Polarisation entanglement engineering at telecom wavelength using guided-wave optics

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We report on the association of a guided-wave optics scheme and an integrated optical photon pair generator for obtaining high-quality photonic polarization entangled states at a telecom wavelength, especially suitable for narrow bandwidth photons.

Today's optical telecommunication networks are mostly built using high-reliability fibre and integrated optical components, enabling data rates on the order of several Tbits/s for single fibre lines. Although such high data rates seem currently unreachable with novel quantum information based applications, for which nowadays rates are rather on the order of several Mbits/s and per ITU channel [2], quantum cryptography can offer security levels unattainable with classical means [1].

Quantum networks mainly rely on sources of either single or entangled pairs of photons. The former ones require typically a small experimental apparatus, but the associated security is based on the assumption that the user's locations are not under control of a potential spy. On the contrary, entanglement based quantum applications could offer device-independent security, at the price of justifiable additional expenses.

In this framework, polarisation entanglement is probably the easiest-to-handle observable, thanks to interferometer-free quantum state analysis. Several telecom polarisation entanglement sources have already been reported, mainly relying on type-II non linear spontaneous parametric down-conversion (SPDC), either in bulk or waveguide crystals [3]. However, in order to guarantee high-quality entanglement, perfect indistinguishability of the created photons needs to be ensured for the temporal, spatial, and spectral observables. In addition, the type-II interaction is relatively weak, such that high pump laser powers might be required, especially when ultra-narrow bandwidth photons are to be used for compatibility with optical quantum memory devices (<1 GHz of absorption bandwidth) [4, 5].

In the following, we apply a polarisation entanglement engineering scheme to a type-0 SPDC photon pair generator from which no polarisation entanglement is initially available. The scheme could be further extended to purify entanglement from type-II sources for which perfect control on all parameters is not possible.

EXPERIMENTAL IMPLEMENTATION

The experimental apparatus is shown in FIG. 1. A 780 nm pump laser is actively stabilised against a ^{87}Rb hyperfine transition to achieve a coherence time of about 3 μs. The laser is then coupled via a single mode fibre into a 4.5 cm long periodically poled lithium niobate waveguide (PPLN/W). The channel waveguide was realised

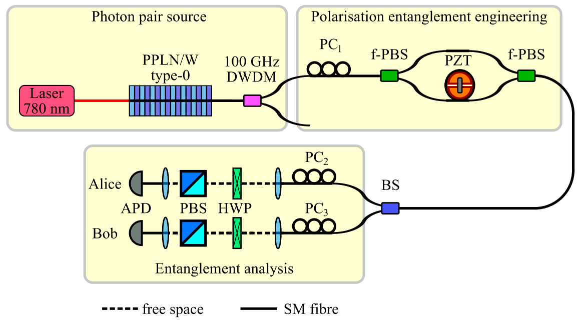

FIG. 1. Experimental setup for polarisation entanglement engineering for photon pairs out of a the type-0 waveguide generator. A 100 GHz DWDM is used for spectral filtering. After the pairs are separated at a beam splitter (BS), the entanglement quality is measured using standard Bell inequality apparatus. Half wave-plate (HWP); polarising beam splitter (PBS); avalanche photodiode (APD).

using the so-called proton exchange technique. This allows exploiting the highest non linear SPDC coefficient (d_{33}) of the crystal, and utilising the type-0 interaction ($V_{\text{pump}} \mapsto V_1 V_2$, the subscripts 1 and 2 describing the two photons). The down-conversion probability of our sample is on the order of 10^{-5} pairs per coupled pump photon. The sample's temperature is stabilised around 387 K so as to reach the desired quasi phase-matching condition, *i.e.* wavelength degenerate paired photons at 1560 nm. In order to make our system compatible with telecom networks at the output of the waveguide, the photons are first collected using a standard single mode fibre, and their natural emission bandwidth ≈ 20 nm $\leftrightarrow$ 2.5 THz) is reduced using a 100 GHz telecom DWDM.

At this stage, the paired photons' polarization state reads $|V\rangle_1|V\rangle_2$, which is clearly a product state although the photons are naturally energy-time entangled. To engineer polarization entanglement on these photons, their states are first rotated diagonal, $|D\rangle_1|D\rangle_2$, using a fibre polarisation controller (PC_1). Then, they are sent to a 7.5 m unbalanced Mach-Zehnder interferometer like birefringent delay line made of two fibre polarising beam splitters (f-PBS) at both its input and output. In this configuration, the $|H\rangle$ component of each photon is delayed by 32 ns compared to the $|V\rangle$ coun-

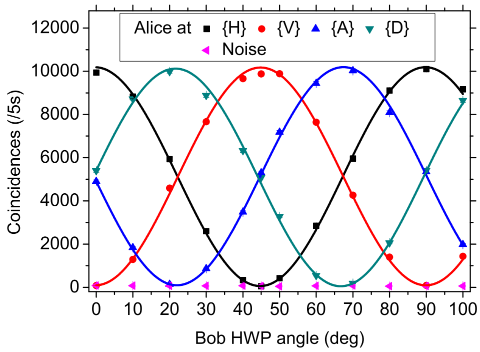

FIG. 2. Two-photon interference patterns for the four standard analysis settings, $\{H;\, V;\, A;\, D\}$, on Alice's side, while Bob's analyser is rotated. Near-unit visibilities underline the high quality entanglement obtained with our setup.

terpart. Polarisation entanglement of the form $|\Phi(\phi)\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 + e^{i\,\phi}|V\rangle_1|V\rangle_2\right)$ is then generated by post selection of photon pairs detected simultaneously. The phase factor ϕ arises from the different path lengths for the two contributions to the entangled state. In order to obtain high-quality entanglement, the photon pair creation time has to be more uncertain than the temporal separation provided by the delay line [6]. This is guaranteed by both the long coherence time of our stabilised laser and the spontaneous character of the photon pair emission. Violating the so-called Bell inequalities further requires ϕ to be constant during the two-photon interference measurement. This is achieved by a home-made stabilisation system comprising a reference laser and a piezo fibre stretcher (PZT) in the delay line (see FIG. 1). The paired photons are then separated using a fibre beam splitter (BS) and sent to standard polarisation analysers at Alice's and Bob's sides. By properly adjusting ϕ with the PZT, we establish the maximally entangled state $|\Phi(0)\rangle$ and proceed to the violation of the Bell inequalities. As shown in FIG. 2, we obtain, for the four standard measurement settings $\{H;\, V;\, A;\, D\}$, raw (net) two-photon interference visibilities exceeding 97±1% (99±1%). This clearly underlines the high quality entanglement achieved with our guided-wave strategy.

CONCLUSION

We have demonstrated a way to engineer polarisation entanglement from initially energy-time entangled paired photon. To do so, a fully fibred birefringent delay line was used and associated with a high-brilliance, wavelength degenerate, type-0 integrated waveguide photon pair generator operating at 1560 nm. We emphasize that this scheme could also be applied in a more general perspective, namely with initial photon pair states that could be subjected to instabilities in the spectral and/or temporal domains. Due to the strong separation of the $|H\rangle$ and $|V\rangle$ components in the delay line (32 ns), this strategy makes it possible to handle single photon bandwidths down to ∼100 MHz [7]. Such narrow bandwidths are of utmost interest for long distance communication protocols based on quantum memories [4, 5].

Moreover, our source delivers near-perfect polarisation entangled pairs of photons at a detected coincidence rate of around 2 kBit/s in a single ITU channel at a pump power of a few tens of μW. Here, the main limitation concerns the rather low maximum detection rates of the employed free-running InGaAs-APDs (IDQuantique id220). This could be circumvented by using high-speed superconducting or frequency up-conversion detectors, with which considerably higher detected coincidence rates should be attainable. In this scope, we calculated that the maximal entangled photon pair rate at the output of this source could reach 1 Mpairs/s, for a pump power of 2 mW, before entanglement quality is degraded by the contribution of double pair emission.

We stress that the association of standard telecom components with a high-brilliance integrated optical biphoton generator, as utilised in this work, is a promising route towards enabling future quantum applications, especially those involving quantum memory devices [4, 5].

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