Generation of Entangled Photons in Fibers and Their System Applications

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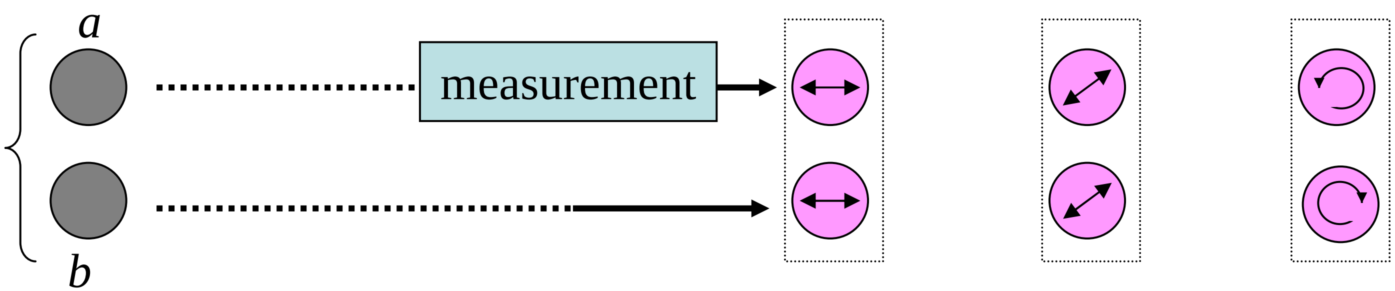
[Contents]

1. What is entangled photons (especially in time-bin) ?
2. How to generate them ?
3. Generation of quantum correlated photons in fiber: experiment
4. Generation of entangled photons in fiber: experiment
5. Quantum key distribution using entangled photons: mechanism and experiment

Quantum entangled photons

A photon pair whose states are ambiguous before measurement.

When the state of one of the pair is determined by measurement, the other photon is determined to be in the correlated state.



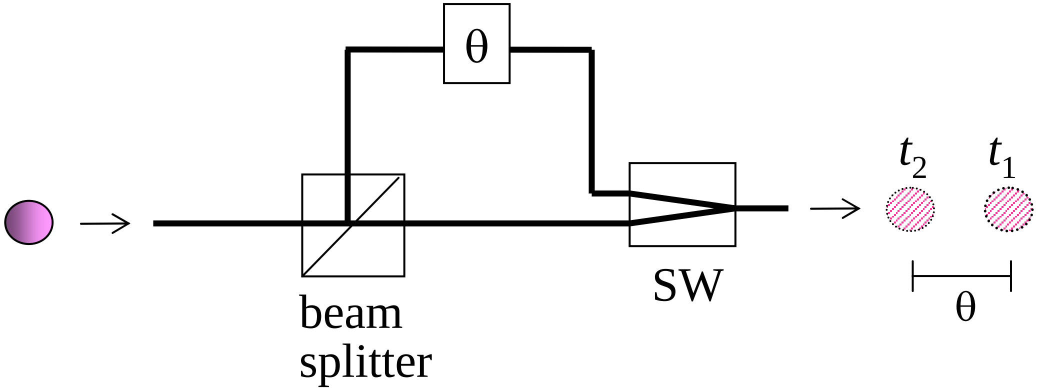
$$|\Psi> = \frac{1}{\sqrt{2}}(|H>_a|H>_b + |V>_a|V>_b) \longrightarrow |H>_a|H>_b$$

$$= \frac{1}{\sqrt{2}}(|+45>_a|+45>_b + |-45>_a|-45>_b) \longrightarrow |+45>_a|+45>_b$$

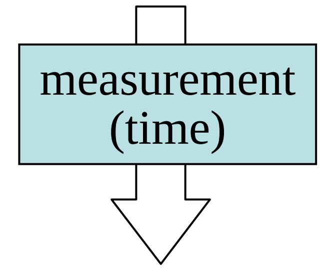
$$= \frac{1}{\sqrt{2}}(|R>_a|L>_b + |L>_a|R>_b) \longrightarrow |L>_a|R>_b$$

Time-bin entanglement

One-photon superposition state in time-bin

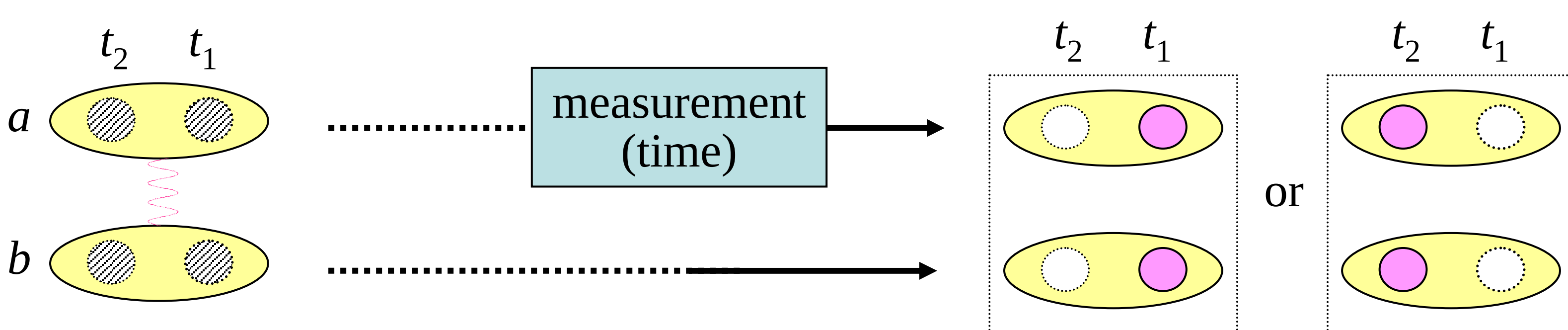


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|t_1\rangle + e^{i\theta}|t_2\rangle\}$$



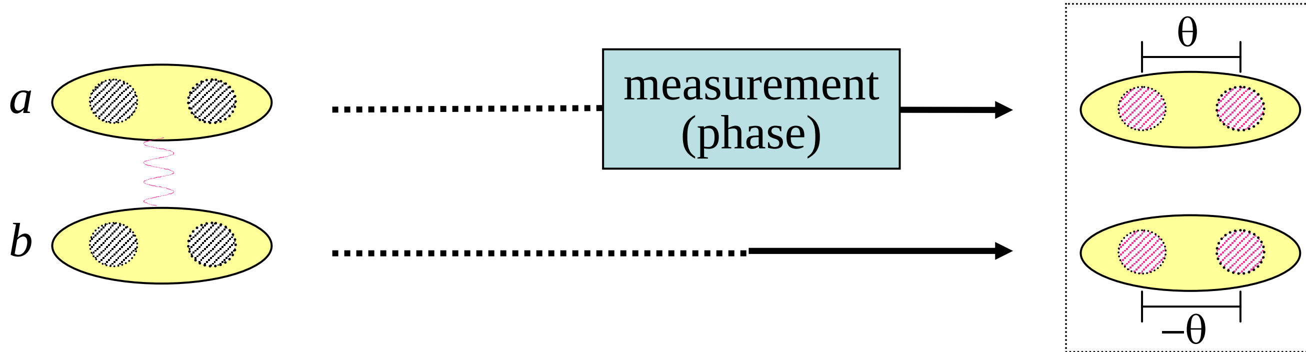
$$|\Psi\rangle = |t_1\rangle \quad \text{or} \quad |t_2\rangle$$

Two photons entangled in time-bin



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|t_1\rangle_a|t_1\rangle_b + |t_2\rangle_a|t_2\rangle_b\} \longrightarrow \quad |t_1\rangle_a|t_1\rangle_b \qquad |t_2\rangle_a|t_2\rangle_b$$

entangled state



(θ: arbitrary)

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|t_1\rangle_a|t_1\rangle_b + |t_2\rangle_a|t_2\rangle_b\}$$

$$= \frac{1}{\sqrt{2}}\{|\phi_+(\theta)\rangle_a|\phi_+(-\theta)\rangle_b + |\phi_-(\theta)\rangle_a|\phi_-(-\theta)\rangle_b\}$$

$$\left(\begin{array}{l} |\phi_+(x)\rangle = \frac{1}{\sqrt{2}}(|t_1\rangle + e^{ix}|t_2\rangle) \\ |\phi_-(x)\rangle = \frac{1}{\sqrt{2}}(|t_1\rangle - e^{ix}|t_2\rangle) \end{array}\right)$$

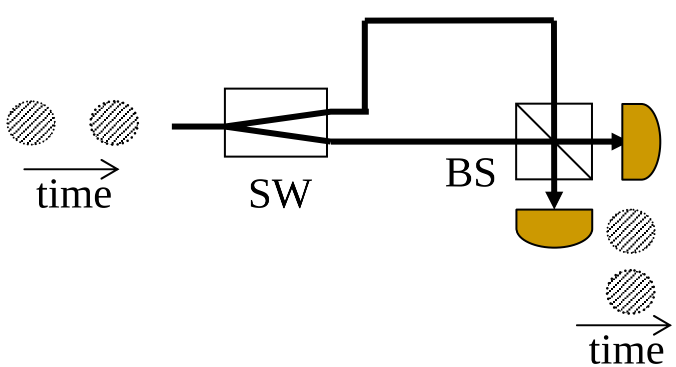
⇒

$$|\phi_+(\theta)\rangle_a|\phi_+(-\theta)\rangle_b$$

or

$$|\phi_-(\theta)\rangle_a|\phi_-(-\theta)\rangle_b$$

Phase measurement



Note

The following state is not entangled.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\{|t_1\rangle_a|t_1\rangle_b + e^{i\phi}|t_2\rangle_a|t_2\rangle_b\}$$

↑ (arbitrary)

$$\neq \frac{1}{\sqrt{2}}\{|\phi_+(\theta)\rangle_a|\phi_+(-\theta)\rangle_b + |\phi_-(\theta)\rangle_a|\phi_-(-\theta)\rangle_b\}$$

[Contents]

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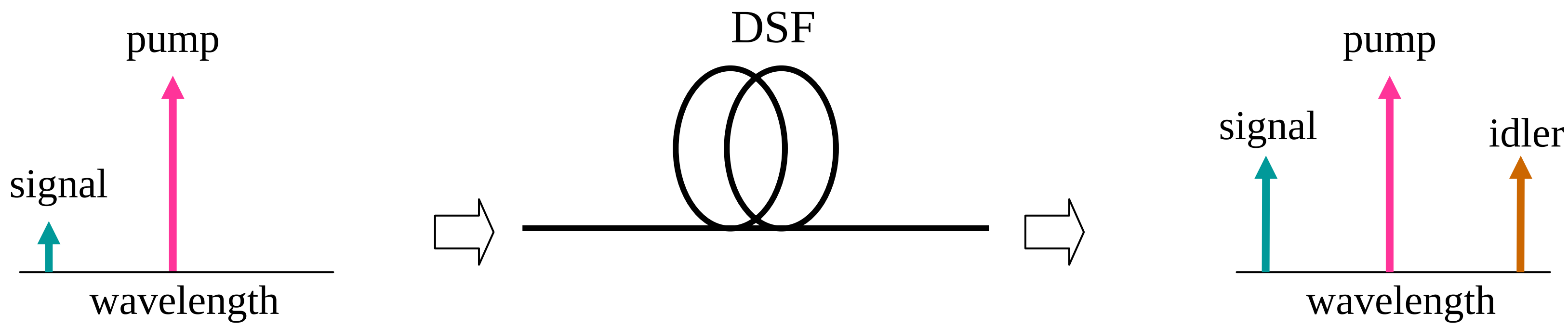
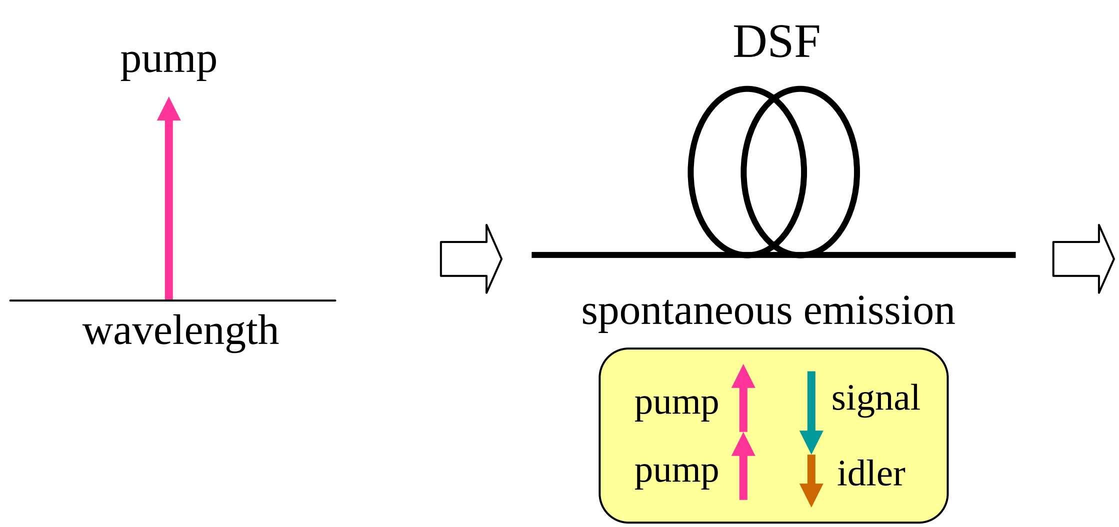
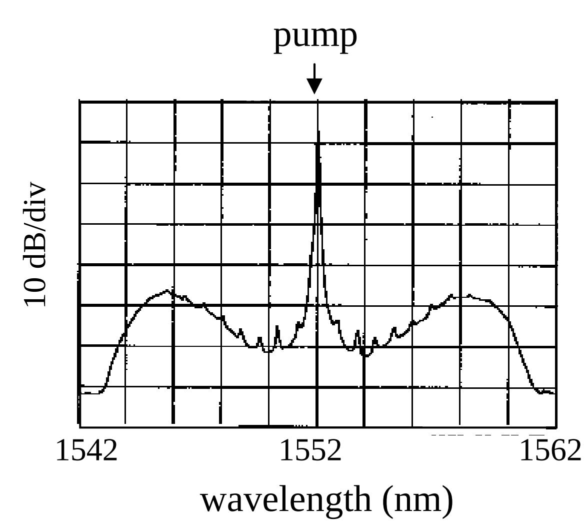
Way to generate entanglement

Fiber parametric amplifier



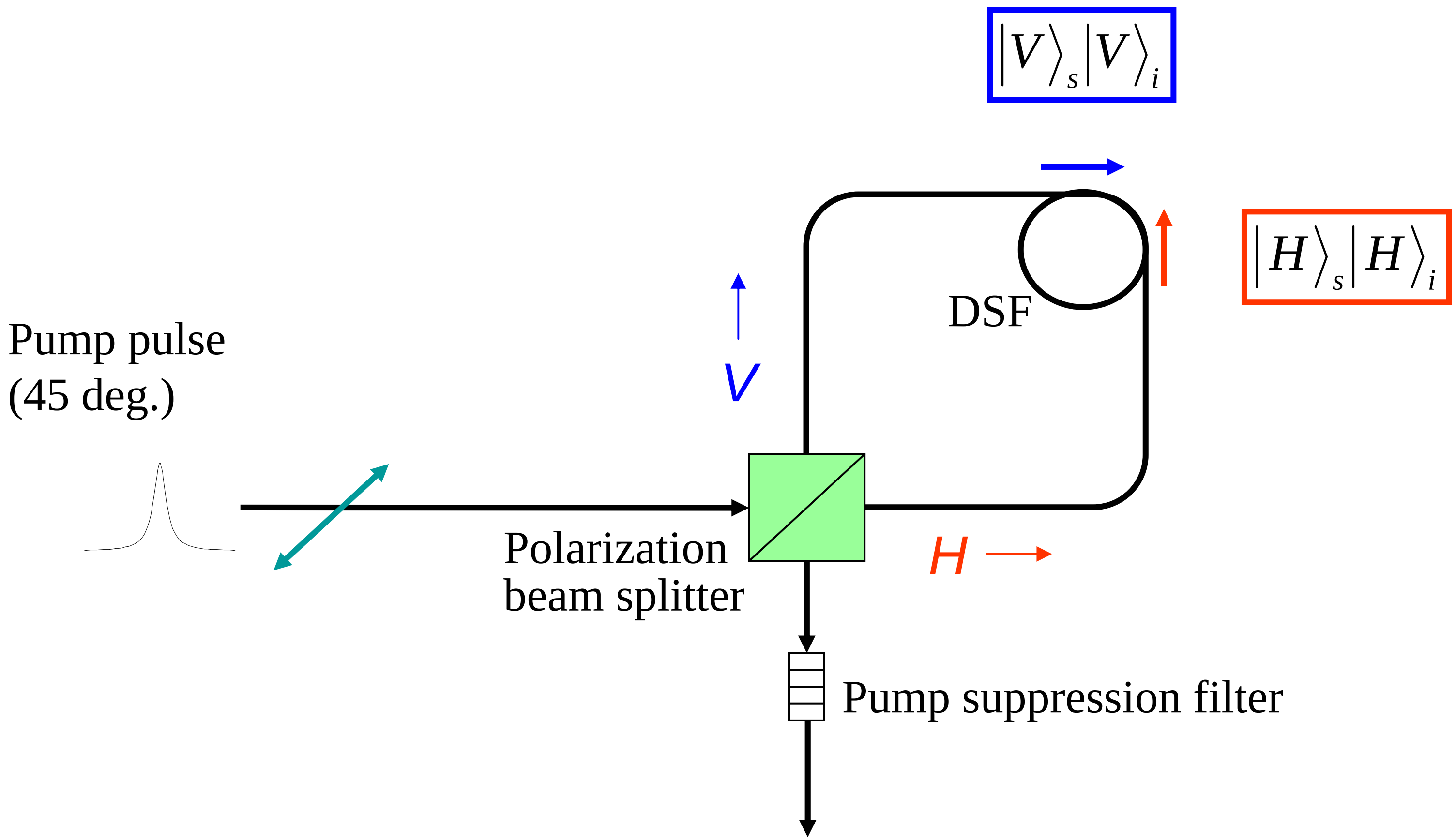




$$2f_{pump} = f_{sig} + f_{idler}$$

$|H\rangle_s|H\rangle_i$ for H-pump

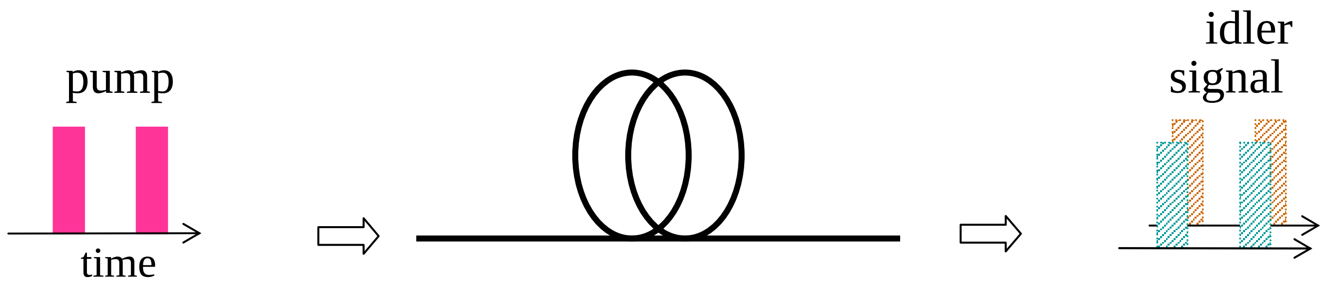
Polarization entanglement generation



Polarization entangled state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_s|H\rangle_i + |V\rangle_s|V\rangle_i\right)$$

Time-bin entanglement generation



The pump power is adjusted so that $r^2 << r(1 - r)$ $\qquad |t_1>_s |t_1>_i + e^{i\phi} |t_2>_s |t_2>_i$

(r: prob. of one pair generation)

<u>Nonlinear coupled equations</u>

$$\begin{cases} \dfrac{dE_s}{dz} = i\gamma E_p^2 E_i^* \\ \dfrac{dE_i}{dz} = i\gamma E_p^2 E_s^* \end{cases}$$

⇨ phase relation

$$\phi_{sig} + \phi_{idler} = 2\phi_{pump}$$

⇨

<u>Output state</u>

$$|t_1>_s |t_1>_i + e^{i2\Delta\phi_p} |t_2>_s |t_2>_i$$

($\Delta\phi_p$: pump phase difference)

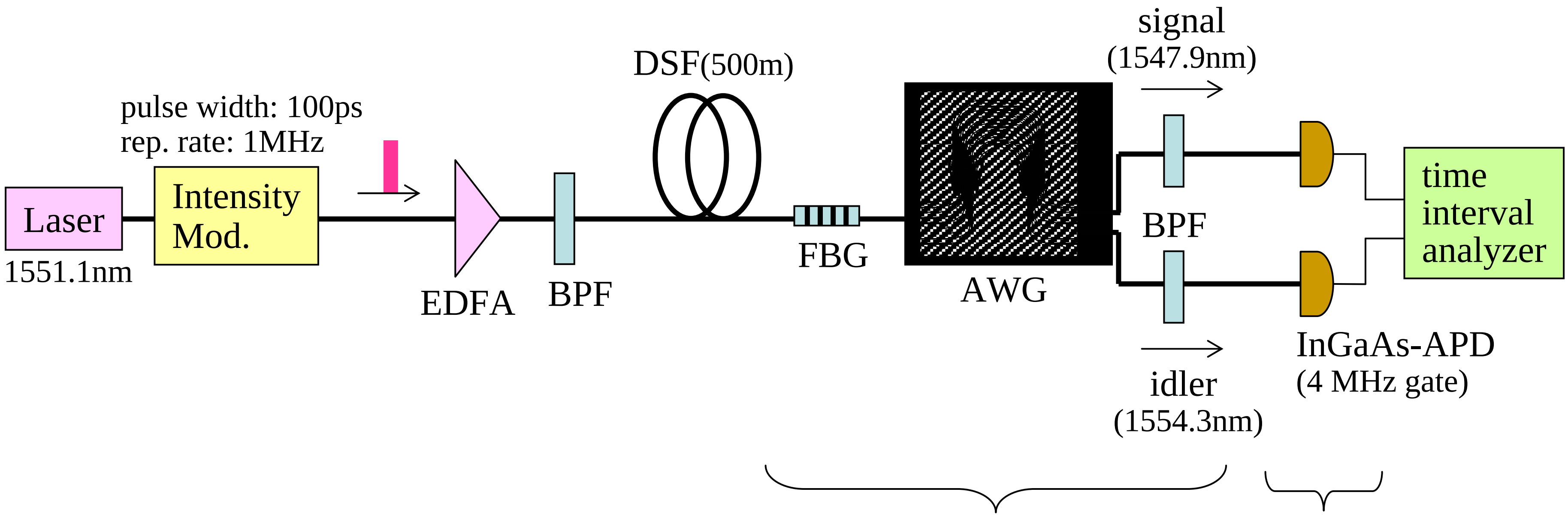
↓ $\Delta\phi_p = 0$

$$|t_1>_s |t_1>_i + |t_2>_s |t_2>_i$$

time-bin entanglement

[Contents]

Coincident signal/idler generation

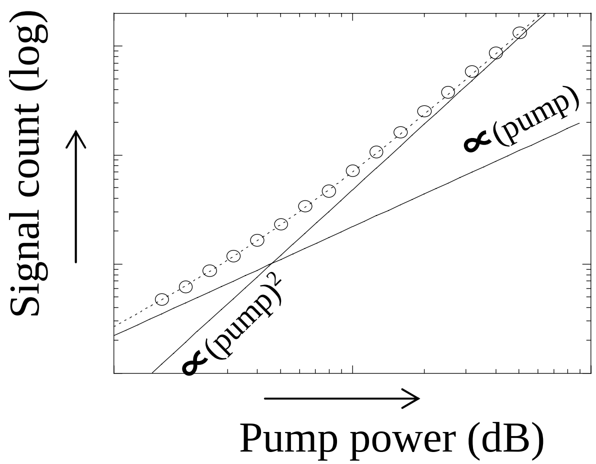


pump rejection > 100 dB
signal loss = 7.5 dB
idler loss = 6.9 dB

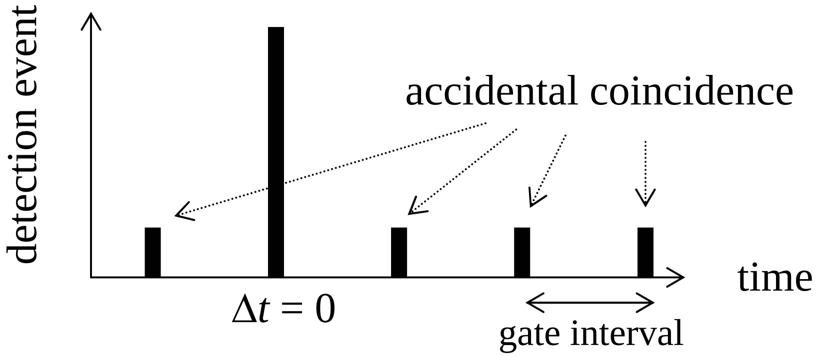
detection efficiency
6.2 % for signal
8.6 % for idler

Measurement results

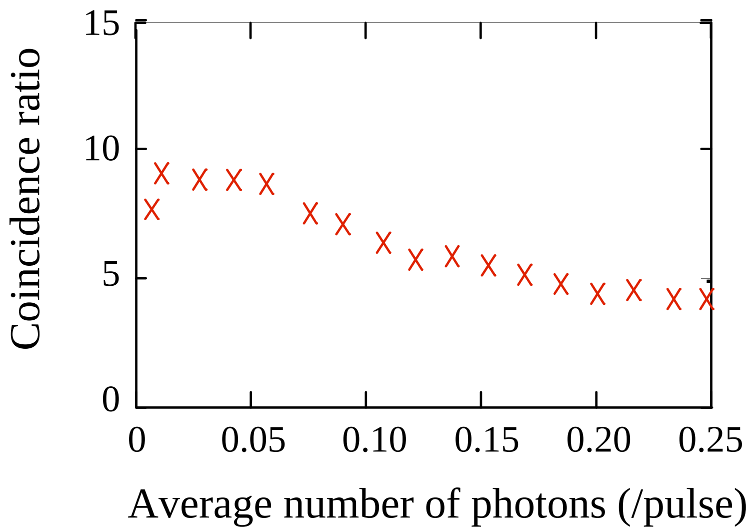
Photon count rate



Record on time interval analyzer



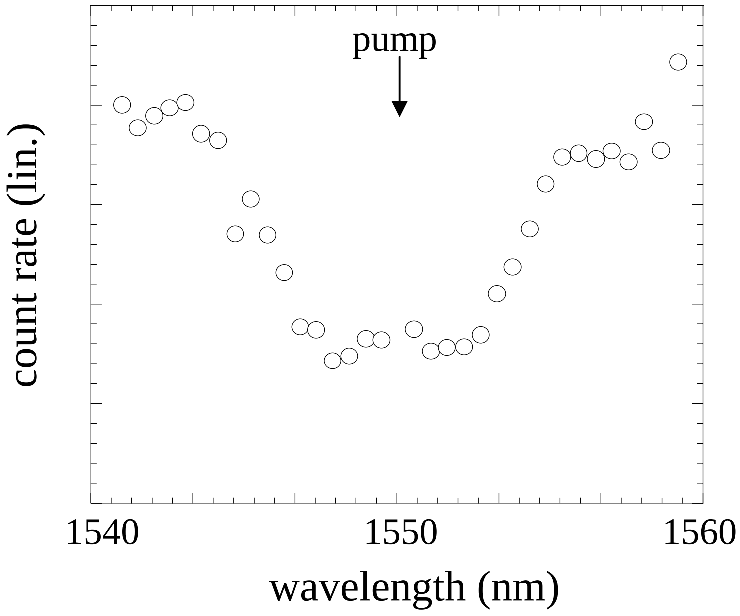
Coincident count relative to accidental



Correlated-photon generation,
but also non-correlated component.

What is the source of the accidental counts ?

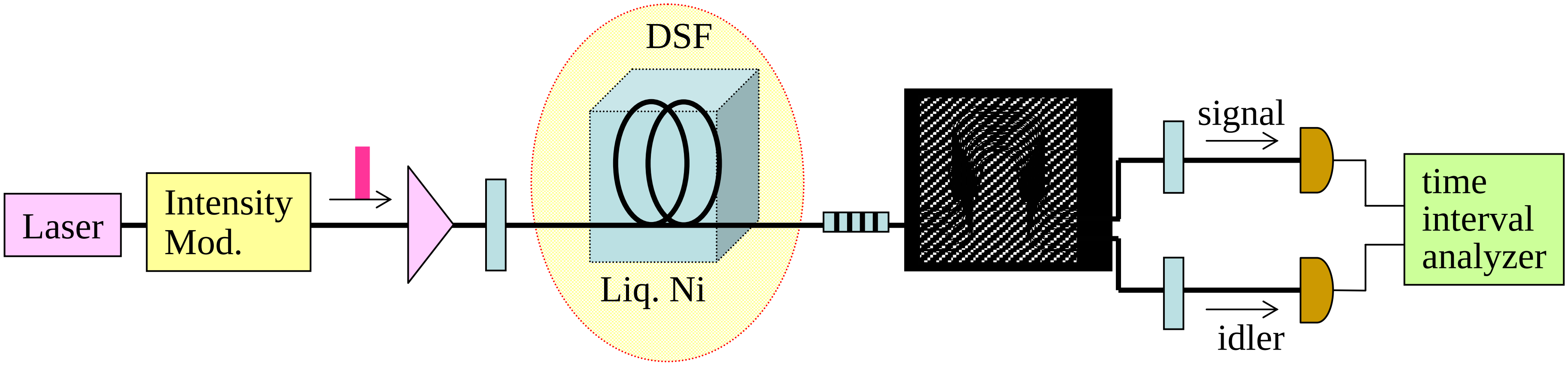
Spectrum of the linear component



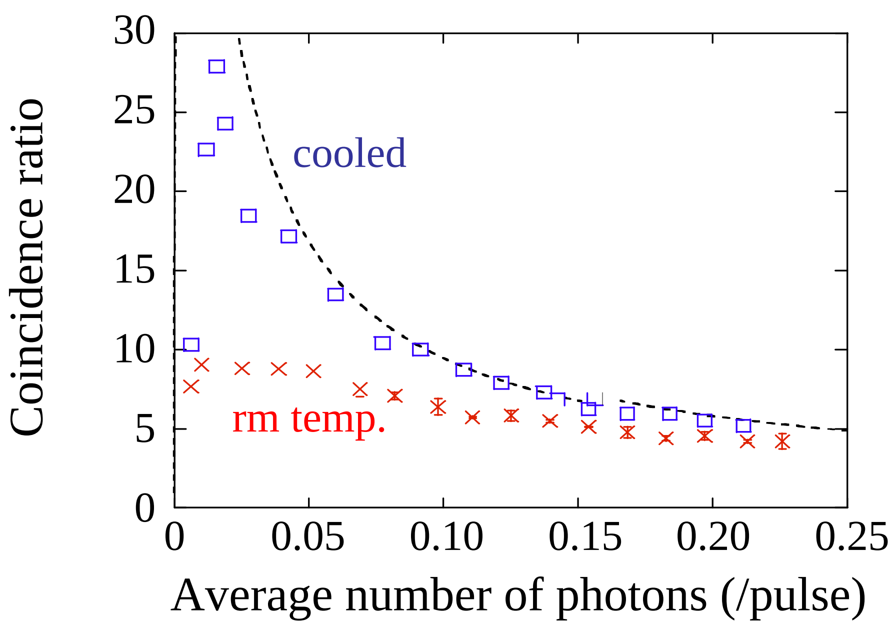
The spectrum suggests spontaneous Raman scattering.

Suppressing Raman scattering by cooling fiber

The number of phonons is small at a low temperature. ➞ Small Raman scattering



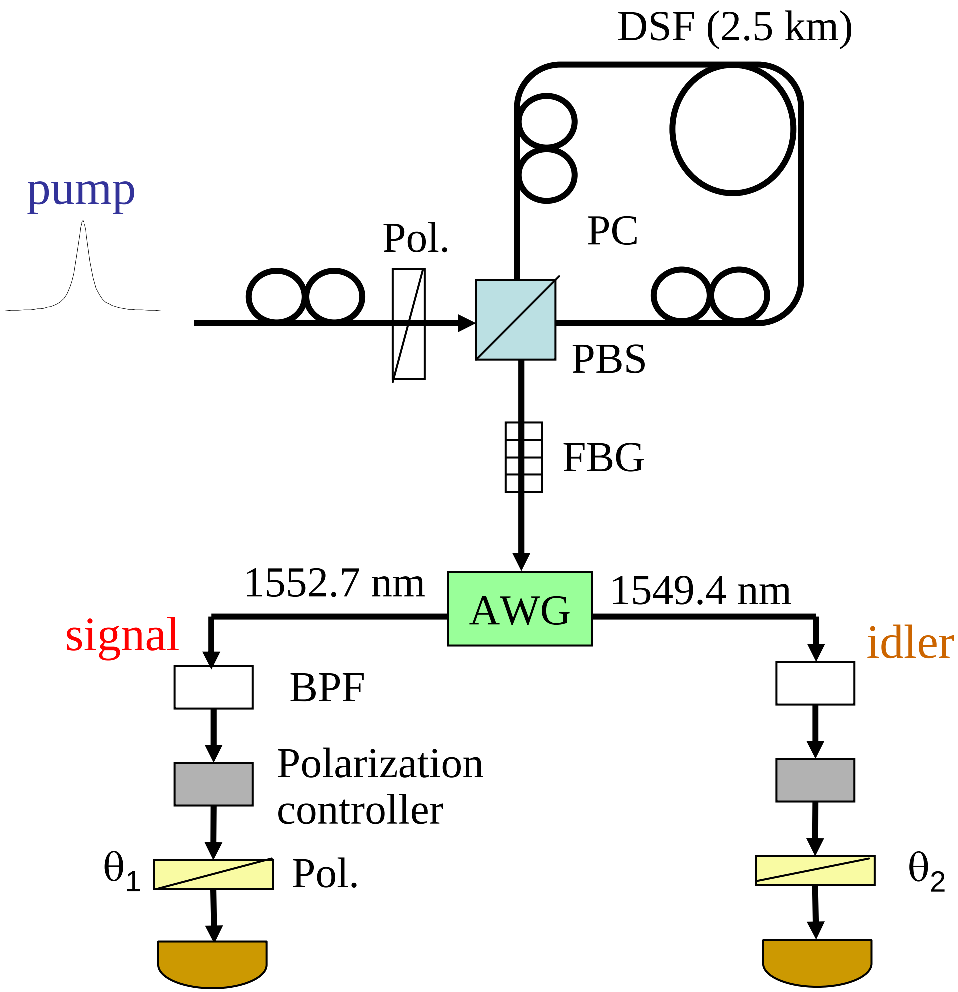
Coincident count relative to accidental

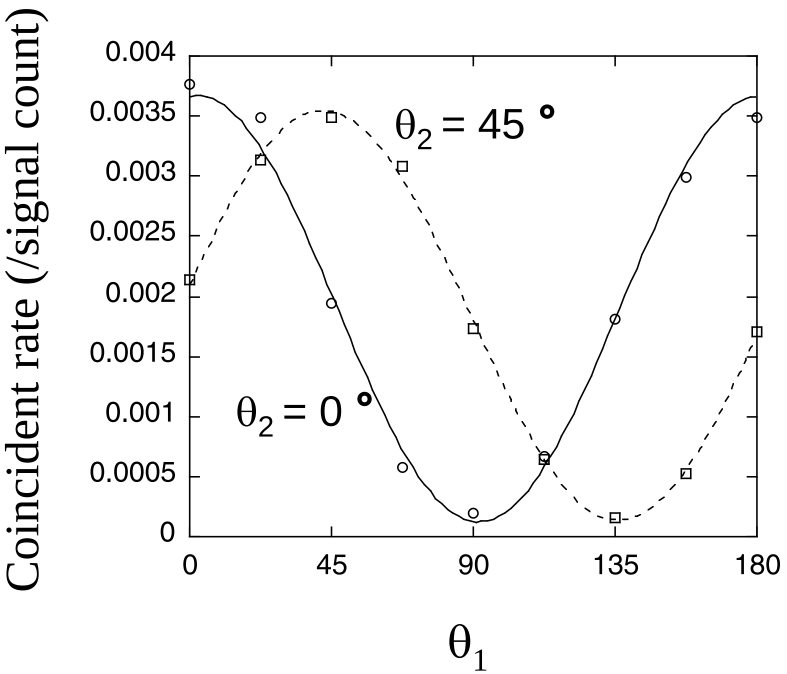


True coincidence increases.

[Contents]

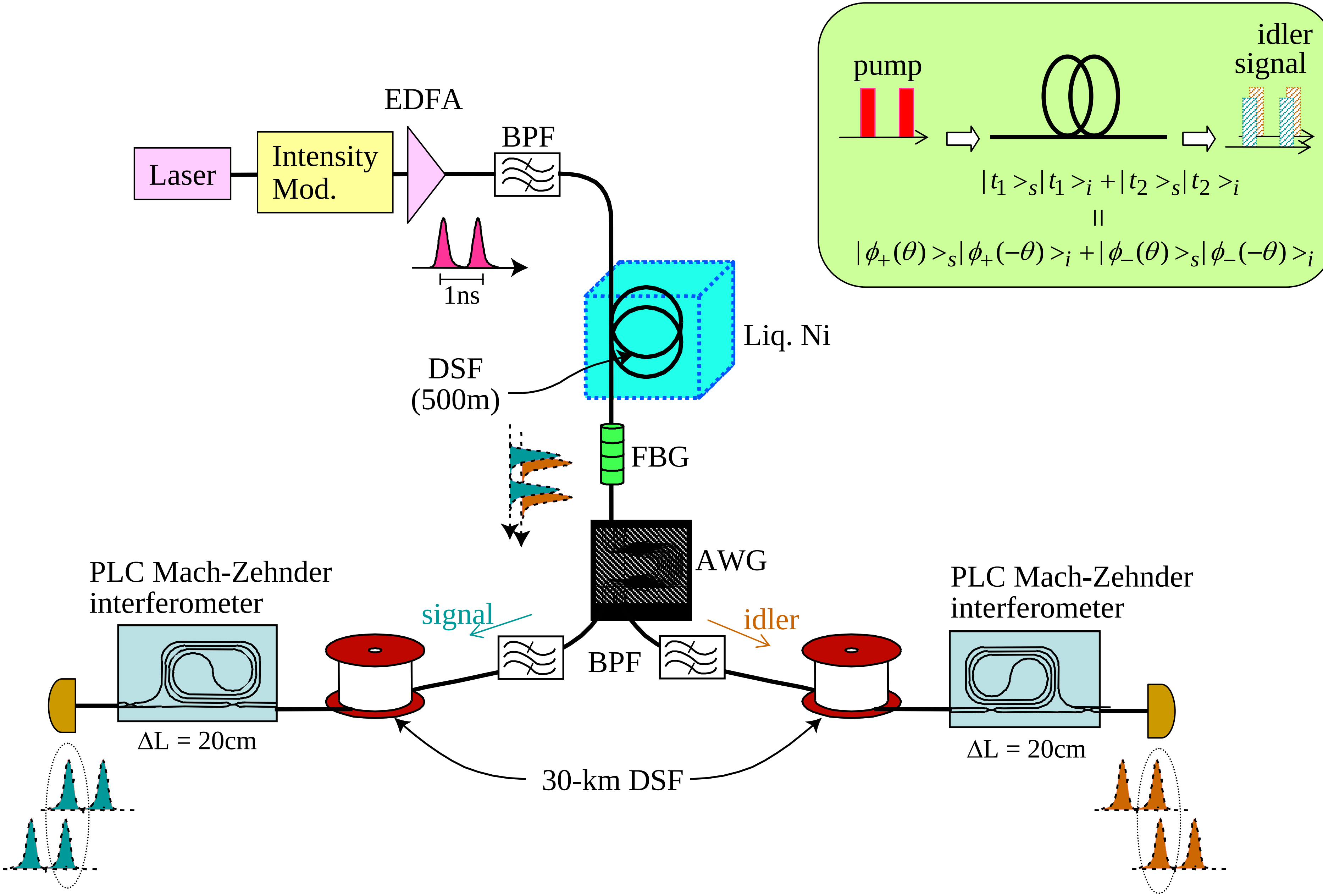
Polarization entanglement generation





$$|\Psi> = \frac{1}{\sqrt{2}}(|H>_s|H>_i + |V>_s|V>_i)$$

Time-bin entanglement generation: Experiment



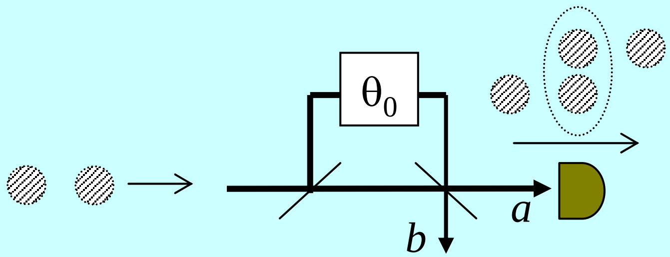
Correlation between signal & idler

initial state

$$|\Psi>=(|t_1>_s|t_1>_i+|t_2>_s|t_2>_i)/\sqrt{2}$$
$$=\{|\phi_+(-\theta)>_s|\phi_+(\theta)>_i+|\phi_-(-\theta)>_s|\phi_-(\theta)>_i\}/\sqrt{2}$$

$$|\phi_+(x)>=(|t_1>+e^{ix}|t_2>)/\sqrt{2}$$
$$|\phi_-(x)>=(|t_1>-e^{ix}|t_2>)/\sqrt{2}$$

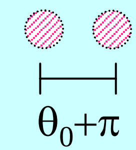
idler meas.



photon count at port *a*

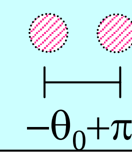
↓

idler state = $|\phi_-(\theta_0)>_i$

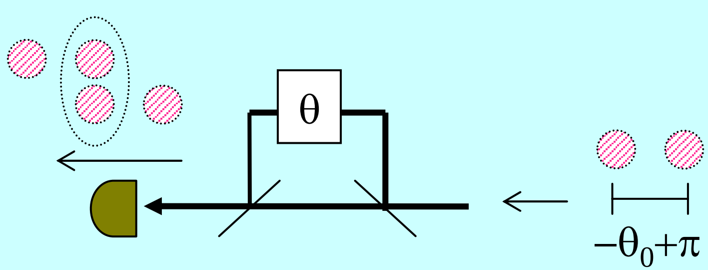


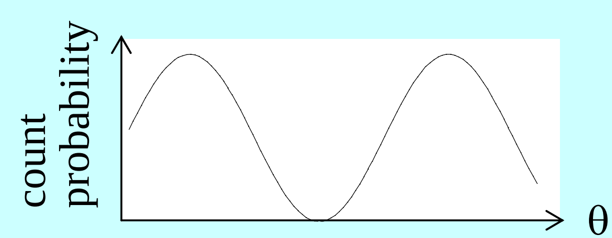
state change

two-photon state = $|\phi_-(-\theta_0)>_s|\phi_-(\theta_0)>_i$ → signal state = $|\phi_-(-\theta_0)>_s$



signal meas.

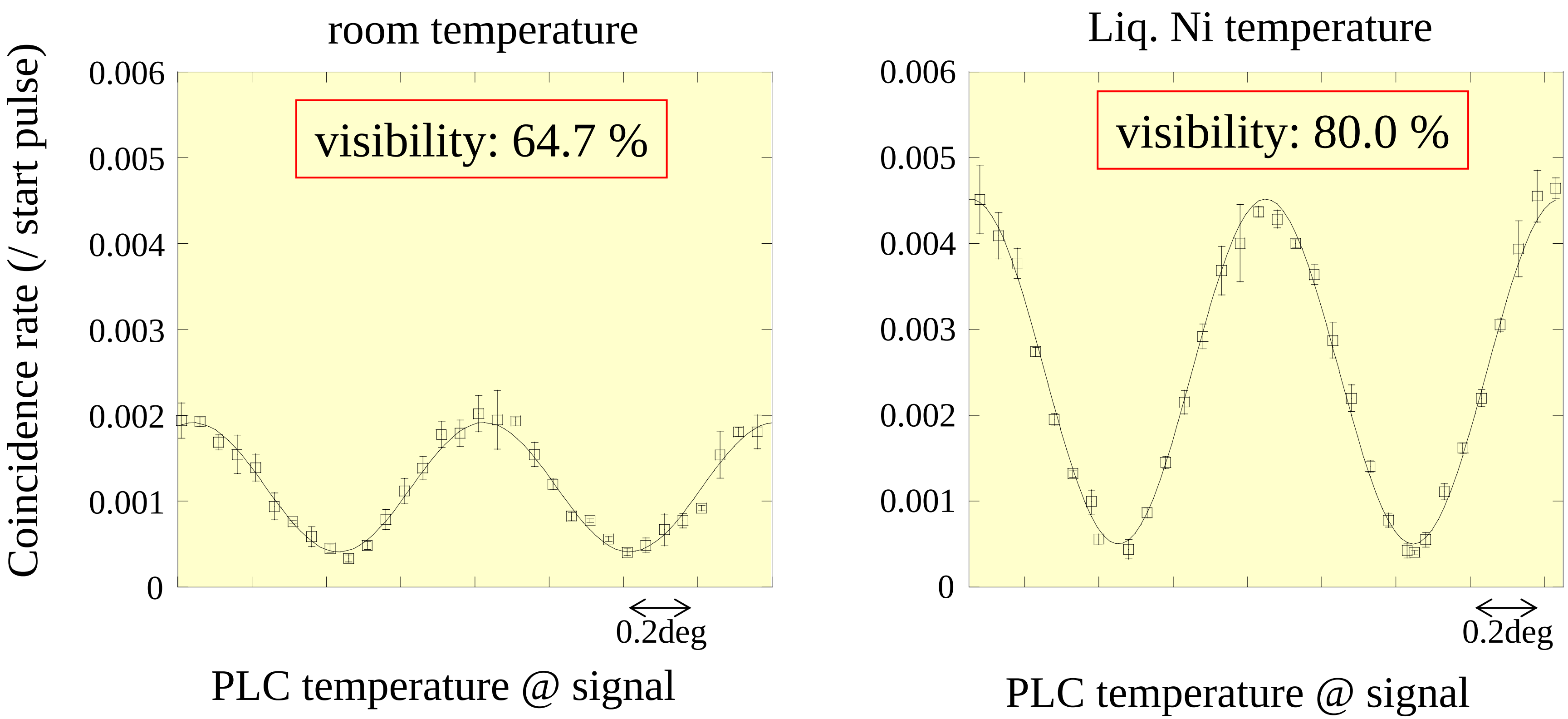




Two-photon interference
– back-to-back –

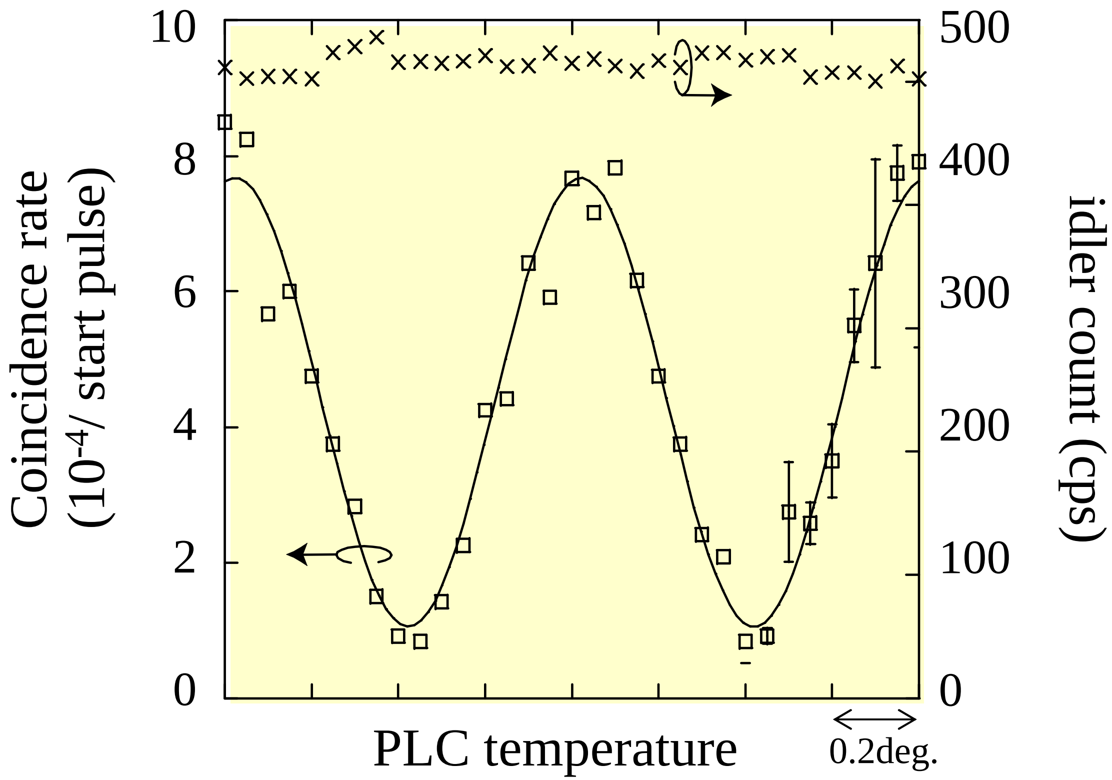
Coincident count between signal & idler when {θ_{signal}:changed, θ_{idler} :fixed}

Average number of photon pairs : 0.06 (/pulse) with pump power of 140mW



Two-photon interference
– (30km✕2)-fiber transmission –

average number of photon pairs : 0.06 (/pulse)
Liq. Ni temp.

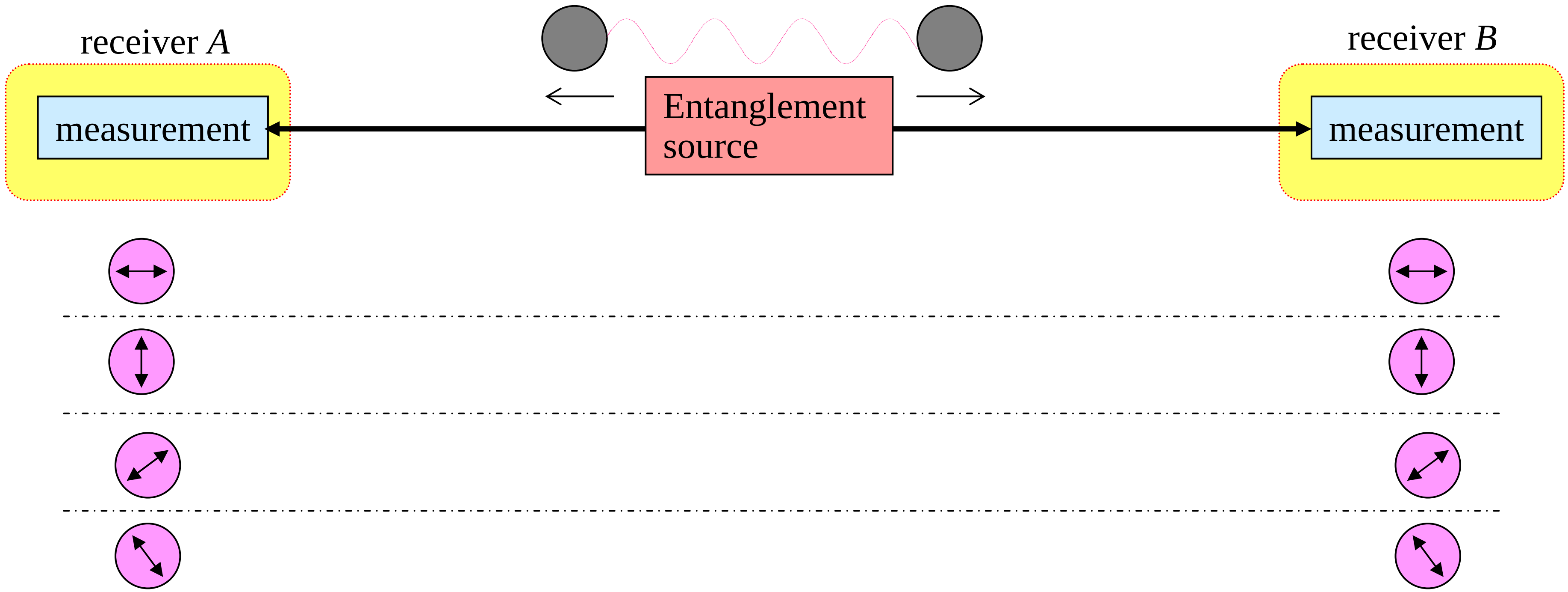


Entanglement is preserved over 60 km.

[Contents]

Application

Quantum key distribution (QKD) utilizing entanglement



Measurement results have correlation between *A* & *B*.

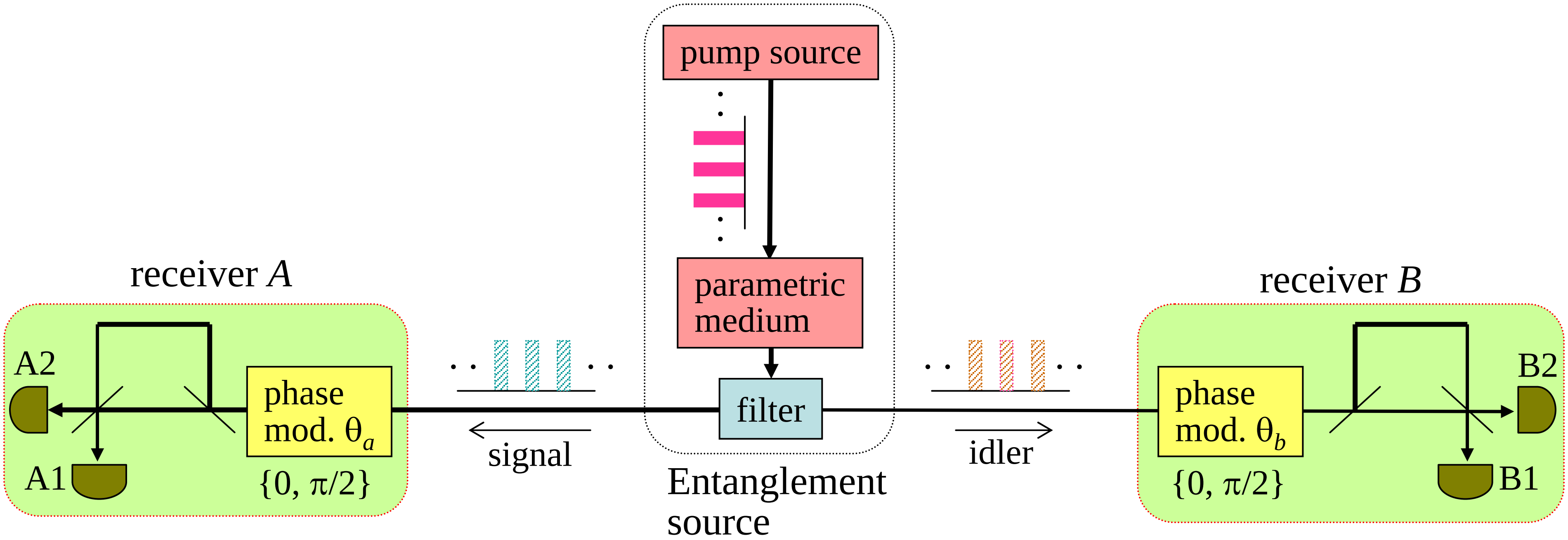
↓

Secret key for ciphering/deciphering a message

(i.e., identical bit string)

The system length is double compared with single-photon QKD.

QKD based on time-bin entanglement



Correlation
in coincident count between *A* & *B*

detection@*A*	$\Delta\theta_a + \Delta\theta_b$: 0	π/2	π
A1	B1	B1/B2	B2
A2	B2	B1/B2	B1

⇨

<u>Key creation</u>

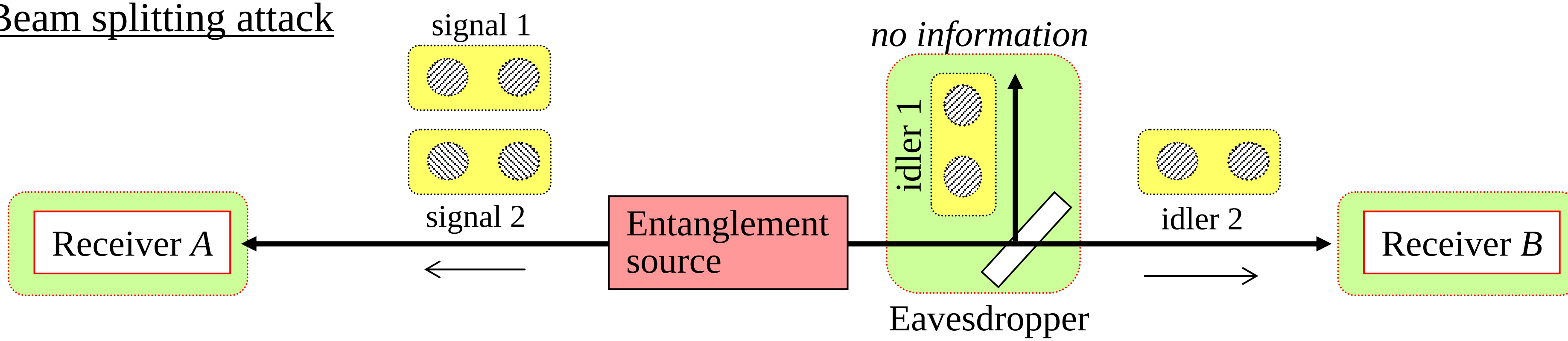
$\Delta\theta_a + \Delta\theta_b = 0$: {A1, B1} = “0”, {A2, B2} = “1”

$\Delta\theta_a + \Delta\theta_b = \pi$: {A1, B2} = “0”, {A2, B1} = “1”

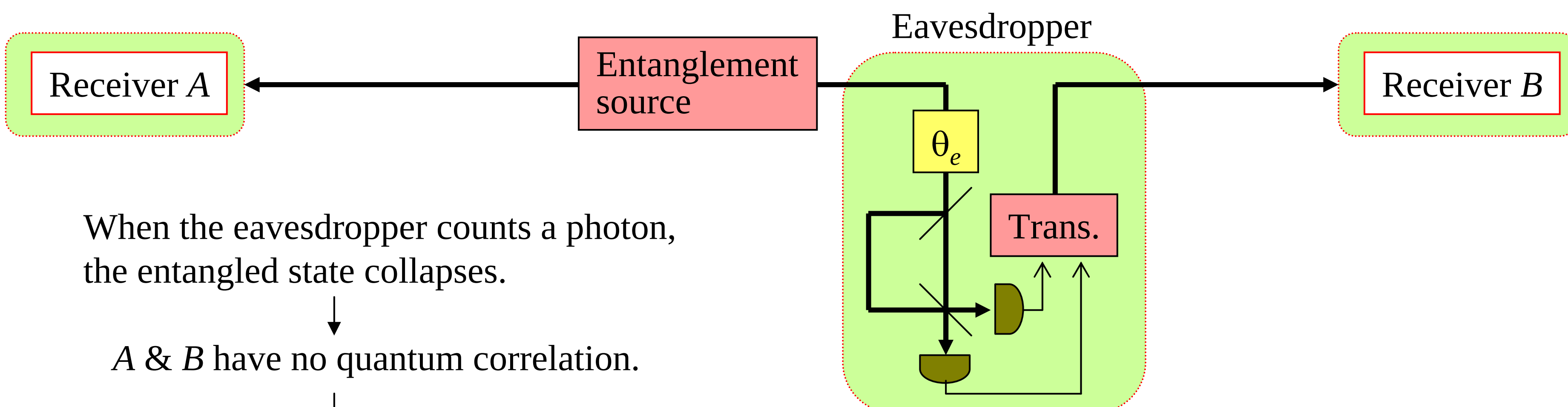
$\Delta\theta_a + \Delta\theta_b = \pi/2$: ignore

Eavesdropping

Beam splitting attack



Intercept-resend attack



When the eavesdropper counts a photon,
the entangled state collapses.

↓

A & *B* have no quantum correlation.

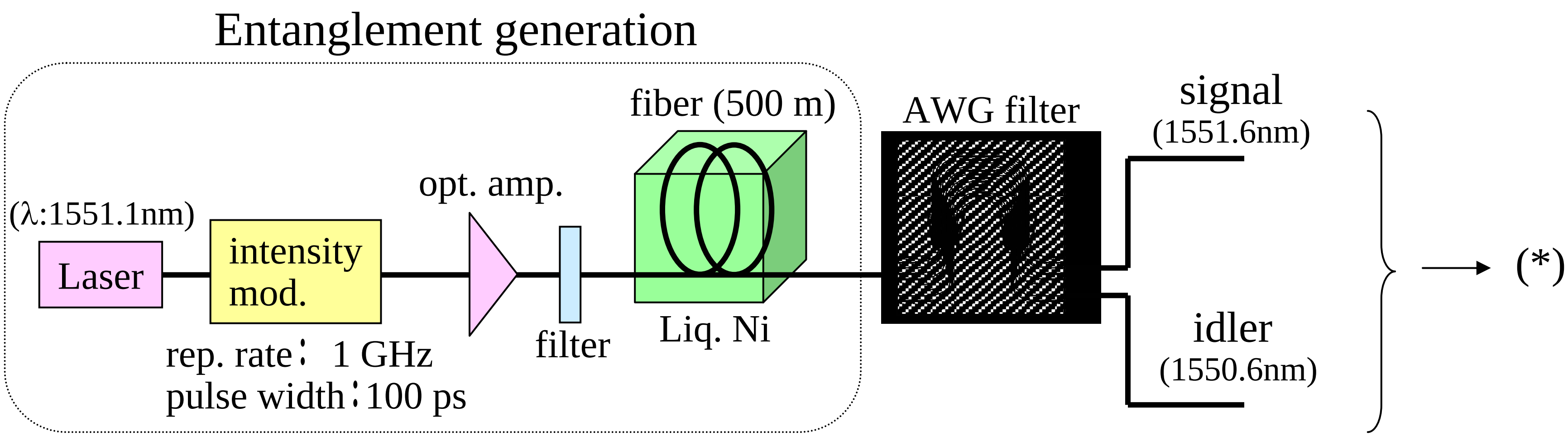
↓

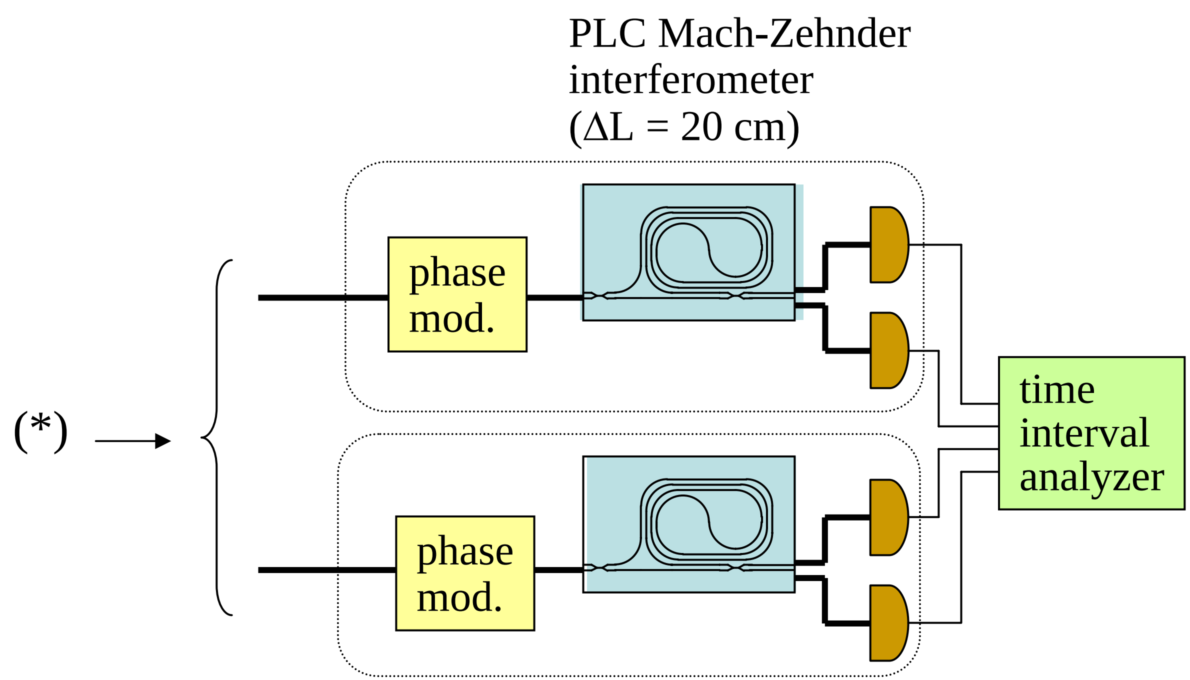
Bit mismatch in *A*'s and *B*'s keys.

↓

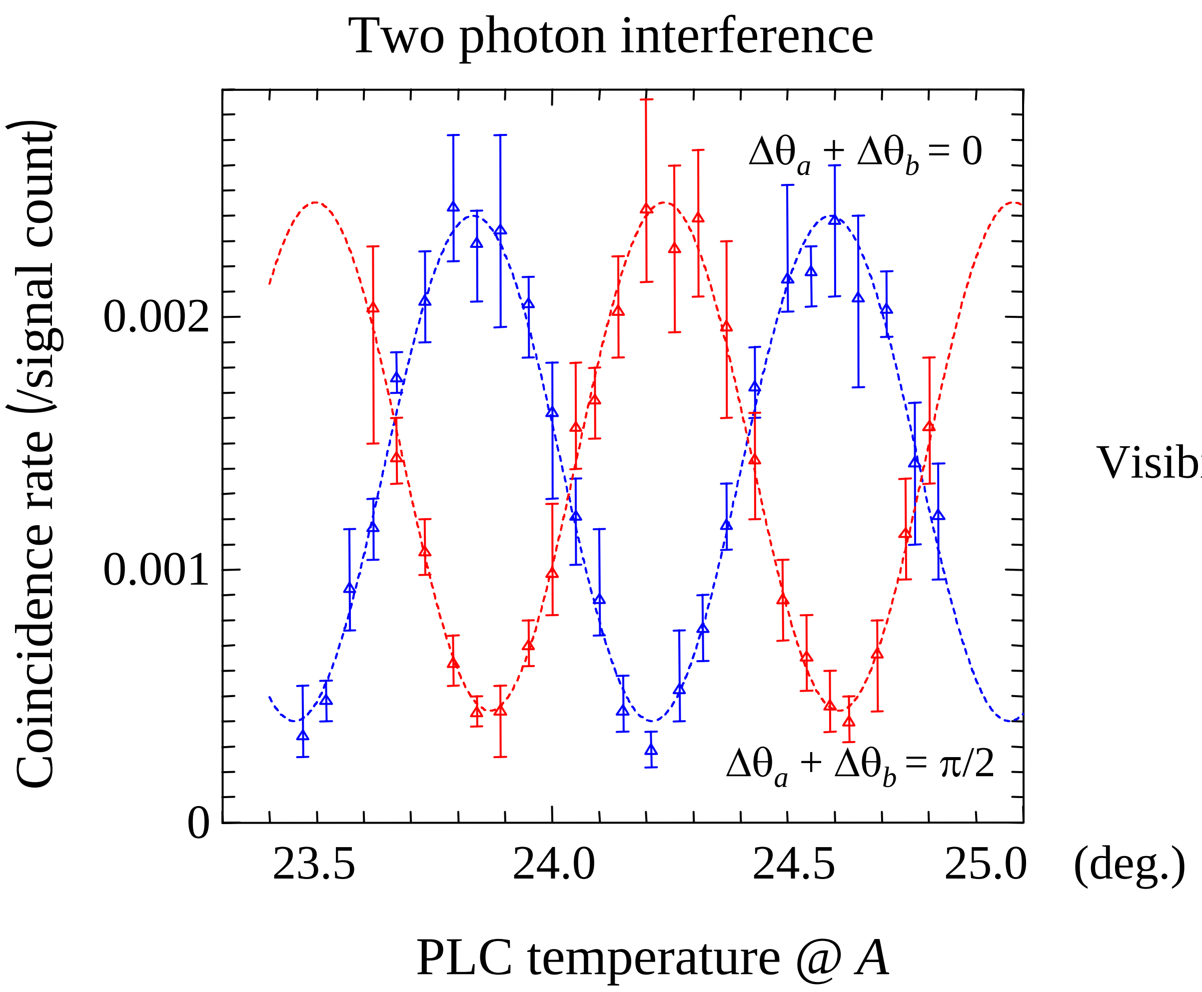
The eavesdropping is revealed by checking some test bits.

QKD Experiment





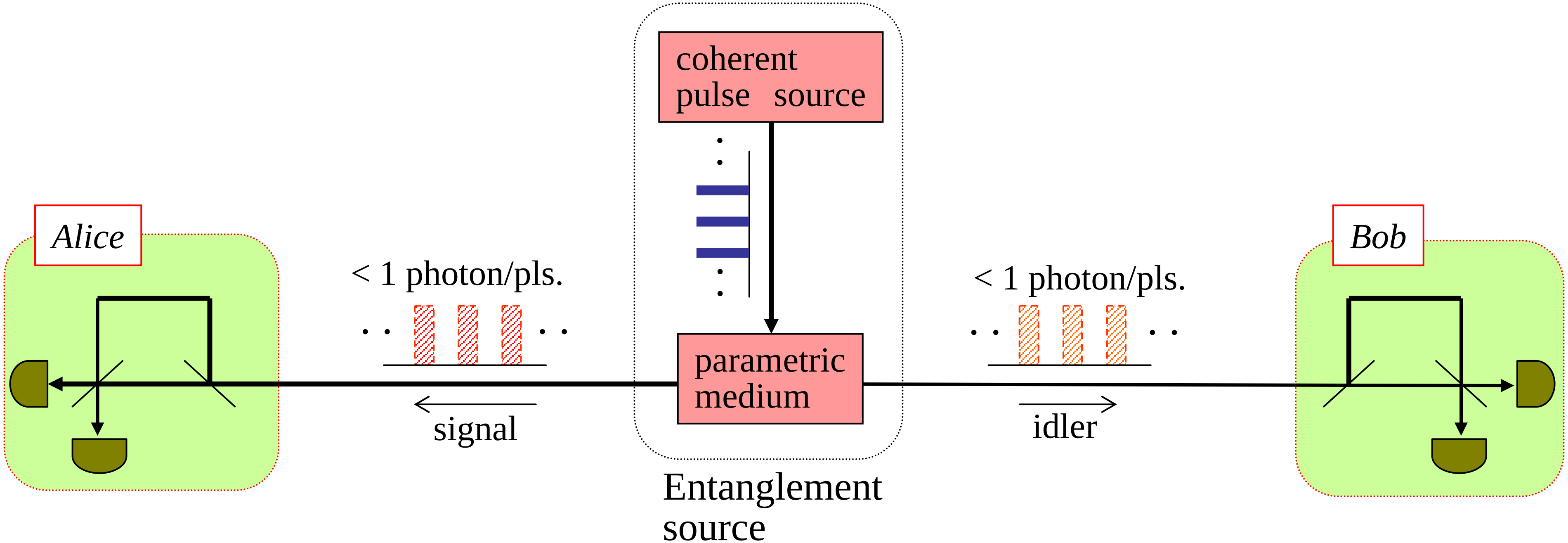
Experimental results



Visibility: 70 %

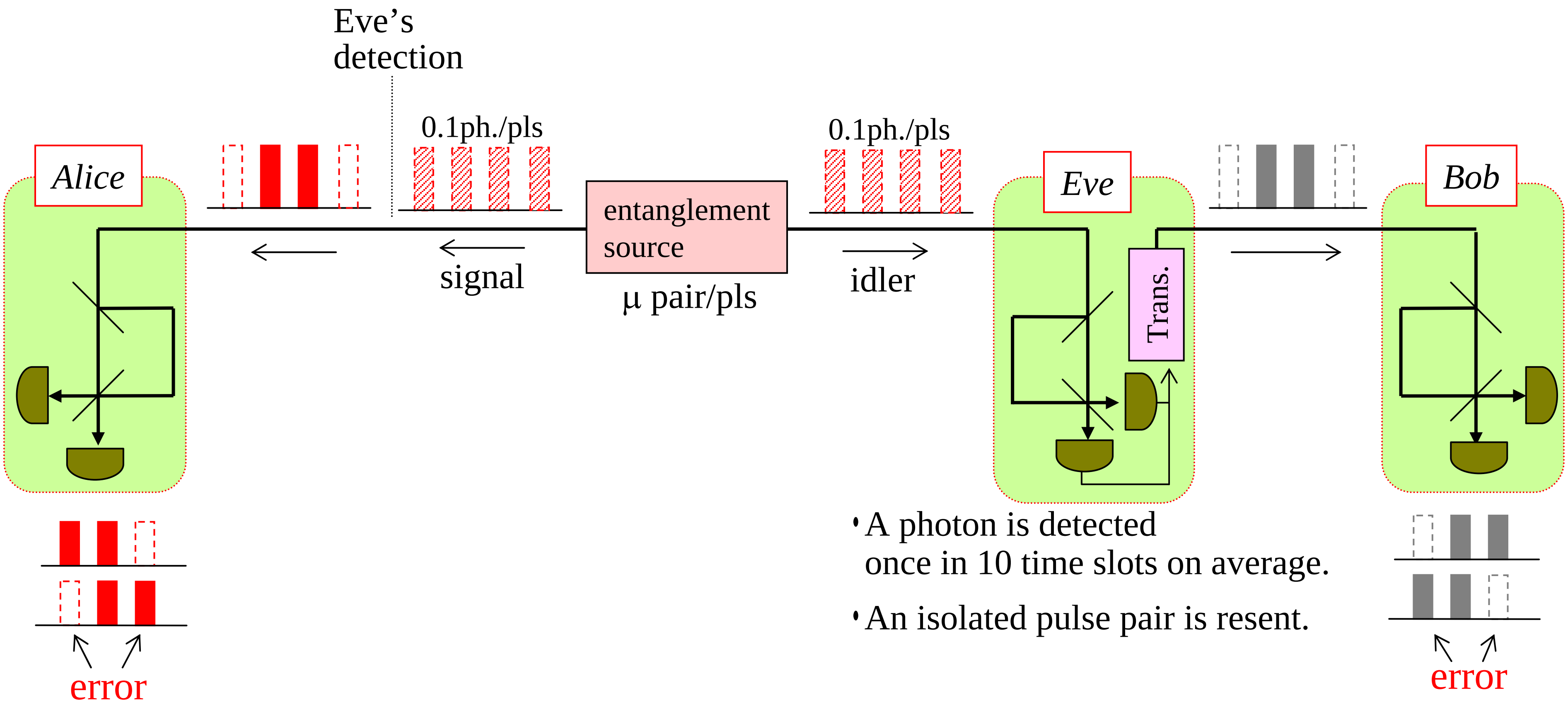
A secret key was created with 0.34bps data-rate and 8.6 % error-rate.

QKD based on time-bin entanglement (2)



No basis selection in measurement

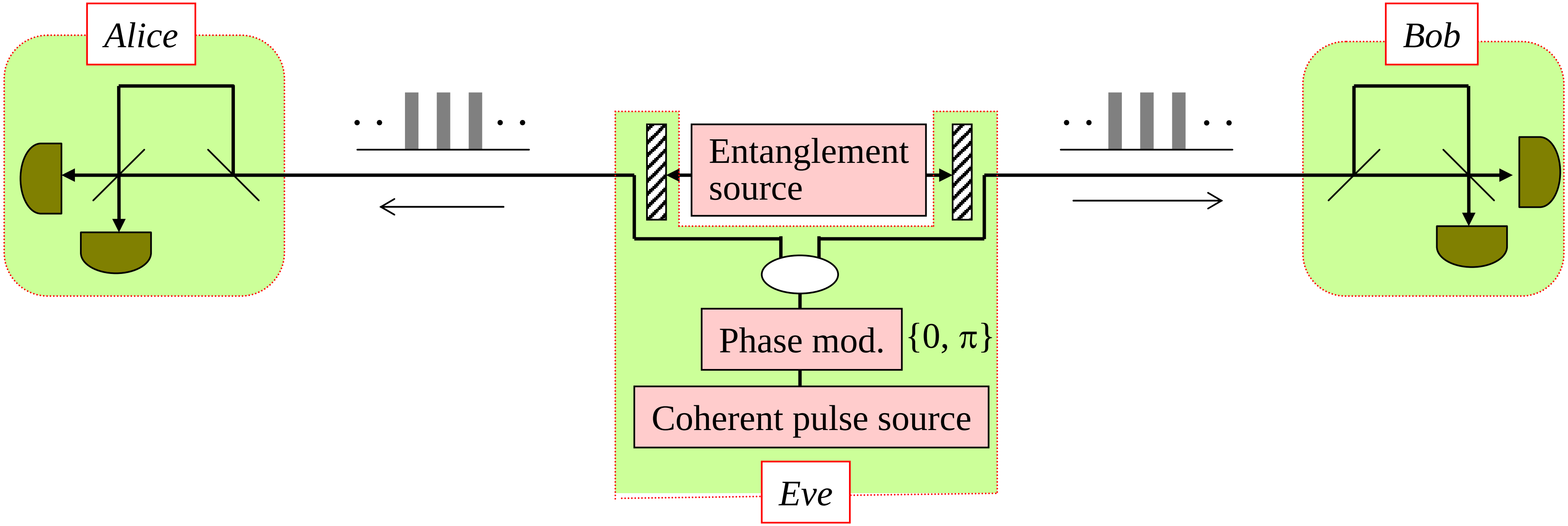
Eavesdropping against Entanglement-based DPS-QKD
- Intercept & Resend -



- ◆ Eavesdropping is revealed from bit error rate.
- ◆ Eavesdropping is also revealed from coincident count rate.

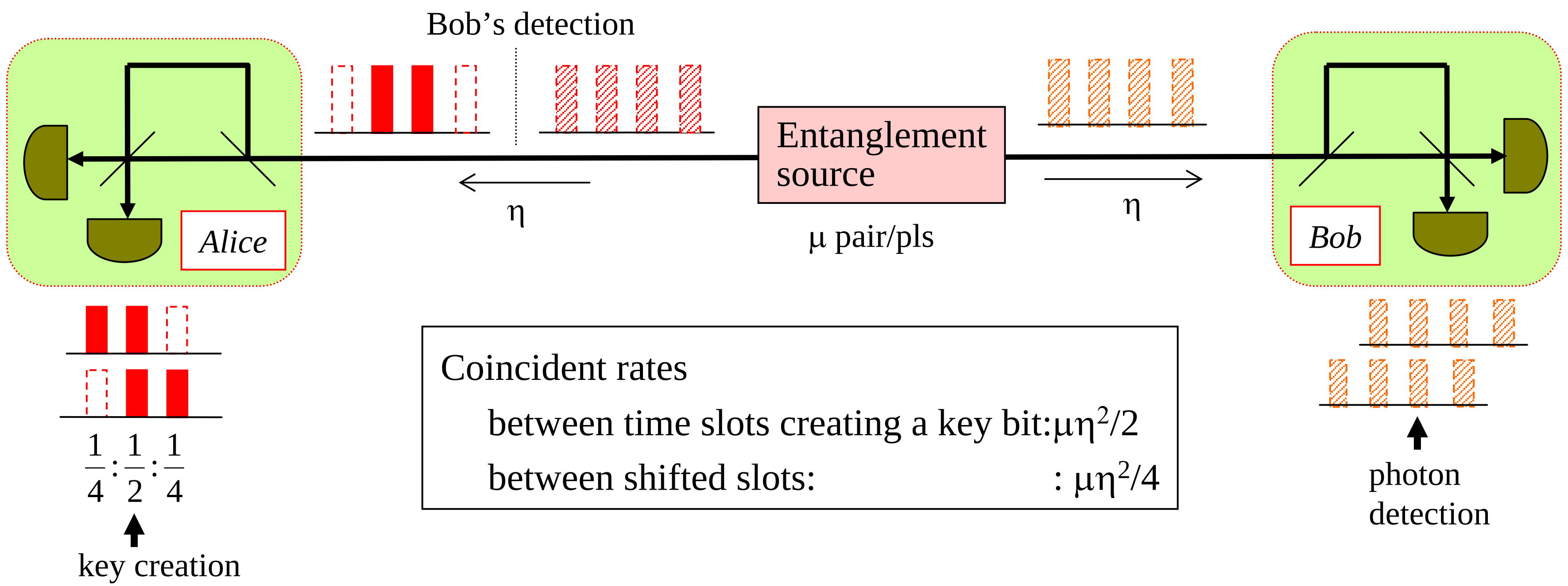
normal: $(1/2)\mu\eta^2$ eavesdropped: $(3/8)\mu\eta^2$ (η: line transmittance)

Eavesdropping against Entanglement-based DPS-QKD
- Source Replacement -

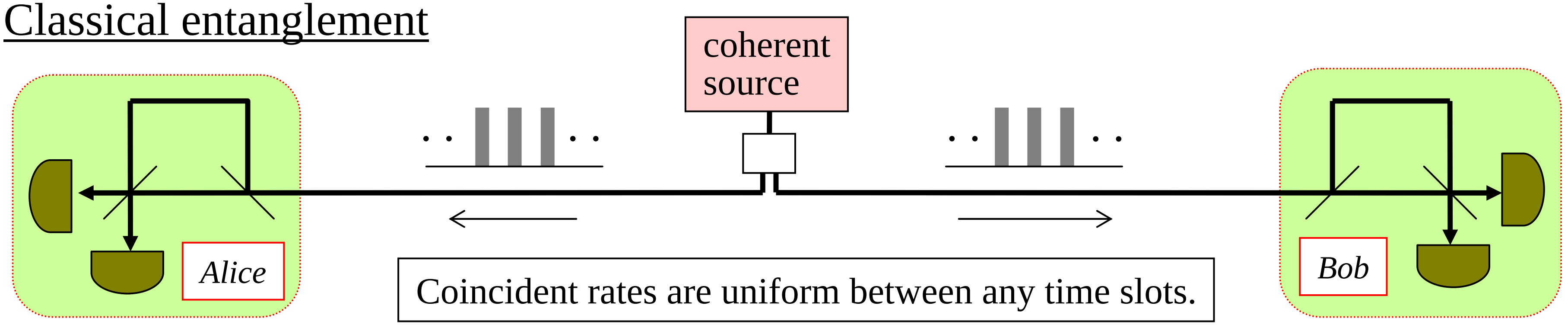


Eve gets key information without inducing bit errors.
However,,,,,

Quantum entanglement



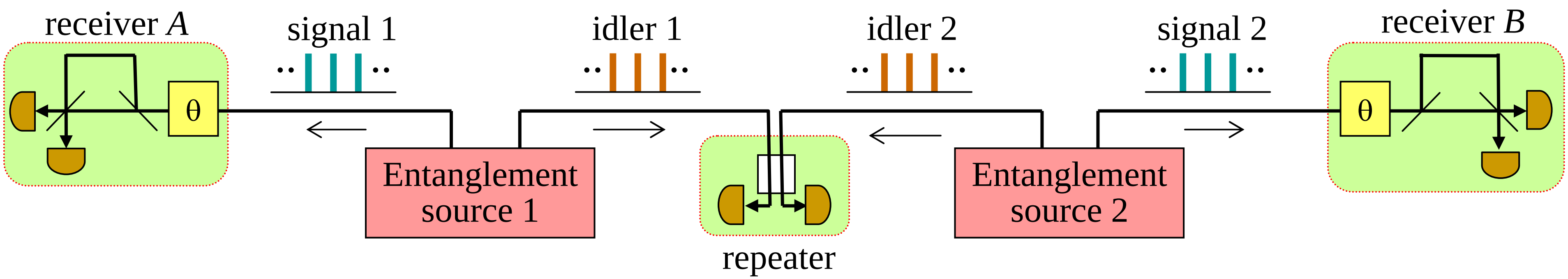
Classical entanglement



The eavesdropping is revealed from the coincident rates.

Further application

Quantum relay utilizing entangled photons



(1) The repeater measures the relationship between idlers 1 & 2.

→ The relationship between idlers 1 & 2 is determined.

→ The relationship between signals 1 & 2 is determined.

(but unknown to the receivers)

(1') Receivers *A* and *B* measure signals 1 and 2, respectively.

(2) The repeater tells the receivers the measurement result.

(3) The receivers know the photon state at the other site from his/her own measurement result and the repeater's information.

↓

secret key

Summary

Generation of entangled photons in fibers and their system applications

- ◆Quantum entangled photons:
  photon pairs that have unique correlation between them.

  Photon states are ambiguous before measurement.
  When the state of one of the pair is determined by measurement,
  the other photon is determined to be in the correlated state.

- ◆Spontaneous four-wave mixing in fiber can be utilized to create entangled photons.

  A signal & an idler photons are simultaneously generated
  from tow pump photons

- ◆Quantum key distribution system can be constructed using entangled photons.

  The system length is longer than single-photon QKD.