Slovenian Quantum Communication
Infrastructure Demonstration

D4.2 Entanglement source

Status Final
Version 1.0

Due Date 30/6/2024
Submission Date 9/7/2024

Related WP All
Related Deliverables D4.1, D3.1

Document Reference D4.2
Dissemination Level* PU

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Keywords: entangled photons, fidelity, contrast visibility, heralding ratio, coincidence, detector efficiency, tangle, CHSH inequality, bandwidth

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Document History			
Version	Date	Change editors	Changes
0.1	18/6/2024	Lara Ulčakar	Document outline, chapter 1
0.2	21/6/2024	Lara Ulčakar	Setup description in chapter 2 and chapter 3, introduction, conclusions
0.3	3/7/2024	Izidor Benedičič, Adrian Udovičič, Lara Ulčakar	Chapter 2 and chapter 3
0.4	7/7/2024	Lara Ulčakar	Text adaptation after internal review
0.5	8/7/2024	Lara Ulčakar	Text adaptation after internal review
1.0			FINAL VERSION

Quality Control		
Role	Who (Partner short name)	Approval Date
Deliverable leader	Lara Ulčakar (FMF)	3/7/2024
Quality manager	Marjan Kavčič (URSIV)	9/7/2024
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List of Acronyms

Acronym	Description
BBM92	Bennett-Brassard-Mermin 1992 protocol
BS	Beam Splitter
CHSH	Clauser-Horne-Shimony-Holt inequality
DCR	Dark Count Rate
DWDM	Dense-Wavelength-Division-Multiplexing
FMF	Faculty of Mathematics and Physics
IJS	Institute Jožef Stefan
PBS	Polarising Beam Splitter
PM	Polarisation Maintaining
PPLN	Periodically-Poled Lithium Niobate
QKD	Quantum Key Distribution
SNSPD	Superconducting Nanowire Single-Photon Detector
SPDC	Spontaneous Parametric Down Conversion
WP	Work Package

Executive Summary

The document presents the design, implementation and the characterization of the sources of entanglement built at FMF and IJS. Entangled photons are used as quantum states shared among receivers in entanglement-based quantum key distribution (QKD). In the scope of the SiQUID project, two QKD networks based on the entanglement distribution will be deployed. The main network connecting the government offices will use an industrialized version of the entanglement source, while the experimental network connecting research institutions will use sources described in this deliverable. The aim is to construct high-brightness and high-fidelity sources that could be used in long-distance entanglement distribution and demonstration of entanglement swapping. Achieving that will be a crucial step towards achieving large scale quantum networks. The groups at FMF and IJS explored two types of sources: a source utilizing type-2 SPDC, and another using type-0 SPDC. Both sources are based on the same design of the Sagnac interferometer. The theory predicts that type-0 spontaneous parametric down-conversion (SPDC) sources have about 10 times higher spectral brightness and 10 times higher bandwidth than type-2 SPDC (Steinlechner, et al., 2014). This deliverable reports on the measured properties of designed sources, such as fidelity, tangle, heralding ratio, coincidence rate and bandwidth. The results are preliminary and the quality of the sources will be further improved before the deployment of the QKD network.

1 Introduction

1.1 Purpose of the document

The document demonstrates the design and the implementation of the experimental sources of entangled photons on the telecom C-band. In particularly, for the production of photon pairs one source utilizes type-2 phase-matching SPDC, and another source type-0 phase-matching SPDC. The document reports on the properties of the two sources, such as brightness, entanglement quality and fidelity.

1.2 Relation to other Project Work

This document relates to deliverable D4.1, which considers the security of the entanglement-based BBM92 QKD protocol. It also relates to D3.1 that reports on the industrialized source of entangled photons.

1.3 Structure of the document

Following this introductory first chapter, the discussion is grouped as follows:

- Chapter 2 presents the type-2 source. The design, implementation and the characterization of the source's quality are demonstrated.
- Chapter 3 presents the type-0 source. The design, implementation and the characterization of the source's quality are demonstrated.
- Chapter 4 summarizes the main findings.

1.4 Glossary adopted in this document

Entanglement source: a device producing pairs of particles (e.g. photon pairs) in a state that is not separable (into a statistical mixture of simple product states of individual particle states).

Bell states: 4 maximally entangled orthogonal two-photons states.

CHSH inequality: an inequality fulfilled by any local-realistic theory but violated by quantum predictions.

Tangle: a measure of how much two quantum objects are entangled. The maximal value is equal to 1. The minimum value is 0.

Dead time: characteristic of a detector. After the detection of a photon, the detector is blind for a period of time called the dead time.

Coincidence: detection of photons by both recipients such that the times of the detection events lie within a predefined time interval, called the coincidence window.

Heralding ratio: the number of coincidences measured on a pair of detectors, divided by the geometric mean of single counts on each detector,

$$\eta = \frac{\mathrm{N_{coincidences12}}}{\sqrt{\mathrm{N_{singles1}}\mathrm{N_{singles2}}}}$$

Fidelity: a measure quantifying how close a produced quantum state is to the desired state. Maximum value is 1.

Contrast visibility: in a given measurement basis, the contrast visibility is the maximal ratio of the number of expected and the number of unexpected coincidences for the state investigated

$$C = \frac{N_{\text{expected}}}{N_{\text{unexpected}}}$$

Detector efficiency: the probability for successful detection of a photon.

Brightness: detected coincidences per second, normalised to the pump laser power and the bandwidth of the photons detected,

$$B = \frac{N_{\text{coincidences}}}{\Delta t\, \Delta\lambda\, P}$$

Quantum state tomography: the process by which a quantum state is reconstructed using results from a set of measurements in conjugate bases performed on an ensemble of identical quantum states.

2 Type-2 entanglement source

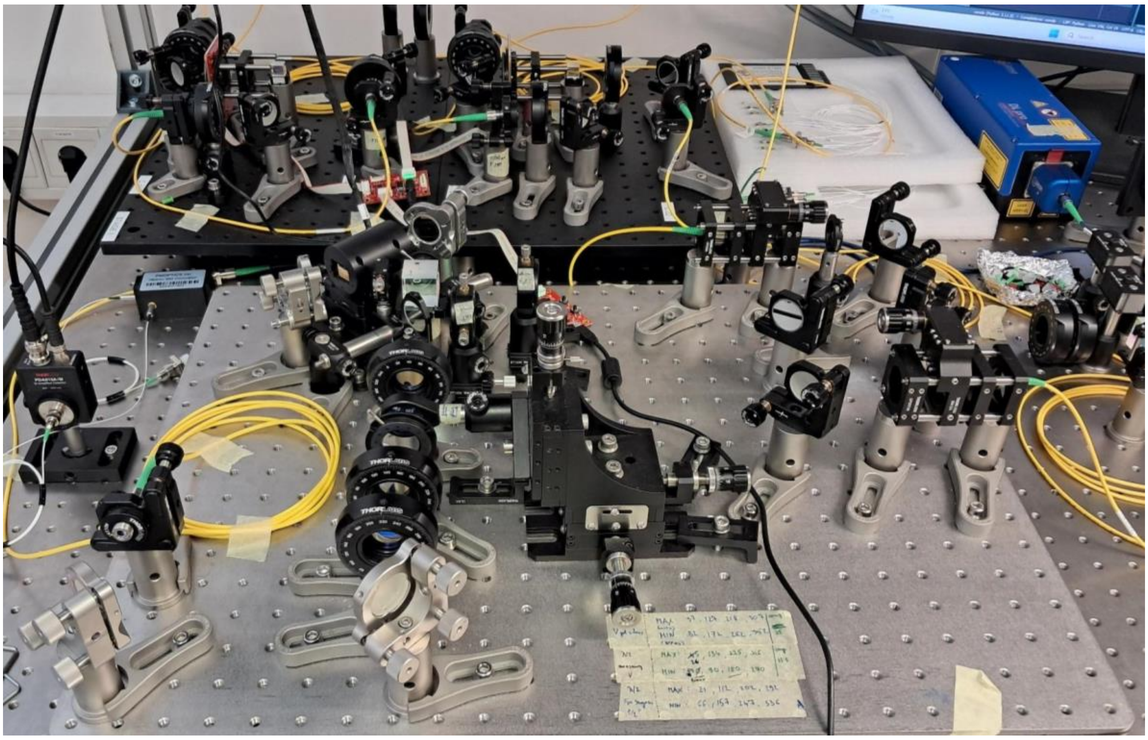

Figure 1: Photo of the optical setup. It consists of a pump laser, a Sagnac source (in front), analysis stages and a DWDM (in the back).

2.1 Design and implementation

A narrow-band continuous-wave (CW) laser with the wavelength of λ = 780 nm is guided through a 50 mm periodically-poled lithium niobate (PPLN) crystal. This laser beam pumps a type-2 SPDC process, which creates pairs of photons at 1560 nm wavelength and about 0.5 nm linewidth (around 100 GHz) and with orthogonal polarisations. The crystal is placed inside an oven which maintains the appropriate phase-matching temperature. The oven with the crystal is placed inside the Sagnac interferometer setup, built according to (Fedrizzi, Herbst,, Poppe, Jennewein, & Zeilinger, 2007). In the interferometer, the laser is split into two counter-propagating modes using the polarizing beam splitter (PBS). An additional λ/2 waveplate is inserted in the interferometer to ensure both beams enter the crystal with the same polarization. These counter-propagating beams generate SPDC photon pairs in the non-linear crystal, and the photon pairs will then travel in opposite directions. Before the photons exit the interferometer, they are again overlapped at the PBS, and the two-photon amplitudes will interfere. As a result, the photons exiting the Sagnac interferometer from the PBS will be entangled in polarization. The target state is the Bell state

$$|\psi_{-}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle).$$

Entangled photons exit the PBS at different outputs and are sent to receivers via optical fibres. In order to reduce the broad spectral background from SPDC, and to better define the wavelength of the entangled photons we want to send via existing fibre networks, we send the entangled photons through a dense-wave-division-multiplexing (DWDM) module. In order to characterize the source, the output of the DWDM is guided to the analysis stage.

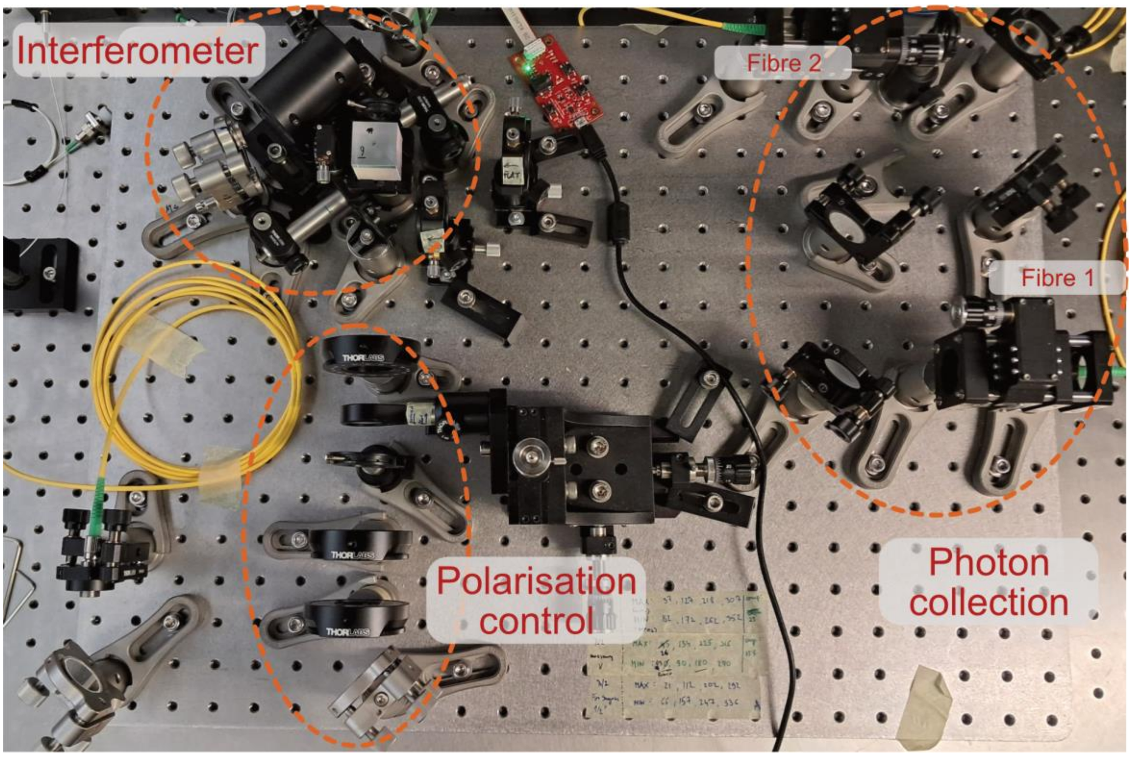

Figure 2: Photo of the entangled photon setup for the type-II source. The pump laser beam enters the optical breadboard via a single-mode fibre on the left. Polarisation control waveplates ensure the correct phase of the generated photon wavefunction.

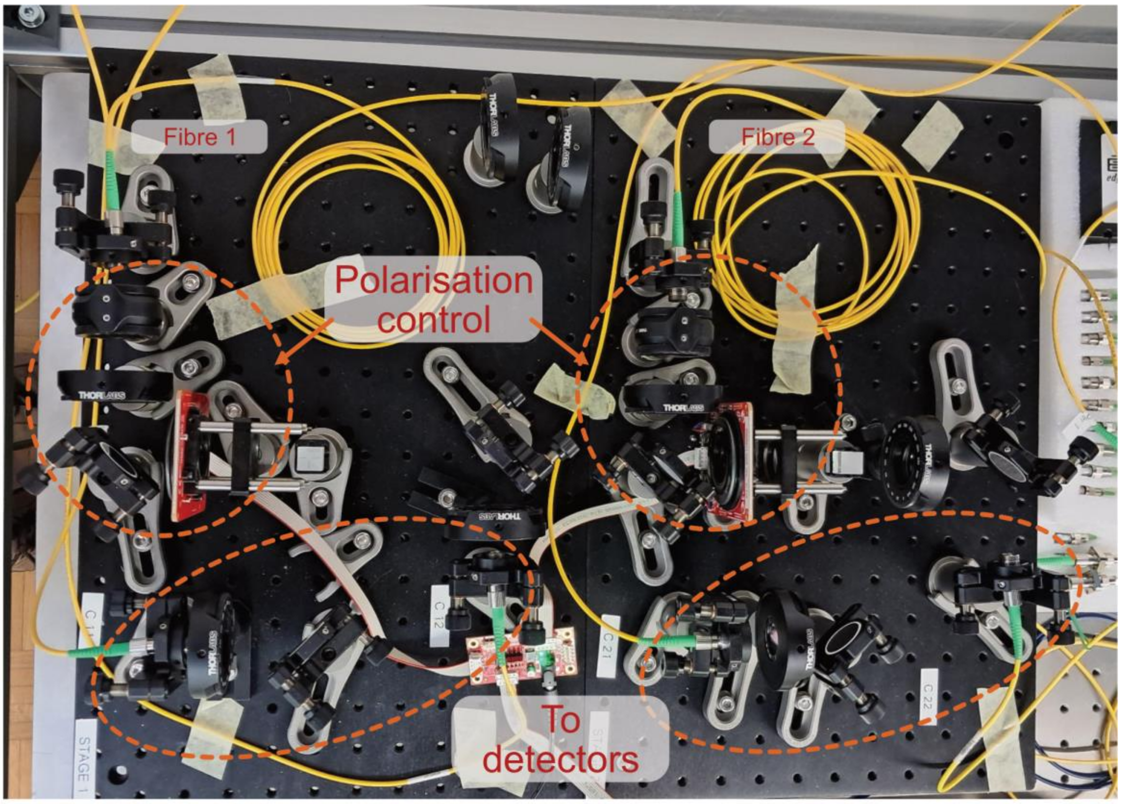

Figure 3: Analysis stages. The photons produced in an SPDC process are guided through a DWDM (right side) with a channel width of 0.8 nm and to a detection stage. The waveplates compensate for polarisation drift in the

fibre and enable measurements in different bases. Each stage has 2 outputs connected via a single-mode fibre to a single-photon detector.

2.2 Characterization

Quantity	Measurement
Pump power	2.7 mW
Detector efficiency	77 - 83 %
Detector type	SNSPD
Number of detectors	4
Dead time	200 ns
Coincidence window	10 ns
Measured coincidences	240/s
Measured singles	3000 - 8000 /s
Heralding ratio	0.05
Brightness	110 cps/mW nm
Tangle	0.927 ± 0.004
Fidelity of the Bell state	0.901 ± 0.001 (with $\|\psi_{-}\rangle$)
CHSH inequality	2.75 ± 0.015
Bandwidth	0.8 nm
Contrast visibility	H/V basis: (89 ± 8) : 1 D/A basis: (74 ± 6) : 1 R/L basis (42 ± 2) : 1

Table 1: Characterization of the type-2 source.

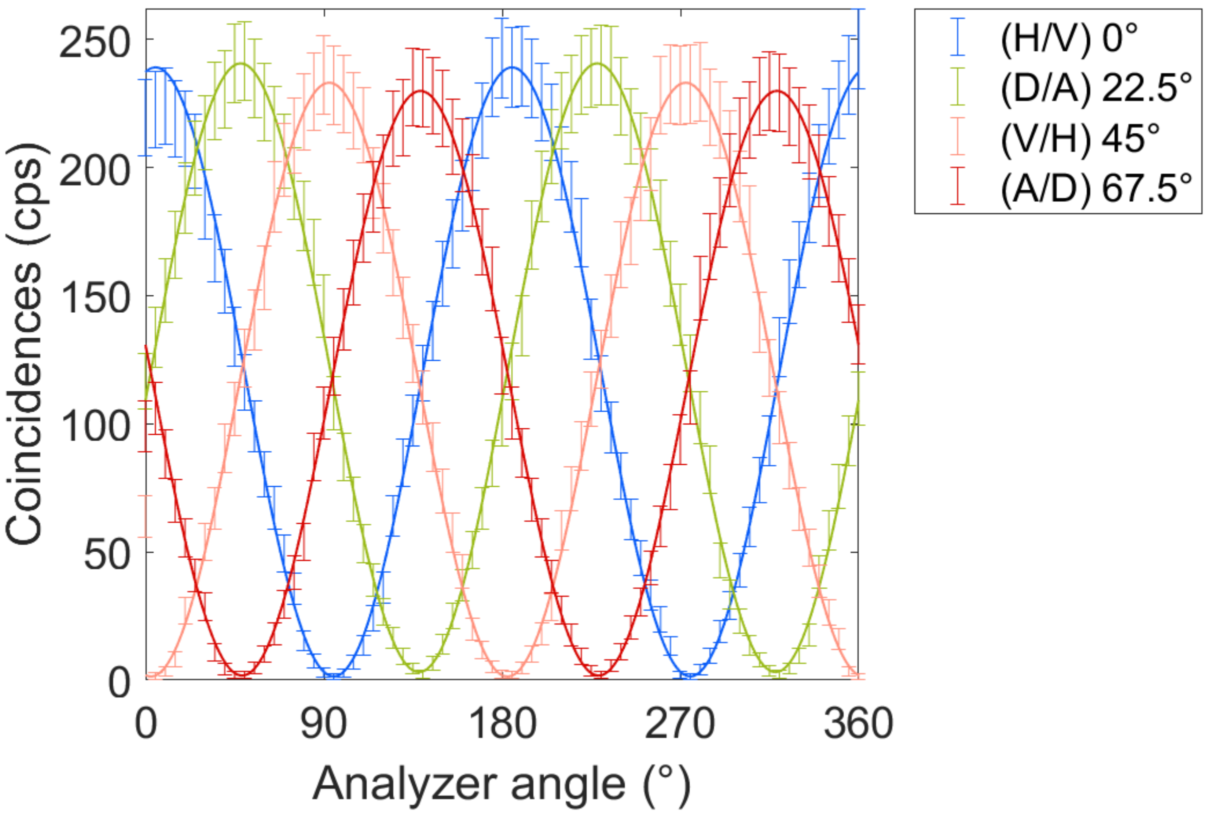

Figure 4: Polarization correlation measurement for the type-2 source. The measurement basis on one analysis stage is set to horizontal/vertical or diagonal/antidiagonal, and the other analysis stage has the linear polarisation rotated by 360 degrees. The violation of CHSH inequality was determined from this measurement.

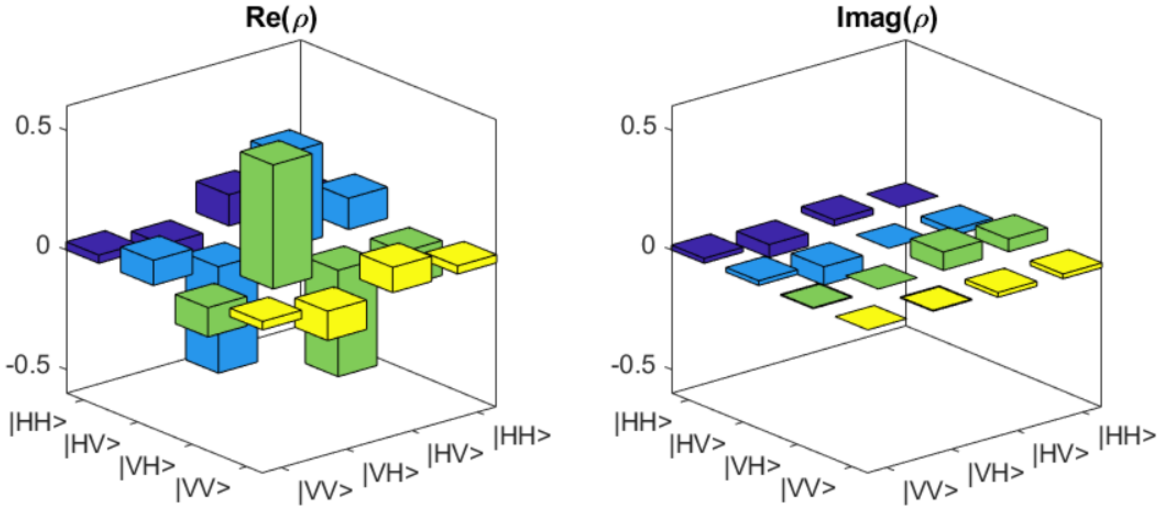

Figure 5: Quantum tomography of the state the type-2 source generates. The density matrix was constructed from 9 linearly independent coincidence measurements using the maximum likelihood method to ensure the density matrix is physical. The high fidelity with state $F(|\psi_-\rangle) = 0.9$, tangle T = 0.927 and purity P = 0.975 indicate the source produces entangled states of high quality. Uncertainty of characterisation values was estimated numerically by adding random noise to the measurement.

3 Type-0 entanglement source

Figure 6: Photo of the optical setup for the type-0 source . It consists of a pump laser (blue fiber on the bottom left), a Type-0 Sagnac source (optical breadboard on the right), analysis stage (on the left) and a DWDM (white box under analysis stage).

3.1 Design and implementation

A narrow-band CW laser at 780.24 nm is guided through a 50 mm periodically-poled lithium niobate (PPLN) crystal. This laser beam pumps a type-0 SPDC process, which creates pairs of photons at 1560 nm wavelength and about 100 nm linewidth and the same polarization. The crystal is heated to the phase-matching temperature and kept stable inside an oven. The crystal is integrated in a Sagnac interferometer that is pumped such that the laser is split into two counter-propagating modes at the PBS in the interferometer (Fedrizzi, Herbst,, Poppe, Jennewein, & Zeilinger, 2007). These counter-propagating beams generate SPDC photon pairs in a non-linear crystal inside the interferometer, and the photon pairs then also travel in opposite directions. Before the photons exit the interferometer, however, they are overlapped at the PBS. The two-photon amplitudes interfere at the PBS. As a result, the photons exiting the Sagnac interferometer from the PBS are entangled in polarization. The target state is the Bell state

$$|\varphi_{+}\rangle = \frac{1}{\sqrt{2}}(|HH\rangle + |VV\rangle).$$

Entangled photons exit the PBS at the same output and are sent to receivers via optical fibres. In order to reduce broad spectral background from SPDC, and to better define the wavelength of the entangled photons we want to send via existing fibre networks, we send the entangled photons through a DWDM module. For characterisation of the photon state, the output of the DWDM is guided to the analysis stage in figure 6.

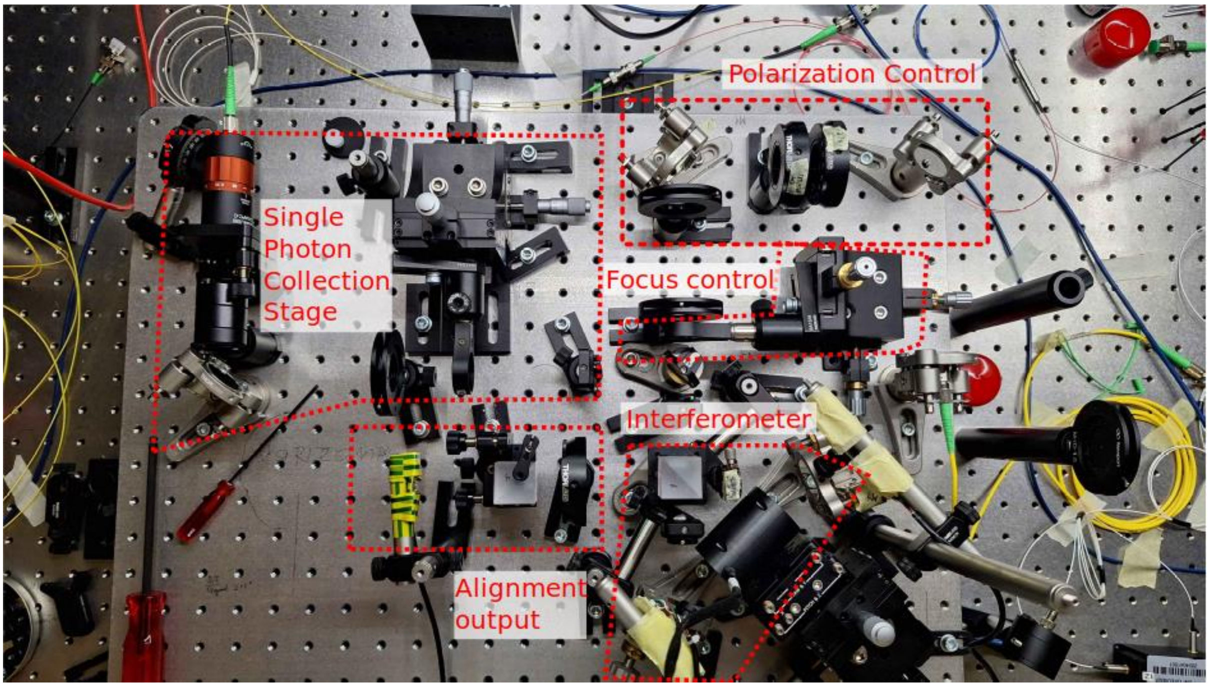

Figure 7: Photo of the optical setup for the type-0 source. It consists of a pump laser (blue fiber on the top going into the yellow fiber on the bottom right), polarization control for setting the pump polarization state, focus control for setting the position of the focus inside the PPLN crystal, a Sagnac interferometer, an alignment stage, and a single photon collection stage, which consists of a collimating lens and longpass filters to filter pump photons from the signal and idler photons.

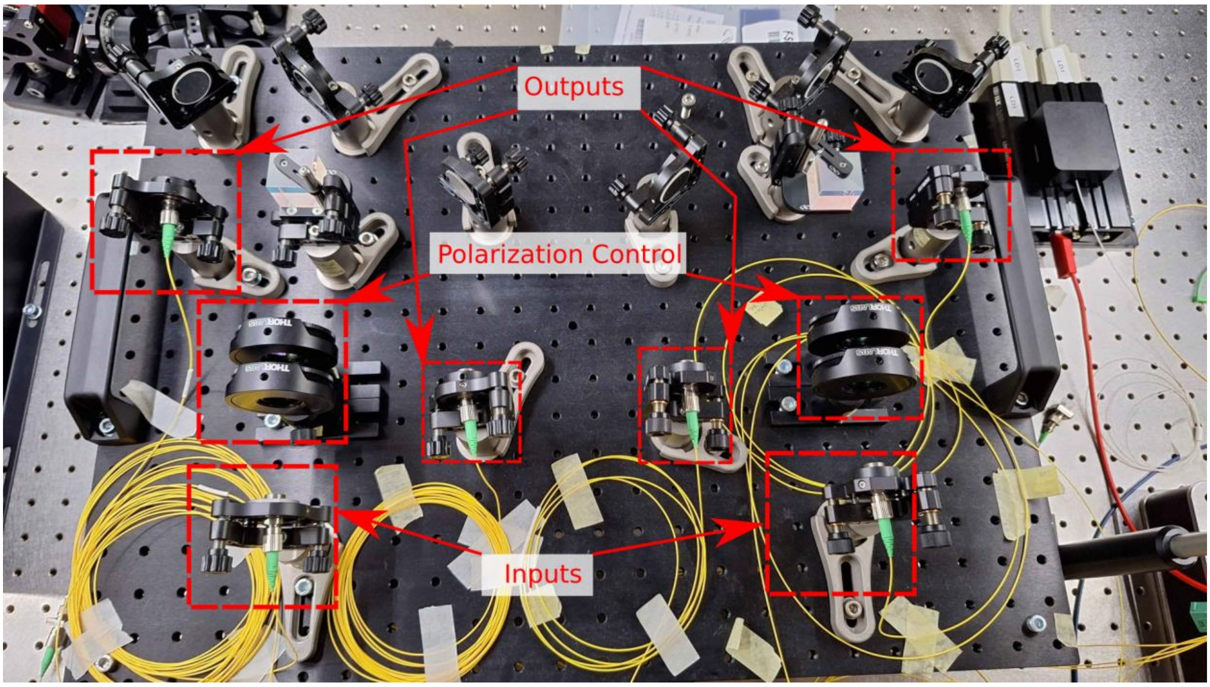

Figure 8: Photo of the analysis stage. It consists of two inputs (yellow fibers connected to DWDM channels 22 and 20 below the setup), polarization control for setting the correct measurement state, and four outputs going to the four detectors in a separate room.

3.2 Characterization

Due to unexpected challenges, only clockwise arm of the Sagnac interferometer was aligned, producing photons in a product state. Thus, we report only on measured counts and coincidences. The properties of entangled state will be measured once the whole interferometer is aligned.

Quantity	Measurement
Pump power	2.8 mW
Detector efficiency	82 – 90 %
Detector type	SNSPD
Number of detectors	4
Dead time	33 – 37 ns
Coincidence window	10 ns
Measured coincidences	15 000
Measured singles	850 000 – 1 000 000
Heralding ratio	0.015 – 0.017
Brightness	6696.6 Hz/(nm*mW)
Tangle	N/A
Fidelity of the Bell state	N/A
CHSH inequality	N/A
Bandwidth	0.8 nm per DWDM channel
Contrast visibility	N/A

Table 2: Characterization of the type-0 source.

4 Conclusion

The document presents sources of entangled photons produced by FMF and IJS. The groups implemented two sources, one based on type-2 SPDC and the other on type-0 SPDC. The sources produce different Bell states, the type-2 source a Bell state with orthogonal polarization and the type-0 source a Bell state with the equal polarization. The sources also differentiate in brightness and bandwidth. The quality of the type-2 source was demonstrated by reporting on the high fidelity, tangle, contrast visibility, and the high rate of measured coincidences. The type-0 source is in a half-finished state, currently producing photon pairs in a product state. The results are preliminary and will be further improved during the project. The sources will be used for deployment of the experimental QKD network and to demonstrate entanglement swapping and long-distance entanglement distribution.

5 Bibliography

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Steinlechner, F., Gilaberte, M., Jofre, M., Scheidl, T., Torres, J. P., Pruneri, V., & Ursin, R. (2014). Efficient heralding of polarization-entangled photons from type-0 and type-II spontaneous parametric downconversion in periodically poled KTiOPO4. *J. Opt. Soc. Am. B*.