Demonstration of GHz Sequential Time-bin Entanglement distribution in a Metropolitan Fiber Network

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Abstract *Entanglement is arguably one of the most important resources in the field of quantum information, with key applications in quantum communication and computing. Here, we report on the distribution of GHz sequential time-bin entanglement in a 30km fiber link by using off-the-shelf components.*

Introduction

The increasing ability of generating quantum states of light has led in the last 20 years to an impetuous development in the field of quantum information. Nowadays, generating high quality and high-rate entanglement has been proven to be pivotal for many applications, in particular for quantum communication and computing [1,2]. Remarkably, this has been recently highlighted by the 2022 Physics Nobel award given to A. Zeilinger, A. Aspect and J. F. Clauser "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

Entangled photons have been generated exploiting different degrees of freedom, such as: polarization, path-entanglement, energy-time (time-bin in the case of pulsed lasers) and angular momentum [3]. Polarization degree of freedom has been often used due to the ease to manipulate the polarization state with standard linear components [4]. However, the intrinsic fiber birefringence poses challenges in the distribution of polarization entangled photons by scrambling their polarization state. Time-bin entanglement has recently attracted attention for long-distance quantum communication via optical fibers, being the entanglement robust against random polarization fluctuations [5]. However, time-bin entanglement demonstrations are typically based on complicated interferometric set-ups, often requiring non-trivial home-made implementations [6].

In this work, we demonstrate a GHz rate entangled photon source using off-the-shelf components. Time-bin entanglement is measured after passing a 30km (9.5dB loss) fiber link in the city of Vienna. By properly compensating the fiber dispersion, a corrected quantum visibility as high as 93% was measured, without any spectral filtering.

Experimental set-up

The experimental set-up employed to generate and measure sequential time-bin entanglement is sketched in Fig.1. The pump source is a continuous wave (CW) distributed feedback (DFB) butterfly laser. The central wavelength is at 1554.13nm, which can be finely tuned as a function of the temperature and current. The laser is externally modulated by a commercial optical pulse generator (ModBox Pulse from Photline Technologies). It consists of an integrated LiNbO3 Mach-Zehnder modulator which is driven by an internal generator with a pulse frequency tunable in the range (1-2.5) GHz and a pulse duration of 150ps. After the pulse generator, the output power is around 0.3 mW which is then amplified by two cascaded EDFAs.

By means of a free-space second harmonic generation (SHG) set-up, the pump frequency is doubled to generate a visible GHz pump beam. The SHG nonlinear crystal is a 5mm long MgO doped periodically poled LiNbO3 (ppLN, Covesion). It has 9 periodically poled gratings, two of them achieving quasi-phase matching at different crystal temperatures. The unconverted telecom pump light is rejected by means of 2 short-pass filters (FESH850 and FESH800 from Thorlabs), providing a total rejection higher than 100dB at 1554nm and 0.12dB insertion loss at 777nm. After optimization, the in-coupler power at 777nm is as high as 20mW.

Photon-pairs at telecom wavelengths are then generated via Spontaneous Parametric Down Conversion process (SPDC). For entanglement-based applications, having photon pairs with high purity (low spectral correlations) is of paramount importance [3]. Owing to the different material properties, periodically poled potassium titanyl phosphate (ppKTP) intrinsically generates photon pairs with higher purity than ppLN at

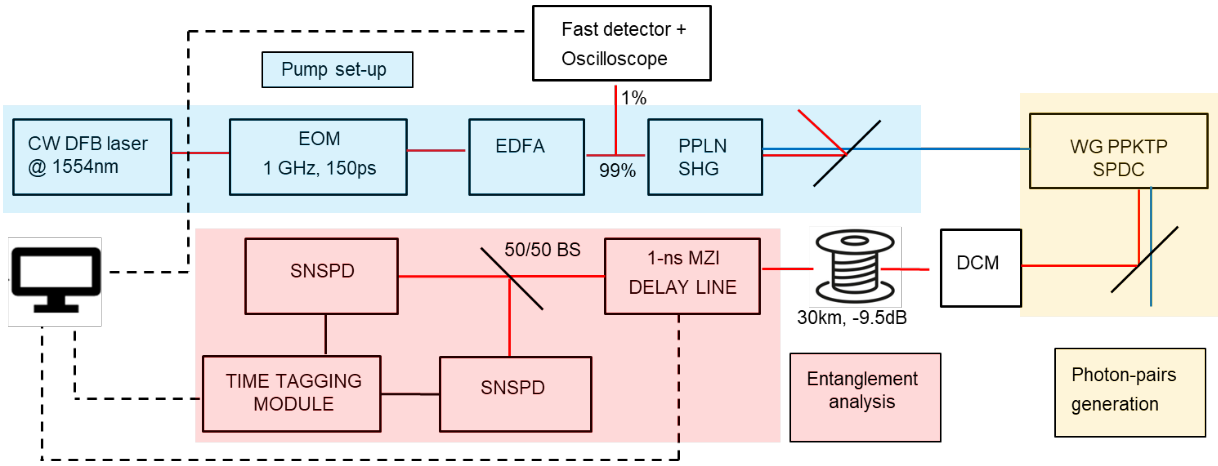

Fig. 1: Experimental set-up used to generate and measure sequential time-bin entangled photons.

telecom wavelengths [7]. In addition to the optical material properties, the spectral purity depends also on the pulse duration and the length from the crystal. We modelled the SPDC process with the software QPMOptics, developed by AIT, designed to investigate the properties of SPDC generated photon pairs [8].

According to the modelling outcome, a SPDC type-II (o -> o + e) pigtailed waveguide-based ppKTP (AdvR) was purchased. The length of the crystal is 10mm and it is characterized by a SPDC efficiency of 1.84*10^-9, corresponding to 7.2 MHz/mW generated power. The input and output coupling efficiency are about 50%. Due to the intrinsically low efficiency of SPDC, it is crucial to properly filter out the visible pump power left in the 1550nm output fiber. This is easily accomplished by just cascading two optical isolators for telecom wavelengths. They have a total insertion loss of 1.24dB at 1550nm and achieve a rejection in the visible of more than 120dB. The spectrum of the generated photons was measured using an optical spectrum analyser (OSA) coupled to an external SPAD. As expected, the spectrum is centred around the SPDC degenerate wavelength of about 1554nm, twice the visible pump wavelength due to energy conservation. The FWHM bandwidth is about 3.4nm, close to the modelling performed with QPMOptics. The generation probability per pulse for an average input power of 0.5mW is 0.18%, well below the 10% threshold for minimizing the contribution of multi pairs in the emitted photon pairs [3]. The fidelity of the generated quantum state is indeed generally reduced by the presence of the higher order terms since the additional photon-pairs are not entangled with each other.

A fiber link connecting the Austrian Institute of Technology (AIT) and the University of Vienna (Univie) was set up in the city of Vienna for distributing the SPDC photons. The fiber link has a total length of 30km with an insertion loss of 9.5dB. A 30km dispersion compensating module (DCM-30-LGX) is placed before the fiber link, with 2.9dB insertion loss. The pump set-up and SPDC crystal are located at AIT. Superconducting Nanowire Single Photon Detectors (SNSPDs) and a commercial 1-ns Mach-Zehnder interferometer (MZI) delay line (Kylia Mint 1GHz) are located at Univie. The detection efficiency of the SNSPDs (Photon Spot) is 80%, with a jitter of about 150-200ps.

Sequential time-bin entanglement

The idea of sequential time-bin entanglement is to pump a nonlinear crystal with two consecutive pump pulses [9]. The coherence time of the pump laser should be longer than the time interval between the two pulses, so that the relative phase is stable. To characterise the entanglement, the photon pairs must pass through imbalanced interferometers with a path-length difference matched with the laser's periodicity.

A telecom commercial Mach-Zehnder interferometer (MZI) delay line is employed for analysing the time-bin entanglement. It has 1.7dB insertion loss and it is polarization independent, which, when operated with photon pairs based on a type-II SPDC source, is a crucial feature, being signal and idler orthogonally polarized. Classical interference of the 1GHz modulated DFB laser showed excellent results, with a visibility of 99.77%.

By injecting the SPDC photons into the MZI delay line and post-selecting only the coincidence in the

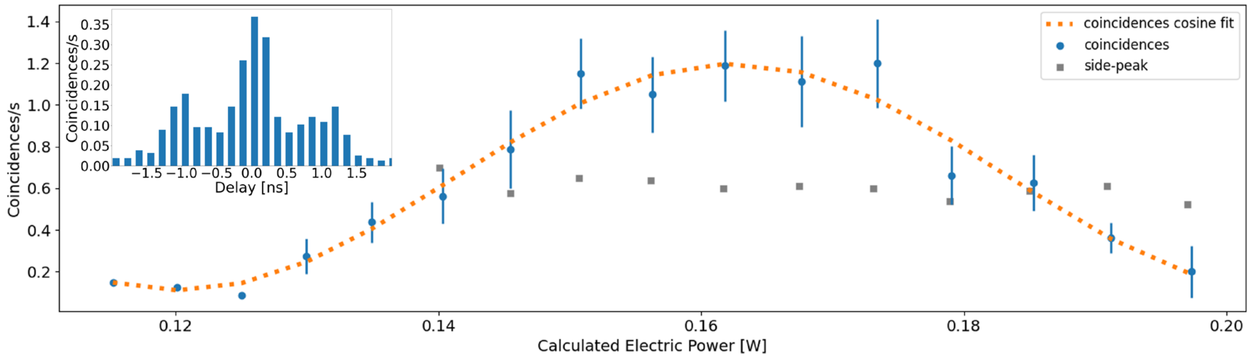

Fig. 2: Coincidence counts in the central (blue points) and side histogram peaks (grey scatters) as a function of the phase variation of the Mach-Zehnder interferometer. The MZI phase is proportional to the dissipated electric power. The coincidences of the central peak are well fitted by a cosine function (orange dashed curve). In the inset, an exemplary time-bin coincidence histogram is reported, showing that the dispersion is well compensated, and the 3 time-bin peaks are clearly visible.

central peak, two photon quantum interference can be observed by tuning the phase of the interferometer. This is enough for certifying entanglement [10]. In Fig. 2 sequential time-bin entanglement is experimentally demonstrated after propagation through 30km fiber link. Coincidences are reported as a function of the interferometer phase, which is proportional to the dissipated electric power from the power supply. The blue points represent the coincidences in the central peak (with error bars) which are well fitted by a cosine fit (orange dashed curve) as expected from the theory [9,10]. The grey scatters represent the coincidences of one satellite peak as a function of the phase difference, which, as expected, are constant within the experimental error. As it can be seen in the inset of Fig.2, the dispersion compensation is effective and the typical 3 peaks of the time-bin entanglement measurement are visible and well defined. The voltage step size of the programmable power supply used to drive the MZI delay line was chosen such to acquire enough experimental points, but at the same time keep the measurement time reasonably low. The measurement is automatized, thanks to a self-written python program changing the voltage and subsequently acquiring the coincidences with the time tagging module. For each voltage setting, coincidences are integrated over one minute, after 5 minutes waiting time to ensure thermal stabilization in the MZI delay line. The full measurement takes typically about 2 hours. The coincidence window is set to 400ps (estimated combined detection unit jitter). The corrected visibility is 93% (raw visibility of 90%).

The high quantum visibility obtained clearly demonstrates high degree of entanglement, well above the CHSH-limit of 71% [3]. The obtained visibility is also larger than the 81% threshold, which indicates the minimum visibility needed to obtain a positive secure key rate [11]. The obtained results thus indicate the possibility of using the presented GHz entangled photon source for entanglement based QKD experiments. We remark the fact that such high quantum visibility is obtained without any spectral filtering of the SPDC bandwidth. The quantum visibility could be further increased by spectral filtering at the cost of reducing the brightness.

Conclusions

In this work we have demonstrated high quality sequential time-bin entanglement after propagation through a 30km fiber link. This has been achieved by using off-the-shelf components with the goal of facilitating a quick development of a deployment-ready source of photonic entanglement.

We stress that, up to our knowledge, this is the first time that a commercial user-friendly MZI delay-line is used for a quantum application, showing excellent results. Provided suitable dispersion compensation and low jitter in detection, the source can be easily scaled to higher repetition rates.

Given the excellent quantum visibility of 93% obtained in a metropolitan fiber link scenario, the developed entangled photon source is suitable for entanglement based QKD with the addition of another MZI delay line.

Future works will also investigate the possibility of integrating the entangled photon source and the Mach-Zehnder delay line on chip.

Acknowledgements

This work was supported by the Austrian FFG Agency (FAQT project, grant n° 884456). We wish to thank the laboratory support of Franziska Divkovic and Thomas Helmel. We also wish to thank Lee Rozema and Michael Antesberger for the support with operating the superconducting nanowires.

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