

Generating and teleporting entanglement for quantum networks

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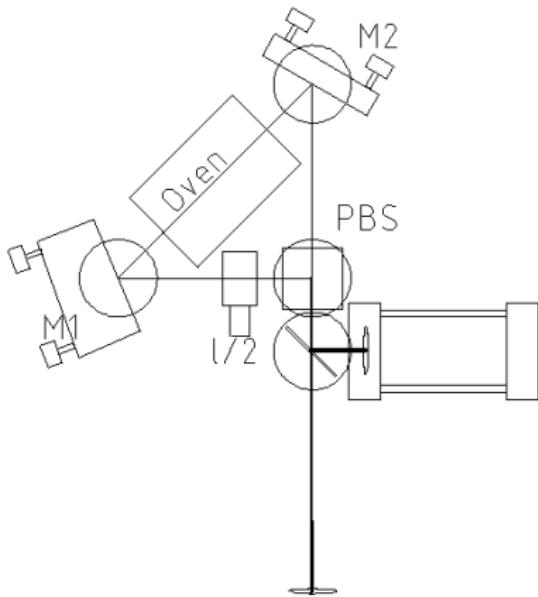
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Motivation

- ▶ SiQUID
 - 1. Training in quantum technologies in Slovenia
 - 2. Entanglement based Quantum Key Distribution (QKD)
 - 3. Testbed for industrialized version
 - ▶ Bright source of entanglement



An example of a Sagnac Interferometer.

Theory

Spontaneous Parametric Downconversion (SPDC)

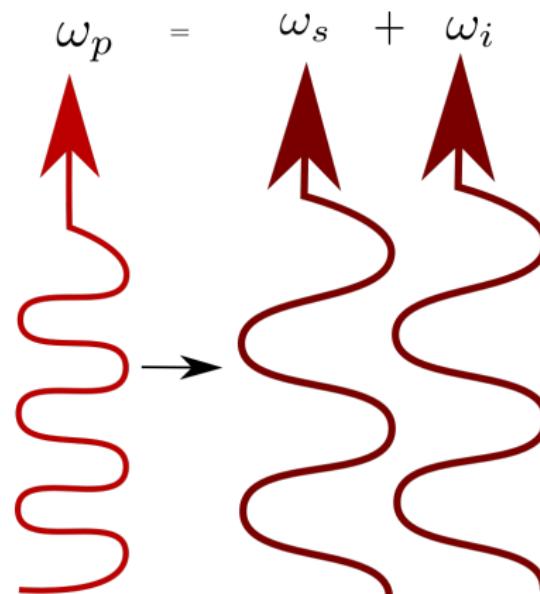


Illustration of SPDC

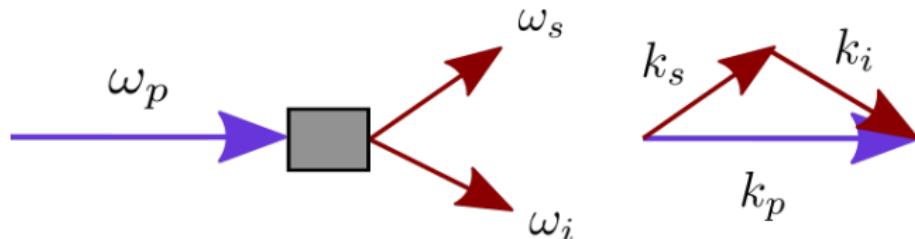
- Degenerate $\omega_i = \omega_s$
- Non-degenerate $\omega_i \neq \omega_s$

Phase Matching

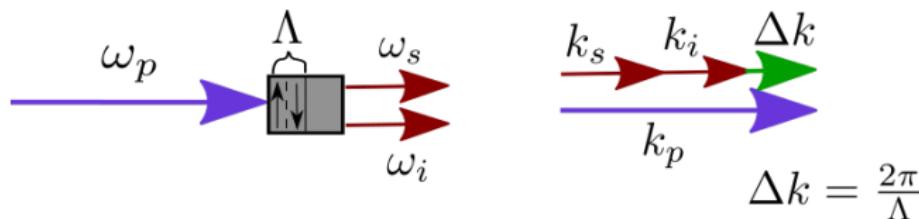
Birefringent Phase Matching, Quasi Phase Matching

What is Phase Matching?

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



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

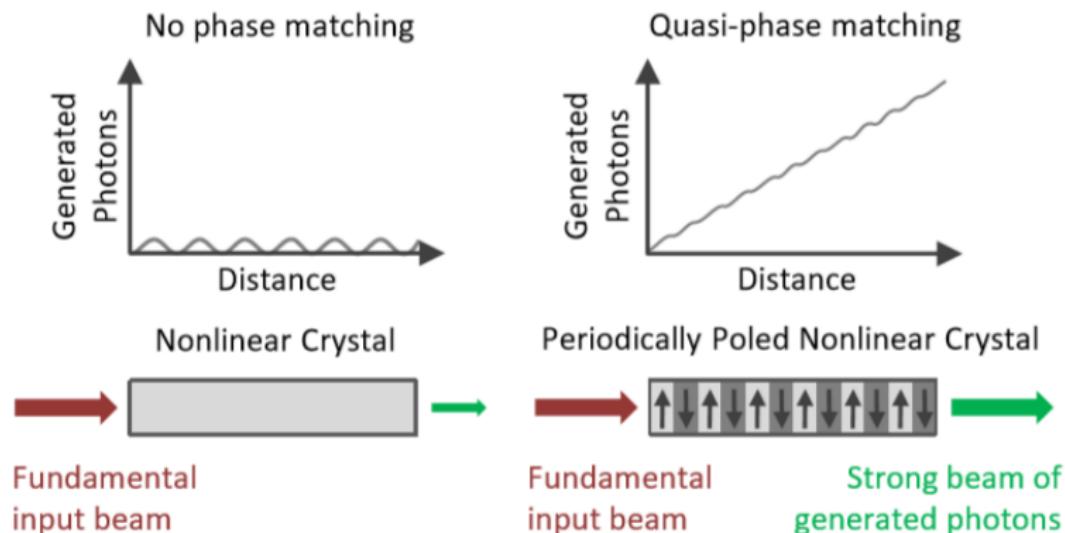


Phase Matching

Crystal Size

Difference in photon generation between a unpoled and poled crystal.

Source: RP-Photonics



Phase Matching

Types

- ▶ Type-0 : $o \rightarrow o + o$
 - ▶ Type-I : $o \rightarrow e + e$
 - ▶ Type-II : $e \rightarrow e + o$

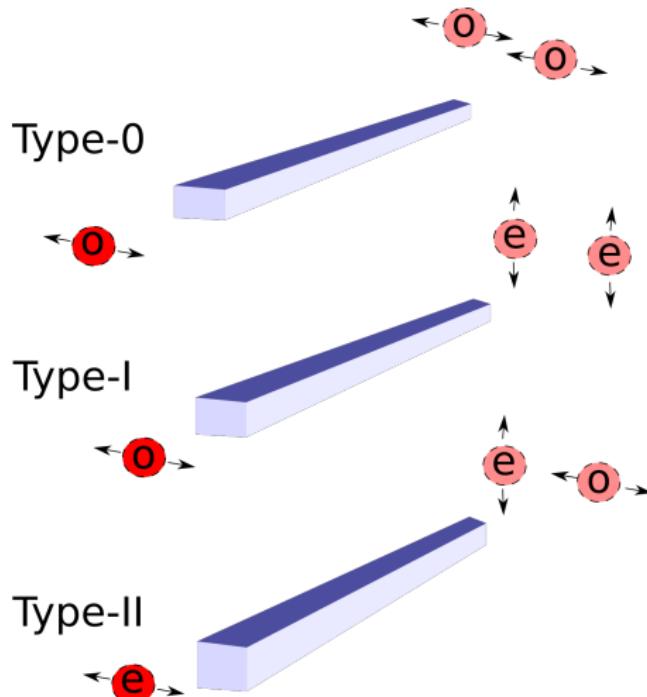
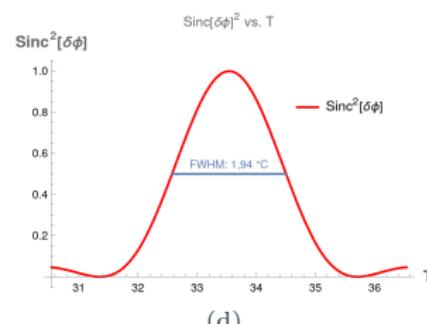
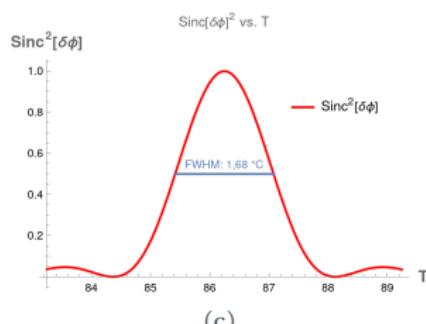
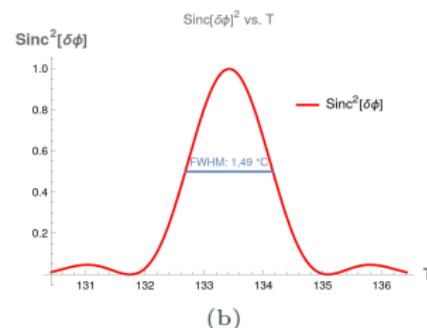
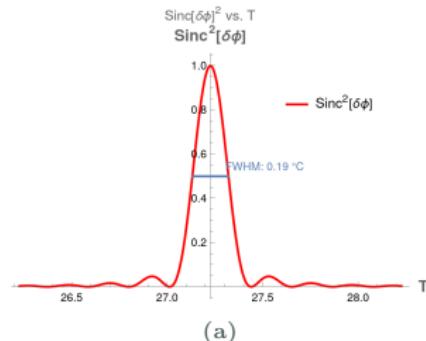


Illustration of different types of polarization conversions.

Theory

Phase Matching Temperature

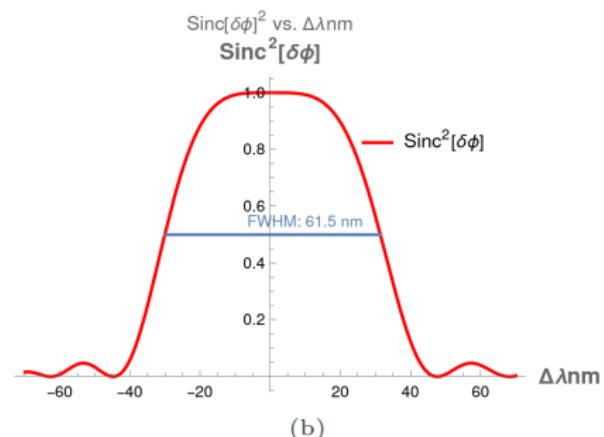
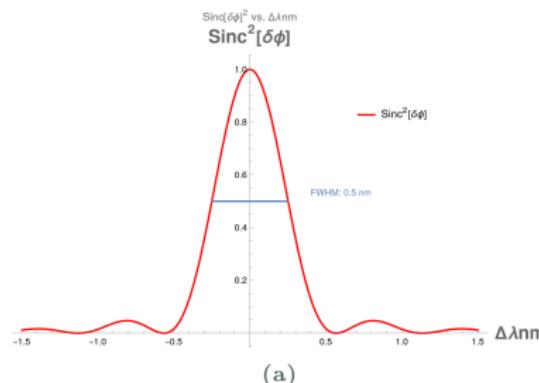
Phase Matching Temperature plots for a) Type-2 crystal of 9,12 μm poling period, b) Type-0, 19,25 μm , c) Type-0, 19,45 μm , d), Type-0 19,65 μm



Theory

Bandwidth

Wavelength bandwidth of a) Type-2 crystal with a poling period of $9.12 \mu\text{m}$
b) Type-0 crystals with poling periods of $19, 25 \mu\text{m}$



Theory

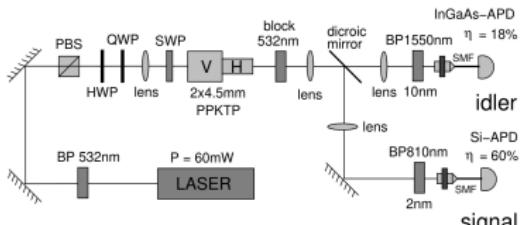
State of the Art

Comparison of different sources

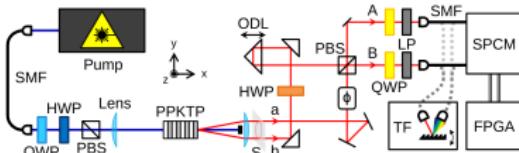
Who When	[1] 2022	[2] 2012	[3] 2007	[4] 2006	[5] 2010
Type	0	0	II	II	II
Brightness [$\frac{\text{Hz}}{\text{mW nm}}$]	$2,5 \times 10^6$	$0,278 \times 10^6$	$0,273 \times 10^6$	$0,005 \times 10^6$	$0,087 \times 10^6$
Bandwidth [nm]	106	2,3	0,3	1	0,3

Different Designs

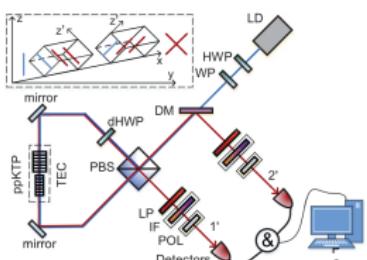
Different design ideas from other groups. a) [6], b) [7], c) [8], d) [9]



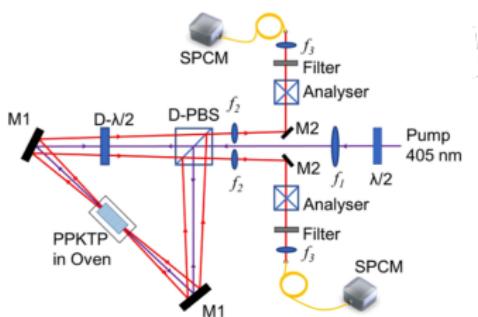
(a)



(b)



(c)



(d)

Why do we care about entanglement?

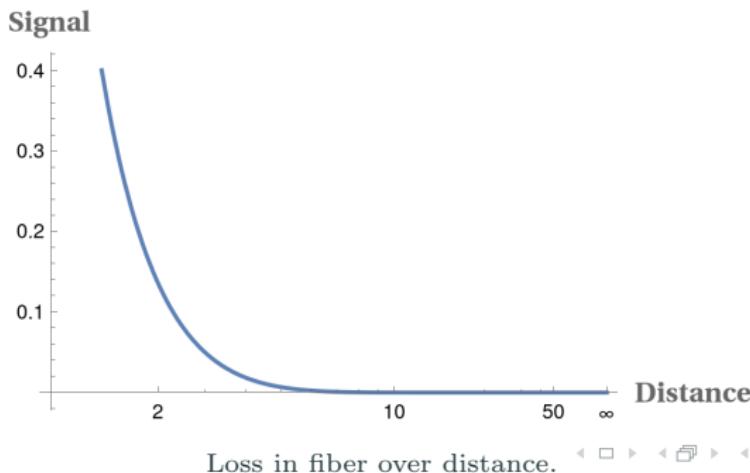
- ▶ Entanglement sources by themselves → useless if you can't use them.
 - ▶ Loss in fiber

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

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

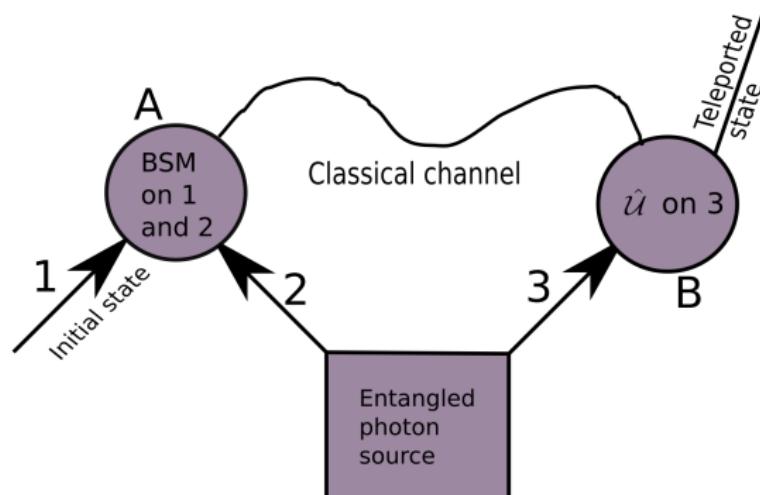
$$|\Psi_{\text{Type-0}}\rangle = \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_H^\dagger(\omega_i) +$$

$$\cos(\alpha)a_V^\dagger(\omega_i)a_V^\dagger(\omega_s))|0\rangle$$

Entanglement Teleportation

Teleportation

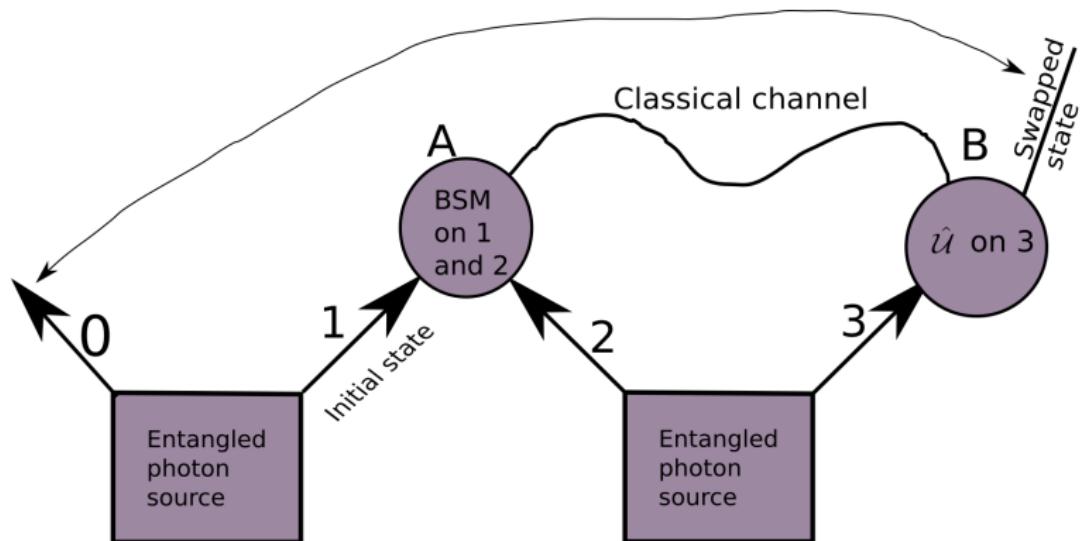
Illustration of Entanglement Teleportation.



Entanglement Swapping

Swapping

Illustration of Entanglement Swapping.



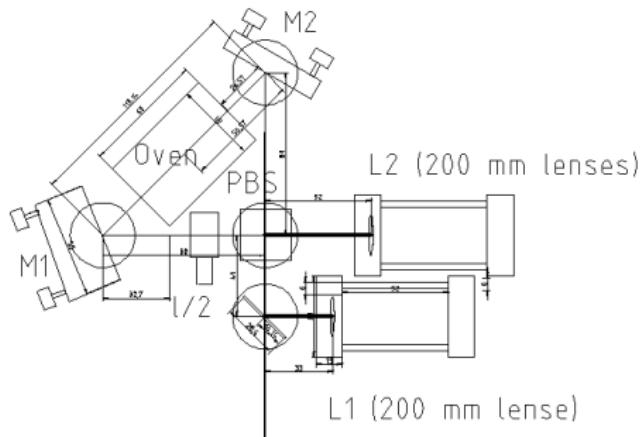
Present state

Parameters

- #### ► Focusing parameters [10]

$$\xi = \frac{L}{kw^2}$$

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

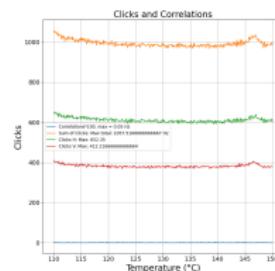


Design of the Sagnac interferometer.

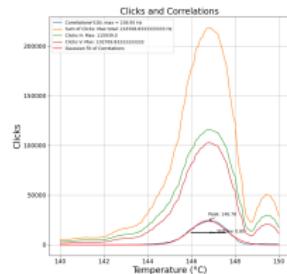
Present state

Phase Matching Temperature

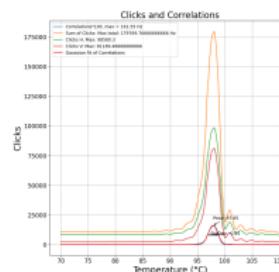
Temperature scans of Type-0 crystals with different poling periods, a) misaligned 19,25 μm , b) 19,25 μm , c) 19,45 μm , d) 19,65 μm



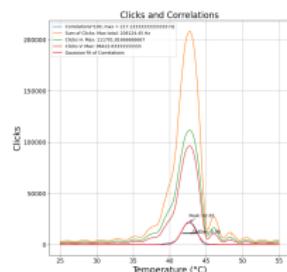
(a)



(b)



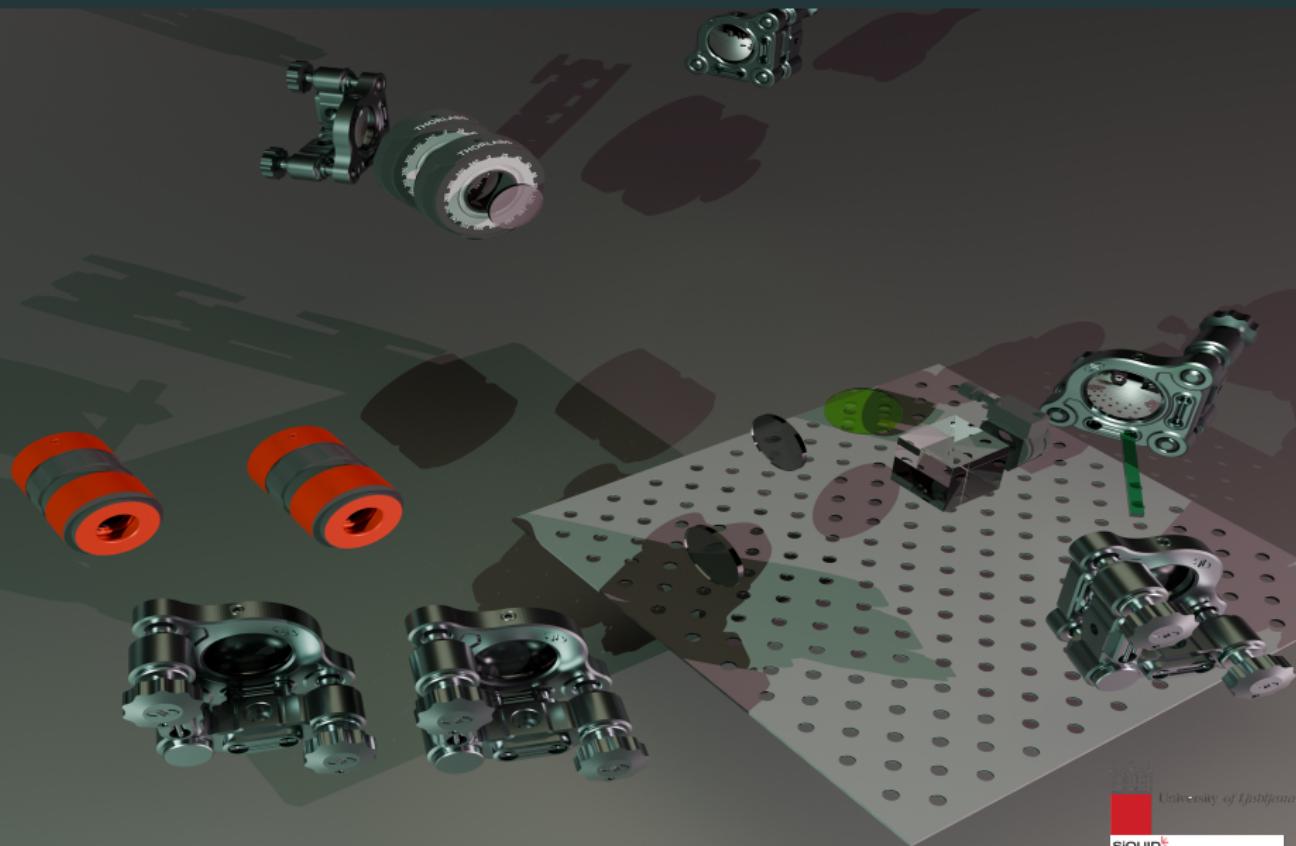
(c)



(d)

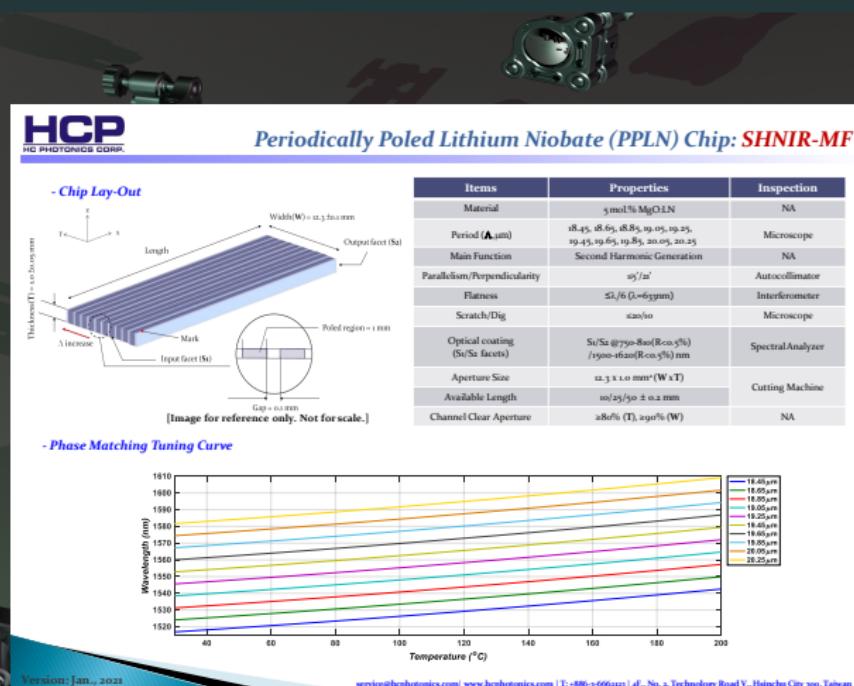
Present state

Building a Sagnac Interferometer



Present state

Building a Sagnac Interferometer



Specifications from the crystal manufacturer.

Source: HC Photonics Corp.

Present State

Current results

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

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

Outlook

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

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