Observation of frequency-domain Hong-Ou-Mandel interference

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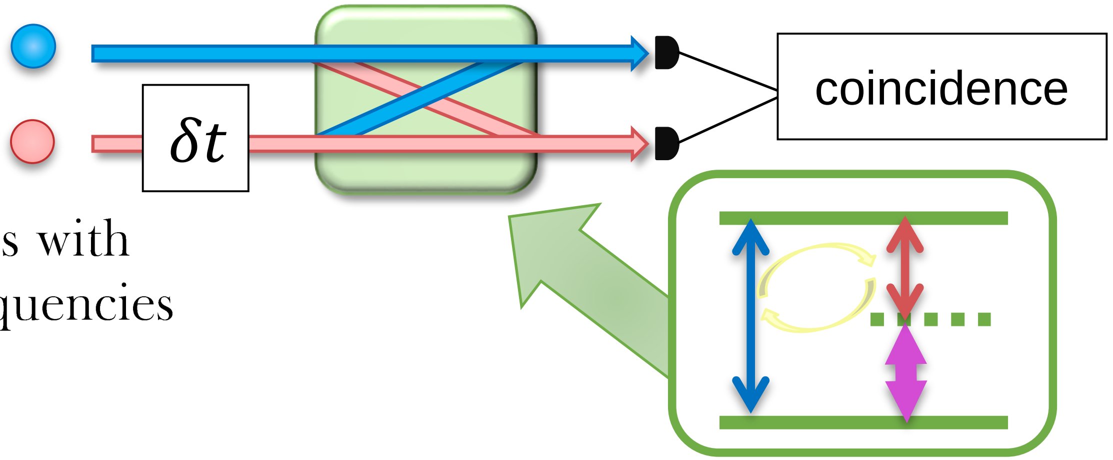
T. Kobayashi *et al.*, *Nat. Photon.* **10**, 441 (2016).

Summary

T. Kobayashi *et al.*, *Nat. Photon.* **10**, 441 (2016).

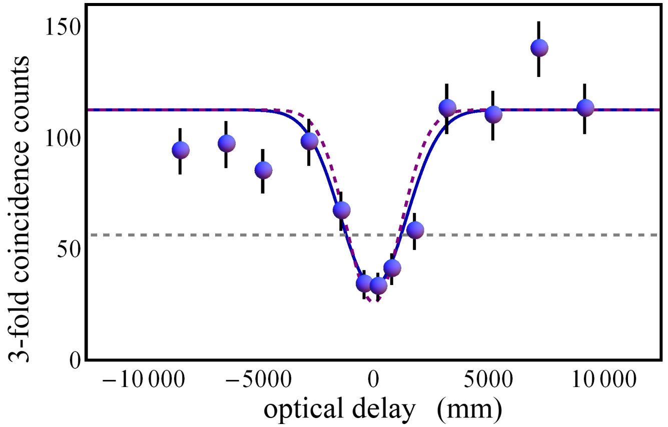
- We report the first observation of the HOM interference between two photons with different frequencies in optical region.
- The frequency-domain HOM interferometer is implemented by a partial frequency conversion in a nonlinear optical medium with a strong pump light.
- Our results have important consequences for manipulating the photonic quantum states encoded in frequency domain.

Frequency-domain beamsplitter (BS)



Two photons with different frequencies

Observed frequency-domain HOM dip

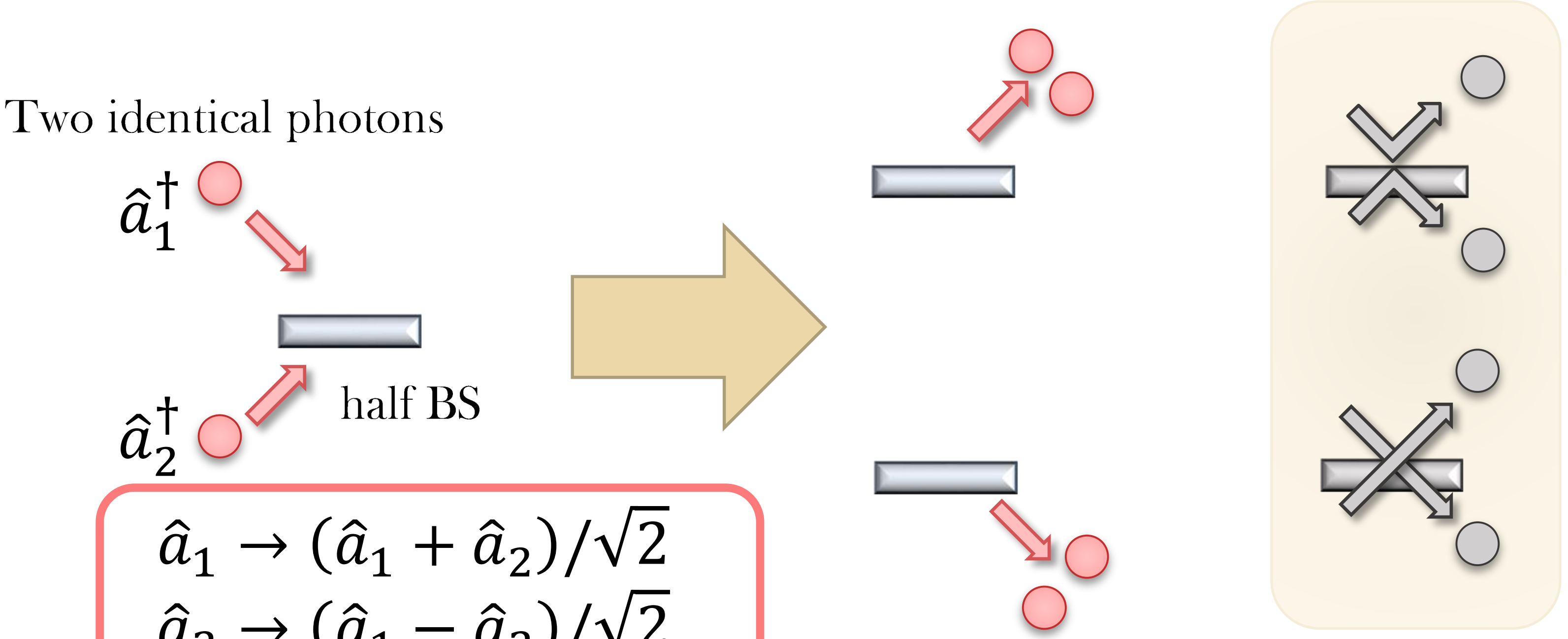


Outline

- Background
  - Hong-Ou-Mandel (HOM) interference
  - Quantum frequency conversion / Frequency-domain beamsplitter
- Frequency-domain HOM interferometer   T. Kobayashi *et al.*, *Nat. Photon.* **10**, 441 (2016).
  - Experimental setup
  - Experimental result
  - Discussion
- Summary

Hong-Ou-Mandel (HOM) interference

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



$$\hat{a}_1 \to (\hat{a}_1 + \hat{a}_2)/\sqrt{2}$$
$$\hat{a}_2 \to (\hat{a}_1 - \hat{a}_2)/\sqrt{2}$$

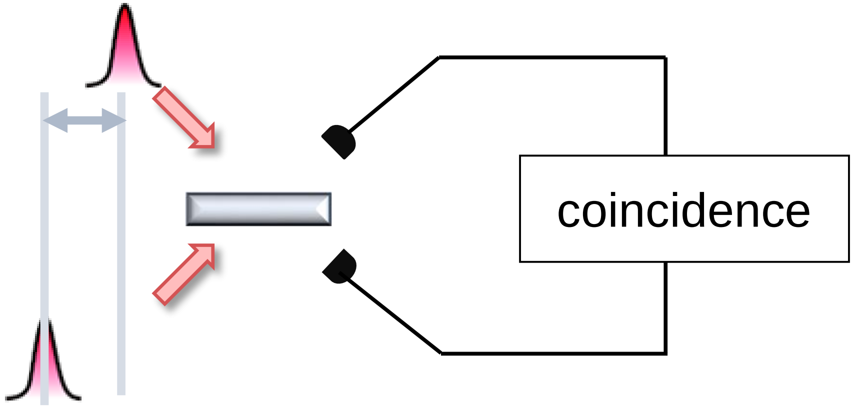
$$\hat{a}_1^\dagger \hat{a}_2^\dagger \to \frac{1}{2}\left(\left(\hat{a}_1^\dagger\right)^2 - \hat{a}_1^\dagger \hat{a}_2^\dagger + \hat{a}_1^\dagger \hat{a}_2^\dagger - \left(\hat{a}_2^\dagger\right)^2\right) = \frac{1}{2}\left(\left(\hat{a}_1^\dagger\right)^2 - \left(\hat{a}_2^\dagger\right)^2\right)$$

HOM interference

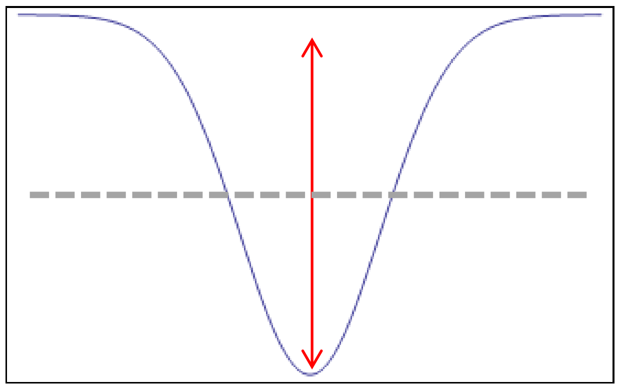
C. K. Hong, Z. Y. Ou, and L. Mandel, PRL **59**, 2044 (1987).

To observe the HOM interference in an experiment, we control a distinguishability of two photons by optical delay, polarization, … and then measure a coincidence counts.

optical delay δt



HOM dip



optical delay δt

Interference visibility $V \equiv \frac{\text{max}-\text{min}}{\text{max}}$

Classical limit : $V = 0.5$

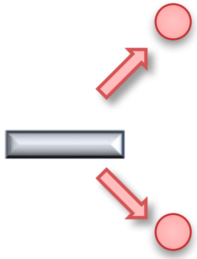
HOM interference

HOM interference revealed fundamental properties in many bosonic particles

✓Photons	C. K. Hong, Z. Y. Ou, and L. Mandel, PRL 59, 2044 (1987).
✓Surface plasmons	G. Di Martino *et al.*, *Phys. Rev. Applied* 1, 034004 (2014); J. S. Fakonas *et al.*, *Nat. Photon.* **8**, 317 (2014).
✓Helium 4-atoms	R. Lopes *et al.*, *Nature* 520, 66 (2015).
✓Phonons	K. Toyoda *et al.*, *Nature* 527, 74 (2015).

Applications are widely spreading.
quantum key distribution, photonic quantum computation, quantum metrology…

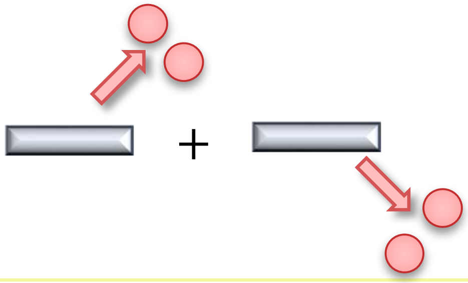
Bell measurement



Postselecting a coincidence event

Anti-symmetric singlet state

NOON state

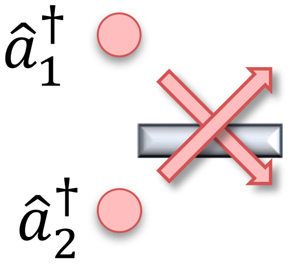


$N = 2$

$|2,0\rangle + |0,2\rangle$

Frequency-domain BS

Conventional (spatial-domain) BS



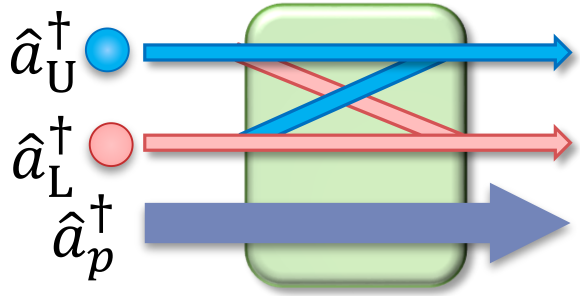
$$\hat{H} = i\hbar\gamma\left(\hat{a}_1^\dagger \hat{a}_2 - \hat{a}_1 \hat{a}_2^\dagger\right)$$

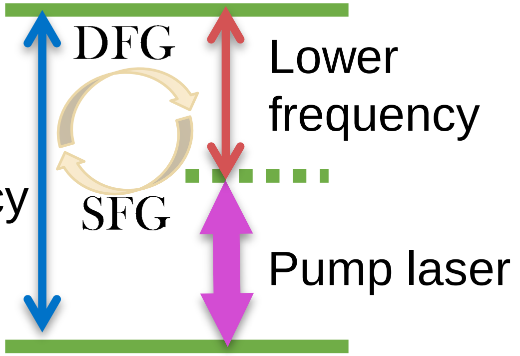
$$\hat{a}_{1,out} = \cos(\gamma)\hat{a}_1 - \sin(\gamma)\,\hat{a}_2$$
$$\hat{a}_{2,out} = \sin(\gamma)\,\hat{a}_1 + \cos(\gamma)\hat{a}_2$$

$$T = \cos^2(\gamma), R = \sin^2(\gamma)$$

Quantum frequency conversion

P. Kumar, *Opt. Lett.* **15**, 1476 (1990).





$$\hat{H} = i\hbar\left(g^* \hat{a}_L^\dagger \hat{a}_U - g\hat{a}_L \hat{a}_U^\dagger\right)$$
$$g = g'\langle \hat{a}_p \rangle$$

$$\hat{a}_{U,out} = \cos(|g|\tau)\hat{a}_U - e^{i\phi}\sin(|g|\tau)\,\hat{a}_L$$
$$\hat{a}_{L,out} = e^{-i\phi}\sin(|g|\tau)\,\hat{a}_U + \cos(|g|\tau)\hat{a}_L$$

$$T = \cos^2(|g|\tau), R = \sin^2(|g|\tau)$$

Previous works - Quantum interface

Quantum frequency conversion can be used as quantum interface

- Frequency-tunable squeezed light — P. Kumar, *Opt. Lett.* **15**, 1476 (1990).
- High efficiency telecom single photon detection — C. Langrock *et al.*, *Opt. Lett.* **30**, 1725 (2005).
- Quantum communication with optical fiber and quantum memory — S. Tanzilli et al., *Nature* **437**, 116 (2005). R. Ikuta et al., *Nat. Commun.* **2** 537 (2011).

The work of S. Tanzilli *et al.* first demonstrated preservation of entanglement

Telecom entangled photons
(suitable for optical fiber)

near alkaline memories wavelength

frequency-up conversion

Previous works - Quantum interface

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- Frequency-tunable squeezed light
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P. Kumar, *Opt. Lett.* **15**, 1476 (1990).

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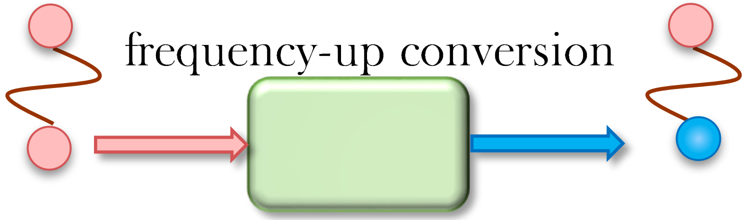
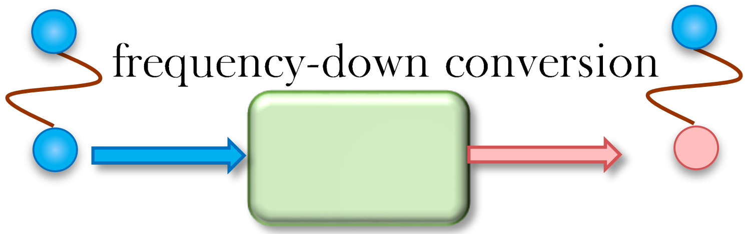


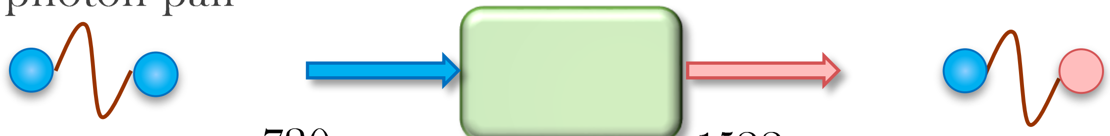
R. Ikuta et al., *Nat. Commun.* **2** 537 (2011).



Previous works – Quantum interface (our group)

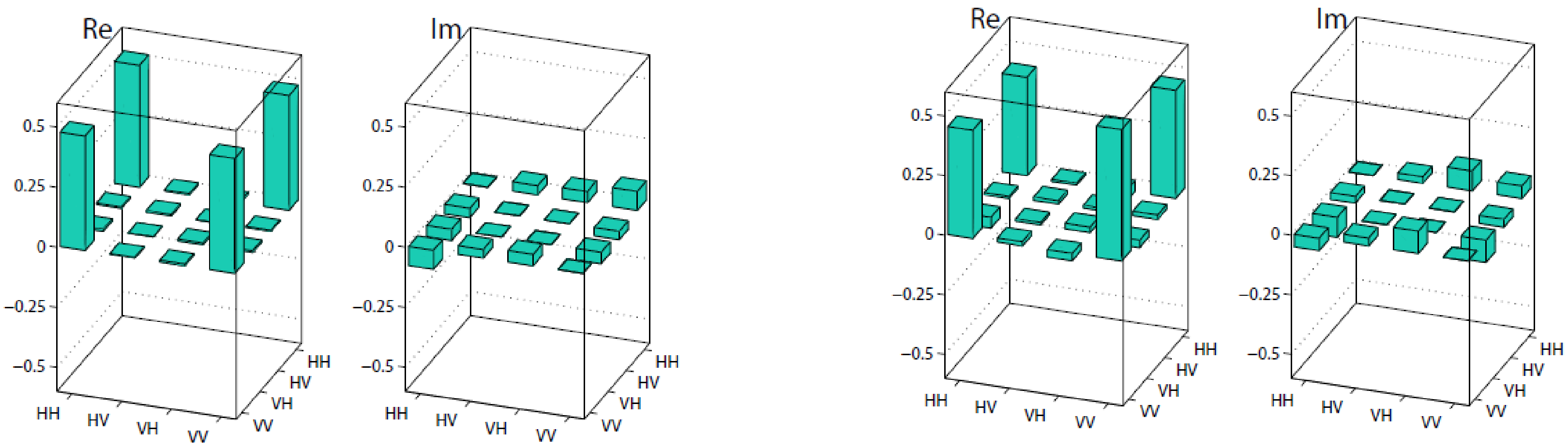
R. Ikuta *et al.*, *Nat. Commun.* **2** 537 (2011); R. Ikuta *et al.*, Phys. Rev. A **87**, 010301(R) (2013).

Polarization-entangled photon pair



$F = 0.97 \pm 0.01$

$F = 0.93 \pm 0.04$



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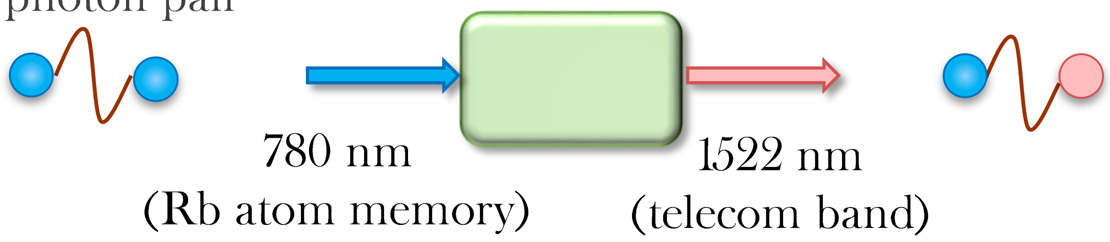
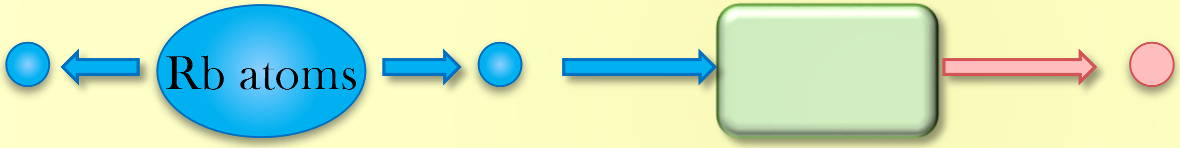
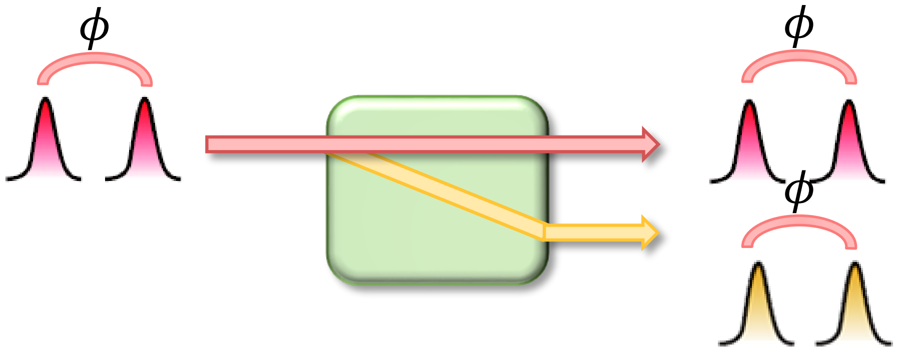


Preservation of nonclassical photon statistics of photons emitted from Rb atomic ensemble



R. Ikuta, T. K. *et al.*, arXiv:1607.01465 [quant-ph].

Previous works – Partial frequency conversion

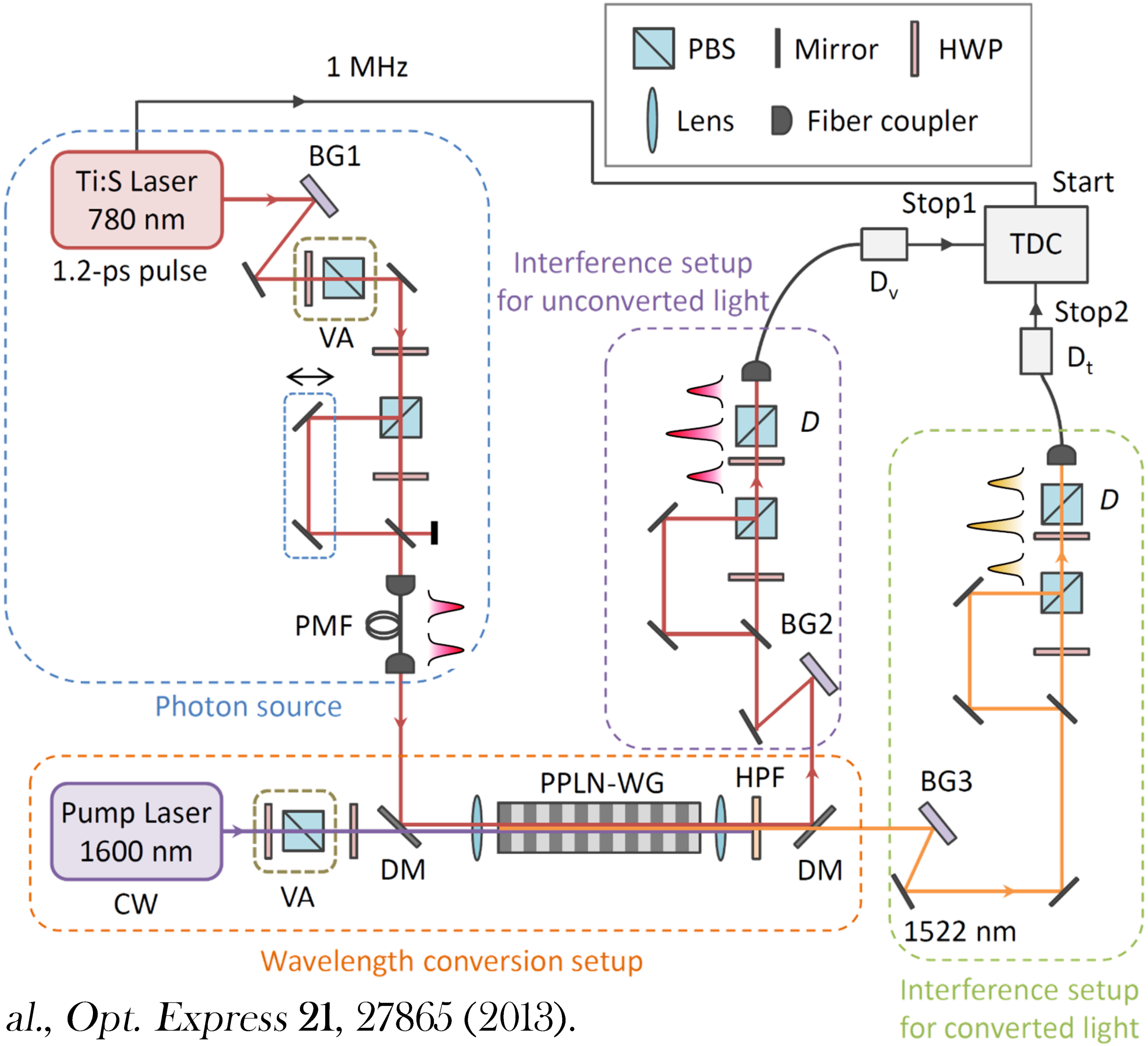


Demonstrations of quantum interface investigated only a converted light.

However, an unconverted light is also important.

R. Ikuta, T. K. *et al.*, *Opt. Express* **21**, 27865 (2013)

We demonstrated preservation of phase information in the converted and unconverted light by using Mach-Zehnder interferometer through a partial frequency conversion.



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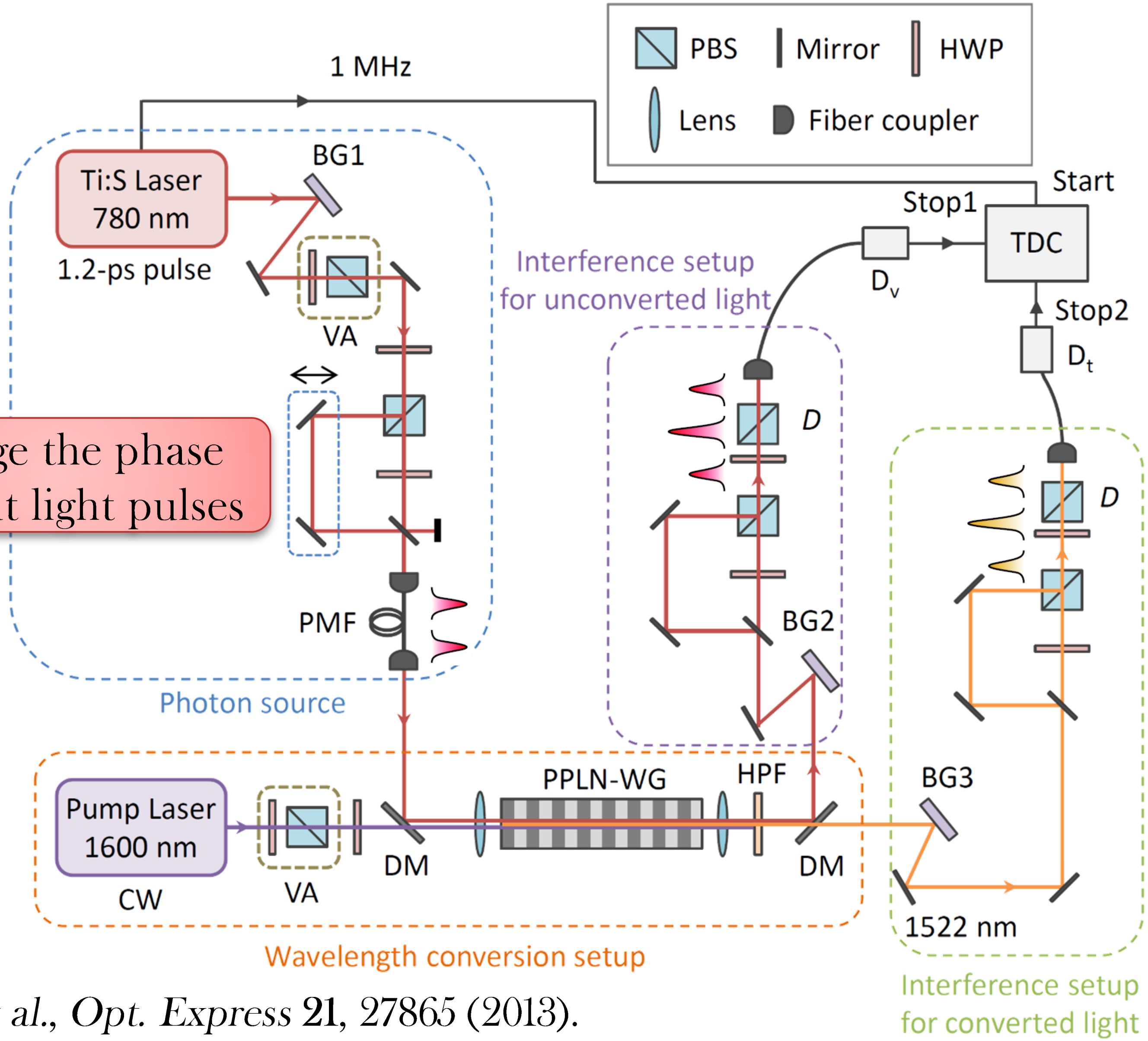
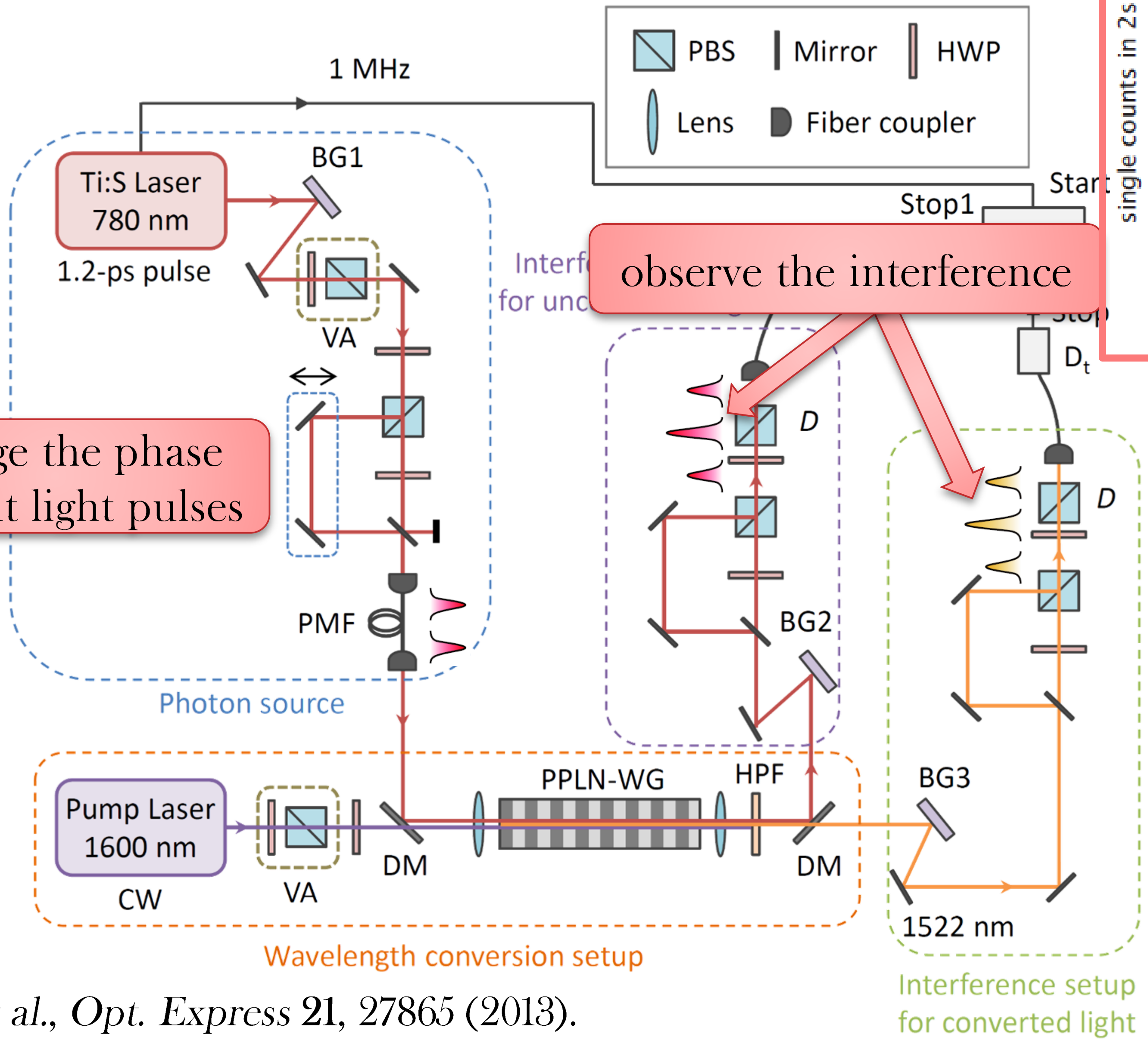


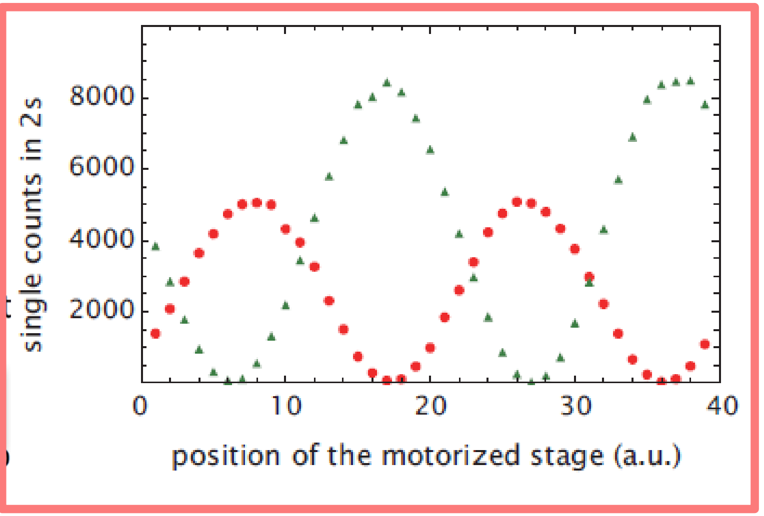
Change the phase of input light pulses

R. Ikuta, T. K. *et al.*, *Opt. Express* **21**, 27865 (2013).

Change the phase of input light pulses

observe the interference





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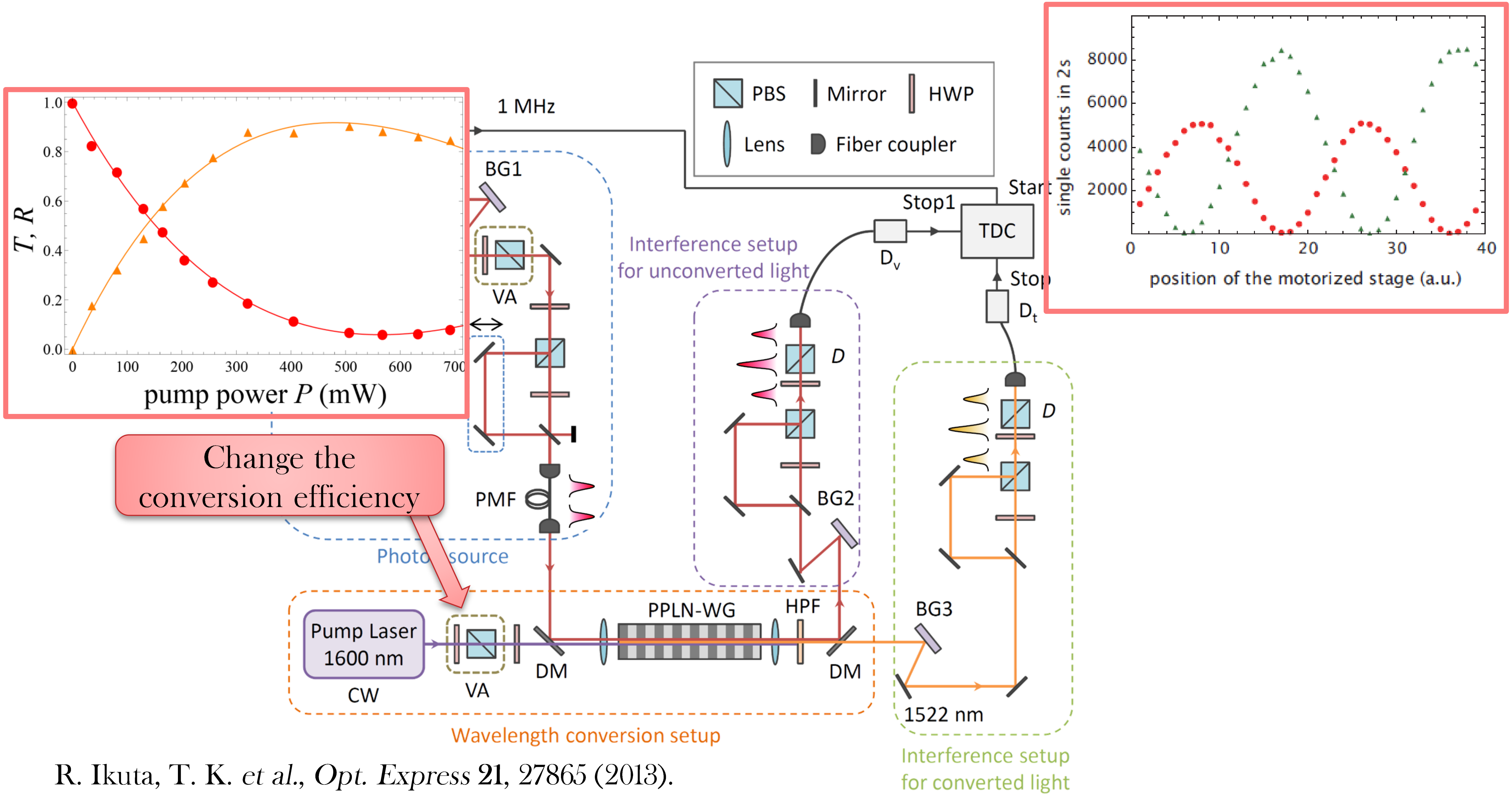

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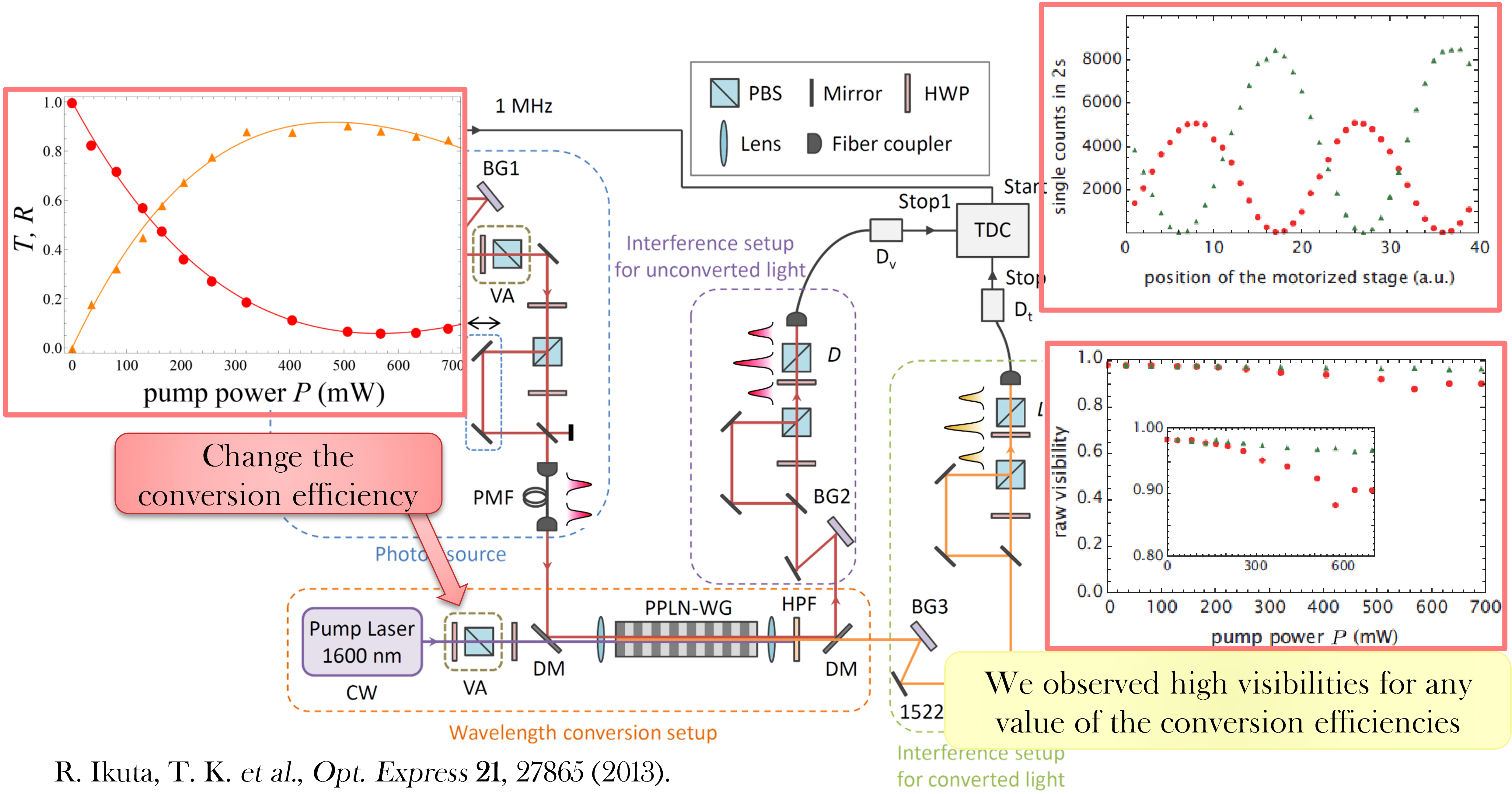

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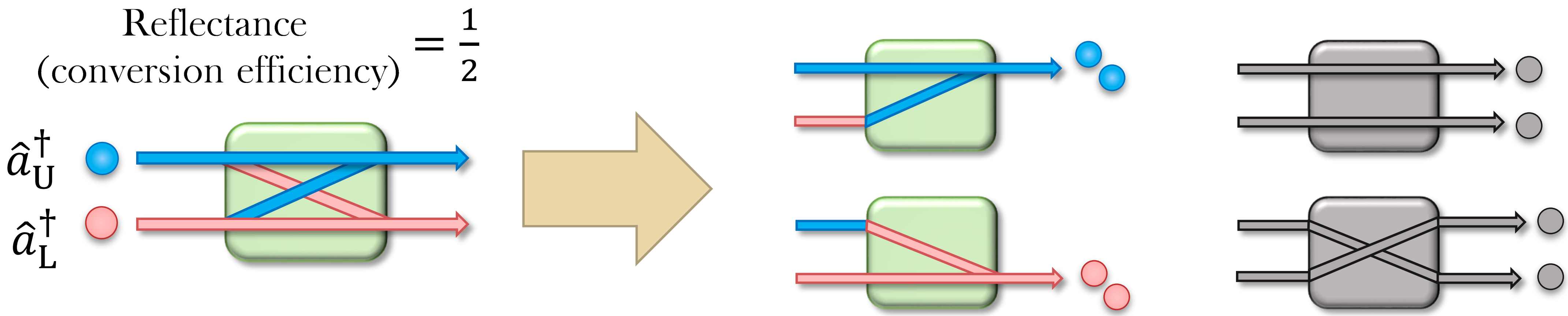
Frequency-domain HOM interference

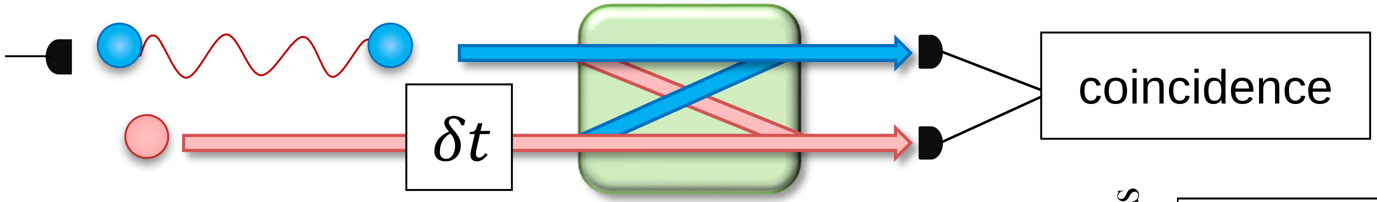


$$\hat{a}_{\mathrm{U}}^{\dagger}\hat{a}_{\mathrm{L}}^{\dagger} \to \frac{1}{2}\left(-\left(\hat{a}_{\mathrm{U}}^{\dagger}\right)^{2} - \hat{a}_{\mathrm{U}}^{\dagger}\hat{a}_{\mathrm{L}}^{\dagger} + \hat{a}_{\mathrm{U}}^{\dagger}\hat{a}_{\mathrm{L}}^{\dagger} + \left(\hat{a}_{\mathrm{L}}^{\dagger}\right)^{2}\right) = \frac{1}{2}\left(-\left(\hat{a}_{\mathrm{U}}^{\dagger}\right)^{2} + \left(\hat{a}_{\mathrm{L}}^{\dagger}\right)^{2}\right)$$

Theoretically proposed by M. G. Raymer *et al.*, *Opt. Commun.* **283**, 747–752 (2010).

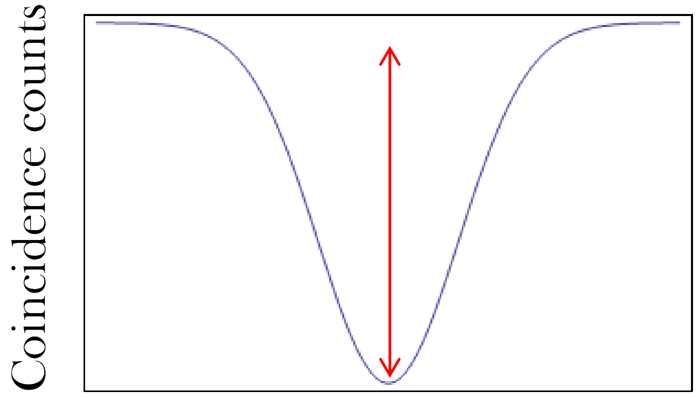
Conceptual setup of experiment

heralded single photon @ 780 nm



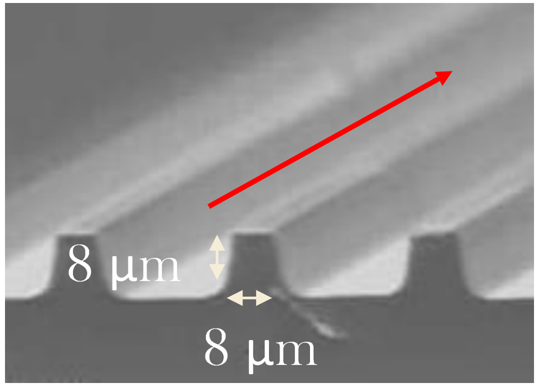
weak coherent pulse @ 1522 nm
average photon number ~ 0.1

optical delay δt



optical delay δt

Type-0 quasi-phase-matched periodically poled LiNbO3 (PPLN) waveguide (NTT Electronics Corp.)

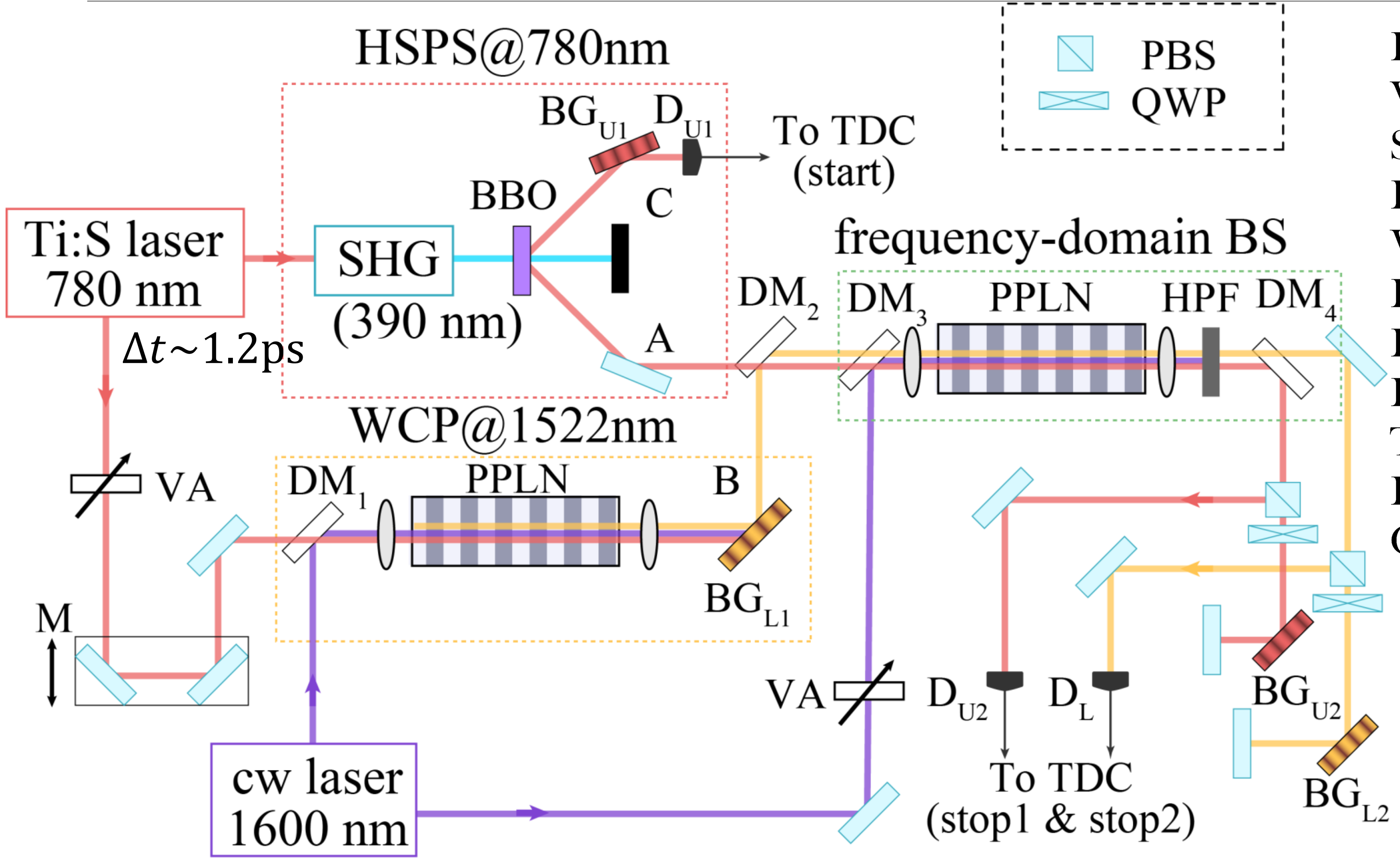


- length : L=20 mm
- poling period : Λ=18 μm
- temperature : 50 ℃
- acceptance bandwidth : 140 GHz

~0.3 nm at 780 nm, ~ 1.1 nm at 1522 nm

- phase matching : e → e + e

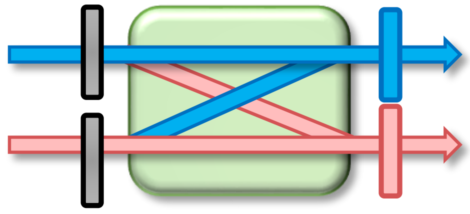
Experimental setup

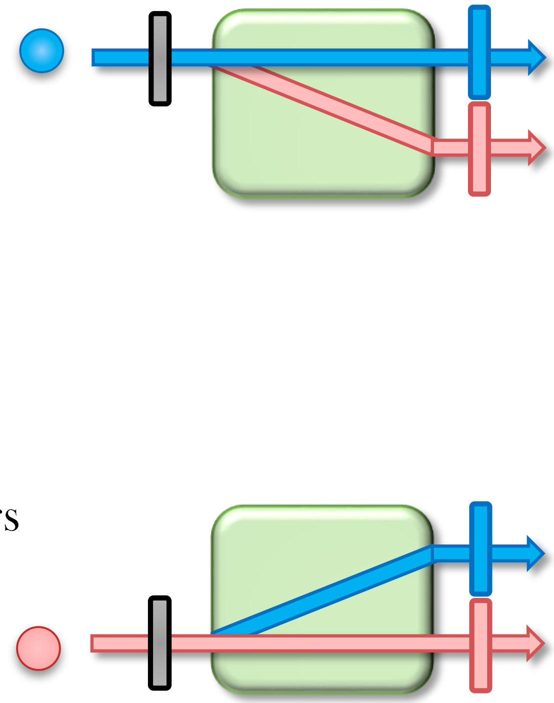


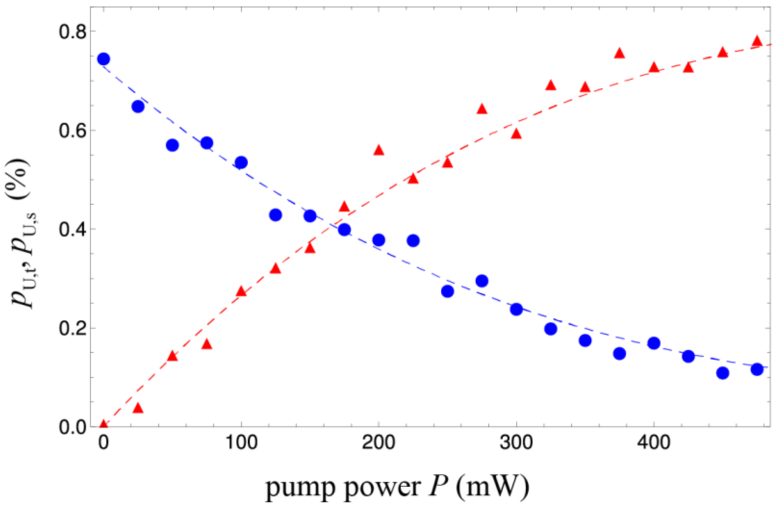
HSPS: heralded single photon source
WCP: weak coherent pulse
SHG: second harmonic generation
BBO: beta barium borate
VA: variable attenuator
BG: Bragg Grating
DM: dichroic mirror
HPF: high-pass filter
TDC: time-to-digital converter
PBS: polarizing beamsplitter
QWP: quarter-wave plate

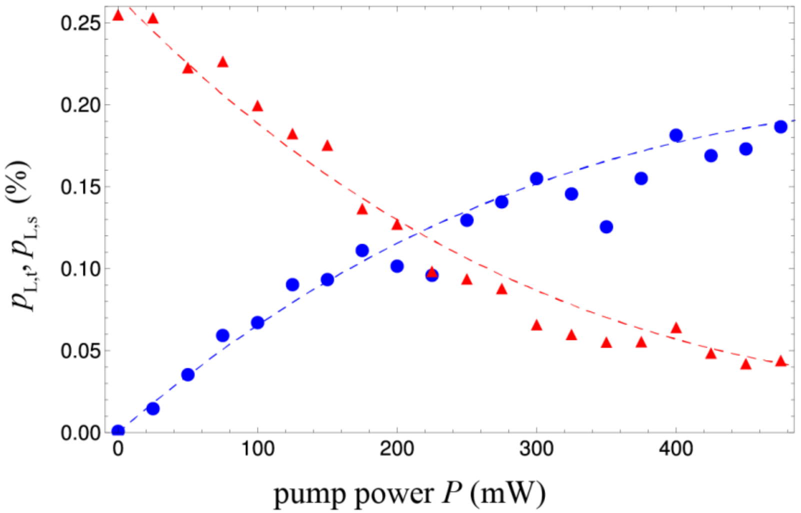
Total Reflectance/Transmittance for each inputs

Theoretical model of BS

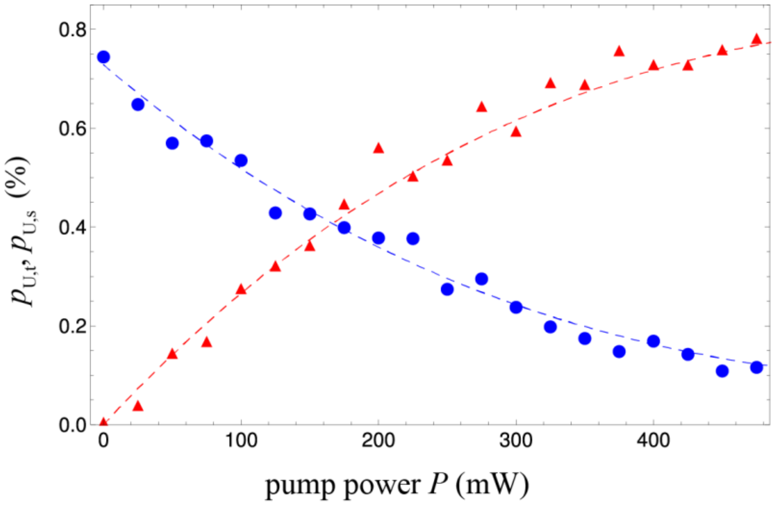


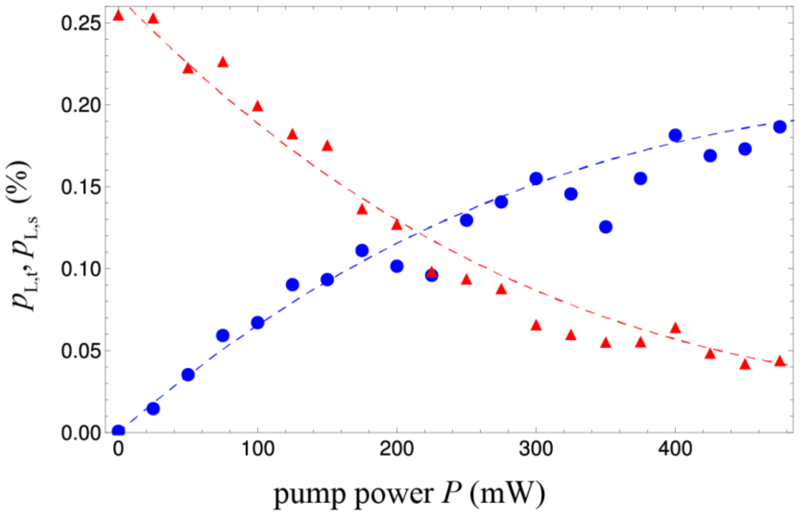




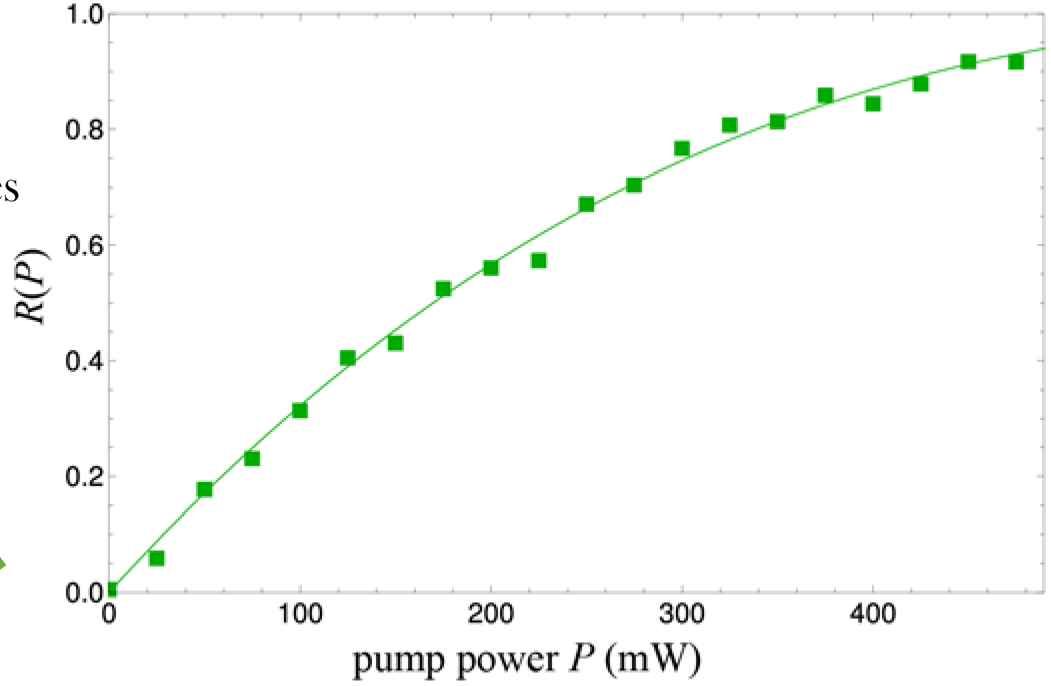


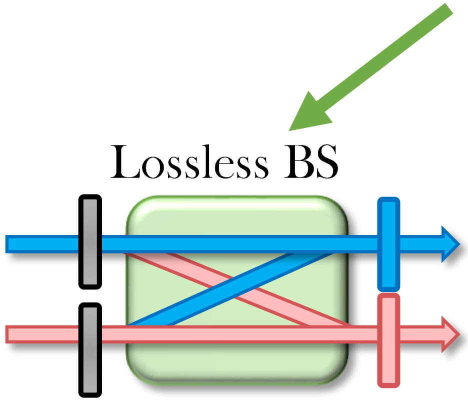
Estimated internal reflectance





Subtraction of the effect of input and output losses

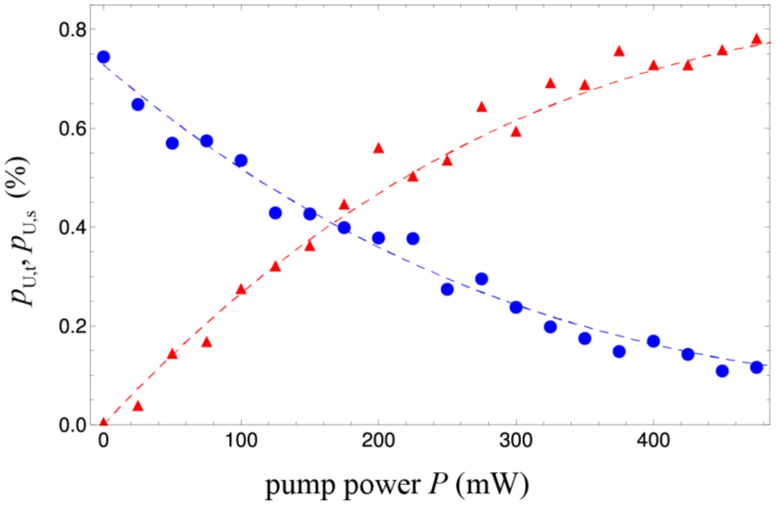


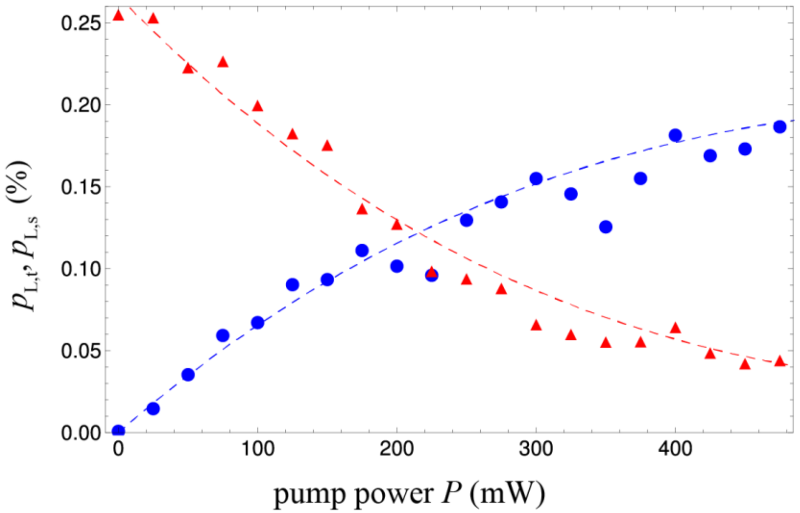


Estimated internal reflectance

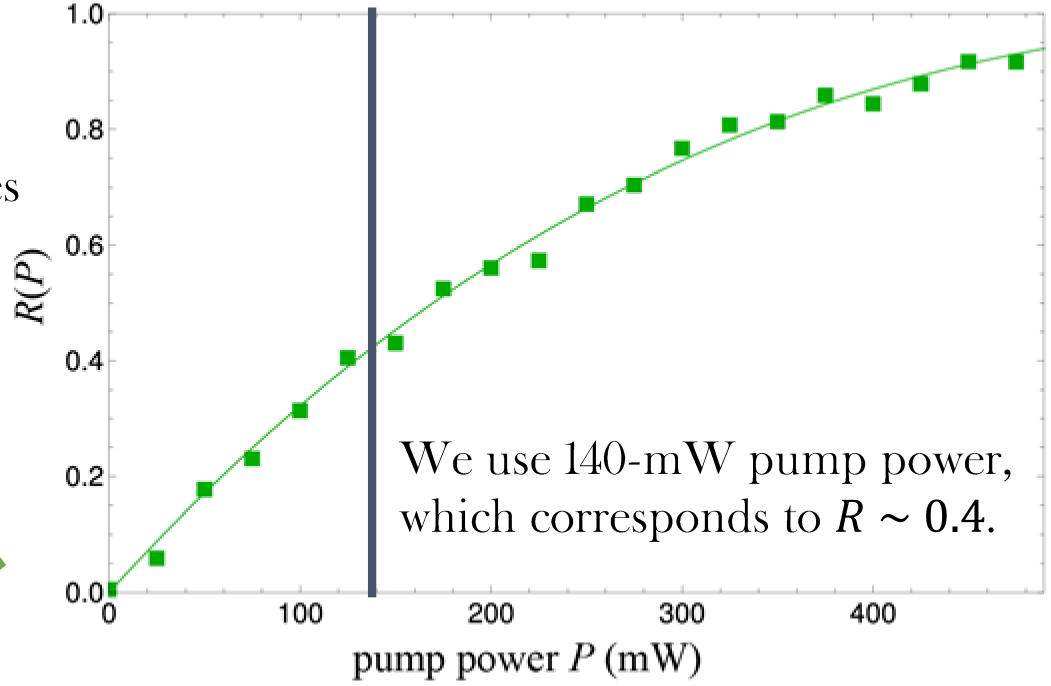
$$R(P) = 0.99\ \sin^2\left(0.06\sqrt{P[\mathrm{mW}]}\right)$$

Estimated internal reflectance

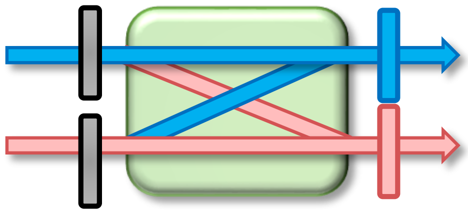




Subtraction of the effect of input and output losses



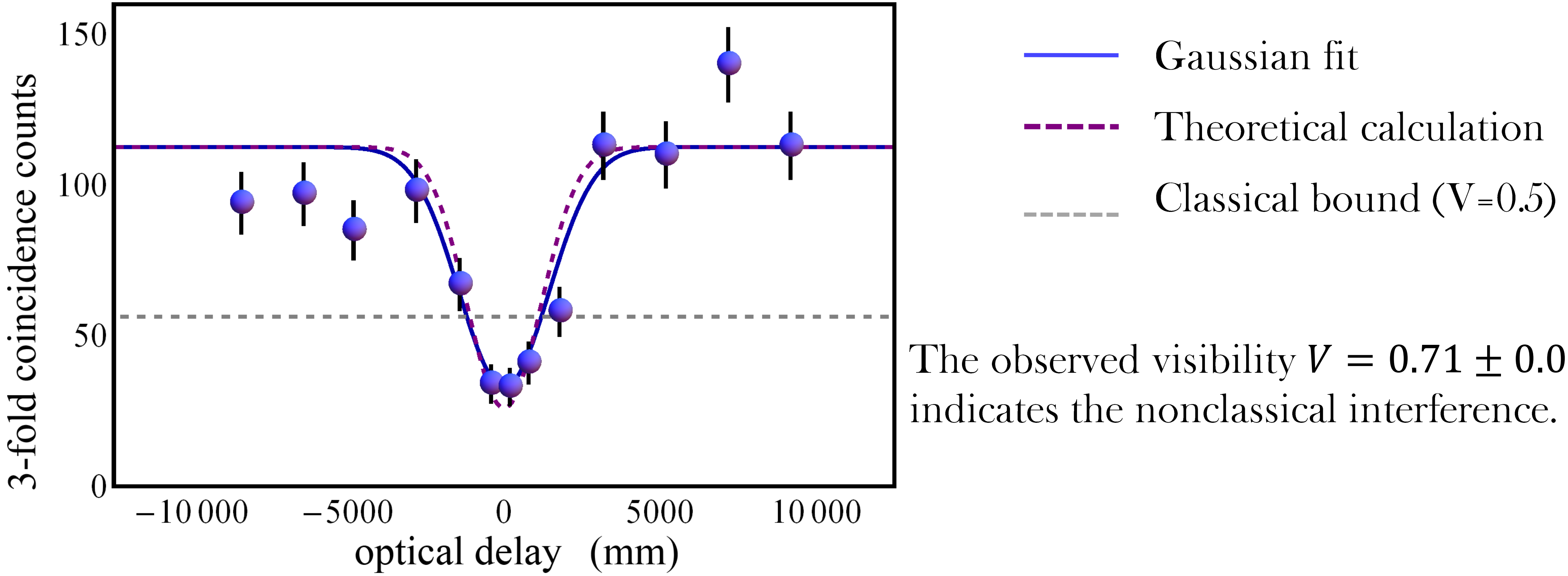
Lossless BS



Estimated internal reflectance

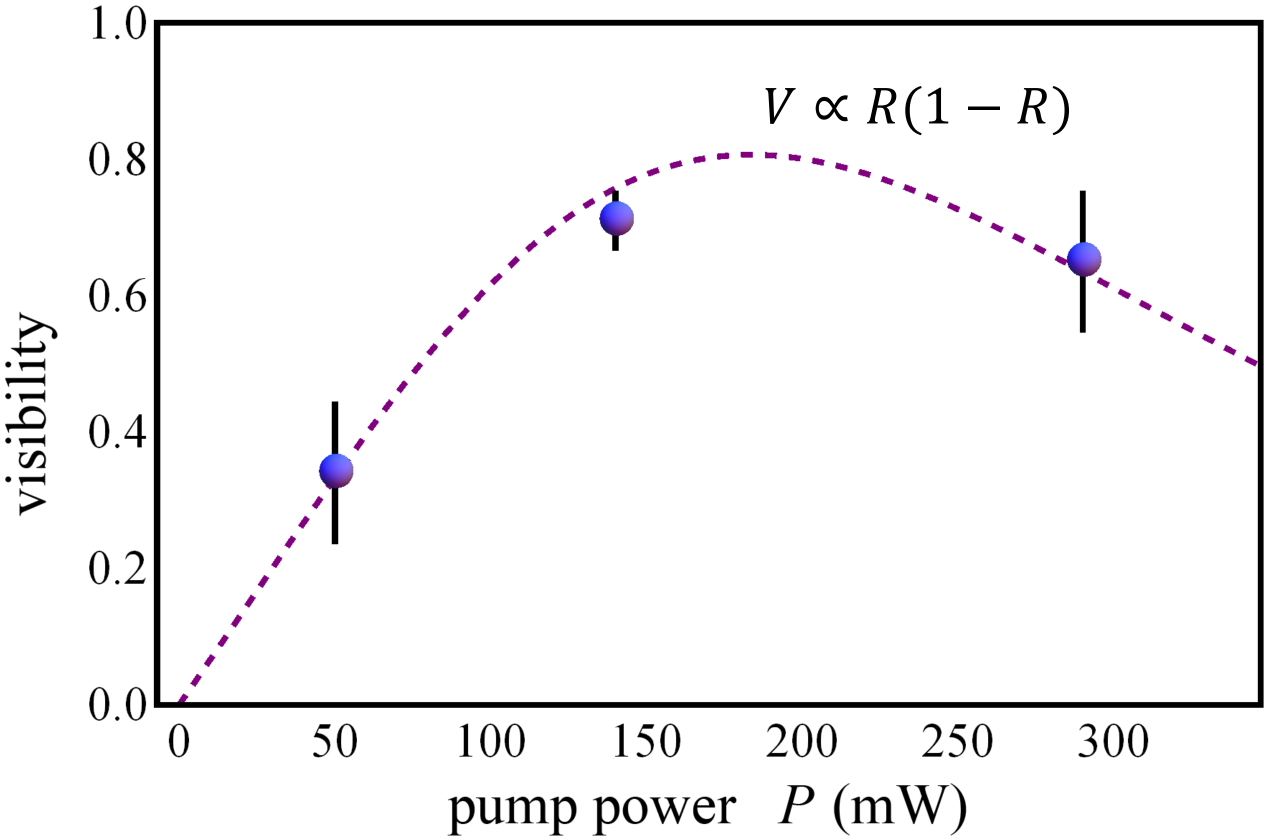
$$R(P) = 0.99 \ \sin^2\left(0.06\sqrt{P[\mathrm{mW}]}\right)$$

Observed HOM dip at 140-mW pump



The observed visibility $V = 0.71 \pm 0.04$ indicates the nonclassical interference.

Pump-power dependency



$V = 0.34 \pm 0.10$
@ 50 mW, $R \sim 0.2$

$V = 0.71 \pm 0.04$
@ 140 mW, $R \sim 0.4$

$V = 0.65 \pm 0.10$
@ 290 mW, $R \sim 0.7$

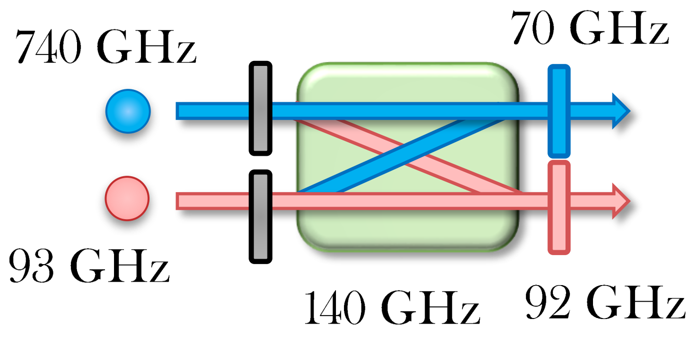
From the theoretical calculation,
$V = 0.81$ @ 190 mW, $R \sim 0.5$

Reasons for degradation of visibility

Main reasons are due to the input light pulses

- The effect of the multiphoton components in the coherent light pulse at 1,522 nm
- The broad bandwidth of the heralded single photon at 780 nm

Bandwidths in our experiment



If we use two single photons,
$V = 0.95$ @ 190 mW, $R \sim 0.5$.
If we use two inputs light with the bandwidth of 93 GHz,
$V = 0.93$ @ 190 mW, $R \sim 0.5$.

If we assume both of improvements,
$V = 0.98$ @ 190 mW, $R \sim 0.5$.

Summary

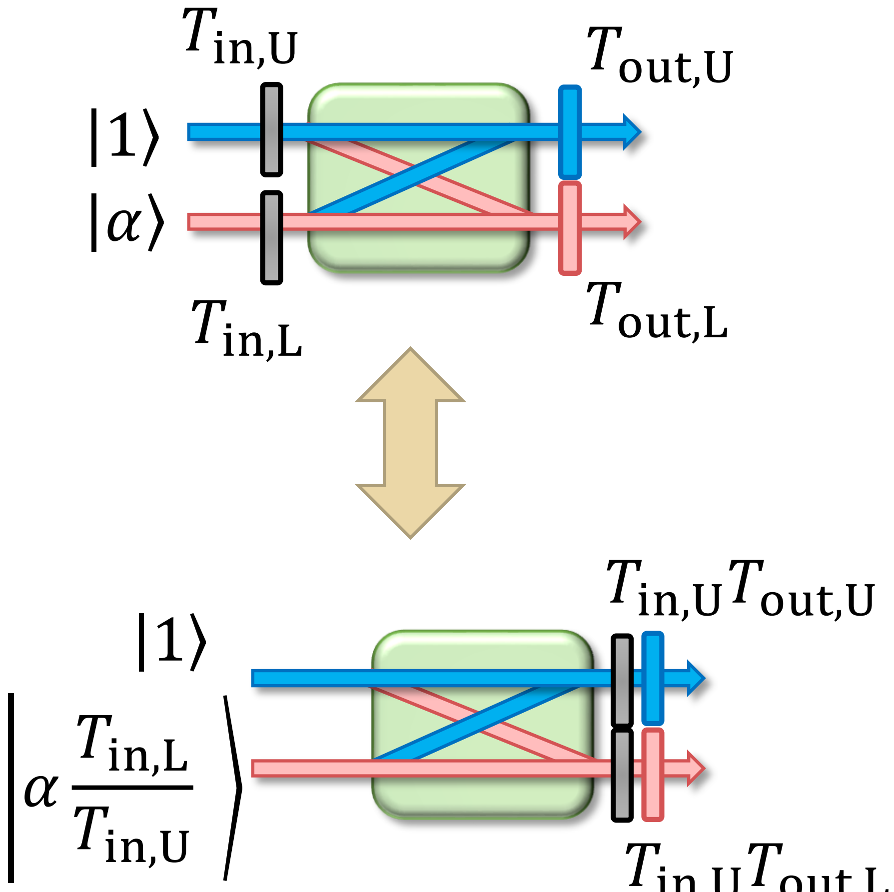
T. Kobayashi *et al.*, *Nat. Photon.* **10**, 441 (2016).

✓The frequency converter by a nonlinear optical medium with a strong pump light works as a frequency-domain BS.

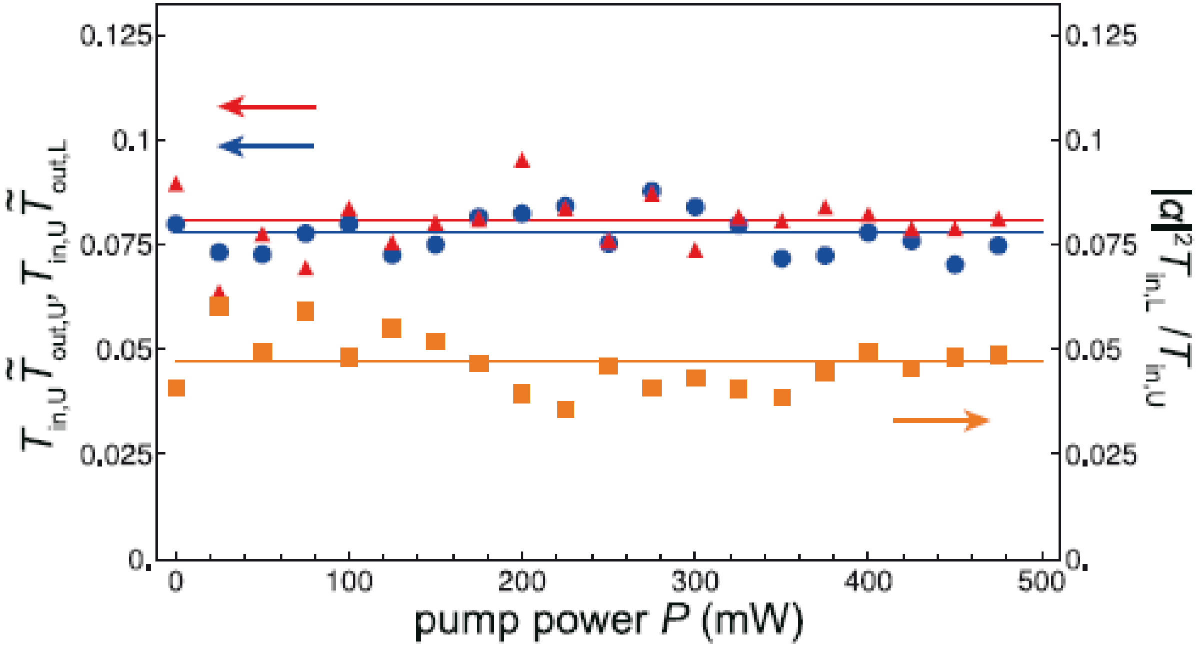
✓We observed the HOM dip by using frequency-domain BS. The observed visibility $V = 0.71 \pm 0.04$ clearly shows the nonclassical interference.

✓The main reasons for the degradation of the visibility are due to the input light pulses. In the case of ideal input photons, we estimated the visibility $V = 0.98$.

We believe that the frequency-domain HOM interferometer will provide a new tool for exploiting quantum phenomena and a way of scaling up quantum information processing.



$T_{\rm in,U}$
$T_{\rm out,U}$
$|1\rangle$
$|\alpha\rangle$
$T_{\rm in,L}$
$T_{\rm out,L}$
$T_{\rm in,U}T_{\rm out,U}$
$|1\rangle$
$\left|\alpha\frac{T_{\rm in,L}}{T_{\rm in,U}}\right\rangle$
$T_{\rm in,U}T_{\rm out,L}$



0.125
0.1
0.075
0.05
0.025
0.
0
100
200
300
400
500
pump power P (mW)
$T_{\rm in,U}\tilde{T}_{\rm out,U}$, $T_{\rm in,U}\tilde{T}_{\rm out,L}$
$|\alpha|^2 T_{\rm in,L}/T_{\rm in,U}$