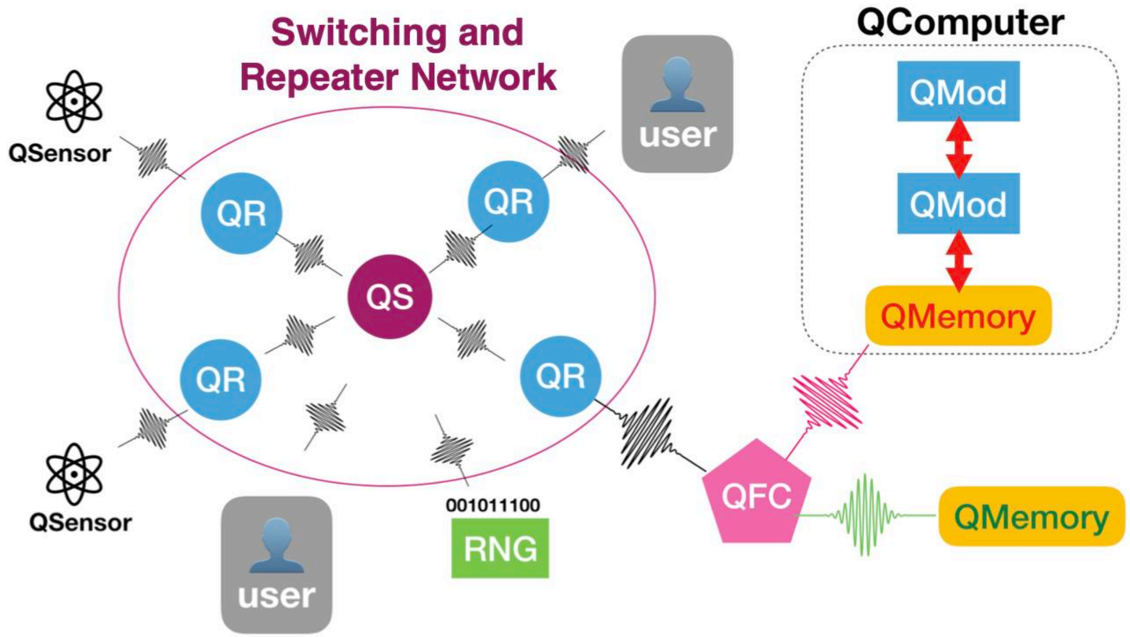
Photonic quantum information processing using frequency degree of freedom

Rikizo Ikuta
The University of Osaka

2025/10/1 QSP2025

Quantum internet/interconnect

D. Awschalom et al., PRX Quantum 2, 017002 (2021). Development of Quantum Interconnects (QuICs) for Next-Generation Information Technologies

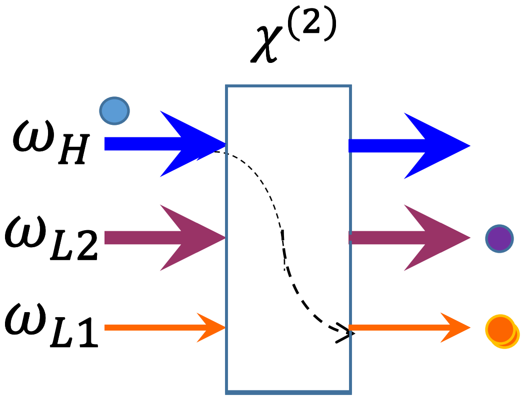


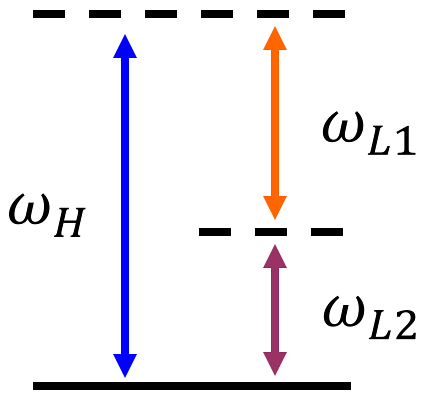
Key Photonic Quantum Devices and Technologies

- Optical communication channels: low-loss optical fibers, Free-space optical links, Satellite-to-ground links
- Switching, routing, polarization/phase control
- Quantum frequency conversion (QFC): Interface of matter systems with telecom photons
- Interconversion and coupling of photonic qubits between different DoF: pol., freq., time-bin, spatial modes
- Entangled photon sources: Nonlinear optical media, fiber-coupled modules
- Multiplexing of frequency, spatial, temporal modes
- Multidimensional encoding (qudits)
- Single-photon detectors: superconducting detectors, avalanche photodiodes (APDs), homodyne detectors

QIP based on second-order nonlinear optical interaction

Hamiltonian : $\hat{\mathcal{H}} = i\hbar g\left(\hat{a}_{L2}^{\dagger}\hat{a}_{H}\hat{a}_{L1}^{\dagger} - \hat{a}_{L2}\,\hat{a}_{H}^{\dagger}\hat{a}_{L1}\right)$





($\omega_H = \omega_{L1} + \omega_{L2}$)

Application 1: Quantum frequency conversion (QFC)

Pump light: L2
Input mode: H or L1 (single photon)
Output mode: L1 or H (single photon)

$$\hat{\mathcal{H}}_{eff} = i\hbar\left(\xi_2\hat{a}_H\hat{a}_{L1}^{\dagger} - \xi_2^{*}\hat{a}_H^{\dagger}\hat{a}_{L1}\right) \qquad \xi_2 = g\langle\hat{a}_{L2}\rangle$$

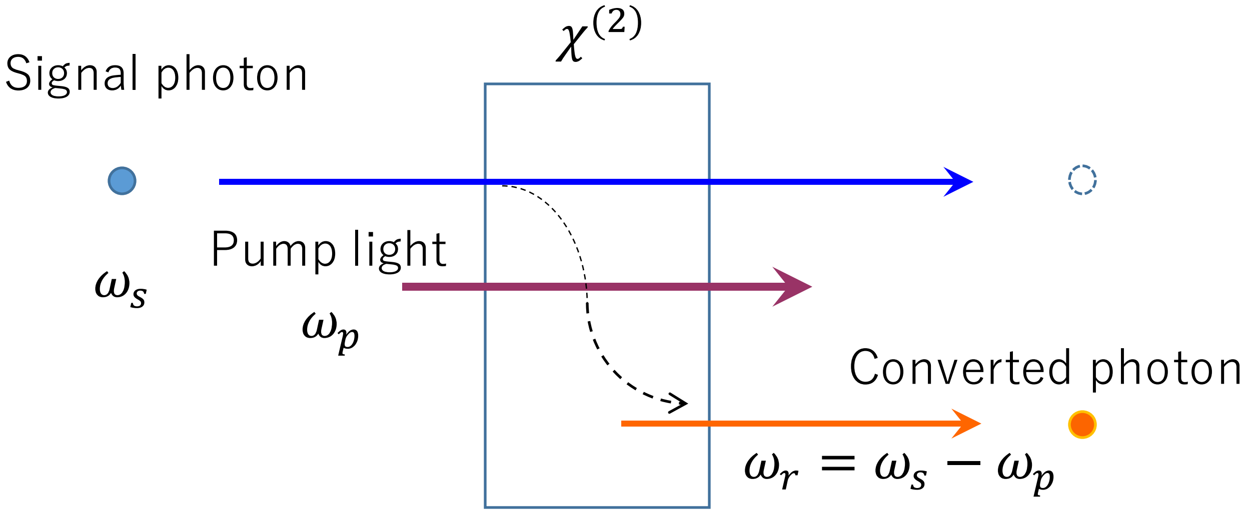
Application 2: Photon pair generation

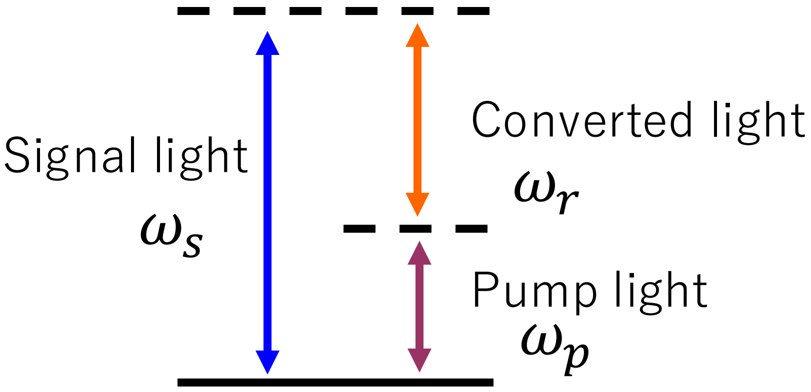
Pump light: H
Input mode: None (vacuum) at L1 and L2
Output mode: L1 and L2 (single-photon pair)

$$\hat{\mathcal{H}}_{eff} = i\hbar\left(\xi_H\hat{a}_{L2}^{\dagger}\hat{a}_{L1}^{\dagger} - \xi_H^{*}\hat{a}_{L2}\hat{a}_{L1}\right) \qquad \xi_H = g\langle\hat{a}_H\rangle$$

Quantum frequency conversion based on $\chi^{(2)}$ nonlinearity

Difference frequency generation





Hamiltonian :
$$\hat{\mathcal{H}} = ig\left(\hat{a}_P^\dagger \hat{a}_s \hat{a}_r^\dagger - \hat{a}_P \hat{a}_s^\dagger \hat{a}_r\right)$$
$$\sim i(\xi^* \hat{a}_s \hat{a}_r^\dagger - \xi \hat{a}_s^\dagger \hat{a}_r)$$

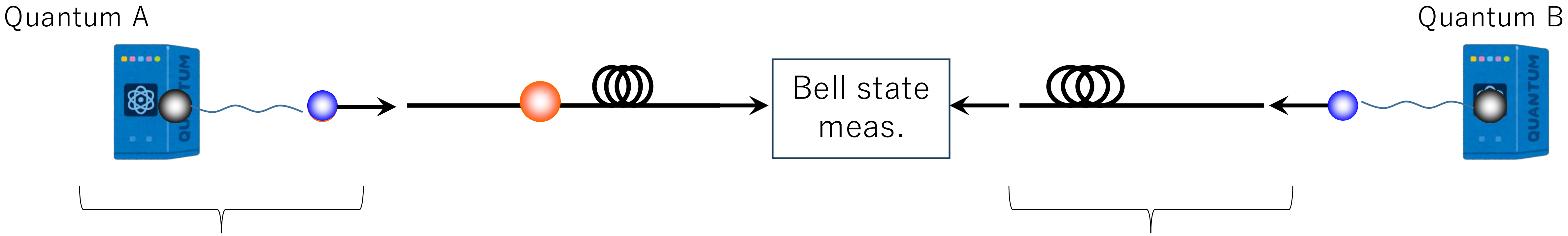
($\xi = g\langle \hat{a}_P \rangle$ Sufficiently strong pump light)

Input-output relation :
$$\begin{pmatrix} a_{s,out} \\ a_{r,out} \end{pmatrix} = \begin{pmatrix} \cos(\theta/2) & -e^{-i\phi}\sin(\theta/2) \\ e^{i\phi}\sin(\theta/2) & \cos(\theta/2) \end{pmatrix} \begin{pmatrix} a_{s,in} \\ a_{r,in} \end{pmatrix},$$
$(\theta/2 = |\xi|\tau)$

For $\theta = \pi$, maximum conversion efficiency is achieved.

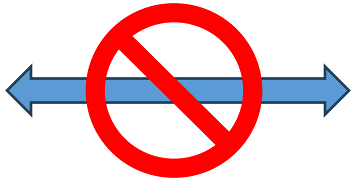
Watt-level pump power is required when a conventional PPLN waveguide is used.

Quantum interconnect via optical fiber communication



Matter-photon entanglement

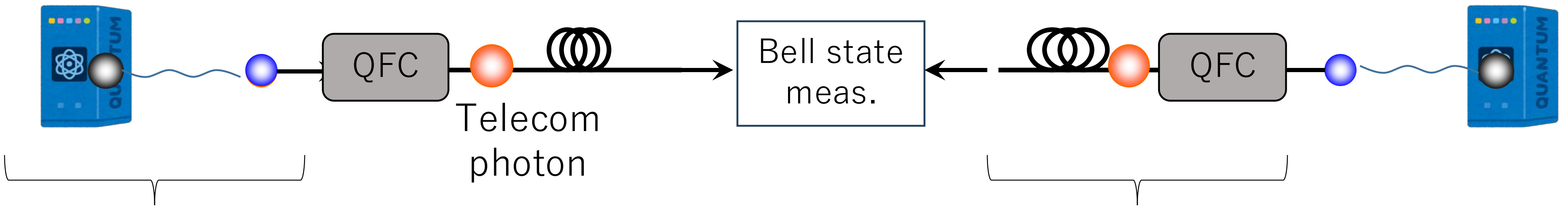
Sr^{+}	: 422 nm
Ba^{+}	: 493 nm
Pr^{3+} : Y_2SiO_5	: 606 nm
NV center	: 637 nm
SiV center	: 738 nm
Rb	: 780 nm, 795 nm
Cs	: 852 nm, 895 nm
Ca^{+}	: 854 nm, 866 nm



Optical fiber communication

O-band	1260 ~ 1360nm (center: 1310nm)
S/C/L-band	1460 ~ 1625nm (center: 1550nm)

Quantum interconnect via optical fiber communication



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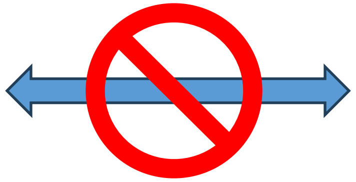
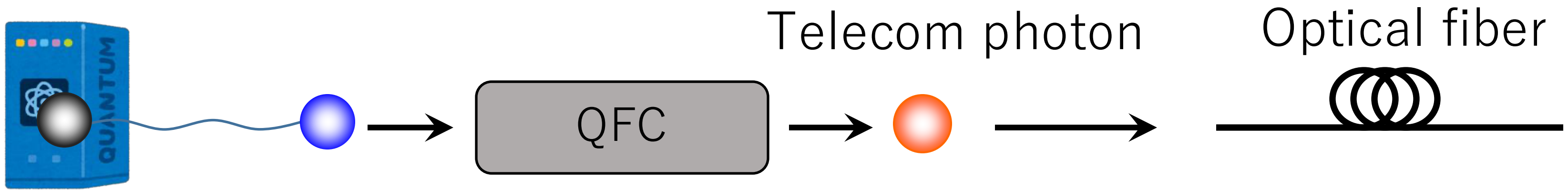


O-band	1260 ~ 1360nm (center: 1310nm)
S/C/L-band	1460 ~ 1625nm (center: 1550nm)

Quantum frequency conversion (QFC) bridges the mismatch.

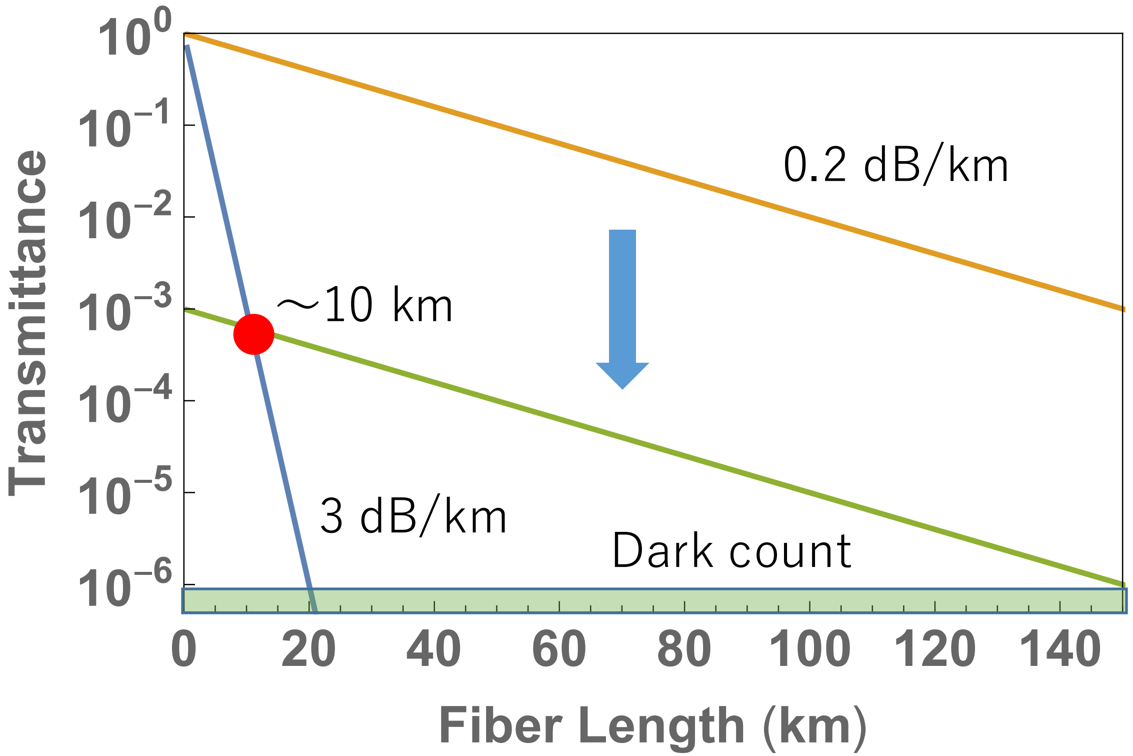
Quantum frequency conversion (QFC)



Transmittance of optical fiber

Fiber length	1 km	10 km	100 km
～ 800 nm　(3 dB/km)	0.5	10^{-3}	10^{-30}
～ 1550 nm（0.2 dB/km)	0.95	0.63	10^{-2}

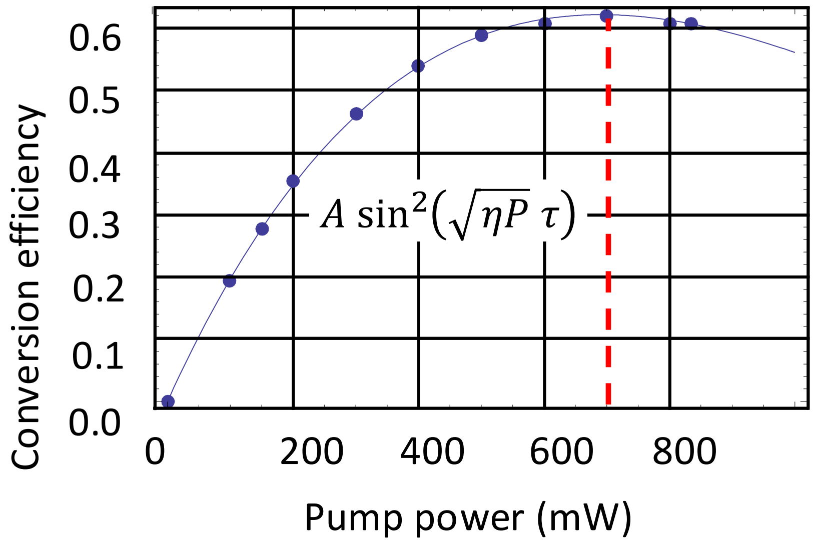
Even if the conversion efficiency of the QFC is 0.1%, the overall efficiency is higher when long-distance communication (e.g., over 10 km) is considered.



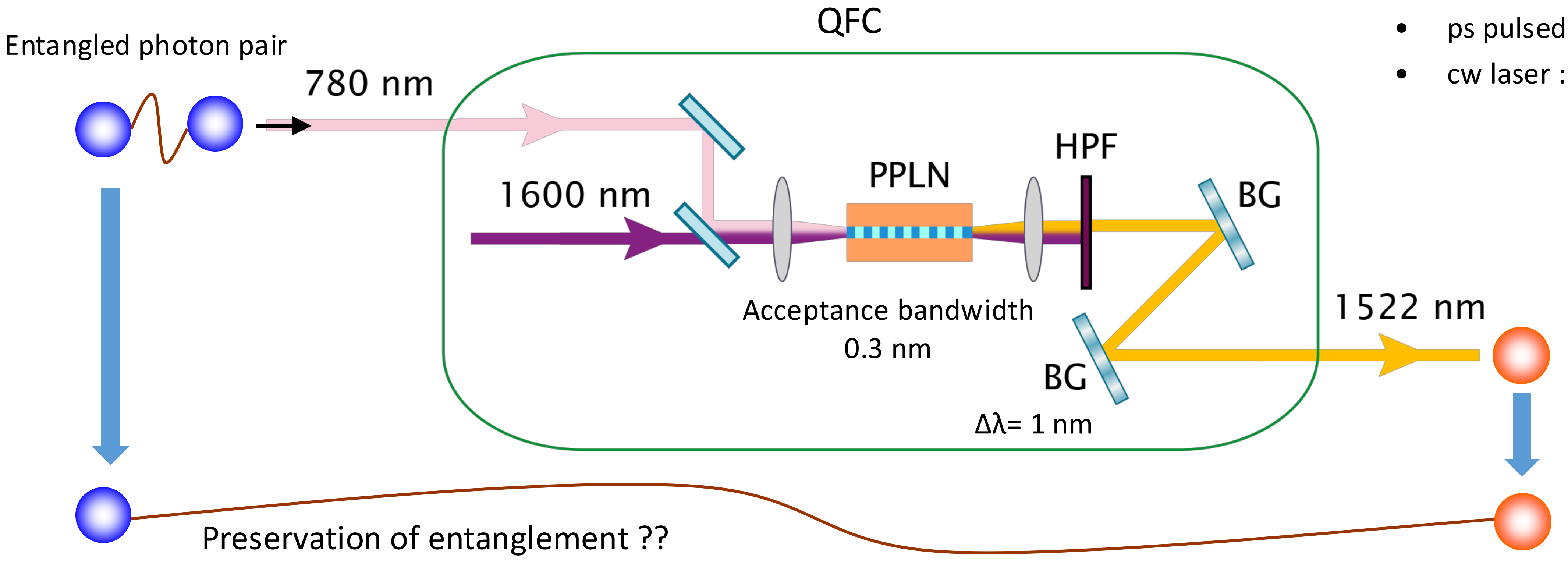
About 60% QFC efficiency was achieved.
(H. Weinfurter Group, PRL 2020)

QFC is an essential building block for the quantum Internet.

QFC experiment using PPLN waveguide



- ps pulsed light : 62 %
- cw laser : 71 %

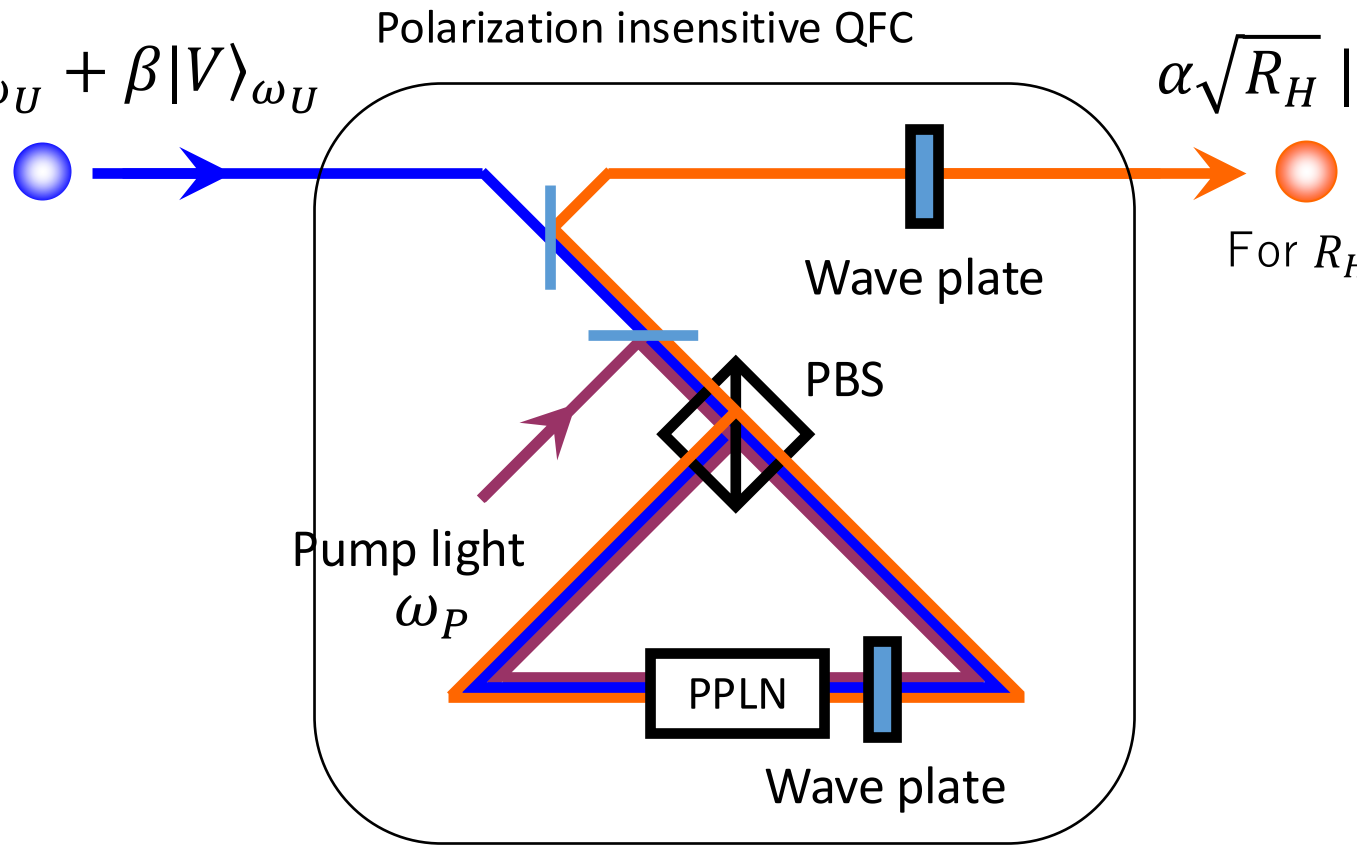


R. Ikuta, Y. Kusaka, T. Kitano, H. Kato, T. Yamamoto, M. Koashi, N. Imoto, Nature Commun. 2, 537 (2011).

Polarization insensitive QFC

- PPLN waveguide for V-polarized photon ＋ Sagnac interferometer

$\alpha|H\rangle_{\omega_U} + \beta|V\rangle_{\omega_U}$



$\alpha\sqrt{R_H}\,|H\rangle_{\omega_L} + \beta\sqrt{R_V}|V\rangle_{\omega_L}$

For $R_H = R_V$, polarization is preserved.

R. Ikuta, T. Kobayashi, T. Kawakami, S. Miki, M. Yabuno, T. Yamashita, H. Terai, M. Koashi, T. Mukai, T. Yamamoto, N. Imoto, Nature Commun. 9, 1997 (2018).

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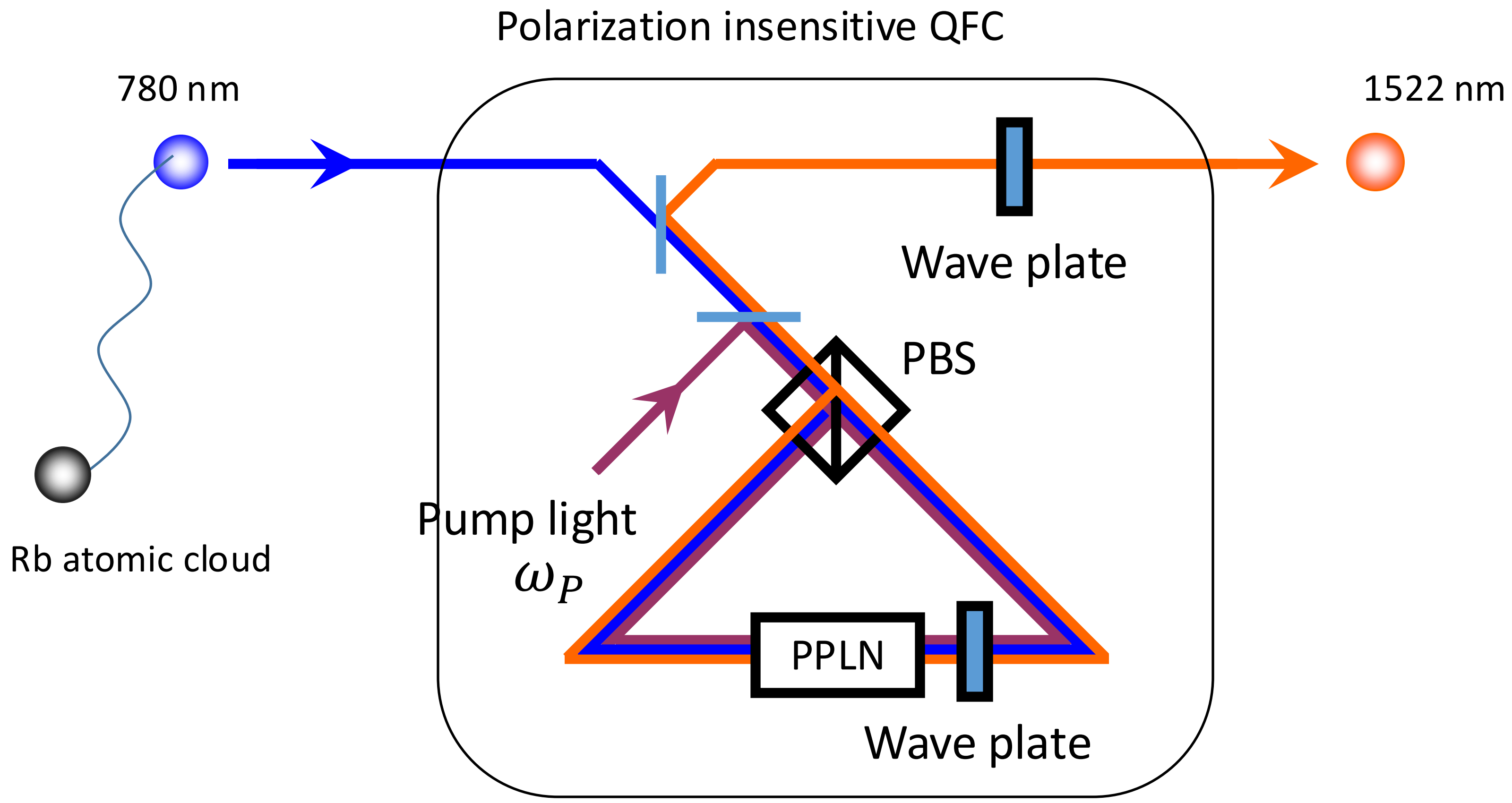
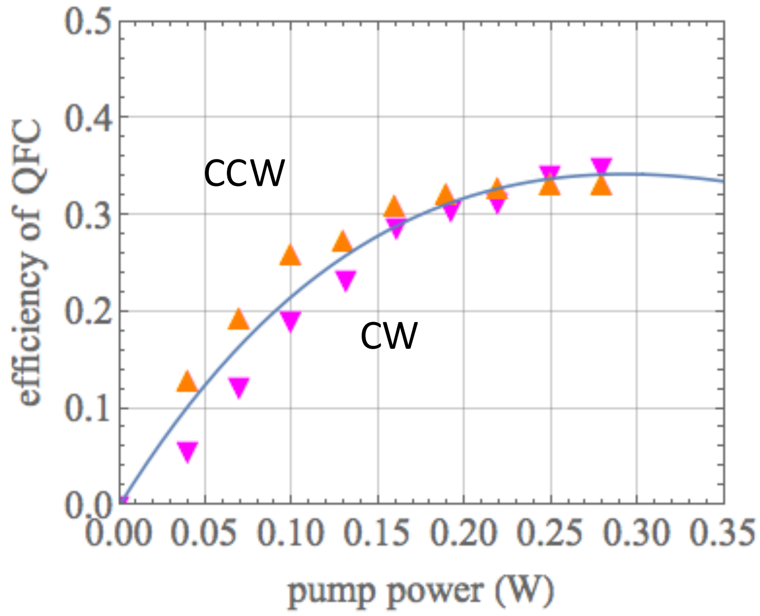




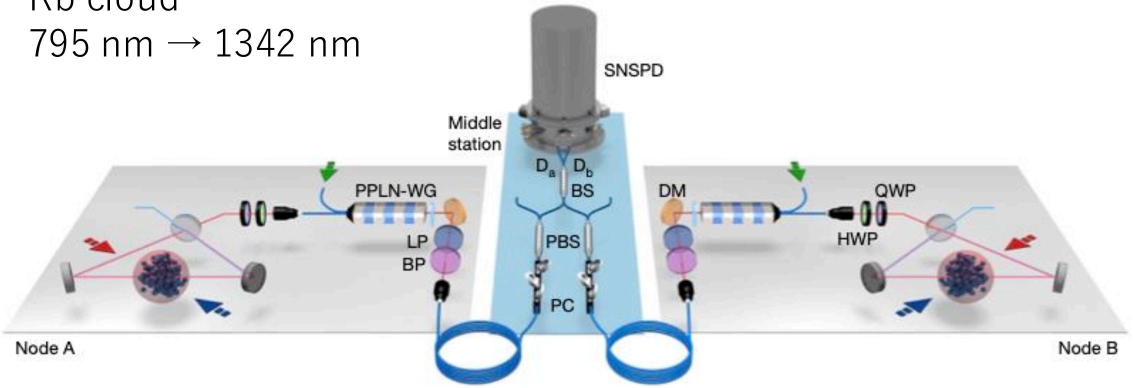
～ 33 % conversion efficiency

R. Ikuta, T. Kobayashi, T. Kawakami, S. Miki, M. Yabuno, T. Yamashita, H. Terai, M. Koashi, T. Mukai, T. Yamamoto, N. Imoto, Nature Commun. 9, 1997 (2018).

Entanglement between remote matter systems using QFC

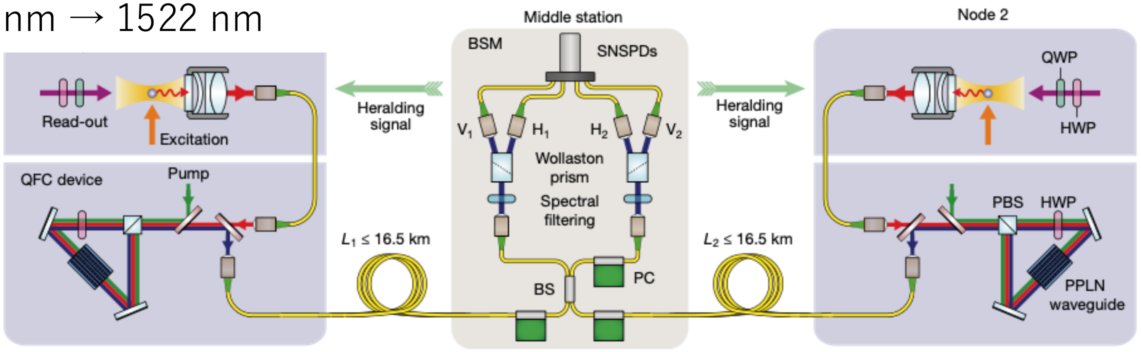
Over 22km deployed fiber (J. W. Pan Group, Nature 2020)

Rb cloud
795 nm → 1342 nm

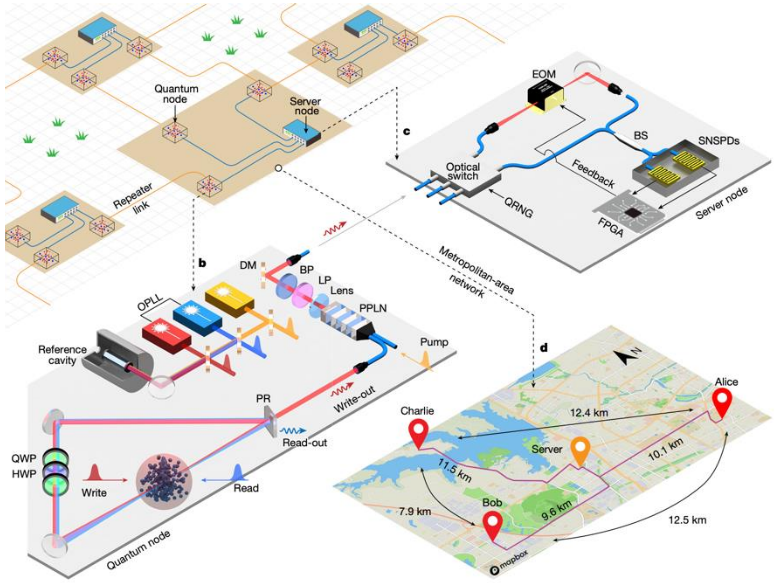


Over 33km fiber (H. Weinfurter Group, Nature 2022)

Single Rb atom
780 nm → 1522 nm

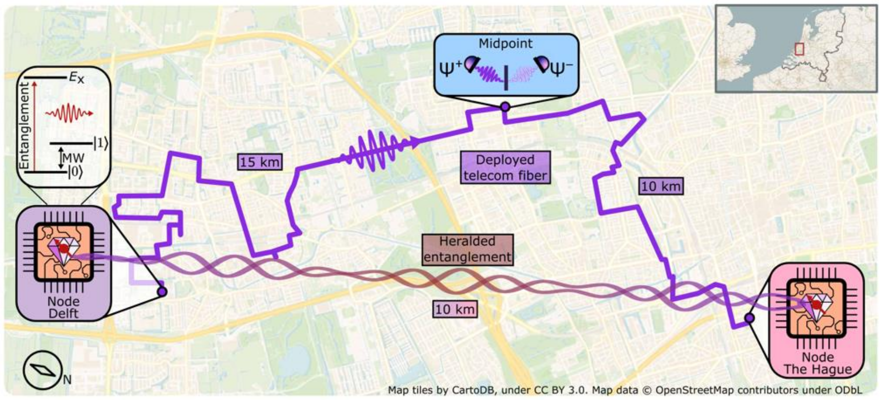


Between any pair of nodes among three
(J. W. Pan Group, Nature 2024)



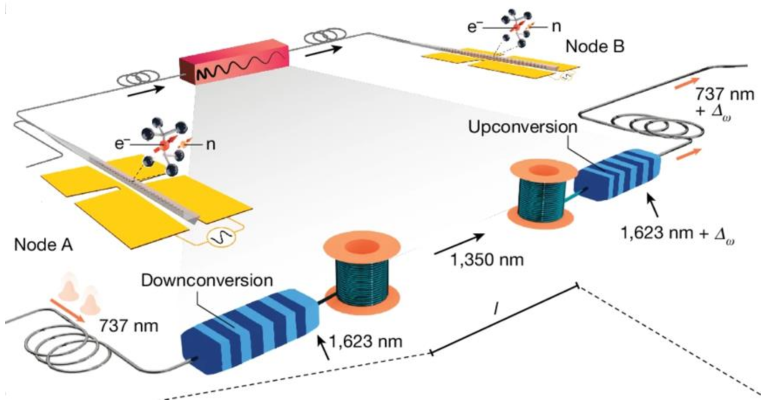
Over 25km deployed fiber
(R. Hanson Group, Sci. Adv. 2024)

NV center
637 nm → 1588 nm



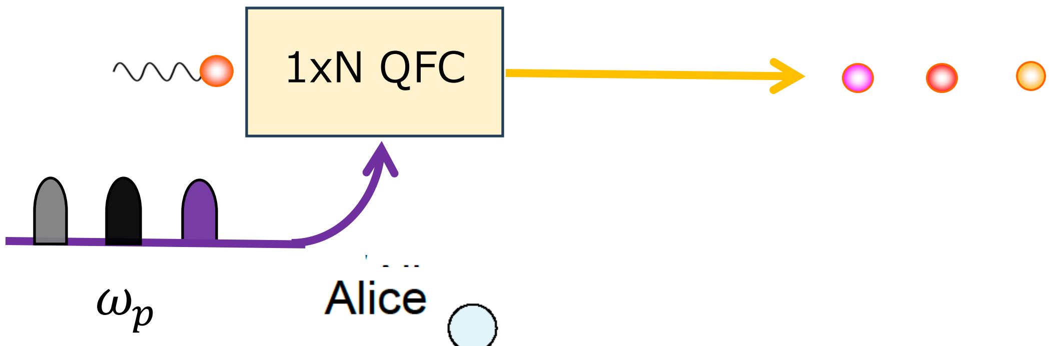
Over 35km deployed fiber
(M. Lukin Group, Nature 2024)

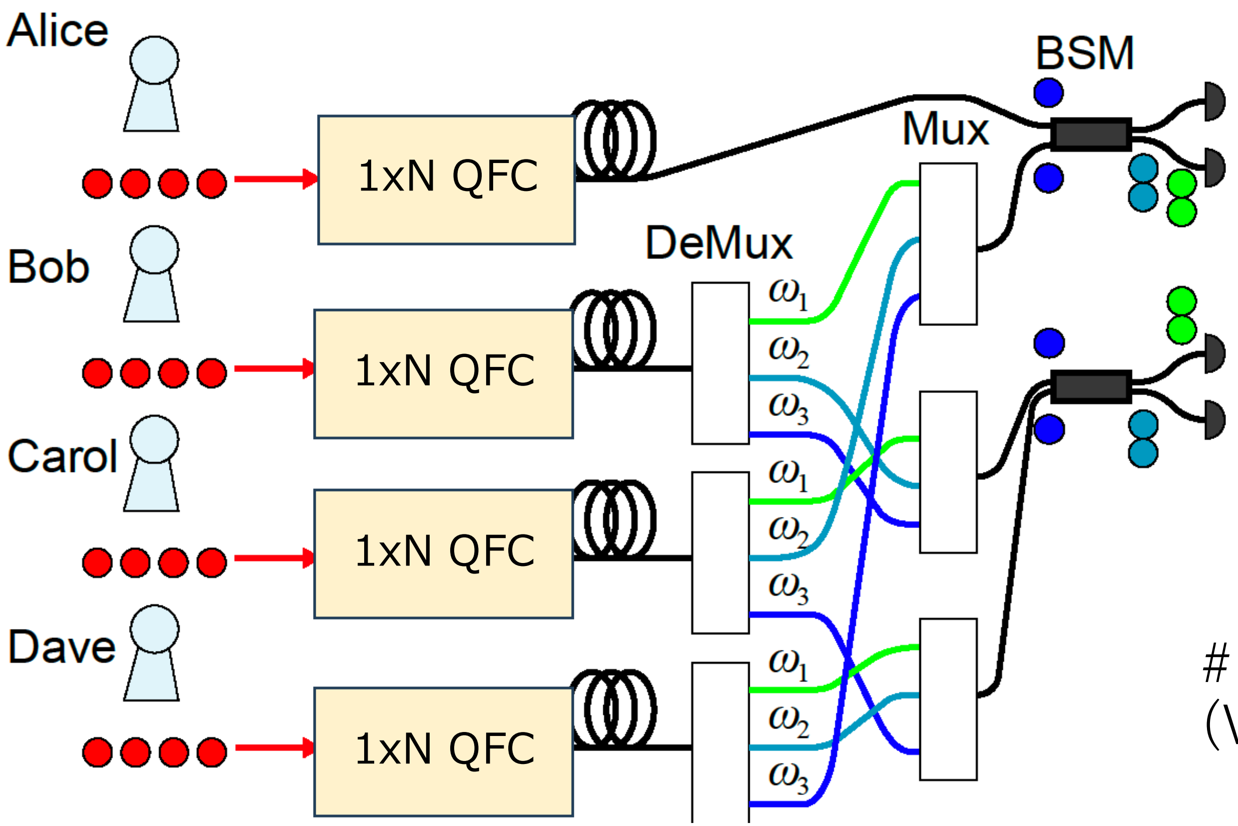
SiV center
737 nm ⇄ 1350 nm

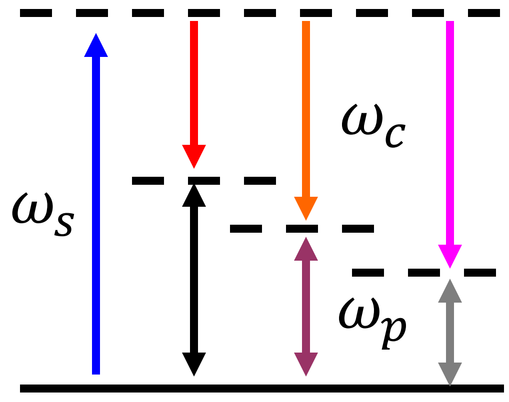


1xN channel selective quantum frequency conversion

T. Arizono et al., arXiv: 2409.08025 (2024)







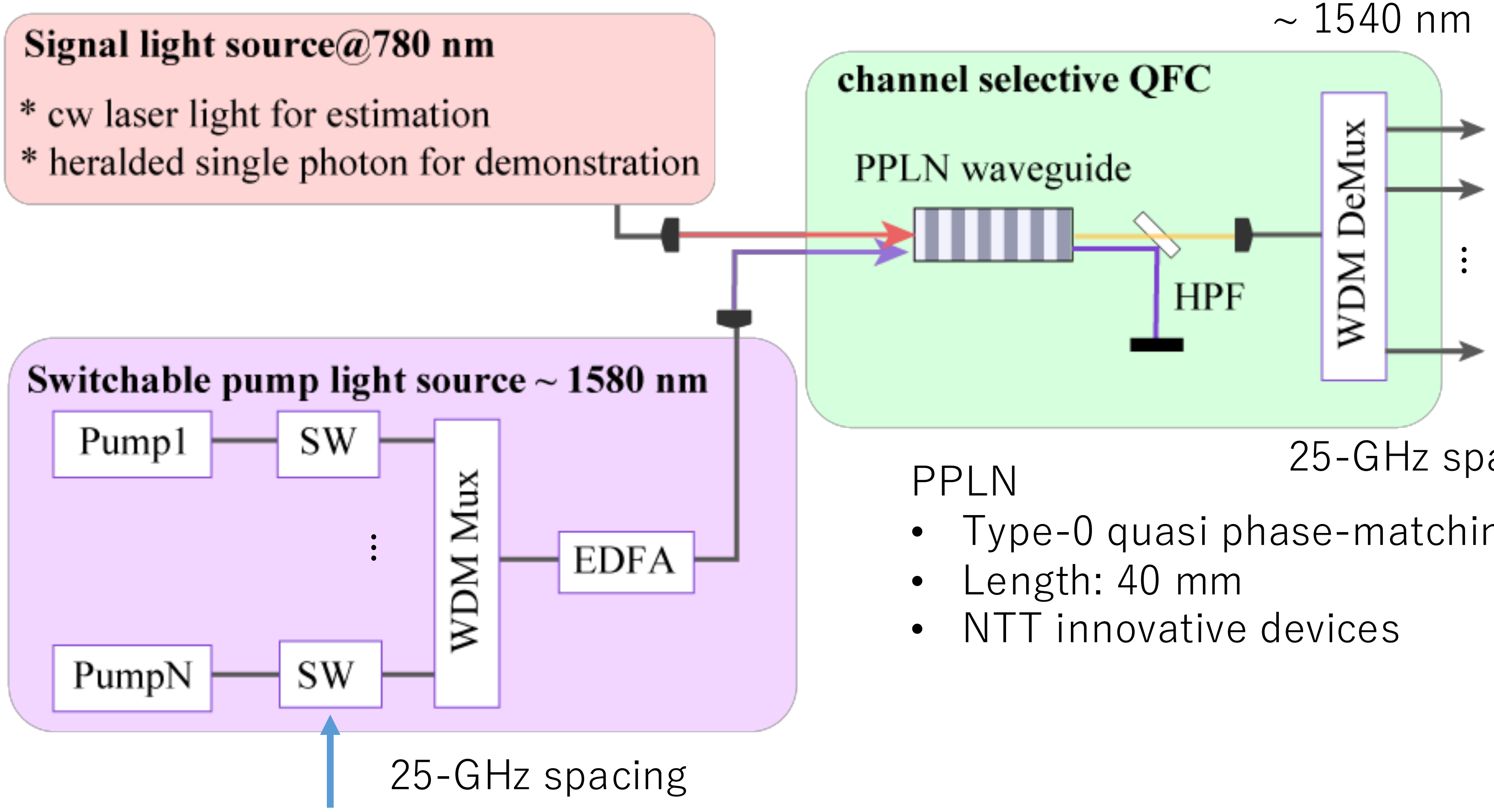
$\omega_c = \omega_s - \omega_p$

# of BSM, MuX, DeMux : $O(N)$
(Vizing's theorem)

Experiemntal setup

T. Arizono et al., arXiv: 2409.08025 (2024)

~ 1540 nm



Measurement

* Power meter
* Photo diode
* Photon counter (SNSPD)

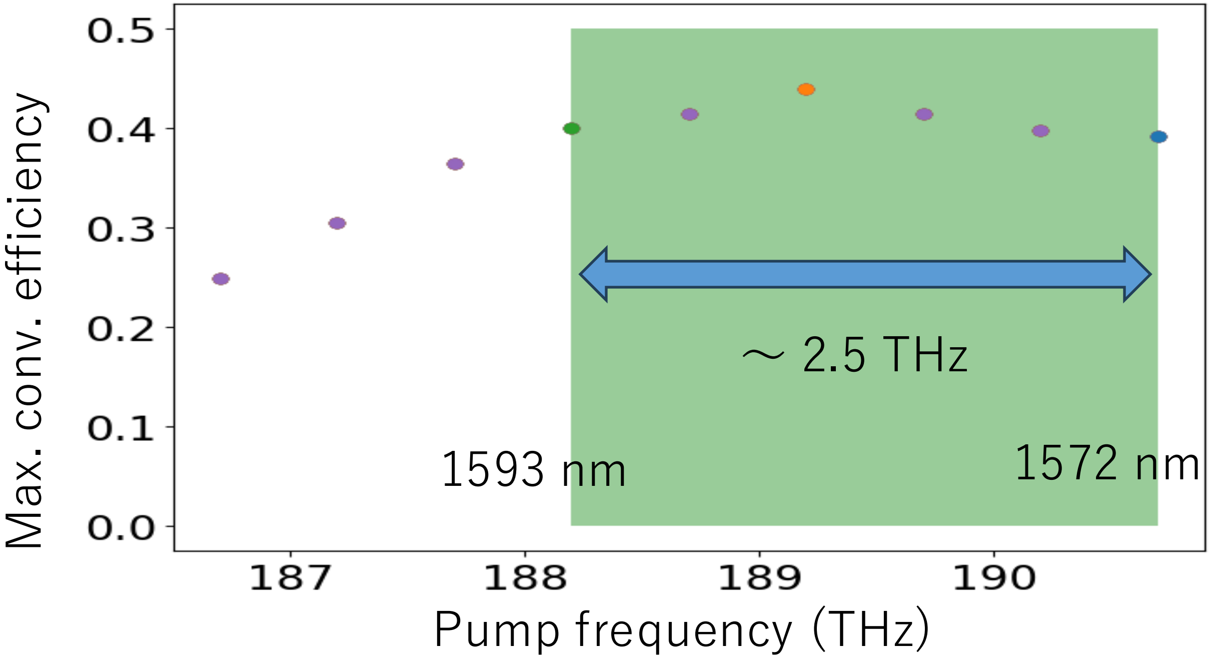
25-GHz spacing

PPLN
- Type-0 quasi phase-matching
- Length: 40 mm
- NTT innovative devices

25-GHz spacing

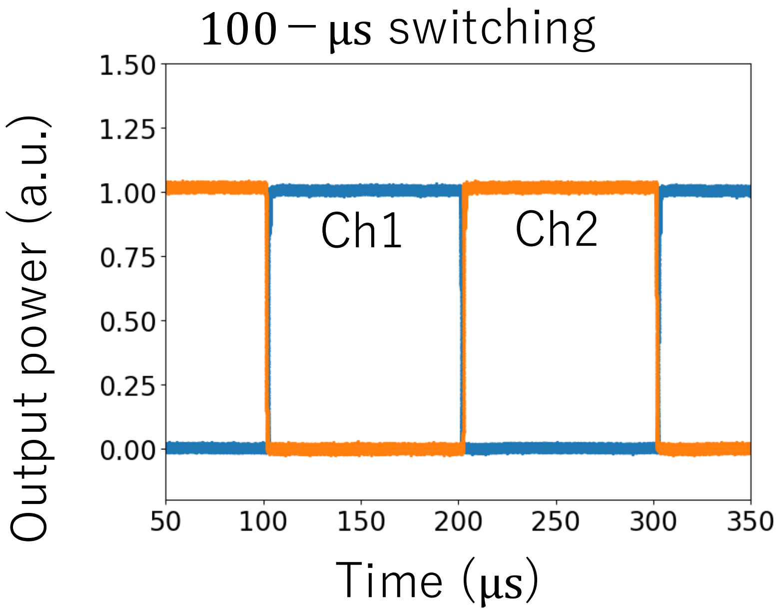
BOA1550PXS, 1ns
w/ controller CLD1015, 4 μs

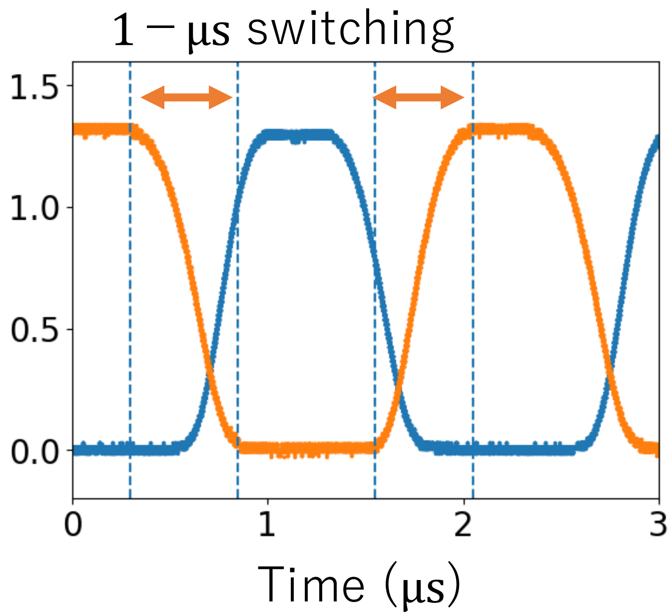
Experimental result: Bandwidth and switching speed



T. Arizono et al., arXiv: 2409.08025 (2024)

Over 100-ch multiplexing is possible with 25-GHz spacing.

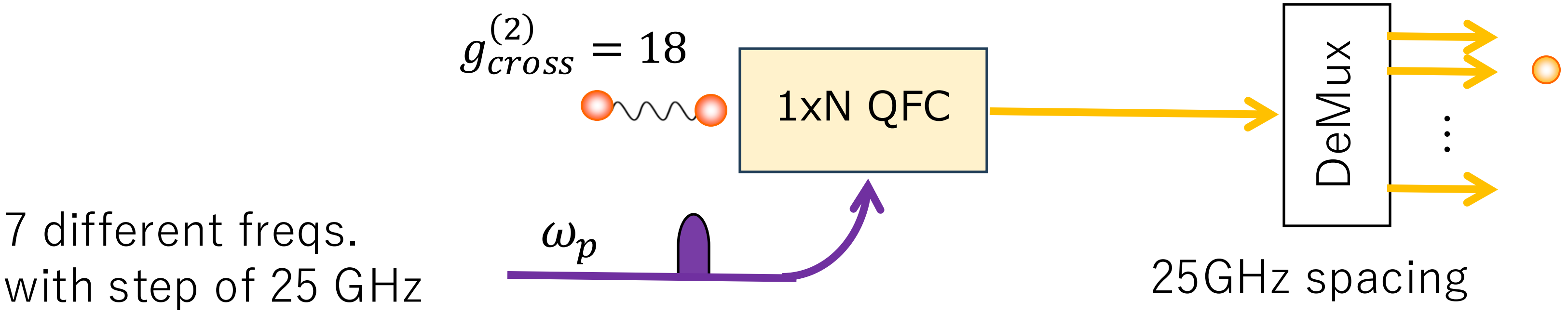




- Rise/Fall time is ~ 0.5 μs
- The speed is enough to route narrowband photons emitted from atomic or ionic systems.

Experimental result: QFC of photons

T. Arizono et al., arXiv: 2409.08025 (2024)



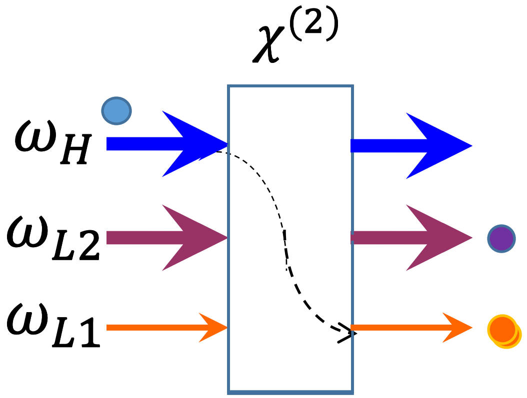
	pump (ch1)	pump (ch2)	pump (ch3)	pump (ch4)	pump (ch5)	pump (ch6)	pump (ch7)
output ch1	7.35 ± 0.22	1.00 ± 0.03	0.97 ± 0.03	1.02 ± 0.02	1.00 ± 0.03	0.99 ± 0.02	1.01 ± 0.02
output ch2	0.96 ± 0.03	7.79 ± 0.17	1.01 ± 0.03	1.00 ± 0.02	1.00 ± 0.03	1.00 ± 0.02	1.00 ± 0.02
output ch3	1.01 ± 0.03	1.03 ± 0.03	7.56 ± 0.17	1.01 ± 0.02	1.02 ± 0.03	0.99 ± 0.02	0.99 ± 0.02
output ch4	0.99 ± 0.03	1.00 ± 0.02	0.98 ± 0.03	7.01 ± 0.14	0.99 ± 0.03	1.01 ± 0.02	1.00 ± 0.02
output ch5	1.00 ± 0.03	1.00 ± 0.02	1.02 ± 0.03	1.03 ± 0.02	6.73 ± 0.21	1.02 ± 0.02	0.98 ± 0.03
output ch6	1.01 ± 0.03	0.99 ± 0.02	1.00 ± 0.03	1.01 ± 0.02	1.01 ± 0.03	6.61 ± 0.13	1.00 ± 0.02
output ch7	0.98 ± 0.03	0.98 ± 0.02	1.00 ± 0.03	1.03 ± 0.02	1.03 ± 0.03	1.02 ± 0.03	6.39 ± 0.13

1xN channel sepective QFC was successfully demonstrated.

QIP based on second-order nonlinear optical interaction

A periodically poled $LiNbO_3$ (PPLN) waveguide is widely used in QIP:

1. A large variety of wavelength selection is possible by adjusting poling period.
2. Waveguide structure gives the long interaction time.



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Pump light: L2
Input mode: H or L1 (single photon)
Output mode: L1 or H (single photon)

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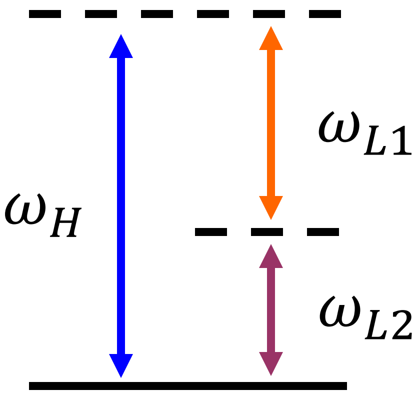

$(\omega_H = \omega_{L1} + \omega_{L2})$

Application 2: Photon pair generation

Pump light: H
Input mode: None (vacuum) at L1 and L2
Output mode: L1 and L2 (single-photon pair)

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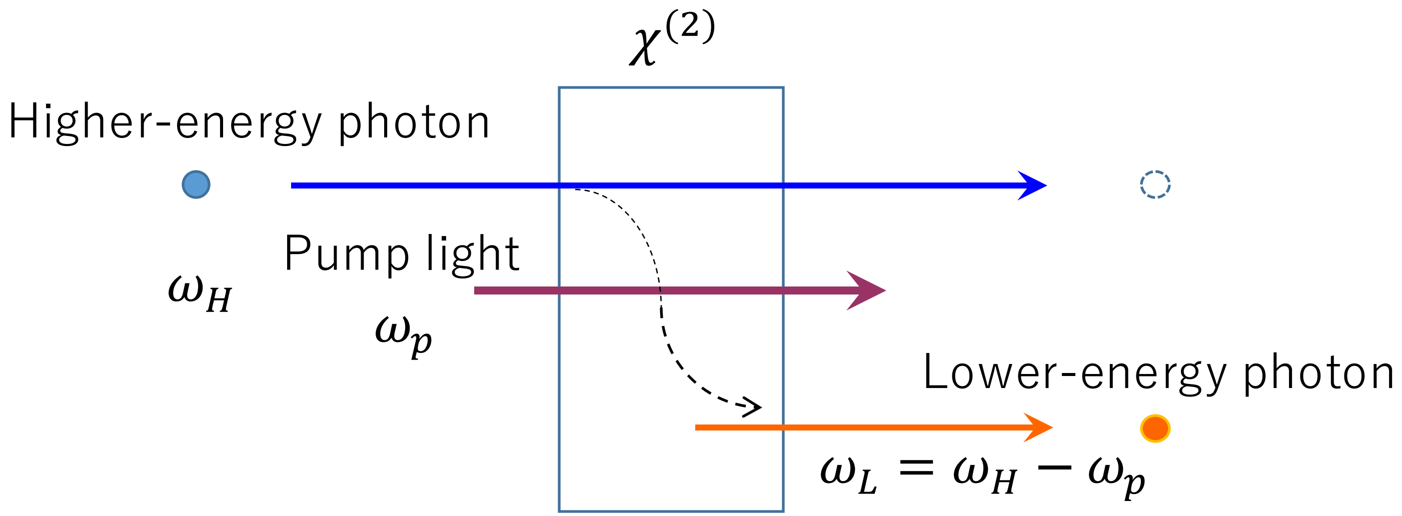
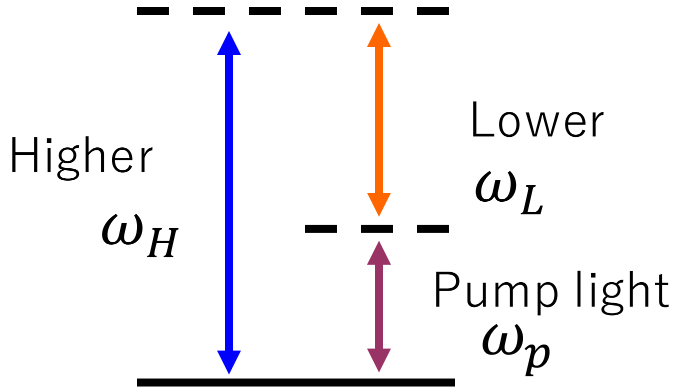
QFC as a frequency-domain beamsplitter





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($\xi = g\langle \hat{a}_P \rangle$ Sufficiently strong pump light)

Input-output relation :

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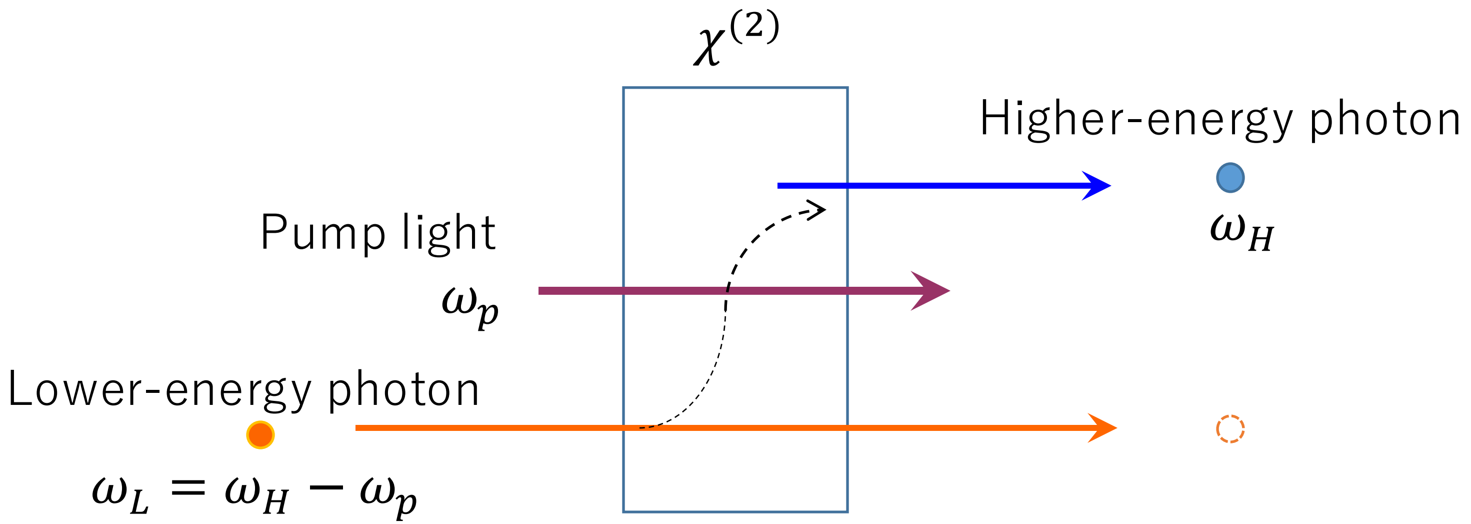
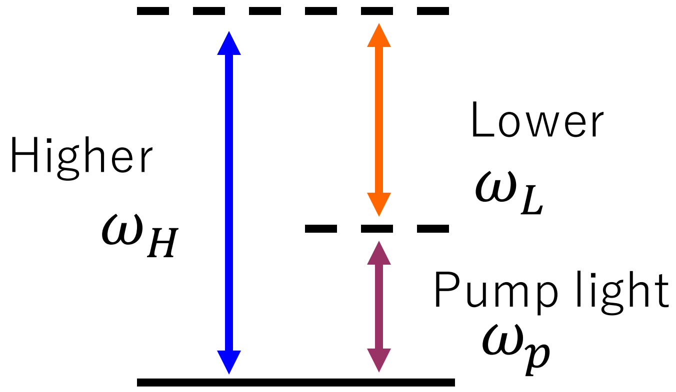
$(\theta/2 = |\xi|\tau)$

QFC as a frequency-domain beamsplitter





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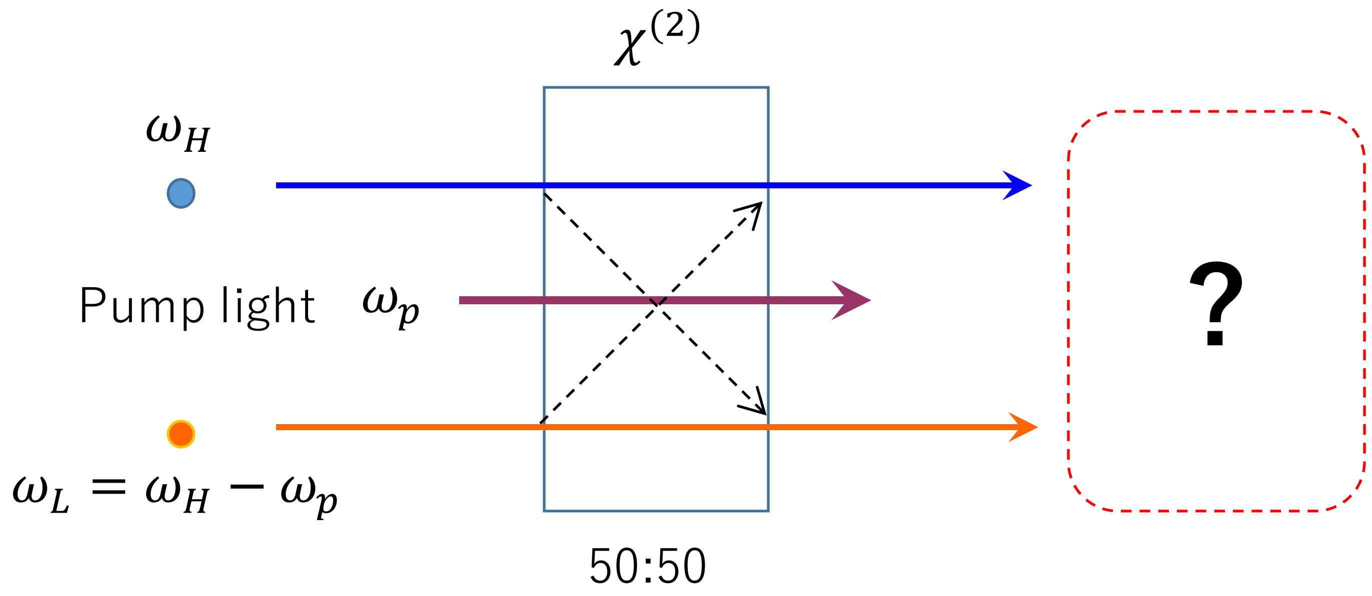
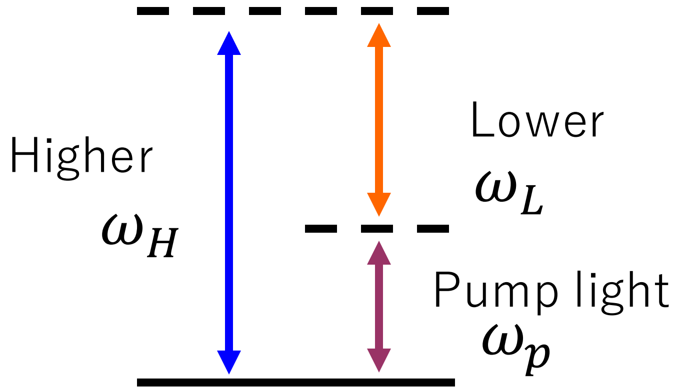
QFC as a frequency-domain beamsplitter





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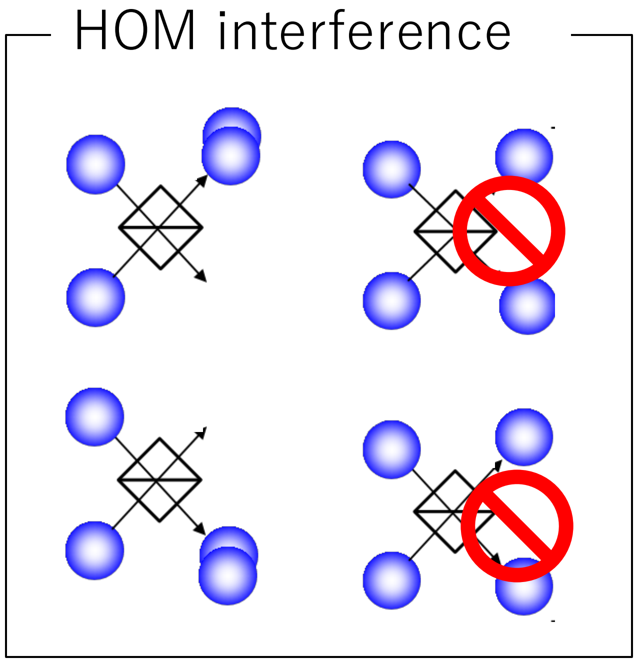
$(\theta/2 = |\xi|\tau)$

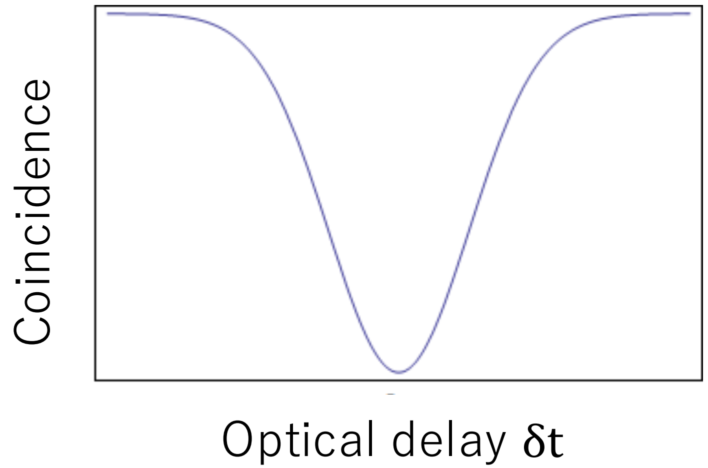
$$\begin{pmatrix} a_{H,out} \\ a_{L,out} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} a_{H,in} \\ a_{L,in} \end{pmatrix}$$

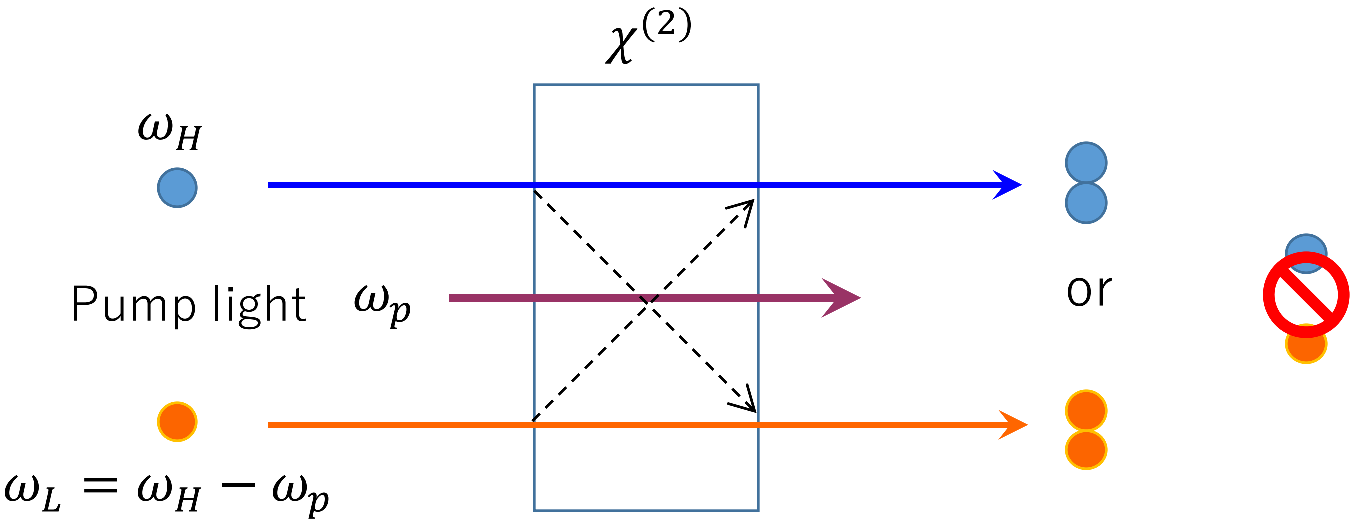
Half beamsplitter

Frequency-domain Hong-Ou-Mandel interference

C. K. Hong, Z. Y. Ou, and L. Mandel, PRL 59, 2044 (1987).





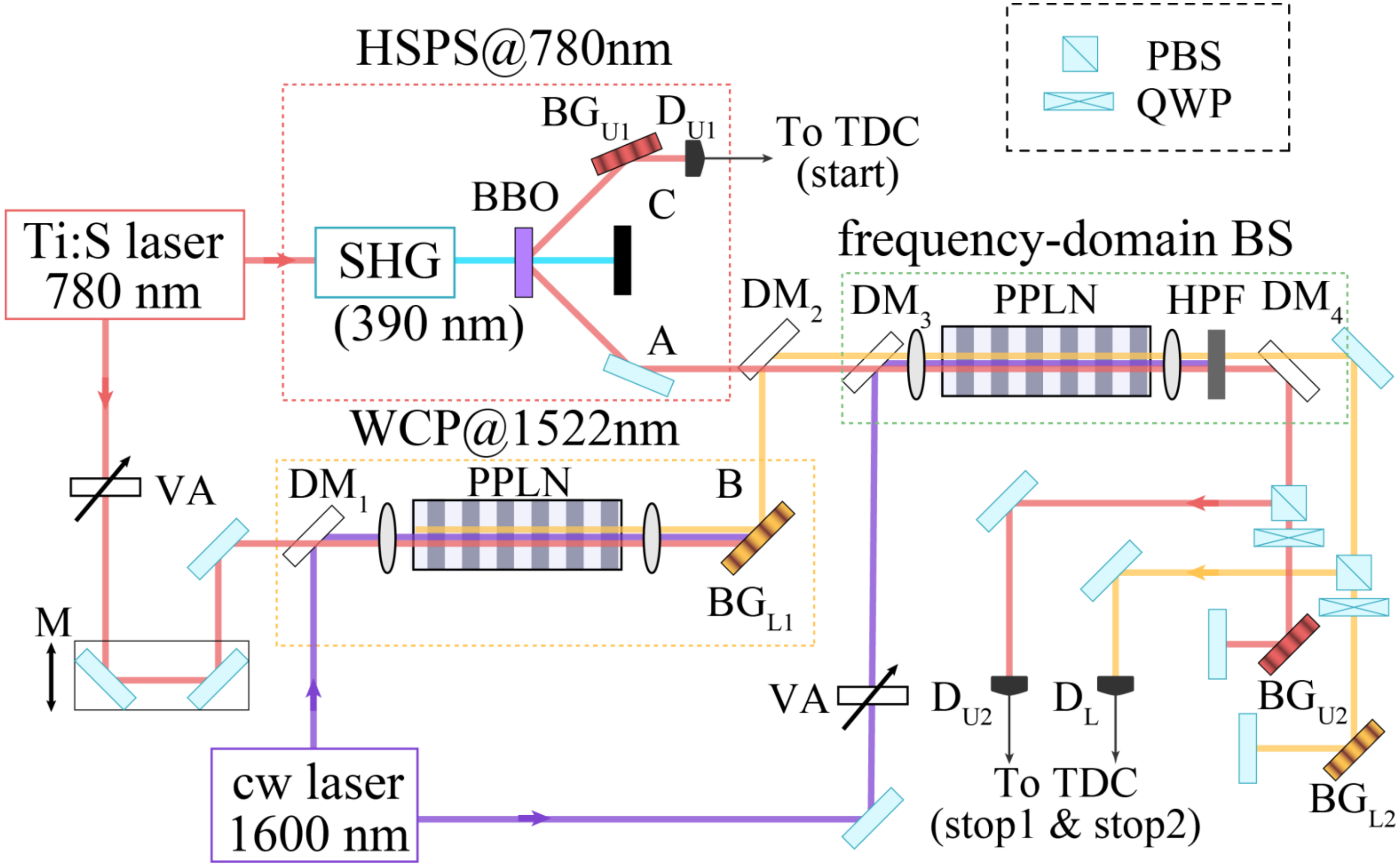


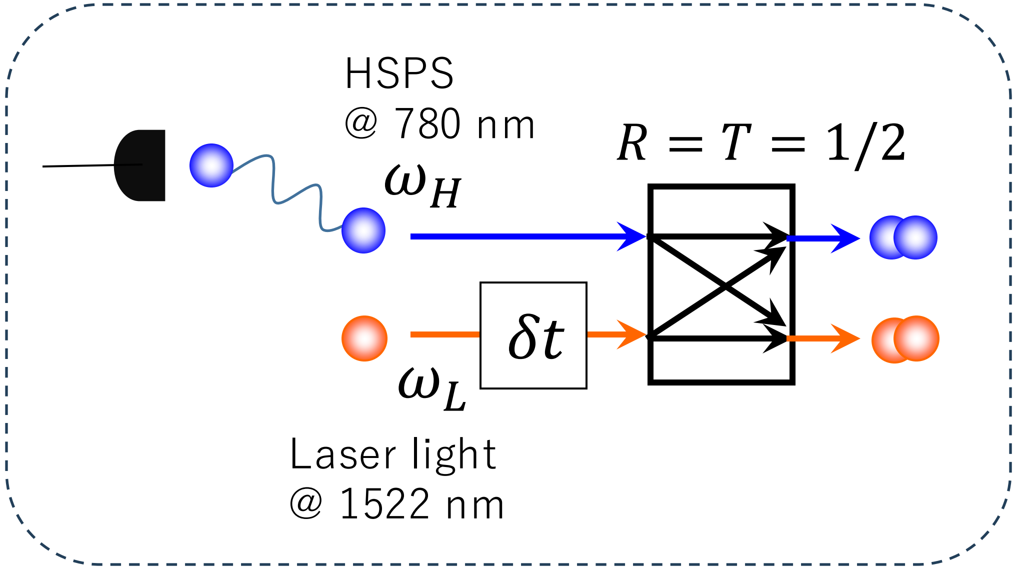
Different-color two photons can interfere!

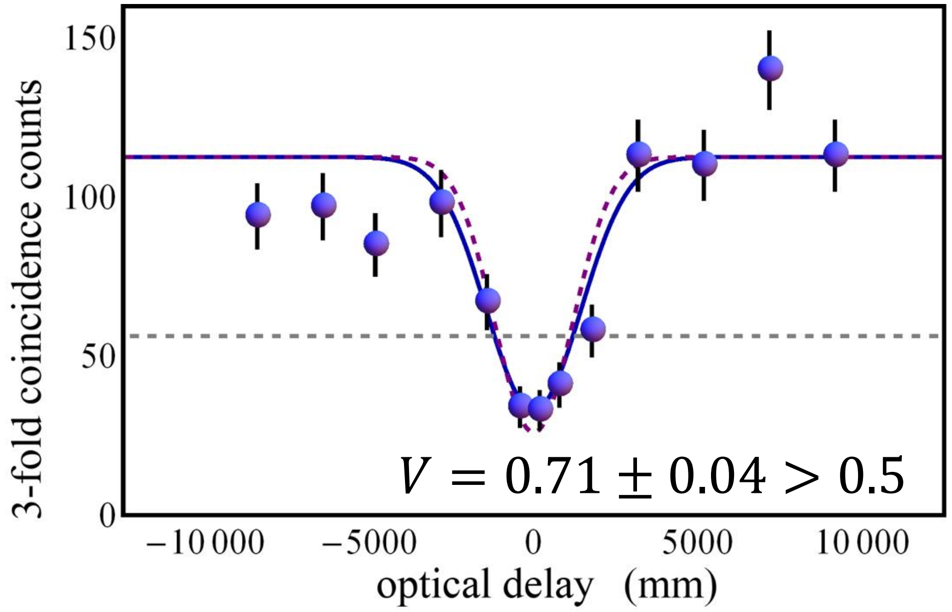
T. Kobayashi, RI et al., Nature Photonics 10, 441 (2016).

Frequency-domain Hong-Ou-Mandel interference

T. Kobayashi, RI et al., Nature Photonics 10, 441 (2016).



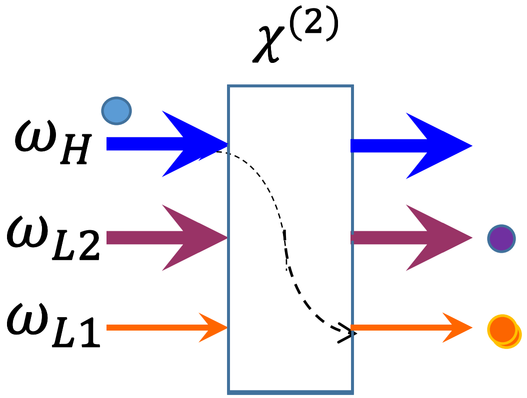




QIP based on second-order nonlinear optical interaction

A periodically poled $LiNbO_3$ (PPLN) waveguide is widely used in QIP:

1. A large variety of wavelength selection is possible by adjusting poling period.
2. Waveguide structure gives the long interaction time.

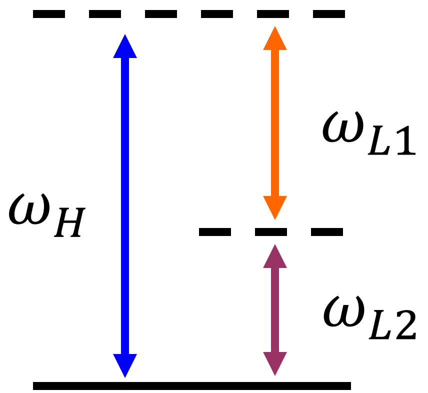


Hamiltonian : $\hat{\mathcal{H}} = i\hbar g\left(\hat{a}_{L2}^{\dagger}\hat{a}_H\hat{a}_{L1}^{\dagger} - \hat{a}_{L2}\hat{a}_H^{\dagger}\hat{a}_{L1}\right)$

Application 1: Quantum frequency conversion (QFC)

Pump light:	L2
Input mode:	H or L1 (single photon)
Output mode:	L1 or H (single photon)

$$\hat{\mathcal{H}}_{eff} = i\hbar\left(\xi_2\hat{a}_H\hat{a}_{L1}^{\dagger} - \xi_2^*\hat{a}_H^{\dagger}\hat{a}_{L1}\right) \qquad \xi_2 = g\langle\hat{a}_{L2}\rangle$$



$(\ \omega_H = \omega_{L1} + \omega_{L2}\ )$

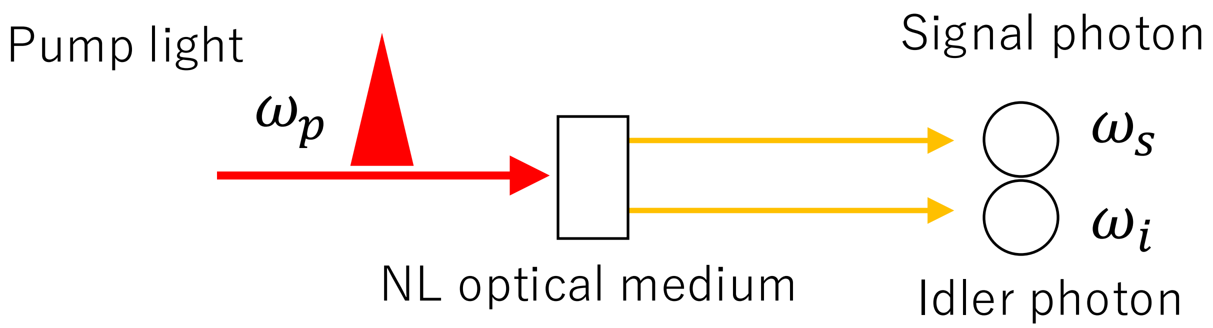
Application 2: Photon pair generation

Pump light:	H
Input mode:	None (vacuum) at L1 and L2
Output mode:	L1 and L2 (single-photon pair)

$$\hat{\mathcal{H}}_{eff} = i\hbar\left(\xi_H\hat{a}_{L2}^{\dagger}\hat{a}_{L1}^{\dagger} - \xi_H^*\hat{a}_{L2}\hat{a}_{L1}\right) \qquad \xi_H = g\langle\hat{a}_H\rangle$$

SPDC-based photon pairs

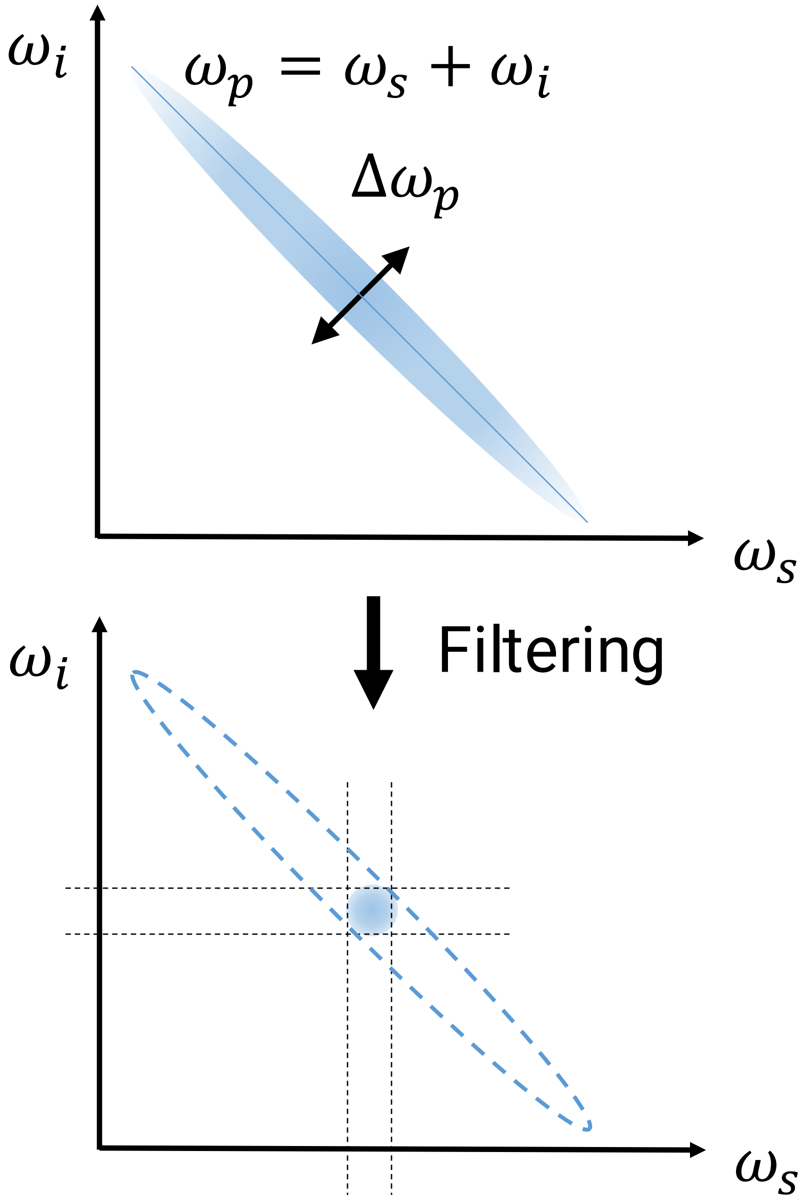
- Photon pairs based on spontaneous parametric down conversion (SPDC) is an important resource for QIP.



- Photon pairs satisfy
  - Energy conservation : $\omega_p = \omega_s + \omega_i$
  - Phase matching condition: $k_p = k_s + k_i$

for $\chi^{(2)}$ medium

SPDC-based photon pairs



- The biphoton spectral range is determined by energy conservation and phase matching condition.

$$\iint d\omega_s d\omega_i f(\omega_p, \Delta\omega_p) a_s^\dagger(\omega_s) a_i^\dagger(\omega_i)$$

- Frequency filters are used for extracting a frequency uncorrelated photon pair mode.

- Effective Hamiltonian

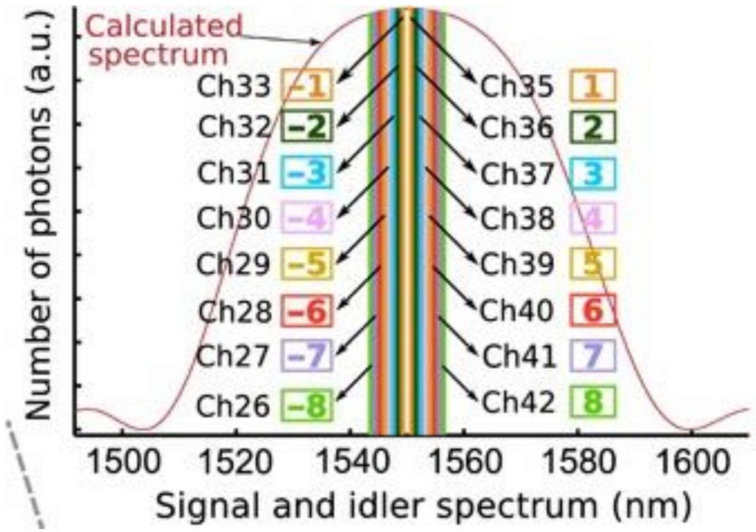
$$H = i\hbar g_p a_s^\dagger a_i^\dagger + H.c.$$

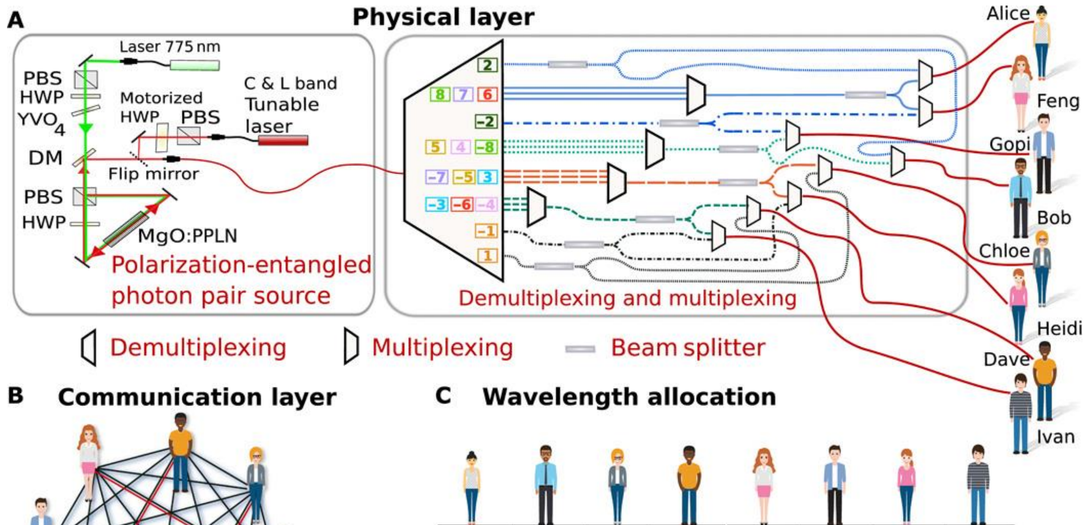
$$\downarrow$$

$$|\phi\rangle \sim \sum_{n=0}^{\infty} \gamma^n |n\rangle_s |n\rangle_i \sim |1\rangle_s |1\rangle_i \ \ (\gamma \ll 1)$$

Frequency-multiplexed entanglement distribution

- Wavelength Division Multiplexing (WDM) technology has been widely used to boost efficiency of entanglement distribution.
- Usually, entanglement distribution has been performed by conventional broadband entangled photon-pair generation based on spontaneous parametric down-conversion (SPDC) followed by application of WDM-compatible frequency filters developed for fiber-optic communication.





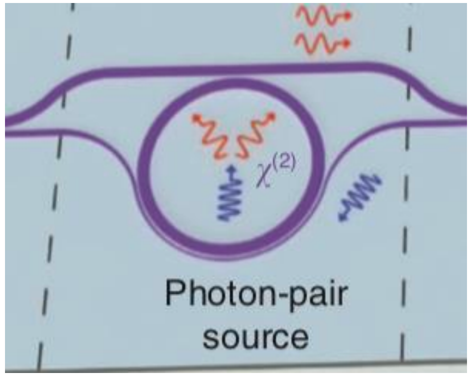
Alice	Bob	Chloe	Dave	Feng	Gopi	Heidi	Ivan
8	-8	-7	-6	8	-8	-7	-6
7	5	-5	-4	7	5	-5	-4
6	4	3	-3	6	4	3	-3
2	2	1	1	-2	-2	-1	-1

S. K. Joshi et al., Sci Adv 6 (2020).

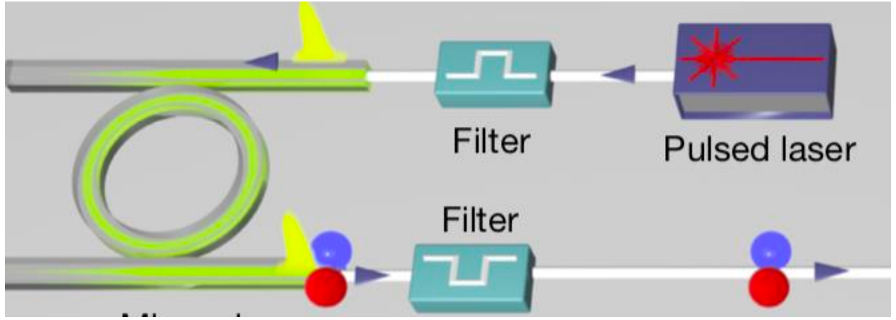
Using 16 wavelength division channels, 8 entangled photon pairs are shared among 8 people.

Frequency multiplexing

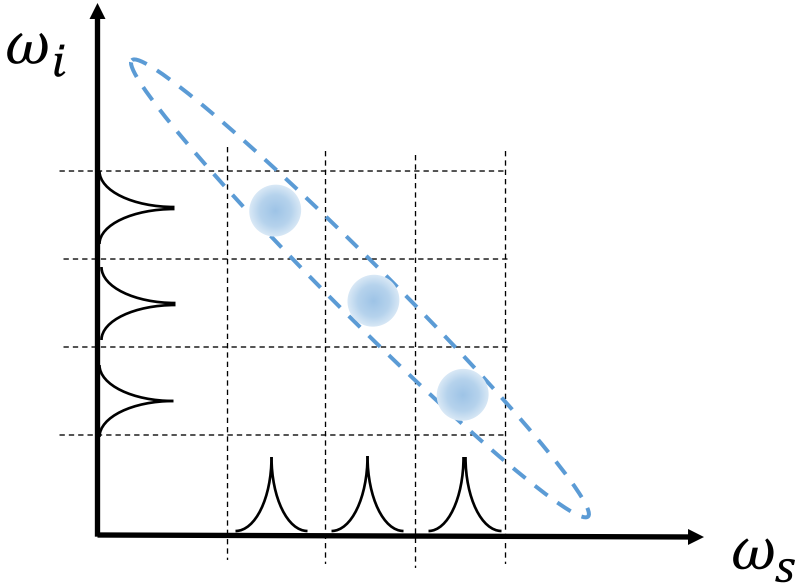
- Optical cavities can be used for frequency multiplexing of photon pairs.



X. Guo et al., Light (2017).



M. Kues et al., Nature (2017).

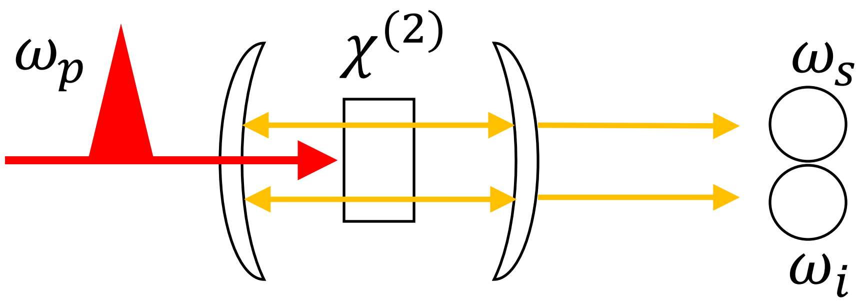


- Photon pairs separated for each FSR of the cavity :

$$|\phi\rangle \sim \sum_{m=-\infty}^{\infty} g_m |\omega_{s,m}\rangle \; |\omega_{i,m}\rangle$$

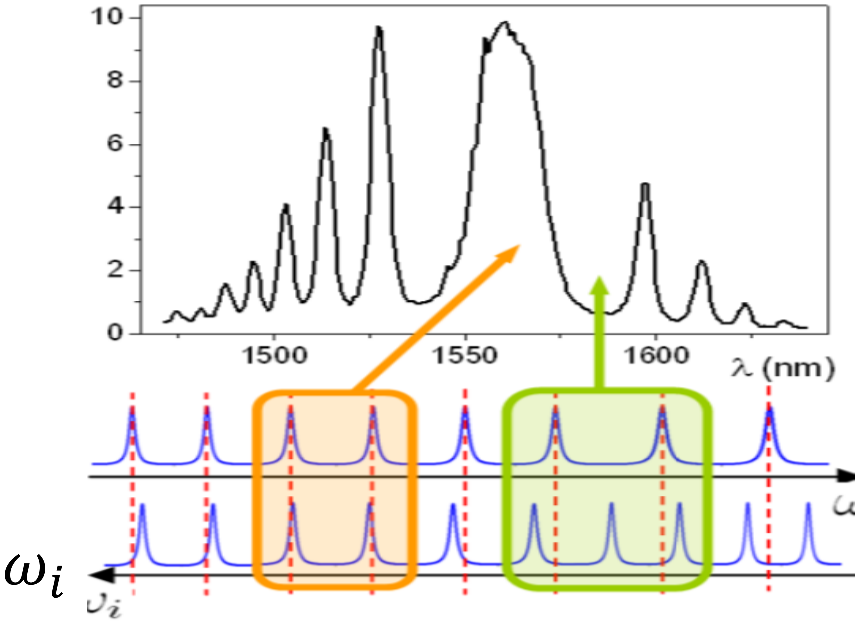
- Biphotons in all modes can be simultaneously used.
  "biphoton frequency comb"

Frequency multiplexing



- Flexible design of target frequencies and optical cavities
- Use of dense frequency modes

- Broadband photon pair generation is prevented by the clustering effect.



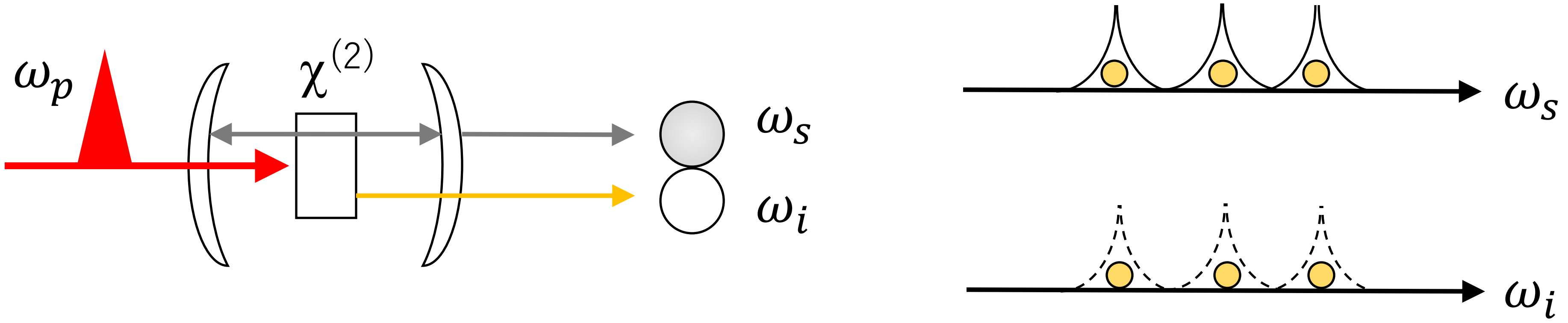
- $FSR = c/(2n(\omega)L)$ depends on frequency.

- Energy conservation and cavity resonant condition is not always satisfied:
  when $\omega_{s0} + \omega_{i0} = \omega_p$ is satisfied,
  $(\omega_{s0}+mFSR_s) + (\omega_{i0} - mFSR_i) \neq \omega_p$??

E. Pomarico et al., NJP (2009)

Our motivation

- We perform singly-resonant photon pair generation with a cavity in which only signal photons are confined (idler photons are not confined).



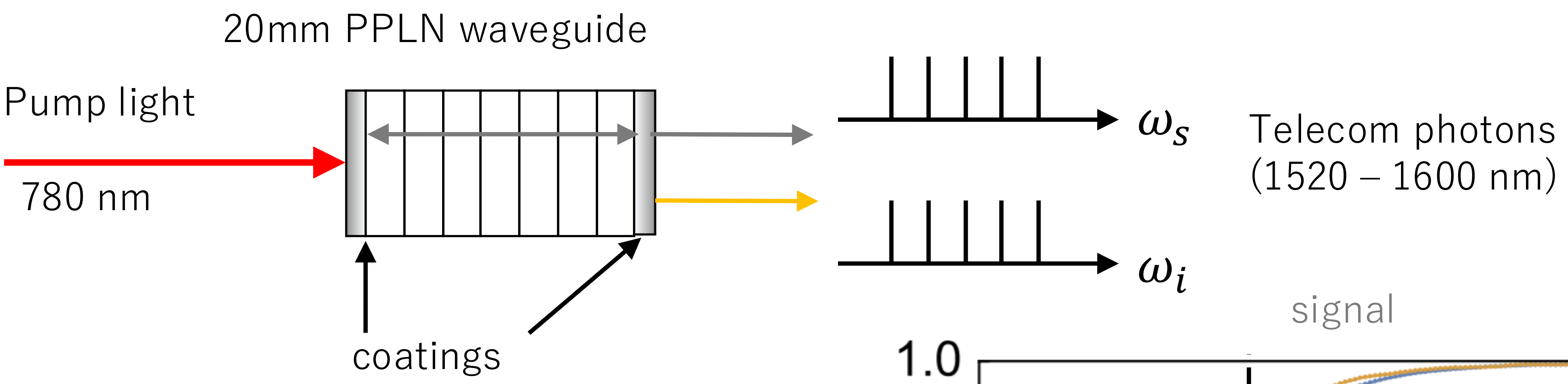
- Due to the energy conservation $\omega_p = \omega_s + \omega_i$, not only the signal but also idler photons have comb-like spectrum as if the idler photons are confined in the cavity.

- No clustering effect. → Broadband photon pair generation is possible.

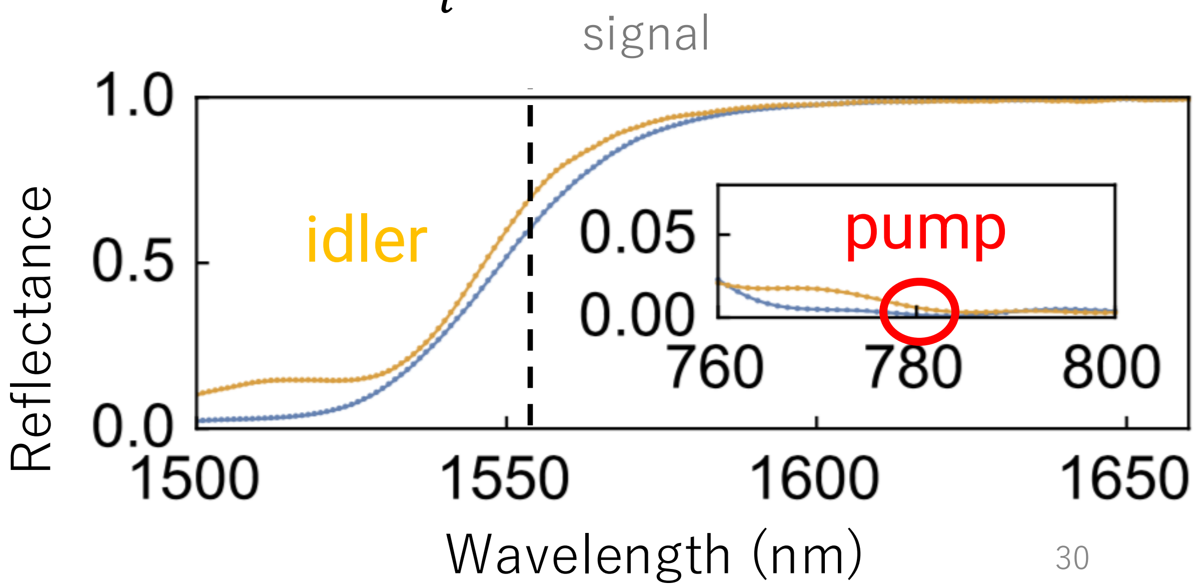
RI et al, "Frequency-Multiplexed Photon Pairs Over 1000 Modes from a Quadratic Nonlinear Optical Waveguide Resonator with a Singly Resonant Configuration," Phys. Rev. Lett. 123, 193603 (2019)

Design of our $\chi^{(2)}$ device with a cavity

- PPLN waveguide + HR/AR coatings at the both ends
  → Singly-resonant PPLN waveguide resonator (PPLN/WR)

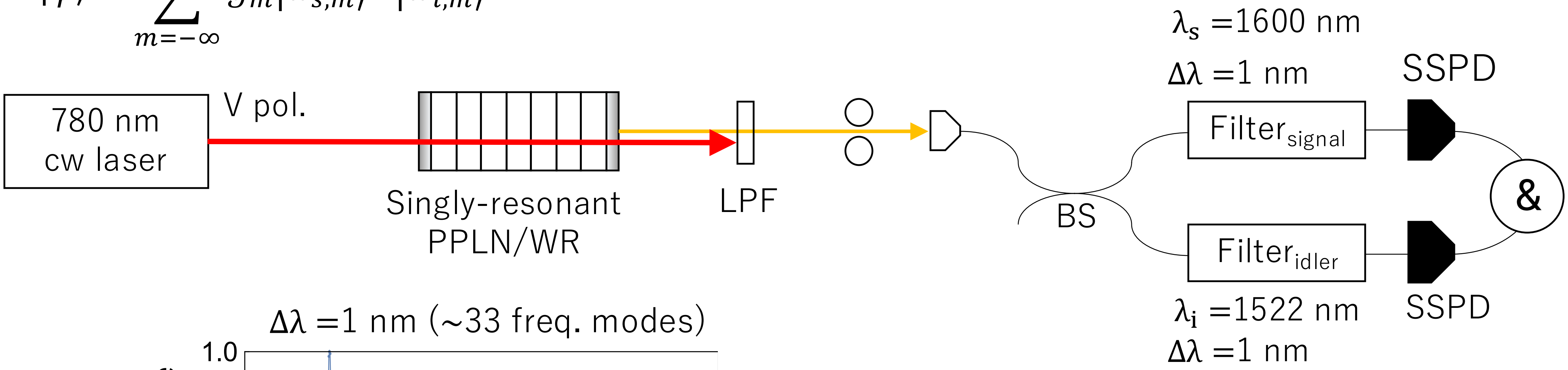


HR: > 1560 nm (signal)
AR: < 1560 nm (idler)
780 nm (pump)

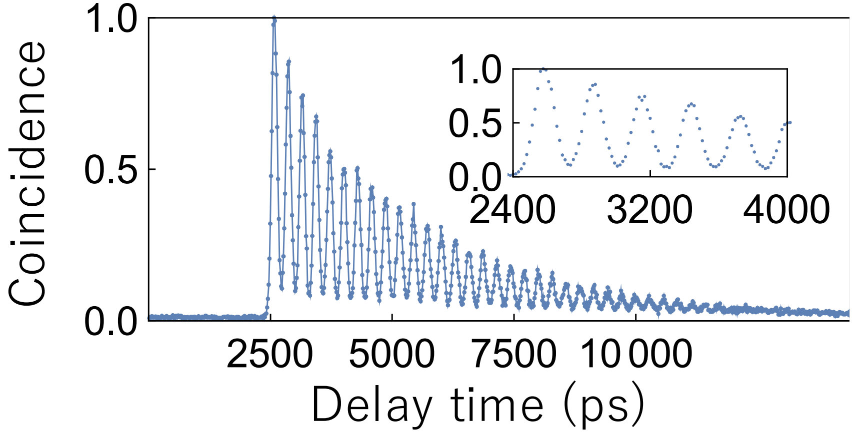


Beat measurement

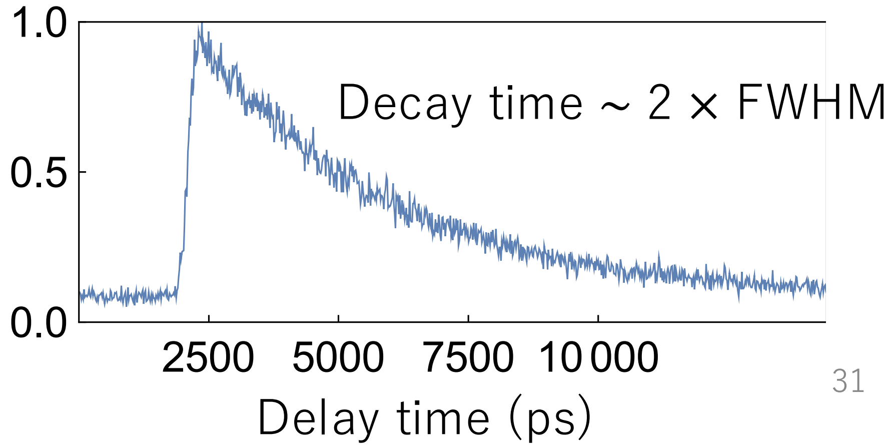
$$|\phi\rangle \sim \sum_{m=-\infty}^{\infty} g_m |\omega_{s,m}\rangle \ |\omega_{i,m}\rangle$$



Δλ =1 nm (~33 freq. modes)



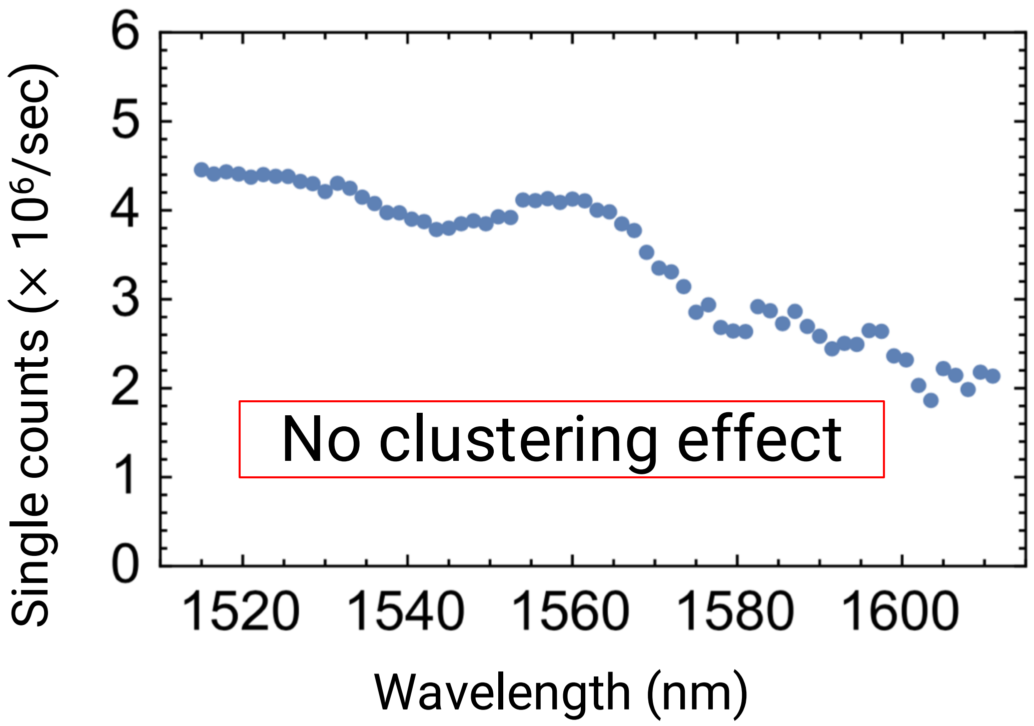
Δλ =0.03 nm (1 freq. mode)



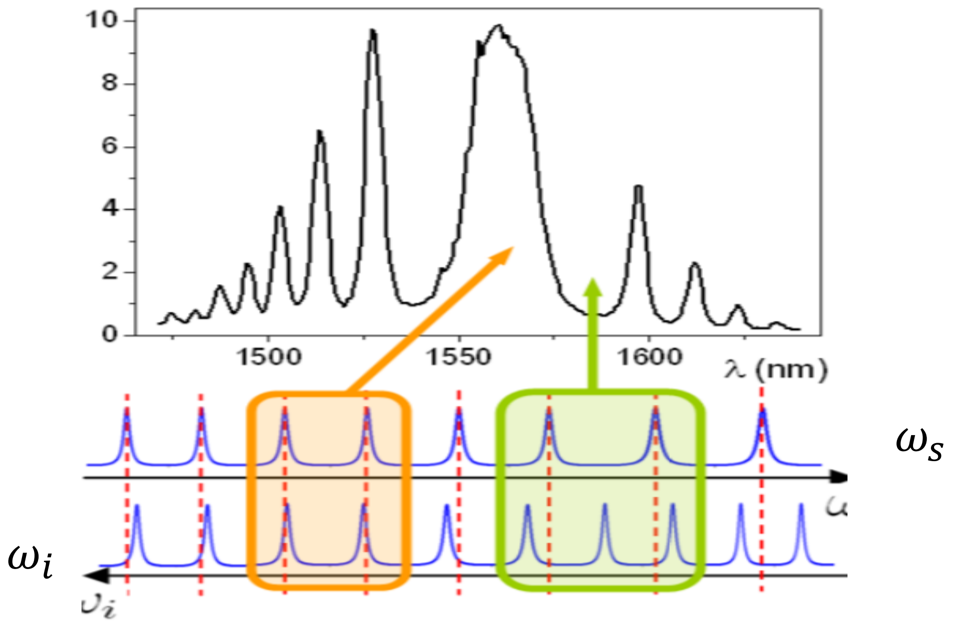
- T = 285 ps (3.5GHz corresponding to FSR)

Observation of no clustering effect

- Single count measurement for various wavelengths with bandwidth $\Delta\lambda = 3$ nm



cf.) Doubly resonant condition

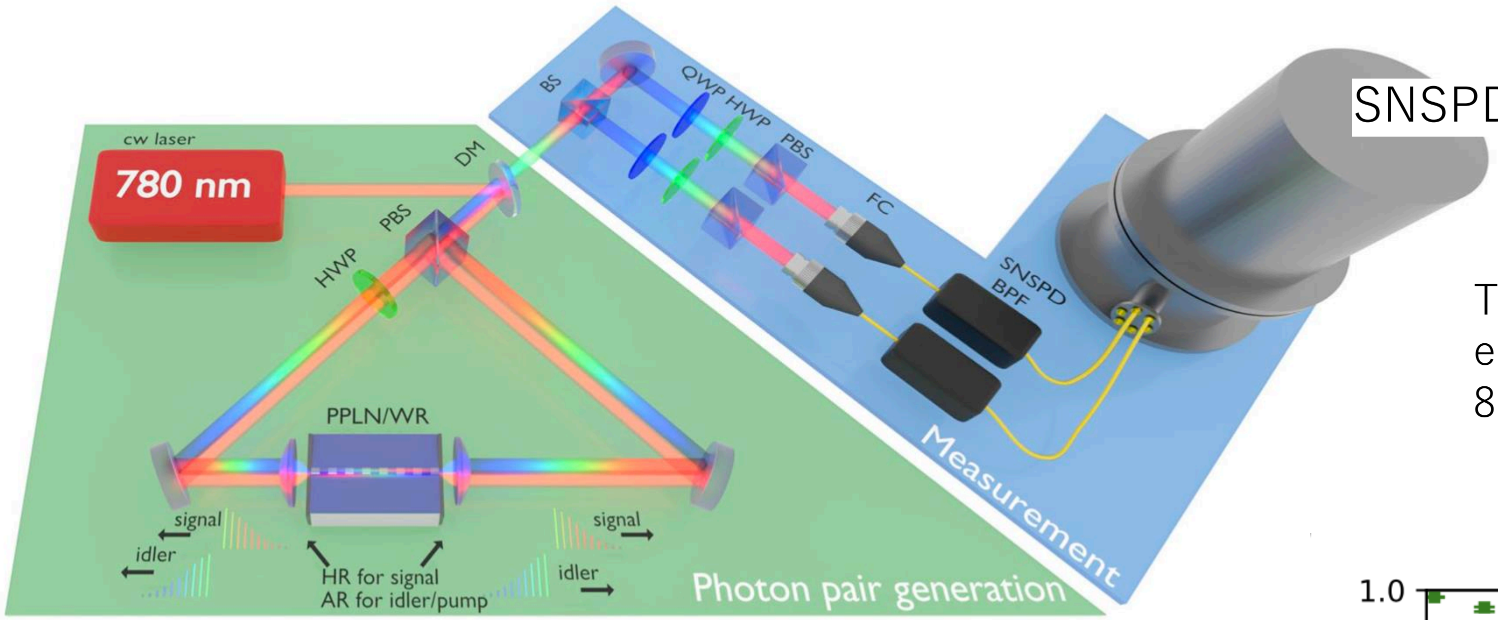


E. Pomarico et al., NJP (2009)

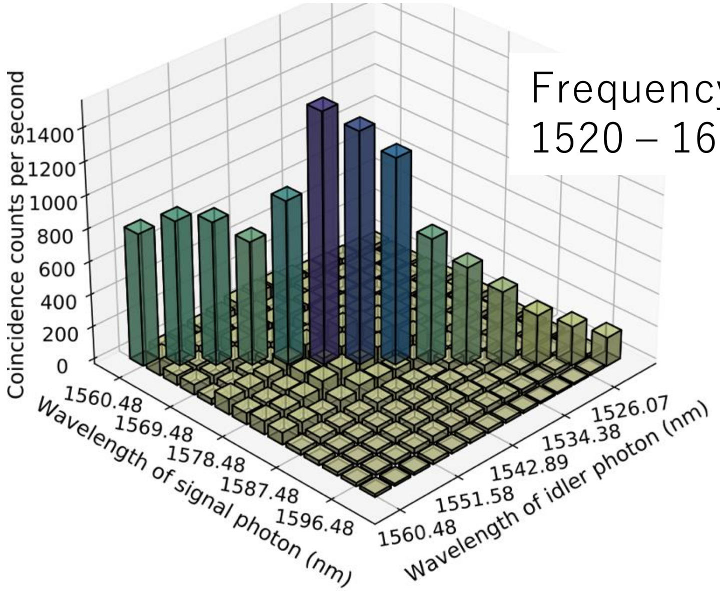
- > 1000 frequency modes (~ 1400 modes) in the range of 1520 nm to 1600 nm

Frequency-multiplexed entangled photon pair generation

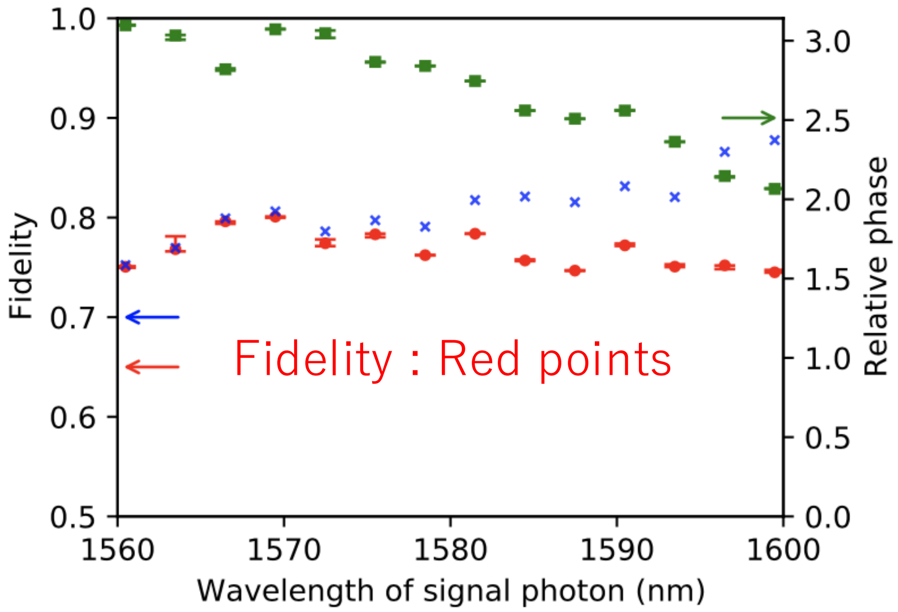
Type-0 PPLN waveguide resonator in the Sagnac type interferometer



T. Yamazaki, RI et al, "Massive-mode polarization entangled biphoton frequency comb," Sci. Rep. 12 8964 (2022)



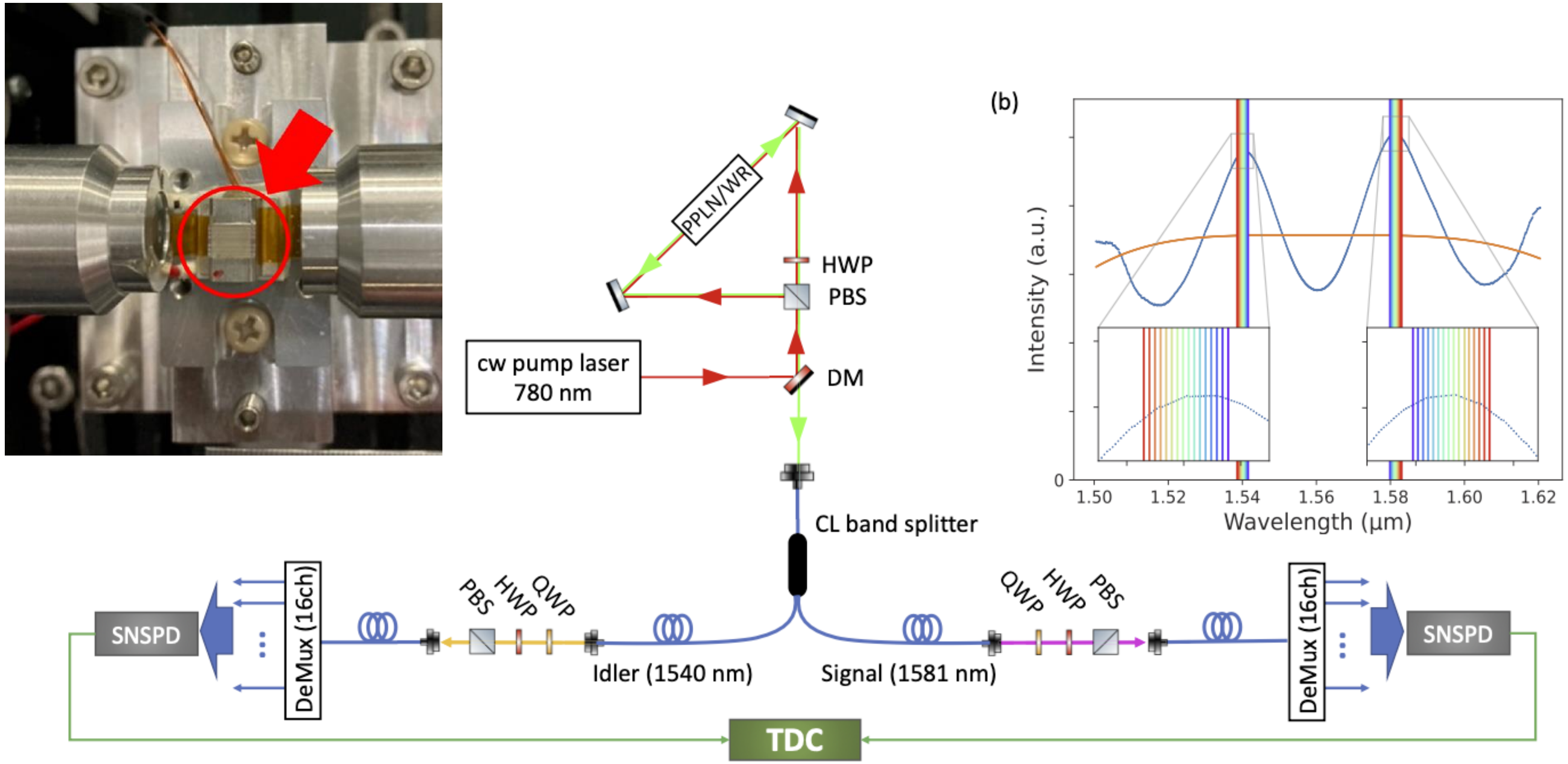
Frequency-correlated photon pairs
1520 – 1600 nm

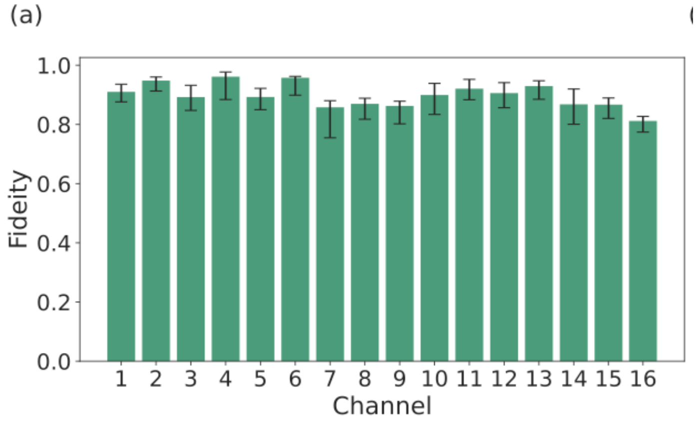


Frequency-multiplexed entanglement distribution

5.6mmL PPLN/WR

Fujimoto et al, Opt. Exp. 30, 36711 (2022)



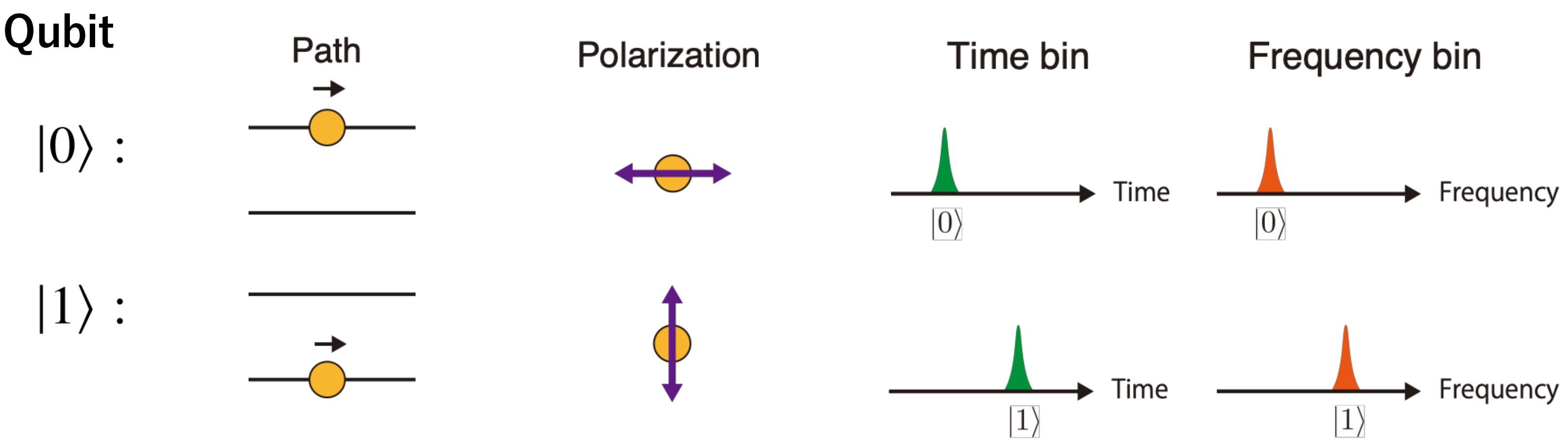


Fidelity > over 90 %

- Using DeMux with 25 GHz spacing,16ch frequency-multiplexed entanglement distribution was successfully performed.

R. Fujimoto, T. Yamazaki, RI et al, “Entanglement distribution using a biphoton frequency comb compatible with DWDM technology,” Opt. Exp. 30, 36711 (2022)

Photonic QIP based on quantum frequency comb



Manipulation	Beam splitters	Wave plates	High-speed switches + another DoF	Electro-optic modulators + wave shapers

P. C. Humphreys et al., Phys. Rev. Lett. (2013)
H. Takesue, Phys. Rev. A (2014)
H.-P. Lo, et al., Appl. Phys. Express (2018)
H.-P. Lo, et al., Phys. Rev. Appl. (2020)

J. M. Lukens et al., Optica (2017)
H.-H. Lu et al., Optica (2018)
H.-H. Lu et al., Phys. Rev. Lett. (2018)
H.-H. Lu et al., npj Quantum Inf (2019)

Use of time-frequency DoF

Error susceptibility ○

Extendability to qudits ○

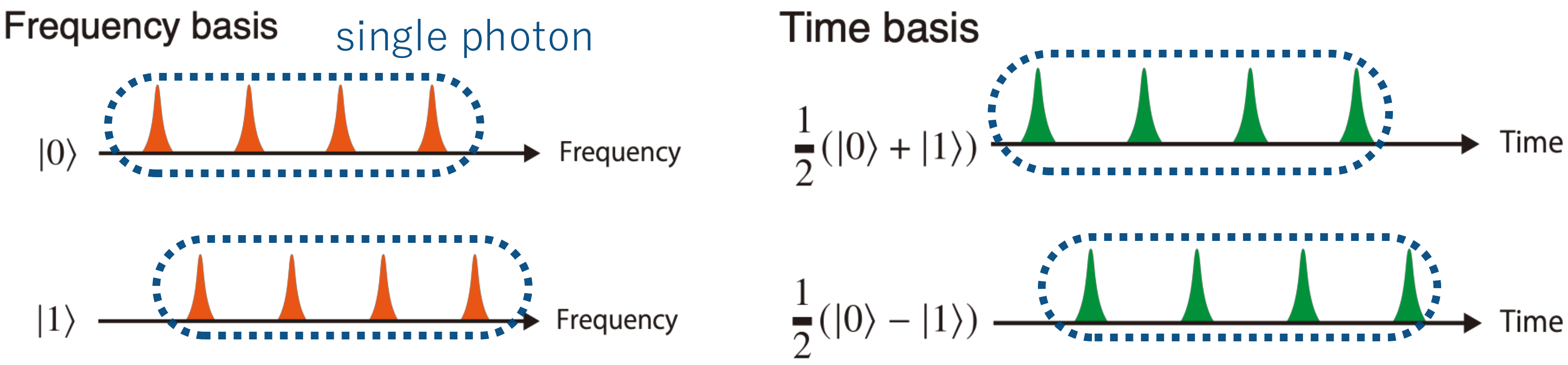
Ease of manipulation ✕

T. Yamazaki, RI *et al.*, “Linear optical quantum computation with frequency-comb qubits and passive devices,” PRL 130, 200602 (2023)

Time-frequency Gottesman-Kitaev-Preskill qubit

T. Yamazaki, RI *et al.*, PRL 130, 200602 (2023)

Encoding a qubit into single-photon frequency combs



This qubit is called Time-frequency Gottesman-Kitaev-Preskill (TF-GKP) qubit

N. Fabre et al., Phys. Rev. A (2020)
N. Fabre et al., Phys. Rev. A (2022)

from an analogy with original GKP code.

D. Gottesman et al., Phys. Rev. A (2001)

This state is discretized in the both time and frequency domains
➡ robust to both temporal- and spectral-shift errors

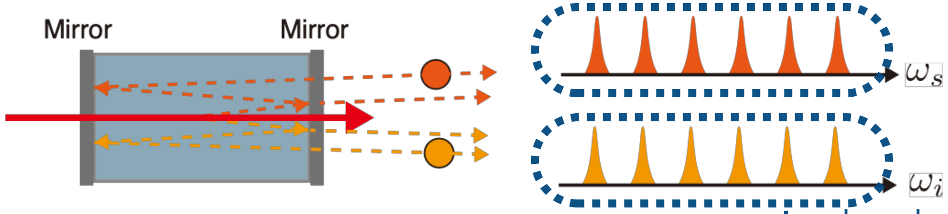
Components for manipulation of TF-GKP qubit

T. Yamazaki, RI *et al.*, PRL 130, 200602 (2023)

Following components are sufficient for universal quantum computation

- state generators

Cavity-enhanced SPDC + time-resolving detector



Simple and efficient generation

- Time-resolving detector

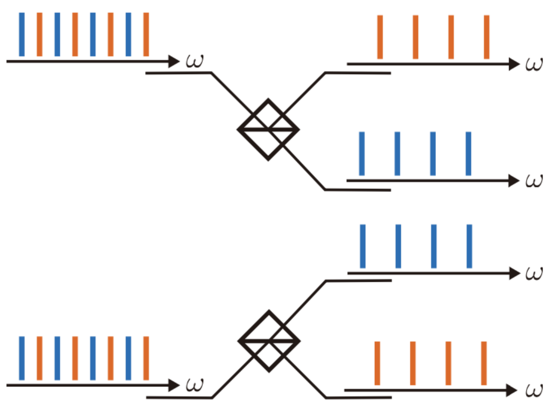
- Optical interleaver (OI)

spatially dividing frequency combs

- (Spatial) beam splitter

independent from time and frequency

2:2 Optical interleaver



Universal QC using TF-GKP qubit

T. Yamazaki, RI *et al.*, PRL 130, 200602 (2023)

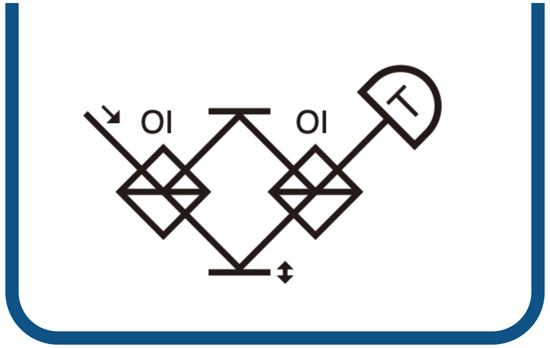
We mimic a polarization-encoding scheme with TFGKP encoding.

D. E. Browne, T. Rudolph, Phys. Rev. Lett. (2005).

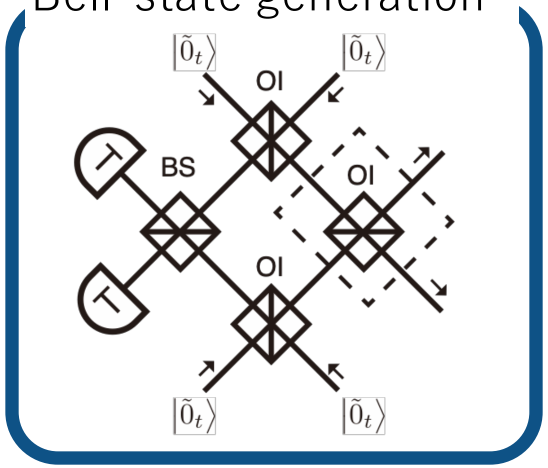
Optical interleaver + detectors = measurement in the Z basis $\{|0\rangle, |1\rangle\}$

Time-resolving detector = measurement in the X basis $\{\frac{1}{2}(|0\rangle \pm |1\rangle)\}$

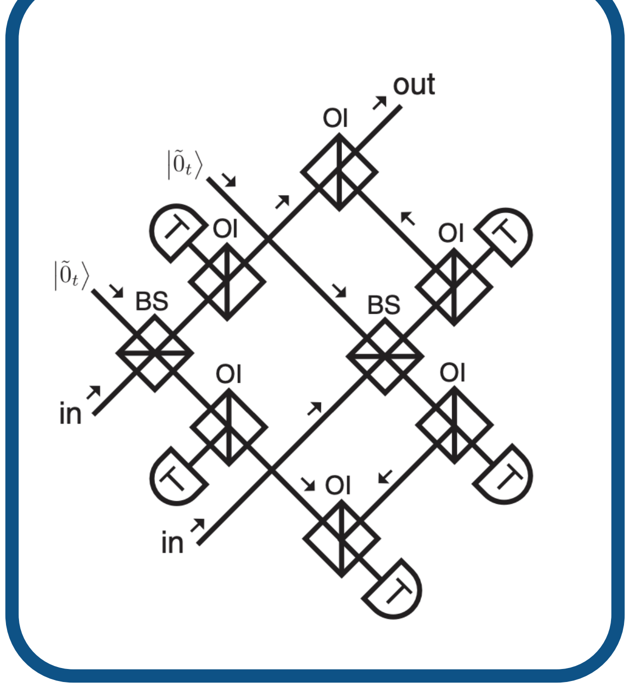
Measurement in the $\mathbf{X}\cos\boldsymbol{\theta} + \mathbf{Y}\sin\boldsymbol{\theta}$ basis



Bell-state generation



Fusion gate



These operations are sufficient for
fault-tolerant measure-based quantum computation

R. Raussendorf et al., Ann. Phys. (2006), R. Raussendorf et al., Phys. Rev. Lett. (2007).

Error analysis

T. Yamazaki, RI *et al.*, PRL 130, 200602 (2023)

Two types of broadenings

Coherent broadening → temporal broadening = spectral compression

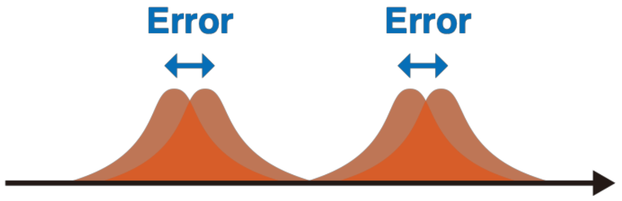
Incoherent broadening → probabilistic temporal/spectral shifts

Two types of error sources

Factor I

Single qubit measurement
Both time and frequency bases
Incoherent + coherent

Factor II



Entangling gates using interference
Only time basis
Incoherent / coherent

Temporal resolution of detectors:
4.3 ps

B. Korzh et al., Nat. Photonics. (2020).

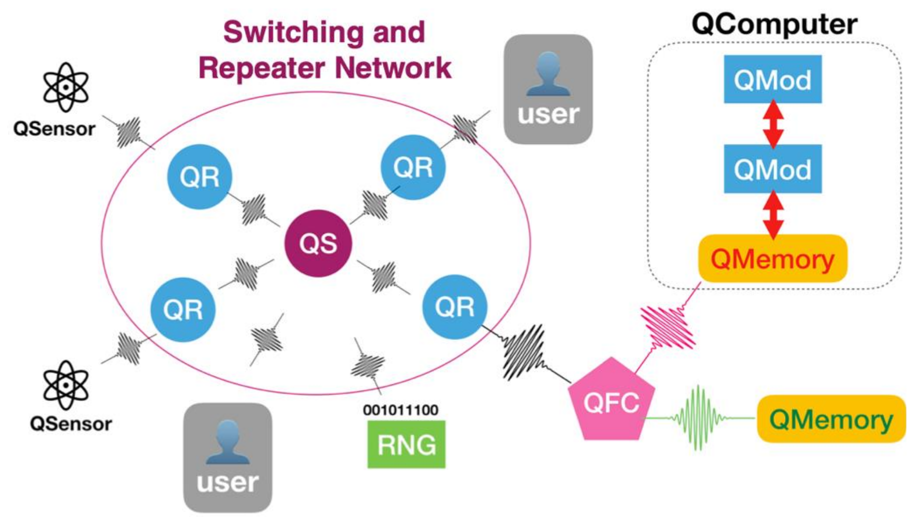
→ Comb spacing of optical interleavers and frequency combs:
12.5 GHz
Optoplex

→ Finesse of frequency comb
~ 60

Our experiment

Error probabilities < 1% is almost achievable by current technologies

Summary and outlook



- Quantum frequency conversion is an essential tool for the quantum internet which includes heterogeneous quantum systems.
- QFC can be regarded as a frequency-domain BS, which paves the way for a photonic QIP based on frequency degree of freedom.
- Singly resonant $\chi^{(2)}$ nonlinearity enables the emergence of novel functionalities in QFC, and SPDC photons.
  - Frequency multiplexed photon pair
  - Quantum frequency comb
  - Time-frequency GKP qubit