ECC2018, November 19, 2018
Osaka University (Suita Campus), Osaka, Japan

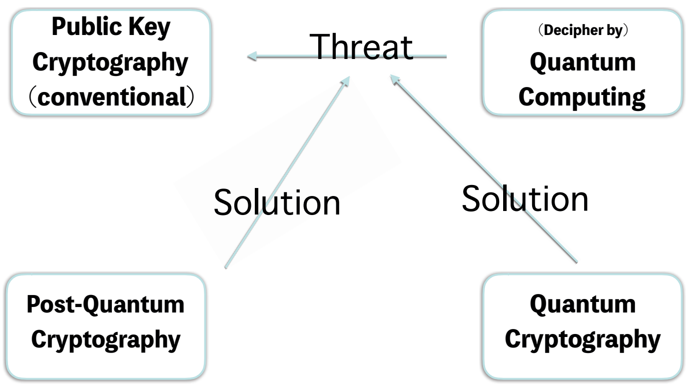
Quantum Information Processing

— Similarities and Differences with Classical Information —

Osaka University

Nobuyuki Imoto

Attacks	Needs
Eavesdropping	P2P secure communication
Cypher breaking	Water printing (invisible ink)
Falsification (change contents)	Signature
Spoofing (impostor scam)	Falsification
Account hacking (takeover)	Auction (Bid)
	Voting (Election)

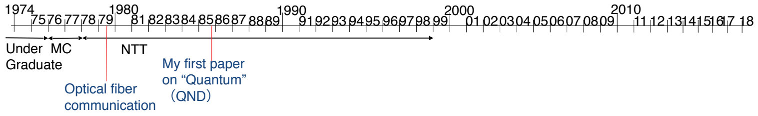


Expiration date of secrets

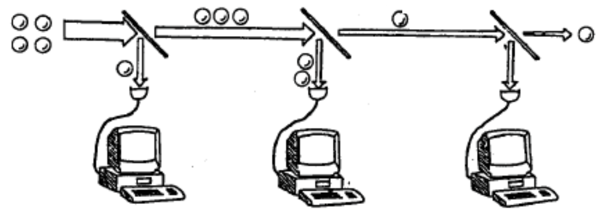
Short: Entrance examination problems

Long: State secrets (25 years? 50 years?)

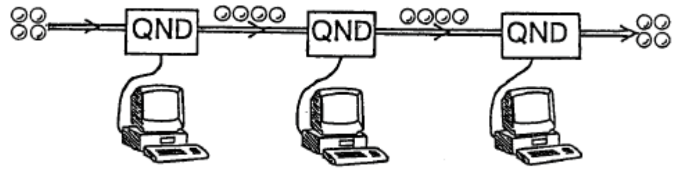
Very long: DNA?, private letters?



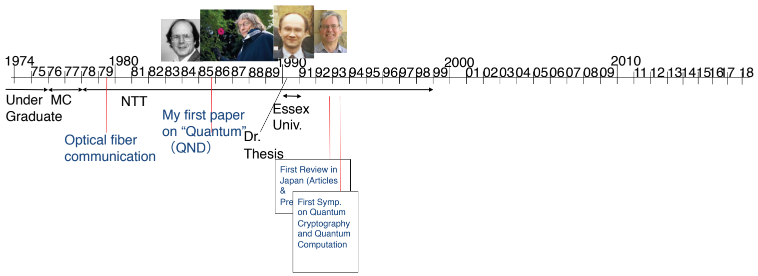
Difference in the ordinary tapping and QND tapping



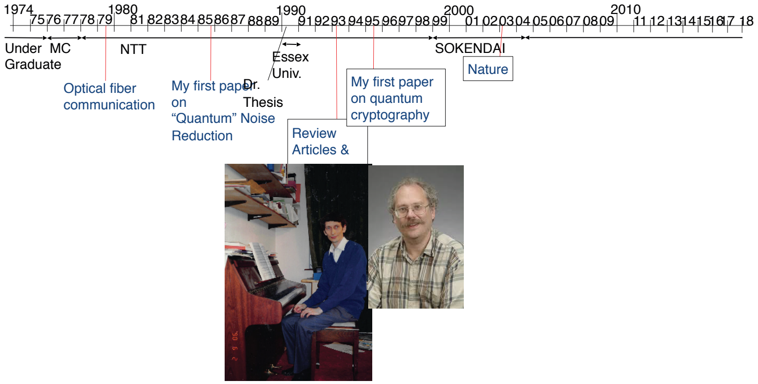
Usual LAN: linear extraction of the signal
→ obeys fluctuation-dissipation theorem
→ additional noise both in the wire-tapped and main signals.



QND LAN: No quantum noise added in any of reflected/transmitted signals.



Quantum Computation & Cryptography Symposium (1993)



SOKENDAI

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SOKENDAI is a Graduate School which Fosters Doctoral Reserchers at 18 Research Institutes.

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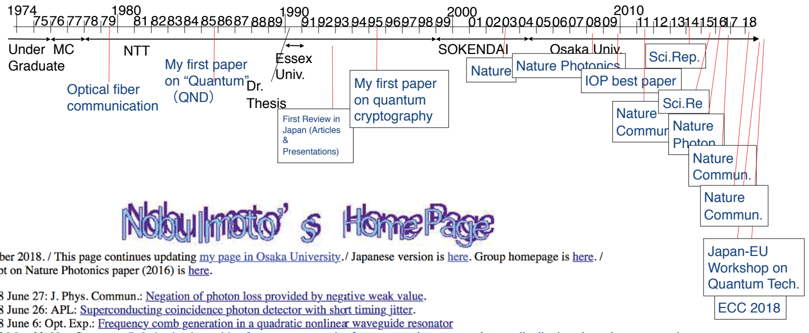
NII
NIG
NIBB
NIPS



Nobu Imoto's Home Page

Updated: 2 October 2018. / This page continues updating my page in Osaka University./ Japanese version is here. Group homepage is here. /
An illustrative ppt on Nature Photonics paper (2016) is here.

- News 2018 June 27: J. Phys. Commun.: Negation of photon loss provided by negative weak value.
- News 2018 June 26: APL: Superconducting coincidence photon detector with short timing jitter.
- News 2018 June 6: Opt. Exp.: Frequency comb generation in a quadratic nonlinear waveguide resonator
- News 2018 May 23: Nat. Commun.: Polarization insensitive frequency conversion for an atom-photon entanglement distribution via a telecom network.
- News 2018 May 16: PRL Long-Distance Single Photon Transmission from a Trapped Ion via Quantum Frequency Conversion.
- News 2018 April 25: PRA Optimal nonlocal conversion of photonic four-partite entanglement from two Bell pairs in quantum networks.
- News 2018 April 17: J. Math. Phys. Various pointer states approaches to polar modular values.
- News 2018 Jan. 23: Sci. Rep. High-fidelity entanglement swapping and generation of three-qubit GHZ state using asynchronous telecom photon pair sources.
- News 2018 Jan. 16: PRA Generalized modular-value-based scheme and its generalized modular value.

Publication Indices (2 Oct. 2018):

h-index = 39(Scopus), 47(Google Scholar)
i10-index = 108(Scopus), 124(Google Scholar)
Cited benchmarking (Scopus): 99%(a), 99%(b), 99%(c), 98%(a), 98%(b), 97%(a), 97%(b), 97%(c), 97%(d), 96%(a), 96%(b), 96%(c), 95%(a), 95%(b), 94%(a), 94%(b), 93%, 92%(a), 92%(b), 91%(a), 91%(b), 90%, omitted hereafter.

Home Registration Program Location

Japan-EU Joint Workshop on Advanced Quantum Technology for Future Innovation

Due to our growing ability to manipulate quantum effects in customized systems and materials, the second quantum revolution will soon be realized, unfolding worldwide and bringing transformative advances to science, economy and society. Last year, the European commission has launched the Quantum Technology (QT) Flagship to consolidate and expand European scientific leadership and excellence in this research area, to kick-start a competitive European industry in Quantum Technologies and to make Europe a dynamic and attractive region for innovative research, business and investments in this field. Meanwhile, Japan has also recognized the significance of QT and funded mainly fundamental research projects of QTs since 2016 through CREST which is one of the major strategic basic research programs of Japan Science and Technology Agency (JST) to promote research and development: "creation of new sources" to explore physics for quantum state control and develop pertinent technologies and "creation of innovative system functions" to provide quantum technologies for social and industrial innovation in the future. This joint workshop is organized by JST, in cooperation with the coordination action on quantum technologies established by the European Commission in the frame of the European Quantum Flagship.

JST-CREST Project

Global Quantum Network

(1) Why necessary?

(2) What are the problems?

(3) How did we deal with these problems?

(4) How are we going to cope with these problems?

(5) Is their any alternative(s)?

JST-CREST Project

Global Quantum Network

(1) Why necessary?

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(5) Is their any alternative(s)?

2018 Oct. A visitor from US:

The Visitor: "Quantum cryptography is driven out by post-quantum cryptography. Don't you think so?"

Nobu Imoto: "Do you think that US will shut down the research on Quantum Cryptography?"

The Visitor: "No."

Nobu Imoto: "That's the answer."

(1) Why necessary?

・long-haul QKD

2018.1.20 Nikkei p.2

究極の暗号通信 中国―欧州間で

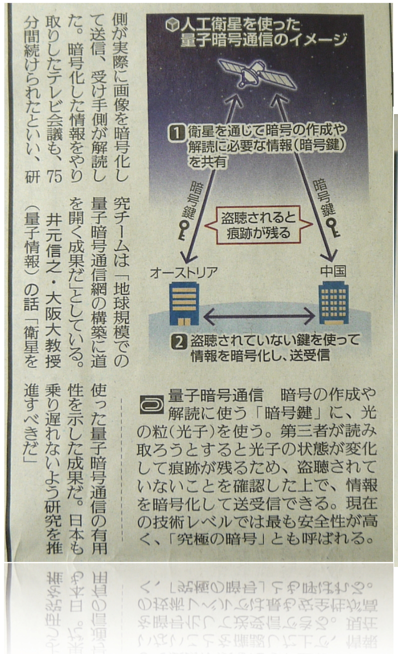
7600キロ初成功

【ワシントン＝三井誠】盗聴やハッキングが不可能とされる「量子暗号通信（㊁）」を、人工衛星を使って中国とオーストリアの間で実施することに成功したと、両国の研究チームが発表した。アジアと欧州をつなぐ長距離の量子暗号通信は初めてという。論文が米物理学会誌「フィジカル・レビュー・レターズ」に掲載された。

衛星を使った量子暗号研究は、日本政府も2018年度から本格化させる方針で、技術開発が各国で激しくなりそうだ。

研究チームは、中国が16年に打ち上げた衛星「墨子号」を使って実験。約7600キロ離れた中国とオーストリアの地上局で、暗号の作成や解読に必要な情報（暗号鍵）を衛星を通じてやりとりし、共有することに成功した。

この暗号鍵を使って、北京―ウィーン間で、送り手



側が実際に画像を暗号化して送信、受け手側が解読した。暗号化した情報をやり取りしたテレビ会議も、75分間続けられたといい、研究チームは「地球規模での量子暗号通信網の構築に道を開く成果だ」としている。

井元信之・大阪大教授（量子情報）の話「衛星を使った量子暗号通信の有用性を示した成果だ。日本も乗り遅れないよう研究を推進すべきだ」

人工衛星を使った量子暗号通信のイメージ

量子暗号通信　暗号の作成や解読に使う「暗号鍵」に、光の粒（光子）を使う。第三者が読み取ろうとすると光子の状態が変化して痕跡が残るため、盗聴されていないことを確認した上で、情報を暗号化して送受信できる。現在の技術レベルでは最も安全性が高く、「究極の暗号」とも呼ばれる。

JST-CREST Project

Global Quantum Network

(1) Why necessary?

(2) What are the problems?
・transmission loss ・noise（decoherence)

(3) How did we deal with these problems?

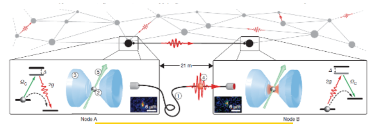
(4) How are we going to cope with these problems?

(5) Is their any alternative(s)?

現状：ラボ内程度から1km程度まで

ARTICLE

An elementary quantum network of single atoms in optical cavities

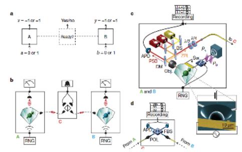


2012, 21 m @ 780 nm

LETTER

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

682 | NATURE | VOL 526 | 29 OCTOBER 2015

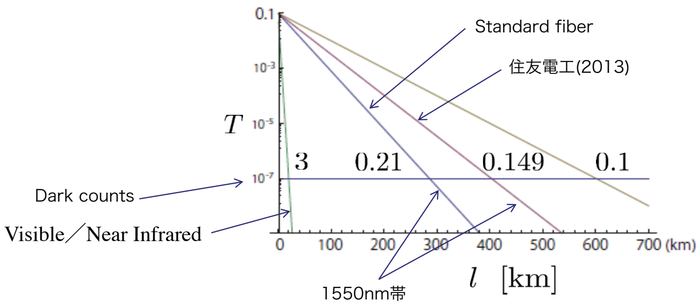


2015, 1.3 km @ 630 nm

Fiber transmissivity $T = 10^{-\alpha l/10}$

Loss per unit length α [dB/km]

Length of fiber l [km]



Long-haul transmission is impossible for V／NI

JST-CREST Project

Global Quantum Network

(1) Why necessary?

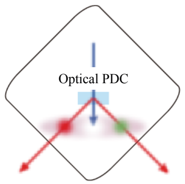
(2) What are the problems?
・transmission loss ・noise（decoherence)

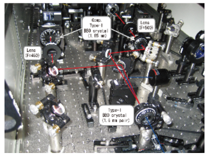
(3) How did we deal with these problems?

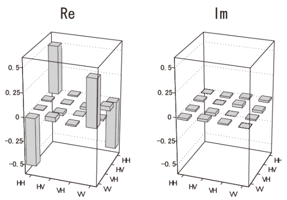
(4) How are we going to cope with these problems?

(5) Is their any alternative(s)?

Entanglement preparation



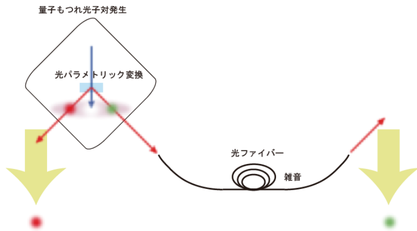


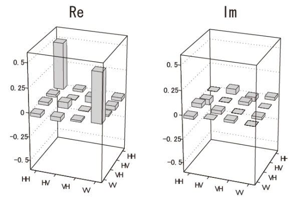


fidelity F=1.00±0.03

0	0.5	1.0
anti correlation	no correlation	correlated

Entanglement decoherence in an optical fiber





Fidelity F=0.46±0.03

↑

Close to 0.5!

JST-CREST Project

Global Quantum Network

(1) Why necessary?

(2) What are the problems?

・transmission loss ・noise（decoherence）

(3) How did we deal with these problems?

・Frequency conversion ・noise cancellation by DFS

(4) How are we going to cope with these problems?

(5) Is their any alternative(s)?

Quantum error correction

・Express a logical qubit by n physical qubits.

→ dim(H:whole Hilbert space) = 2^n

$$\mathrm{H} = \text{Logical Qubit Space} \otimes \text{Error Correction Space}$$

$$\rightarrow \dim(\mathrm{H}) = \dim(\mathrm{LQS}) \times \dim(\mathrm{ECS}) = 2 \times \dim(\mathrm{ECS})$$

$$\rightarrow \dim(\mathrm{ECS}) = 2^{n-1}$$

・Assume at most 1 error occurs among n qubits.

→ We need to specify “which physical qubit suffered from which error?” ($3n$ cases) or “no error?” (1 case) → total $3n + 1$ cases.

→ In order to specify all $3n + 1$ cases by 2^{n-1} dimensional space, $2^{n-1} \geqq 3n+1$ becomes a necessary condition.

→ The minimum number of n to satisfy this is 5.

Actually, 5 is sufficient!

5-qubit error correction code

$$\begin{aligned}|0_L\rangle = &|00000\rangle + |10010\rangle + |01001\rangle + |10100\rangle + |01010\rangle + |00101\rangle \\ &- |11110\rangle - |01111\rangle - |10111\rangle - |11011\rangle - |11101\rangle \\ &- |01100\rangle - |00110\rangle - |00011\rangle - |10001\rangle - |11000\rangle\end{aligned}$$

$$\begin{aligned}|1_L\rangle = &|11111\rangle + |01101\rangle + |10110\rangle + |01011\rangle + |10101\rangle + |00101\rangle \\ &- |00001\rangle - |10000\rangle - |01000\rangle - |00100\rangle - |00010\rangle \\ &- |10011\rangle - |11001\rangle - |11100\rangle - |01110\rangle - |00111\rangle\end{aligned}$$

Syndrome observables (for finding which error occurred on which qubit):

$$\hat{M}_1 \equiv \hat{X}_1\hat{Z}_2\hat{Z}_3\hat{X}_4\,, \quad \hat{M}_2 \equiv \hat{X}_2\hat{Z}_3\hat{Z}_4\hat{X}_5\,, \quad \hat{M}_3 \equiv \hat{X}_1\hat{X}_3\hat{Z}_4\hat{Z}_5\,, \quad \hat{M}_4 \equiv \hat{Z}_1\hat{X}_2\hat{X}_4\hat{Z}_5$$

For any $j = 1, 2, 3, 4$, it is easy to show

$$\hat{M}_j|0_L\rangle = |0_L\rangle\,, \quad \hat{M}_j|1_L\rangle = |1_L\rangle$$

That is, measurement of any $\hat{M}_j$ keeps $\alpha|0_L\rangle + \beta|1_L\rangle$ as it is.

Also, any two syndromes commutes → all are observable simultaneously.

Now, assume that the bit-flip error occurred on the extreme left qubit. ($\hat{X}_1$)

$$\begin{aligned}|0'_L\rangle = &|10000\rangle + |00010\rangle + |11001\rangle + |00100\rangle + |11010\rangle + |10101\rangle \\ &- |01110\rangle - |11111\rangle - |00111\rangle - |01011\rangle - |01101\rangle \\ &- |11100\rangle - |10110\rangle - |10011\rangle - |00001\rangle - |01000\rangle\end{aligned}$$

$$\begin{aligned}|1'_L\rangle = &|01111\rangle + |11101\rangle + |00110\rangle + |11011\rangle + |00101\rangle + |10101\rangle \\ &- |10001\rangle - |00000\rangle - |11000\rangle - |10100\rangle - |10010\rangle \\ &- |00011\rangle - |01001\rangle - |01100\rangle - |11110\rangle - |10111\rangle\end{aligned}$$

Then the measured value for the syndrome operators become,

$$\langle 0'_L|\hat{M}_1|0'_L\rangle = 1\,, \quad \langle 0'_L|\hat{M}_2|0'_L\rangle = 1\,, \quad \langle 0'_L|\hat{M}_3|0'_L\rangle = 1\,, \quad \langle 0'_L|\hat{M}_4|0'_L\rangle = -1$$

$$\langle 1'_L|\hat{M}_1|1'_L\rangle = 1\,, \quad \langle 1'_L|\hat{M}_2|1'_L\rangle = 1\,, \quad \langle 1'_L|\hat{M}_3|1'_L\rangle = 1\,, \quad \langle 1'_L|\hat{M}_4|1'_L\rangle = -1$$

This means that for any arbitrary (and unknown) state the state $\alpha|0_L\rangle + \beta|1_L\rangle$ is unchanged by the measurement of the four syndromes, resulting in (1,1,1,-1), which indicates that "bit flip occurred for the extreme left qubit."

Then, once knowing (1,1,1,-1), the error can be corrected by applying the inverse of $\hat{X}_1$ which is $\hat{X}_1$ itself. (quantum error correction)

Considering the 15 error cases, the relation between the syndrome values and the kind of error is summarized as:

	$\hat{X}_1$	$\hat{X}_2$	$\hat{X}_3$	$\hat{X}_4$	$\hat{X}_5$	$\hat{Y}_1$	$\hat{Y}_2$	$\hat{Y}_3$	$\hat{Y}_4$	$\hat{Y}_5$	$\hat{Z}_1$	$\hat{Z}_2$	$\hat{Z}_3$	$\hat{Z}_4$	$\hat{Z}_5$
$\hat{M}_1$	1	-1	-1	1	1	-1	-1	-1	-1	1	-1	1	1	-1	1
$\hat{M}_2$	1	1	-1	-1	1	1	-1	-1	-1	-1	1	-1	1	1	-1
$\hat{M}_3$	1	1	1	-1	-1	-1	1	-1	-1	-1	-1	1	-1	1	1
$\hat{M}_4$	-1	1	1	1	-1	-1	-1	1	-1	-1	1	-1	1	-1	1

The 16th case, 1,1,1,1 (= no error), is not listed here.

This idea is cool! However,

- It is difficult to realize experimentally.
- We assume that the error correction circuit operates error-free.
- High-frequency operation is needed since "at most 1 error" is assumed.
- When there is a loss of qubit (transmissivity T), the whole system sufferes from T^{5} (T^{7} for another famous code and T^{9} for yet another code).

Quantum error correction

- Express a logical qubit by n physical qubits.

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$$H = \text{Logical Qubit Space} \otimes \text{Error Correction Space}$$

$$\rightarrow \dim(H) = \dim(LQS) \times \dim(ECS) = 2 \times \dim(ECS)$$

$$\rightarrow \dim(ECS) = 2^{n-1}$$

- Assume at most 1 error occurs among n qubits.

→ We need to specify "which physical qubit suffered from which error?" ($3n$ cases) or "no error?" (1 case) → total $3n + 1$ cases.

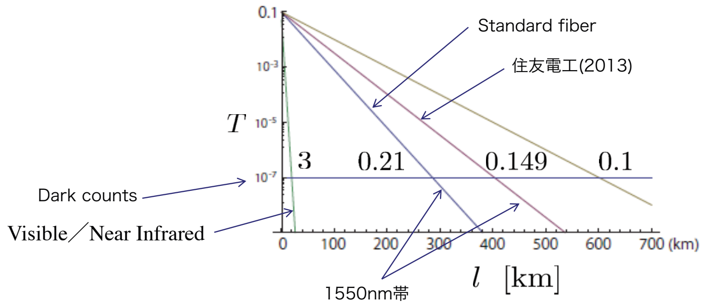
→ In order to specify all $3n + 1$ cases by 2^{n-1} dimensional space, $2^{n-1} \geqq 3n+1$ becomes a necessary condition.

→ The minimum number of n to satisfy this is T^5

Fiber transmissivity $T = 10^{-\alpha l/10}$

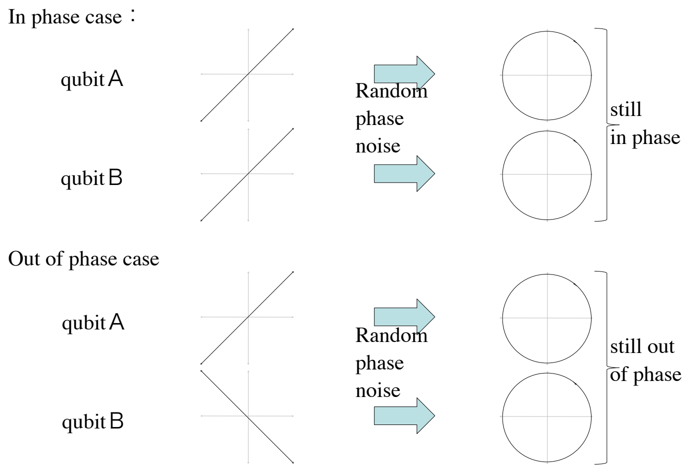
Loss per unit length α [dB/km]

Length of fiber l [km]



Long-haul transmission is impossible
for V／NI

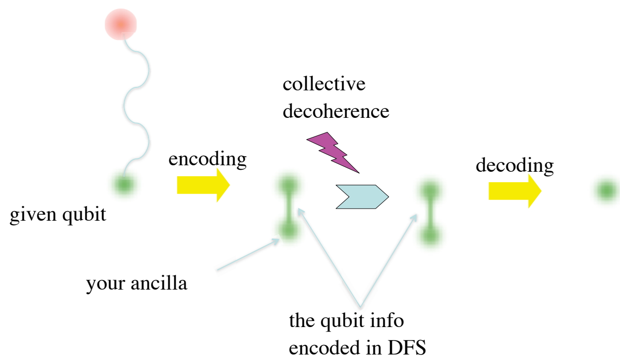
Use of two qubits

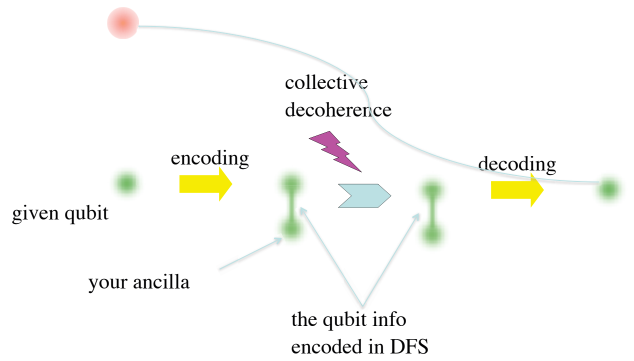


Let's use "in phase" and "out of phase" as the new computational bases "0" and "1."

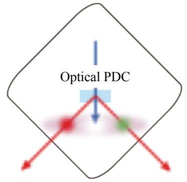
This is easy if one can prepare two qubits from the beginning.

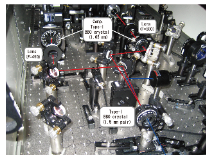
The problem is how to encode the given qubit state into given+ancilla qubits.

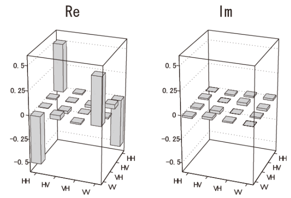




(1) Entanglement preparation



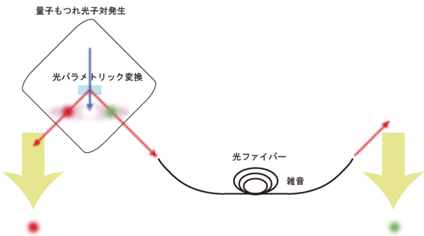


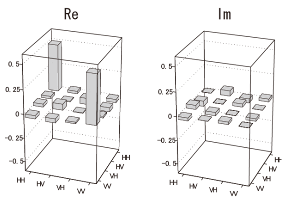


fidelity F=1.00±0.03

0 0.5 1.0
anti correlation / no correlation / correlated

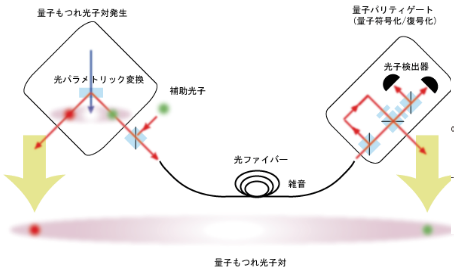
Entanglement decoherence in an optical fiber

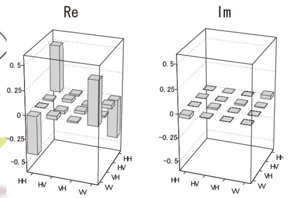




Fidelity F=0.46±0.03
↑
Close to 0.5!

Extraction of the entanglement protected in the DFS

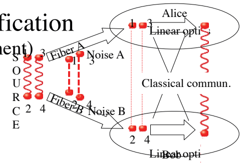




fidelity F=0.87±0.07

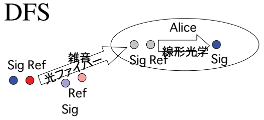
Progress in suppressing collective noise using DFS (1)

[1]Entanglement purification
(for a specific entanglement)



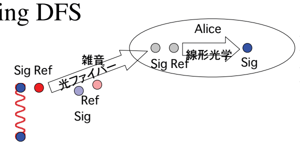
Theory：PRA(2001)
Experiment：Nature(2003)
(・beam optics
・artificial phase noise)

[2] QI protection using DFS
(for arbitrary isolated state)



Theory：PRL(2005)
Experiment：NJP(2007)
(・10m fiber
・natural phase noise)

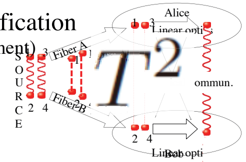
[3] QI protection using DFS
(for entangled states)



Experiment：
Nature Photonics(2008)
(・500m fiber
・natural phase noise)

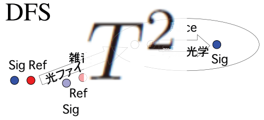
Progress in suppressing collective noise using DFS (1)

[1]Entanglement purification
(for a specific entanglement)



Theory：PRA(2001)
Experiment：Nature(2003)
(・beam optics
・artificial phase noise)

[2] QI protection using DFS
(for arbitrary isolated state)



Theory：PRL(2005)
Experiment：NJP(2007)
(・10m fiber
・natural phase noise)

[3] QI protection using DFS
(for entangled states)

Experiment：
Nature Photonics(2008)
(・500m fiber
・natural phase noise)

Efficiency improvement of faithful entanglement distribution using decoherence-free subspace

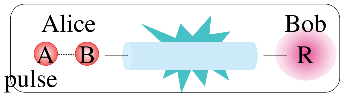
Rikizo Ikuta, Yohei Ono, Toshiyuki Tashima,
Takashi Yamamoto, Masato Koashi, and Nobuyuki Imoto

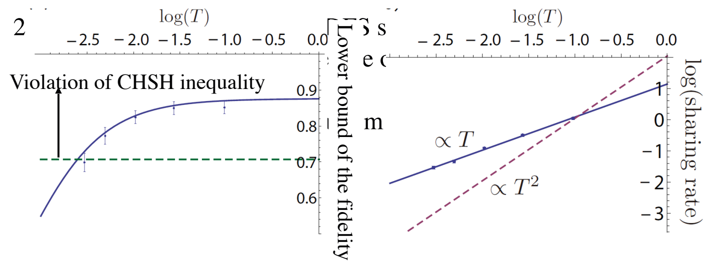
Division of Materials Physics, Department of Materials Engineering Science,
Graduate School of Engineering Science,
Osaka University

Ikuta et al: Phys. Rev. Lett. 106, 110503 (2011).

Overview

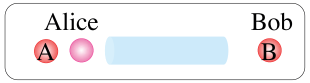
1. We have proposed a scheme for boosting up the efficiency of entanglement distribution based on a decoherence-free subspace (DFS)
over lossy quantum channels.
→ Bob prepares a coherent light pulse
instead of a single photon
as an ancillary system for the DFS.



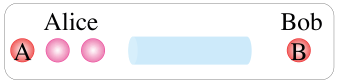


Error analysis for the multi-photon events

Success event



Main error event



γ: photon-pair generation rate
μ: average photon number of the coherent light pulse at Alice's side
T: transmittance of the quantum channel

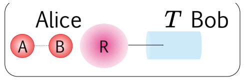
Success probability / Error probability

Requirement : $\mathcal{O}(\gamma T\mu) \gg \mathcal{O}(\gamma T\mu^2)$

$\longrightarrow 1 \gg \mu$

(This condition is independent of T.)

c.f. : T. Yamamoto *et al*, Nature Photonics **2**, 488 (2008).



$\mathcal{O}(\gamma T\mu) \gg \mathcal{O}(\gamma\mu^2)$

$\longrightarrow T \gg \mu$

Distribution efficiency of entangled states $\mathcal{O}(\gamma T\mu) \propto T$

Error analysis for the multi-photon events

Success event
Main error event

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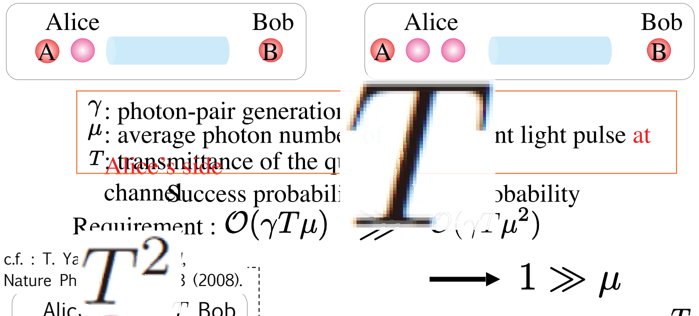

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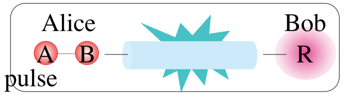
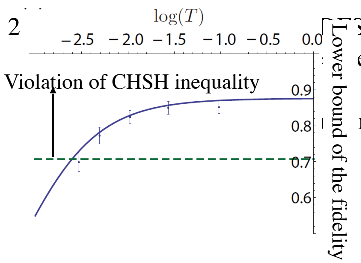
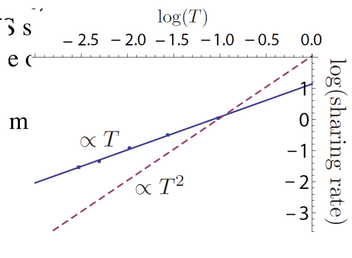
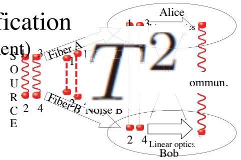






Progress in suppressing collective noise using DFS (2)

[1]Entanglement purification
(for a specific entanglement)



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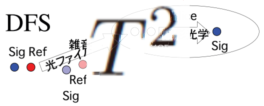

Theory : PRL(2005)
Experiment : NJP(2007)
(・10m fiber
・natural phase noise)

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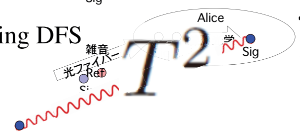
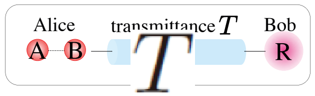


Experiment :
Nature Photonics(2008)
(・500m fiber
・natural phase noise)

[4] Use of counter propagating strong coherent ancilla



PRL106, 110503 (2011)
$\eta \propto T$ attained

Progress in suppressing collective noise using DFS (3)

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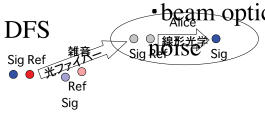
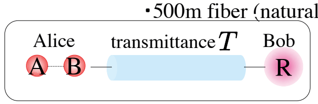


[3] QI protection using DFS (for entangled states) — Experiment: Nature Photonics(2008) ・500m fiber (natural phase noise)

[4] Use of counter propagating strong coherent ancilla — PRL106, 110503 (2011) $\eta \propto T$ attained



Progress in suppressing collective noise using DFS (3)

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Only the phase noise

Only the phase noise

Only the phase noise

Only the phase noise

[5] Scientific Reports 7, 4819 (2017 July)
"Experimental demonstration of robust entanglement distribution over reciprocal noisy channels assisted by a counter-propagating classical reference light"
Rikizo Ikuta, Shota Nozaki, Takashi Yamamoto, Masato Koashi & Nobuyuki Imoto

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Our present CREST project
phase & polarization noise

JST-CREST Project

Global Quantum Network

(1) Why necessary?

(2) What are the problems?
・transmission loss ・noise (decoherence)

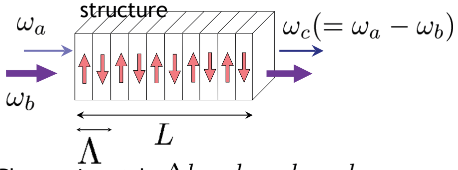
(3) How did we deal with these problems?
・Frequency conversion ・noise cancellation by DFS

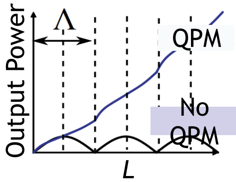
(4) How are we going to cope with these problems?

(5) Is their any alternative(s)?

Quasi-Phase matched (QPM) crystal

Periodically poled structure compensates phase mismatch



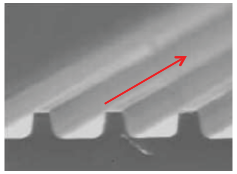


Phase mismatch $\Delta k = k_c - k_a - k_b$

QPM $\Delta \tilde{k} = k_c - k_a - k_b - \frac{2\pi}{\Lambda} = 0$

Properly adjusting Λ,
phase mismatch will be compensated.

In our experiment:
Wave guided PPLN(periodically poled lithium niobate)



T. Nishikawa *et al*. Opt. Express **17**, 17792 (2009)

Observation of wavelength conversion

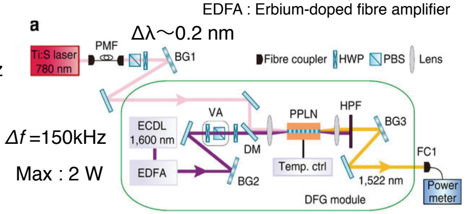
ECDL : external cavity diode laser
EDFA : Erbium-doped fibre amplifier

λ=780 nm
f = 82 MHz
τ=1.2 ps

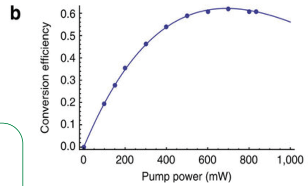
Δλ〜0.2 nm

Δf=150kHz

Max : 2 W



Conversion efficency ： 0.62
（0.70@ cw laser light）



- Crystal length L=20mm
- Polling period Λ〜19µm
- temp 50°C
- Band width 0.3 nm

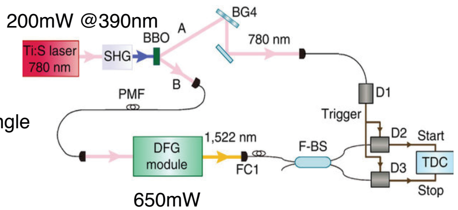
Conversion efficiency $\eta = \sin^2(\sqrt{rP}L)$

P : pump power L : crystal length r : contstant

Wavelenth conversion of single photon

200mW @390nm

Helarded single photon



650mW @1600nm

Intensity correlation

$$g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t)\rangle}{\langle I(t+\tau)\rangle\langle I(t)\rangle}$$

Single photon $g^{(2)}(0) = 0$

Laser light $g^{(2)}(0) = 1$

Classical light $g^{(2)}(0) \geq 1$

$g^2(0) = 0.17 \pm 0.04 < 1$

Observation of Non classicality

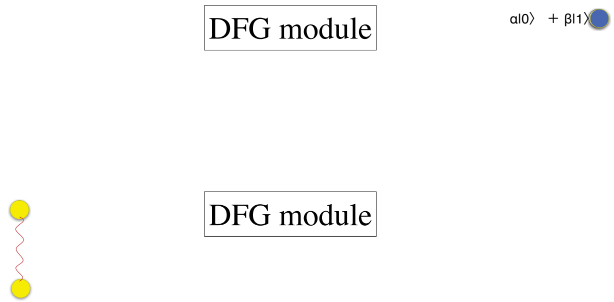
Observation of entangled photon conversion

α|0〉 + β|1〉

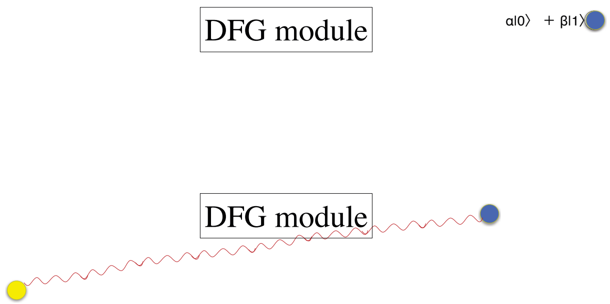
DFG module

Observation of entangled photon conversion

Observation of entangled photon conversion



Observation of entangled photon conversion



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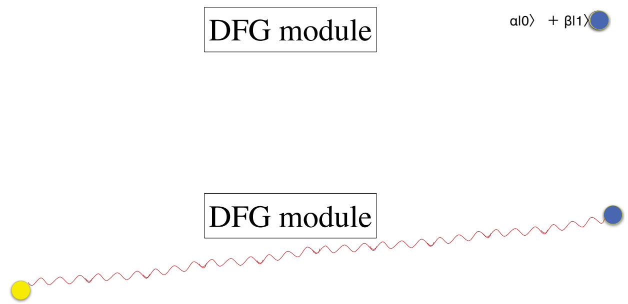
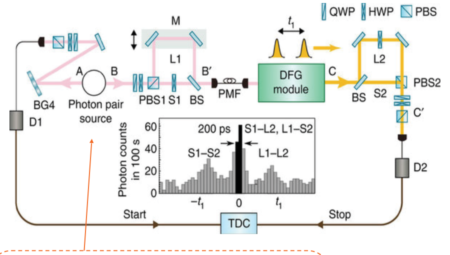
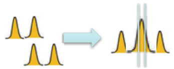
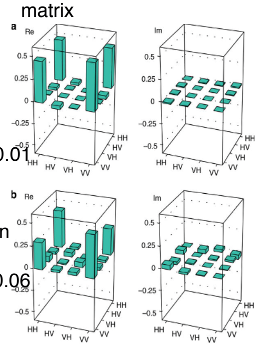


Observation of entangled photon conversion

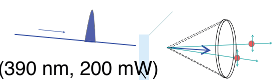




Reconstructed density matrix



Parametric down converion



UV(390 nm, 200 mW)

Polarization entangled photon pair

Before conversion

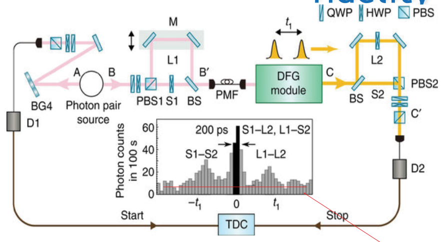
fidelity：0.95±0.01

After conversion

fidelity ：0.75±0.06

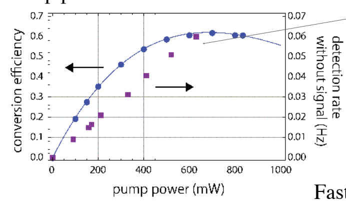
R. Ikuta, Y. Kusaka, T. Kitano, H. Kato, T. Yamamoto, M. Koashi, N. Imoto, Nat. Commun. 2 537 (2011).

Reasons of the degradation of the fidelity



Unexpected photon counts

Pump power VS noise counts



75%:Raman scattering from Pump

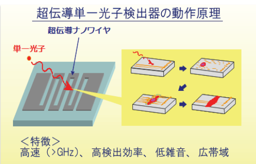
25%:Dark counts of the detector

Timing jitter of the detectors

～300 ps @Si-APD, InGaAs-APD

Faster detectors will decrease the noise counts

Superconducting single photon detectors (SSPD)



S. Miki, T. Yamashita, M. Fujiwara, M. Sasaki, and Z. Wang
Optics Letters, Vol. 35, Issue 13, pp. 2133-2135 (2010)

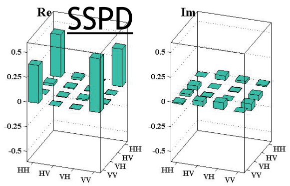
	Si-APD	InGaAs-APD
efficiency	～50% @800 nm	～25% @1550 nm
Dark counts	100 Hz	1.6×10⁵ Hz
Timing jitter	300 ps	300 ps

Experimental results

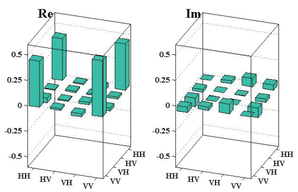
Quantum state tomography

Ikuta et.al.,PRA (2013)

1. APD + SSPD



2. SSPD + SSPD



	F	EoF	S（Bell paramet
Before conv.	0.97±0.01	0.97±0.03	2.73±0.02
After conv. (APD + SSPD)	0.87±0.06	0.68±0.15	2.35±0.10
After conv. (SSPD + SSPD)	0.93±0.04	0.88±0.10	2.62±0.09

> 2

Almost noise-free conversion has been observed by using SSPDs

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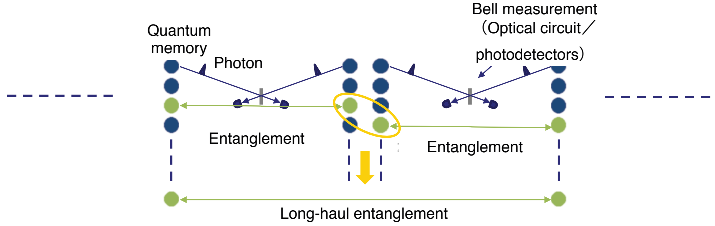
Quantum repeaters

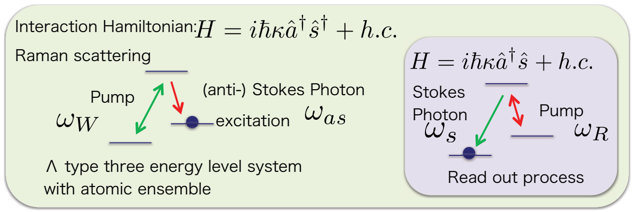


→ Quantum cryptography, Quantum teleportation, Quantum dense coding, Quantum cloud computing

Elementary devices／technologies

1. Long lifetime quantum memories
2. Memory-photon entanglement
3. High-efficiency fiber transmission of photons
4. High-efficiency & low noise photodetectors

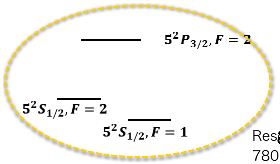
Single excitation of Rb atom with single photon emission



Cold Rb atomic ensemble

$$\omega_W - \omega_{as} = \omega_R - \omega_s$$

$$k_W + k_R = k_{as} + k_s$$



Cold ^{87}Rb　Atomic Ensemble

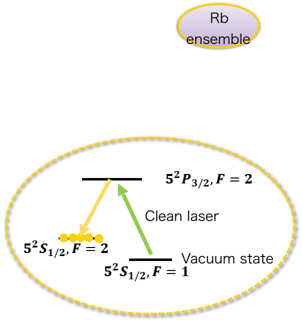
Λ-type three level system in Rb atom

Resonance wavelength between upper level and two lower levels: 780 nm

Resonance frequency between two lower levels:　6.8Ghz

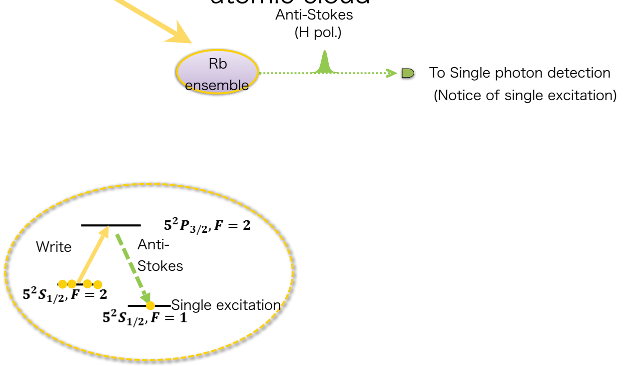
Initialization

Initialization: Polarization of atomic state



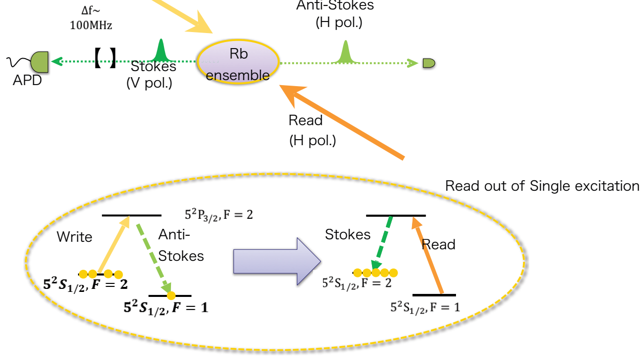
Single excitation in atomic cloud

Preparation of single excitation in atomic cloud



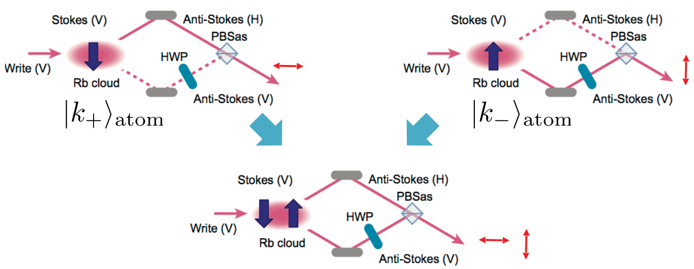
Read out of single excitation

Read out of single excitation from atomic cloud



Atom-Photon Entanglement

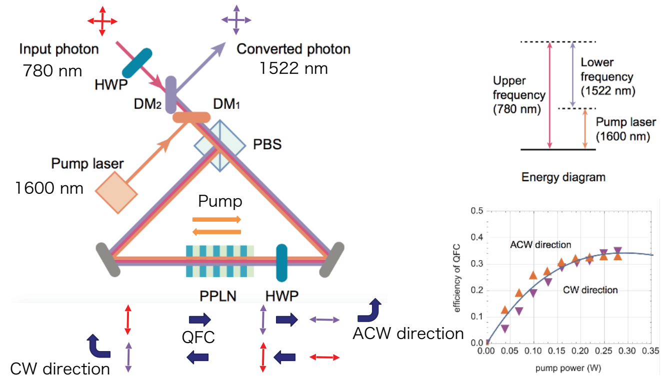
Momentum of collective spin excitation in atomic ensemble



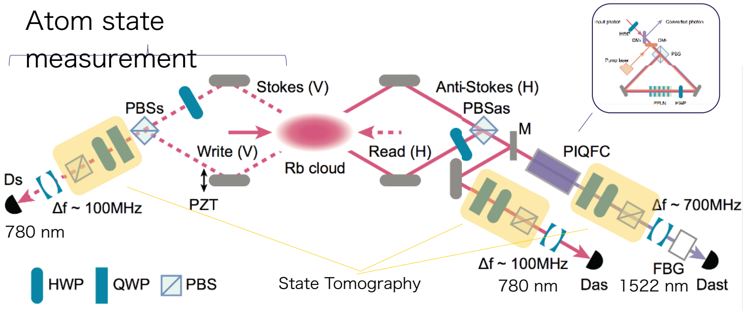
$$(|H\rangle_{AS}|k_+\rangle_{\text{atom}} + |V\rangle_{AS}|k_-\rangle_{\text{atom}})/\sqrt{2}$$

Polarization Insensitive QFC

QFC installed in Sagnac interferometer



Atom-Telecom Photon Entanglement

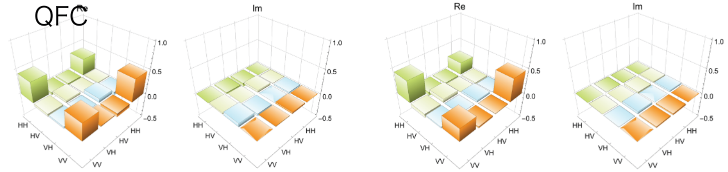


R. Ikuta, T. Kobayashi, T. Kawakami, S. Miki, M. Yabuno, T. Yamashita, H. Terai, M. Koashi, T. Mukai, T. Yamamoto, N. Imoto, "Polarization insensitive frequency conversion for an atom-photon entanglement distribution via a telecom network"
NATURE COMMUNICATIONS 9, 1997 (2018).

Experimental results

Density Matrix without QFC

Density Matrix with QFC



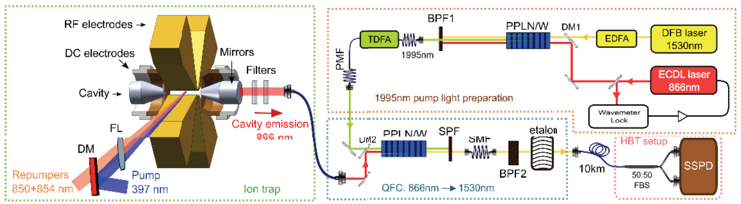
F=0.78±0.05
EOF=0.37±0.11

F=0.69±0.07
EOF=0.25±0.13

R. Ikuta, T. Kobayashi, T. Kawakami, S. Miki, M. Yabuno, T. Yamashita, H. Terai, M. Koashi, T. Mukai, T. Yamamoto, N. Imoto, Polarization insensitive frequency conversion for an atom-photon entanglement distribution via a telecom network. arXiv:1710.09150

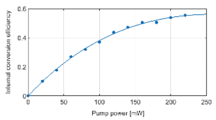
Ion-Telecom Photon Interface

Ca+ ion single photon source with our QFC



Conversion Efficiency
866 nm -> 1530 nm

g(2)=0.67±0.07 over 10 km



Joint work with Hayasaka@NICT in Tanaka Team and M. Keller@Sussex Univ.

T. Walker, K. Miyanishi, R. Ikuta, H. Takahashi, S. V. Kashanian, Y. Tsujimoto, K. Hayasaka, T. Yamamoto, N. Imoto, M. Keller, "Long-distance single photon transmission from a trapped ion via quantum frequency conversion"
Phys. Rev. Lett. 120, 203601 (2018)

Summary

Global Quantum Network

(1) Why necessary?

(2) What are the problems?
・transmission loss ・noise (decoherence)
(3) How did we deal with these problems?
・Frequency conversion ・noise cancellation by DFS
(4) How are we going to cope with these problems?
・Incorporating quantum memories such as Rb, Ca
(5) Is their any alternative(s)?