Generating and teleporting entanglement for quantum networks

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SiQUID
Slovenian Quantum Communication Infrastructure Demonstration

Contents and introduction

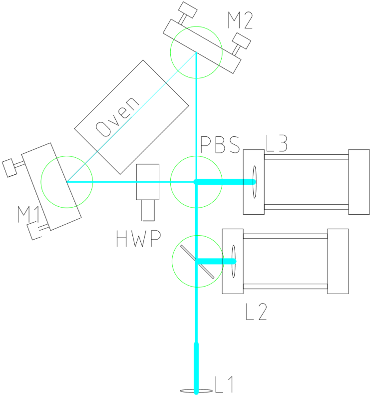
Motivation

- SiQUID
  0. Proof of concept
  1. Entanglement distribution
  2. Quantum Key Distribution (QKD)
  3. Training in Quantum Technologies
  4. Testbed for industrialized version

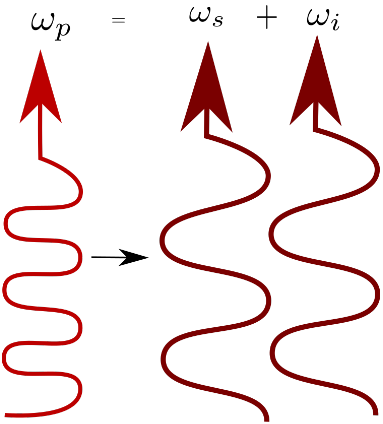
Example of Slovenian Quantum Network.

Motivation

- SiQUID
  0. Proof of concept
  1. Entanglement distribution
  2. Quantum Key Distribution (QKD)
  3. Training in quantum technologies in Slovenia
  4. Testbed for industrialized version
- Bright source of entanglement
- Why Sagnac?



An example of a Sagnac Interferometer.



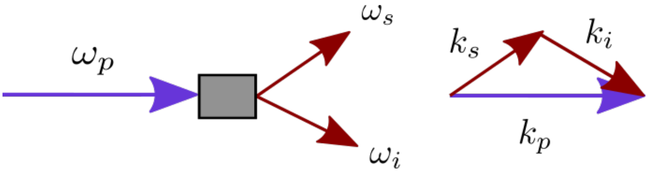
$$\Delta\omega = \omega_p - \omega_s - \omega_i$$

Illustration of SPDC

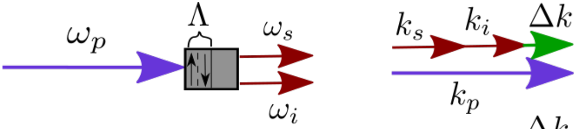
- Degenerate $\omega_i = \omega_s$
- Non-degenerate $\omega_i \neq \omega_s$

What is Phase Matching?

Illustration of Birifringent Phase Matching $k_p - k_i - k_s = 0$ and



Quasi Phase Matching $k_p - k_i - k_s - \Delta k = 0$.



$$\Delta k = \frac{2\pi}{\Lambda}$$

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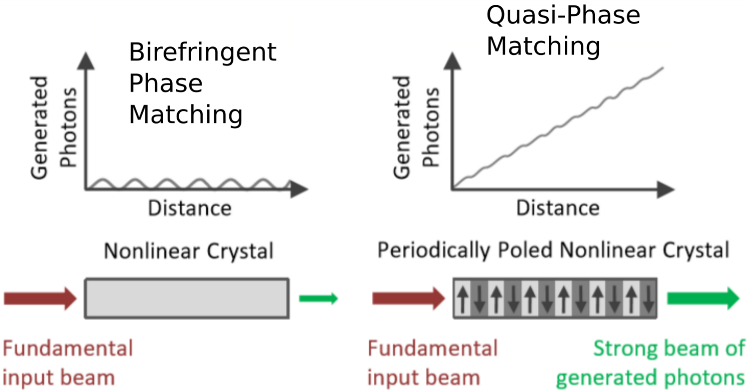
Difference in photon generation between a unpoled and poled crystal.
Source: Covesion.



- Type-0 : o → o + o
  or : e → e + e
- Type-I : o → e + e
  or : e → o + o
- Type-II : e → e + o
  or : o → e + o

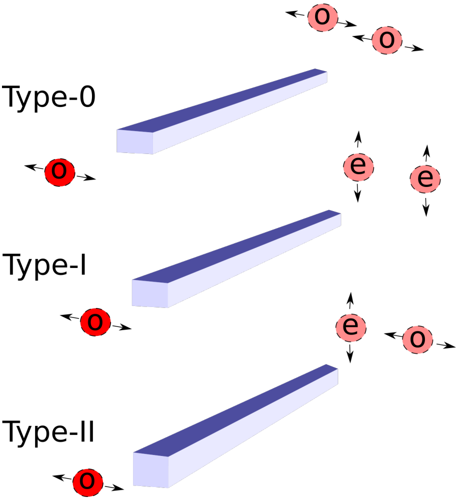
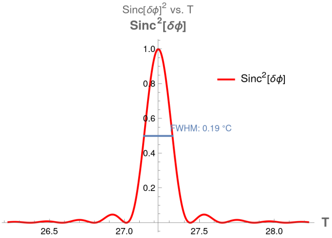
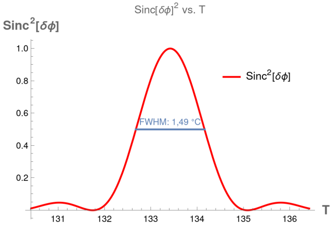


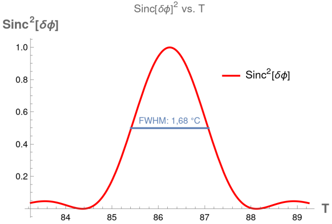
Illustration of different types of polarization conversions (Type-0).

Type-II, 9,12 μm poling period, $\delta\phi = \frac{L\Delta k}{2}$

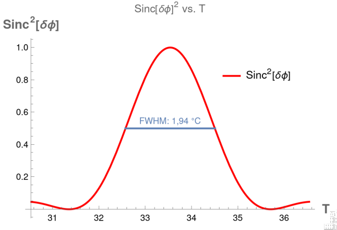


Type-0, 19,25 μm,



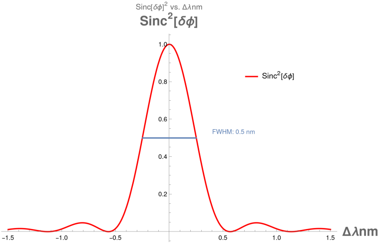


19,45 μm,

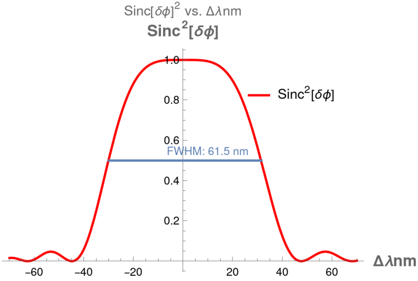


19,65 μm.

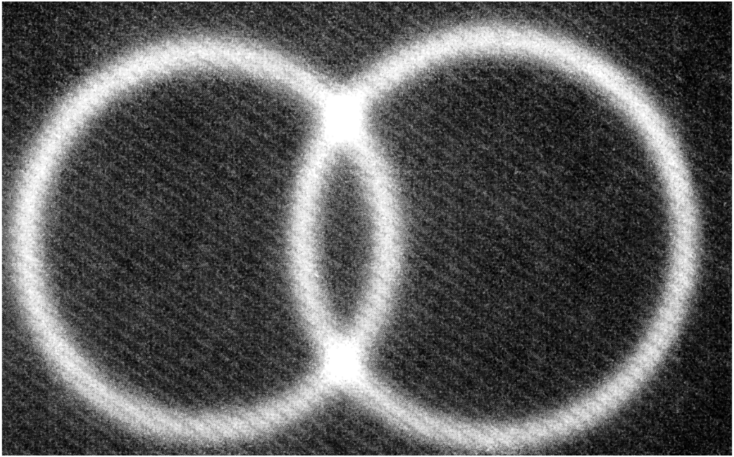
Wavelength bandwidth of a) Type-2 crystal with a poling period of 9,12 μm b) Type-0 crystals with poling periods of 19,25 μm



(a)

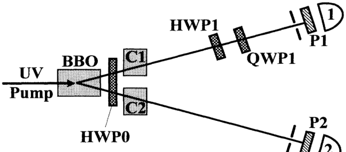


(b)

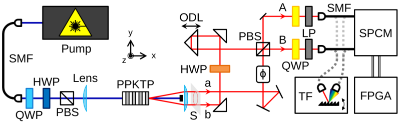


Type-II SPDC cones. Image Rotated, Phys. Rev. Lett., 75, 4337, (1995).

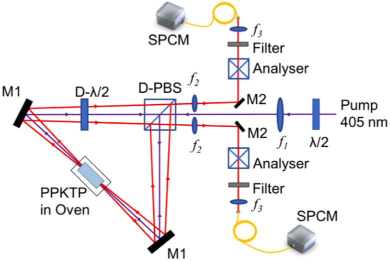
Different designs



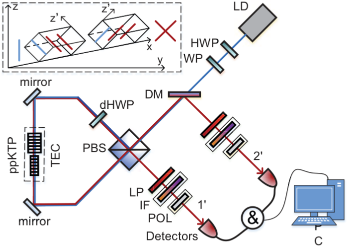
Phys. Rev. Lett. 75, 4337 (1995) [1].



Opt. Express 24, 2941-2953 (2016) [3].



Sci Rep 7, 12613 (2017) [2].



Phys. Rev. Lett. 121, 200502 (2018) [4].

$$|\Psi_p\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger(\omega_p) + e^{i\phi}a_V^\dagger(\omega_p))\,|0\rangle$$

$$|\Psi_{\text{Type-2}}\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger(\omega_s)a_V^\dagger(\omega_i) + e^{i\phi}a_V^\dagger(\omega_i)a_H^\dagger(\omega_s))\,|0\rangle$$

$$|\Psi_{\text{Type-0}}\rangle = \frac{1}{\sqrt{2}}(a_H^\dagger(\omega_s)a_H^\dagger(\omega_i) + e^{i\phi}a_V^\dagger(\omega_i)a_V^\dagger(\omega_s))\,|0\rangle$$

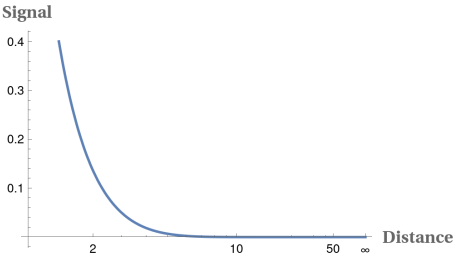
Entanglement

What is it good for?

- Entanglement source applications:
  1. Distributed Quantum Computation [5],
  2. Quantum Sensing [6],
  3. Single Photon Source - Calibration [7].
- Loss in fiber → Entanglement swapping!

Relevant fiber loss. *Source: Thorlabs*

λ [nm]	430	532	780	1310	1550	1900
Loss [dB/km]	50	30	12	0.32	0.18	5



Loss in fiber over distance.

Illustration of Quantum Teleportation: Basis of Entanglement Swapping.

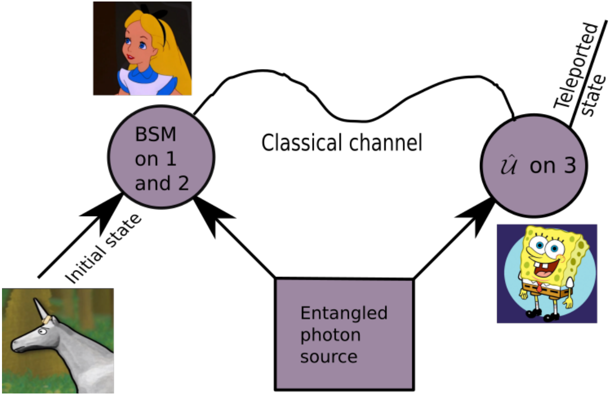
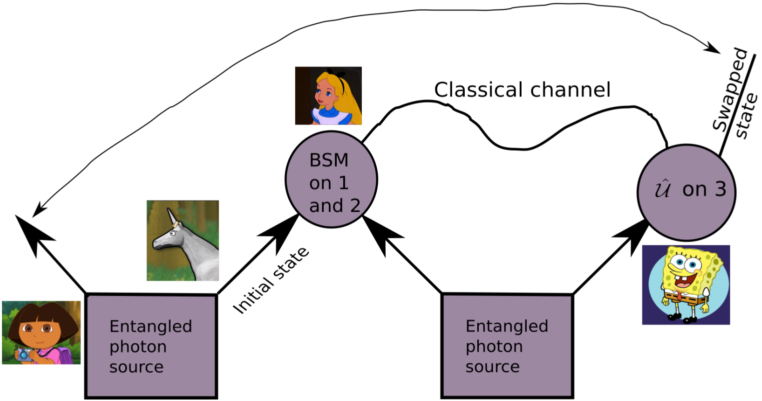
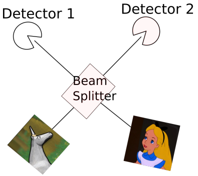
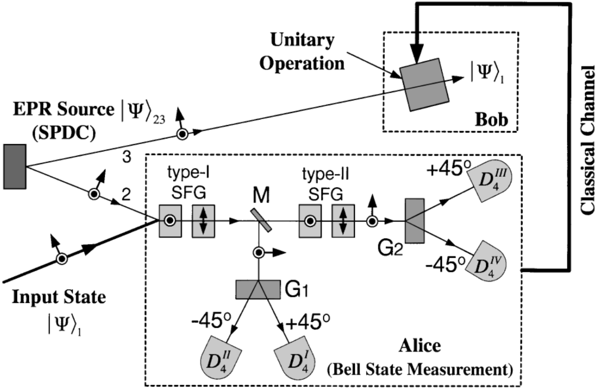


Illustration of Entanglement Swapping: Prerequisite for a Quantum Repeater.





(a)



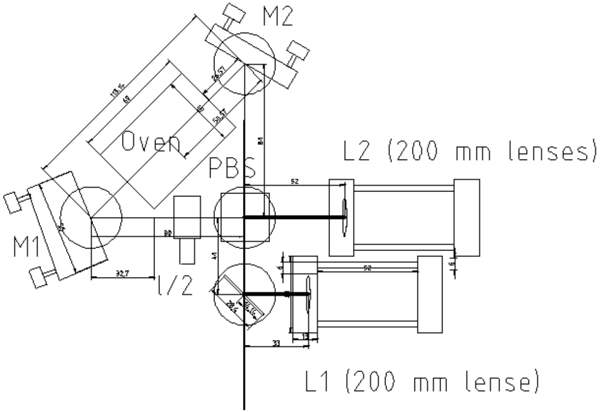
(b)

The simplest and the complete (PhysRevLett.86.1370, 2000) BSM.

- Focusing parameter [8]

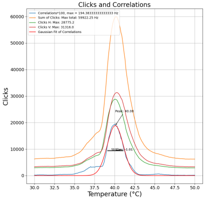
$$\xi = \frac{L}{2z_R} = 2.08$$

- Appropriate lenses and distances for efficient coupling

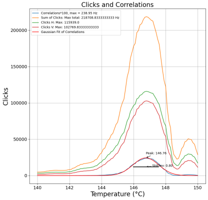


Design of the Sagnac interferometer.

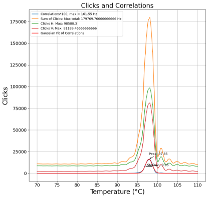
Temperature scans of Type-II and Type-0 crystal with different poling periods, a) Type-II, 9,12 μm, b) 19,25 μm, c) 19,45 μm, d) 19,65 μm



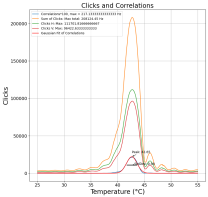
(a)



(b)



(c)



(d)

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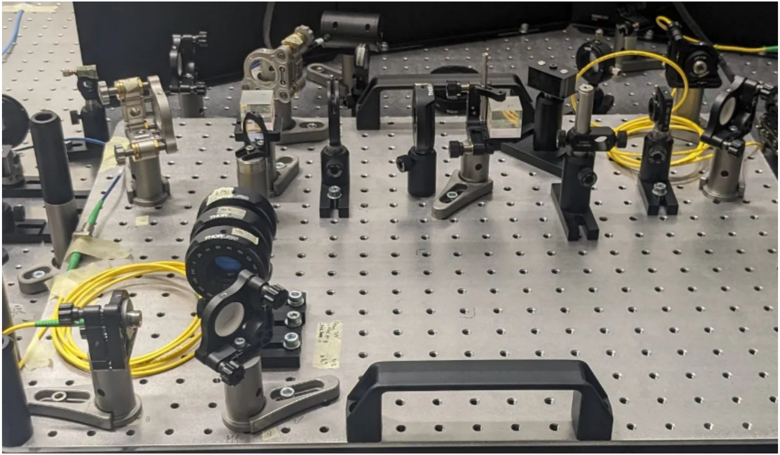
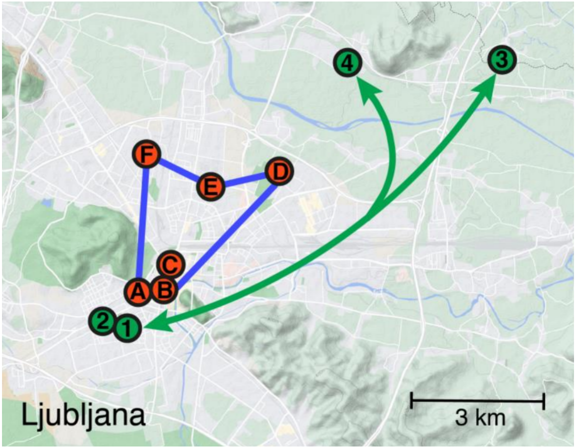


Sagnac in the lab.

Possible realization of the network in Ljubljana

Where?

- FMF/IJS
- Nodes in Ljubljana



Proposal for the experimental (green) and governmental (red) nodes in Ljubljana.
Source: https://siquid.fmf.uni-lj.si/.

Possible realization of the Slovenian network

Final user | Relay / Switch (trusted node) | Relay (trusted node - optional) | Quantum ground station

Example of the Slovenian Quantum Network.
Source: https://siquid.fmf.uni-lj.si/.

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Outlook

- Complete the source
- Characterize the source
- Entanglement swapping between FMF and IJS
  - Bell State Measurements
- Free space link to IJS
- Fiber link to reactor
- In future might use Quantum Memory from IJS group

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2 R. Ursin et al, "Polarization entanglement by time-reversed hong-ou-mandel interference," Physical Review Letters, vol. 121, no. 20, Nov. 2018

3 Sang Min Lee, Heonoh Kim, Opt. Express 24, 2941-2953 (2016)

4 V. Jabir et al., "Robust, high brightness, degenerate entangled photon source at room temperature," Sci Rep 7, 12613 (2017)

5 M. Caleffi, M. Amoretti, D. Ferrari, D. Cuomo, J. Illiano, A. Manzalini, and A. S. Cacciapuoti, "Distributed quantum computing: a survey," 2022

6 C. Degen, F. Reinhard, and P. Cappellaro, "Quantum sensing," Reviews of Modern Physics, vol. 89, no. 3, Jul. 2017. [Online]. Available: http://dx.doi.org/10.1103/RevModPhys.89.035002

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8 R. S. Bennink, "Optimal collinear gaussian beams for spontaneous parametric down-conversion," Phys. rev. A 81, 053805 (2010)

Present State

Current results

Current brightness estimation [$\frac{\text{Hz}}{\text{mWnm}}$]

FMF		**IJS**
Type-II	**Type-0**	**Type-II**
$7{,}8 \times 10^{6}$ [1]	$2{,}6 \times 10^{7}$ [1]	$0{,}05 \times 10^{6}$ [2]
Bandwidth [nm]		
0,81	0,81	0,81

[1] Linear setup

[2] Sagnac interferometer

Comparison of different sources

Who When	[9] 2022	[10] 2012	[11] 2007	[12] 2006	[13] 2010
Type	0	0	II	II	II
Brightness [$\frac{\text{Hz}}{\text{mW nm}}$]	$2{,}5\times10^6$	$0{,}278\times10^6$	$0{,}273\times10^6$	0.005×10^6	0.087×10^6
Bandwidth [nm]	106	2,3	0,3	1	0,3

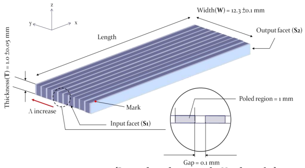
Phase Matching

Choosing a crystal

HC PHOTONICS CORP.

Periodically Poled Lithium Niobate (PPLN) Chip: SHNIR-MF

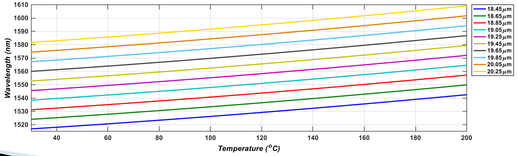
- Chip Lay-Out



[Image for reference only. Not for scale.]

Items	Properties	Inspection
Material	5 mol.% MgO:LN	NA
Period (Λ, μm)	18.45, 18.65, 18.85, 19.05, 19.25, 19.45, 19.65, 19.85, 20.05, 20.25	Microscope
Main Function	Second Harmonic Generation	NA
Parallelism/Perpendicularity	≤5'/21'	Autocollimator
Flatness	≤λ/6 (λ=633nm)	Interferometer
Scratch/Dig	≤20/10	Microscope
Optical coating (S1/S2 facets)	S1/S2 @750-810(R<0.5%) /1500-1620(R<0.5%) nm	Spectral Analyzer
Aperture Size	12.3 x 1.0 mm² (**W** x **T**)	Cutting Machine
Available Length	10/25/50 ± 0.2 mm	
Channel Clear Aperture	≥80% (**T**), ≥90% (**W**)	NA

- Phase Matching Tuning Curve



Version: Jan., 2021

service@hcphotonics.com | www.hcphotonics.com | T: +886-3-6662123 | 4F., No. 2, Technology Road V., Hsinchu City 300, Taiwan

Specifications from the crystal manufacturer.
Source: HC Photonics Corp.

P. G. Kwiat, K. Mattle, H. Weinfurter, A. Zeilinger, A. V. Sergienko, and Y. Shih, "New high-intensity source of polarization-entangled photon pairs," *Phys. Rev. Lett.*, vol. 75, pp. 4337–4341, Dec 1995.

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