Session 6a, 09:00 on Thursday 22 Sept 2011

Novel photon detector utilizing superconducting optical detection technology

Daiji Fukuda, G. Fujii, A. Yoshizawa, T. Numata, K. Amemiya, S. Inoue, and H. Tsuchida

[1]*National Institute of Advanced Industrial Science and Technology, NMIJ*

[2]*Nihon University*

11th International Conference on New Developments and Applications in Optical Radiometry, Grand Wailea Resort, Sep. 19-23, 2011

Outline

- **Background**
  - Requirements to optical photon detectors
- **Current status of superconducting TES(transition edge sensor) technology**
  - NMIJ/AIST
  - InRiM and NIST
- **Applications of TES**

Ideal photon detector

- Detection efficiency
  - Probability of one single photon detection $\eta \sim 100\ \%$
- Dark-count rate
  - Rate of pulses in the absence of photons $D \sim 0\ \mathrm{Hz}$
- Dead time
  - Incapable time after a photon detection $\tau_{dead} \sim 0\ \mathrm{s}$
- Timing jitter
  - Variation of photon detecting time $\delta t \sim 0\ \mathrm{s}$

- Photon number resolving Yes
  - Ability to distinguish the number of photons $\Delta E \sim 0$ eV

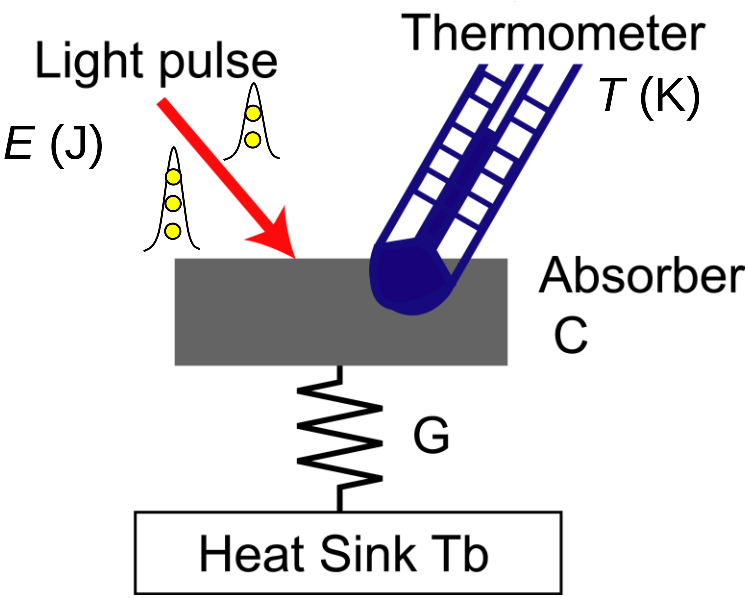
Performance of PNRD

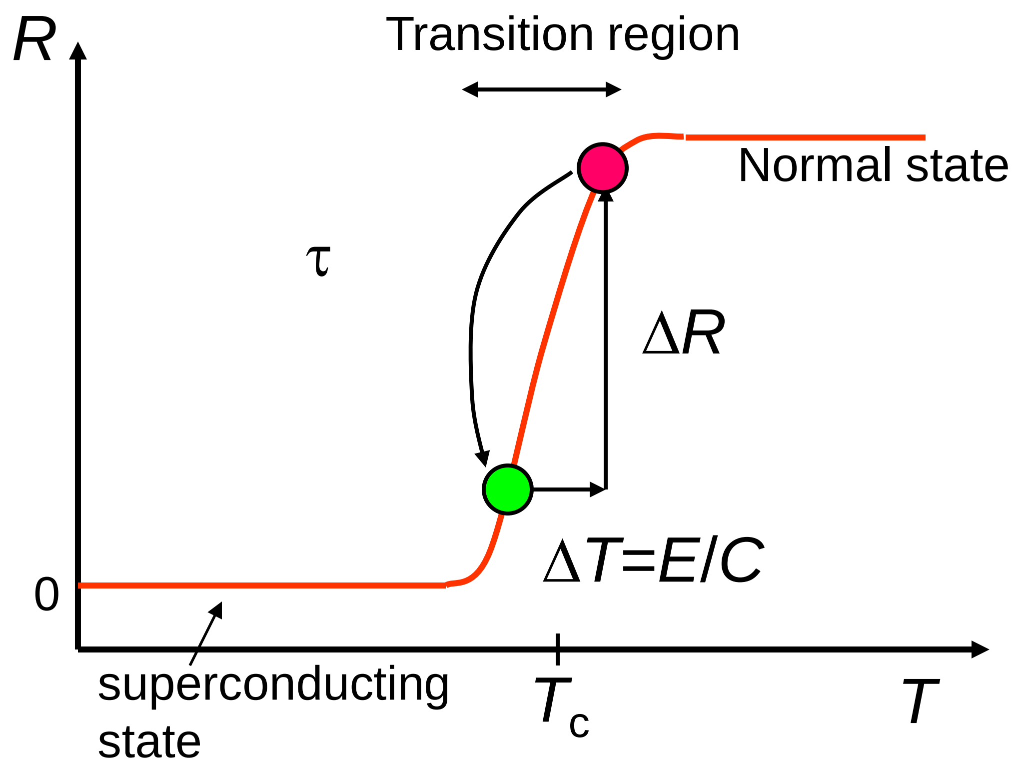
PNRD	D.E. η	Jitter	Dark count	Count rate
PMT	40 %@500 nm 2 %@1,550 nm	300 ps	100 Hz 200 kHz	10 MHz
Si SPAD	40 %@532 nm	300 ps	25 kHz	30 MHz
InGaAs SPAD	10 %@1,550 nm	-	-	-
CIPD	80 %@1310 nm	-	-	100 Hz
VLPC	88 %@694 nm	40 ns	20 kHz	10 MHz
W-TES	95 %@1,550 nm	100 ns	3 Hz	100 kHz

- Among photon number resolving detectors(PNRDs), superconducting ***Transition Edge Sensors*(TESs)** have high D.E. & extremely low Dark count.
- Drawback is slow response speed.
- AIST has been making efforts to enhance TES performances.

Transition edge sensor(TES)

Schematics of calorimeters





C: Heat capacity (J/K)

G: Thermal conductance (W/K)

α: Thermal sensitivity (V/K)

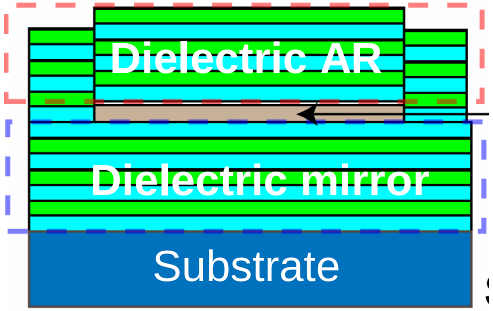
Our approaches

- Relatively high T_c superconductor
  - Improve response time, time jitter and timing resolution
  - Titanium T_c~360 mK

T_c of superconductors

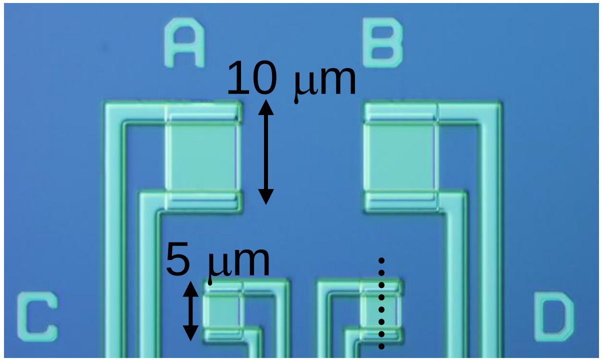
W	100 mK
Ir	112 mK
Hf	165 mK
Ti	360 mK

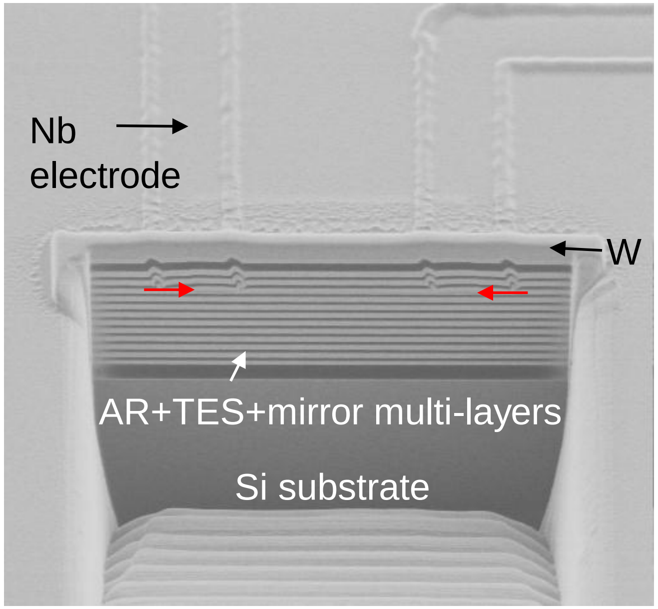
- Multi-layered optical cavity structure
  - Anti-reflection/TES/High reflection mirror
  - Dielectric films of Ta_2O_5 and SiO_2
  - High absorption and wide bandwidth
  - Optimized at any wavelength



D. Fukuda, Proc. SPIE 7236C(2009)

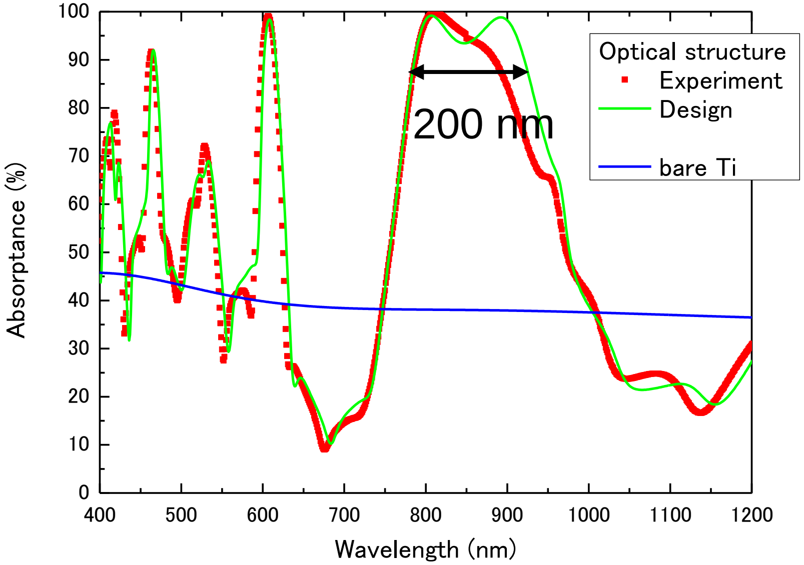
Ti-TES with optical cavity



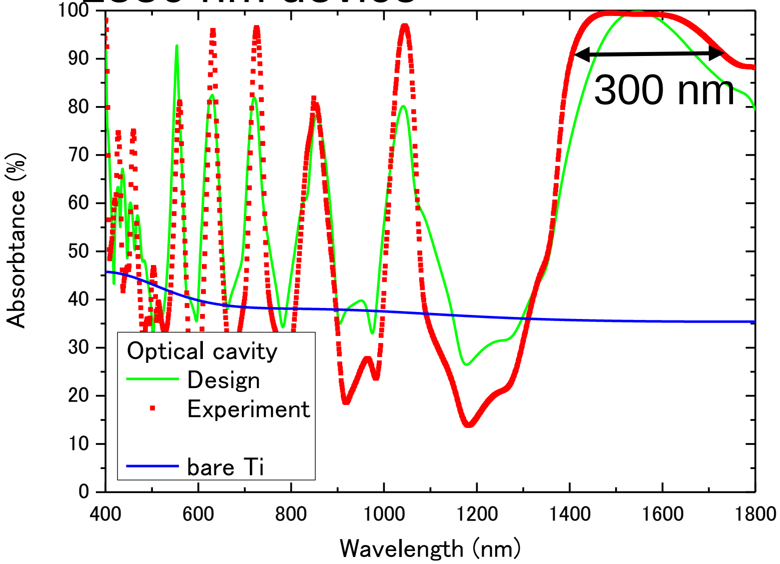


D. Fukuda, *Opt.Express*, **19**, 870, (2011)

850 nm device

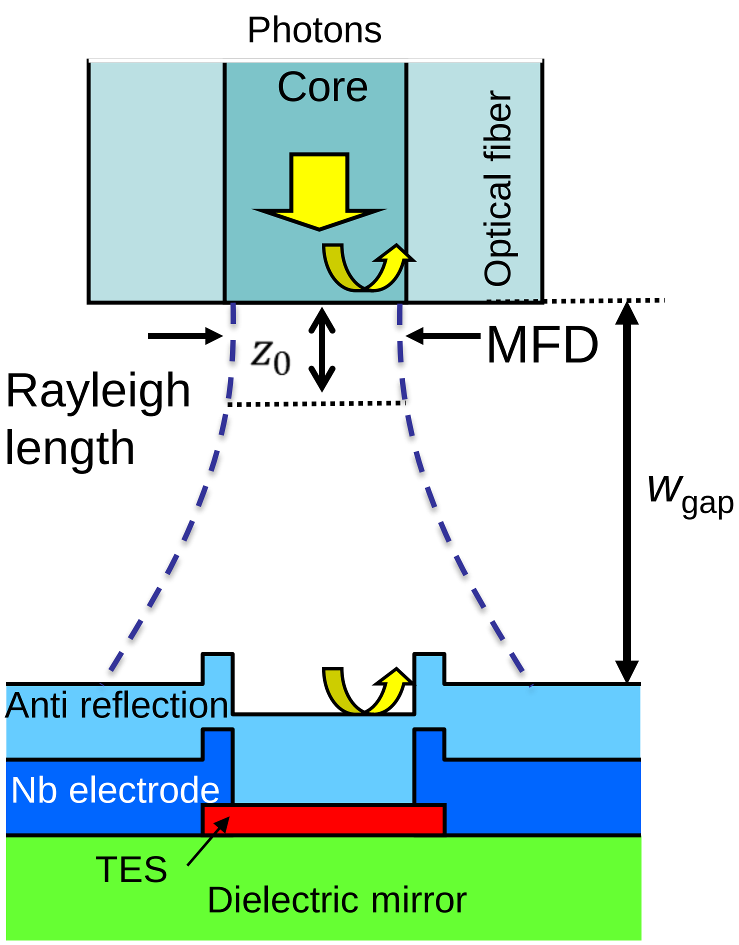


1550 nm device



Optical fiber coupling

Typical fiber coupling method



- Spot size will be divergent in case of $W_{gap} > z_0$.
- Wavelength dependence due to optical interference.

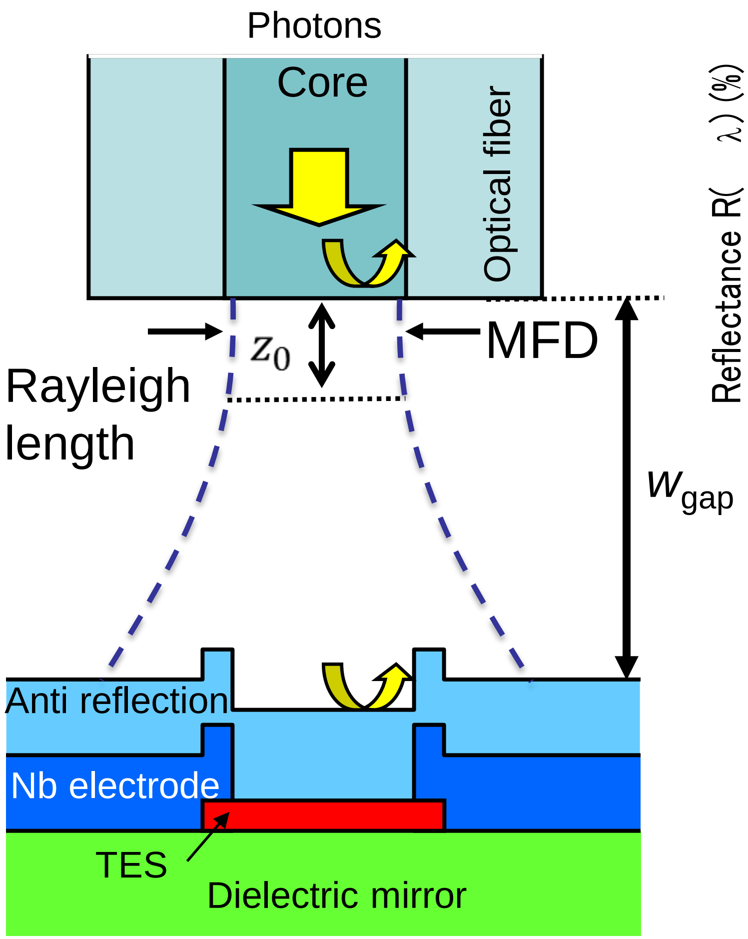
Rayleigh length

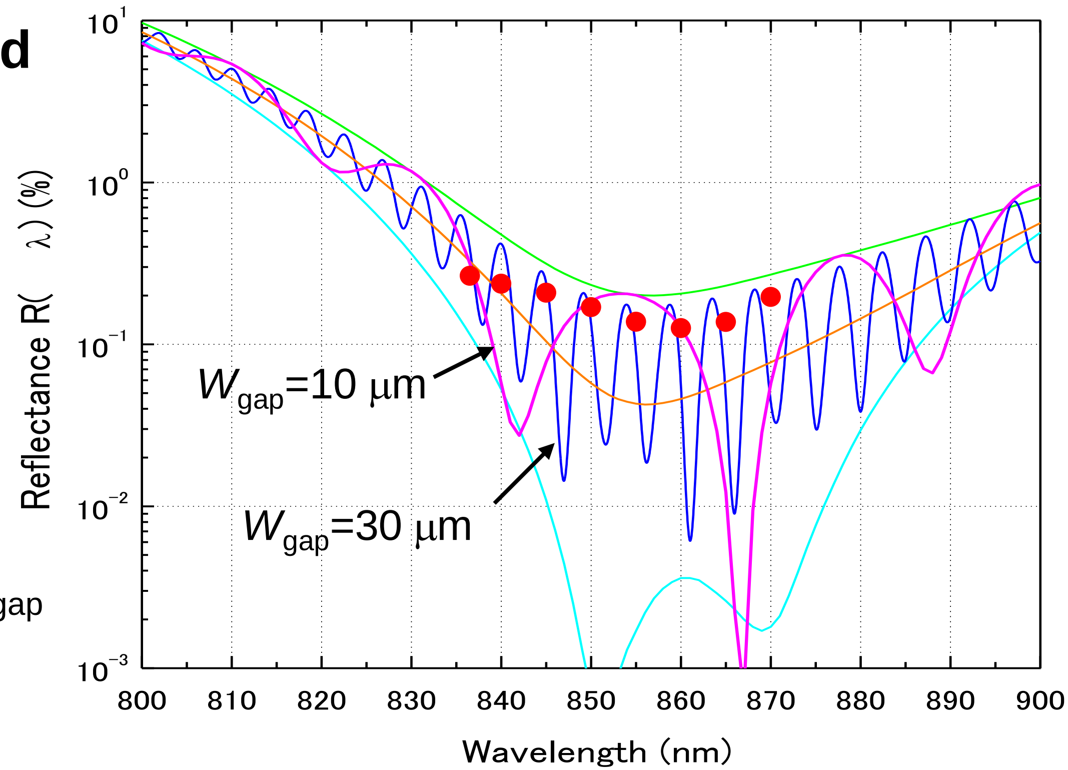
$$z_0 = \frac{\pi \varpi_0^{\,2}}{\lambda}, \varpi_0 = MFD/2$$

MFD: mode field diameter

Optical fiber coupling

Typical fiber coupling method





Rayleigh length

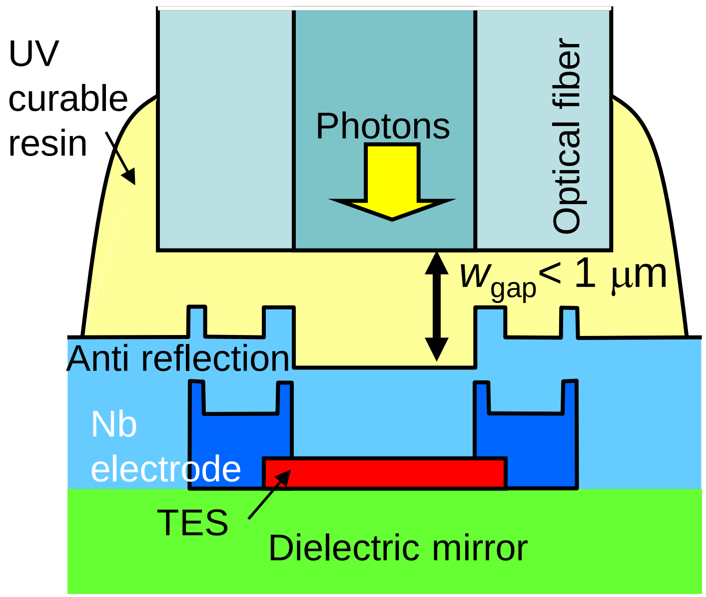
$$z_0 = \frac{\pi \varpi_0^{\,2}}{\lambda}, \varpi_0 = MFD/2$$

MFD: mode field diameter

Optical fiber coupling

Our fiber coupling method

(small-gap & index-matched)

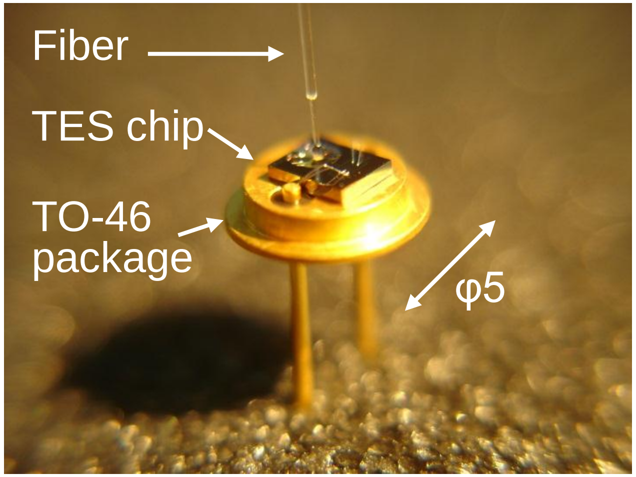


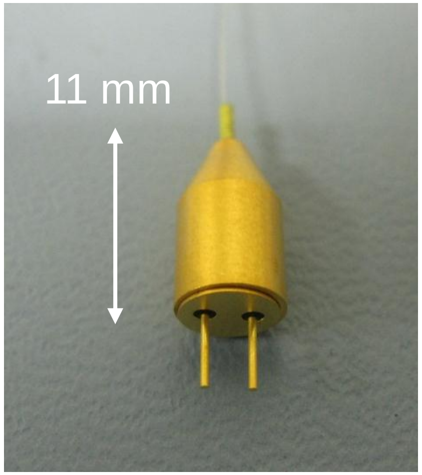
D. Fukuda, *Opt.Express*, **19**, 870, (2011)

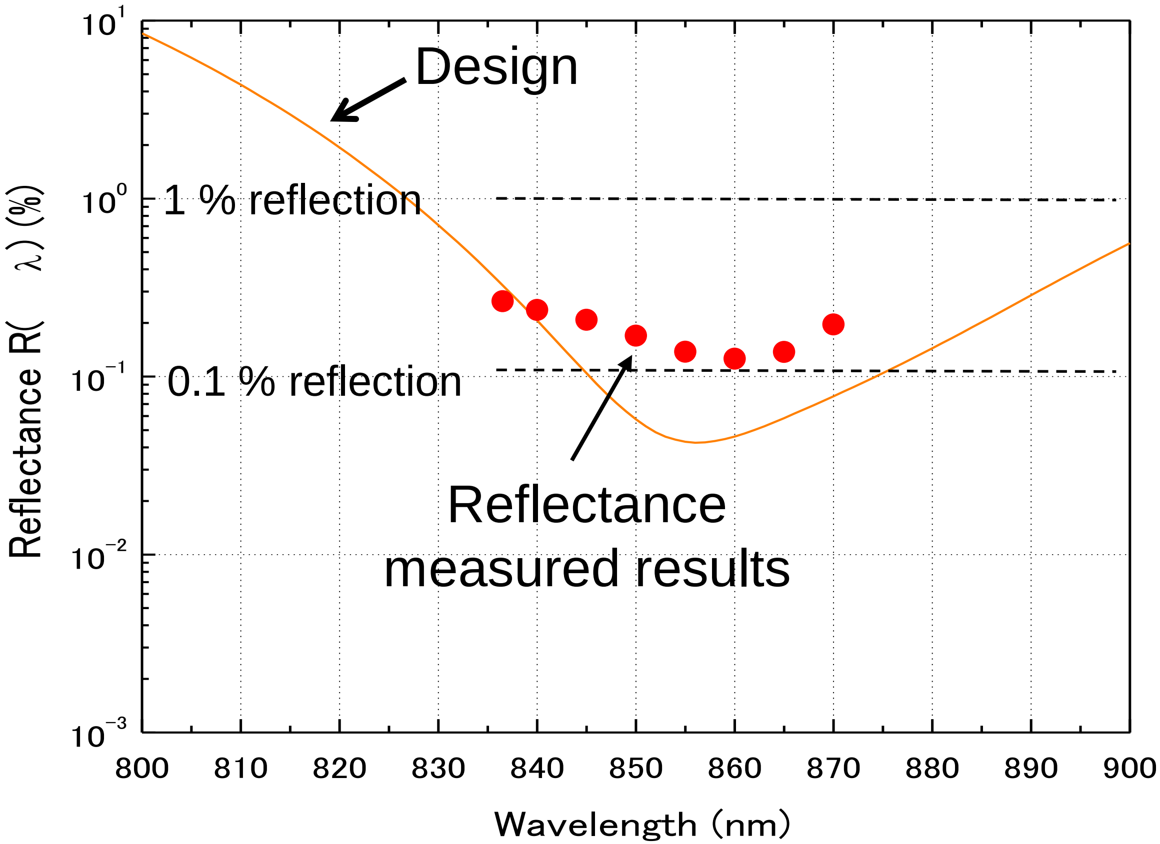
- The optical fiber is placed just closely on TES surface.
- The gap is filled with UV curable resin (n ~1.5).

- w_{gap}< 1 μm can be possible.
- The TES size can be as small as the MFD of the fiber.
- Interference effect small.

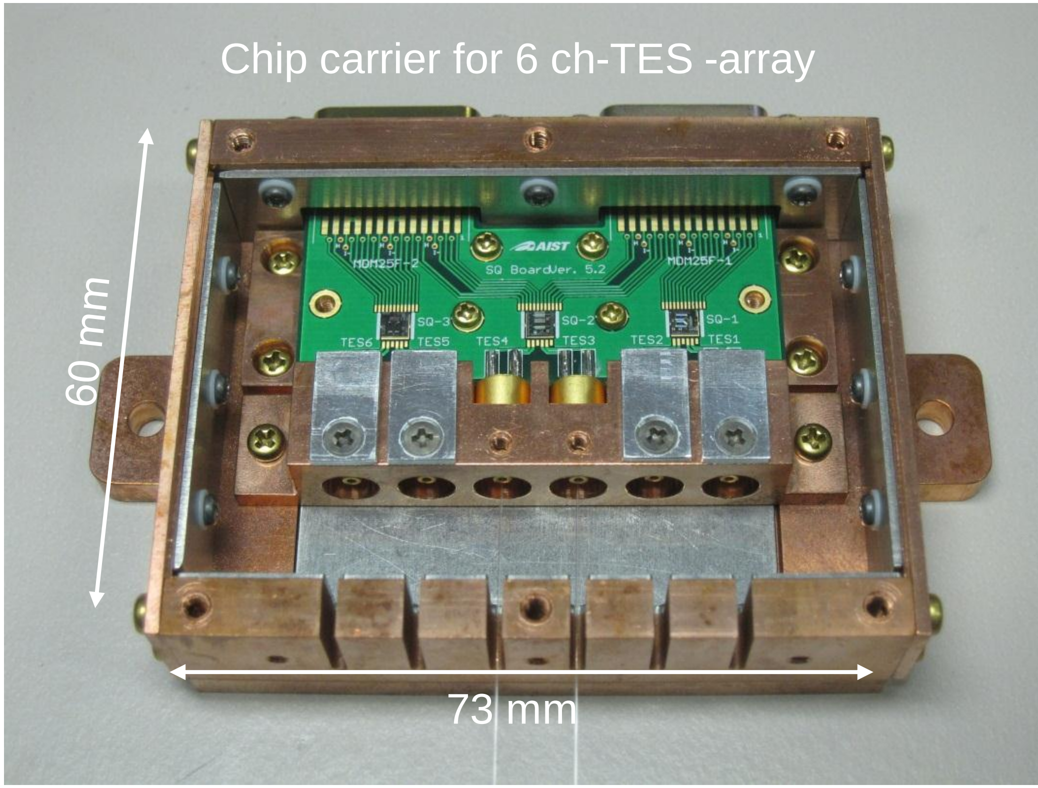
Fiber coupled TES device







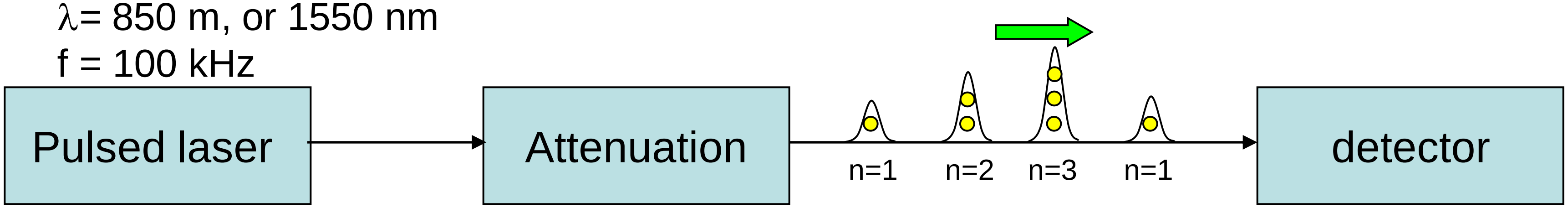
•The reflectance of the fiber coupled device was measured with return loss measurement method (IEC 61300-3-6).



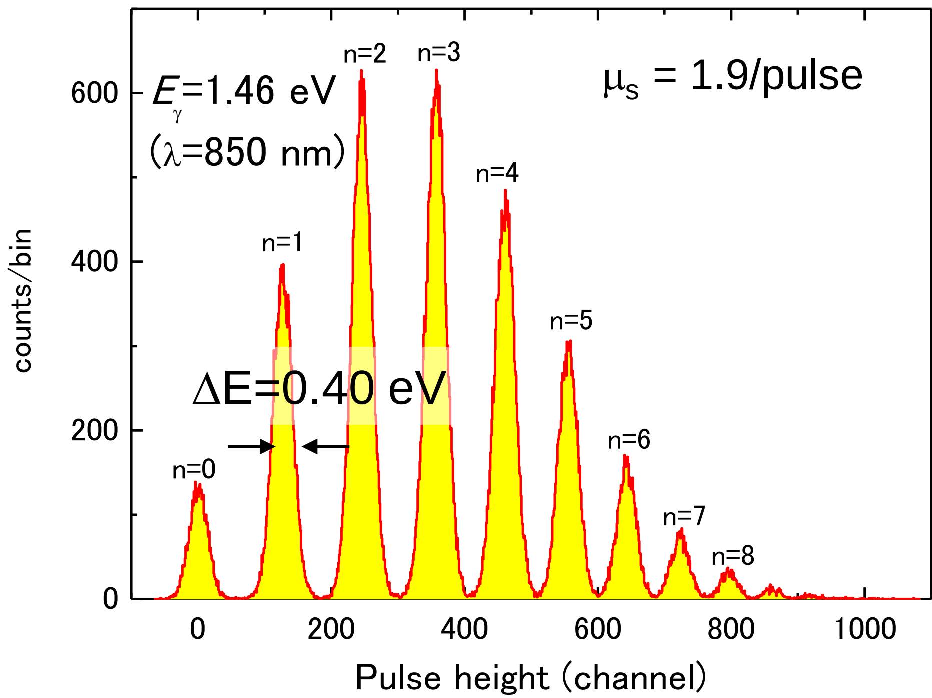
- A chip carrier for 6-ch TES array is placed in cryogen free ADR(adiabatic demagnetization refrigerator)
- Turn-key operation in ADR, the minimum temperature~50 mK

Photon number resolving capability

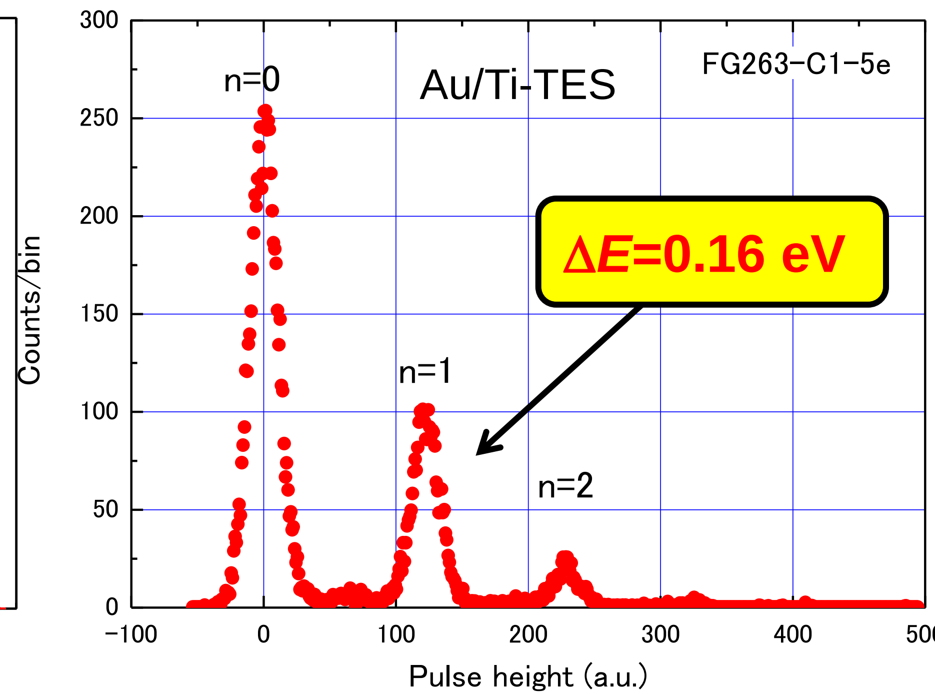
λ= 850 m, or 1550 nm
f = 100 kHz



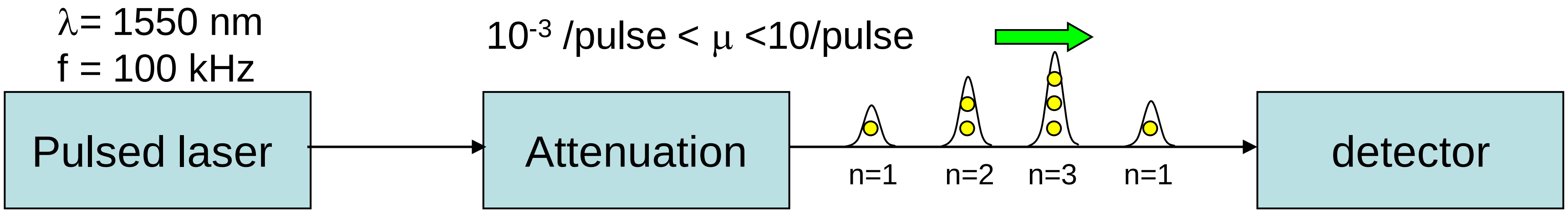
10 μm size device@ 850 nm(Ti-TES)

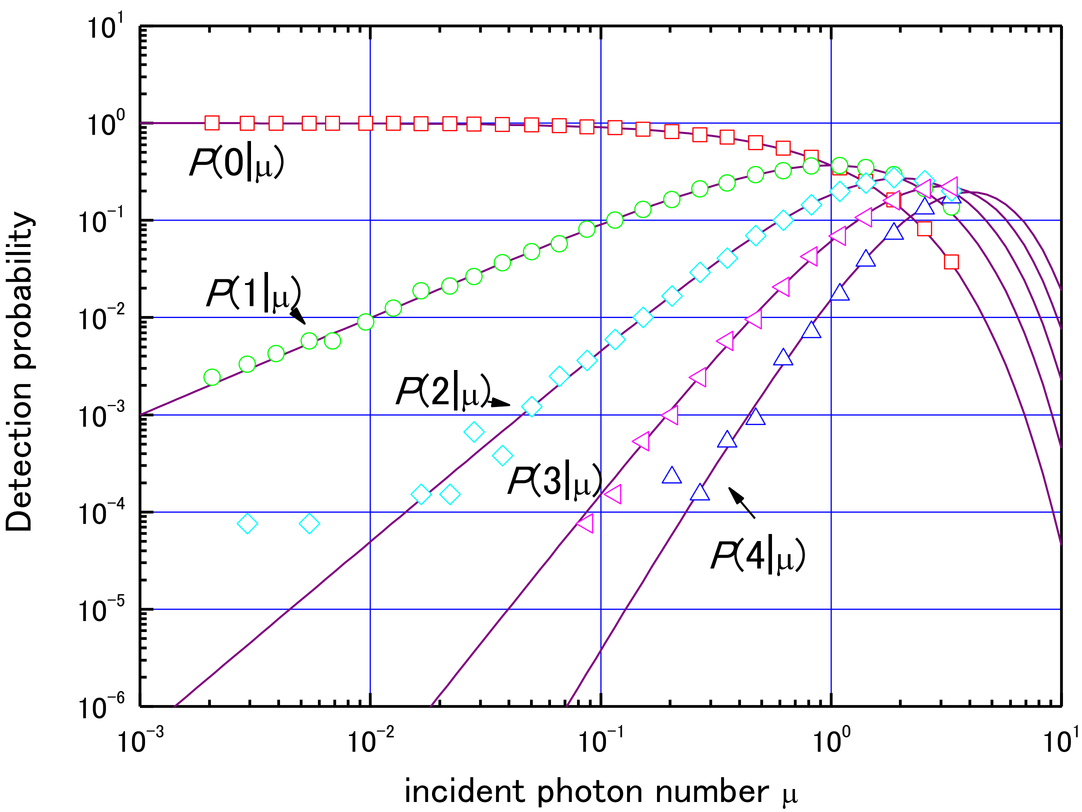


5 μm size @ 1.5 μm(Ti/Au-TES)



Detection efficiency





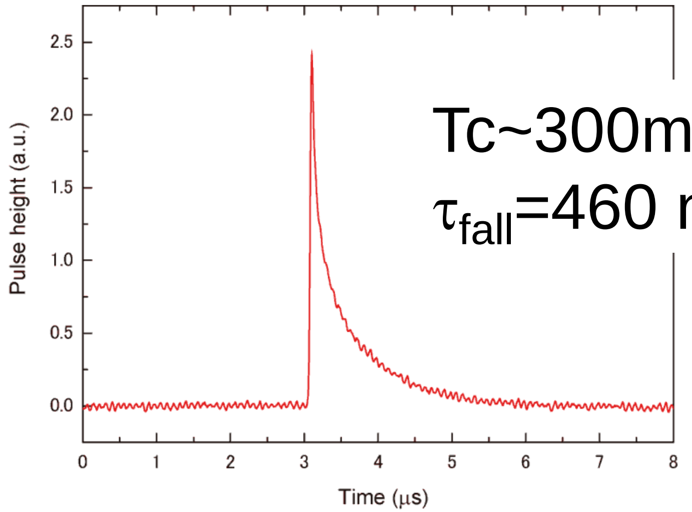
Photon detection probability with a free parameter η,

$$P_\eta(n\,|\,\mu) = \frac{(\eta\mu)^n e^{-\eta\mu}}{n!}$$

μ: Incident average photon number
n: Photon number
η: Detection efficiency

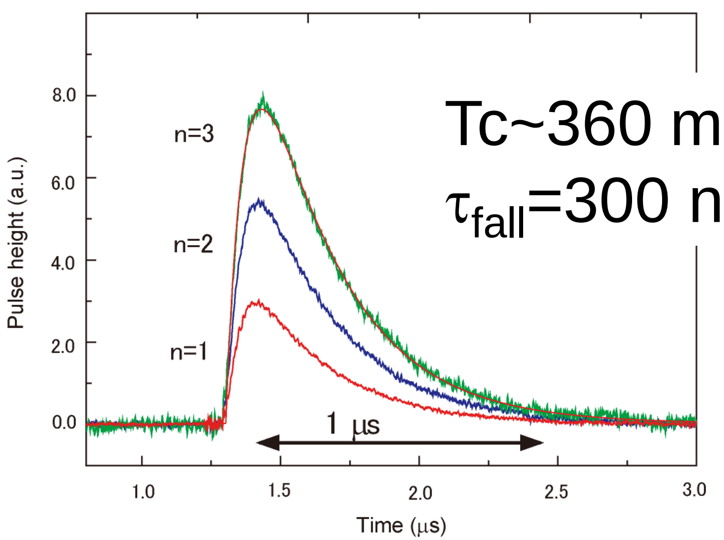
$\eta = 98\,\% \pm 1\,\%$ (*k*=1)
@ 844 nm

Response speed

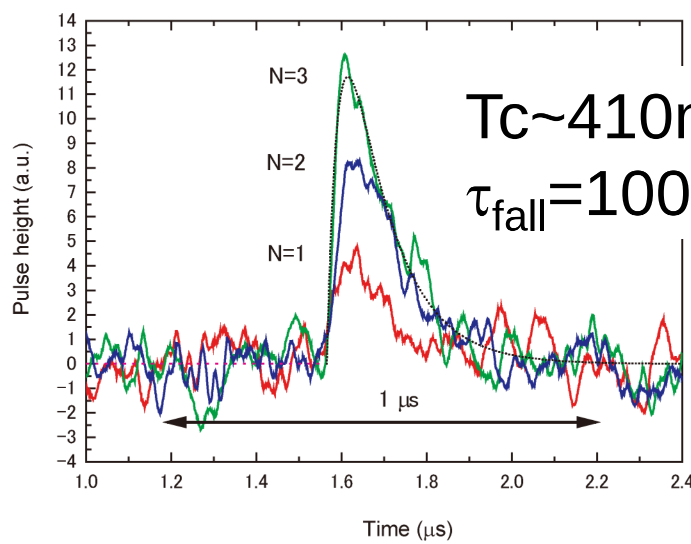


Tc~300mK
τ_{fall}=460 ns

$$\tau_{fall} = \frac{\gamma\rho}{5\Sigma T_c^{\,3}} \frac{1}{1+\alpha/n} \propto T_c^{-3}$$



Tc~360 mK
τ_{fall}=300 ns



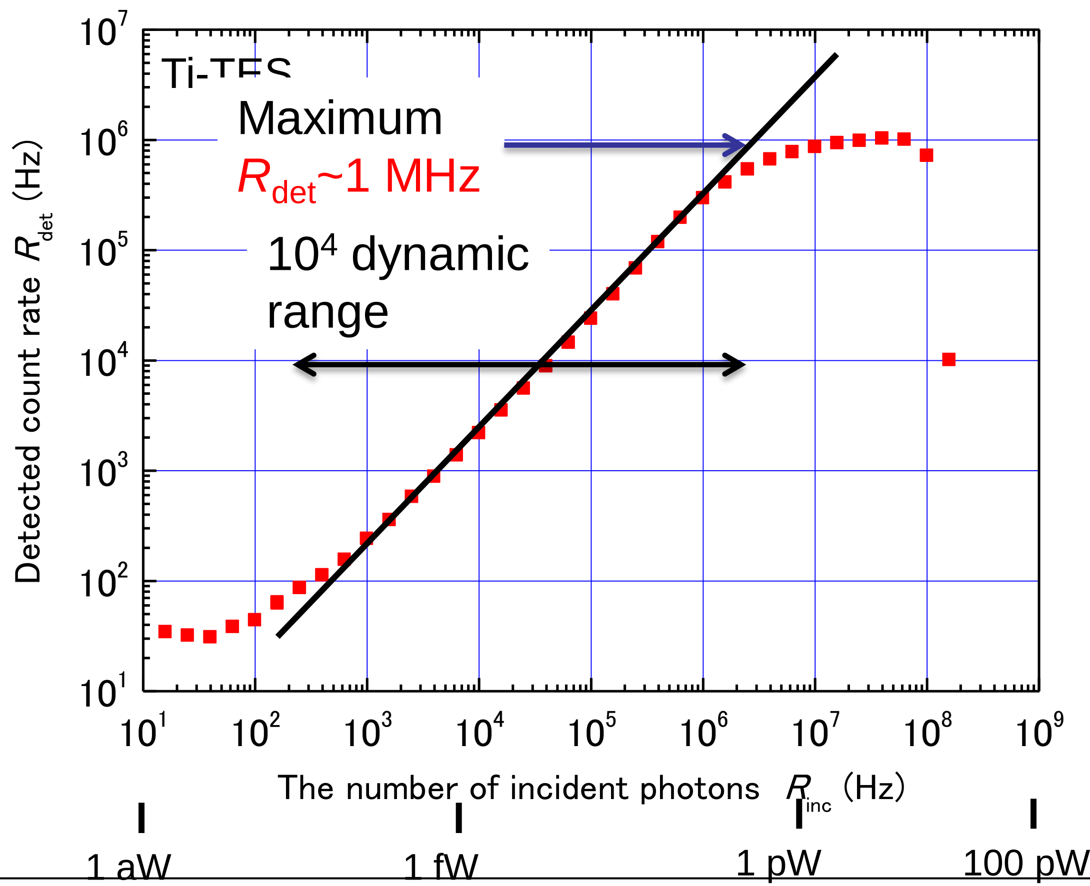
Tc~410mK
τ_{fall}=100 ns

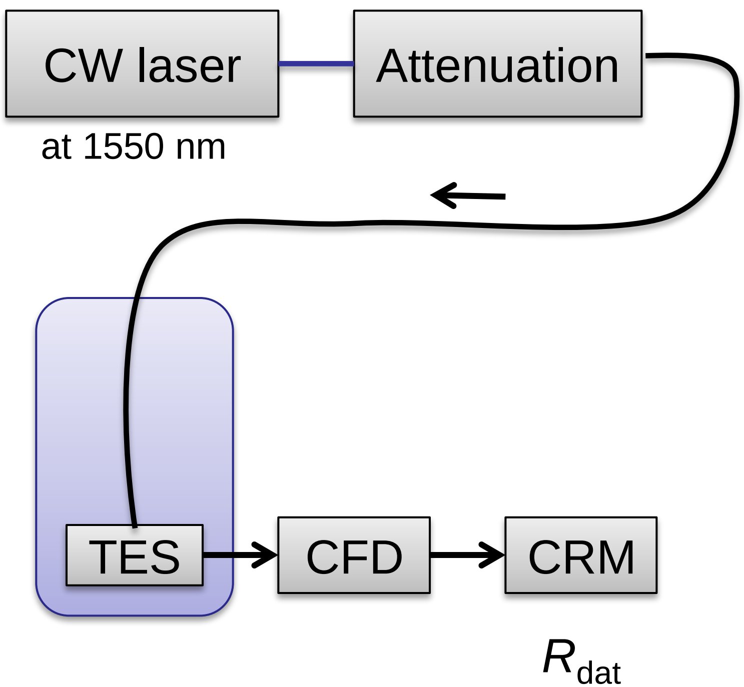
Maximum count rate

- Count rate measurement to continuous wave (CW) laser.
- Incident rate of the photon number per second : R_{inc}
  $R_{inc}=P\lambda/hc$;
  P is the incident power, and λ is the wavelength.

10 Hz<R_{inc}<1 GHz

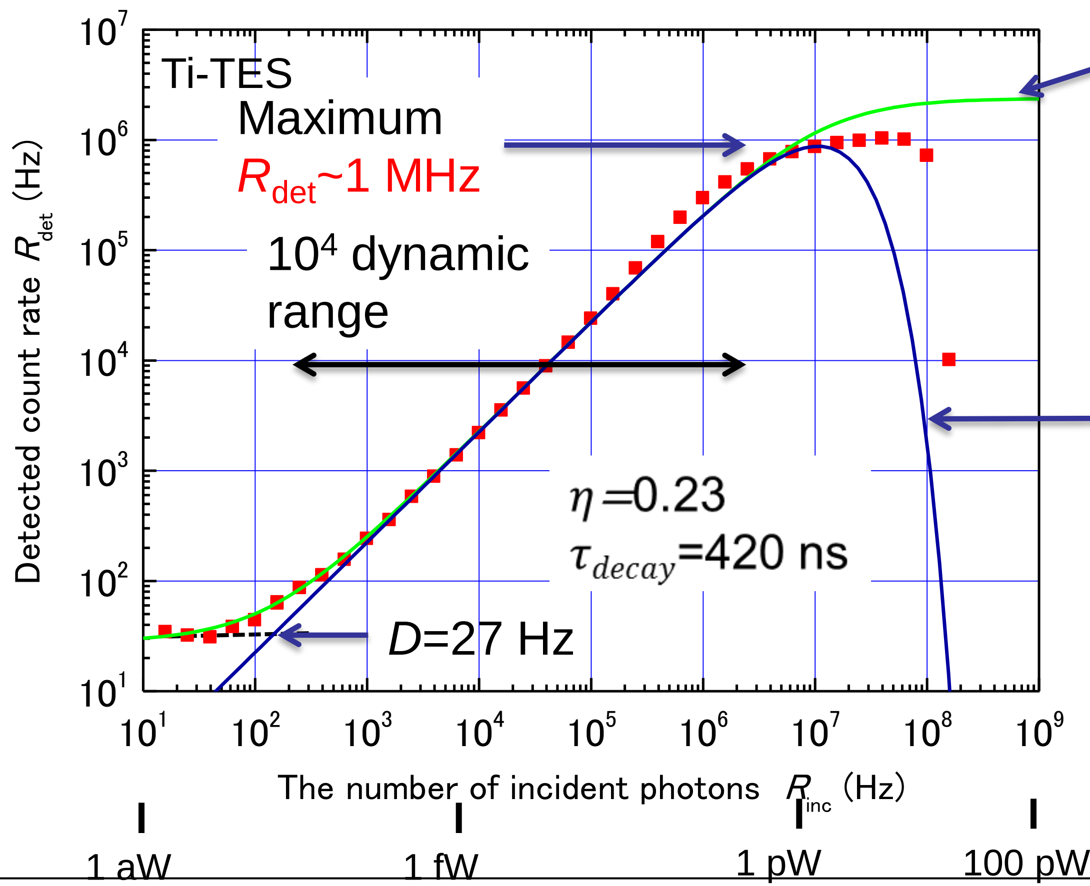
1 aW<P_{inc}<100 pW





Maximum count rate

- Count rate measurement to continuous wave (CW) laser.
- Incident rate of the photon number per second : R_{inc}
  $R_{inc}=P\lambda/hc$;
  P is the incident power, and λ is the wavelength.



Non-paralysable model

$$R_{det} = \frac{\eta R_{inc} + \frac{D}{1 - D\tau}}{1 + \tau\left(\eta R_{inc} + \frac{D}{1 - D\tau}\right)}$$

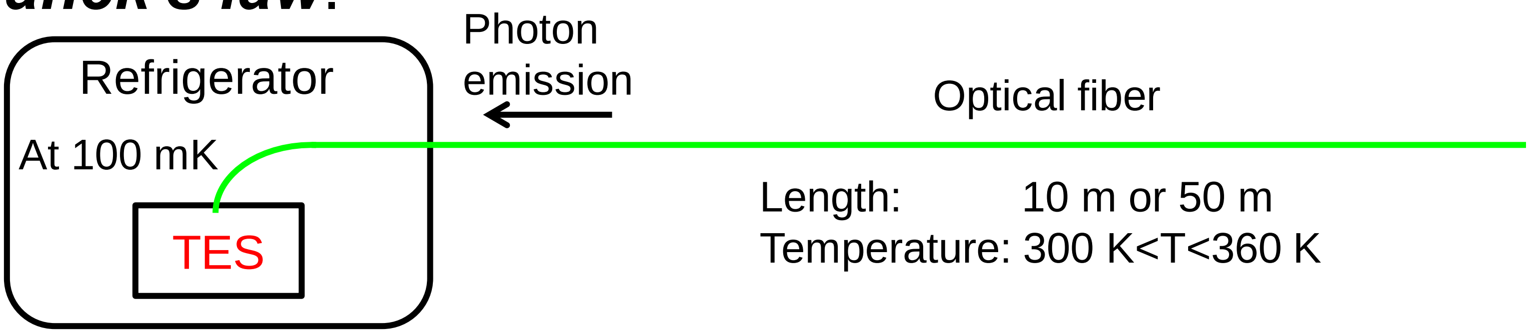
Paralysable model

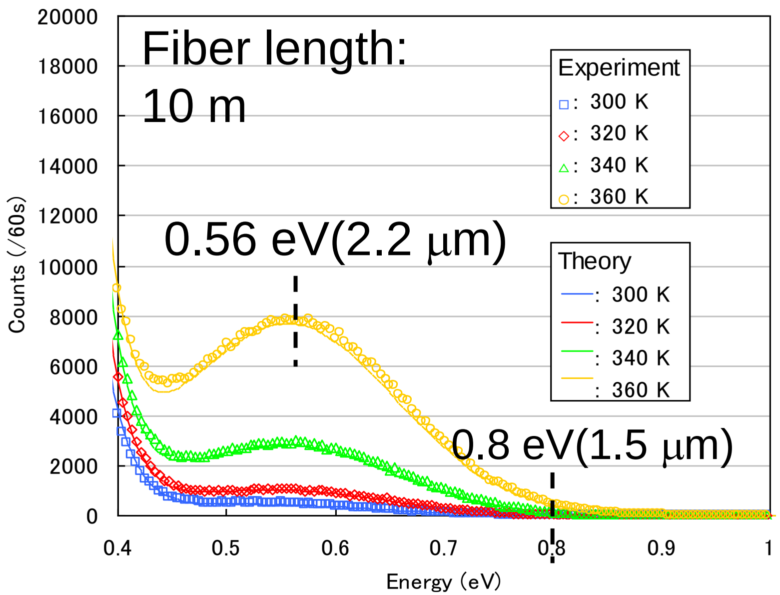
$$R_{det} = \eta R_{inc} e^{-\tau\eta R_{inc}}$$

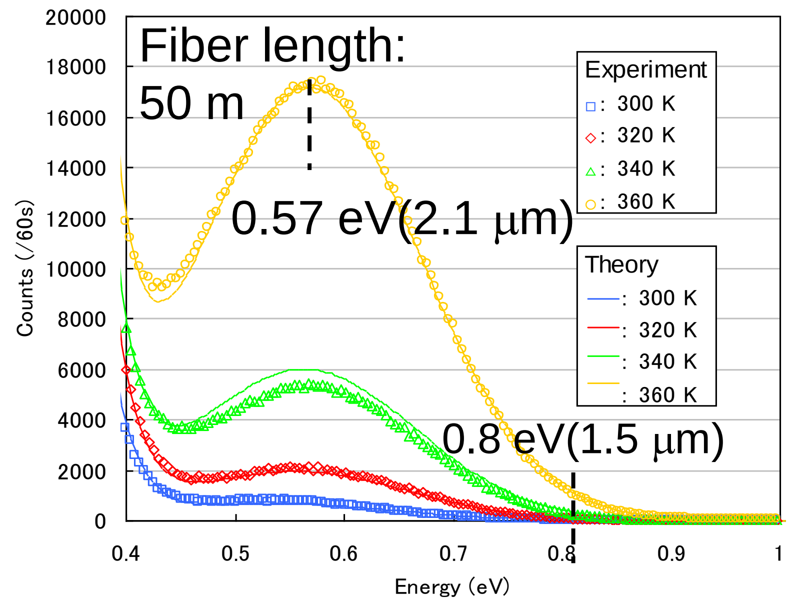
D : dark count (Hz)
τ : dead time (s)

Dark count

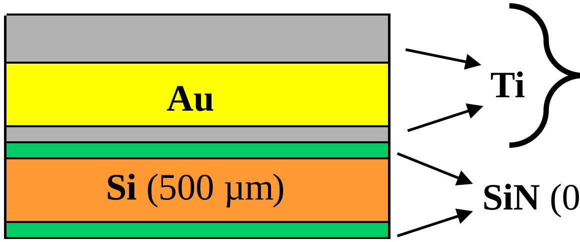
- Intrinsically, the TES should show **no** dark count !
- However, the optical fiber itself at room temperature would be a source of dark count, due to black body radiation in ***Planck's law***.





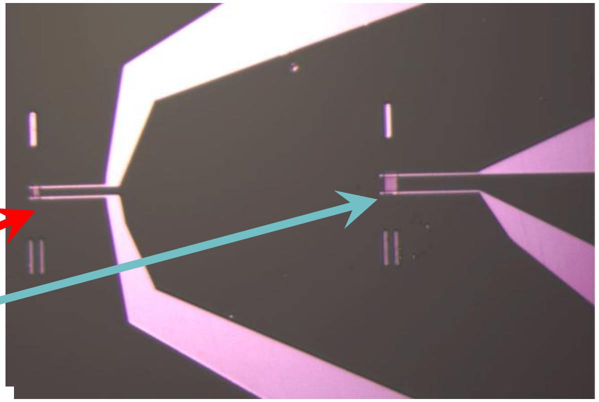


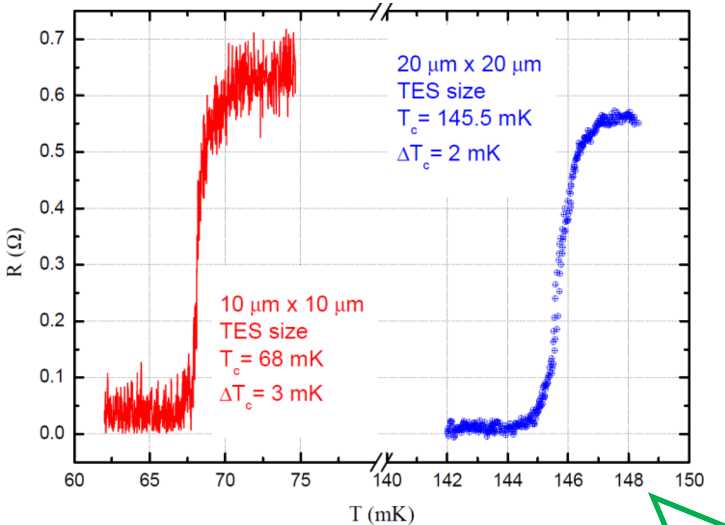
i.N.Ri.M. Ti/Au TES



Overall TES Thickness ~ 90 nm

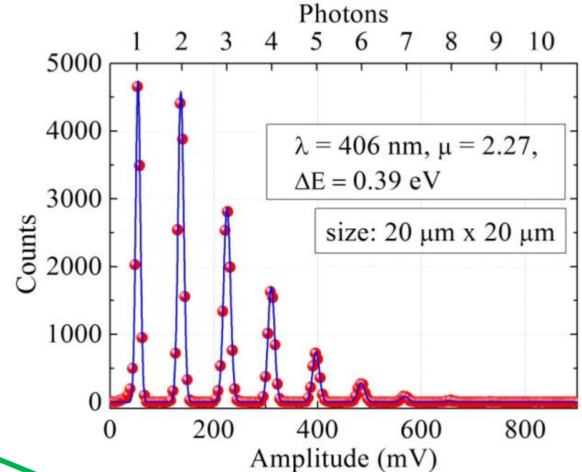
active area
10 x 10 µm²
20 x 20 µm²

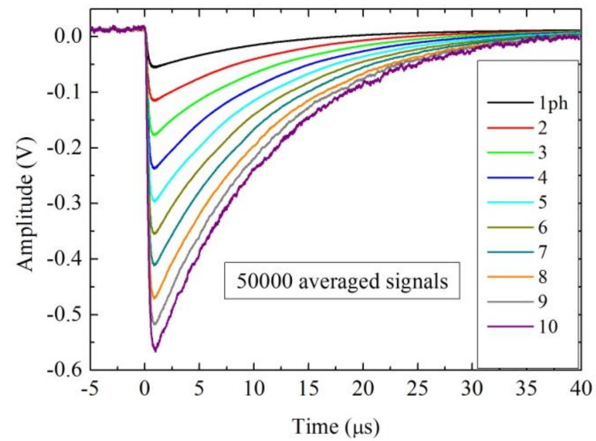




Critical Temperature:
60 mK ÷ 160 mK

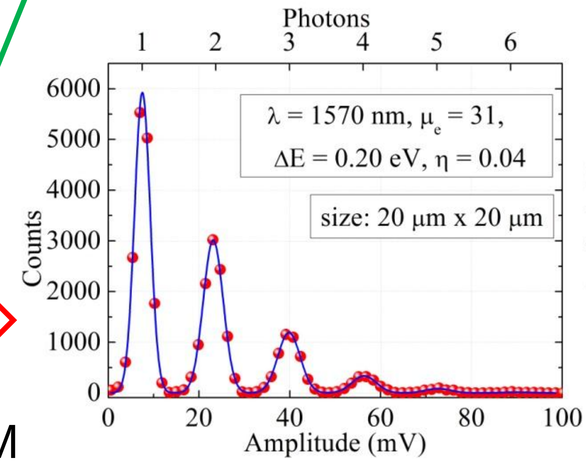
406 nm

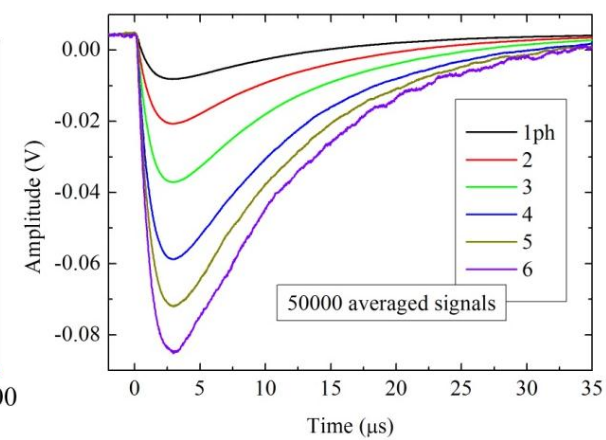




Wide spectral range: from visible to telecom wavelengths

1570 nm



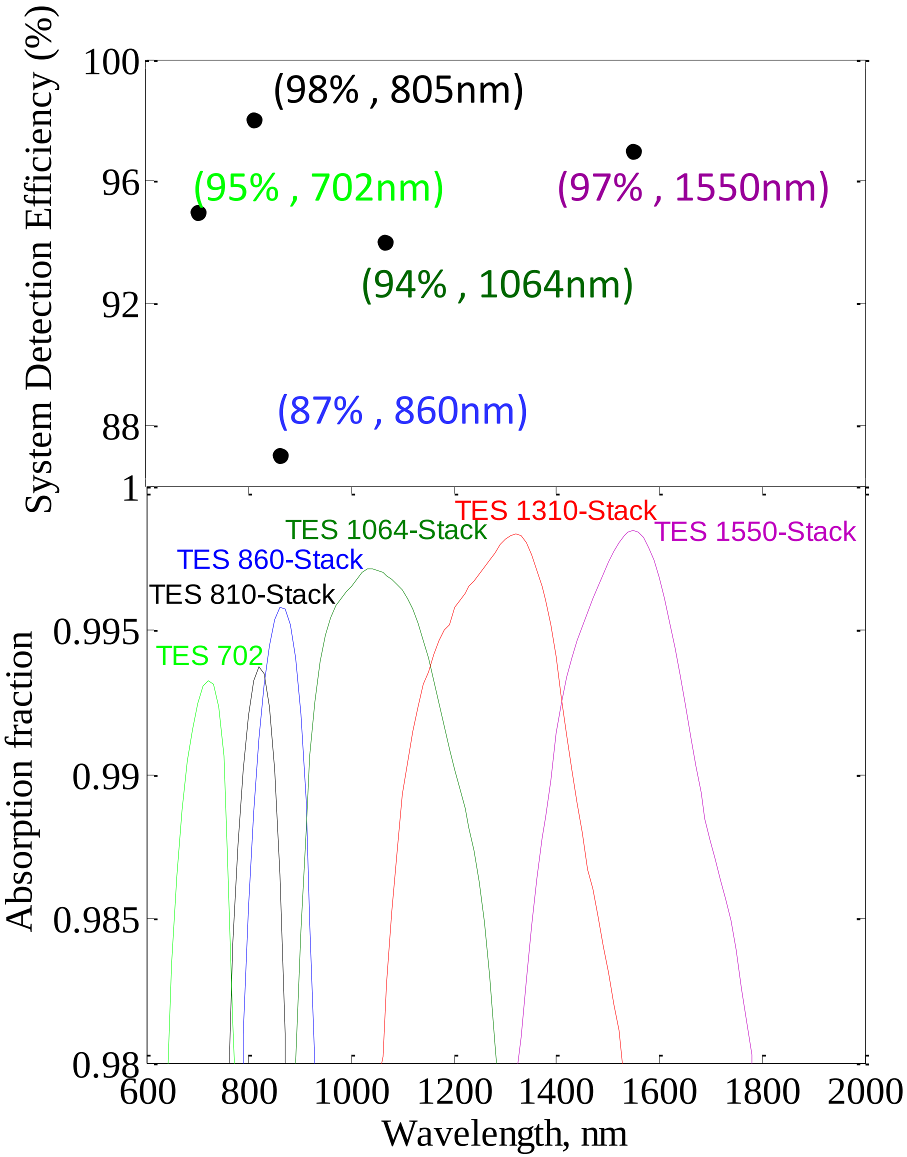


Courtesy of Mauro Rajteri in InRiM

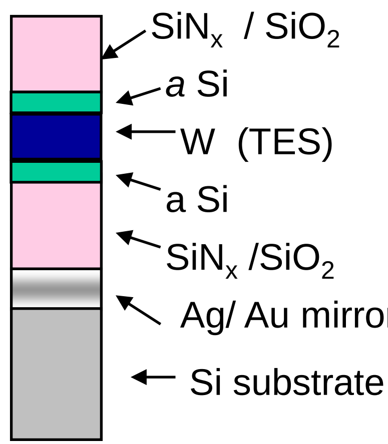
Tungsten (W) Transition Edge Sensor

NIST National Institute of Standards and Technology

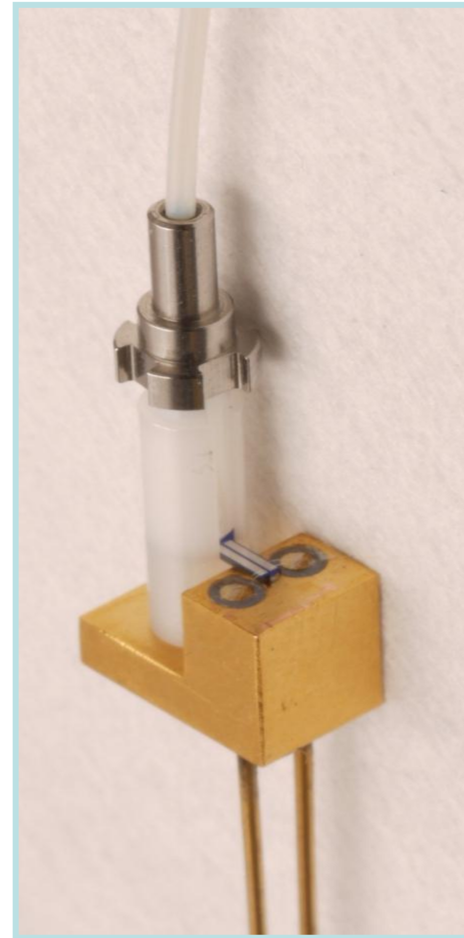
Measurements of TES Detection Efficiency and Optical Stack Expected Absorption



Optical stack



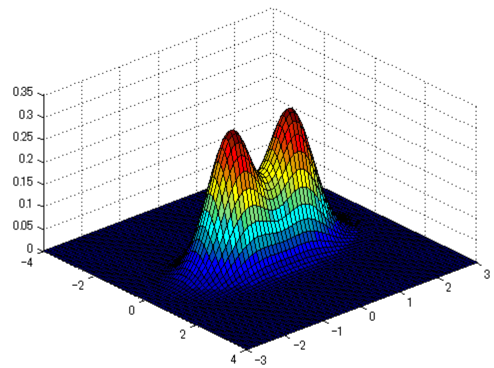
Fiber coupled self-aligned TES < 1% coupling loss



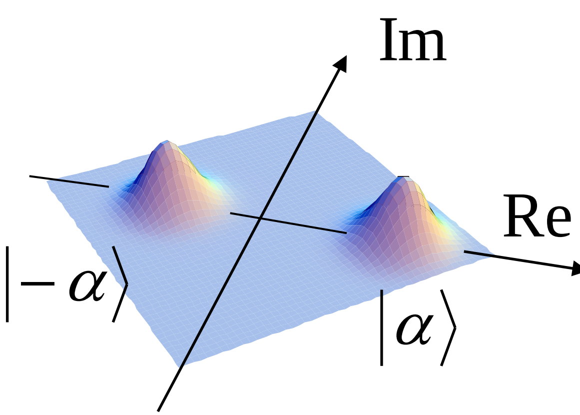
Courtesy of Adriana NIST

Applications of TES

- Industrial use, biotechnology…
  - Scattered photon measurement
  - Single photon camera
- Quantum information
  - Generation of non-Gaussian state
  - Quantum optimal receiver
  - QKD, and more!
- Metrology
  - Qu-candera
  - Highly precise phase determination
  - Highly precise evaluation for single or *entangled photon sources*



Namekata et al., Nature Photonics 4, 655(2010)



K. Tsujino, D. Fukuda, PRL 106, 250503 (2011)

Bit error rate can surpass Standard quantum limit (SQL).

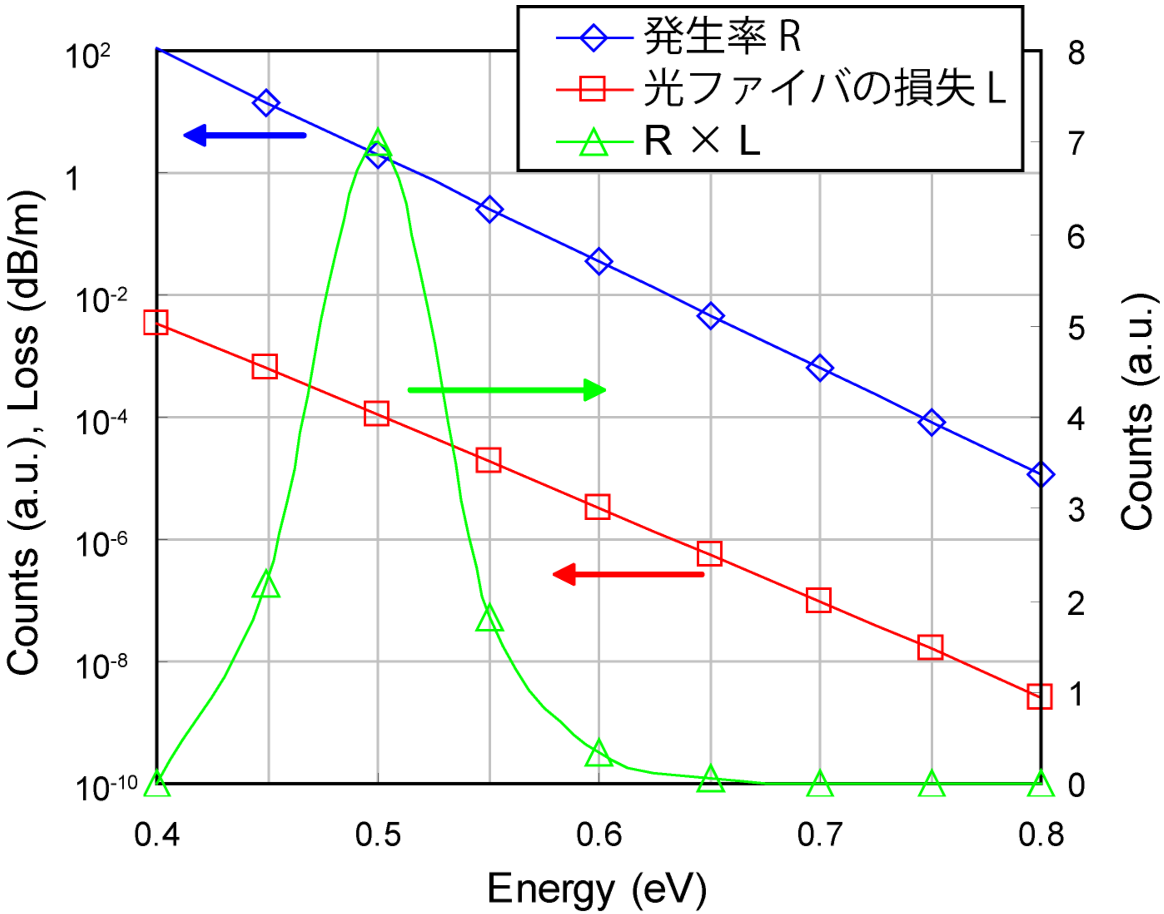
Conclusion

- Our results of TES performances
  - Energy resolution ΔE
    - 0.24 eV(5 μm Ti-TES), 0.16 eV(5 μm Ti/Au-TES)
    - 0.40 eV(10 μm Ti-TES)
  - Detection efficiency η
    - 98%@ 850 nm, >84 %@1550 nm
  - Timing jitter δt
    - <25 ns@(10 μm Ti-TES), 23.5 ns@ (5 μm Ti/Au-TES)
  - Decay time constant τ
    - 100 ns to 460 ns(depending on T_c)
- TES PNRD are demonstrating high performance photon detection capability in various fields.

Thank you for your attention.

d.fukuda@aist.go.jp

Black body derived photons



Plank's law

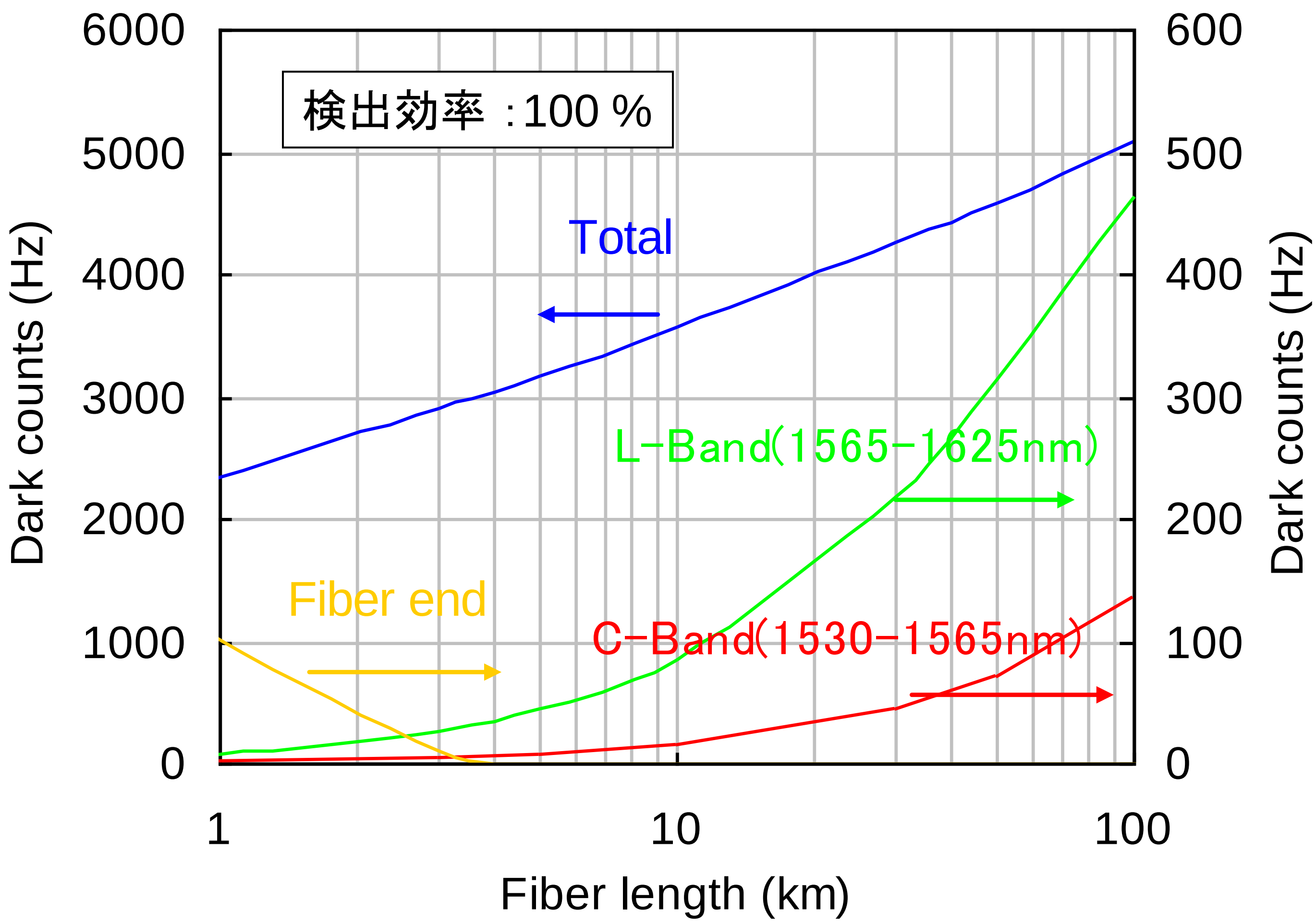
$$n(\varepsilon,T)d\varepsilon = \frac{4\pi\varepsilon^2}{(hc)^2}\frac{d\varepsilon}{e^{\varepsilon/kT}-1}$$

ε: Photon energy
T : Temperature

Transmission loss

- SiO_2 absorption
- Mode mismatch

Dark count dependence on the fiber length



Evaluation of entangled photon source

Background

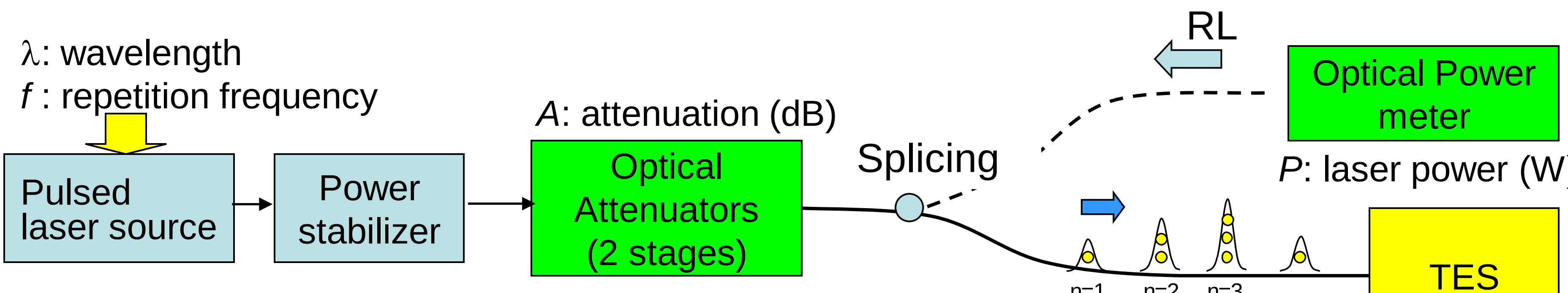
- Quantum entanglement is an essential resource for quantum information and few photon metrology.
- Polarization entangled photon pair generated by Parametric down conversion.

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

- Evaluation of ***Purity*** and ***Fidelity*** is very important.

→ TES technology is applied to the evaluation of entangled photon pairs.

Detection efficiency determination

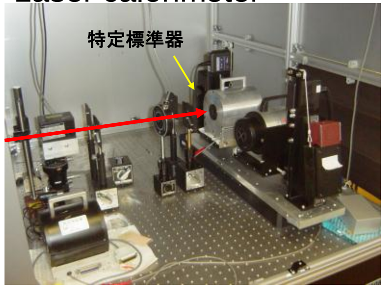


Incident mean photon number

$$\mu_i = \frac{\lambda P_d \times 10^{-A/10}}{fhc(1-\mathrm{RL})}$$

- The "femto W candela" system.
- *A* and *P* should be traceable to "Attenuation" and "power scale", which are equivalent to International Standards, for precise QE measurement.

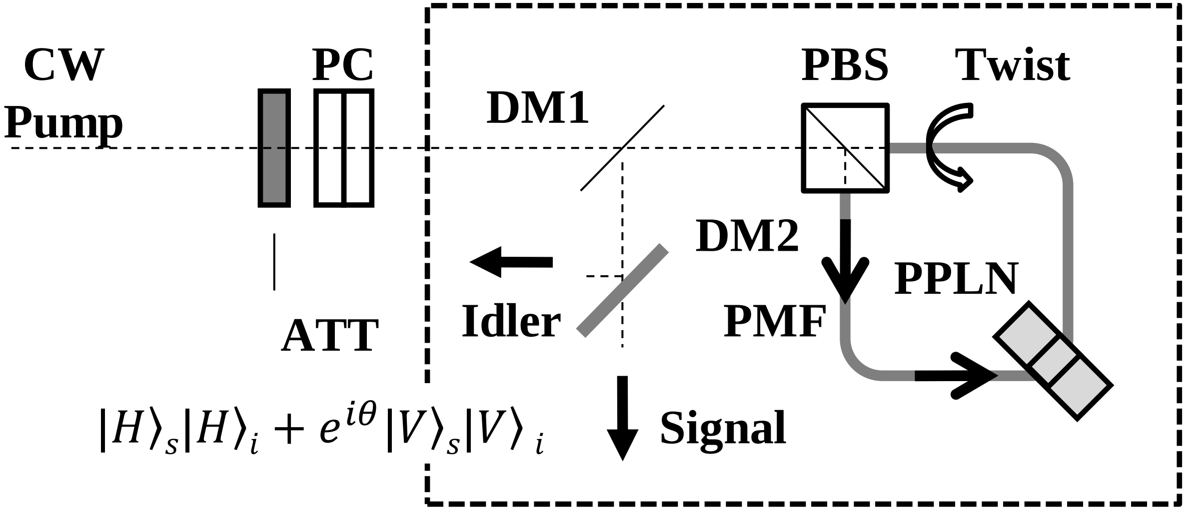
Laser calorimeter



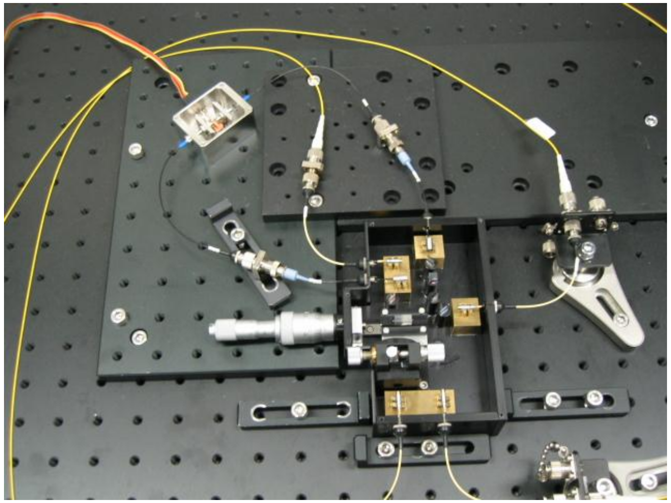
Superimposed attenuation

"Trilateral optical power meter comparison between NIST, NMIJ/AIST, and METAS", Appl. Optics, 46, p643-647, (2007).
APMP.PR-S5(fiber attenuation), APMP.PR-S6(laser power)

Generation of entangled photon pairs



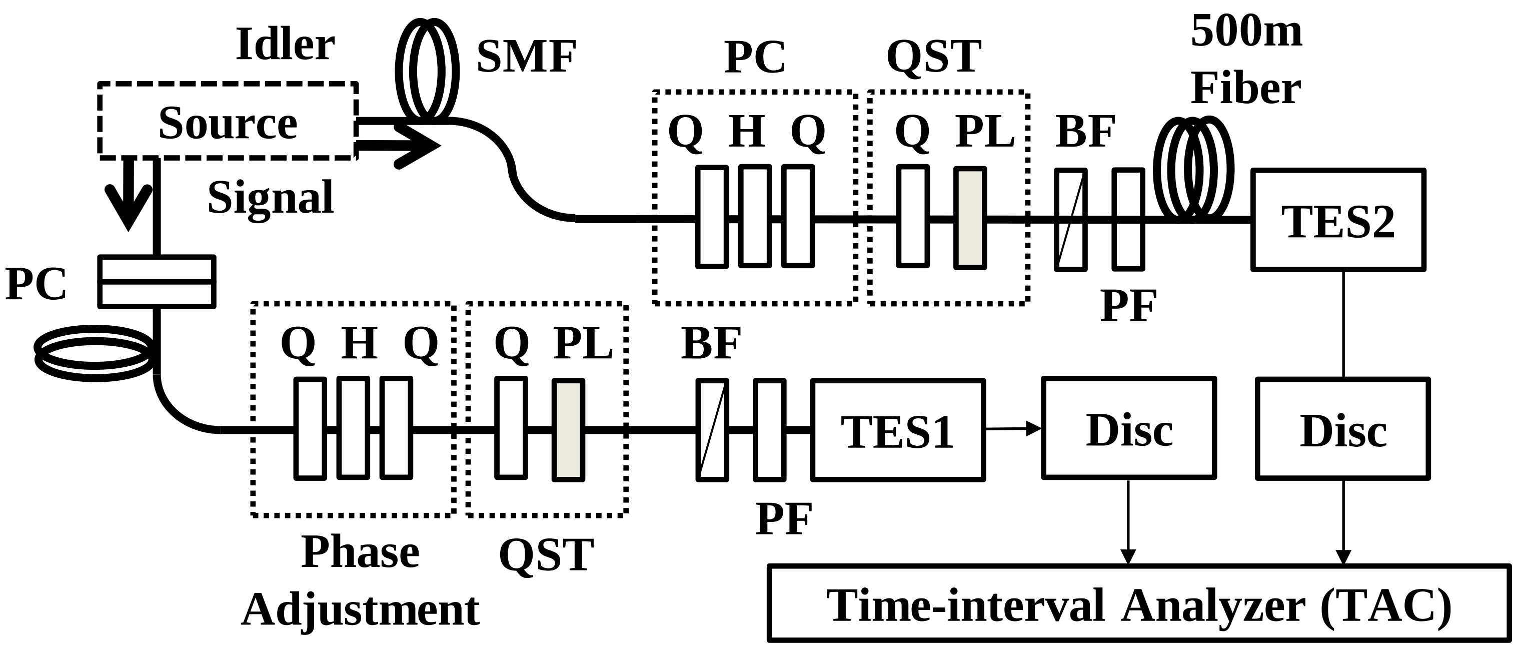
PC: polarization controller, ATT: attenuator, DM1-2: dichroic mirror, PBS: polarization beamsplitter, PPLN: periodically poled lithium niobate waveguide



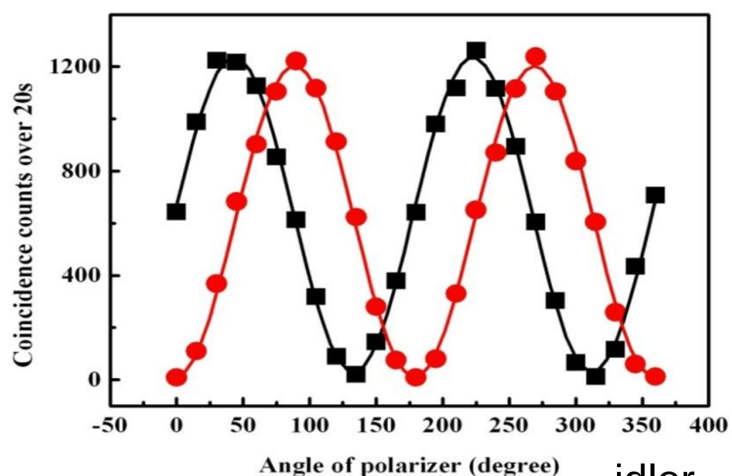
H.C. Lim, A. Yoshizawa et al., *Opt.Express*, **16**, 12460, (2008)

- CW pump tunable laser at 775 nm with 15 mW
- MgO-doped PPLN waveguide with 1 mm long (type 0)
- PMF is twisted by 90 degree in the fiber loop
- Signal and idler photons(~1550 nm) are separated at DM2.

Set up for quantum-state tomography



- Q-tomography is a frequently used method to reconstruct a density matrix.
- Coincident events are counted by two TES.
- The dependence of the coincidence counts on the polarization states of signal and idler photons are evaluated.
- The visibility is > 97.4 % in right figure.

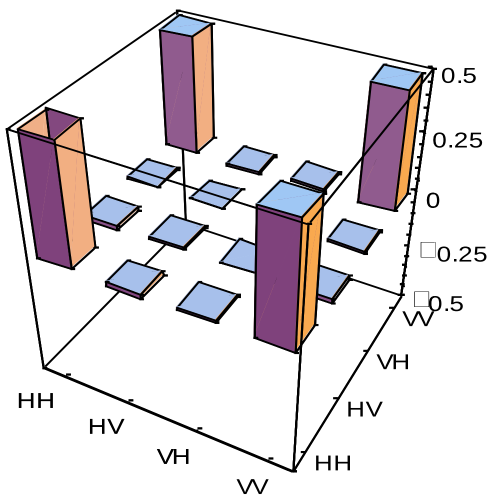


idler

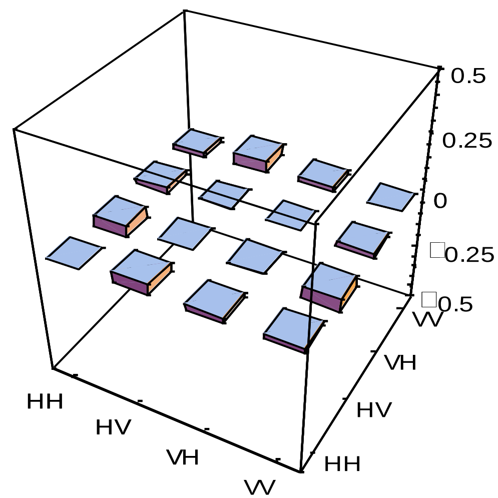
Results of quantum-state tomography

Density matrix ρ obtained by Q-tomography

Real part of ρ



Imaginary part of ρ



Coincident count rate=60 Hz

Purity $=Tr(\eta^2)=$ 98.3%

Fidelity $= \langle\phi|\rho|\phi\rangle$=98.5%

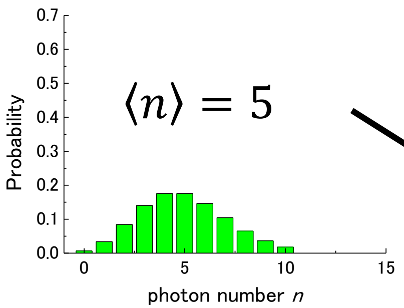
- In this experiment, DE of the TES is reduced to $\eta\sim50$ % because of dark count.
- Nevertheless, 10 times larger coincidence count is obtained compared to that with InGaAs-APD ($\eta\sim15$ %) in the same experimental condition.
- High purity and fidelity > 98 % is successfully achieved.

- The band pass filter will reduce the dark count. Photon number resolving power will enhance fidelity in case of multi-pair-photon generation region (future work).

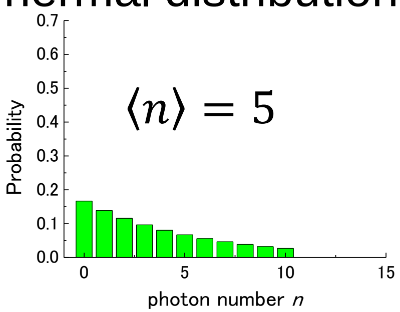
Why so high DE is crucial ?

Incident photon state

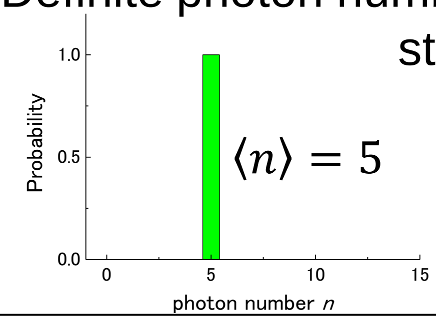
Poisson distribution



Thermal distribution



Definite photon number state



$$\eta = 99.9\ \%$$

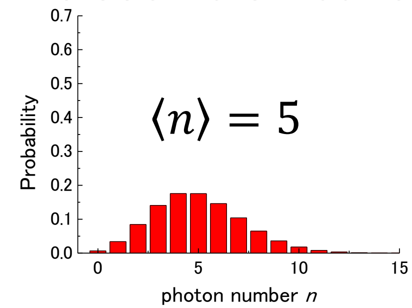
Response function of ideal detector $B(\eta)$
(Bernoullian process)

$$P_{m,\mathrm{det}}(\eta) = \sum_{n=m}^{\infty} {}_{n}\mathrm{C}_{m}\,\eta^{m}(1-\eta)^{n-m} P_{n,\mathrm{inc}},$$

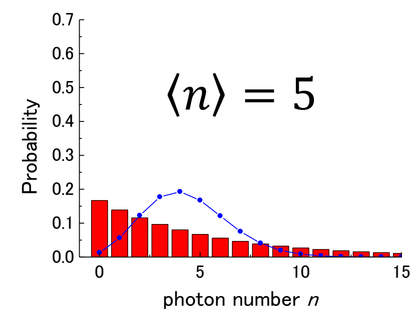
η : DE

Observed photon state

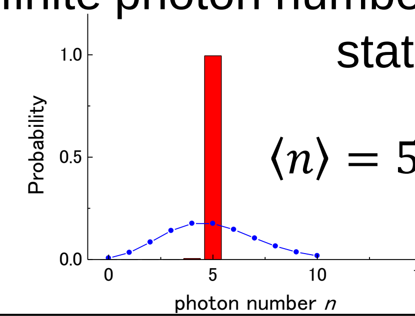
Poisson distribution



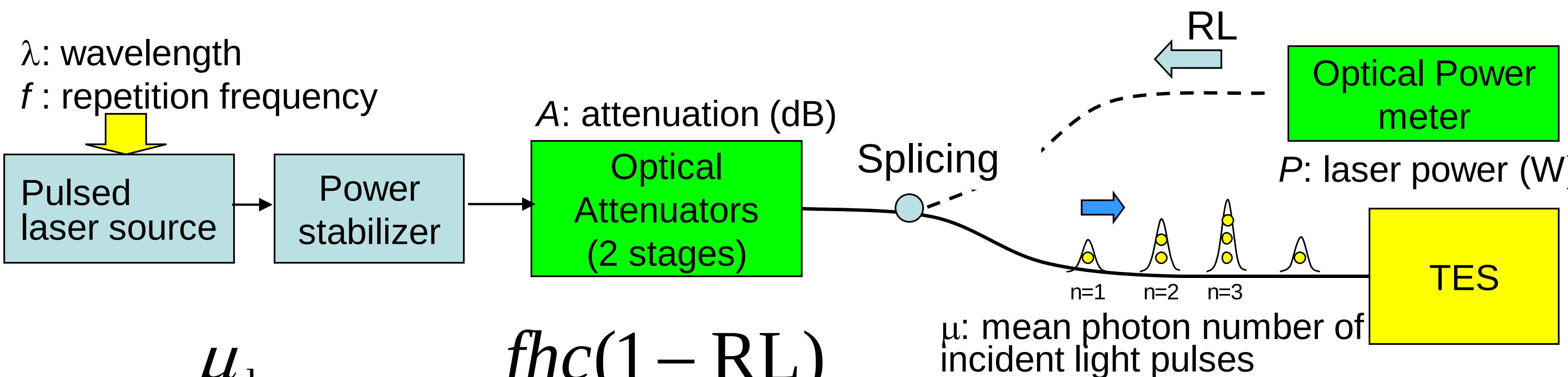
Thermal distribution



Definite photon number state



Detection efficiency determination

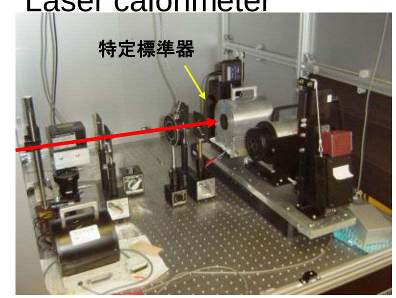


$$\eta = \frac{\mu_\mathrm{d}}{\mu_\mathrm{i}} = \mu_d \times \frac{fhc(1-\mathrm{RL})}{\lambda P_d \times 10^{-A/10}}$$

- The "femto W candela" system.
- *A* and *P* should be traceable to "Attenuation" and "power scale", which are equivalent to International Standards, for precise QE measurement.

"Trilateral optical power meter comparison between NIST, NMIJ/AIST, and METAS", Appl. Optics, 46, p643-647, (2007).
APMP.PR-S5(fiber attenuation), APMP.PR-S6(laser power)

Laser calorimeter

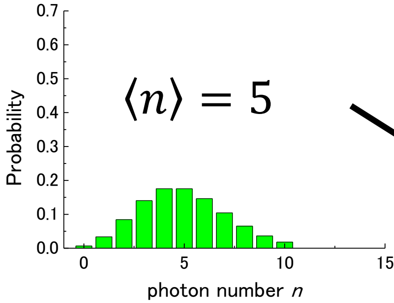


Superimposed attenuation

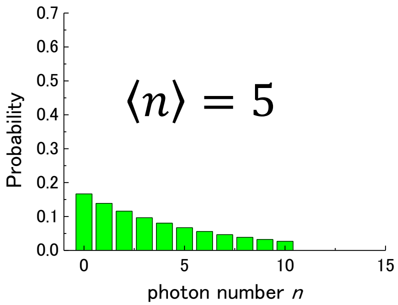
Why so high DE is crucial ?

Incident photon state

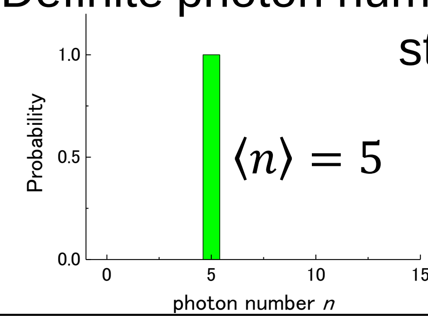
Poisson distribution



Thermal distribution



Definite photon number state



$$\eta = 50\ \%$$

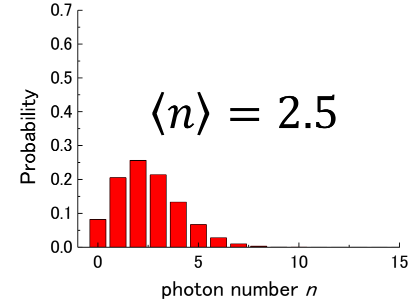
Response function of ideal detector $B(\eta)$
(Bernoullian process)

$$P_{m,\mathrm{det}}(\eta) = \sum_{n=m}^{\infty} {}_n\mathrm{C}_m \eta^m (1-\eta)^{n-m} P_{n,\mathrm{inc}},$$

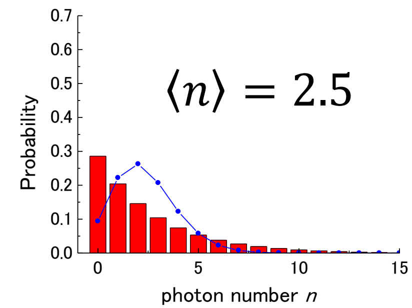
$$\eta : \mathrm{DE}$$

Observed photon state

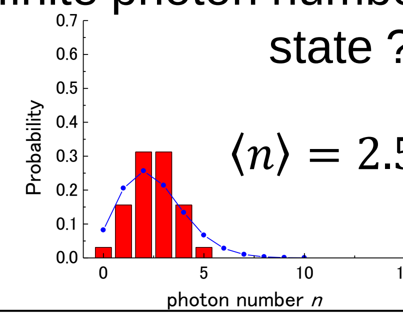
Poisson distribution



Thermal distribution



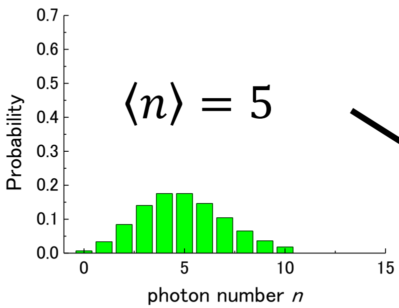
Definite photon number state ?



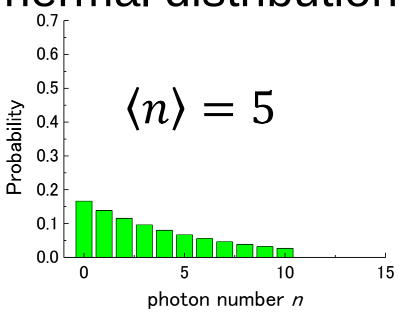
Why so high DE is crucial ?

Incident photon state

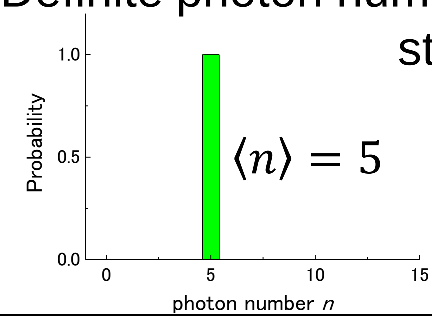
Poisson distribution



Thermal distribution



Definite photon number state



$$\eta = 10\ \%$$

Response function of ideal detector *B*(η)
(Bernoullian process)

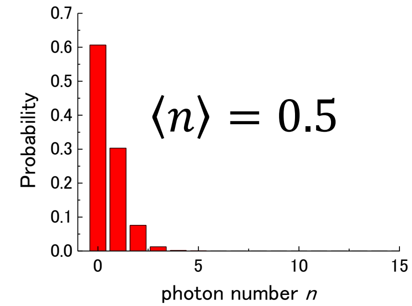
$$P_{m,\mathrm{det}}(\eta) = \sum_{n=m}^{\infty} {}_{n}\mathrm{C}_{m}\, \eta^{m} (1-\eta)^{n-m} P_{n,\mathrm{inc}},$$

$$\eta : \mathrm{DE}$$

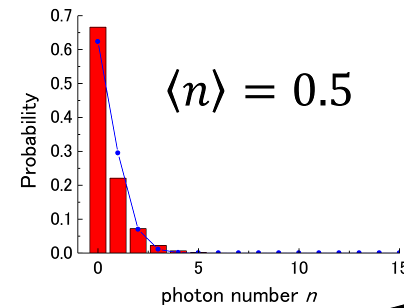
- All incident photon states resulted in Poisson like.
- It is impossible to know exactly the incident photon state for η<<1.

Observed photon state

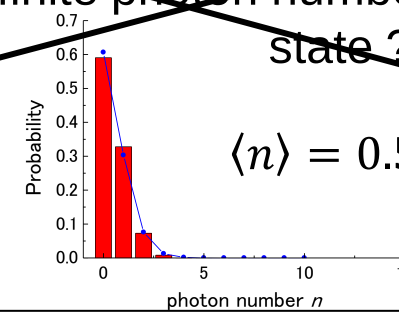
Poisson distribution



Thermal distribution



~~Definite photon number state ?~~



Conclusion

- Ti-TES
  - Energy resolution ΔE
    0.24 eV @ 5 μm × 5 μm size
    0.40 eV @ 10 μm × 10 μm size
  - Detection Efficiency η
    98 %@850 nm, 84 %@1550 nm
  - Decay time τ_{etf}
    100 ns to 460 ns (Depends on T_c)
  - Time jitter
    25 ns, and 18 ns(50 % DE) @ 850 nm

Evaluation of entangled photon source

Background

- Quantum entanglement is an essential resource for quantum information and few photon metrology.
- Polarization entangled photon pair generated by Parametric down conversion.

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

- Evaluation of ***Purity*** and ***Fidelity*** is very important.

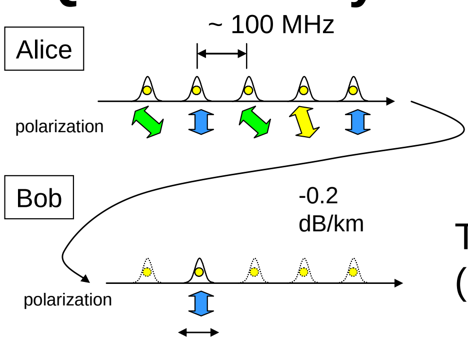
Advantages of TES

- High DE improves the provability of coincident counts.
- Low dark count reduced accidental coincident counts.
- Possibility to discriminate multi photon generation events.

Expectations to superconducting sensors in quantum information(QI)

- In QI, people need to full-control photons; photon numbers, phase, polarization, time of photon creation.
- People desire perfectly ideal photon detectors.

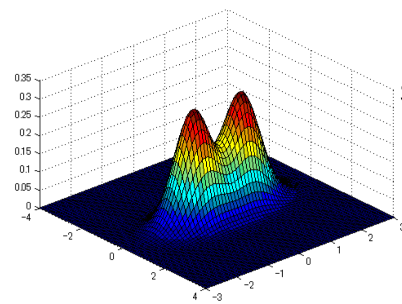
Quantum key distribution(QKD)



Highly secure telecommunication

Takesue, Nature Photonics (2007)

Quantum circuit(quantum gate)

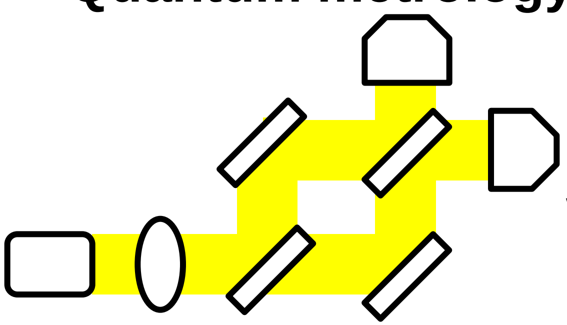


Non Gaussian distribution by photon subtraction from squeezed light

Namekata, Nature Photonics (2010)

Gerrits, PRA (2010)

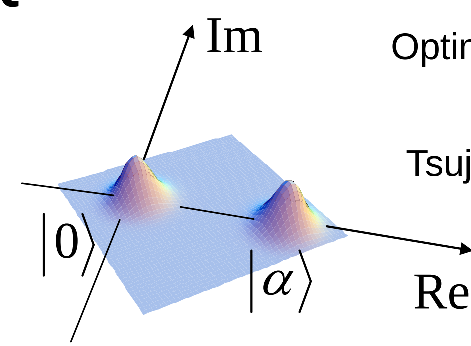
Quantum metrology



Mach-Zehnder interferometer

Phase determination with quantum limit

Quantum telecommunication



Optimal quantum receiver

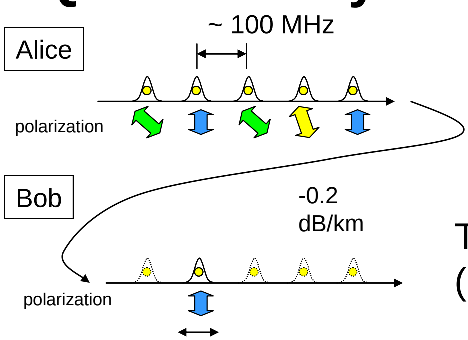
Tsujino, Opt. Express (2010)

Quantum photolithography, quantum imaging, quantum candera, and so many!

What can TES do ?

- In QI, people need to full-control photons; photon numbers, phase, polarization, time of photon creation.
- People desire perfectly ideal photon detectors.

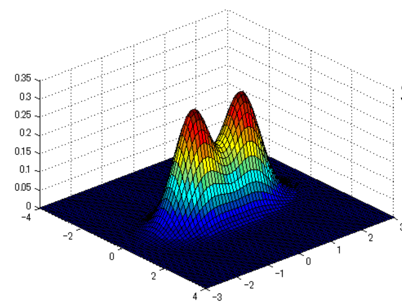
Quantum key distribution(QKD)



Highly secure telecommunication

Takesue, Nature Photonics (2007)

Quantum circuit(quantum gate)

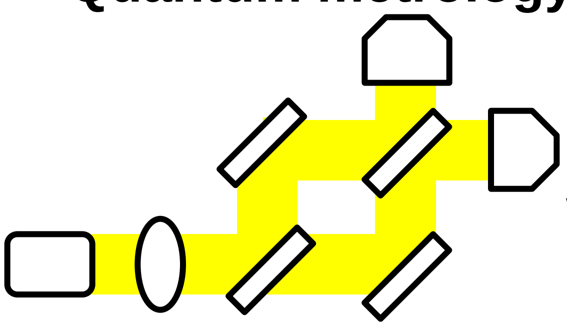


Non Gaussian distribution by photon subtraction from squeezed light

Namekata, Nature Photonics (2010)

Gerrits, PRA (2010)

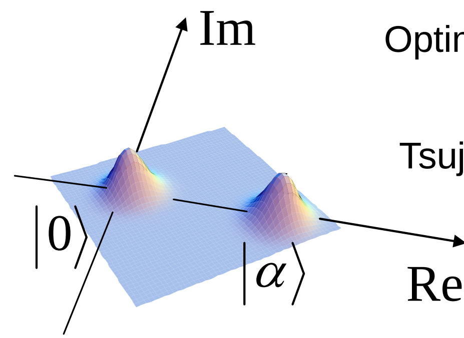
Quantum metrology



Mach-Zehnder interferometer

Phase determination with quantum limit

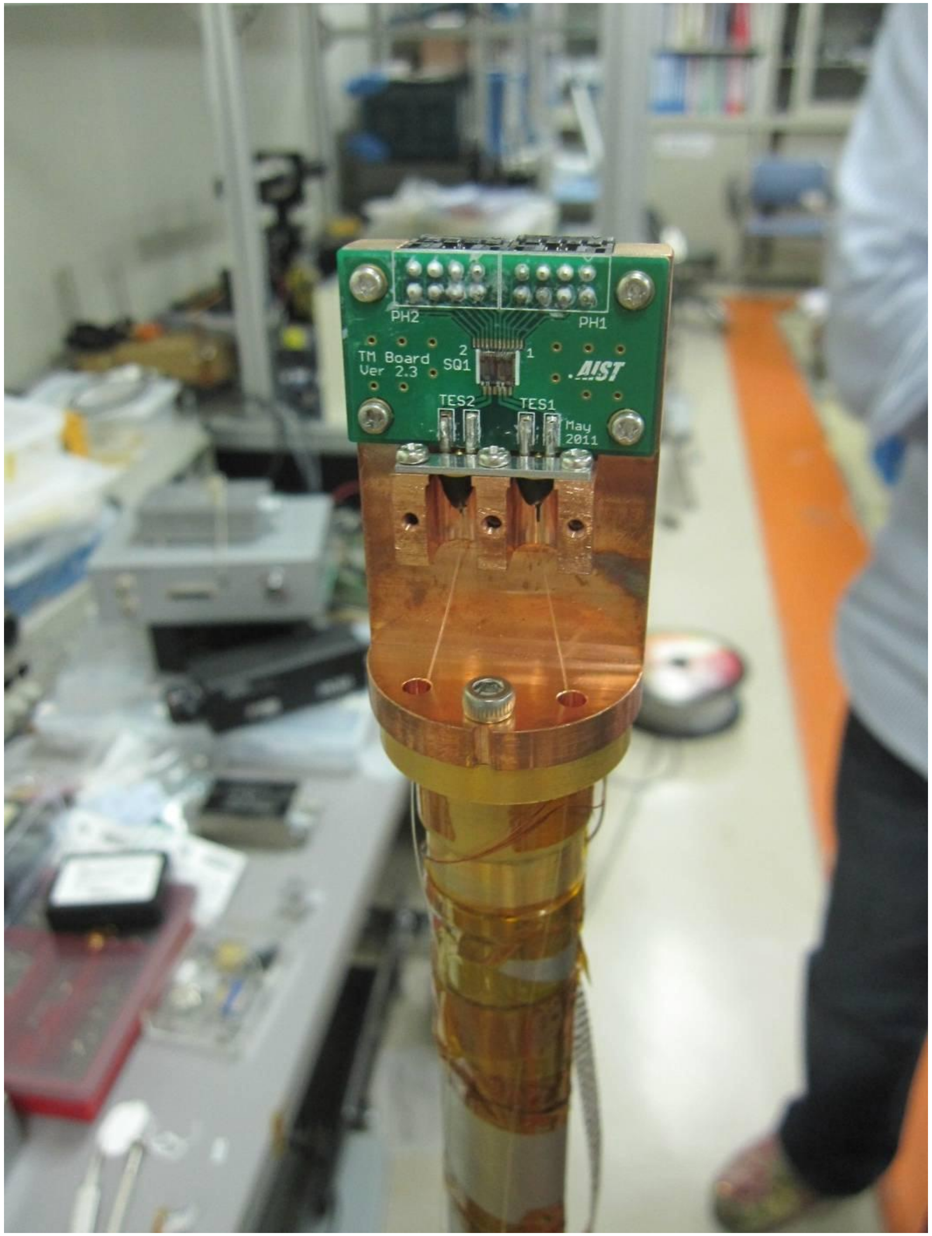
Quantum telecommunication



Optimal quantum receiver

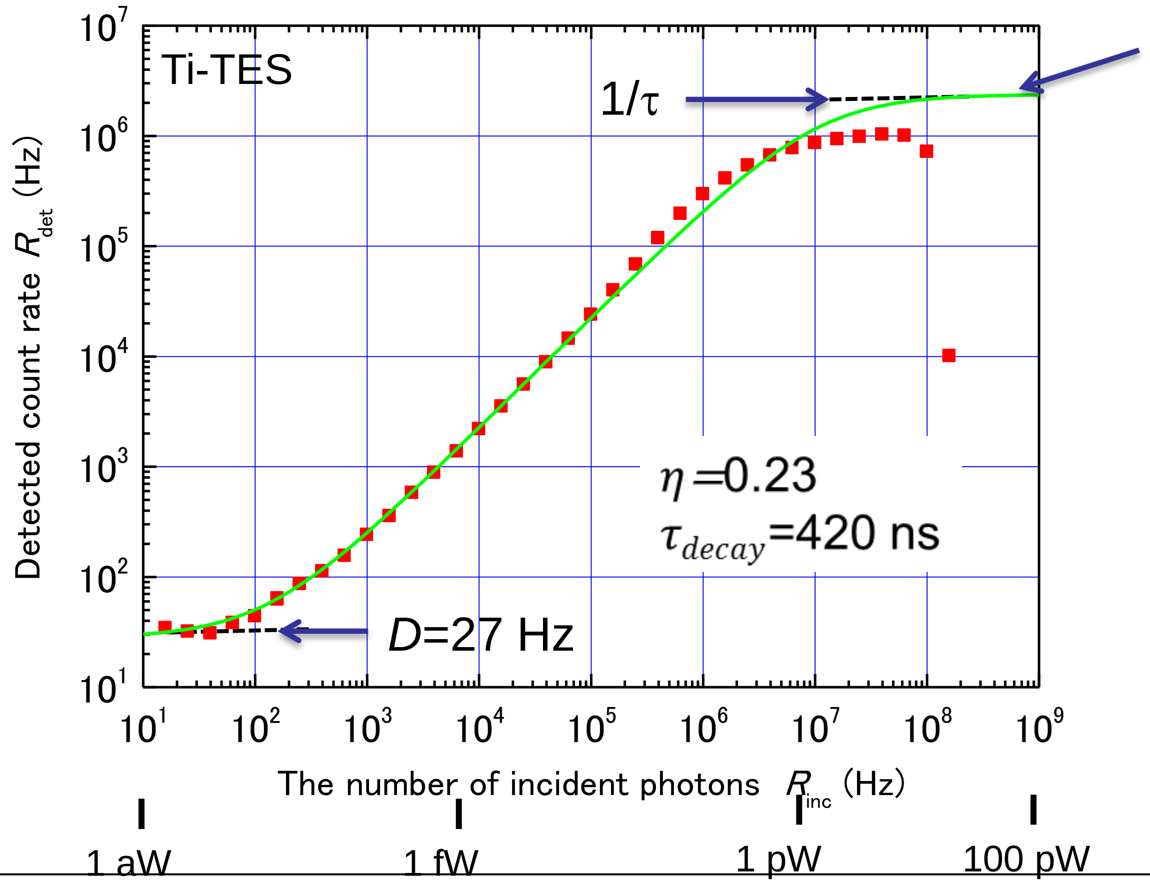
Tsujino, Opt. Express (2010)

Quantum photolithography, quantum imaging, quantum candera, and so many!


PH2
PH1
TM Board
Ver 2.3
2
SQ1
1
AIST
TES2
TES1
May
2011

Maximum count rate

- Count rate measurement to continuous wave (CW) laser.
- Incident rate of the photon number per second : R_{inc}
  $R_{inc}=P\lambda/hc$;
  P is the incident power, and λ is the wavelength.



$$R_{det} = \frac{\eta R_{inc} + \frac{D}{1-D\tau}}{1+\tau\left(\eta R_{inc} + \frac{D}{1-D\tau}\right)}$$

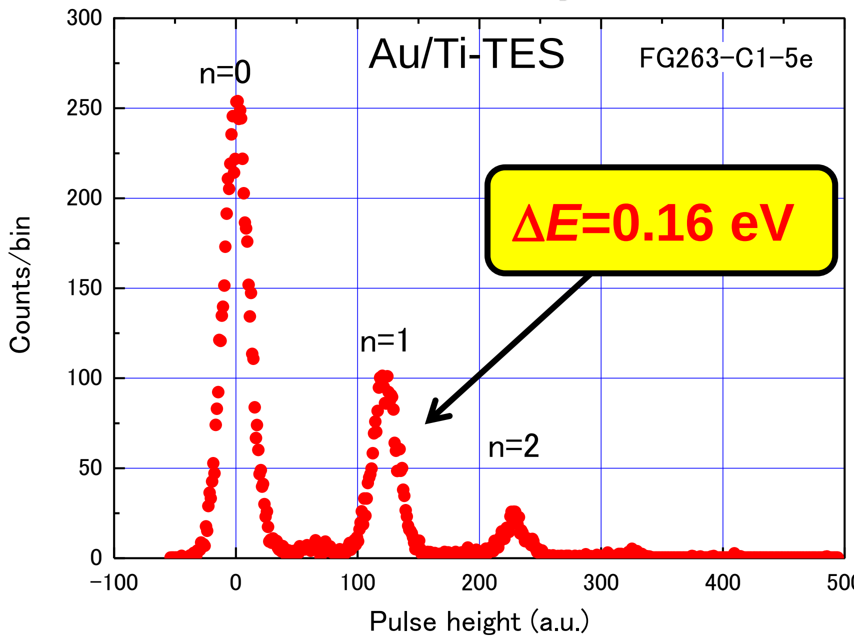
D : dark count (Hz)
τ : dead time (s)

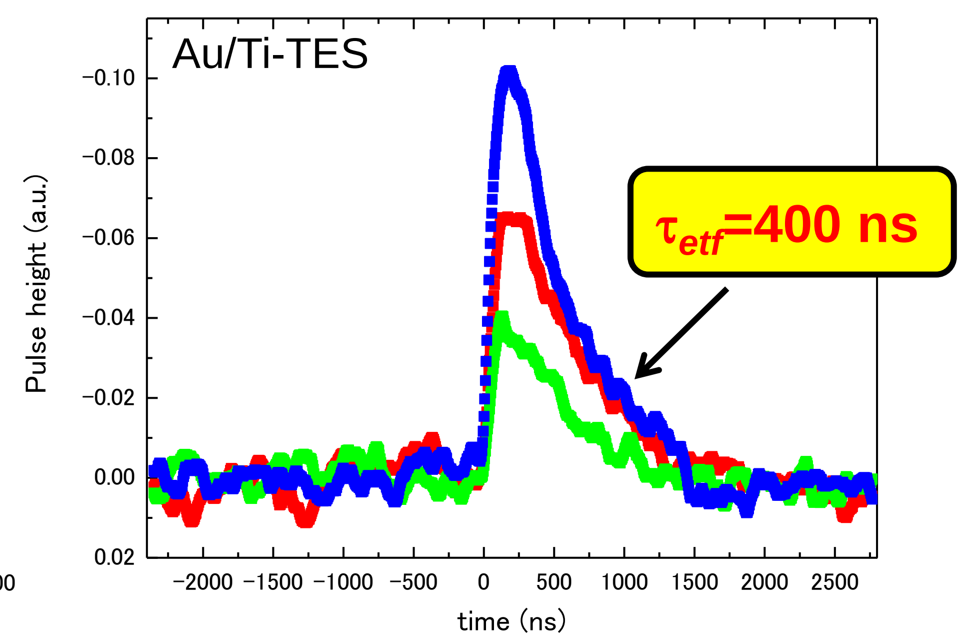
Thin gold covered Ti-TES at AIST

- Au(10 nm)/Ti(26 nm)-TES
  - Energy resolution ΔE: 0.16 eV @ 5 μm × 5 μm size
  - Detection Efficiency η: 84 %@1550 nm
  - Decay time τ_{etf} : 400 ns @ T_c 320 mK
  - Jitter : 23 ns @ 1550 nm

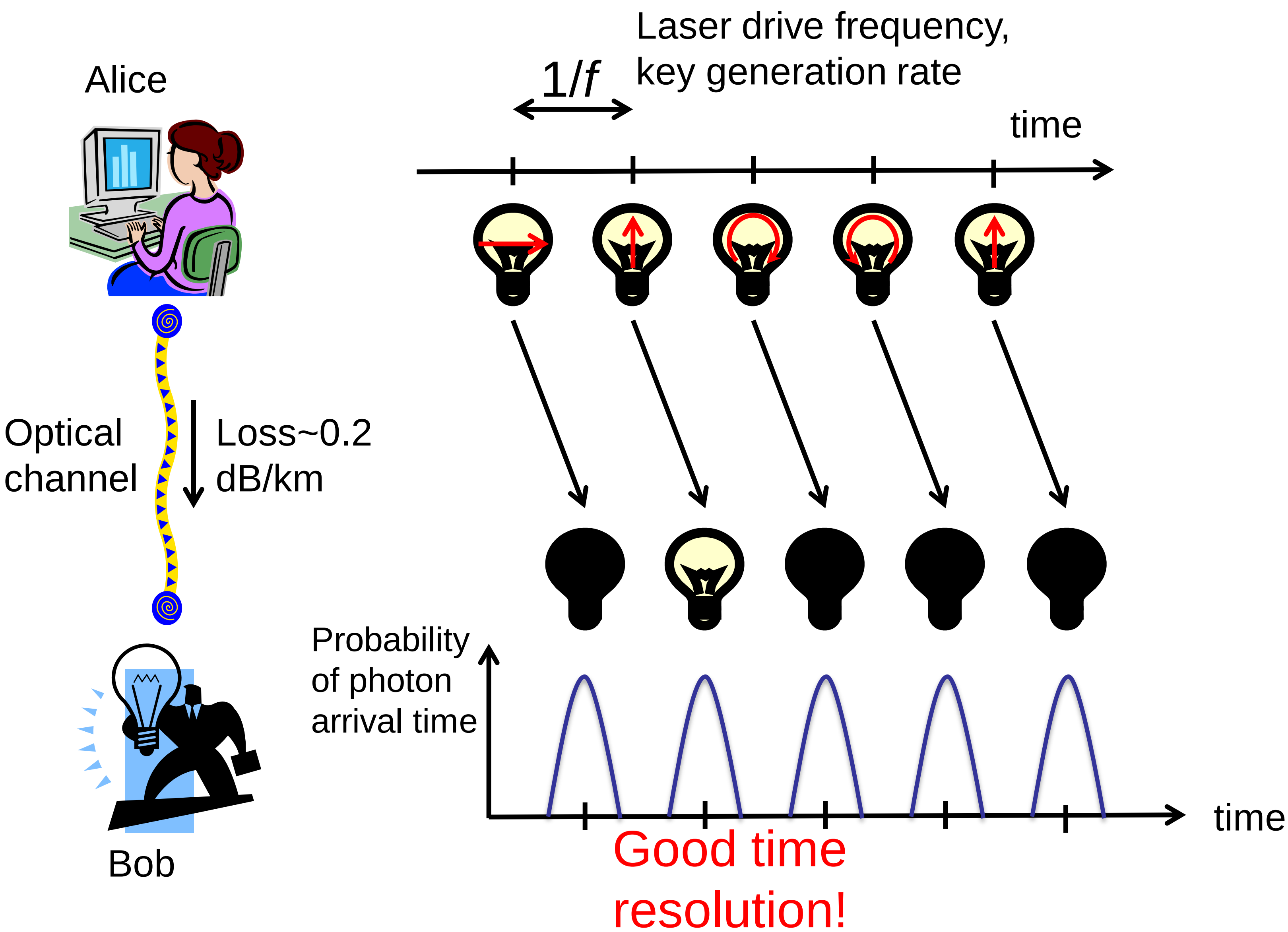
R_n 10.3 Ω(Ti)

R_n 2.4 Ω(Au/Ti)

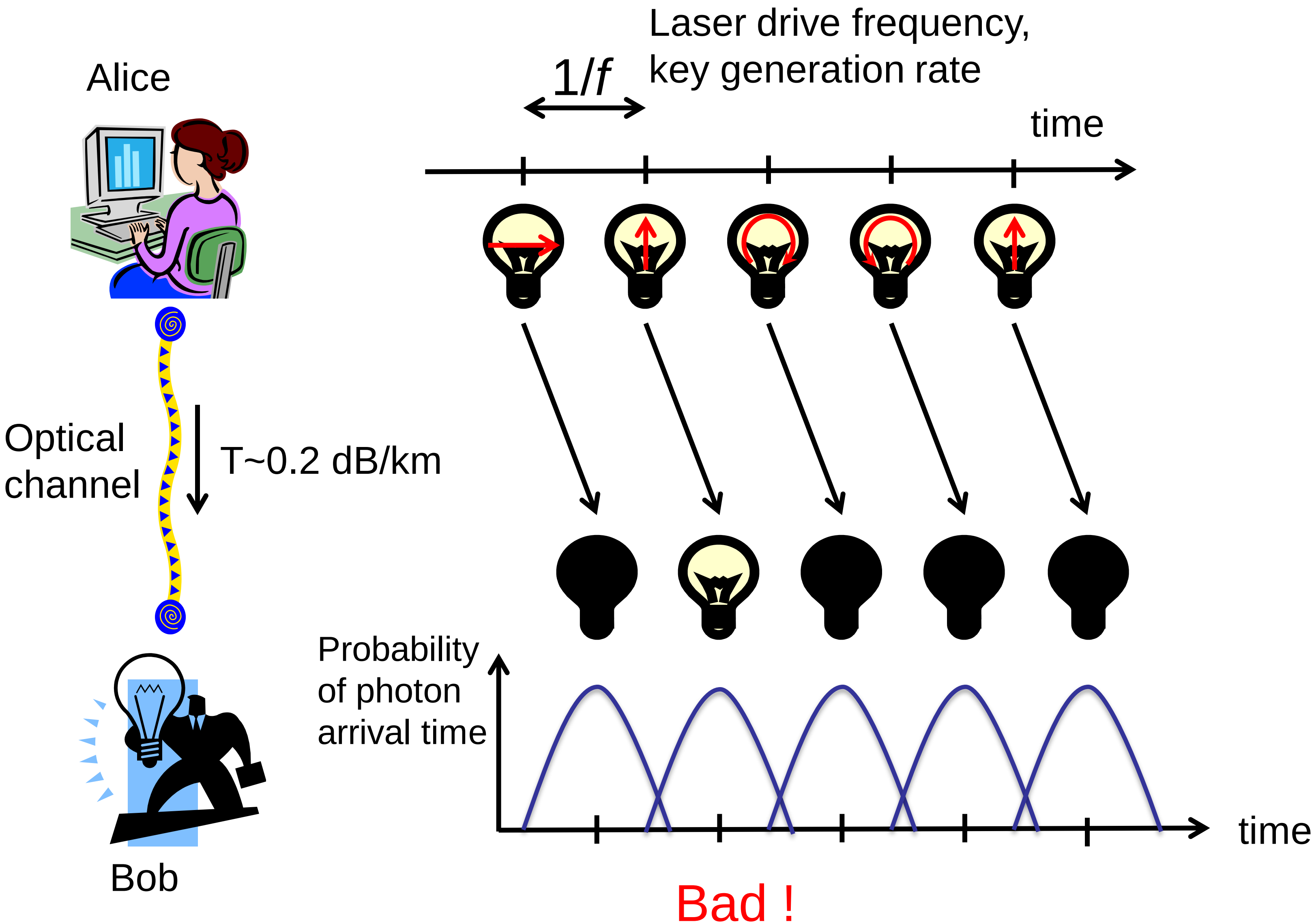




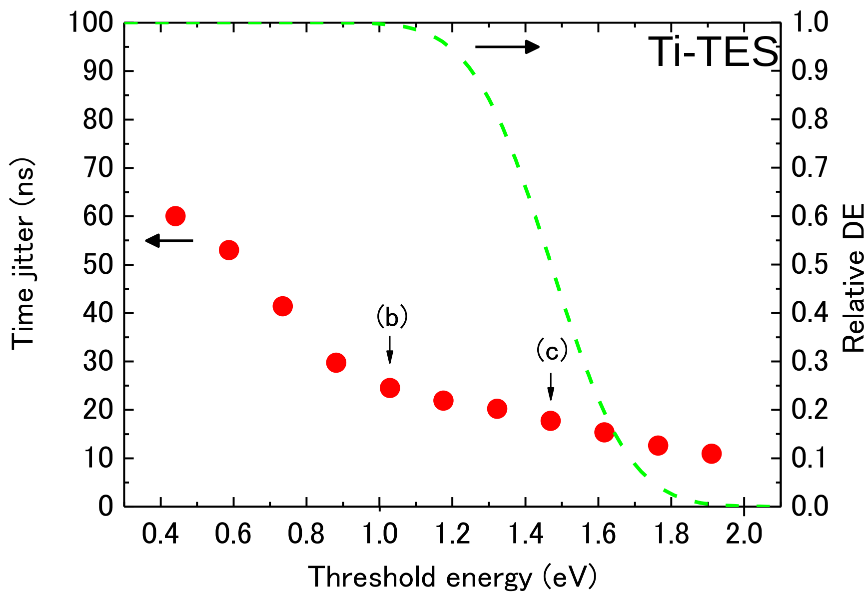
Time jitter

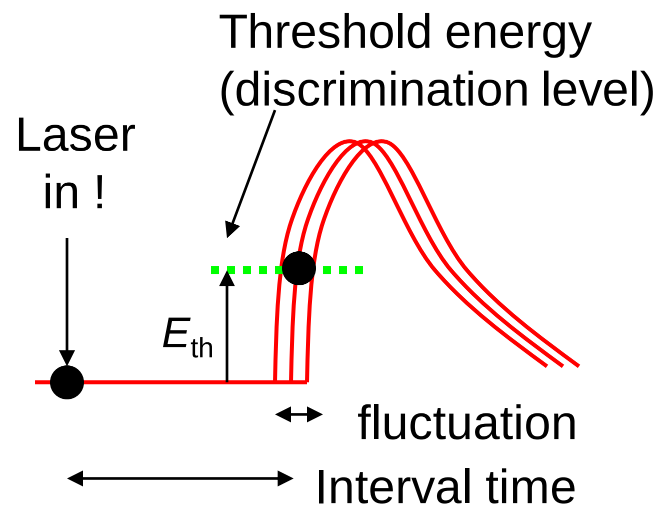

Laser drive frequency,
key generation rate
1/f
time
Alice
Optical
channel
Loss~0.2
dB/km
Bob
Probability
of photon
arrival time
time
Good time
resolution!

Time jitter

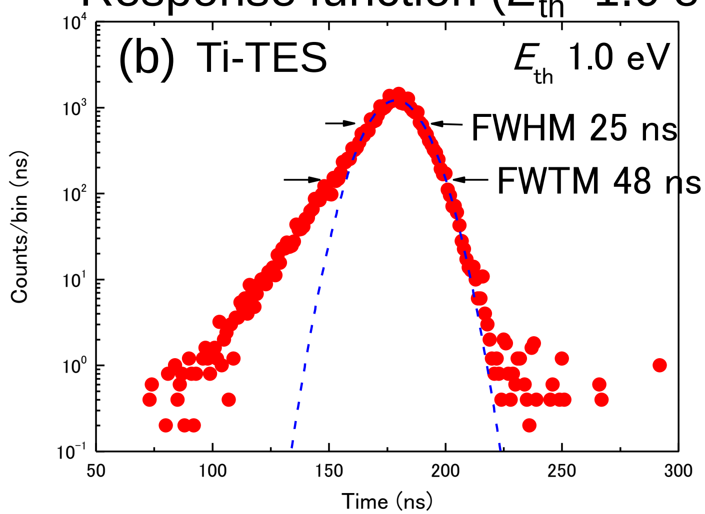

Alice
Laser drive frequency,
key generation rate
1/f
time
Optical
channel
T~0.2 dB/km
Probability
of photon
arrival time
time
Bob
Bad !

Time jitter measurement

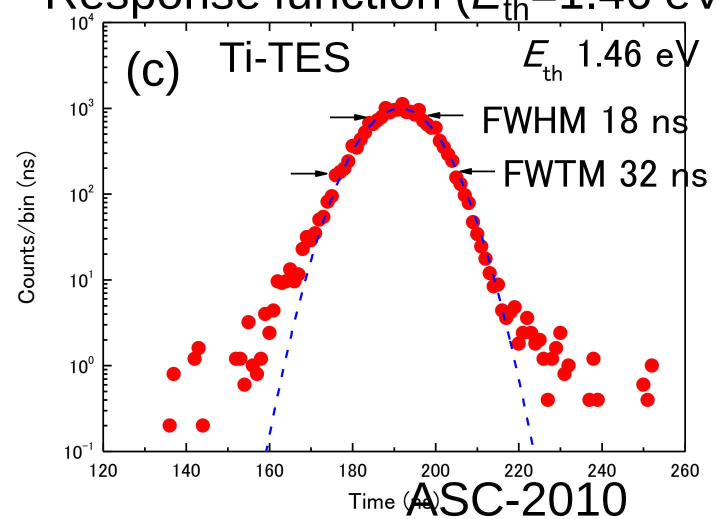




Response function (E_{th}=1.0 eV)



Response function (E_{th}=1.46 eV)

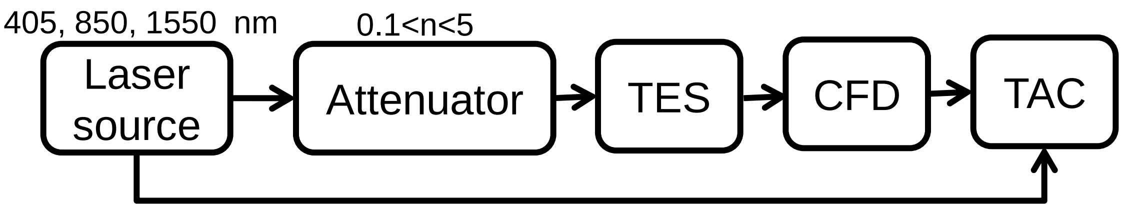


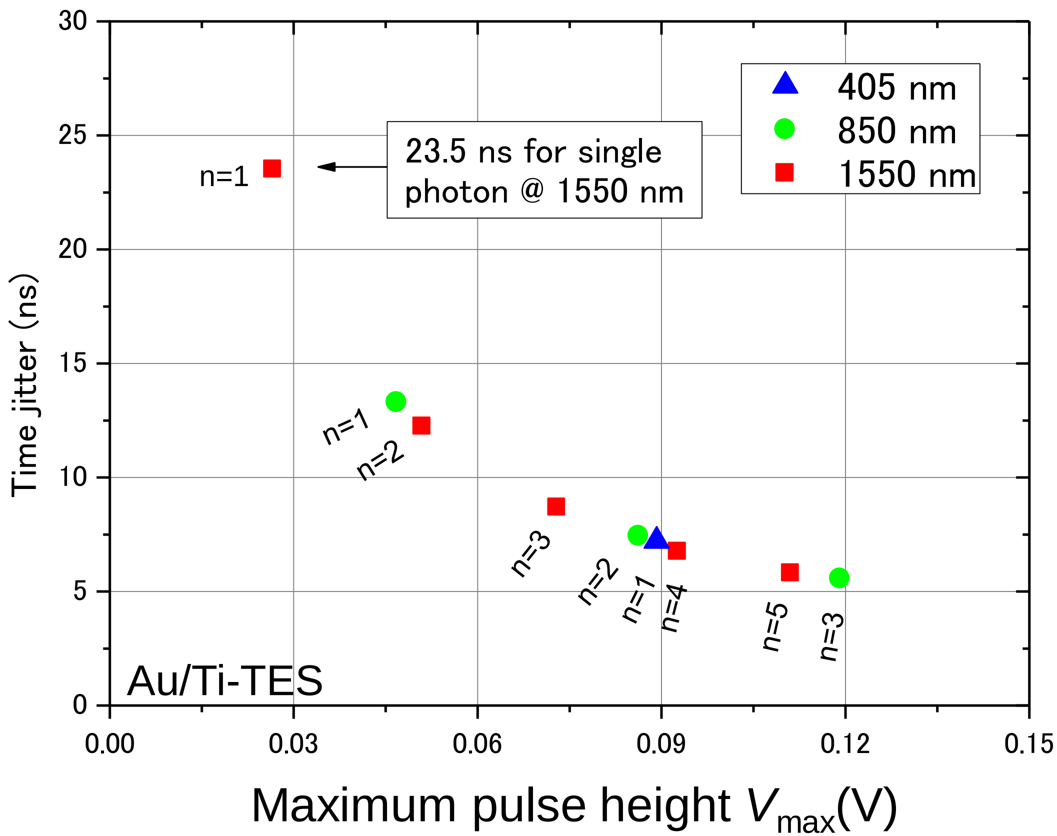
ASC-2010

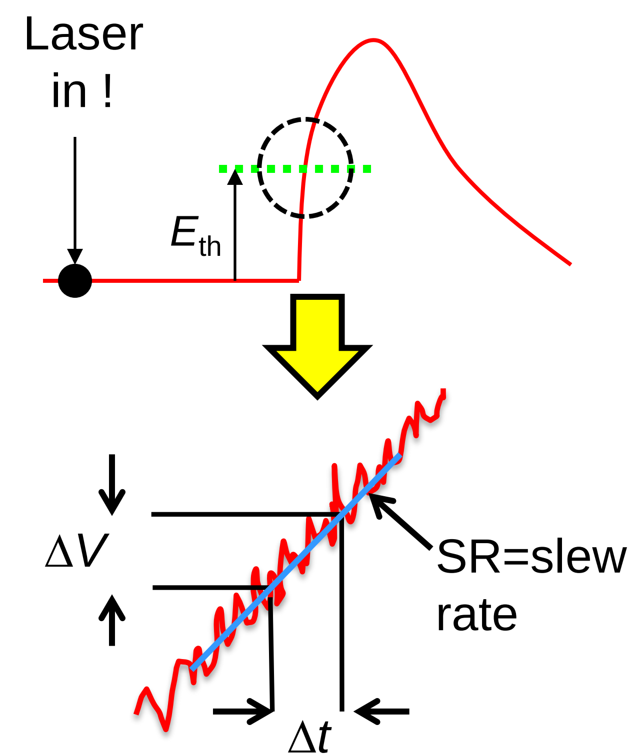
D.Fukuda, IEEE AS(2011)

Dependence on incident energy

Jitter measurement results by CFD for pulsed laser



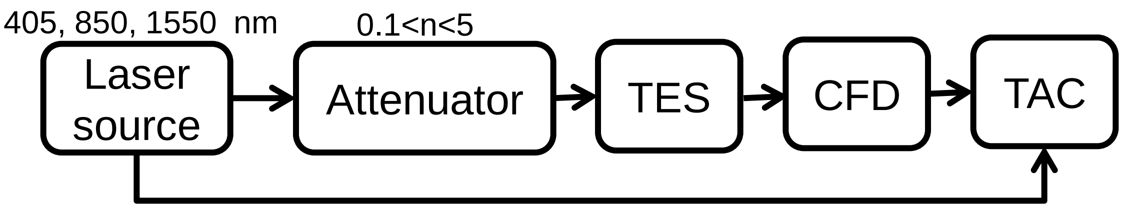


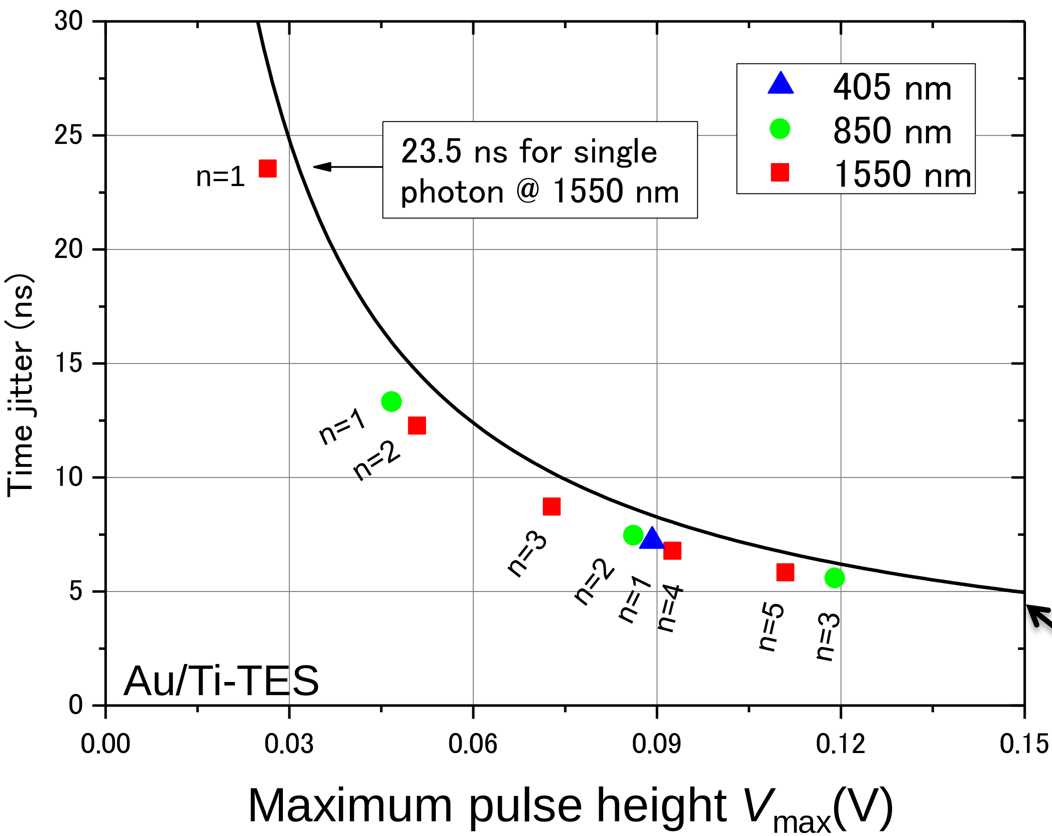


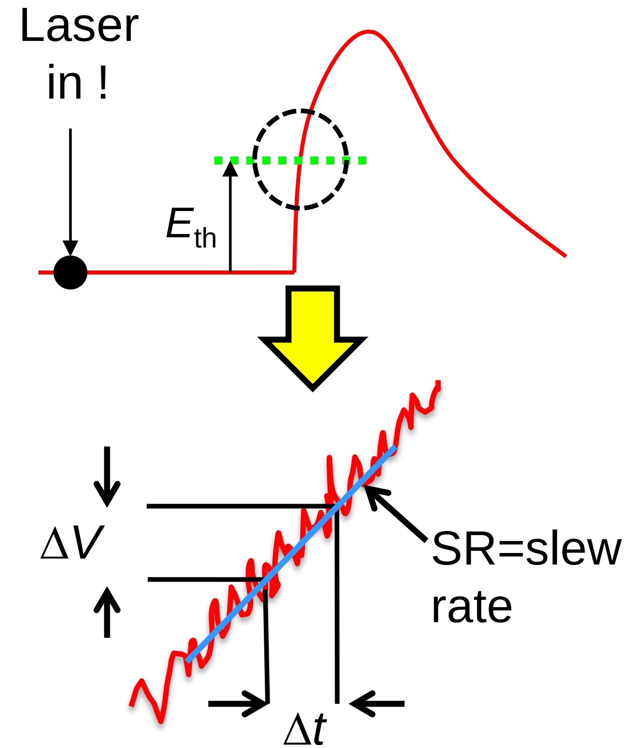
$$\Delta t = \frac{\Delta V}{SR} \propto \frac{1}{V_{max}}$$

Dependence on incident energy

Jitter measurement results by CFD for pulsed laser







$$\Delta t = \frac{\Delta V}{SR} \propto \frac{1}{V_{max}}$$

$$\Delta t = \frac{\sqrt{V(V_{max})V^2{}_1}}{SR(1-f)} \frac{\Delta E}{E} \frac{1}{V_{max}}$$

Dark count

- What causes the dark count ?

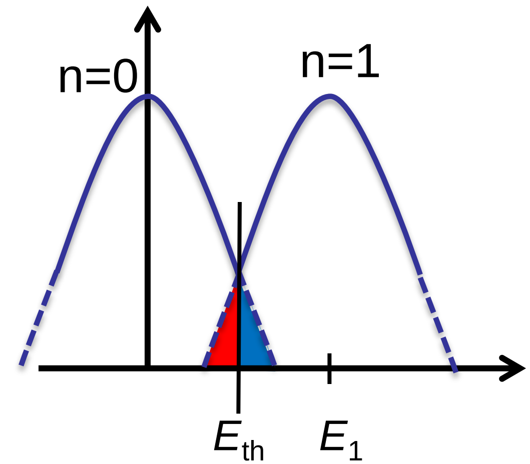
1. Error counts derived from the insufficient ΔE
   - Overlap of the vacuum and single photon state
   - Two problems are caused.

     ① Dark count probability

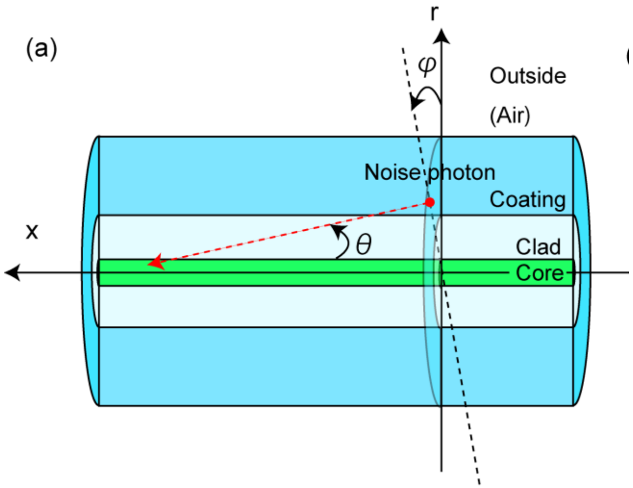
     $$p_{dark}(E_{th}) = \frac{1}{2}\left\{1 - \mathrm{erf}\left(\frac{E_{th}}{\sqrt{2\pi}\sigma}\right)\right\}$$

     ② Loss of single photon counts

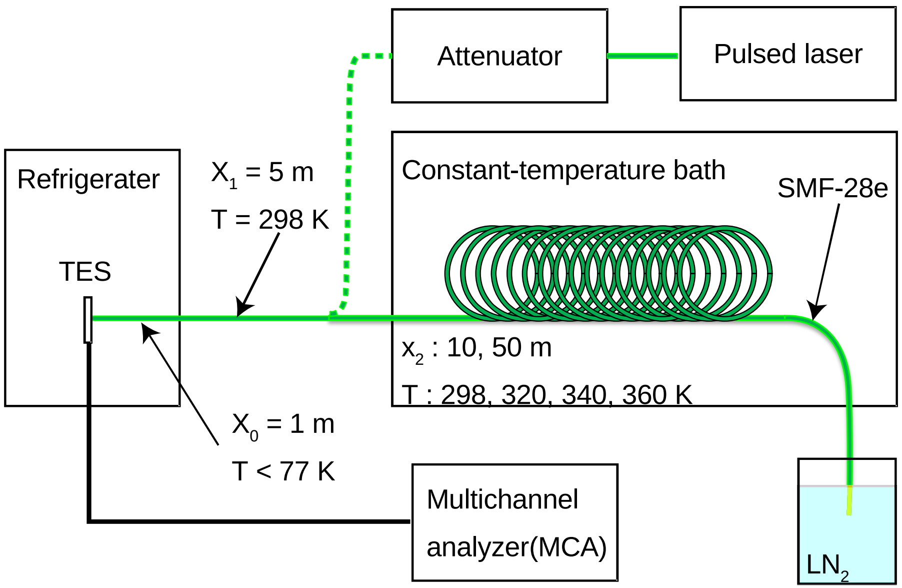
     $$p_{loss}(E_{th}) = \frac{1}{2}\left\{1 + \mathrm{erf}\left(\frac{E_{th} - E_1}{\sqrt{2\pi}\sigma}\right)\right\}$$

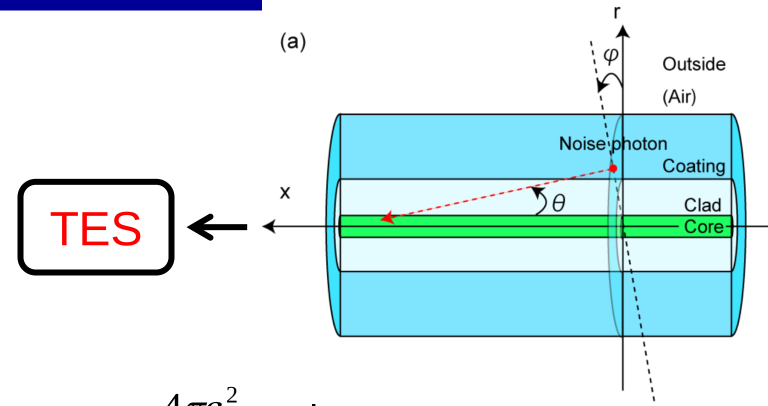


2. Black body radiation
   - Probably dominant for 1550 nm TES
   - BB photons at fiber end (A.J. Miller and et al., Proc. 8th QCMC, pp. 445)
   - BB photons comes from the optical fiber.



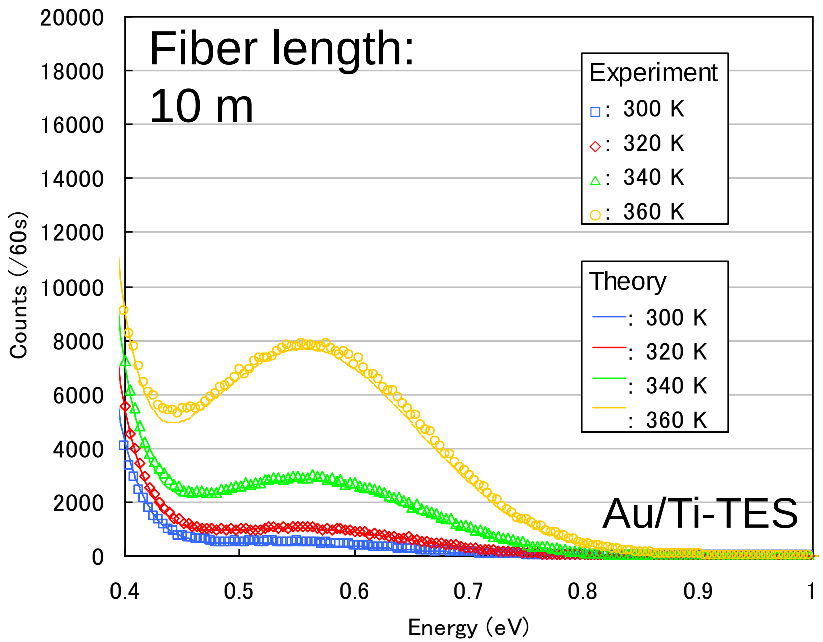
Thu-186, presented by Fujii-kun.

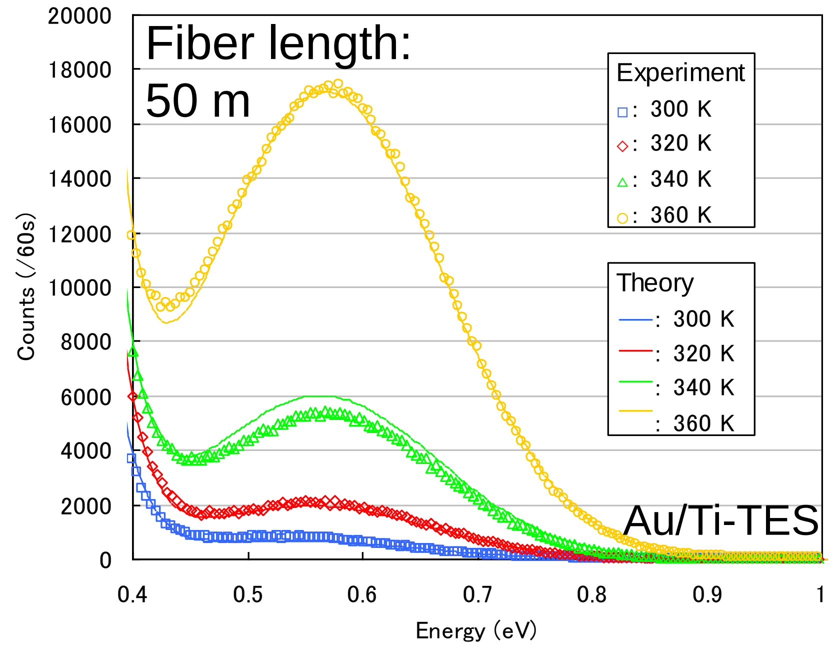




$$n(\varepsilon,T)=\frac{4\pi\varepsilon^2}{(hc)^2}\frac{1}{e^{\varepsilon/kT}-1}$$

$$N(T,x)=2\int_0^x dx'\int_0^r dr'\int_0^{2\pi} d\varphi\int_0^{\infty} d\varepsilon\, n(\varepsilon,T)L(\varepsilon)C(r)$$



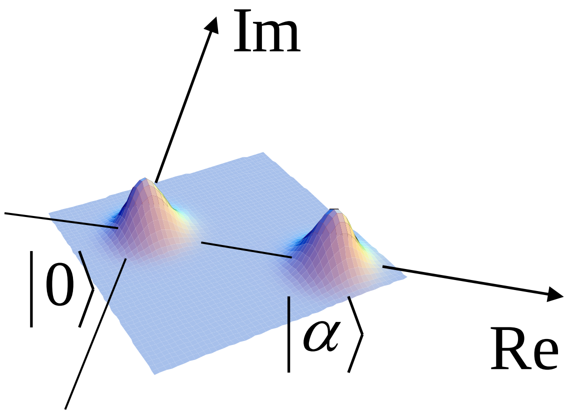


Application of optical TES to QI

- Quantum receiver(QR)
  - Large capacity communication with much low power
  - Reduce the number of repeaters in long-distance fiber network
  - Deep space telecommunication, satellite-ground link are possible.

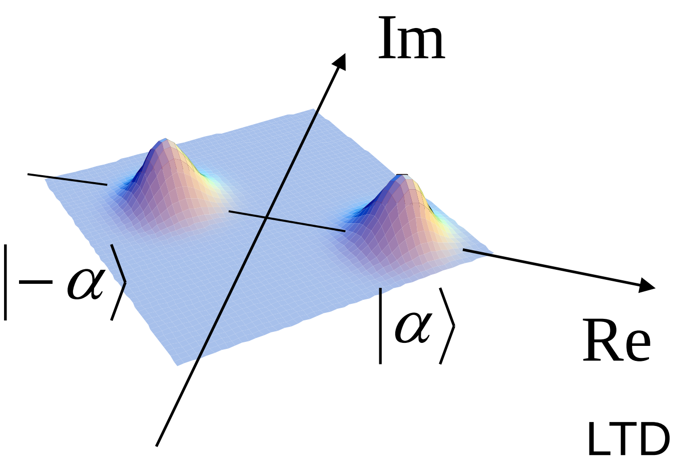
- Type of QR

ON/OFF key



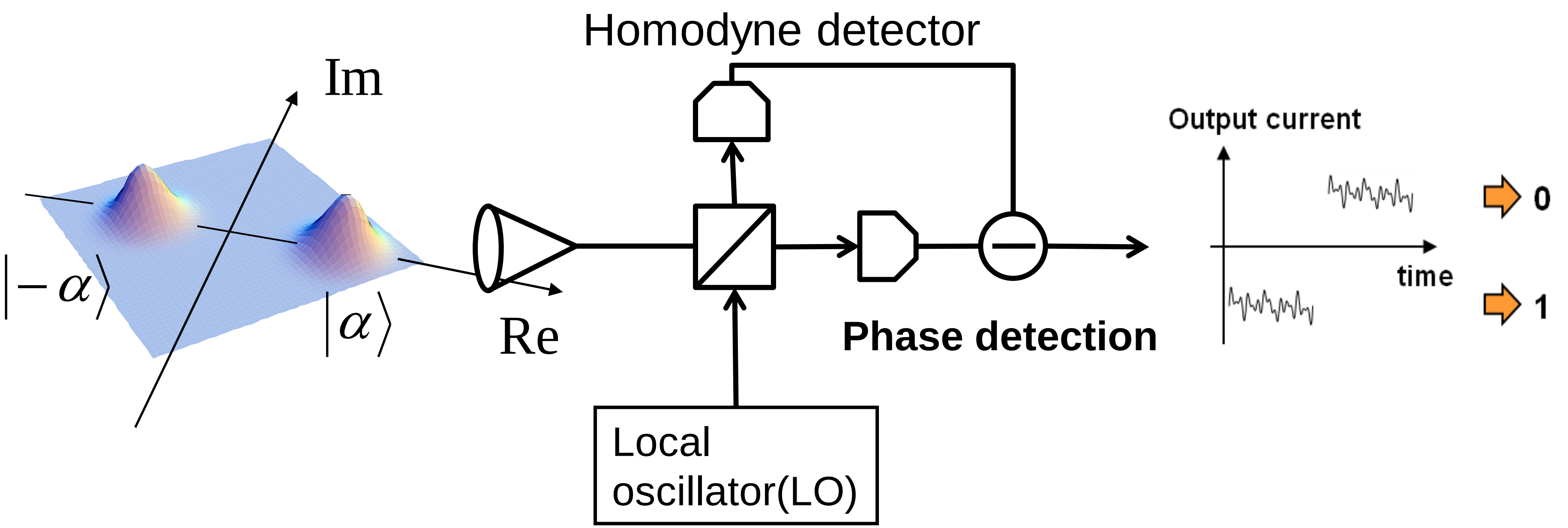
LTD-13

Binary phase shifted key(BPSK)



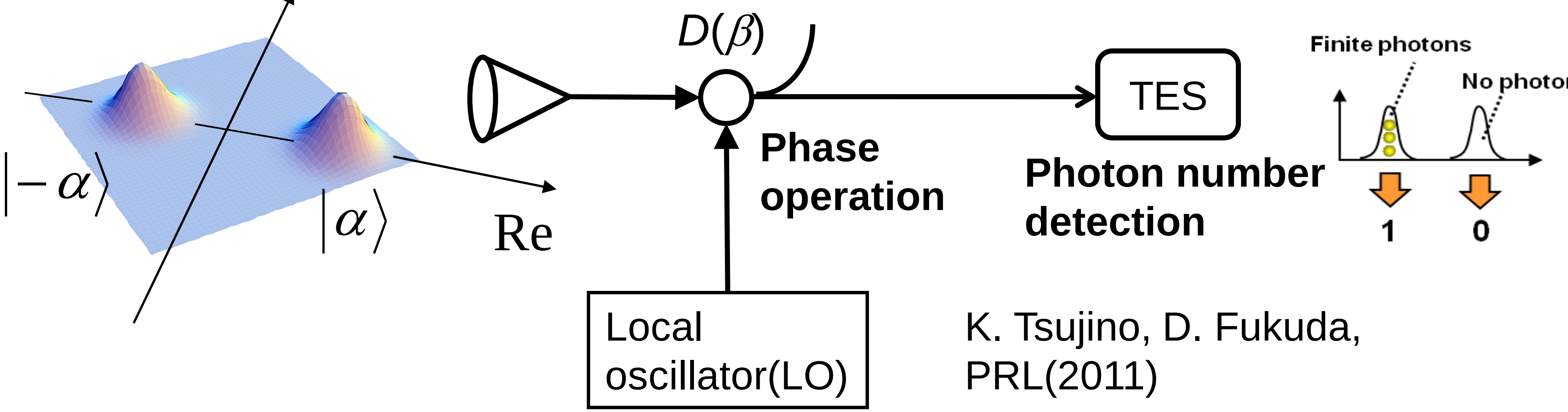
LTD-14

Realization of QR with TES



- What we want do; to establish the minimum bit error rate(BER) with the incident coherent state $|\alpha|^2<1$
- Standard method; to use homodyne detector (phase sensitive detector, and “God” detector) ➡ Standard quantum limit(SQL)

Realization of QR with TES

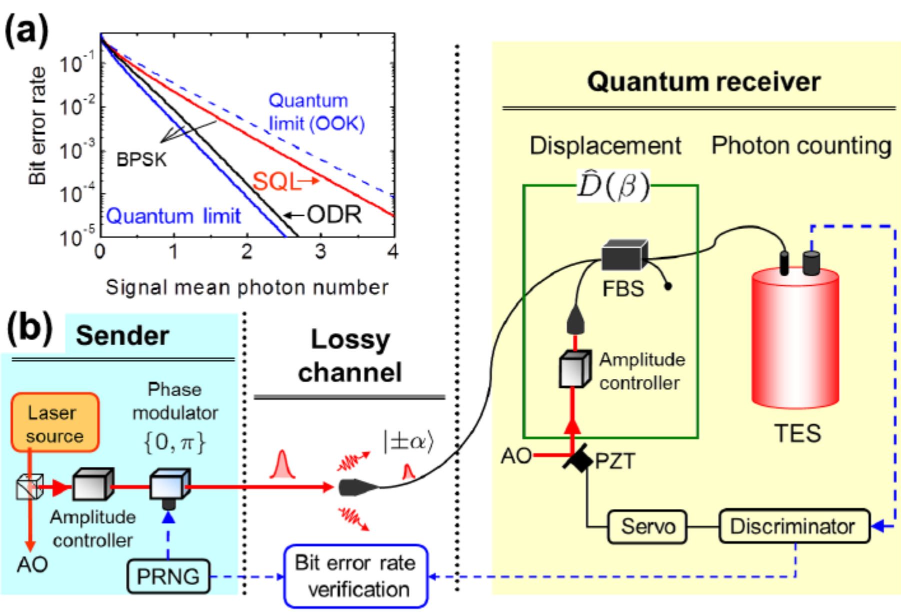


K. Tsujino, D. Fukuda, PRL(2011)

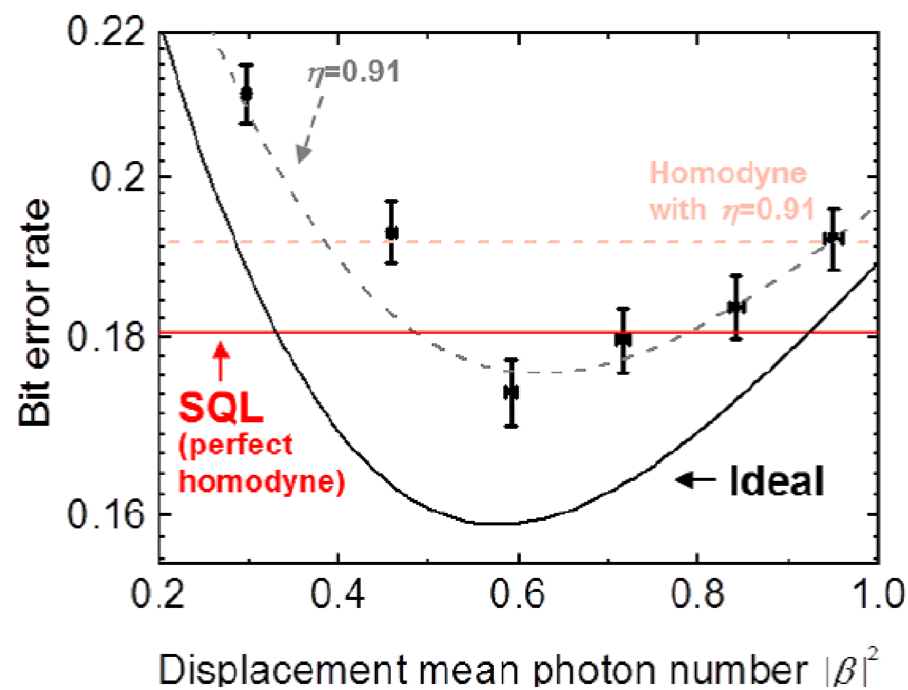
- What we want do; to establish the minimum bit error rate(BER) with the incident coherent state $|\alpha|^2<1$
- Standard method; to use homodyne detector (phase sensitive detector, and "God" detector) ➡ Standard quantum limit(SQL)
- our method; to use a displacement operator and TES !

OR in BPSK with $D(\beta)$ and TES

Experimental setup



Bit error rate dependence on $|\beta|^2$

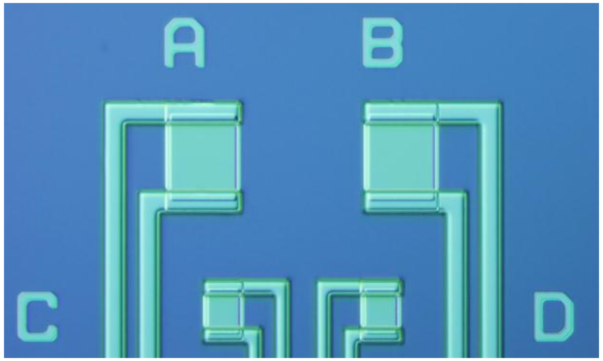


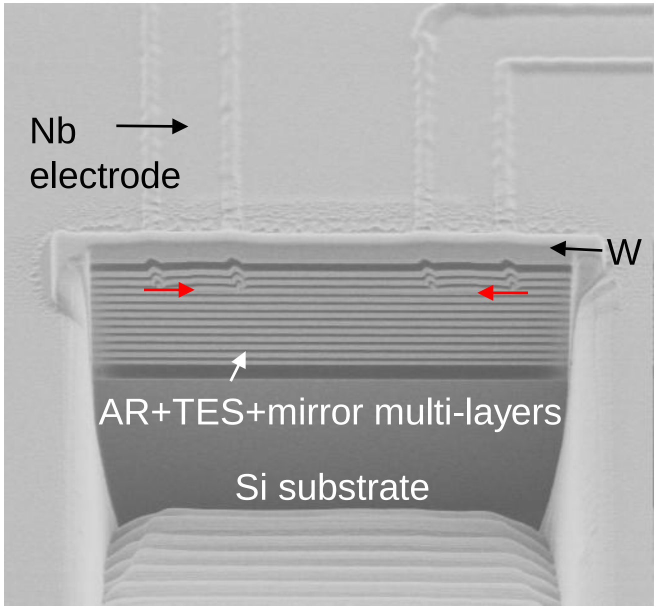
- Yes, bit error rate < SQL !

K. Tsujino, D. Fukuda, PRL(2011)

- **Thank you for your attention.**

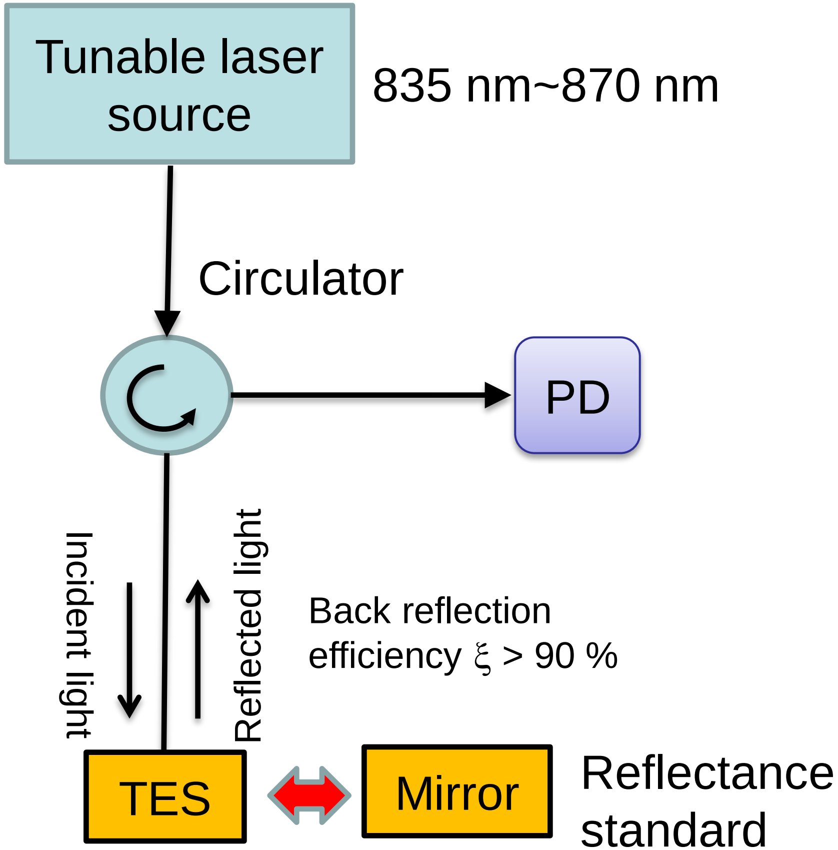
Reflectance of fiber-coupled TES





SEM image by Focused ion beam milling

Absolute reflectance measurement of fiber coupled Ti-TES device



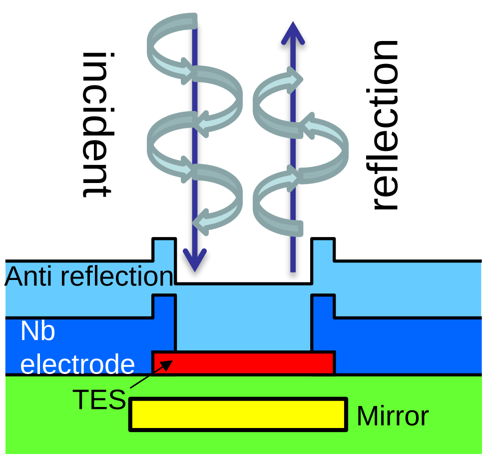
How to improve DE ?

Absorptance of photons in superconducting

- Complex refractive index n=6.1+4.3i for Ti
- Photon absorption~30 %
- An optical resonant cavity

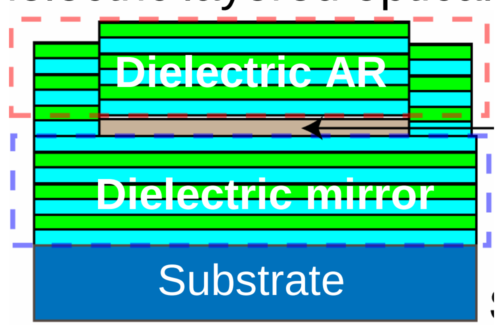
Coupling efficiency to optical fiber

- Optical spot divergence by diffraction(NA~0.14)
- Wavelength dependent η_{coup} caused by optical interference
- Fresnel reflection at fiber end.



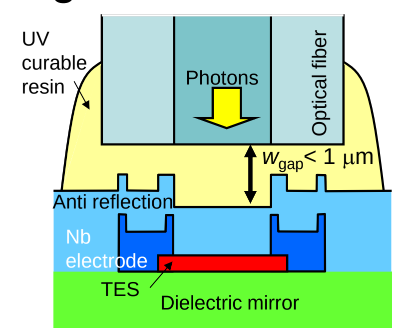
Rosenberg, IEEE AS(2005)

Dielectric layered optical cavity



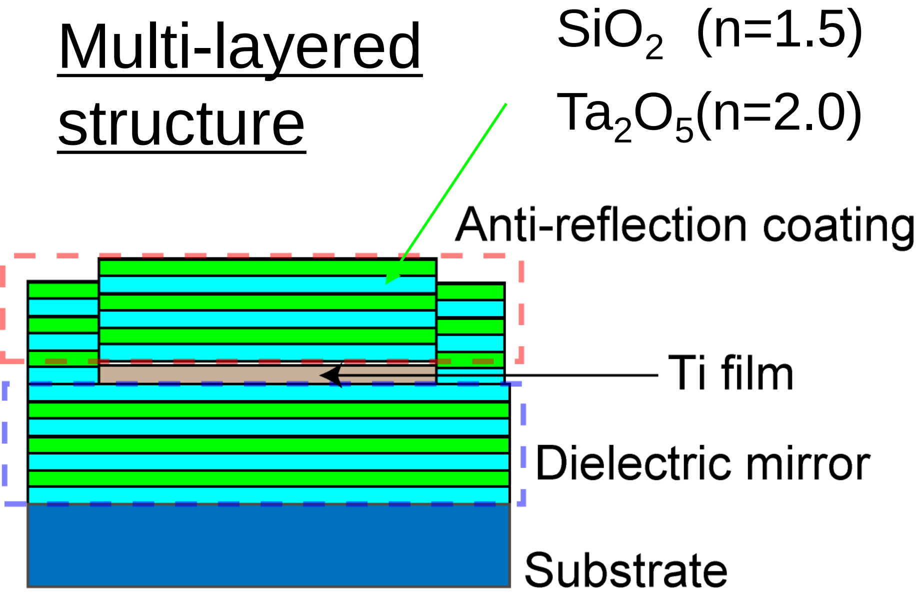
D. Fukuda, Proc. SPIE 7236C(2009)

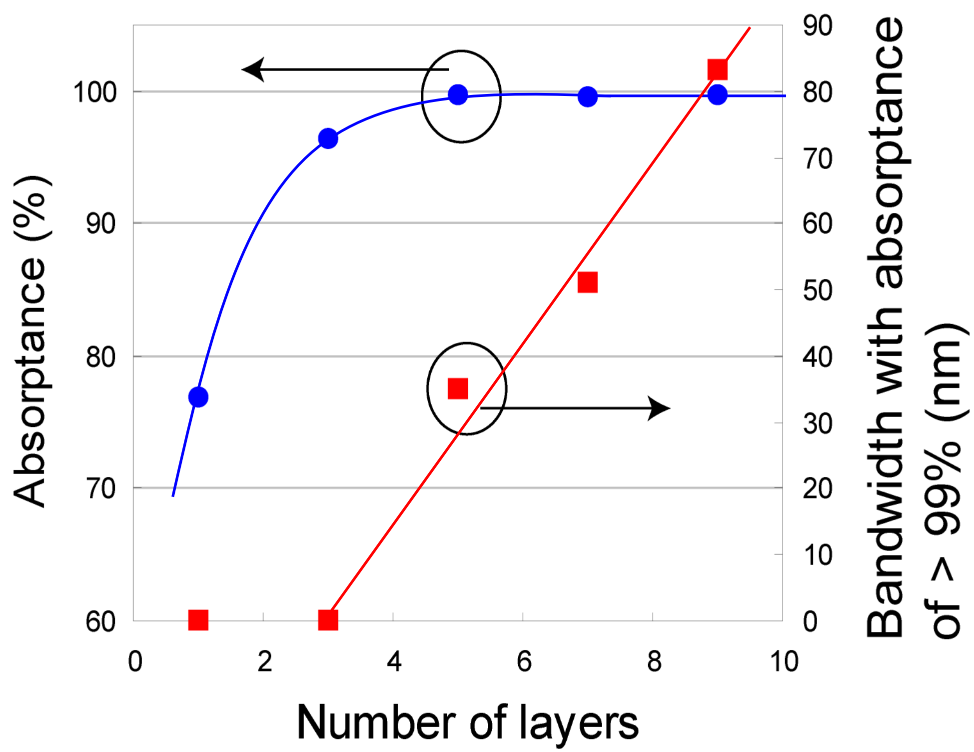
Index-matched less-gap fiber coupling method



D. Fukuda, Opt. Express(2011)

Multi-layered dielectric optical resonant cavity

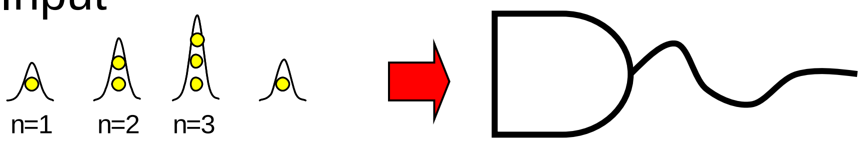




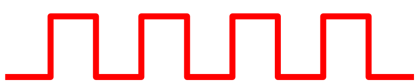
Single photon & photon number resolving detector

Single photon detector

Input



Output

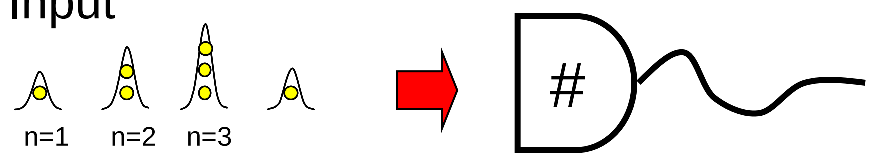


The same output signal for varying photon number input

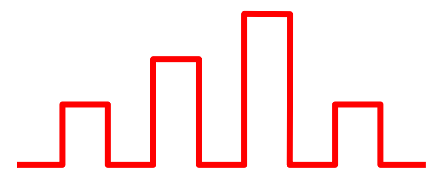
Applications: QKD, quantum optics measurement, etc.

Photon number resolving detector (PNRD)

Input



Output

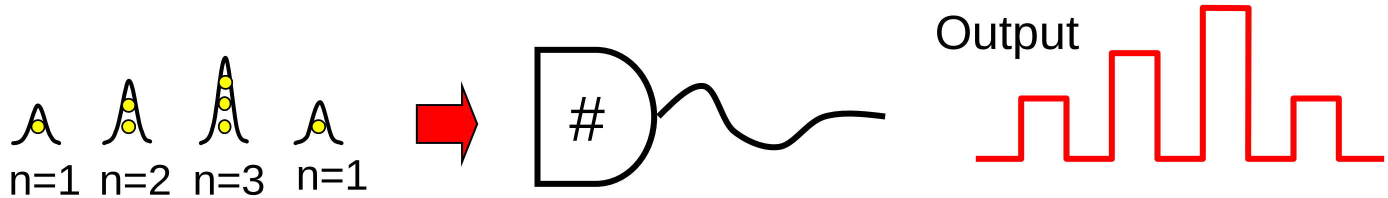


Output signal proportional to the incident photon number

Applications: linear optical quantum computing, more complex QI protocols, which deal with many photons.

True photon number resolving; detection efficiency

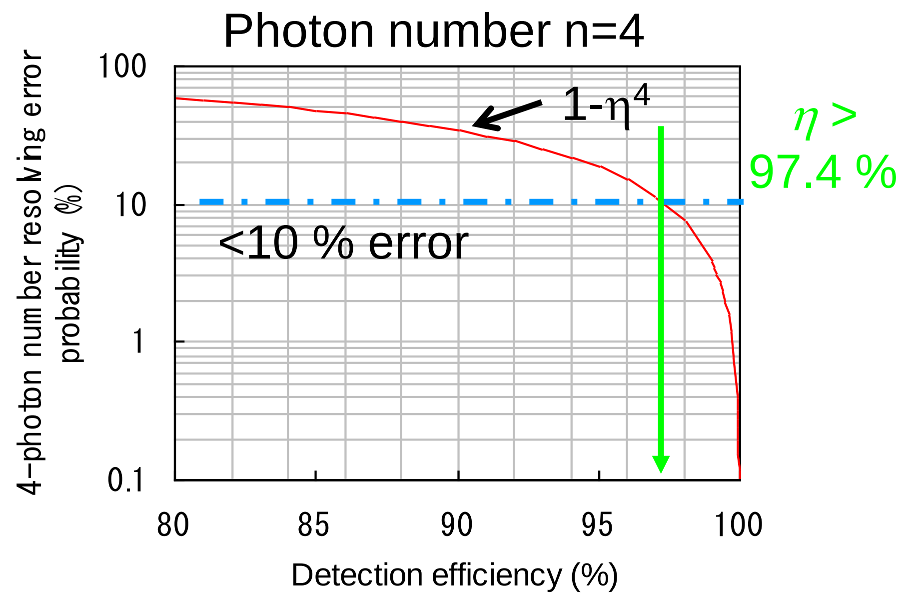
Input



Output

Detection efficiency: η

Input	Detection probability of n photons
n=1	η^1
n=2	η^2
n=3	η^3
..	..
For n photons	η^n



For PNRD, η is a very important parameter !

Collaborators

AIST

• Go Fujii	Device fabrication
• Takayuki Numata	Fiber coupling
• Masahiro Ukibe	Device fabrication
• Taro Itatani	Optical dielectric film
• Akio Yoshizawa	Quantum optics
• Hidemi Tsuchida	Quantum optics
• Mauro Rajteri	Executive Program
• Shuichiro Inoue	Nihon University
• Masahide Sasaki	NICT

INRIM Istituto Nazionale di Ricerca Metrologica

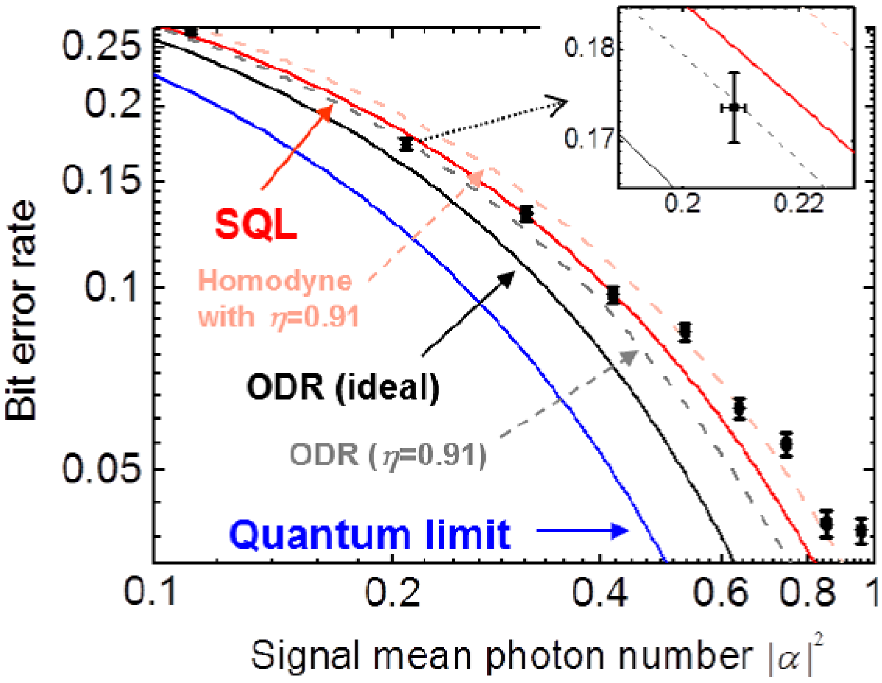
Institute of Quantum Science NIHON UNIVERSITY

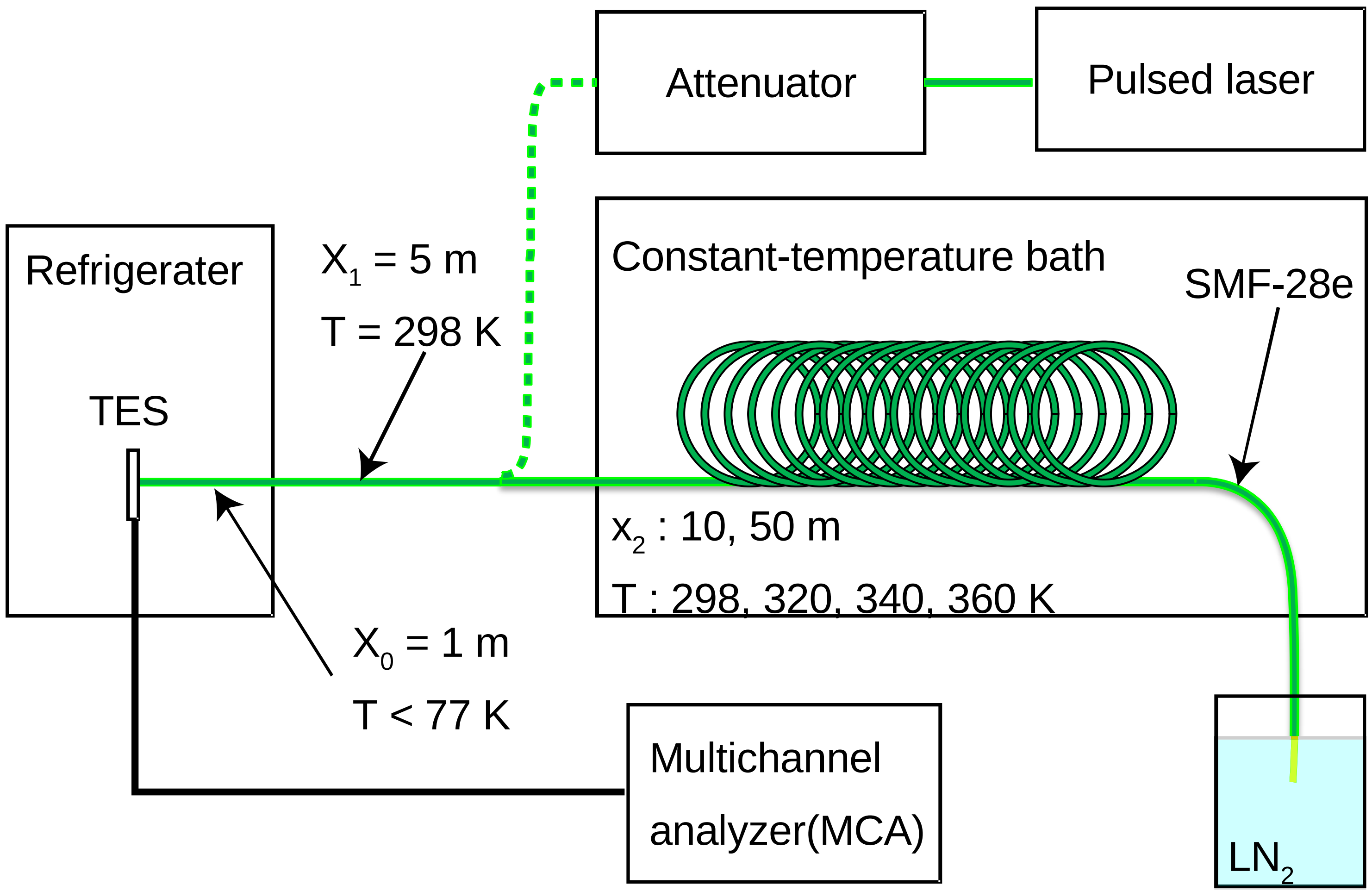
NICT National Institute of Information and Communications Technology

Outline

- Expectations to superconducting detectors in QI
- What do we need ?
  - Detection efficiency
    - Optical absorption
    - Optical fiber coupling efficiency
  - Fast response
    - Decay time constant
    - Time jitter
  - Dark counts (Actually, we do not need this)
    - Derived from ΔE
    - Derived from Black body radiation
- Application of optical TES technology to QI
  - Realization of surpassing a SQL in BPSK optimal quantum receiver

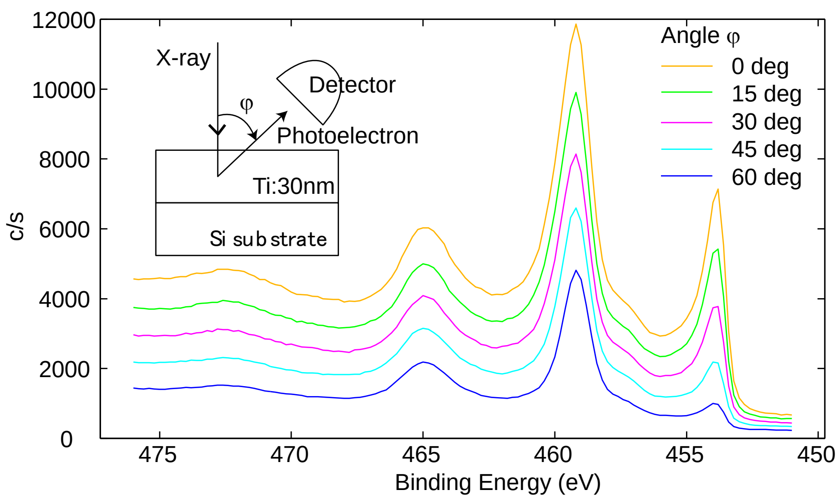
Bit error rate dependence on $|\beta|^2$

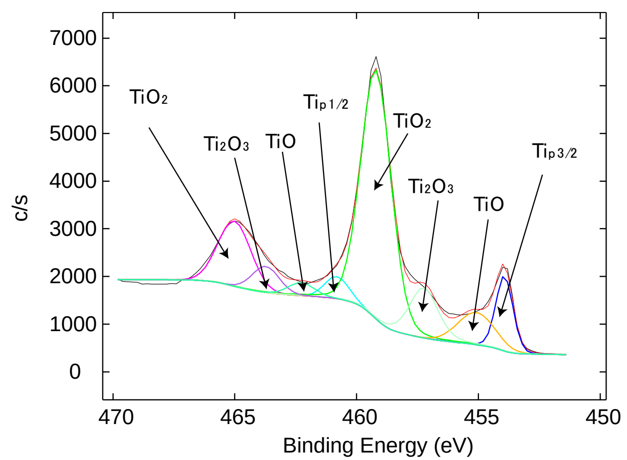



Attenuator
Pulsed laser
Refrigerater
TES
X1 = 5 m
T = 298 K
Constant-temperature bath
SMF-28e
x2 : 10, 50 m
T : 298, 320, 340, 360 K
X0 = 1 m
T < 77 K
Multichannel
analyzer(MCA)
LN2

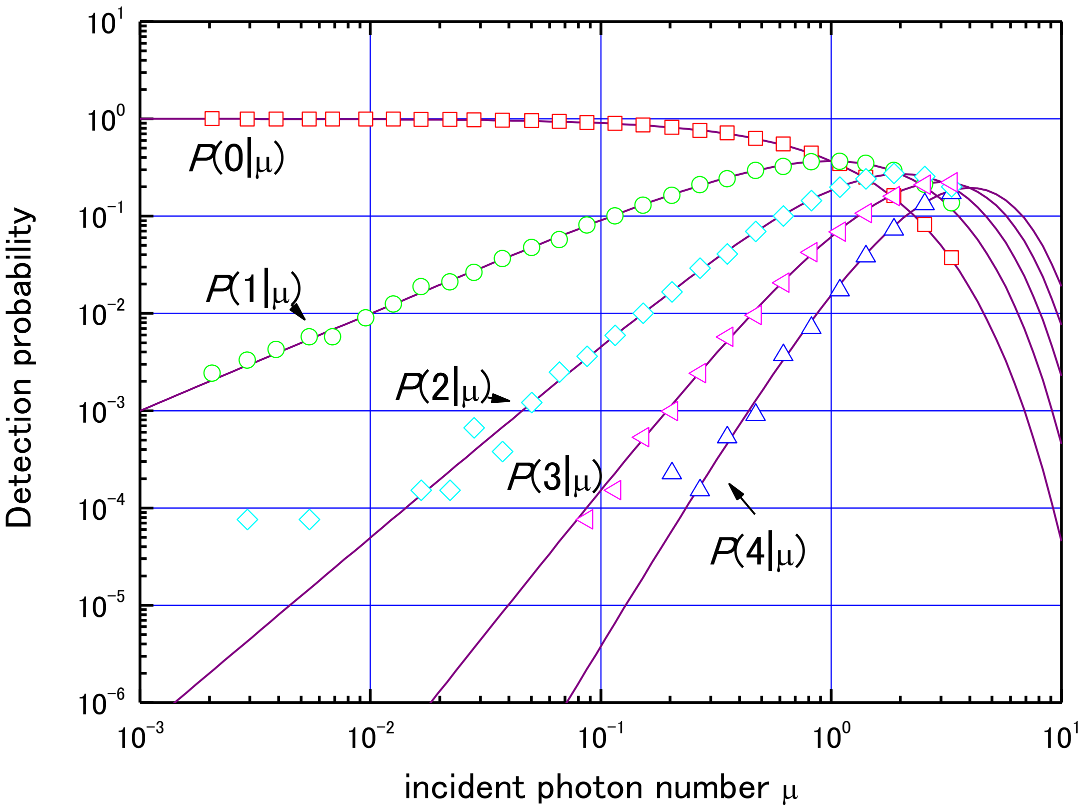
Challenge to new optical TES

- Problem of Ti-TES
  - Poor energy resolution
  - Difficulty of the cavity design
    - Existence of TiO2 on surface





Energy resolution and Detection efficiency at 844 nm



Photon detection probability with a free parameter η,

$$P_\eta(n\,|\,\mu) = \frac{(\eta\mu)^n e^{-\eta\mu}}{n!}$$

μ: Incident average photon number
n: Photon number
η: Detection efficiency

$\eta = 98\,\% \pm 1\,\%$

@ 844 nm

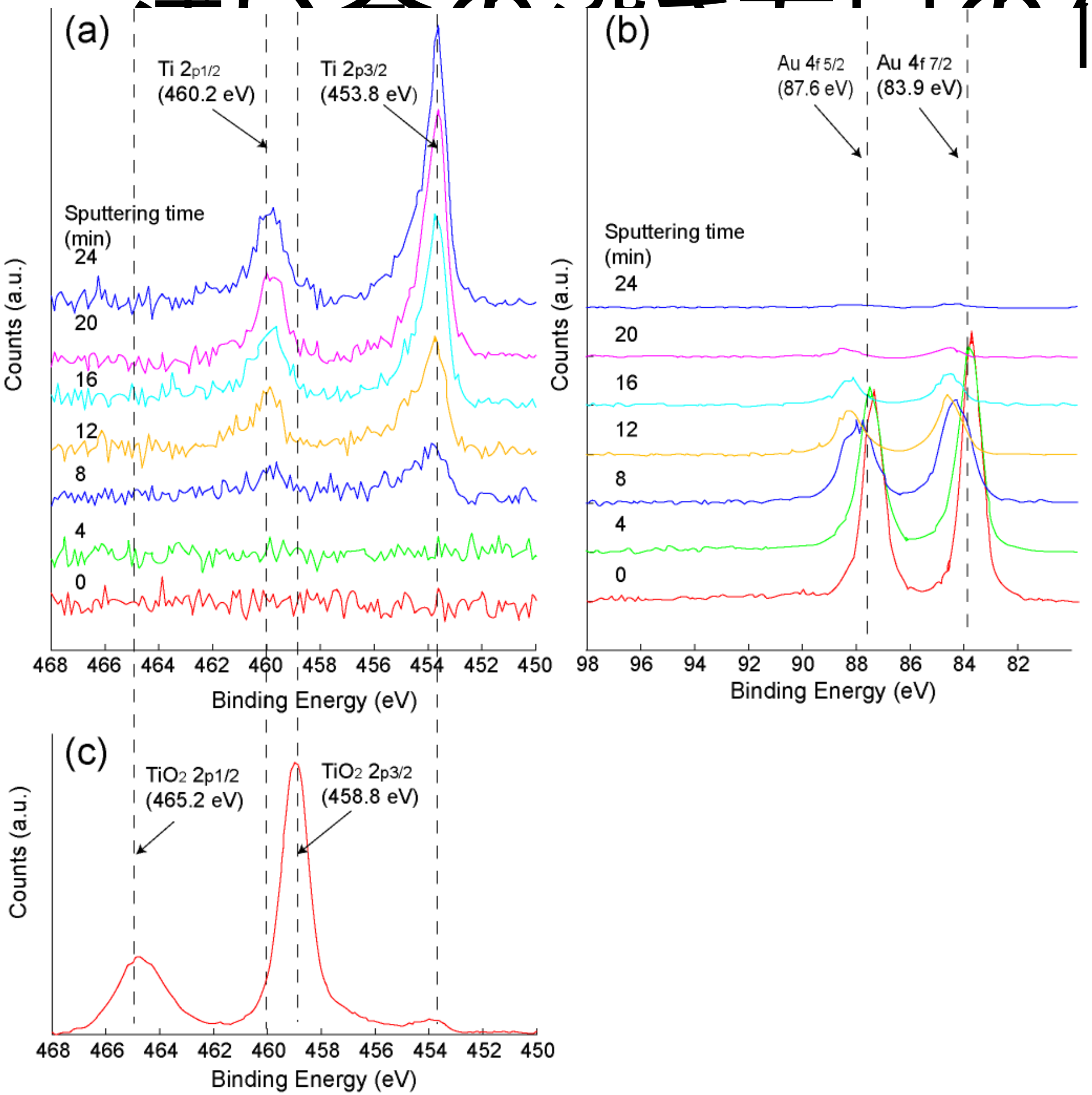
表面保護層の適用

- Thin gold film to protect Ti surface
  - SRONの例
  - 金は反射が高い。高い量子効率は可能か？

Optical cavity design

- 薄い金を用いた時の吸収率

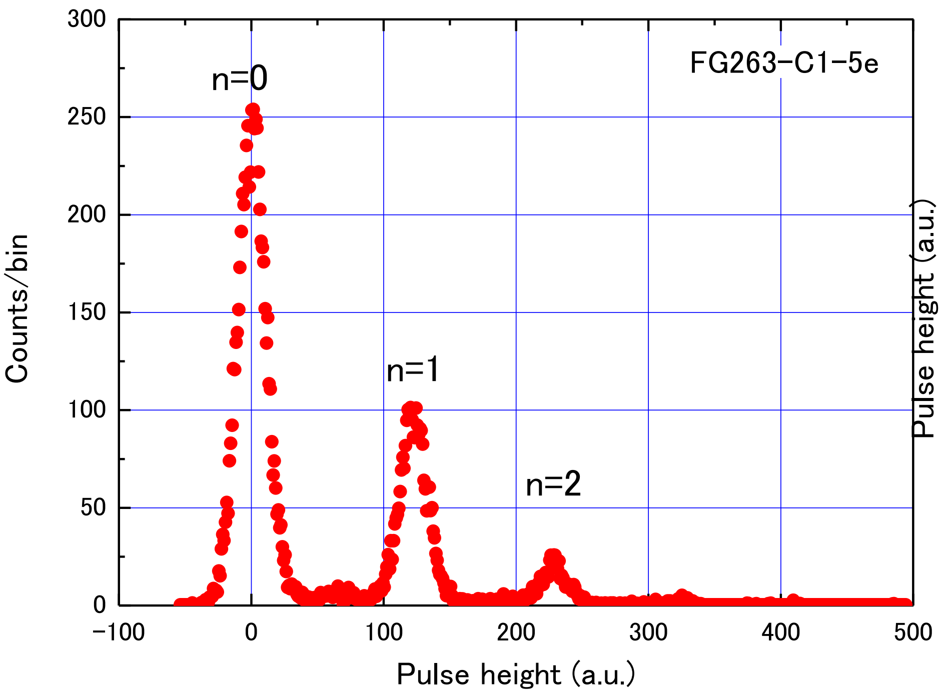
薄い金の深さ方向の化学状態

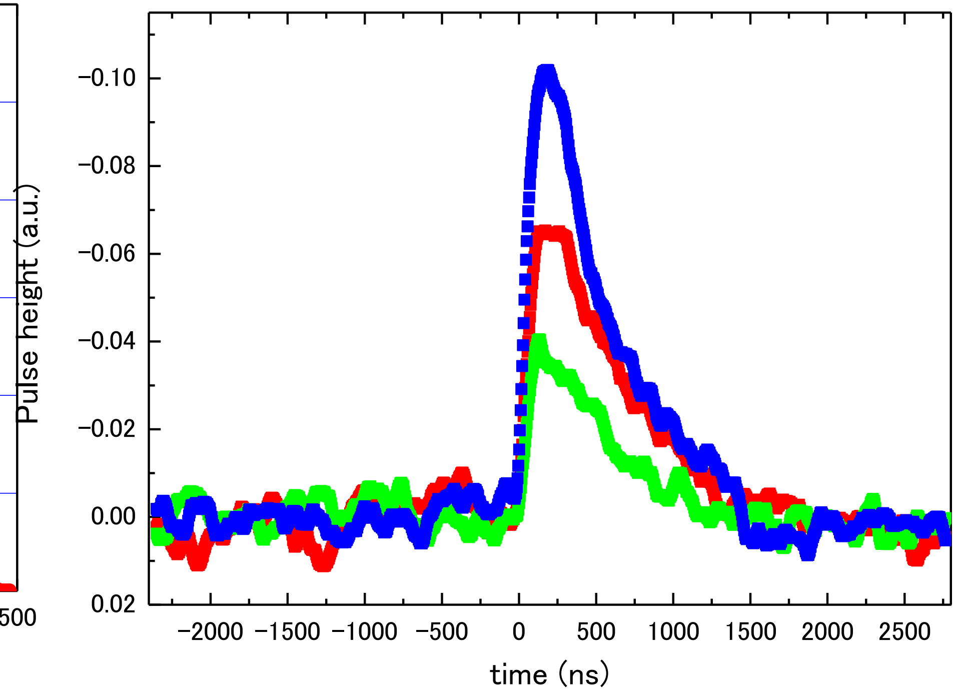


薄膜金による光子数識別

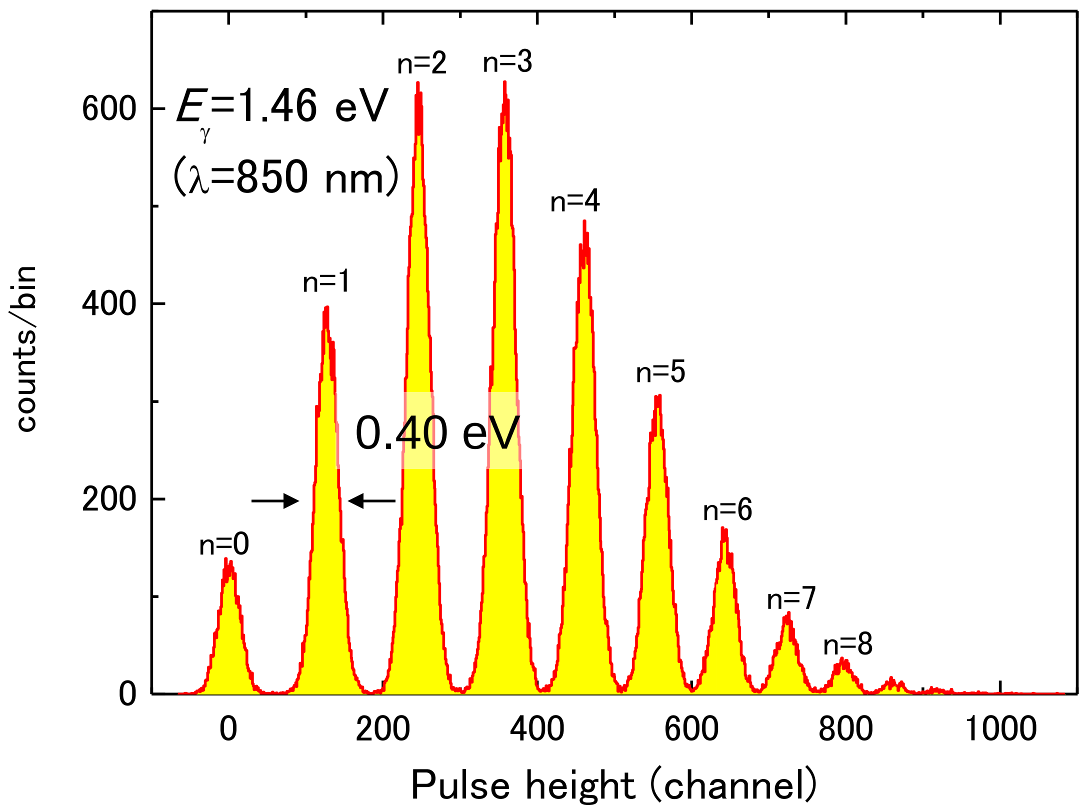
- 分解能と速さ

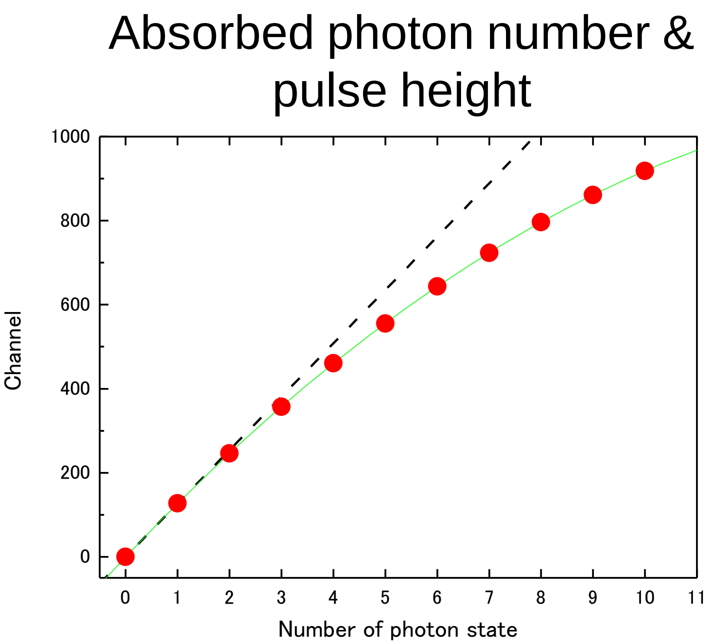
tETF~400 ns





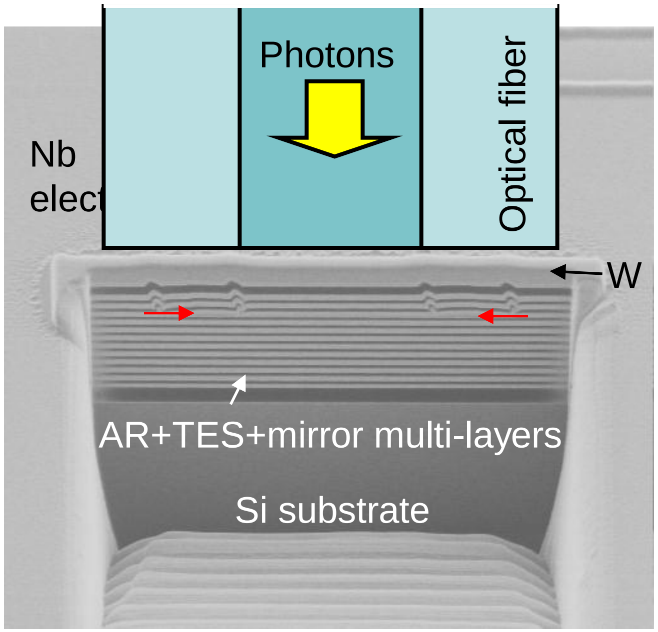
Photon number resolving capability



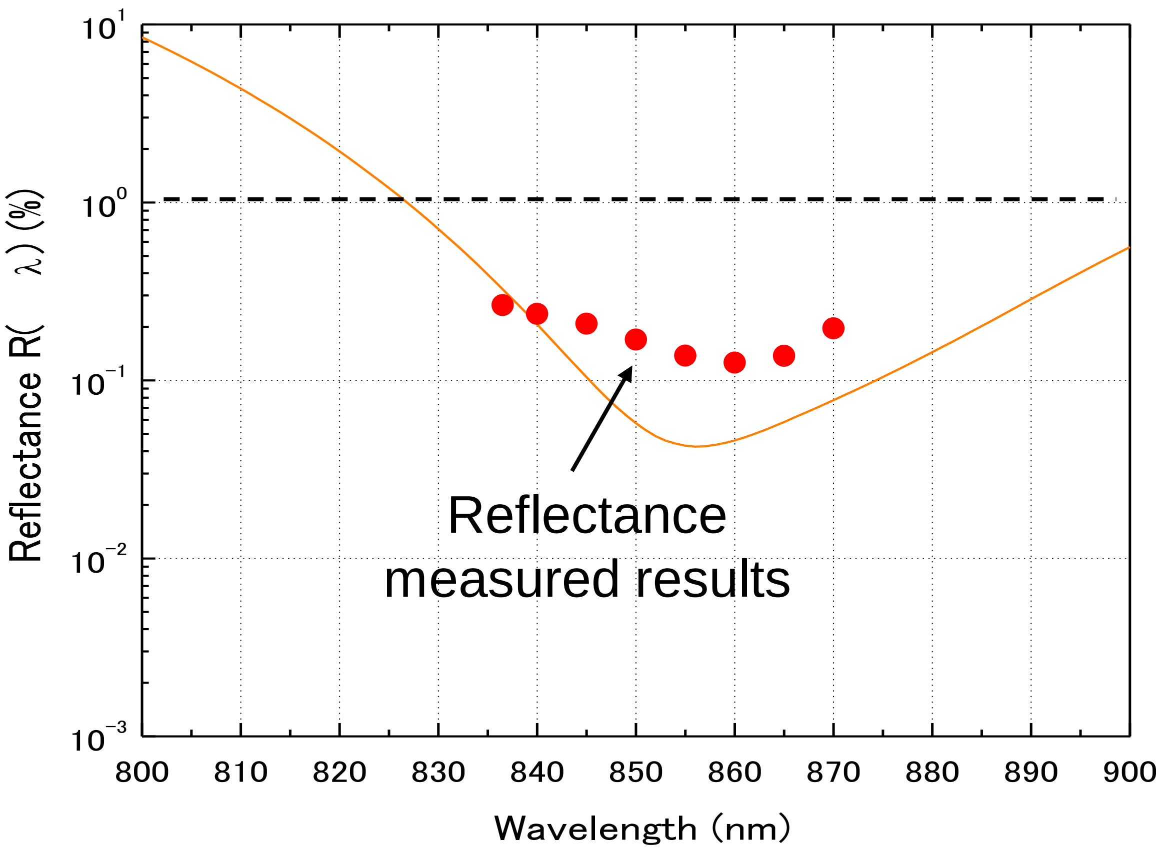


- Saturation tendency is observed (n > 4).
- Saturation affects observed photon distribution ?
- Is there any drawback in multi-layered structure?

Reflectance of fiber-coupled TES

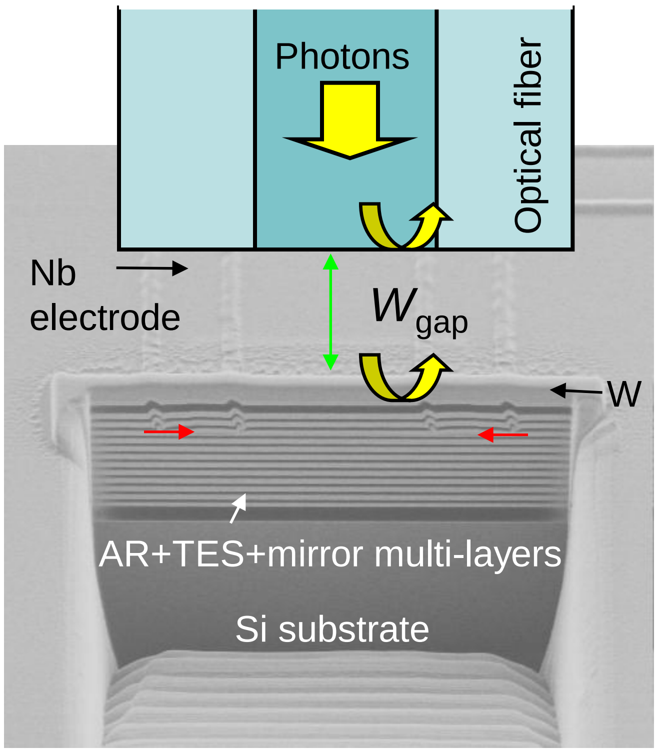


SEM image by Focused ion beam milling

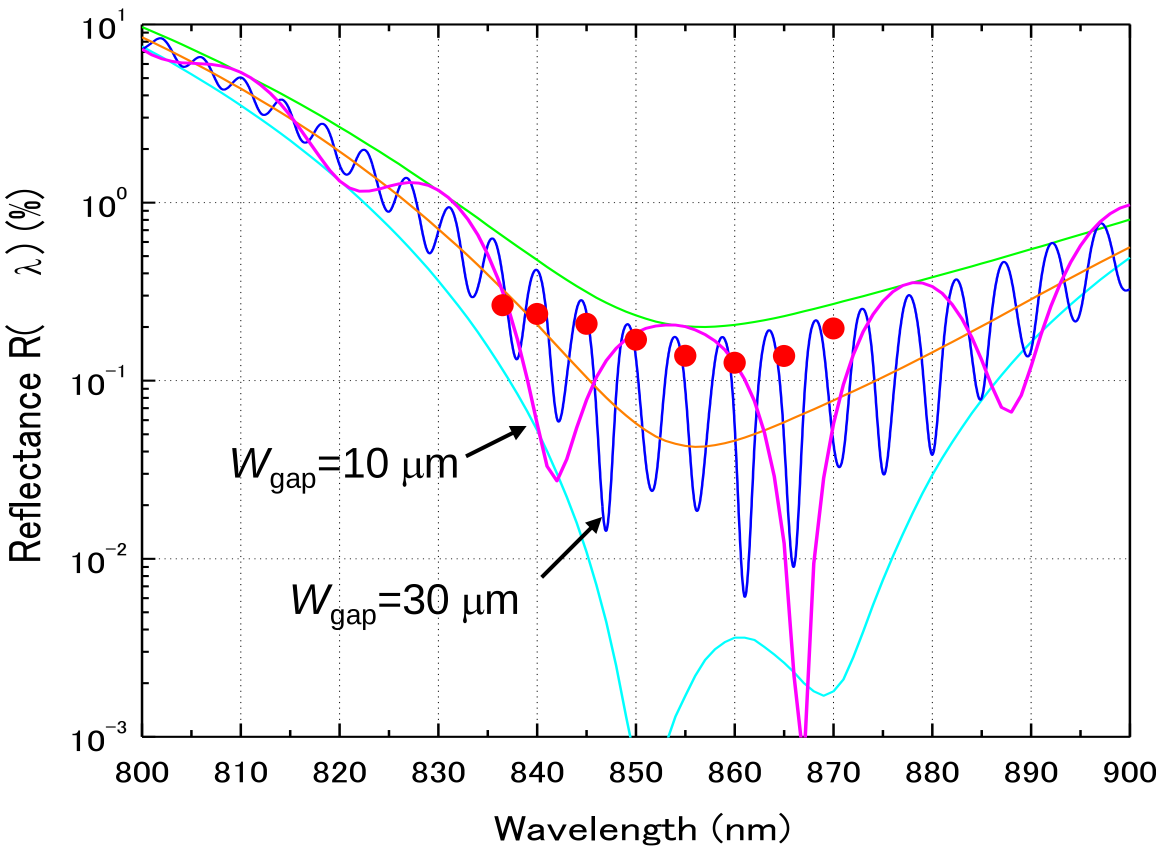


•The reflectance of the fiber coupled device was measured with return loss measurement method (IEC 61300-3-6).

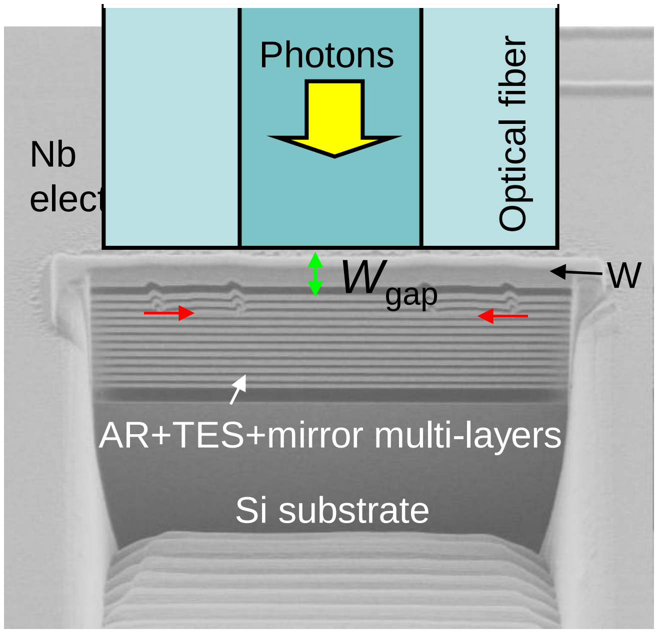
Reflectance of fiber-coupled TES



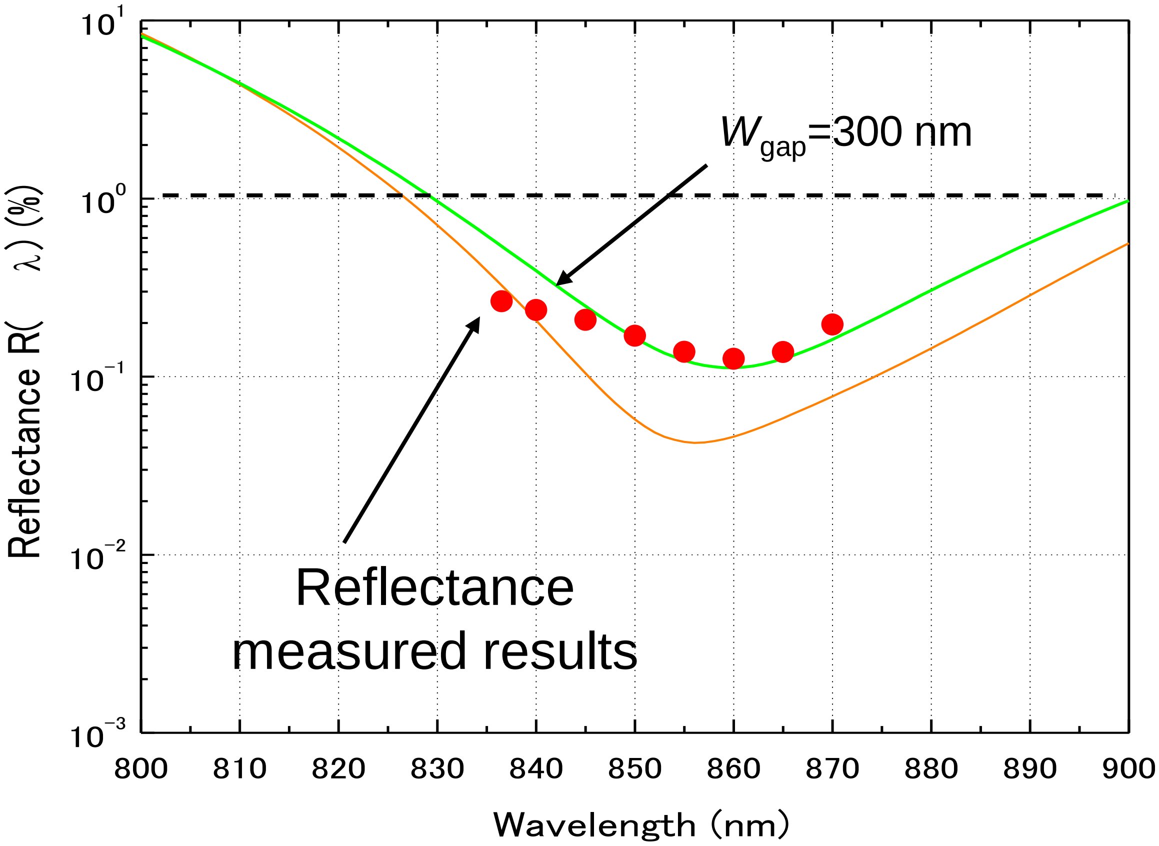
SEM image by Focused ion beam milling



Reflectance of fiber-coupled TES

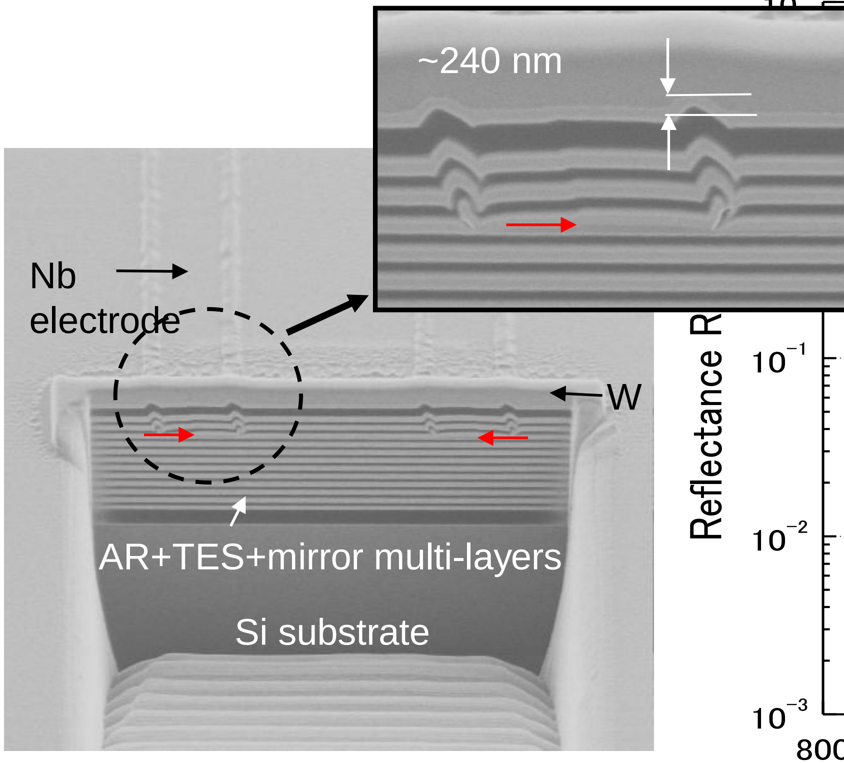


SEM image by Focused ion beam milling

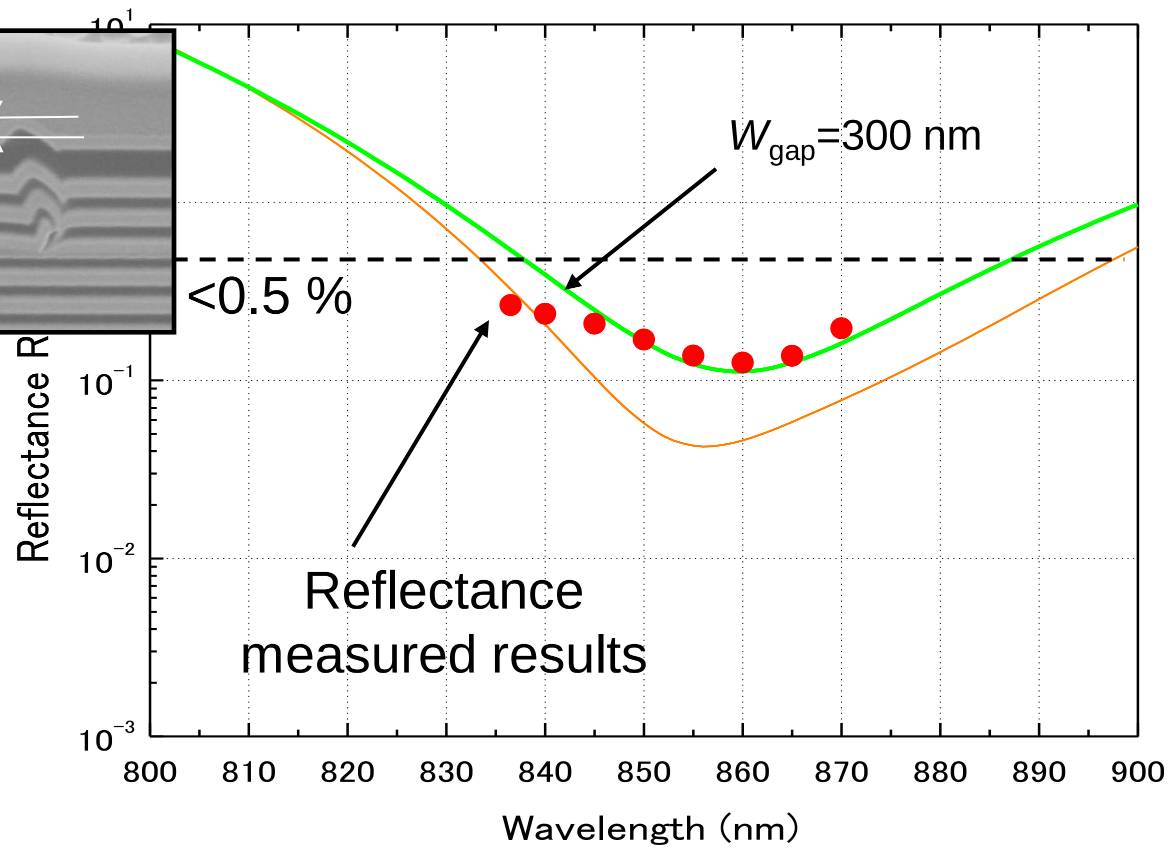


- Optical interference of reflections on the fiber edge and the TES surface.

Reflectance of fiber-coupled TES



SEM image by Focused ion beam milling



- $w_{gap} < 1\ \mu m$
- Absorbance of cavity > 99.5 %

超伝導転移端センサに対する黒体輻射の影響

Effect of black body radiation on the performance of superconducting transition edge sensors

藤井剛[1,2]、福田大治[1]、沼田孝之[1]、吉澤明男[1]
土田英実[1]、井上修一郎[2]

1　産業技術総合研究所

2　日本大学　量子科学研究所

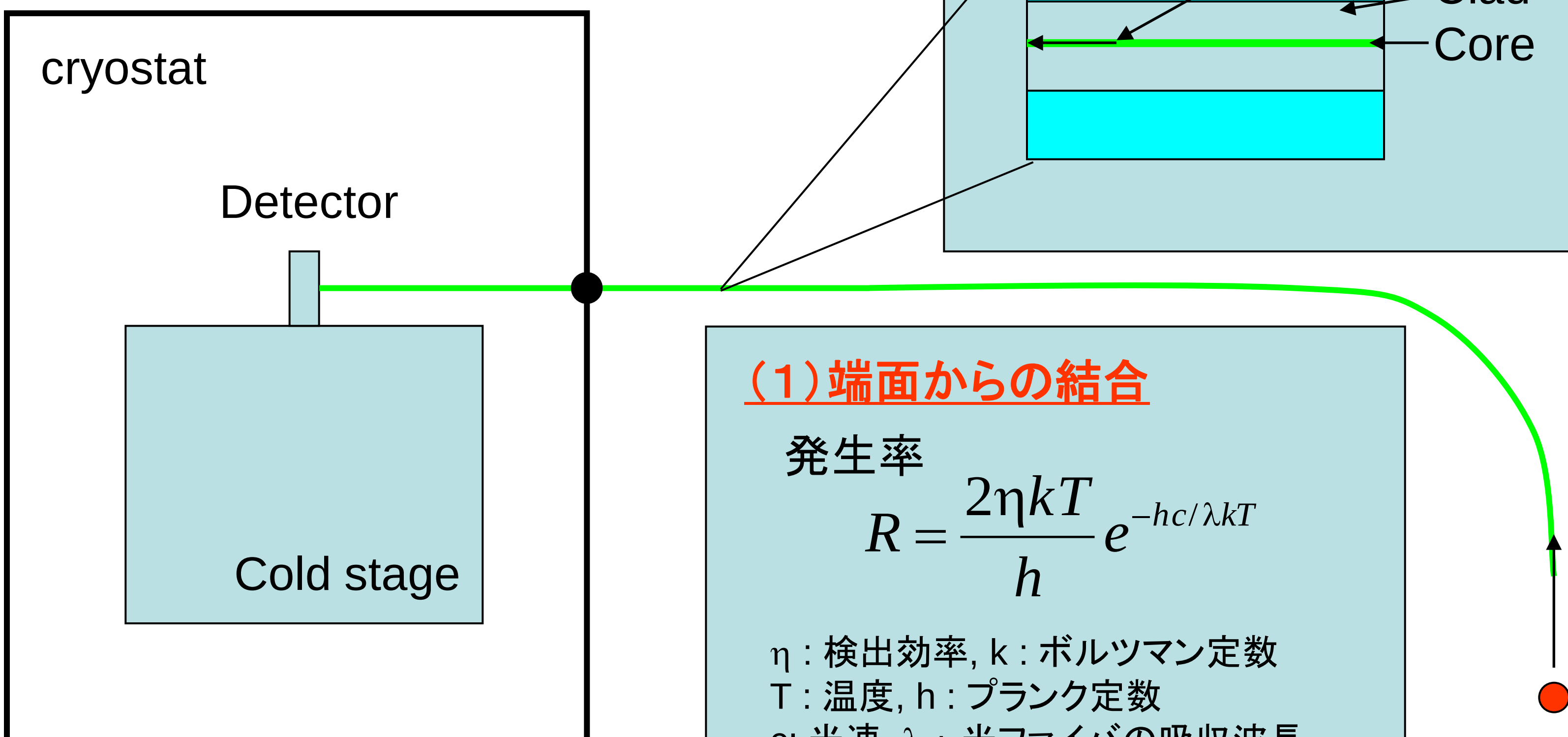
本研究の一部は、総務省戦略的情報通信研究開発推進制度の委託研究として実施しました。
また、デバイス作成に関し、(独)産業技術総合研究所IBEC イノベーションプラットフォームの支援を受けております。

研究背景

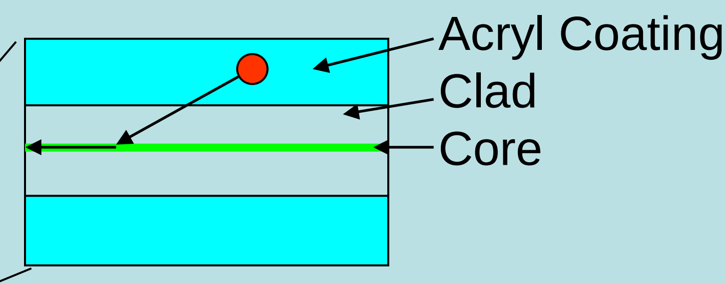
- 超伝導転移端センサ(TES)や超伝導ナノワイヤ単一光子検出器(SNSPD)などの超伝導光子検出器は、半導体検出器では得られない特徴をもっているため、量子情報通信の分野で応用されている。
  - TES：高検出効率、低暗計数、光子数識別能力
  - SNSPD：高時間分解能、低暗計数
- 超伝導光子検出器は、広検出帯域かつ高感度なため、室温での黒体輻射によって発生する近赤外の光子を検出することが暗計数の大きな要因となっている。
- 黒体輻射によって発生した光子が光ファイバの端面から結合し、検出器で検出することが報告されている。300 Kでは、数10 Hz程度である[1]。
- 今回、光ファイバの端面以外で発生する光子について評価を行った。

[1] A. J. Miller, et. al., Proc. 8th Int. Conf. of QCMC, pp. 445 (2007)

黒体輻射によってファイバ中で発生する光子



(2) 光ファイバの断面



(1) 端面からの結合

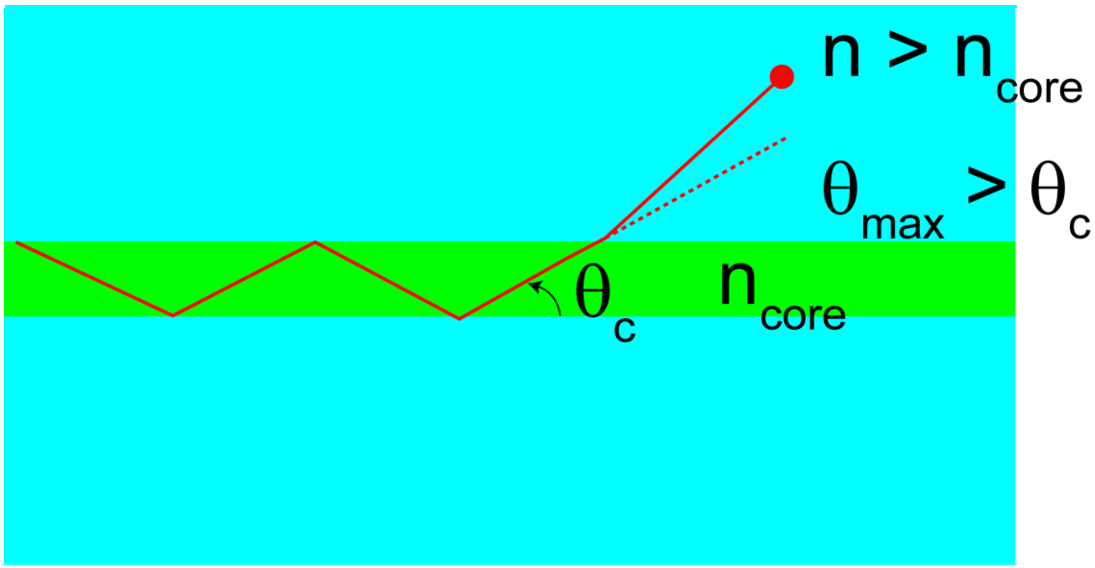
発生率

$$R = \frac{2\eta kT}{h} e^{-hc/\lambda kT}$$

η : 検出効率, k : ボルツマン定数
T : 温度, h : プランク定数
c: 光速, λ : 光ファイバの吸収波長

[1] A. J. Miller, et. al., Proc. 8th Int. Conf. of QCMC, pp. 445 (2007)

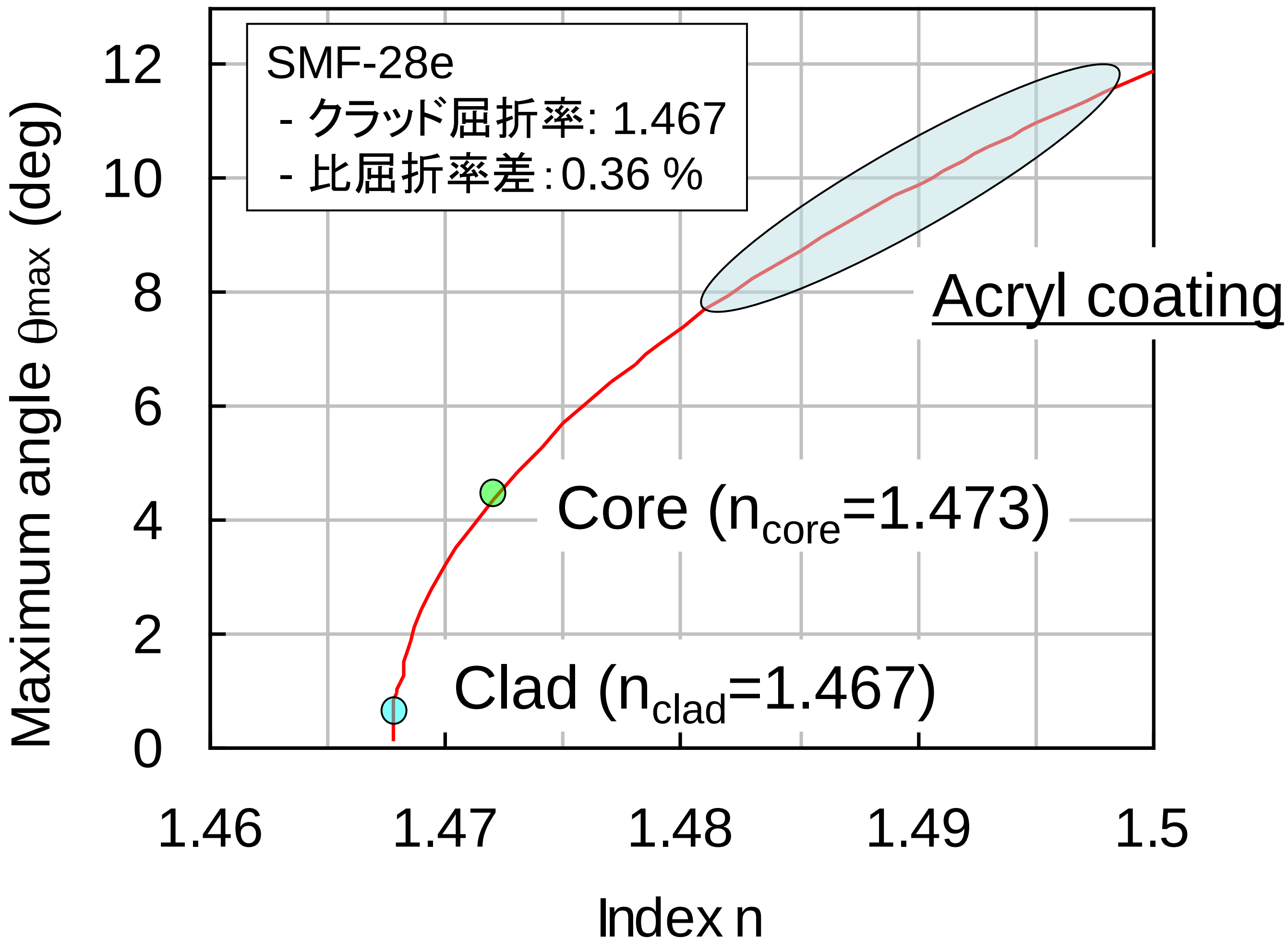
光子の光ファイバへの結合



- n < n_{core}
  → $\theta_{max} < \theta_c$
  → $P_{coupling}$が下がる。
- n > n_{core}
  → $\theta_{max} > \theta_c$
  → $P_{coupling}$が上がる。

- $n_{core}\sin(1-\theta_c) = n\sin(1-\theta)$
  （スネルの法則）
- 臨界角 $\theta_c=\cos^{-1}(n_{clad}/n_{core})$

シングルモードファイバでの最大結合角



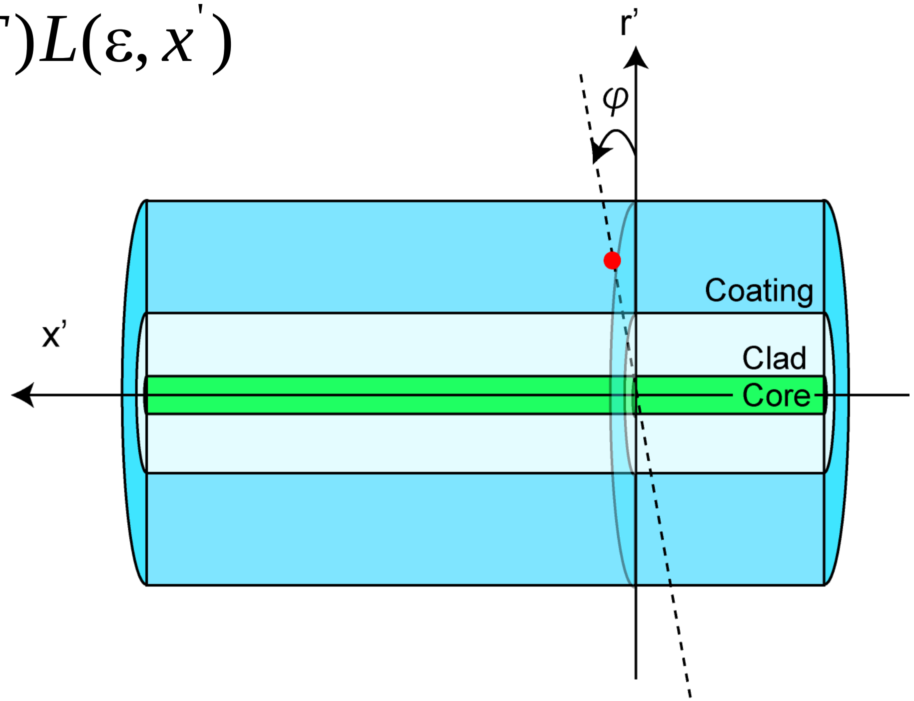
光ファイバで発生した光子

検出器に照射される光子の総数 N

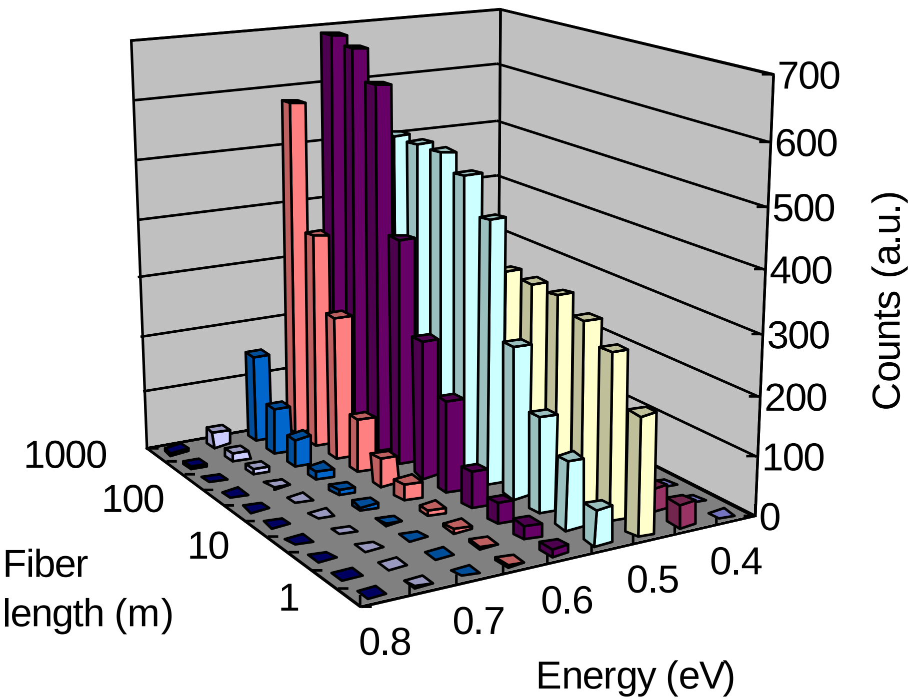
$$N(T,x)=\int_0^x dx'\int_0^r dr'\int_0^{2\pi} d\varphi\int_0^\infty d\varepsilon\, 2n(\varepsilon,T)L(\varepsilon)P_{Coupling}(r)$$

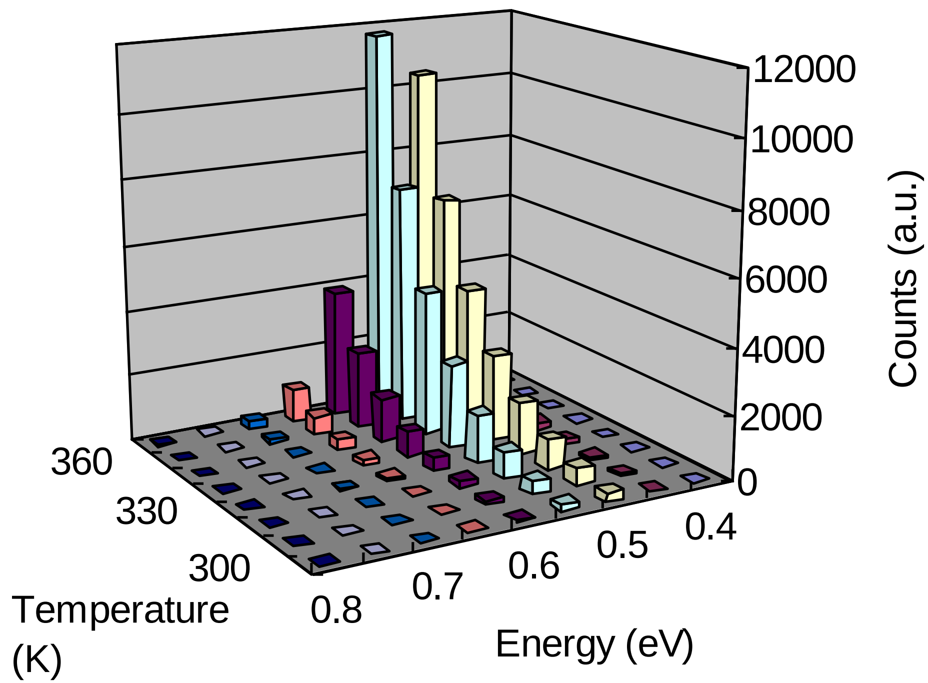
$$N(T,x)=4\pi A\sum_{\varepsilon=0}^{\infty}\Delta\varepsilon\int_0^x dx'\, n(\varepsilon,T)L(\varepsilon,x')$$

x : ファイバ長, r : ファイバ半径
ε: エネルギー， T : 温度
$n(\varepsilon,T)$: 単位体積当りの発生率
$L(\varepsilon)$: ファイバでの損失
$P_{\mathrm{Coupling}}(r)$: コアへの結合効率
A : 定数



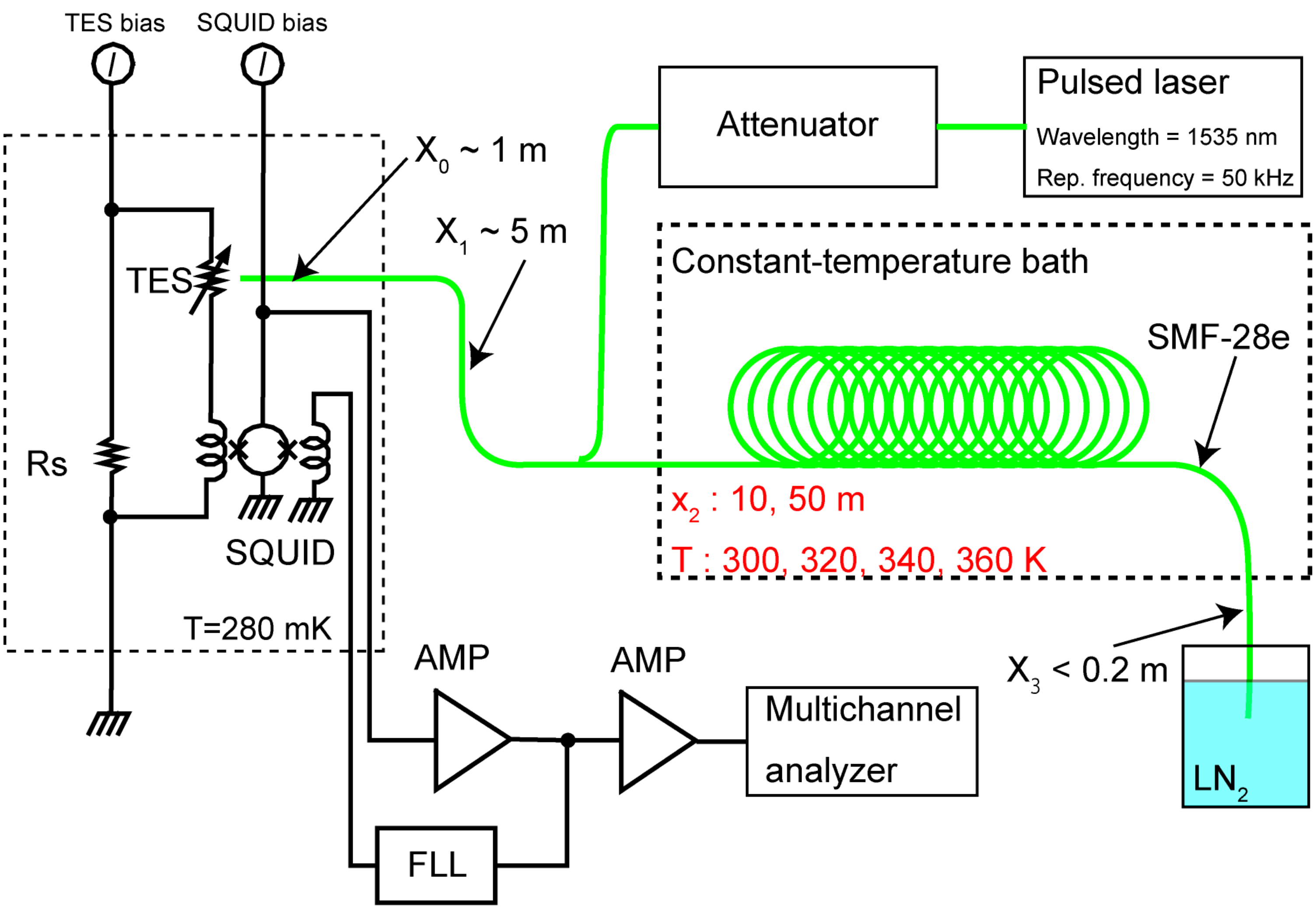
ファイバ長と温度に対する検出される光子のエネルギー分布



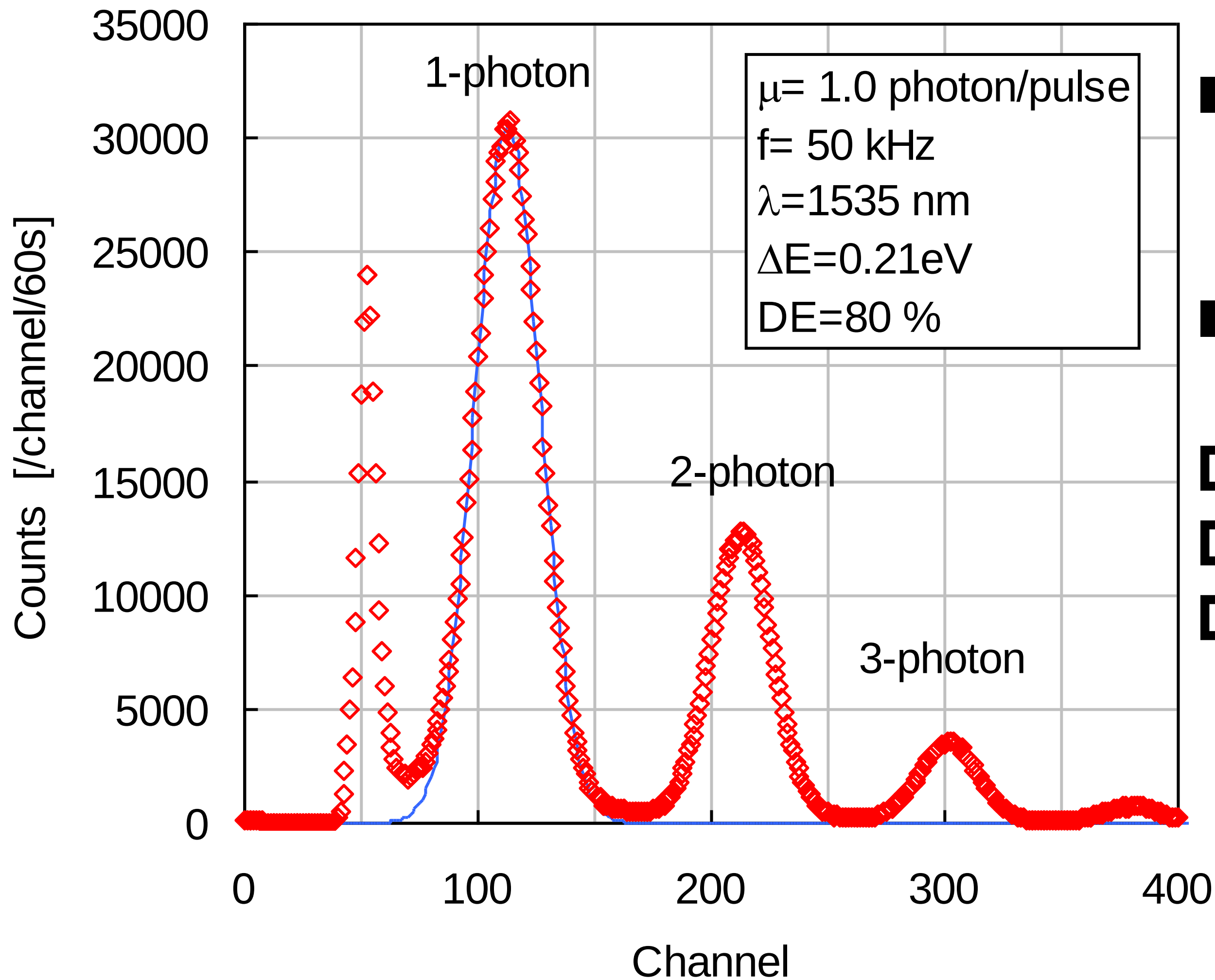


■ ファイバ長が長くなるにつれて、高エネルギー（短波長）の光子が大幅に増加する。
■ 温度が上昇するにつれて、全体の光子の発生率が大幅に増加する。

実験系


TES bias
SQUID bias
I
I
X0 ~ 1 m
X1 ~ 5 m
TES
Rs
SQUID
T=280 mK
Attenuator
Pulsed laser
Wavelength = 1535 nm
Rep. frequency = 50 kHz
Constant-temperature bath
SMF-28e
x2 : 10, 50 m
T : 300, 320, 340, 360 K
X3 < 0.2 m
LN2
AMP
AMP
Multichannel analyzer
FLL

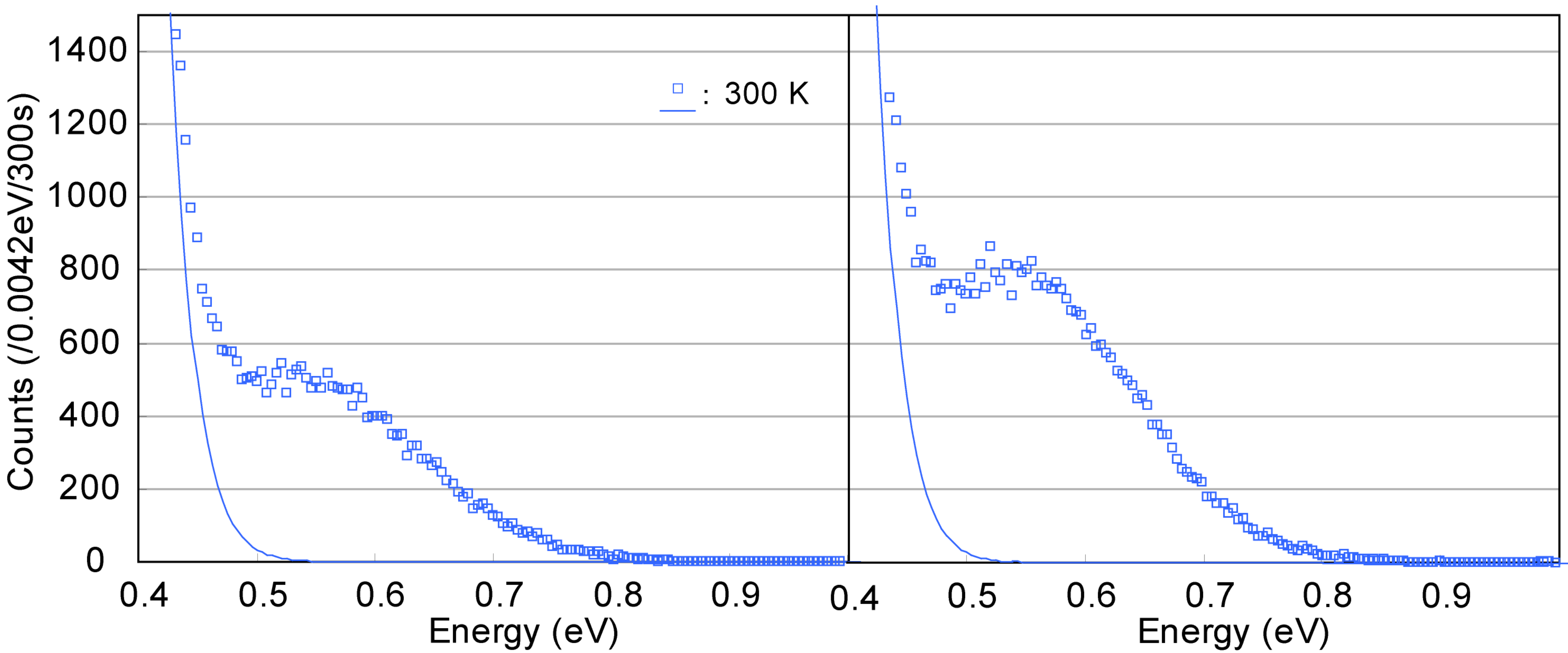
波長1550 nmの光子測定



- ■ 波高値と
  エネルギーの関係
  : 0.808 eV / 115 ch
- ■ エネルギー分解能
  : 0.21 eV
- □ 応答時間 : 260 ns
- □ 時間ジッタ : 28 ns
- □ 検出効率@1550 nm
  : 80 %

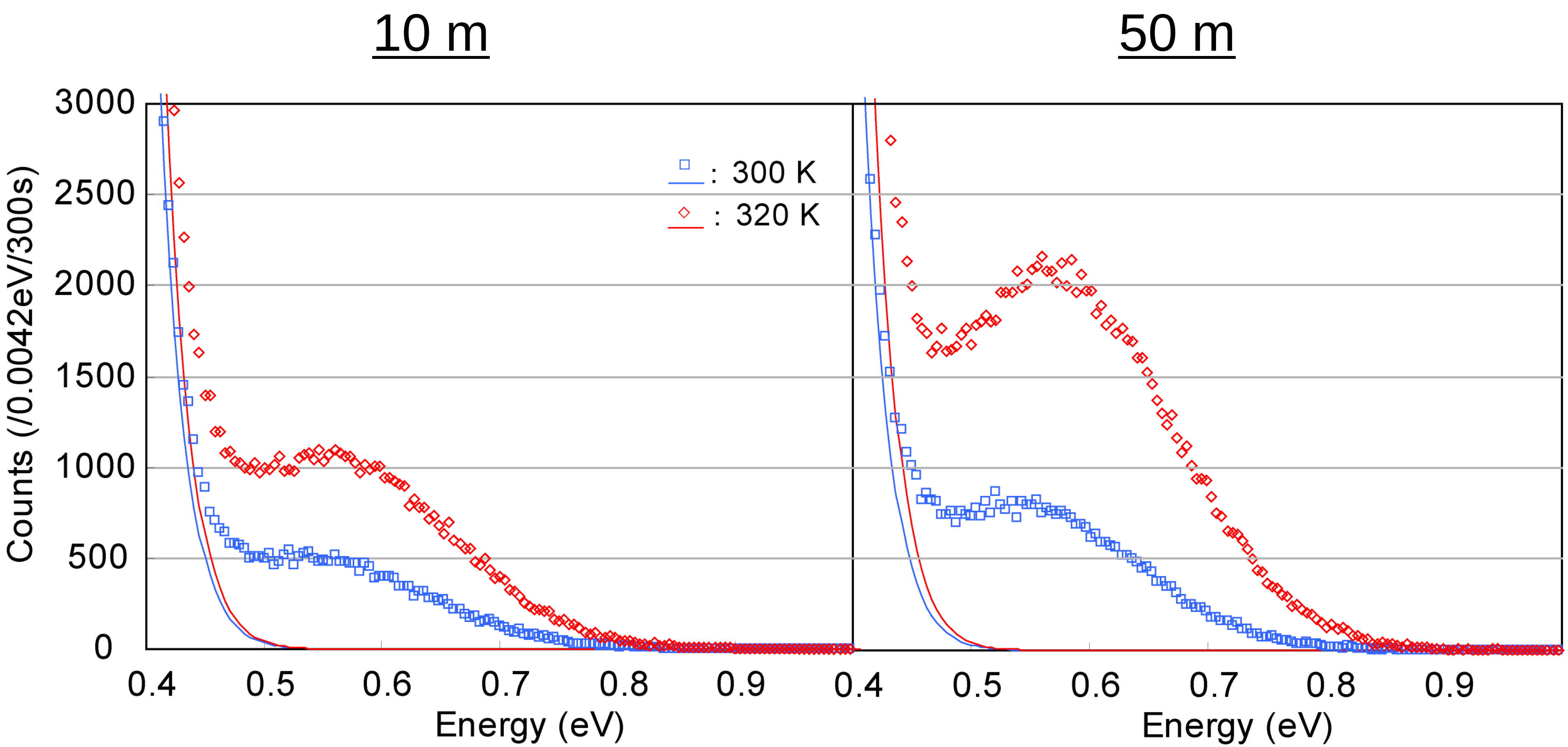
ファイバ中で発生した光子測定 (300 K)

10 m　　50 m



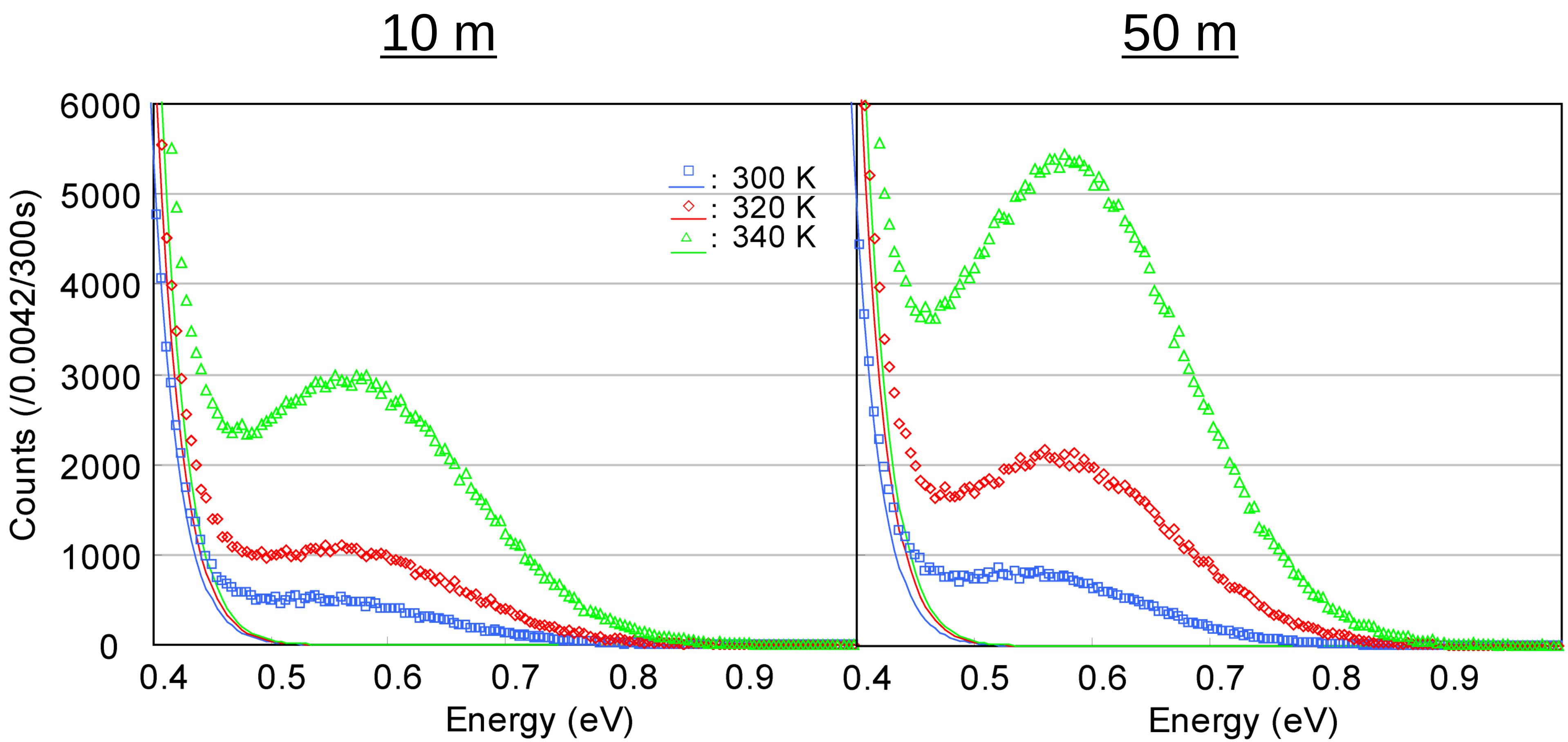
$$f(E) = A_{0,T,x_2} \exp\left(-\frac{E}{\sqrt{2}\sigma}\right)^2$$

ファイバ中で発生した光子測定 (320 K)



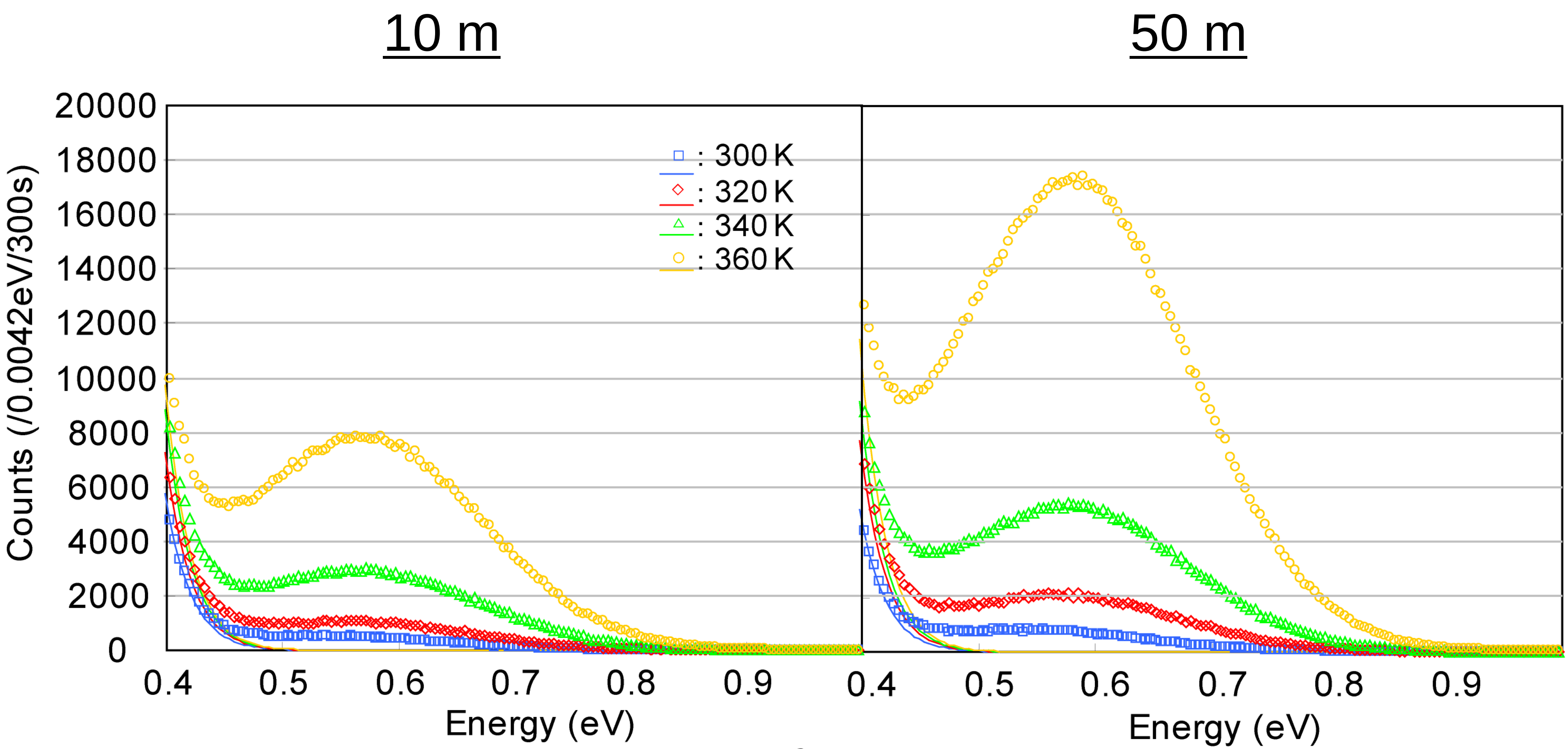
$$f(E) = A_{0,T,x_2} \exp\left(-\frac{E}{\sqrt{2\sigma}}\right)^2$$

ファイバ中で発生した光子測定 (340 K)



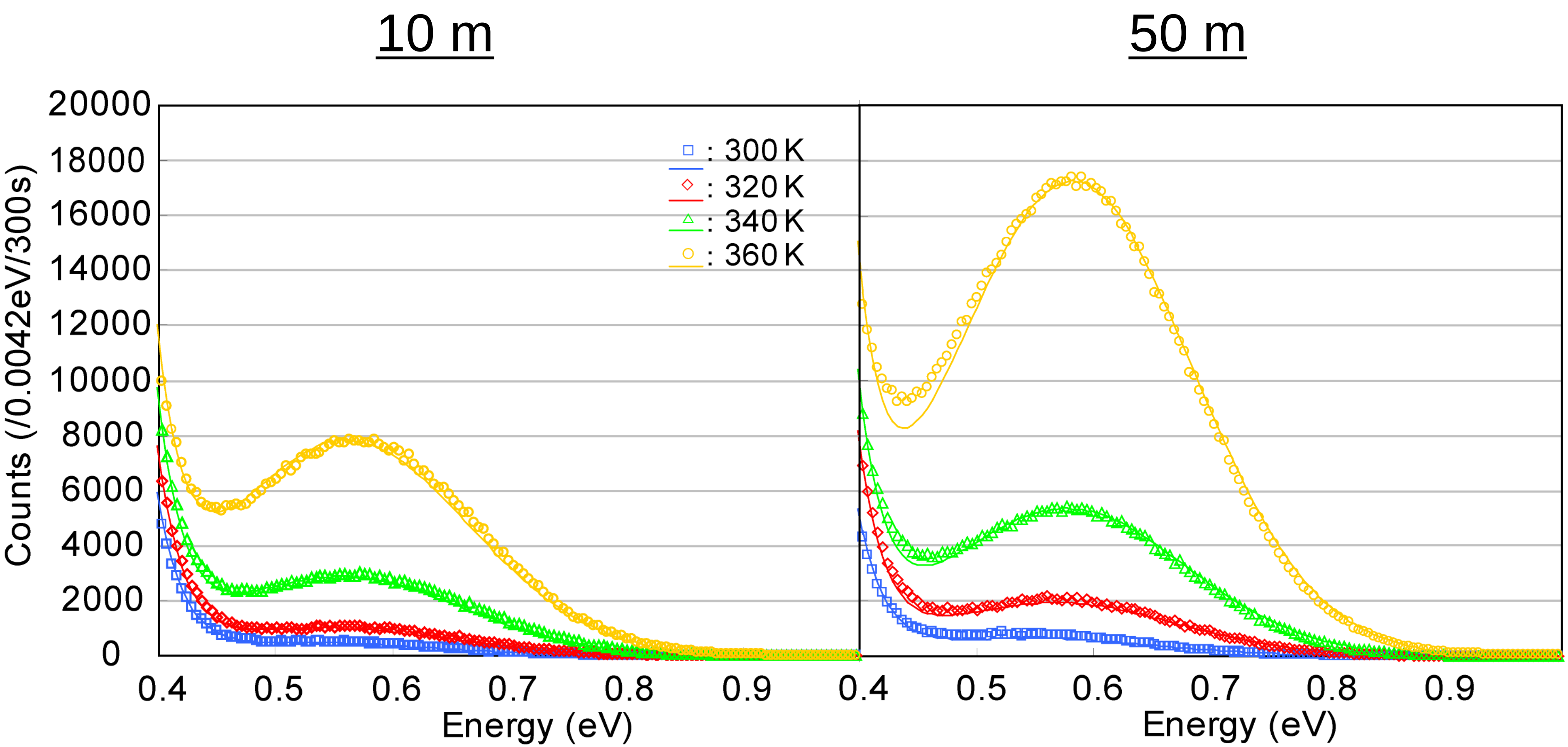
$$f(E) = A_{0,T,x_2} \exp\left(-\frac{E}{\sqrt{2}\sigma}\right)^2$$

ファイバ中で発生した光子測定 (360 K)



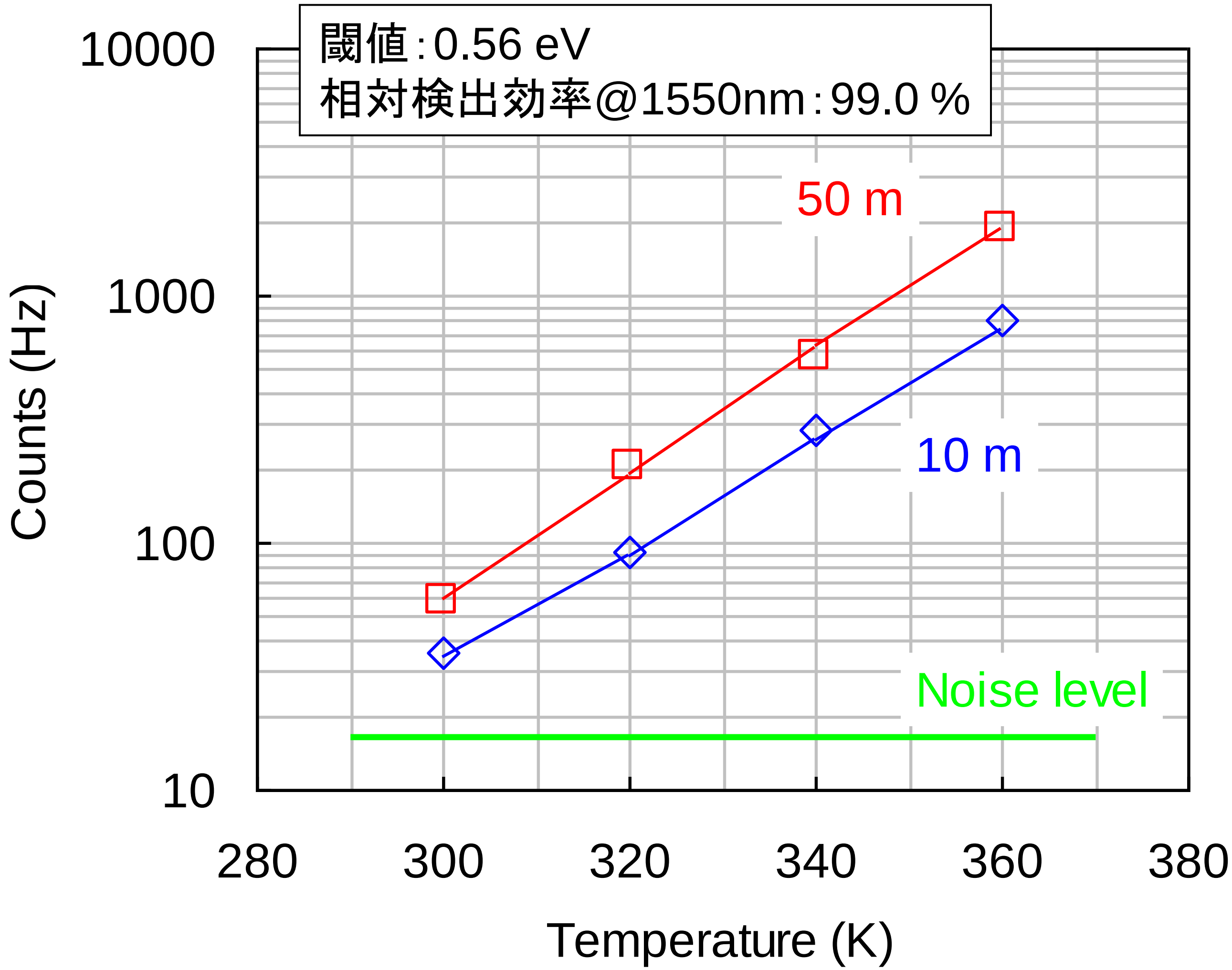
$$f(E) = A_{0,T,x_2} \exp\left(-\frac{E}{\sqrt{2}\sigma}\right)^2$$

ファイバ中で発生した光子測定（Fitting）



$$f(E,T,x_2)=A_{0,r,x_2}\exp\left(-\frac{E}{\sqrt{2}\sigma}\right)^2+A_1\sum_{\varepsilon=0.4}^{0.8}\frac{DE(\varepsilon)\{L(\varepsilon,1m)N'(298K,5m)+L(\varepsilon,6m)N'(T,x_2)\}}{\sqrt{2\pi}\sigma}$$

暗計数の評価


閾値:0.56 eV
相対検出効率@1550nm:99.0 %
10000
1000
100
10
Counts (Hz)
50 m
10 m
Noise level
280
300
320
340
360
380
Temperature (K)

まとめ

- 室温の黒体輻射によって、光ファイバ中で発生する光子の評価を行った。
- 発生する光子は、ファイバ長及び温度が増加するにしたがって大幅に増加した。
- 測定結果は、プランクの輻射式及び光ファイバでの損失からなる理論式と非常によく一致した。
- 長いファイバをつないだ場合、C-Bandの光子も大量に発生すると予想される。