QuComm *IST-1999-10033*

Long Distance Photonic Quantum Communication

QuComm Deliverable D19

Dissemination level: Public

DELIVERABLE D19 (REPORT)

Entangled State Teleportation

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ABSTRACT

Quantum teleportation strikingly underlines the peculiar features of the quantum world as it allows the transfer of the quantum state from one system to another distant one. The most interesting case of quantum teleportation occurs when the teleported state itself is entangled. This means that what is really teleported is not the state of one system but the way that system relates to the other one it is entangled with. This procedure is also known as "Entanglement Swapping" [ZZHE93]. Here we present two experimental realizations of entanglement swapping recently proposed in the scope of QuComm. The achievements presented here are the first implementation of an advanced, more-complete BSM for the entanglement swapping of polarisation entanglement (EXPVIE), and different steps towards the realization of entanglement swapping with time-bin entangled qubits at telecom wavelength (GAP).

Report Version: 1
Report Preparation Date: 2002-12-20
Classification: Public

Project funded by the European Community under the "Information Society Technologies" Programme (1998-2002)

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INTRODUCTION

Quantum teleportation [BBC+93] is a means to communicate quantum information independently of the physical realization of the very qubit that we want to send. Quantum teleportation crucially depends on two components: entanglement and Bell-state analysis. Entanglement is the quantum physical notion that describes inseparable states of separate systems. Bell-state analysis refers to the ability to analyse the state of two particles in a basis of entangled states. In this paper we discuss the teleportation of an entangled state, which is called entanglement swapping [ZZHE93], and is considered the most generall test of teleportation. The concept of entanglement swapping is highly interesting, as it allows the development of quantum networks (Fig. 1), where entanglement may be arbitrarily distributed between several qubits or communication partners.

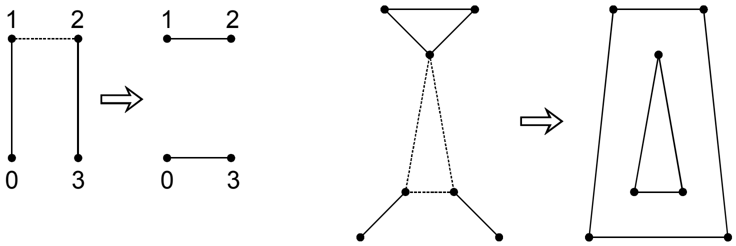

Figure 1: Entanglement swapping in the most basic case (left) and in a generalized case (right). The dashed lines represent entangled state projection measurements, whereas the solid lines mean the presence of entanglement between the connected dots.

The left part of Fig. 1 shows directly a teleportation of an entangled state, i.e. entanglement swapping. In the schematic, particle 1 can be thought of as being teleported onto particle 3. Consequently the entanglement between 0 and 1 is transferred to entanglement between 0 and 3. The quality of the final entanglement between 0 and 3 as compared to the quality of the initial entanglement between 0 and 1 is just the fidelity of the teleportation. Entanglement swapping is the essential ingredient for establishing long-distance links in quantum communication [BDCZ98], where it can be used to establish entanglement between observer stations separated by larger distances than those which is possible to cover by using links with individual pairs only. Because of this close link between teleportation and entanglement swapping we will use both terms in the following to describe our work.

The most important measure of quality of entanglement is established by Bell's inequality. It provides a boundary between classical and nonclassical behaviour. Once a correlation measurement breaks this limit it cannot be explained by a local realistic theory.

BELL'S INEQUALITY

Bell's inequality [Bel64] is a statement about possible correlations in predictions of local realistic theories. As quantum physics predicts very strong nonlocal correlations for entangled systems Bell's inequality allows to decide experimentally whether quantum physics or local realism is ruling nature. Up to now nearly all experiments were in favour of quantum physics. With the advent of quantum information Bell's inequality, previously of mostly philosophical interest, became a tool for the quantification of quantum behaviour and separability. Therefore it is now omnipresent in quantum information physics, although its role in comparison with other measures is not completely clear [HHH96].

A widely used form is the CHSH form [CHSH69] that states that the so-called Bell parameter

$$S = |E(a,b) - E(a,b')| + |E(a',b) + E(a',b')|$$

should always have a value less than 2 for local realistic theories. Quantum physics, however, predicts a value of $2\sqrt{2}$ for suitably chosen measurements on a maximally entangled two-particle system. The quantity $E(a,b)$ is the correlation of a polarization measurement in direction a on one particle and in direction b on the other one, where the individual measurements can take place arbitrarily far apart.

TECHNOLOGY OF ENTANGLEMENT SWAPPING EXPERIMENTS WITH PHOTONS

The subsequent considerations on entanglement swapping experiments are based on a set-up as shown in Fig. 2 which is realized with entangled photon pairs produced in parametric down-conversion. The Bell-state analysis (measurement) is presently performed via the interference of photons in linear optical systems, which allows the detection of Bell-states with 50% efficiency at best. Bell-state analysis with linear optical elements is based on Hong-Ou-Mandel interferometry [HOM87]. Just as in any other interferometer it is the mutual coherence of the interfering processes – or the indistinguishability – that governs the achievable visibility apart from imperfection of the components and the like. In our case one wants to interfere photons that are components of two independently created pairs.

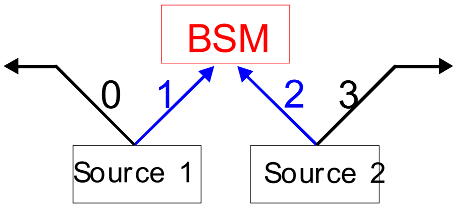

Figure 2 Schematic of the entanglement swapping or teleportation of entanglement experiment. Two pairs of particles are created in sources 1 and 2. Particle 1 is teleported over to particle 3, whereby the entanglement between particles 0 and 1 is transferred to entanglement between particles 0 and 3. The Bell-state measurement (BSM) is a projective measurement in an entangled state (Bell-) basis. In our photonic case the BSM is done interferometrically.

The achievements presented here (D19) is the implementation of an advanced, more-complete BSM for the entanglement swapping of polarisation entanglement (EXPVIE), and the different steps towards entanglement swapping with time-bin entangled qubits (GAP).

ENTANGLEMENT SWAPPING EXPERIMENTS BASED ON POLARIZATION-CODED QUBITS

The work on entanglement swapping performed at EXPVIE within WP4 is based on polarization coded photons as the qubits, which was also used in several previous experiments on teleportation. So far, all previous experiments on teleportation and entanglement swapping used a Bell-state analyzer only capable of identifying one of the four Bell-states. Here we present an experimental demonstration of more-complete entanglement swapping, which uses an extended Bell-state analyzer, capable of detecting two of the four Bell-states.

ENTANGLEMENT SWAPPING SETUP

A schematic drawing of the entanglement swapping setup is shown in Figure 3. The system was based on two entangled photon pairs produced by type-II parametric down conversion in a BBO crystal. The down conversion was pumped by femtosecond UV-laser pulses, which travel through the crystal in opposite directions in order to produce two separate photon pairs in opposite directions. Through spectral filtering with a FWHM of 3.5 nm for photons 0 and 3 and FWHM of 1 nm for photons 1 and 2, the coherence time of the photons was made longer than the pulse width of the UV-laser, making the two entangled photon pairs indistinguishable in time, a necessary criterion for performing operations with photons from independent down conversions. All photons were collected in single-mode optical fibers for further analysis and detection. Single-mode fibers offer the high benefit that the photons can be guided, yet remain in a perfectly defined spatial mode allowing high fidelity interference. For performing the Bell-state analysis, photons 1 and 2 interfered at a fiber beam splitter, where one arm contained a polarization controller for compensating the polarization rotation introduced by the optical fibers. In order to optimize the temporal overlap between photon 1 and 2 at the beam splitter the UV-mirror was mounted on a motorized translation stage. Photons 0 and 3 were sent to Bob's two-channel polarizing beam splitters for analysis. These arms each contained polarization controllers to set the angles of polarization measurements as required. All photons were detected with silicon avalanche photo diodes, with a detection efficiency of about 40%. The logic circuit detectes coincidences between detectors D1H, D1V, D2H and D2V for determining the Bell-state of photons 1 and 2, and also the coincidences between D0+,D0-, D3+ and D3- for measuring the correlation between photons 0 and 3. It is essential, that the detection events of photons 0 and 3 are orederd into subsets, corresponding to the two possible Bell-state. Later it can be determined whether the detection events of photons 0 and 3 violate Bell's inequality. A photo of the experimental Setup is shown in Figure 5.

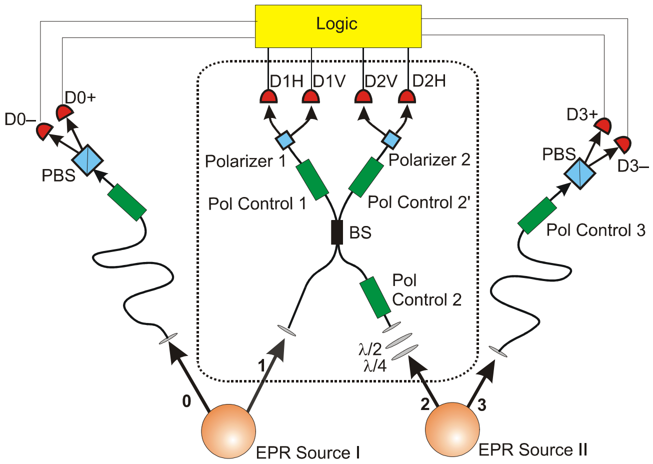

Figure 3: Experimental scheme of more-complete Entanglement swapping. The Bell-state analyzer shown here is the more-complete version.

BELL-STATE ANALYSIS WITH LINEAR OPTICS

It has been shown that using linear optical elements the efficiency of any BSA is limited to maximally 50% [CaL01]. In the case of the usual four Bell-states for the entanglement of two qubits, at best two of the four Bell-states can be identified with certainty. A configuration for detecting polarization entangled states is to have two photons 1 and 2 brought to interference at a 50:50 beam splitter, as illustrated in Figure 4. This scheme is able to exactly identify two Bell-states, and the remaining two only together, as demonstrated in [MWKZ96]. Particularly easy to identify is the antisymmetric state $\left|\psi^{-}\right\rangle$, as only in this case the two photons can be detected in separate outputs of the beam splitter, and a measurement of their polarization is not necessary. In the $\left|\psi^{+}\right\rangle$ case, the photons will take the same output of the beam splitter, however they will still have orthogonal polarizations in the **H**,**V**-Basis. This case is identified with additional polarizing beam splitters placed in the outputs of the beam-splitter, and the two interfering photons will be found in the separate outputs of the polarizer.

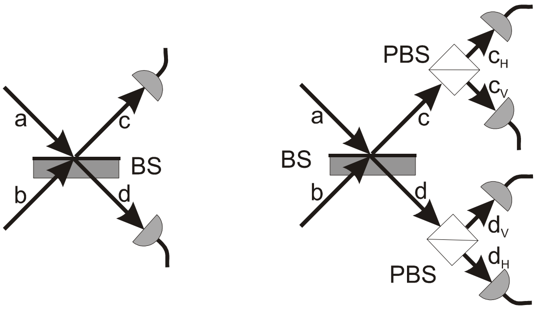

Figure 4 Bell-State analysis for polarization entanglement. The simple Bell-state measurement (left) consist of a beam splitter BS. The two photons enter the BS via modes a and b

respectively, and emerge from the BS via modes c and d. Only when the two input photons are entangled in a $\left|\psi^-\right\rangle$ *state, will they take the separate ouput modes, and consequently lead to a coincdence detection in the two detectors. The more-complete Bell-state measurement (right) runs as follows: when a photon is detected in either output arm of the beam splitter, and in opposite outputs of the polarizers PBS, then a* $\left|\psi^-\right\rangle$ *Bell-state was observed (either detectors* c_H *and* d_V *fire, or* c_V *and* d_H*). If two photons are detected in the same output arm, however in different outputs of the polarizer, then a* $\left|\psi^+\right\rangle$ *Bell-state was observed (either* c_H *and* c_V *fire, or* d_H *and* d_V*).*

FIBER BASED BELL-STATE ANALYSIS

As is mentioned in D18, several considerations regarding the fidelity of teleportation experiments have led to the realization of a fiber based Bell-state analyzer. The schematic shown in Fig. 4 was implemented fully with fiber optic components which made polarization control necessary in every arm. The big advantage of using fiber optic components instead of free space optics is that different photon modes perfectly overlap due to the confinement of the optical field in the fibers.

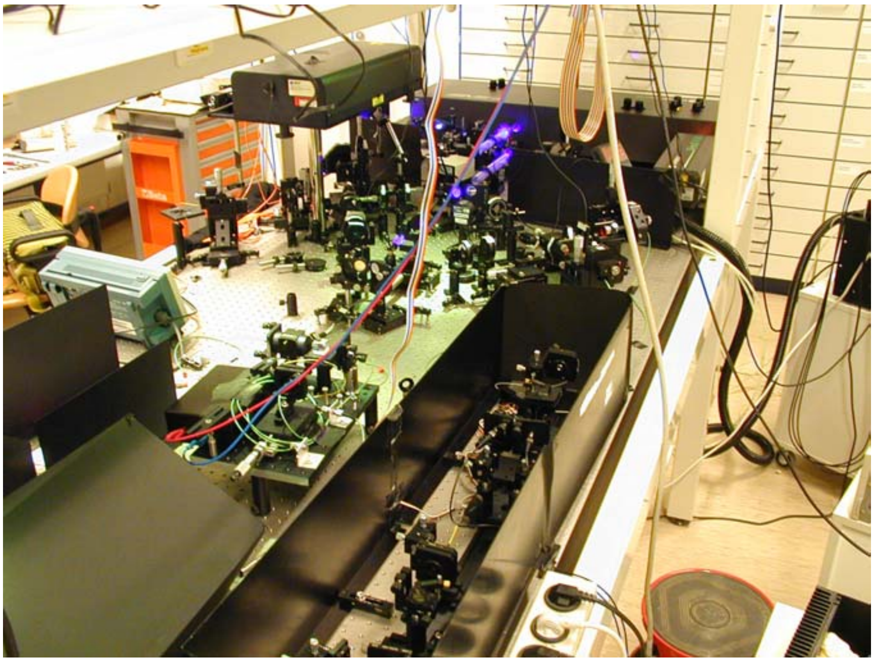

Figure 5 Photograph of the entanglement-swapping experiment. In the foreground one can see the polarization measurements of photons 0 and 3. In the center, Alice's Bell-state analyser rests in an elevated box above the table. At the head of the table sits the frequency doubled Ti:Sapphire laser system.

RESULTS FOR ENTANGLEMENT SWAPPING BASED ON THE SIMPLE BELL-STATE ANALYZER

This experiment was performed earlier with the simple Bell-state analyzer, and was already explained in D18. However, the entanglement swapping experiment based on a simple Bell-state analyzer, Figure 4(left) showed high fidelity of the Bell-state analysis. The following table summarizes the experimental correlation data $E(a,b)$ as measured for particles 0 and 3:

	0°	45°
22.5°	– 0.628 ± 0.046	– 0 .541 ± 0.045
67.5°	+ 0.677 ± 0.042	– 0 .575 ± 0.047

These numbers lead to **S = 2.421 ± 0.091,** more than four standard deviations above the local realistic limit, and show a clear violation of Bell's inequality. D18 contains more details on this measurement as well as a general fidelity measurement. We would like to note, that an article about this work appeared in PRL in the beginning of 2002 [JPWZ02].

RESULTS FOR MORE-COMPLETE ENTANGLEMENT SWAPPING

The entanglement swapping experiment was extended with the more-complete Bell-state analyzer, as shown in Fig. 4 (right) by including extra polarizing beam splitters in the ouputs of the normal beam splitter. The scheme of the setup is shown in Figure 3. Since this is accomplished via fibre optic components, this extension of the system was clear-cut. However, the extra required polarization controllers significantly increased the time necessary for alignment of the system, and also lowered the system stability.

To show the function of the more-complete entanglement swapping, a scan measurement was performed with the polarization analyzers for photons 0 and 3 set at 45°. The observed correlation is shown in Figure 6, and shows a high fidelity of the entanglement, well above the limit required for violating Bell's inequality.

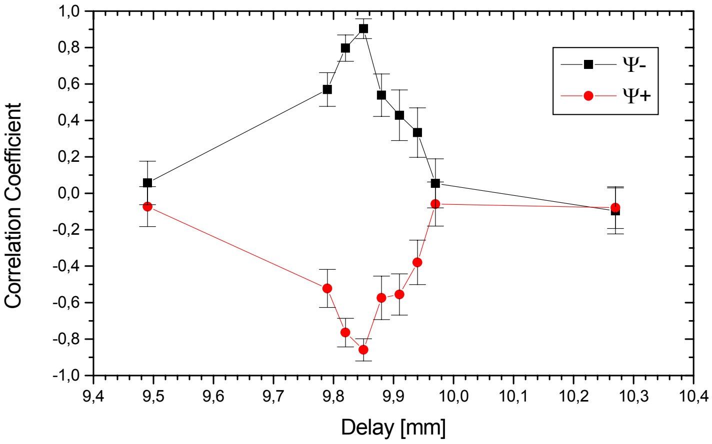

Figure 6: Correlation measurement of the entangled photons 0 and 3 after entanglement swapping, for analyzers both at 45°. The delay is scanned by a motorized mirror, and represents the timing offset between the two photons interfering in the beam splitter. Depening on the observed state for the Bell-measurement on photons 1 and 2 (Psi- or Psi+), the correlation between photon 0 and 3 is either Psi- or Psi+. These data are taken in a single run of the experiments.

The measurements required for violation of the CHSH inequality were performed at the same time for the $\left|\psi^-\right\rangle$ and $\left|\psi^+\right\rangle$ case, and the observed correlation values are shown in Table1. To summarize, the results for the Bell-parameter S is **S=2,60795 ± 0,09251** for the $\left|\psi^-\right\rangle$ state, and **S=2,30233 ± 0,08958** for the $\left|\psi^+\right\rangle$ state, which represents a clear violation of the Bell-inequality limit of **S≤2**. This proves, that the Bell-measurement performed on photons 1 and 2 can decide which kind of entanglemen the independent photons 0 and 3 will show.

	0°	45°
67.5°	-0,80286 ± 0,04217 -0,60118 ± 0,03979	0,64136 ± 0,05126 -0,48203 ± 0,04636
22.5°	0,61061 ± 0,04358 0,55343 ± 0,04169	0,55312 ± 0,04747 -0,66569 ± 0,05054

Table 1: Correlation measurements for the"more-complete" entanglement swapping. The parameters of the columns and rows are the setting of polarizer 0 and 3 respectively. The correlation value in the top half of the cell is for the $\left|\psi^-\right\rangle$ case for photons 1 and 2, and in the lower half of the $\left|\psi^+\right\rangle$ case of photons 1 and 2. The two correlation values were always measured in the same measurement run.

INDEPENDENCE OF THE PHOTONS

One might question the ``independence" of photons 1 and 2 which interfere in the BSA, since all photons are produced by down conversion from one and the same UV-laser pulse, and the photons could take on a phase coherence from the UV laser. It should be noted, that the UV mirror was placed 13 cm behind the crystal, which greatly exceeds the pump pulse width of 60 micron. We investigated the influence of a phase relation between the photons by performing a Mach-Zehnder interference measurement of a laser on the BSM to measure the relative phase drifts due to instabilities of the optical paths. The statistical analysis of the temporal phase variation was done using the Allan variance [Allan87], which we suggest as an appropriate measure, Figure 7. Accordingly, the phase drifted in a random walk behavior accumulated a 1-sigma statistical drift of one wavelength within 400 s, and had a maximum drift of 15 wavelengths during 10 h. In a single measurement which lasted 16000 seconds, any (hypothetical) phase relation between the two photons that interfered in the BSA would have been washed out completely. Therefore the contribution of such a phase relation to the outcome of the experiments can be ruled out.

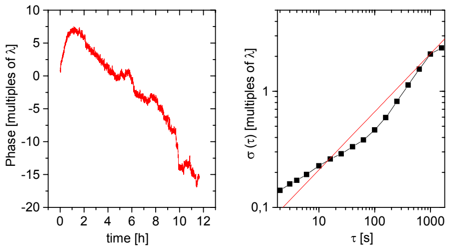

Figure 7: (Left) Relative phase drift of the inputs of the Bell-state Analyzer over time. The phase is measured in multiples of the wavelength (788 nm). (Right) Root-Allan-variance analysis of the phase drift. The positive slope of the variance indicates random-walk noise. Accordingly, a drift of 1-wavelenght ocurrs after about 400 s, which is considerably faster than the measurement time of 16000 s. This means, that any phase information of the photons would be washed out during the measurement time.

EXTENDING ENTANGLEMENT SWAPPING TO TIME-BIN ENTANGLED QUBITS

P05 (GAP) proposed a scheme using time-bin entangled qubits, i.e photon pairs created in a coherent superposition of two emission times. This type of entanglement is well suited for transmission over long distance in optical fibres, since it is not sensitive to polarisation fluctuations and to polarisation mode dispersion, unavoidable in optical fibres. Robustness over 11 km has been demonstrated [RTT+02]. In the GAP scheme, the two entangled pairs are at telecom wavelength and are created in two spatially separated source.

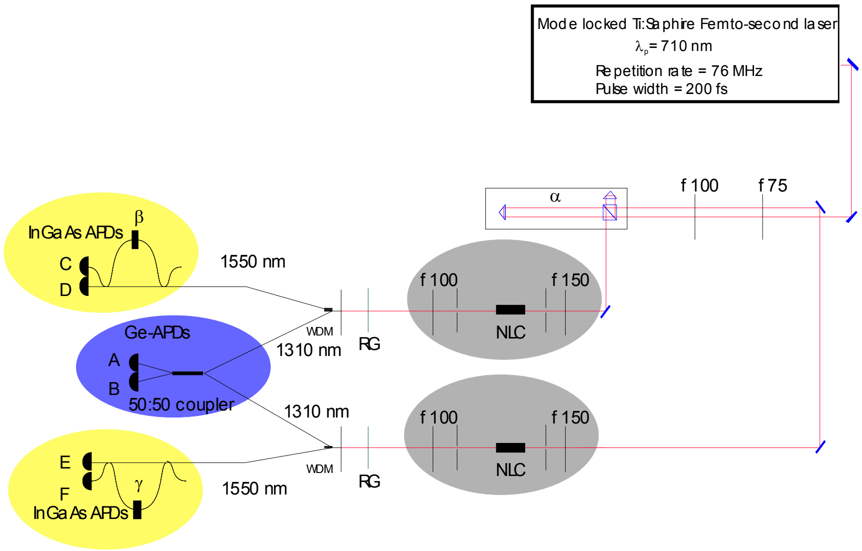

Figure 8 Proposed experimental setup to implement entanglement swapping with time-bin entangled qubits created in spatially separated sources.A short pulse emitted by a Ti:Saphire fs laser is split into two subsequent pulses by means of a folded Mach-Zehnder Interferometer. Each output then pumps a non-linear crystal (NLC), generating time bin entangled qubits at wavelengths of 1310 and 1550 nm, respectively. The photons forming a pair are separated using a wavelength demultiplexer (WDM), and the two lower wavelength photons are subjected to Bell measurement by means of a 50:50 fibre coupler. To confirm that the two 1550 nm photons indeed get entangled, they are subjected to a Franson-type test of Bell inequalities using two equally balanced Mach-Zehnder Interferometers.

The proposed experimental configuration to implement entanglement swapping with time-bin entangled qubits is shown in Figure 8. The setup uses a bulk interferometer inserted before the crystals, in order to create time-bin-entangled qubits. The long arm introduces a delay $\Delta\tau$ with respect to the short one.

The Bell measurement takes place on the 50/50 fibre coupler. Projection on the $\left|\psi^-\right\rangle$ Bell state is obtained when detectors A and B click with a time difference $\Delta\tau$, while projection on the $\left|\psi^+\right\rangle$ state is obtained when two photons are detected in mode A or in mode B with a time difference of $\Delta\tau$. The Bell measurement projects the two 1550 nm photons onto an entangled state, which is measured with fibre interferometers.

STEPS TOWARDS ENTANGLEMENT SWAPPING

Time-bin entangled qubits created with femtosecond pulses

Quantum teleportation experiments require ultrashort pump pulses. The quality of femtosecond time bin entanglement has been measured with Franson type Bell tests. Two-photon interferences with visibilities of more than 90% have been observed. This result shows that the entanglement is sufficient to be used in quantum communication protocols. [MRT+02].

Mandel-Dip Interference with photons created in different crystals

An important step towards quantum teleportation and entanglement swapping with spatially separated sources is the observation of quantum interference (Mandel dip) with photons created in different crystals [RMT+02]. For this purpose, two non-degenerate photon pairs (1310&1550 nm) are created at the same time in two different crystals, with femtosecond pulses. The photons of each pair are separated and the two 1310 nm photons are mixed on a 50/50 fibre coupler. We record the coincidence count rates at the two outputs of coupler, as a function of the delay of one photon. If the two photons arrive at the same time at the beam splitter, the coincidence count rate should drop (Mandel dip), because the probability amplitudes of either photons being transmitted or both reflected cancel each other. When we record 3-fold coincidences (two photons at the output of the beam splitter + laser clock) we cannot discard the events where two pairs are created in the same crystal. Due to stimulated emission, the probability of creating two pairs in one of the two crystals is twice as high as the probability of creating one pair in each crystal at the same time. Therefore in this case, the visibility of the dip is limited to 33%. We observe experimentally a visibility of 28%. The way to recover 100% of visibility is to post-select the events where we create one pair per source. This can be done by detecting 4 photons coincidences. When recording 5-fold coincidences (4 photons + laser clock) as a function of the delay of one photon, we observed a dip with a net visibility of 84%. The results are shown in Figure 9.

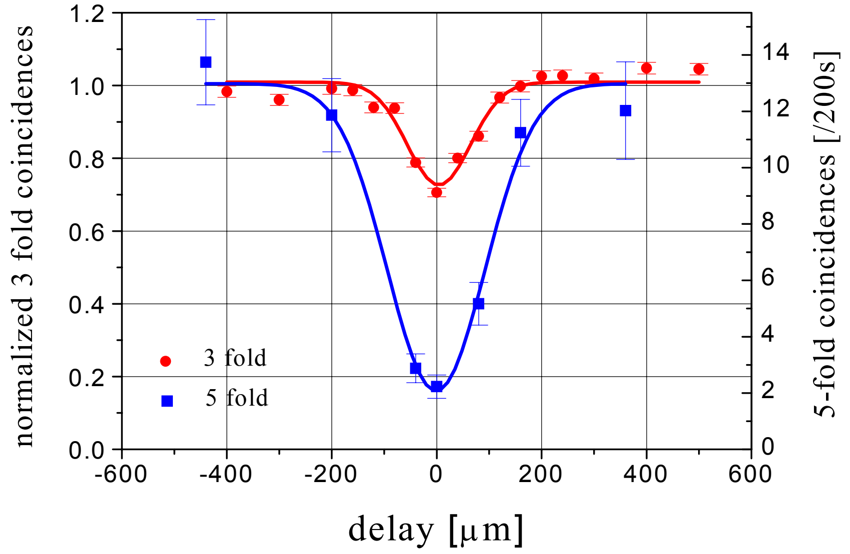

Figure 9: Mandel dip with photons created in different sources. The red points show the 3-fold (2 photons+ laser clock) coincidence count rate as a function of the delay of one photon. The blue points show the 5-fold coincidence count rates (4 photons+laser). The lines are gaussian fits, from which we can infer a visibility of 28% (max theoretical visibility=33%) for the 3-fold and of 84% for the 5-fold coincidences

OUTLOOK

Entanglement swapping is an important procedure in quantum information because it not only allows us to check teleportation but it can also be used to enhance entanglement links via quantum repeater protocols [BDCZ98] and it is at the heart of purification of entangled states. Therefore the work within QuComm has to be extended in three directions.

The more-complete entanglement swapping realized with polarization qubits now can be advanced by including also an unitary operation, realized by actively switched Pockels cell, which will enable us to push the efficiency of teleportation to 50%, the limit for linear optical elements. There is the theorem that with linear optical elements a perfect BSA can not be built [CaL01]. However, Knill *et al.* [KLM00], by giving a nice example have shown explicitly that this does not prohibit scalability, and it is believed that indeed small quantum computers could be built with linear optical elements only. Furthermore, we will investigate concepts of bringing entanglement swapping and purification of entanglement together in order to perform the quantum repeater. We hope to obtain relevant experimental results on active switched teleportation and purification of entanglement at EXPVIE before the end of QuComm.

Concerning the entanglement swapping with time-bin qubits, there are still some technical issues which must be overcome to perform the experiments. All the setup is built, but due to the low quantum efficiencies of detectors at telecom wavelengths, the 4-photons coincidence count rate is presently not high enough to perform the entanglement swapping experiment. An improvement in the setup stability is needed. Nevertheless, by slightly modifying the setup, a successful implementation of quantum teleportation of a time-bin qubit over 2 km of optical fibres between two labs separated by 55m has been carried out [MRT+]. This implied the detection of only 3 photons, leading to an higher coincidence count rate. The results of this experiment will be presented in D23, since it is not an entangled state teleportation.

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