

# Generating and teleporting entanglement for quantum networks

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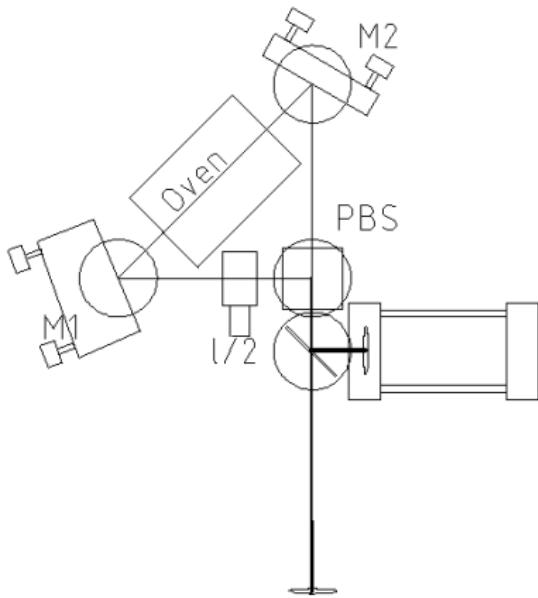
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## Motivation

- ▶ 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)

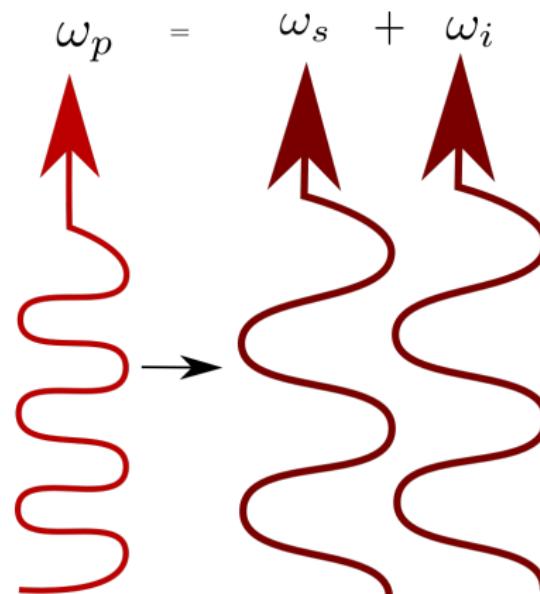


Illustration of SPDC

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

## Phase Matching

## Types

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

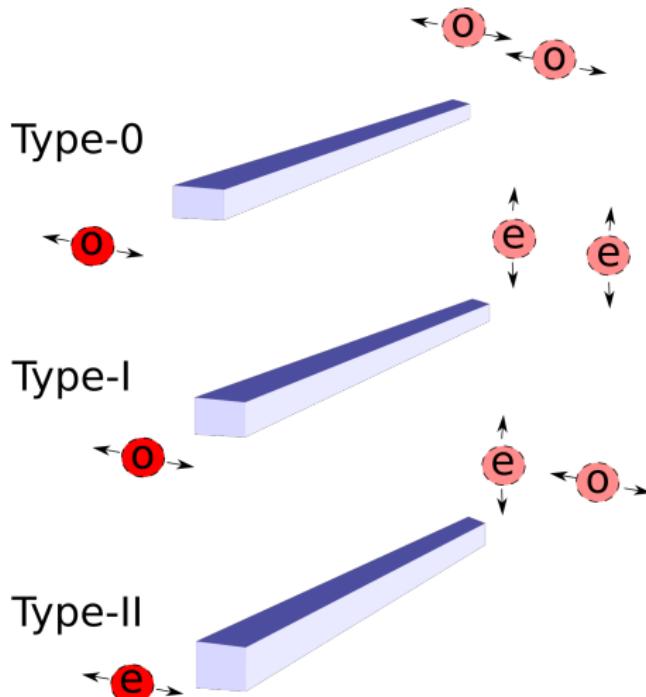


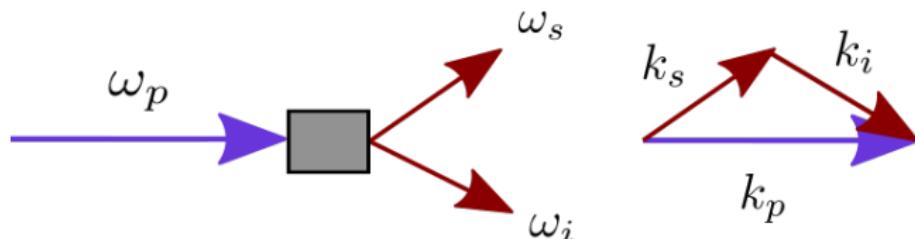
Illustration of different types of polarization conversions.

## Phase Matching

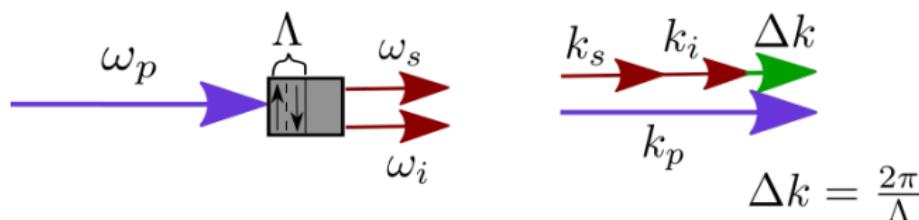
## Birefringent Phase Matching, Quasi Phase Matching

### What is Phase Matching?

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



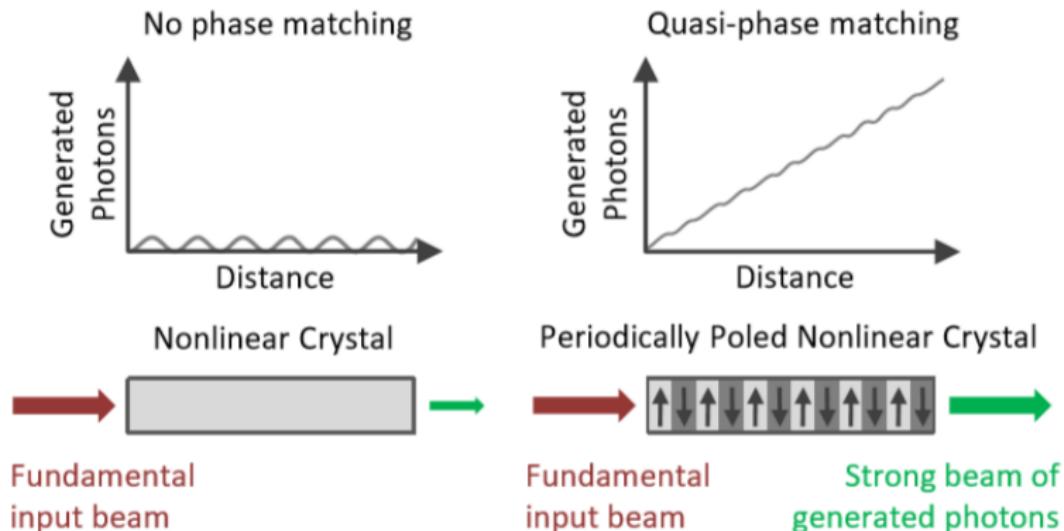
Quasi Phase Matching  $k_p - k_i - k_s - \Delta k = 0$ .



## Theory

### Crystal Size

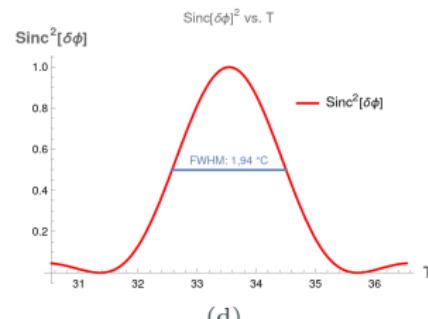
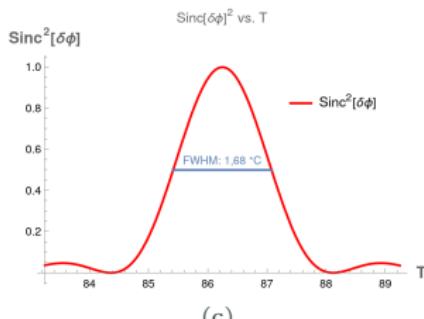
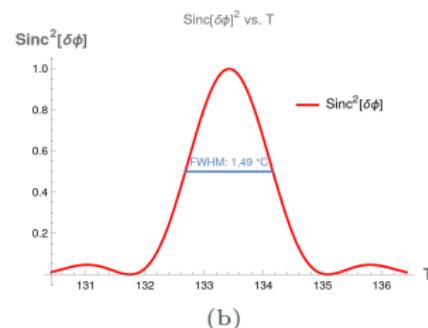
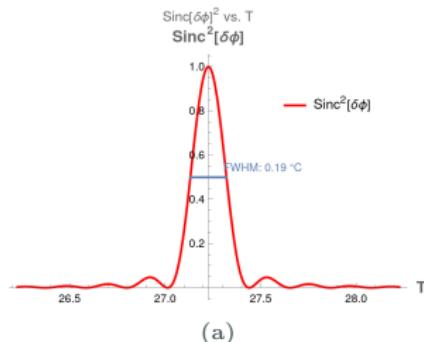
Difference in photon generation between a unpoled and poled crystal.  
Source: RP-Photonics



## Theory

## Phase Matching Temperature

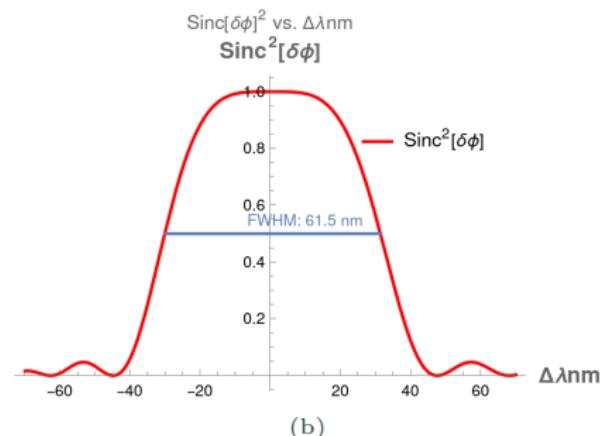
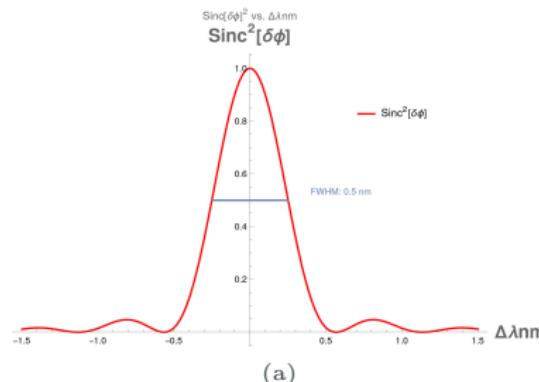
Phase Matching Temperature calculations for a) Type-2 crystal of 9,12  $\mu\text{m}$  poling period, b) Type-0, 19,25  $\mu\text{m}$ , c) Type-0, 19,45  $\mu\text{m}$ , d), Type-0 19,65  $\mu\text{m}$



# 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

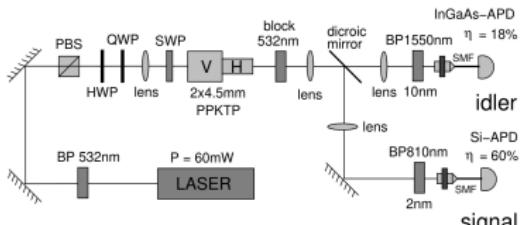
## State of the Art

### Comparison of different sources

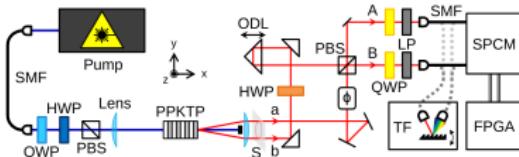
Who When	[1] 2022	[2] 2012	[3] 2007	[4] 2006	[5] 2010
Type	0	0	II	II	II
Brightness [ $\frac{\text{Hz}}{\text{mW nm}}$ ]	$2,5 \times 10^6$	$0,278 \times 10^6$	$0,273 \times 10^6$	$0,005 \times 10^6$	$0,087 \times 10^6$
Bandwidth [ nm ]	106	2,3	0,3	1	0,3

## Different Designs

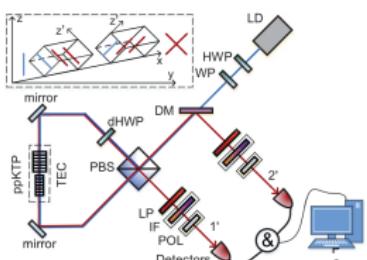
Different design ideas from other groups. a) [6], b) [7], c) [8], d) [9]



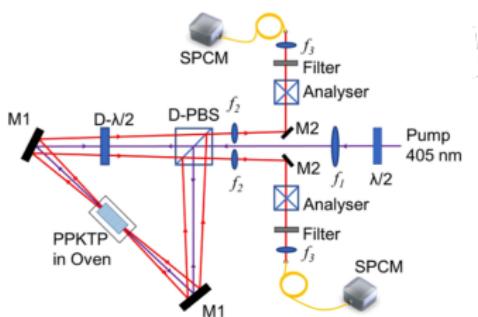
(a)



(b)



(c)



(d)

Why do we care about entanglement?

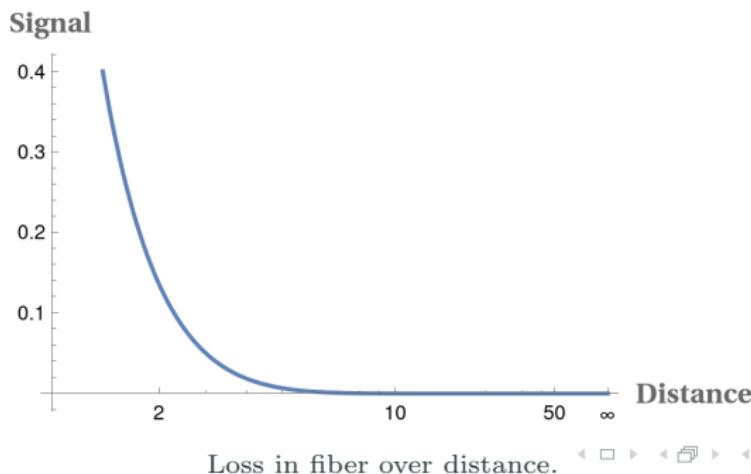
- ▶ Entanglement sources by themselves → useless if you can't use them.
  - ▶ Loss in fiber

Relevant fiber loss.  
*Source:* Thorlabs

$\lambda$ [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

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

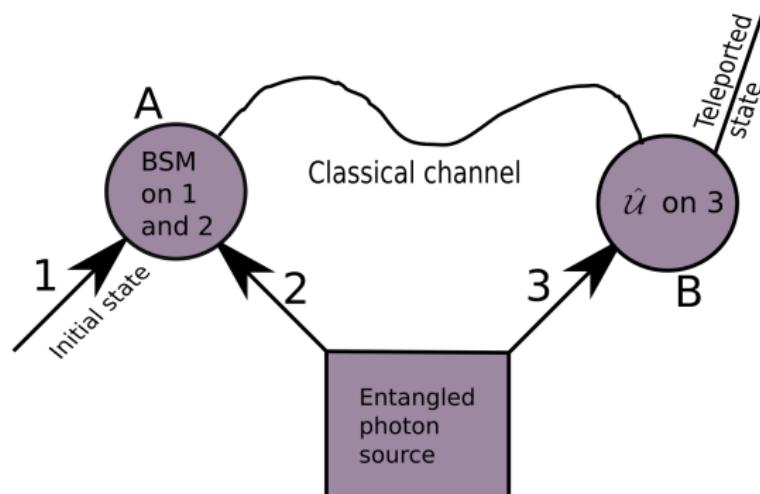
$$|\Psi_{\text{Type-0}}\rangle = \frac{1}{\sqrt{2}}(\sin(\alpha)a_H^\dagger(\omega_s)a_H^\dagger(\omega_i) +$$

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

Entanglement Teleportation

## Teleportation

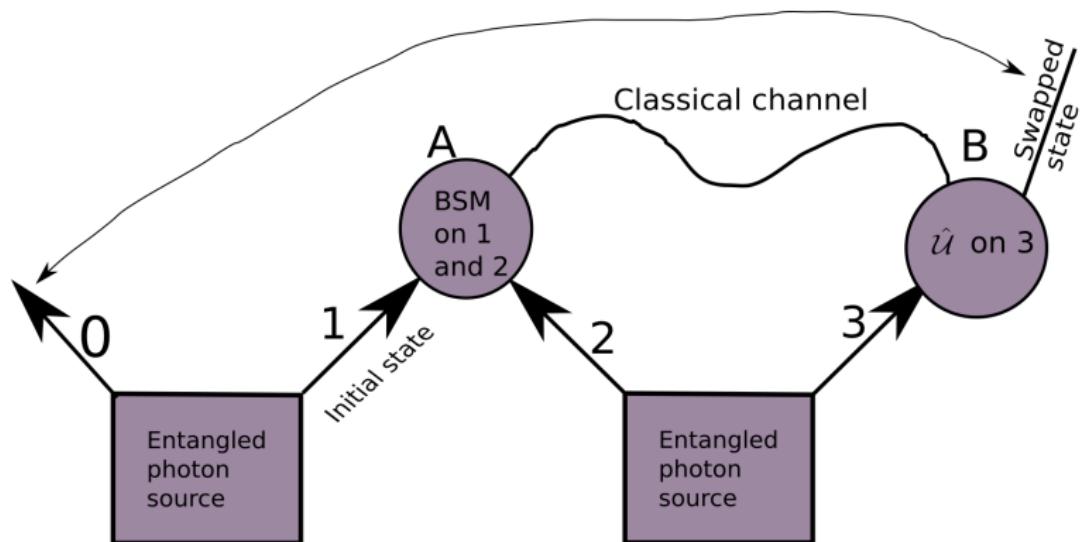
### Illustration of Entanglement Teleportation.



## Entanglement Swapping

## Swapping

### Illustration of Entanglement Swapping.



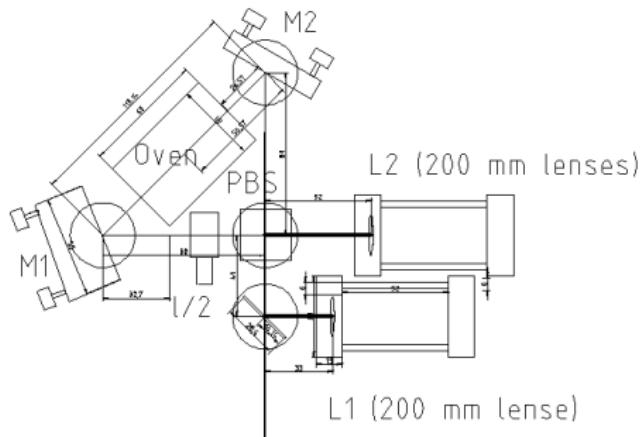
## Present state

### Parameters

- #### ► Focusing parameters [10]

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

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

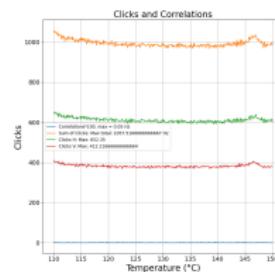


## Design of the Sagnac interferometer.

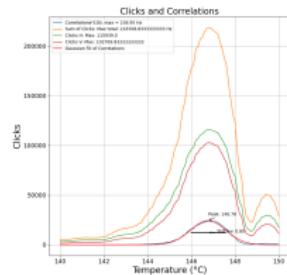
# Present state

## Phase Matching Temperature

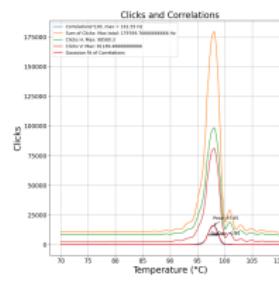
Temperature scans of Type-0 crystals with different poling periods, a) misaligned 19,25  $\mu\text{m}$ , b) 19,25  $\mu\text{m}$ , c) 19,45  $\mu\text{m}$ , d) 19,65  $\mu\text{m}$



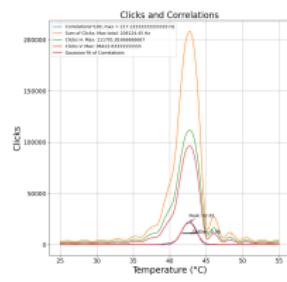
(a)



(b)



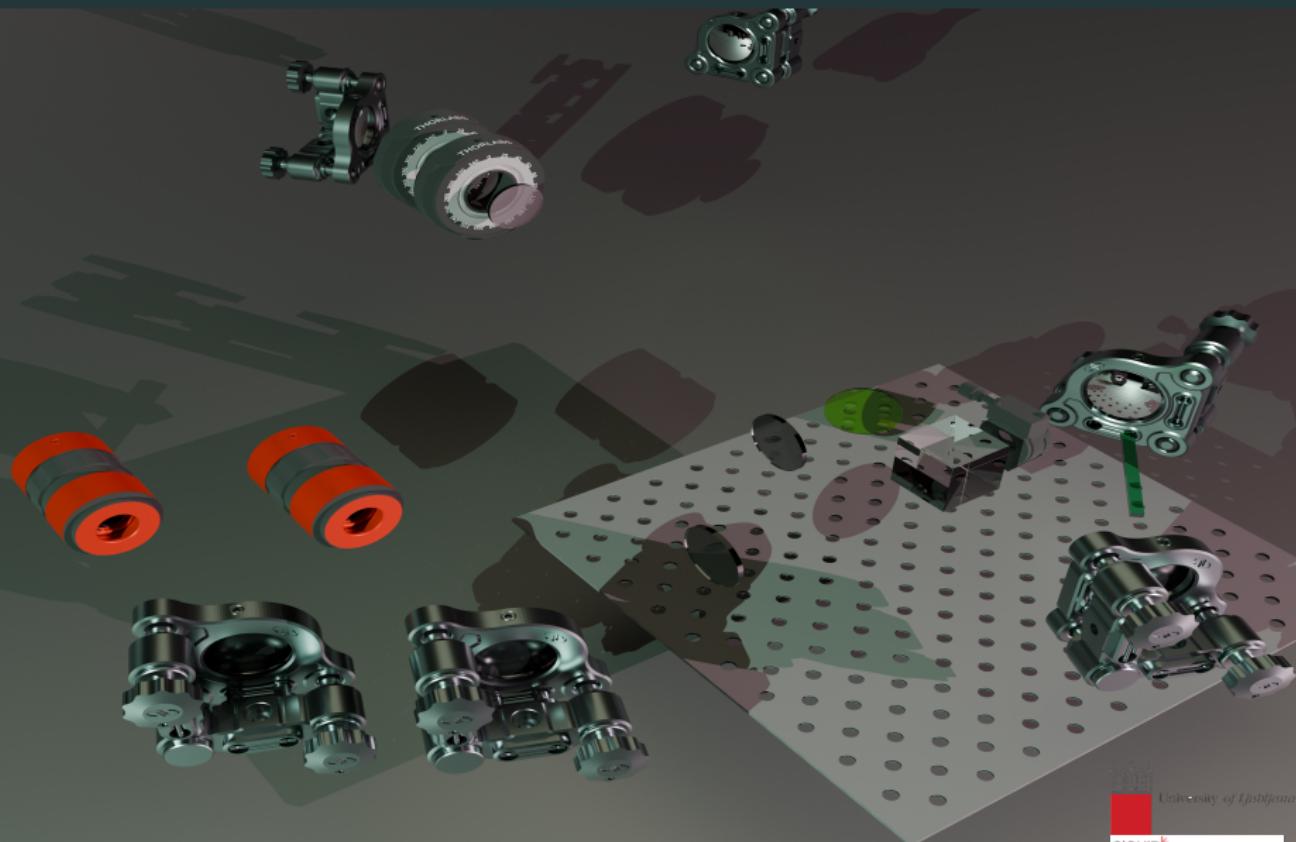
(c)



(d)

## Present state

## Building a Sagnac Interferometer



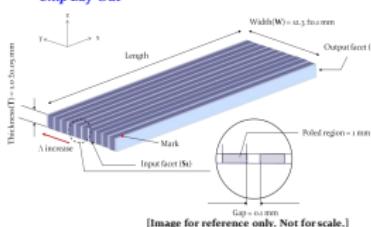
# Present state

## Building a Sagnac Interferometer



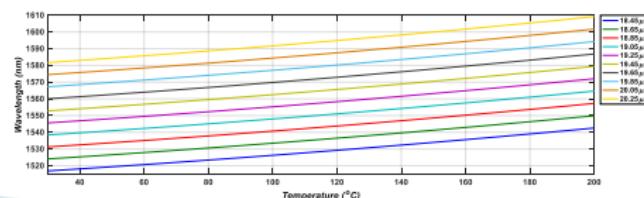
### Periodically Poled Lithium Niobate (PPLN) Chip: SHNIR-MF

#### - Chip Lay-Out



[Image for reference only. Not for scale.]

#### - Phase Matching Tuning Curve



Version: Jan. 2023

service@hephotonics.com | www.hephotonics.com | T: +886-3-6662211 | 4F., No. 2, Technology Road V, Hsinchu City 300, Taiwan

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

# References

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