

Generating and teleporting entanglement for quantum networks

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- ▶ SiQUID
- ▶ Bright source of entanglement
- ▶ Training in quantum technologies in Slovenia
- ▶ Quantum Network for Slovenia
- ▶ Testbed for industrialized version
- ▶ Entanglement based QKD

Theory

1. SPDC
2. Distributing Entanglement

Theory

SPDC

- #### ► Spontaneous Parametric Downconversion

$$\omega_p = \omega_s + \omega_i$$

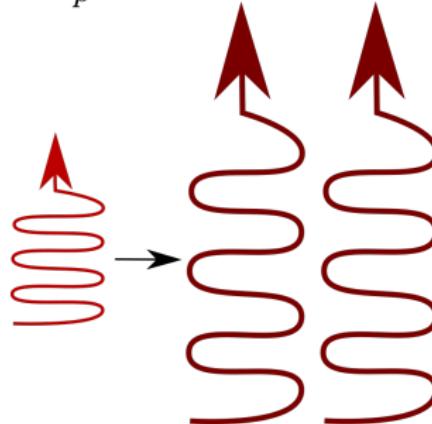


Illustration of SPDC

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

Theory

State of the Art

Comparison of different sources

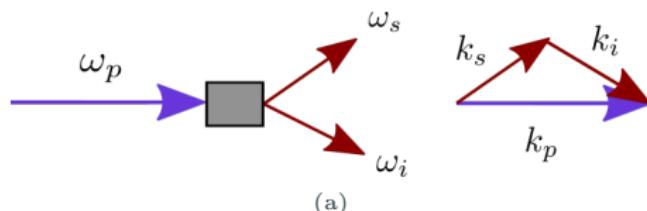
Who When	[1] 2022	[2] 2010	[3] 2007	[4] 2006	[5] 2012
Type	0	II	II	II	0
Brightness [$\frac{pairs}{smWnm}$]	$2,5 \times 10^6$	$87,5 \times 10^3$	273×10^3	5×10^3	278×10^3
Bandwidth [nm]	106	0,3	0,3	1	2,3

SPDC

Phase Matching, Quasi Phase Matching, Bandwidth

- Birefringent Phase Matching, Quasi Phase Matching

Illustration of a) Birefringent Phase Matching $k_p = k_i + k_s$ and



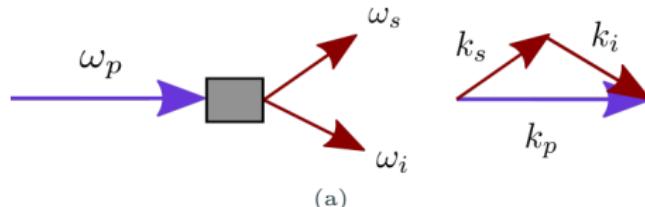
(a)

SPDC

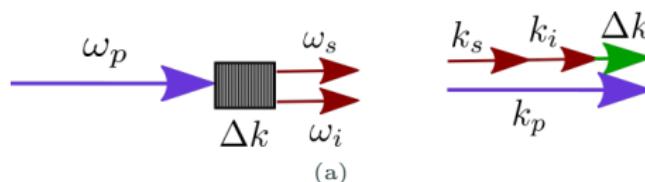
Phase Matching, Quasi Phase Matching, Bandwidth

- #### ► Birefringent Phase Matching, Quasi Phase Matching

Illustration of a) Birefringent Phase Matching $k_p = k_i + k_s$ and



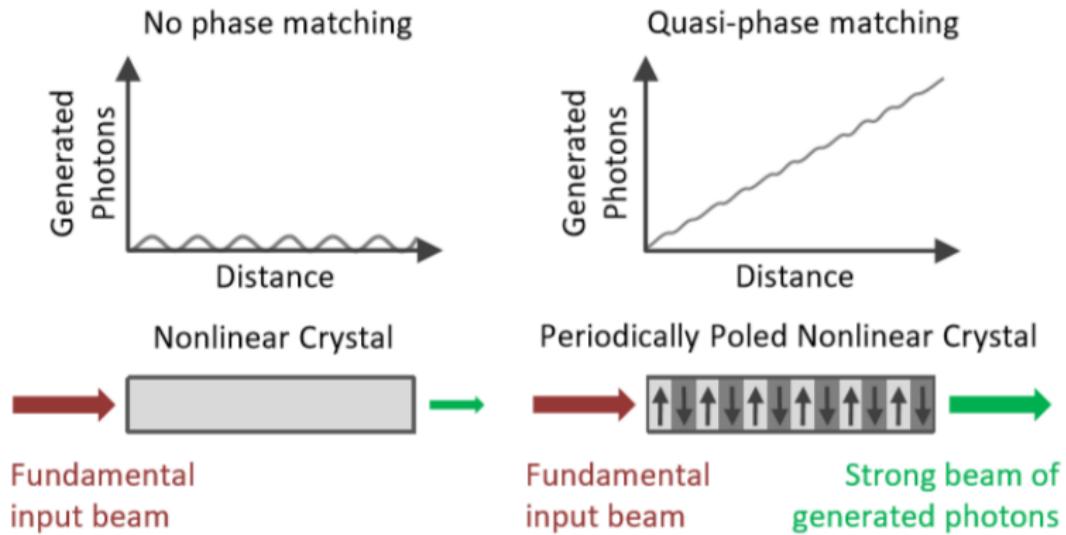
b) Quasi Phase Matching $k_p - k_i - k_s - \Delta k = 0$.



$$I \propto \text{sinc}^2 \left(\frac{L\delta k}{2} \right)$$

Theory

Polling



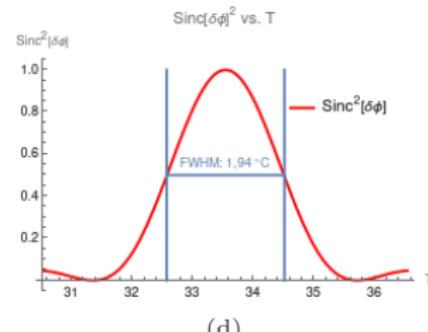
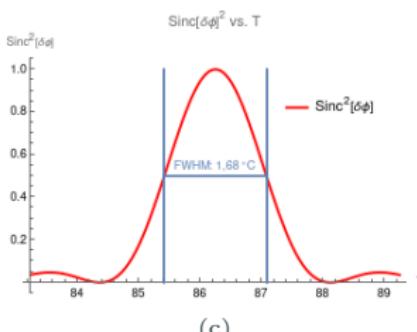
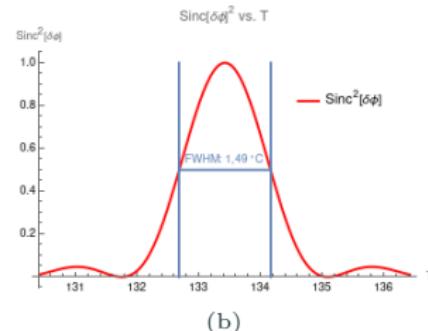
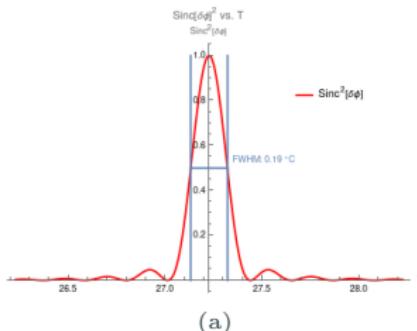
Difference in photon generation between a unpolled and polled crystal.

Source: RP-Photontics

Theory

Phase Matching Temperature

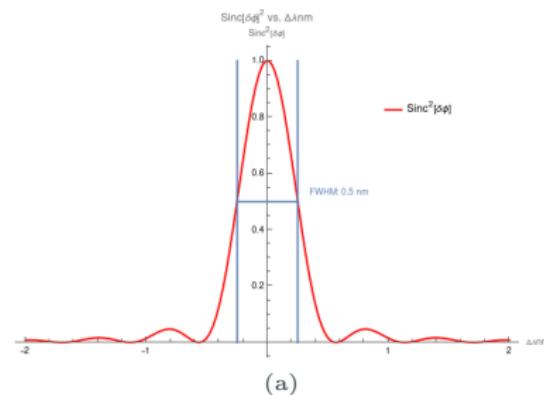
Phase Matching Temperature calculations for a) Type-2 crystal of 9,12 μm polling period, b) Type-0, 19,25 μm , c) Type-0, 19,45 μm , d), Type-0 19,65 μm



Theory

Bandwidth

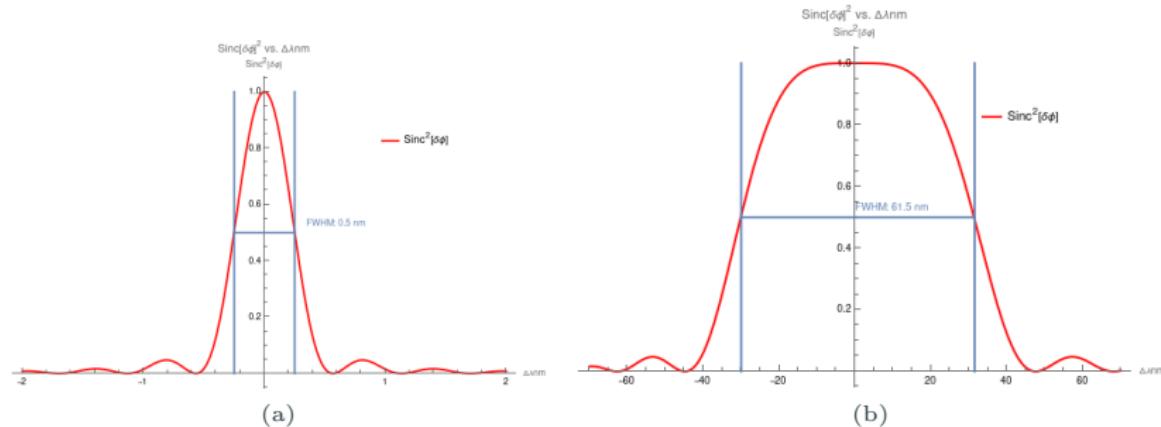
Wavelength bandwidth of a) Type-2 crystal with a polling period of 9,12 μm
b) Type-0 crystals with polling periods of 19,25 μm



Theory

Bandwidth

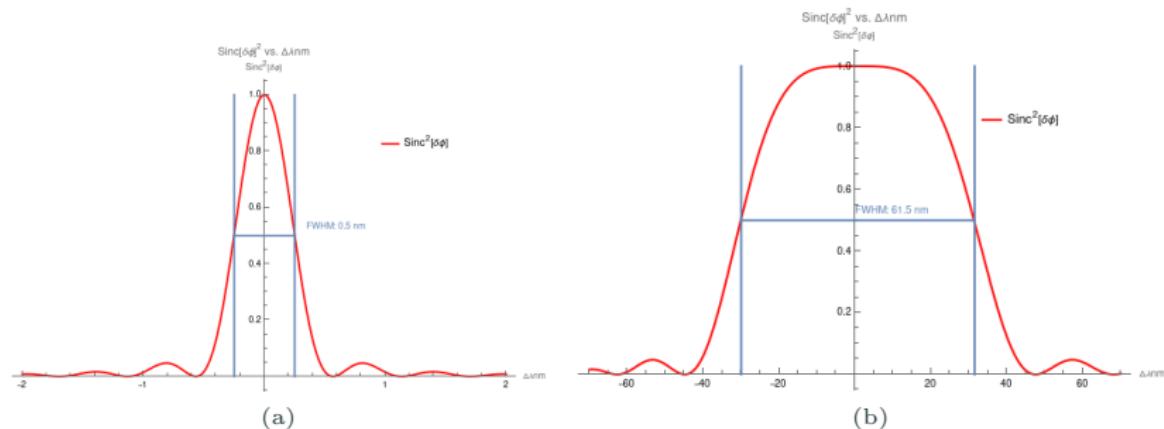
Wavelength bandwidth of a) Type-2 crystal with a polling period of 9,12 μm
 b) Type-0 crystals with polling periods of 19,25 μm



Theory

Bandwidth

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



$$\begin{aligned}
|\Psi_p\rangle &= \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger + \cos(\alpha)a_V^\dagger)|0\rangle & |\Psi_{\text{Type-0}}\rangle &= \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_H^\dagger(\omega_i) + \\
|\Psi_{\text{Type-2}}\rangle &= \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_V^\dagger(\omega_i) + & \cos(\alpha)a_V^\dagger(\omega_i)a_V^\dagger(\omega_s))|0\rangle \\
&\quad \cos(\alpha)a_V^\dagger(\omega_i)a_H^\dagger(\omega_s))|0\rangle
\end{aligned} \tag{2}$$

Theory

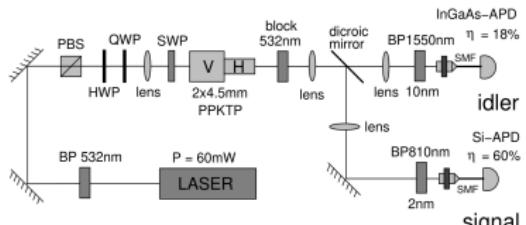
Current brightness between FMF and IJS

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

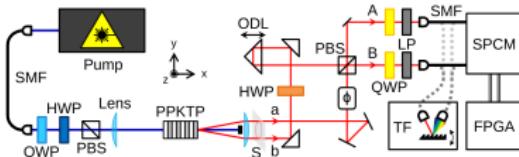
FMF		IJS
Type-II	Type-0	Type-II
$7,8 \times 10^6$	$2,6 \times 10^7$	$0,05 \times 10^6$
Bandwidth [nm]		
0,81	0,81	0,81

Different Designs

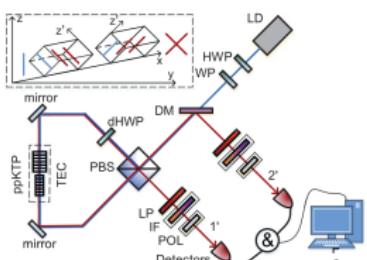
Different design ideas from other groups. a) [6], b) [7], c) [8], d) [9]



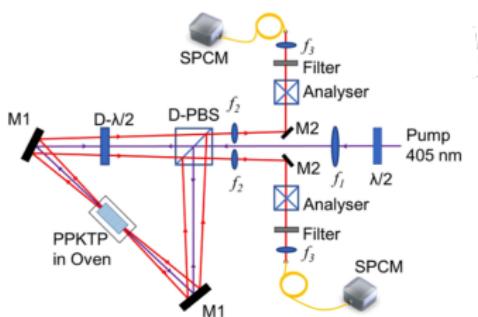
(a)



(b)



(c)



(d)

Why do we care about entanglement?

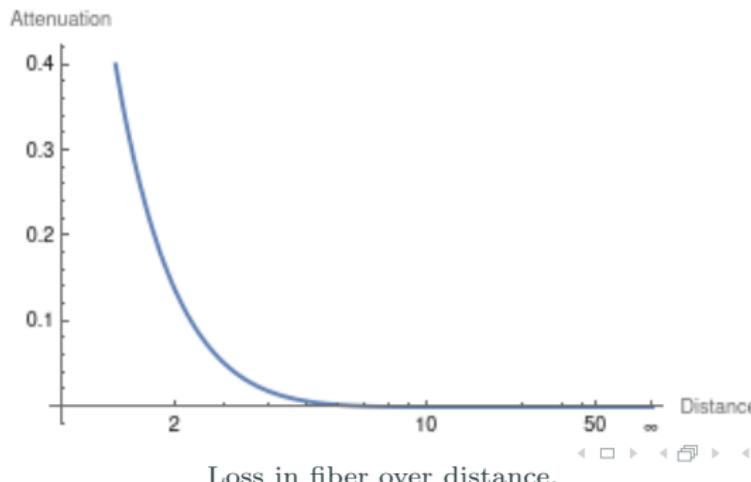
- ▶ Entanglement sources by themselves → useless if you can't use them.
- ▶ Loss in fiber

Relevant fiber loss.
Source: Thorlabs

λ [nm]	1310	1550
Loss [dB/km]	0.32	0.18

Example: Loss in fiber for 1550/1560 nm

200 km of fiber $\rightarrow 10^4$ loss.



Distributing Entanglement

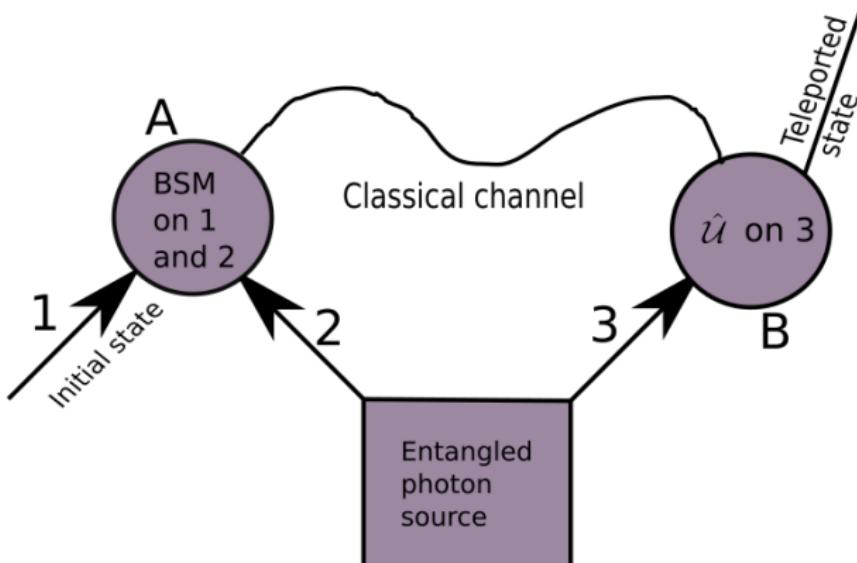
Introduction

- ▶ No specific form required - arbitrary states can be teleported
 1. Bell State Measurements
 2. Will try to use Quantum Memory from IJS group
- ▶ FMF/IJS
- ▶ Government buildings in Ljubljana

Entanglement Teleportation

Teleportation

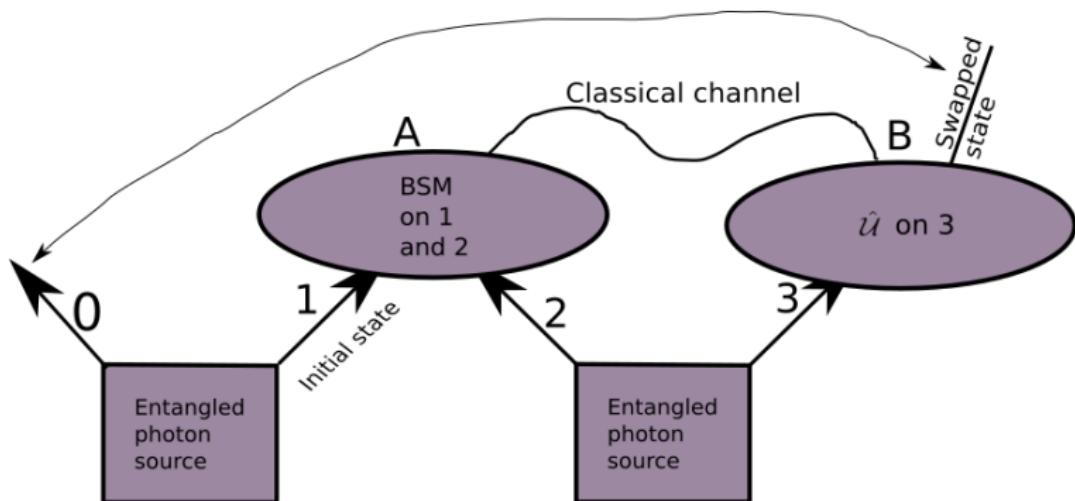
Illustration of Entanglement Teleportation.



Entanglement Swapping

Swapping

Illustration of Entanglement Swapping.



Present state

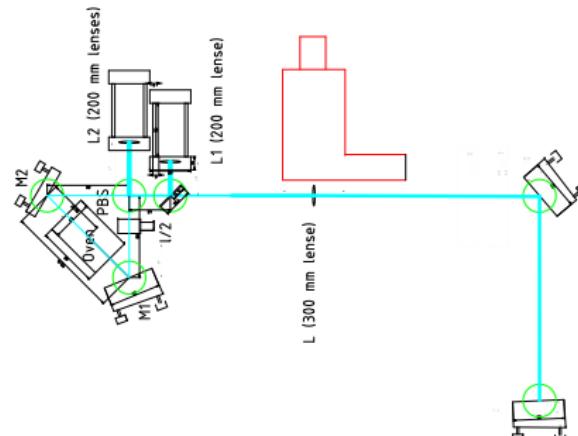
Parameters

- #### ► Focusing parameters [10]

$$\xi = \frac{L}{kw^2} \quad (3)$$

Photon generation

- ▶ Correct lenses and distances for efficient coupling
 - ▶ Correct size of coupler aperture

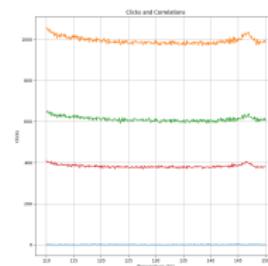


Design of the Sagnac interferometer.

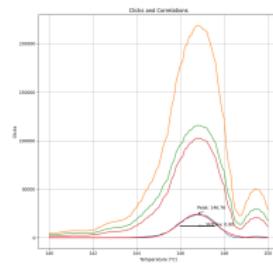
Present state

Phase Matching Temperature

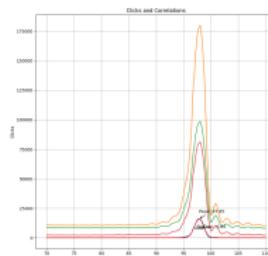
Temperature scans of Type-0 crystals with different polling periods, a) misaligned 19,25 μm , b) 19,25 μm , c) 19,45 μm , d) 19,65 μm



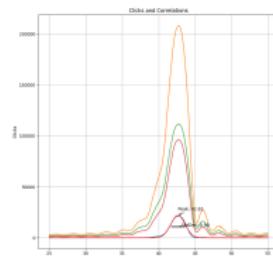
(a)



(b)



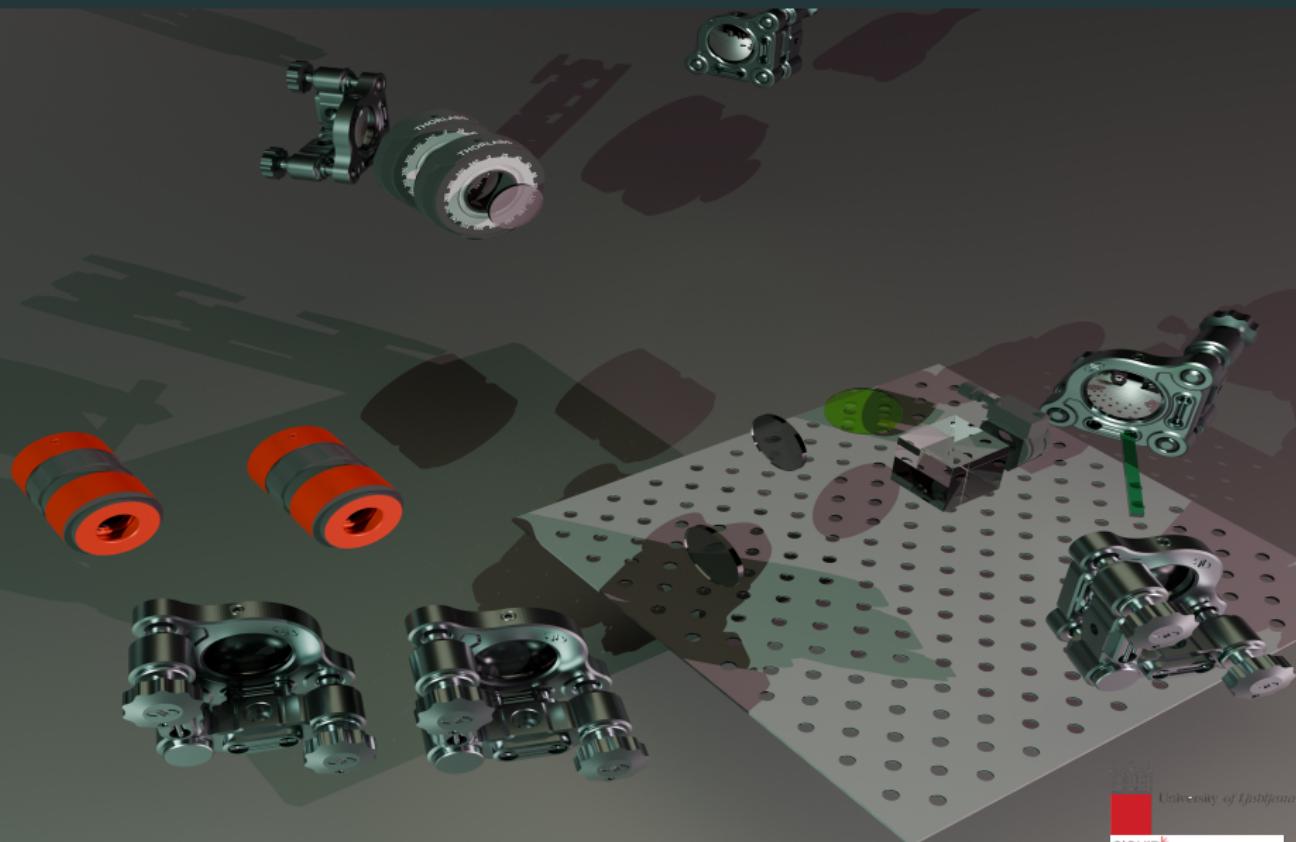
(c)



(d)

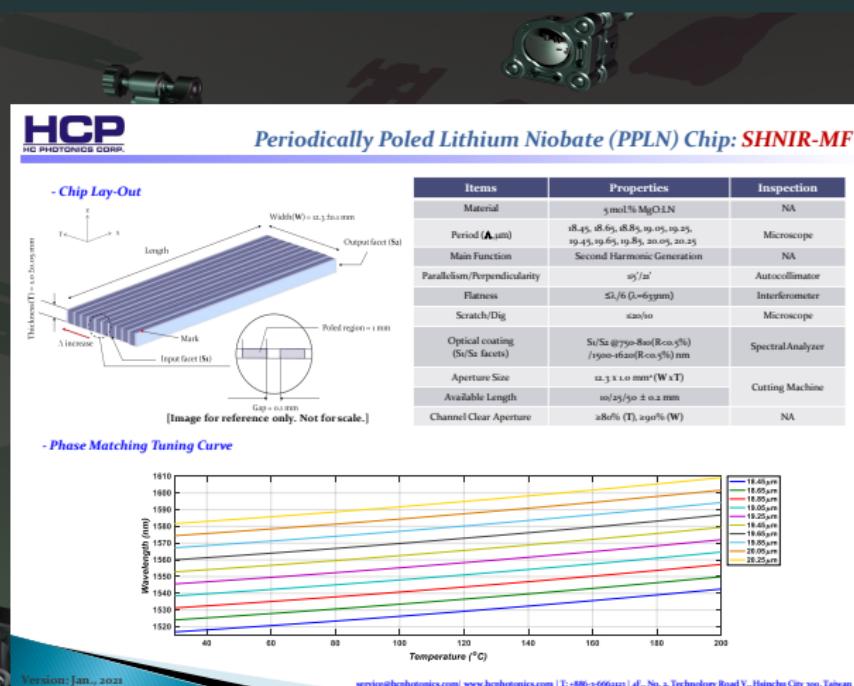
Present state

Building a Sagnac Interferometer



Present state

Building a Sagnac Interferometer



Specifications from the crystal manufacturer.

Source: HC Photonics Corp.

Outlook

- ▶ SiQUID
- ▶ Entanglement swapping between FMF and IJS
- ▶ Building quantum network
- ▶ Free space link to reactor

Thank you

References

-  S. P. Neumann, M. Selimovic, M. Bohmann, and R. Ursin, "Experimental entanglement generation for quantum key distribution beyond 1 Gbit/s," *Quantum*, vol. 6, p. 822, Sep. 2022.
-  A. F. e. a. Hübel H., Hamel D., "Direct generation of photon triplets using cascaded photon-pair sources," *Nature* 466, 601–603 (2010).
-  A. Z. et al., A. Fedrizzi, "A wavelength-tunable fiber-coupled source of narrowband entangled photons," *Opt. Express* 15, 15377-15386 (2007).
-  F. N. C. W. T. Kim, M. Fiorentino, "Phase-stable source of polarization-entangled photons using a polarization sagnac interferometer," *Optica Publishing Group*, (2006), paper JTUh5.
-  F. S. et al, "A high-brightness source of polarization-entangled photons optimized for applications in free space," *Opt. Express* 20, 9640-9649 (2012).
-  M. C. S. M. Lee, H. Kim and H. S. Moon, "Polarization-entangled photon-pair source obtained via type-ii non-collinear spdc process with ppktp crystal," *Opt. Express* 24, 2941-2953 (2016).
-  M. C. H. S. M. Sang Min Lee, Heonoh Kim, *Opt. Express* 24, 2941-2953 (2016).
-  Y. Chen, S. Ecker, S. Wengerowsky, L. Bulla, S. K. Joshi, F. Steinlechner, and R. Ursin, "Polarization entanglement by time-reversed hong-ou-mandel interference," *Physical Review Letters*, vol. 121, no. 20, Nov. 2018.
-  G. K. S. M. V. Jabir, "Robust, high brightness, degenerate entangled photon source at room temperature," *Sci Rep* 7, 12613 (2017).
-  R. S. Bennink, "Optimal collinear gaussian beams for spontaneous parametric down-conversion," *Phys. rev. A* 81, 053805 (2010).