

Generating and teleporting entanglement for quantum networks

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Motivation

► SiQUID

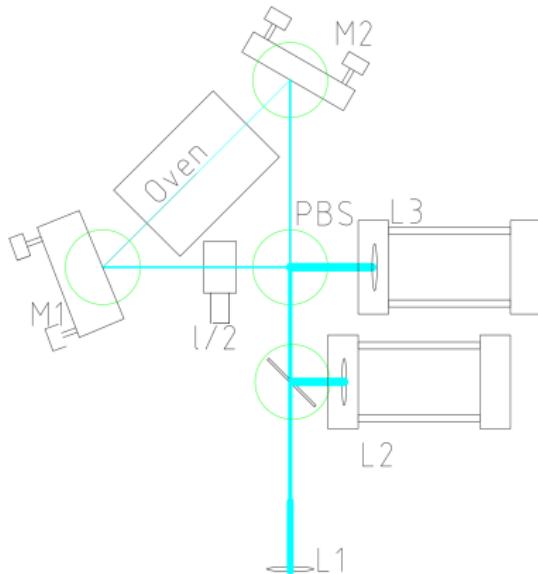
0. Proof of concept
 1. Entanglement distribution
 2. Entanglement based Quantum Key Distribution (QKD)
 3. Training in quantum technologies in Slovenia
 4. Testbed for industrialized version



Example of Slovenian Quantum Network.

Motivation

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



An example of a Sagnac Interferometer.

SPDC

Spontaneous Parametric Downconversion (SPDC)

Illustration of SPDC

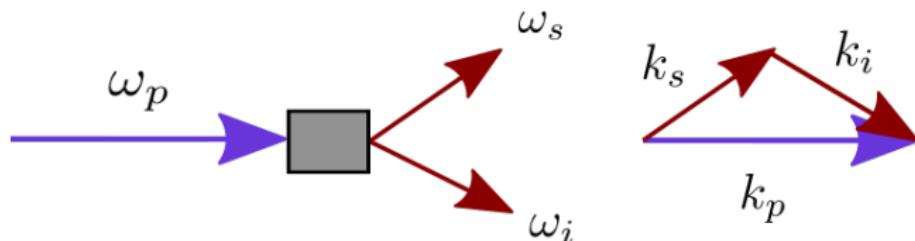
- Degenerate $\omega_i = \omega_s$
 - Non-degenerate $\omega_i \neq \omega_s$

Phase Matching

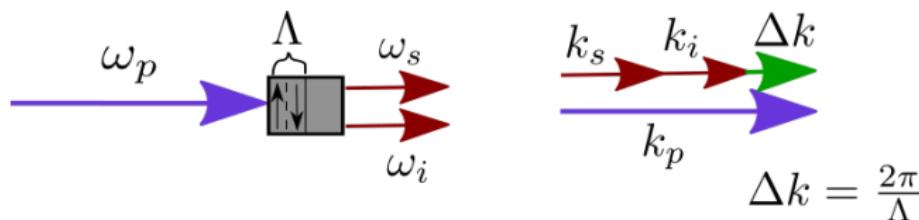
Birefringent Phase Matching, Quasi Phase Matching

What is Phase Matching?

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



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

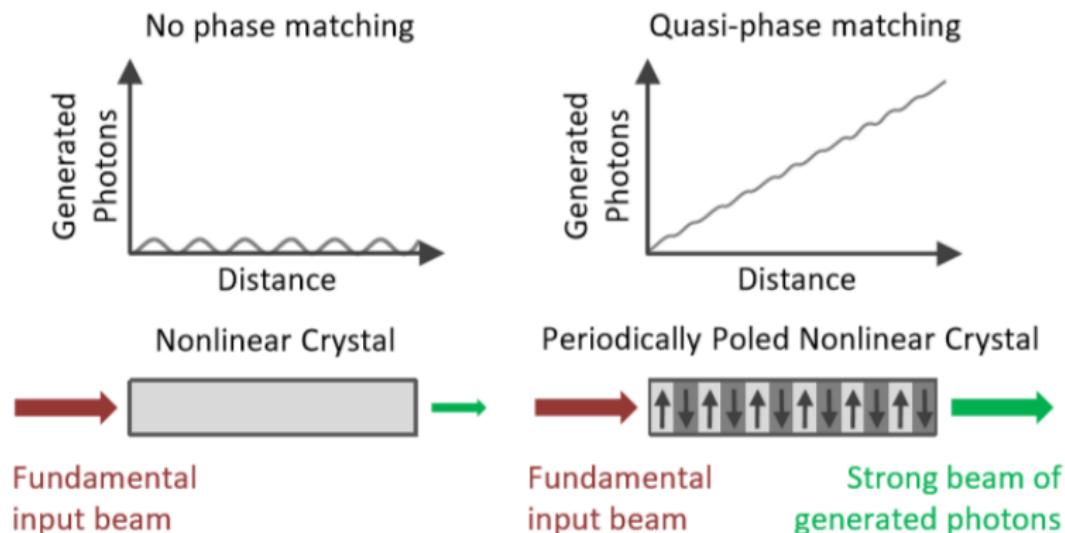


Phase Matching

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 : $e \rightarrow e + o$

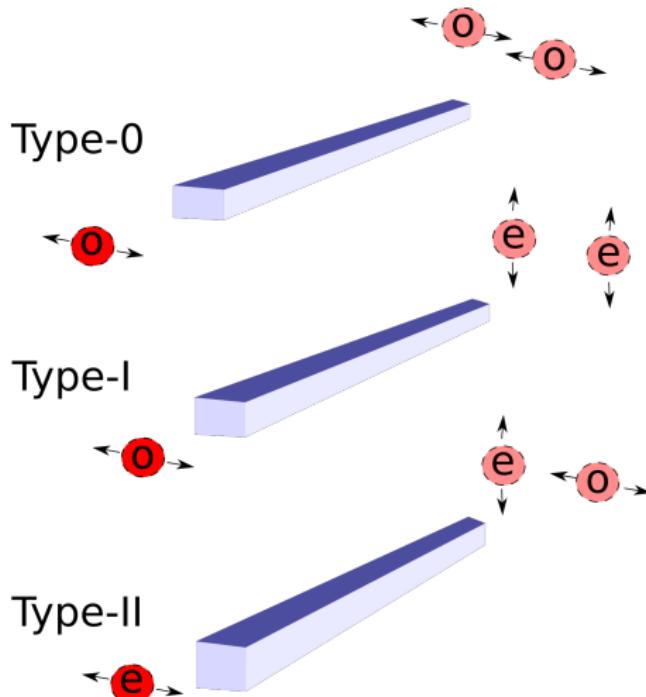
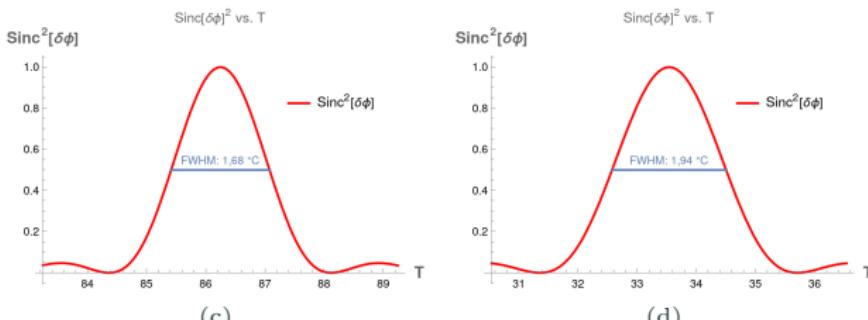
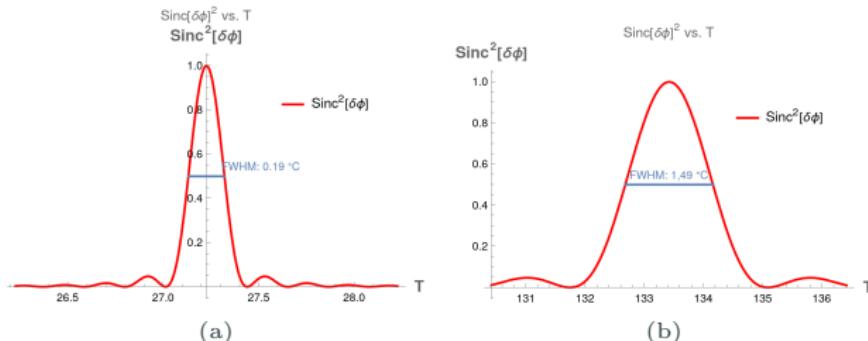


Illustration of different types of polarization conversions.

Phase Matching

Phase Matching Temperature

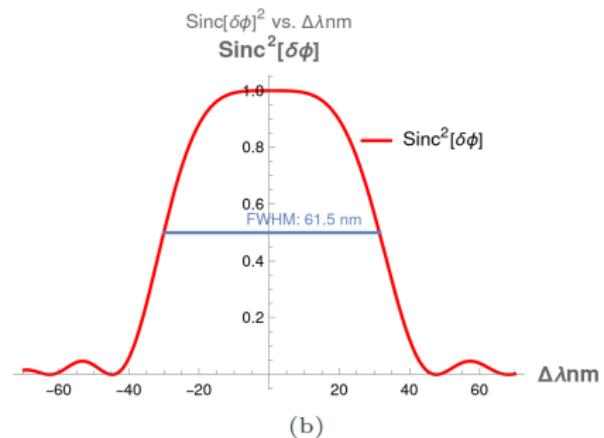
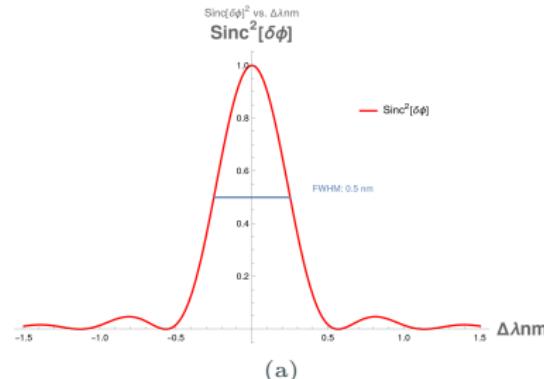
Phase Matching Temperature plots for a) Type-2 crystal of $9,12 \mu\text{m}$ poling period, b) Type-0, $19,25 \mu\text{m}$, c) Type-0, $19,45 \mu\text{m}$, d), Type-0 $19,65 \mu\text{m}$. $\delta\phi = \frac{L\Delta k}{2}$



Phase Matching

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 $19, 25 \mu\text{m}$



Existing sources

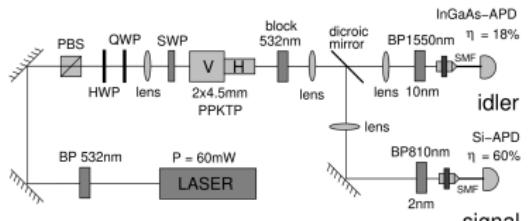
Comparison between different groups

Comparison of different sources

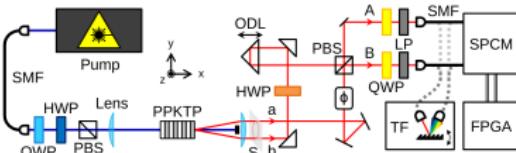
Who When	[1] 2022	[2] 2012	[3] 2007	[4] 2006	[5] 2010
Type	0	0	II	II	II
Brightness [$\frac{\text{Hz}}{\text{mW nm}}$]	$2,5 \times 10^6$	$0,278 \times 10^6$	$0,273 \times 10^6$	$0,005 \times 10^6$	$0,087 \times 10^6$
Bandwidth [nm]	106	2,3	0,3	1	0,3

Different Designs

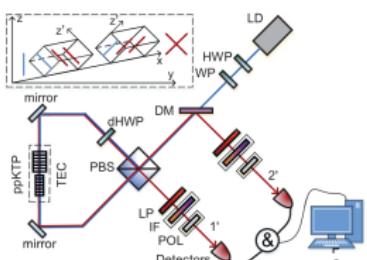
Different design ideas from other groups. a) [6], b) [7], c) [8], d) [9]



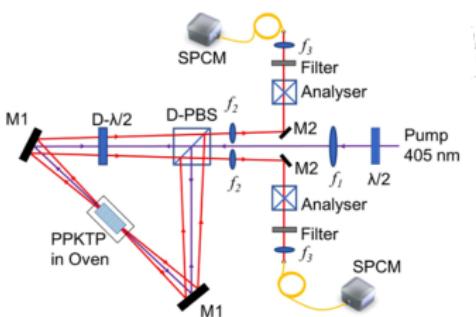
(a)



(b)



(c)



(d)

Distributing Entanglement

Introduction

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

- ▶ FMF/IJS
- ▶ Nodes in Ljubljana

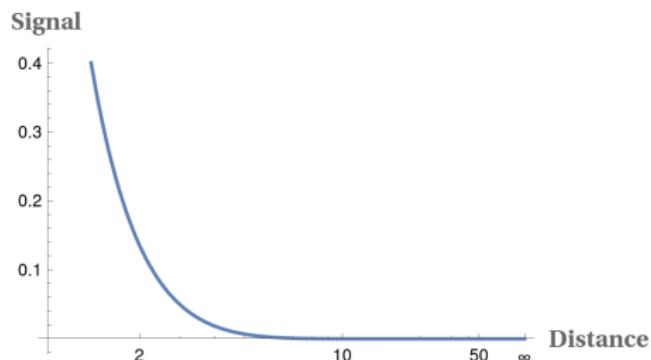
Entanglement

What is it good for?

- ▶ Entanglement source applications:
 1. Distributed Quantum Computation - Send a state then receive a result on the entangled pair,
 2. Quantum Sensing,
 3. Single Photon Source - Calibration
- ▶ 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

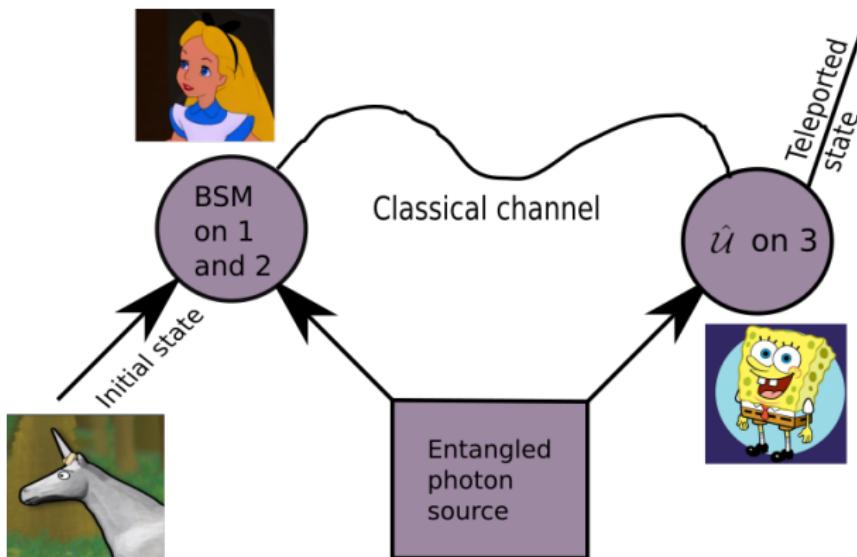


Loss in fiber over distance.

Distributing entanglement

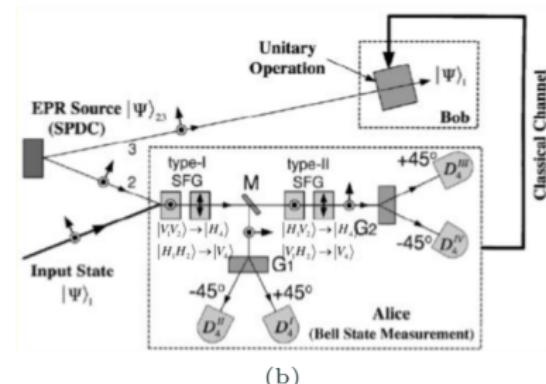
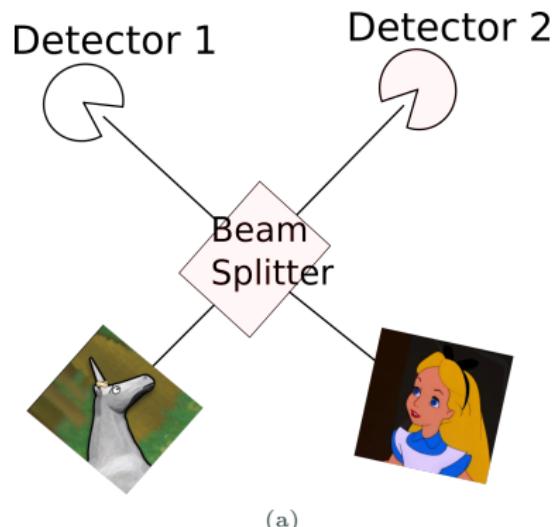
Teleportation

Illustration of Quantum Teleportation: Basis of Entanglement Swapping.



Entanglement Distribution

Bell State Measurement

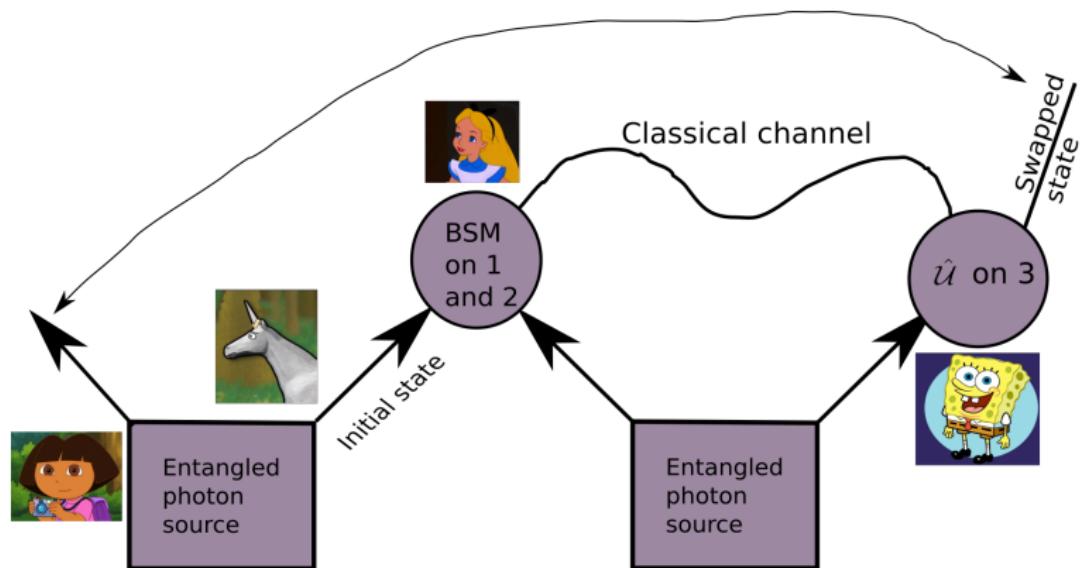


The simplest and the not so simple Bell State Measurement.

Distributing entanglement

Swapping

Illustration of Entanglement Swapping: Prerequisite for a Quantum Repeater.



Possible realization of the Slovenian Network



● Final user

● Relay / Switch
(trusted node)

● Relay
(trusted node - optional)

● Quantum
ground station

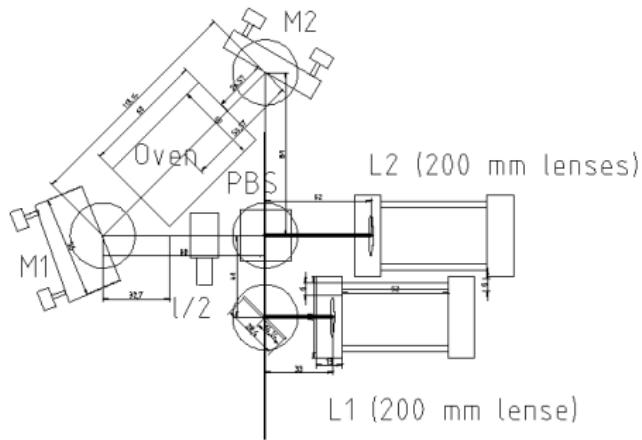
Present state

Parameters

- #### ► Focusing parameters [10]

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

- Correct lenses and distances for efficient coupling

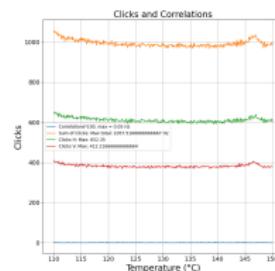


Design of the Sagnac interferometer.

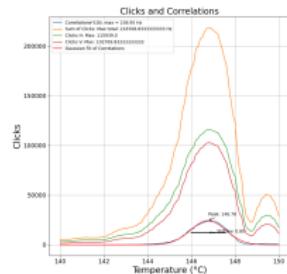
Present state

Phase Matching Temperature

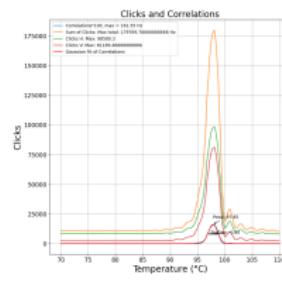
Temperature scans of Type-0 crystals with different poling periods, a) misaligned 19,25 μm , b) 19,25 μm , c) 19,45 μm , d) 19,65 μm



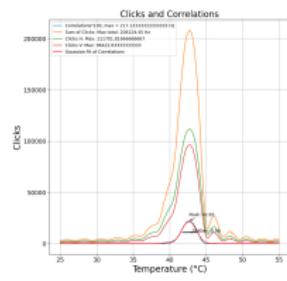
(a)



(b)



(c)



(d)

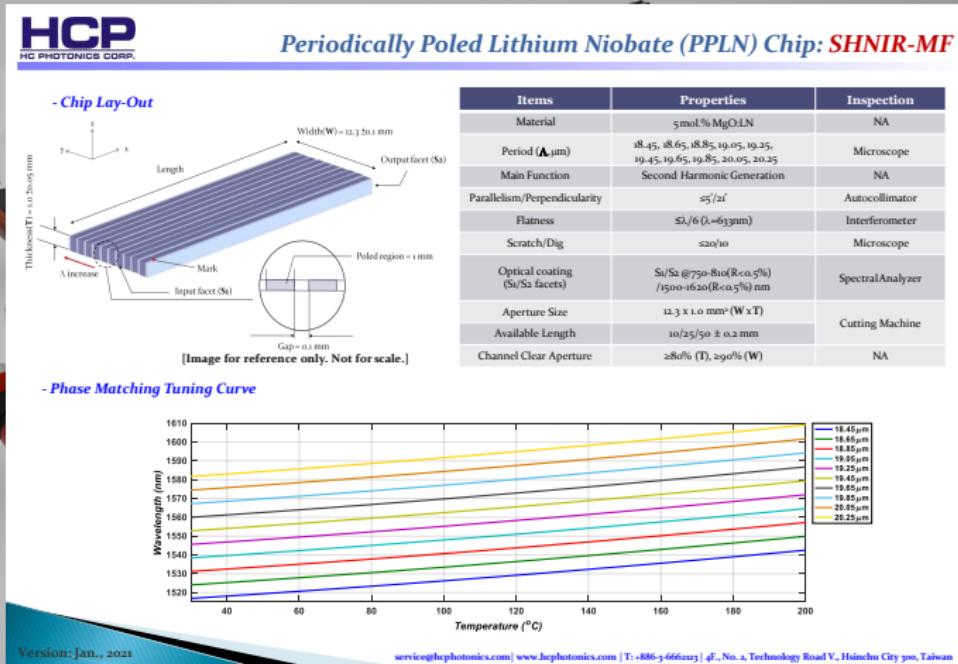
Present state

Building a Sagnac Interferometer



Present state

Building a Sagnac Interferometer



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

¹Linear setup

²Sagnac interferometer

Outlook

- ▶ Build the source
- ▶ Bell State Measurements
- ▶ Entanglement swapping between FMF and IJS
- ▶ Free space link to IJS
- ▶ Fiber link to reactor
- ▶ Use Quantum Memory from IJS group
- ▶ SiQUID
 - ▶ Building quantum network:
 1. Experimental network
 2. Government network

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