarization entangled photons, as fibre birefringence would associate polarization states with transmitted wavelengths and reduce, as a consequence, the entanglement purity. To avoid this effect, we place the filtering stage right after the PPLN/W, i.e. where both photons have the same polarization state (\( |V\rangle_1 |V\rangle_2 \)). Using a fibre polarization controller (PC\(_1\)), the bi-photon state is oriented along one of the filter’s fibre axes, such that the two photons experience the same filtering behaviour.

In our experiment, we utilize two different PS-FBGs centred at 1560 nm, one featuring 58% transmission and 540 MHz bandwidth (AOS GmbH) and the other 72% transmission and 25 MHz bandwidth (Teraxion).

In the case of non-degenerate photon-pair emission, a filtering stage involving two PS-FBGs, arranged in a dual channel configuration thanks to two standard WDMs, would be necessary. Note that no further phase stabilization would be required for this arrangement, since it would be placed before the paired photons are subjected to the transcriber.

A.4. The single-photon detectors (SPDs) employed

For the measurements displayed in figures 3 and A.1, Alice and Bob each employ a free-running indium–gallium–arsenide (InGaAs, IDQ-220) avalanche photodiode as single-photon detector (SPD). Each detector features 20% detection efficiency and \( 10^{-6} \text{ ns}^{-1} \) probability of dark-count. Such a level of dark-count is reasonably low for recording the data of the experiments associated with figures 3 and A.1, which are considered as preliminary characterizations. They are also suitable for measuring the quality of the produced entanglement when considering single-photon bandwidths of 80 GHz and 540 MHz, which require relatively short integration times for entanglement post-selection as the coincidence peaks are narrow (see figure 3). However, utilization of the 25 MHz bandwidth filter requires considerably longer integration times, thus increasing the probability of detecting a dark-count. This strongly reduces the signal to noise ratio. To circumvent this problem for the entanglement measurement displayed in figure 4, the two InGaAs SPDs are advantageously replaced by two super-conducting devices (Sontel TCOPRS-001). Compared to InGaAs SPDs, their figures of merit are a reduced detection efficiency of 7% but a much lower dark-count probability of \( 10^{-6} \text{ ns}^{-1} \). A review article on state-of-the-art SPD techniques in the framework of optical quantum information applications, reporting the advantages and disadvantages of each system depending on the operation wavelength, has recently been published [33].

References

[1] Einstein A, Podolsky B and Rosen N 1935 Can quantum-mechanical description of physical reality be considered complete? Phys. Rev. 47 777–80
[2] Bell J S 1964 On the Einstein–Podolsky–Rosen paradox Physics 1 195–200
[3] Clauser J F, Horne M A, Shimony A and Holt R A 1969 Proposed experiment to test local hidden-variable theories Phys. Rev. Lett. 23 880–4
[4] Aspect A, Grangier P and Roger G 1982 Experimental realization of Einstein–Podolsky–Rosen–Bohm gedankenexperiment: a new violation of Bell’s inequalities Phys. Rev. Lett. 49 91–4
[5] Peruzzo A, Shadbolt P, Brunner N, Popescu S and O’Brien J L 2012 A quantum delayed-choice experiment Science 338 634–7
[6] Kaiser F, Coudreau T, Milman P, Ostrowsky D B and Tittel W 2009 Optical quantum communication Quantum Inform. Comput. 1 3–56
[7] Tittel W and Weihs G 2001 Photonic entanglement for fundamental tests and quantum communication Quantum Science 3–56
[8] Scarani V, Bechmann-Pasquinucci H, Cerf N J, Dušek M, Lütkenhaus N and Peev M 2009 The security of practical quantum key distribution Rev. Mod. Phys. 81 1301–50
[9] Aboussouan P, Alibart O, Ostrowsky D B, Baldi P and Tanzilli S 2010 High visibility two-photon interference at a telecom wavelength using picosecond-regime separated sources Phys. Rev. A 81 021801(R) and references therein
[10] Lyovsky A I, Sanders B C and Tittel W 2009 Optical quantum memory Nature Photon. 3 706–14 and references therein
[11] Sangouard N, Simon C, de Riedmatten H and Gisin N 2011 Quantum repeaters based on atomic ensembles and linear optics Rev. Mod. Phys. 83 3–73 and references therein
[12] Lettner M, Mücke M, Riedl S, Vo C, Hahn C, Baur S, Bochmann J, Ritter S, Dürr S and Rempe G 2011 Remote entanglement between a single atom and a Bose–Einstein condensate Phys. Rev. Lett. 106 210503
[13] Kubo Y et al 2010 Strong coupling of a spin ensemble to a superconducting resonator Phys. Rev. Lett. 105 140502
[14] Tanzilli S, Martin A, Kaiser F, De Micheli M P, Alibart O and Ostrowsky D B 2012 On the genesis and evolution of integrated quantum optics Laser Photon. Rev. 6 140502
[15] Kuślewicz C E, Wong F N C and Shapiro J H 2006 Time-bin-modulated biphotons from cavity-enhanced down-conversion Phys. Rev. Lett. 97 223601
[16] Palacios A, Beveratos A, Thew R T, Jorel C, Zbinden H and Tittel W 2009 Optical quantum memory Nature Photon. 3 706–14 and references therein
[17] Sangouard N, Simon C, de Riedmatten H and Gisin N 2011 Quantum repeaters based on atomic ensembles and linear optics Rev. Mod. Phys. 83 3–73 and references therein
[18] Lettner M, Mücke M, Riedl S, Vo C, Hahn C, Baur S, Bochmann J, Ritter S, Dürr S and Rempe G 2011 Remote entanglement between a single atom and a Bose–Einstein condensate Phys. Rev. Lett. 106 210503
[19] Tanzilli S, Martin A, Kaiser F, De Micheli M P, Alibart O and Ostrowsky D B 2012 On the genesis and evolution of integrated quantum optics Laser Photon. Rev. 6 140502
[20] Kuślewicz C E, Wong F N C and Shapiro J H 2006 Time-bin-modulated biphotons from cavity-enhanced down-conversion Phys. Rev. Lett. 97 223601
[21] Palacios A, Beveratos A, Thew R T, Jorel C, Zbinden H and Tittel W 2009 Optical quantum memory Nature Photon. 3 706–14 and references therein
[22] Sangouard N, Simon C, de Riedmatten H and Gisin N 2011 Quantum repeaters based on atomic ensembles and linear optics Rev. Mod. Phys. 83 3–73 and references therein
[19] Yan H, Zhang S, Chen J F, Loy M M T, Wong G K L and Du S 2011 Generation of narrow-band hyperentangled nondegenerate paired photons Phys. Rev. Lett. 106 033601 and references therein

[20] Kaiser F, Issautier A, Ngah L A, Dănilă H, Herrmann O, Sohler W, Martin A and Tanzilli S 2012 High-quality polarization entanglement state preparation and manipulation in standard telecommunication channels New J. Phys. 14 085015

[21] Yoshino K-I et al 2012 High-speed wavelength-division multiplexing quantum key distribution system Opt. Lett. 37 223–5

[22] Fulconis J, Alibart O, O’Brien J L, Wadsworth W J and Rarity J G 2007 Nonclassical interference and entanglement generation using a photonic crystal fiber pair photon source Phys. Rev. Lett. 99 120501

[23] Medic M, Altepeter J B, Hall M A, Patel M and Kumar P 2010 Fiber-based telecommunication-band source of degenerate entangled photons Opt. Lett. 35 802–4

[24] Dousse A, Suffczynski J, Beveratos A, Krebs O, Lemaitre A, Sagnes I, Bloch J, Voisin P and Senellart P 2010 Ultrabright source of entangled photon pairs Nature 466 217–20

[25] Dudin Y O, Radnaev A G, Zhao R, Blumoff J Z, Kennedy T A B and Kuzmich A 2010 Entanglement of light-shift compensated atomic spin waves with telecom light Phys. Rev. Lett. 105 260502

[26] Ribordy G, Brendel J, Gautier J-D, Gisin N and Zbinden H 2000 Long-distance entanglement-based quantum key distribution Phys. Rev. A 63 012309

[27] Sanaka K, Kawahara K and Kuga T 2002 Experimental probabilistic manipulation of down-converted photon pairs using unbalanced interferometers Phys. Rev. A 66 040301

[28] Reim K F, Nunn J, Lorenz V O, Sussman B J, Lee K C, Langford N K, Jaksh D and Walmsley I A 2010 Towards high-speed optical quantum memories Nature Photon. 4 218–21

[29] Saglamyurek E, Sinclair N, Jin J, Slater J A, Oblak D, Bussieres F, George M, Ricken R, Sohler W and Titili W 2011 Broadband waveguide quantum memory for entangled photons Nature 469 512–5

[30] Tanji H, Ghosh S, Simon J, Bloom B and Vuletić V 2009 Heralded single-magnon quantum memory for photon polarization states Phys. Rev. Lett. 103 043601

[31] Clausen C, Usmani I, Bussieres F, Sangouard N, Afzelius M, de Riedmatten H and Gisin N 2011 Quantum storage of photonic entanglement in a crystal Nature 469 508–11

[32] Martin A, Smirr J-L, Kaiser F, Diamanti E, Issautier A, Alibart O, Frey R, Zaquine I and Tanzilli S 2012 Analysis of elliptically polarized maximally entangled states for Bell inequality tests Laser Phys. 22 1105–12

[33] Hadfield R H 2007 Single-photon detectors for optical quantum information applications Nature Photon. 1 696–705

[34] Tanzilli S, Titili W, Halder M, Alibart O, Baldi P, Gisin N and Zbinden H 2005 A photonic quantum information interface Nature 437 116–20

[35] Curtz N, Thew R, Simon C, Gisin N and Zbinden H 2010 Coherent frequency-down-conversion interface for quantum repeaters Opt. Express 18 22099–104