Single photon spectral imaging with optical transition edge sensors

D. Fukuda [1], Kazuki Niwa [1], Fuminori Hirayama [1], Satoshi Kohjiro [1], Toshio Konnno [1], Naoki Nakada [1,2], Yuki Nakashima [1,2], Nobuhiko Nomura[3], Chigusa Okano[3], Akira Sato[1], Sachiko Takasu[1], Hirotake Yamamori[1], Ryo Yamamoto[1], Yutaka Yawata[3]

[1] AIST, [2] Univ. Tokyo, [3] Tsukuba Univ.

22-26 JULY 2019 MILANO LTD 18 LOW TEMPERATURE DETECTORS

LTD-18, Milano, Italy, 21 July, 2018
Low Temperature Detector Applications

National Institute of Advanced Industrial Science and Technology AIST

Why imaging at low photon flux?

- Bio-imaging
  - Transmission/Fluorescence/Phase shifted
  - Biological effect triggered by single photons (ex. retina phototransduction)
  - Fragile/delicate sample (optical damage/ Photobleaching)
- Quantum imaging
  - Single-photon emitter (ex. Quantum dots in GaAs, NV centers in diamond)
  - Quantum ghost imaging and spectroscopy
  - Quantum illumination

⇒ There are strong demands for imaging at ultra low intensity photon flux.

Challenges

- Diffraction limit
- Shot noise limit

Are there any enhancement to these qualities at extremely low photon flux imaging ?

Overcome restrictions

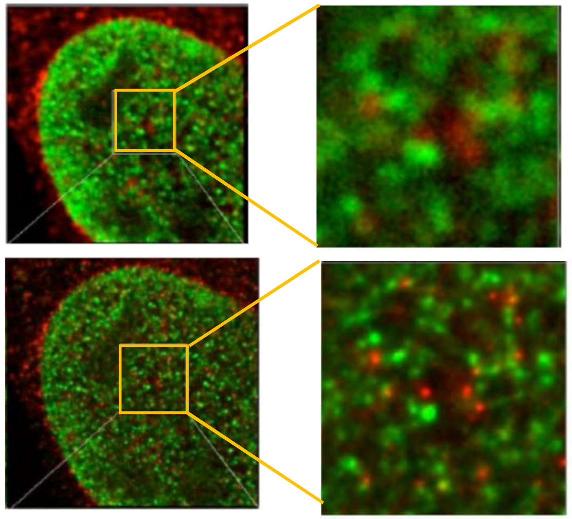
- Diffraction limit (DL)
  - The maximum obtainable imaging resolution
  - Abbe's law: $$R \simeq \frac{0.61\lambda}{NA}$$

Super-resolution imaging with $R < DL$ can be possible;

Stimulated emission depletion (STED) and Ground state depletion (GSD)

Standard confocal microscope

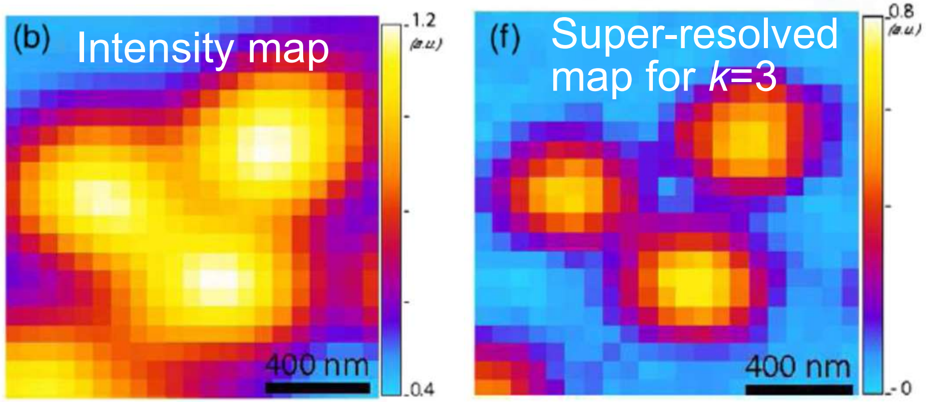
STED



Pictures are from Leica HP

- won by Nobel Prize in 2014.
- Highly non-linear optical absorption

Super-resolution via non-classical photon statics PRL 113, 143602 (2014).



Auto-correlation function $$g^{(k)} = \frac{\langle \Pi_{i=0}^{k-1}(\hat{N} - i)\rangle}{\langle \hat{N} \rangle^{k}}$$

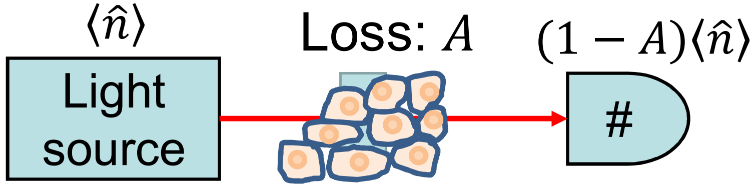
Enhancement $R \propto 1/\sqrt{k}$

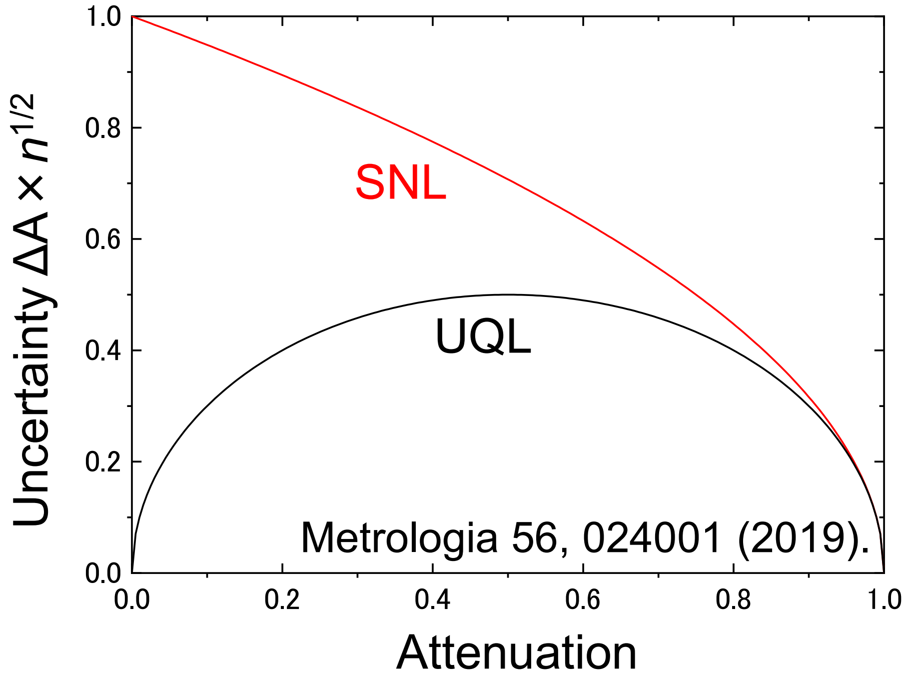
Overcome restrictions

- Shot noise limit (SNL)
  - Sensitivity: the minimum measureable variation of the quantity of interest in a certain point.
  - In classical, plane wave is expressed by a coherent state;

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

- In non-classical sources;
  - Possible to surpass the SNL by using like Fock states. $|n\rangle$
  - Restricted by the ultimate quantum limit (UQL)





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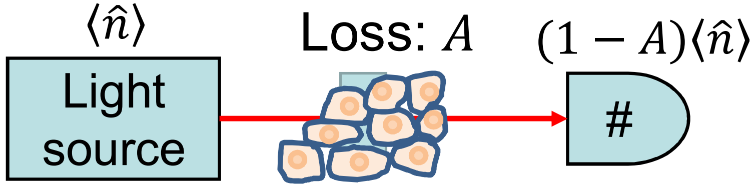

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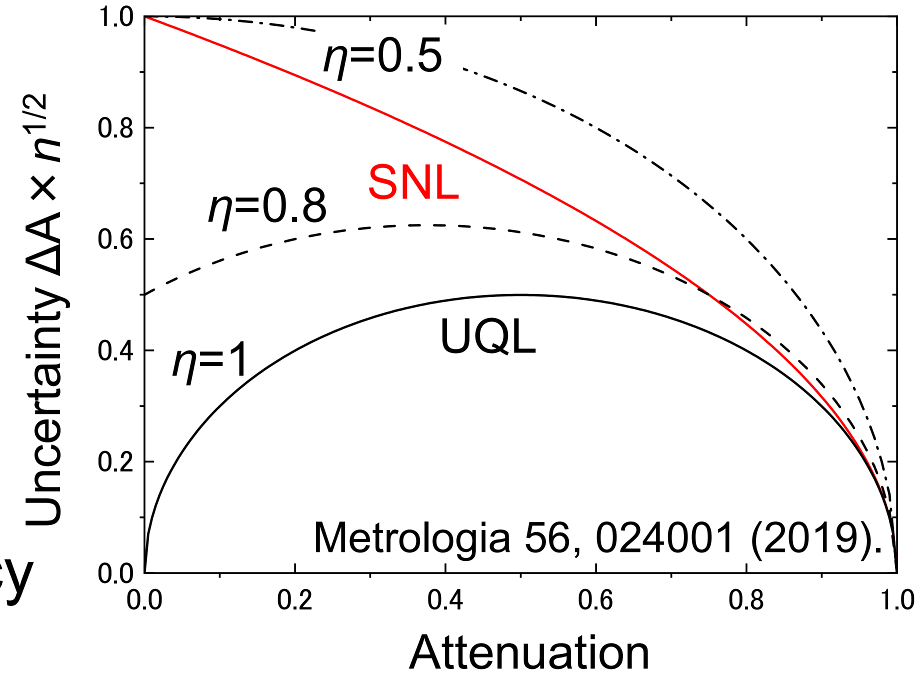
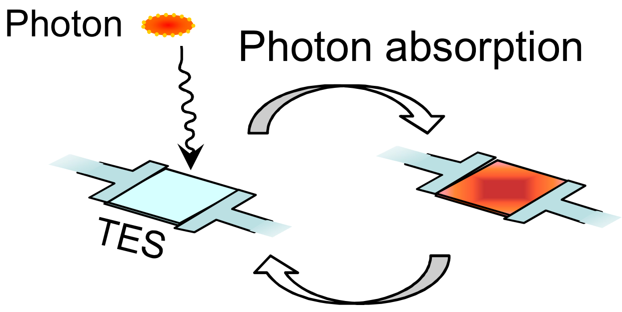
→ high detection efficiency is crucial.



Optical TES

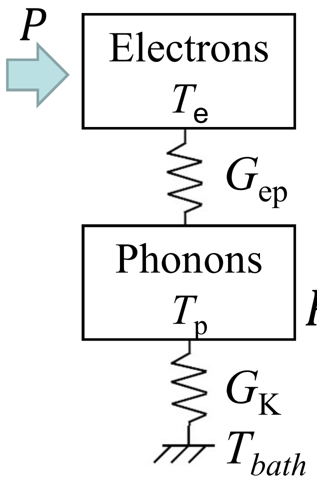
$E = h\nu \sim 0.8 - 3$ eV



Recovery $(\tau \propto T_c^{-3})$

Thermodynamic system of “Hot electron effect”

Phys. Rev. B, 49, 5942, (1994).



$$P = \Sigma\Omega(T_e^5 - T_p^5)$$

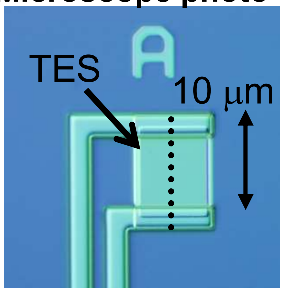
$$P = K(T_p^4 - T_{bath}^4)$$

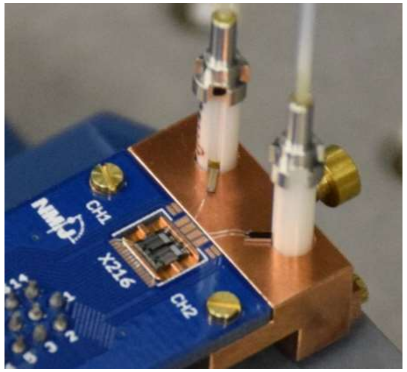
- TES material
  - W : B. Cabrera et al., Appl. Phys. Lett. 73, 735-737 (1998).
    A. E. Lita et al, Opt. Express 16, 3032 (2008).
  - Ti/Au : D. Fukuda et al, Opt. Express 19, 870 (2011).
    L. Lolli et al., Appl. Phys. Lett. 103, 041107 (2013).
  - Ir : Y. Miura et al, J. Low Temp. Phys. 193, 344-348 (2018).
- Energy resolving capability: $\Delta E \sim 0.1 - 0.2$ eV
- Signal response: $\tau_{\mathrm{ETF}} \sim 100$ ns – few μs, $\tau_{\mathrm{jitter}} < 10$ ns
- Detection efficiency: $\eta > 0.9$ at fixed λ
- Negligible dark count or dark count free

Optical TES developed at AIST

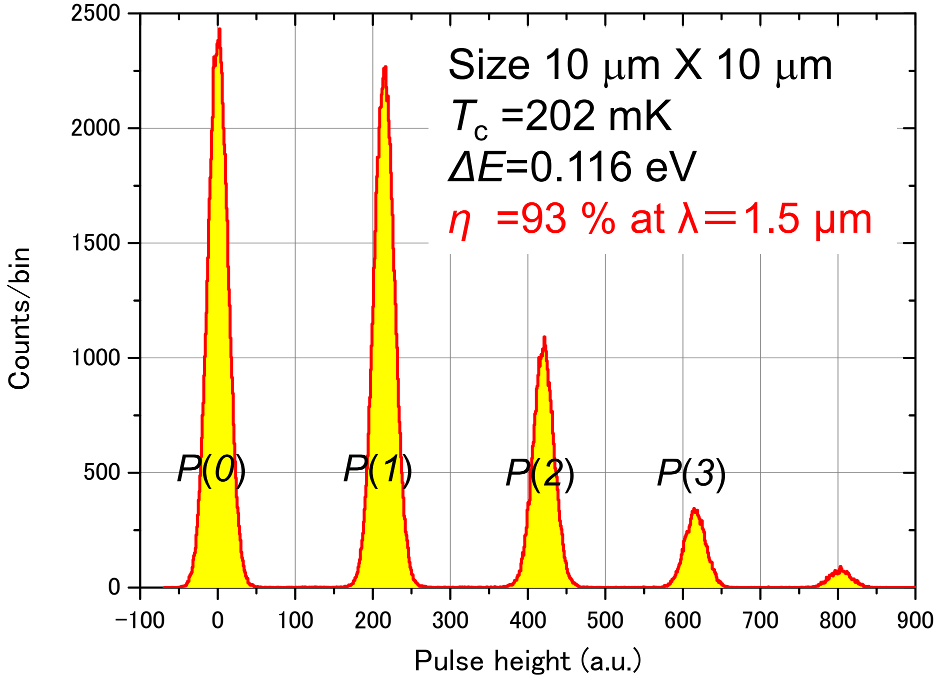
- TiAu TES D. Fukuda, *Opt.Express*, **19**, 870, (2011).
  - Tc: 200 mK~300 mK
  - 10 μm × 10 μm size
- Excellent energy resolution *ΔE*~0.1 eV

Microscope photo



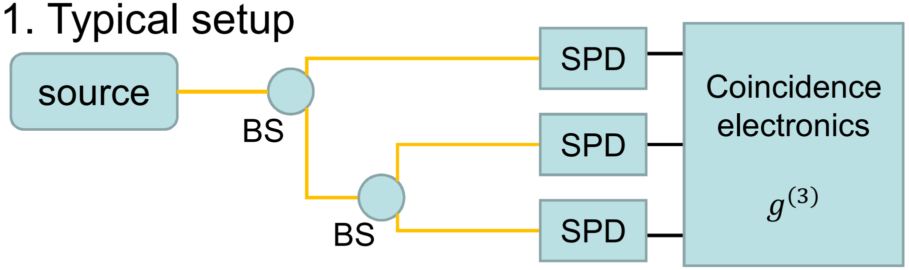


Photon number distribution

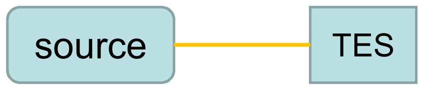


Auto-correlation measurement

1. Typical setup



2. Setup with TES



$$g^{(k)} = \frac{n^{(k)}}{\langle n_{\mathrm{exp}} \rangle^k}$$

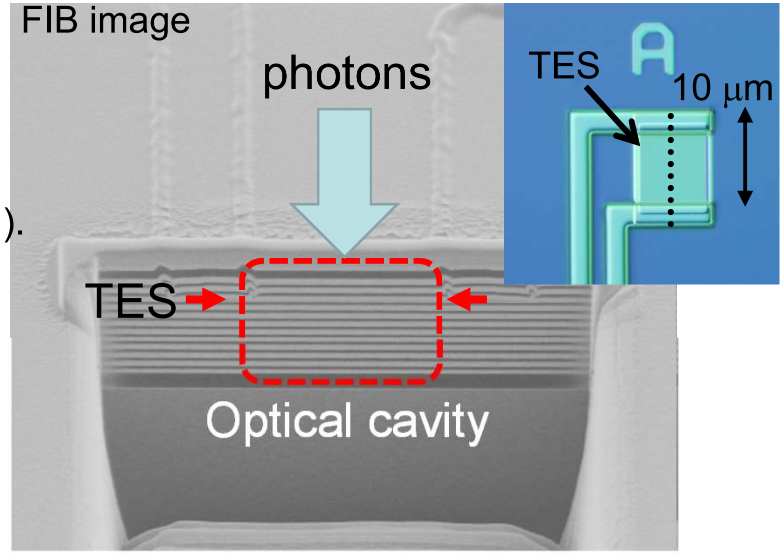
$$n^{(k)} = \sum_{n=k}^{\infty} \frac{n!}{(n-k)!} P(n), \qquad \langle n_{\mathrm{exp}} \rangle = \sum_{n=0}^{\infty} n P(n)$$

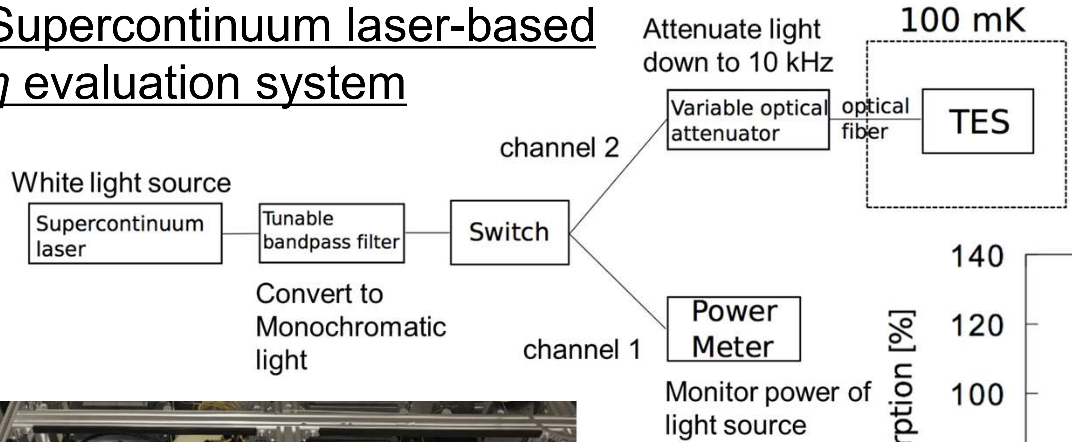
P(*n*): Detection probability for *n* photons

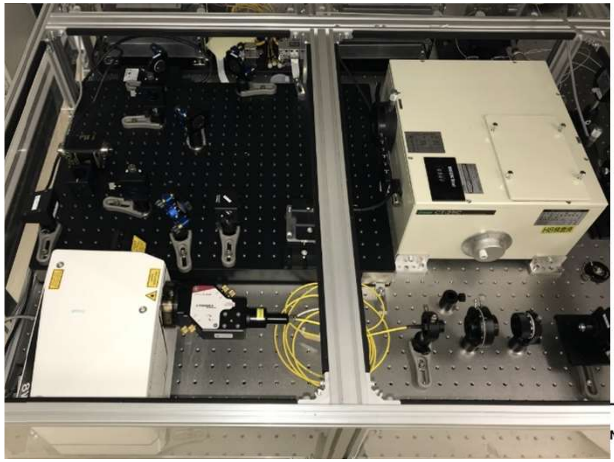
K. Wakui et al, *Sci. Rep.* 4, 4535 (2014).

Optical TES developed at AIST

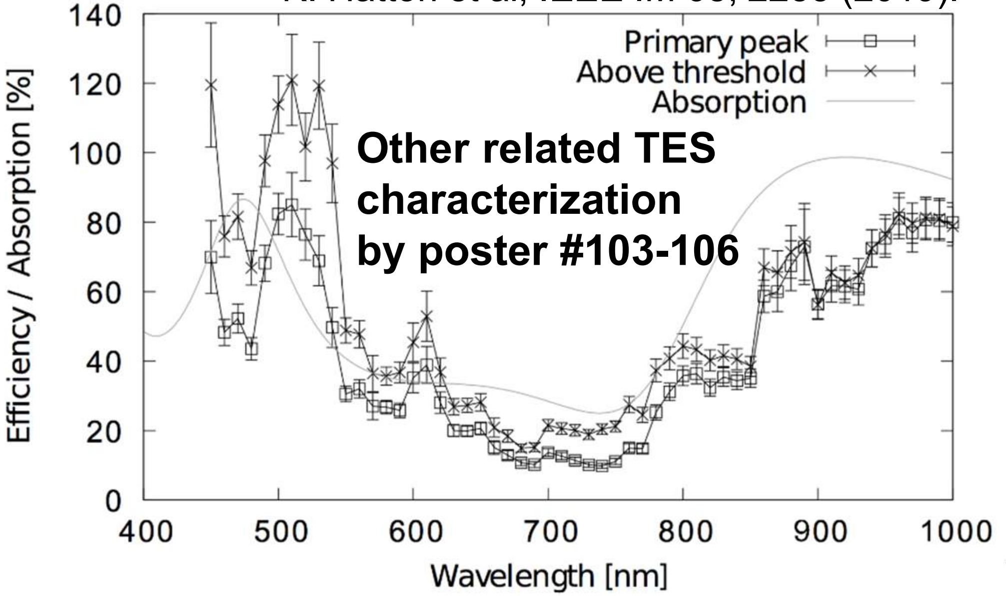
- TiAu TESs embedded in a photon absorption cavity by dielectric-multi layered films. D. Fukuda, *Opt.Express*, **19**, 870, (2011).
- Efficiency *η* 98 %@850 nm







K. Hattori et al, IEEE IM 68, 2253 (2019).



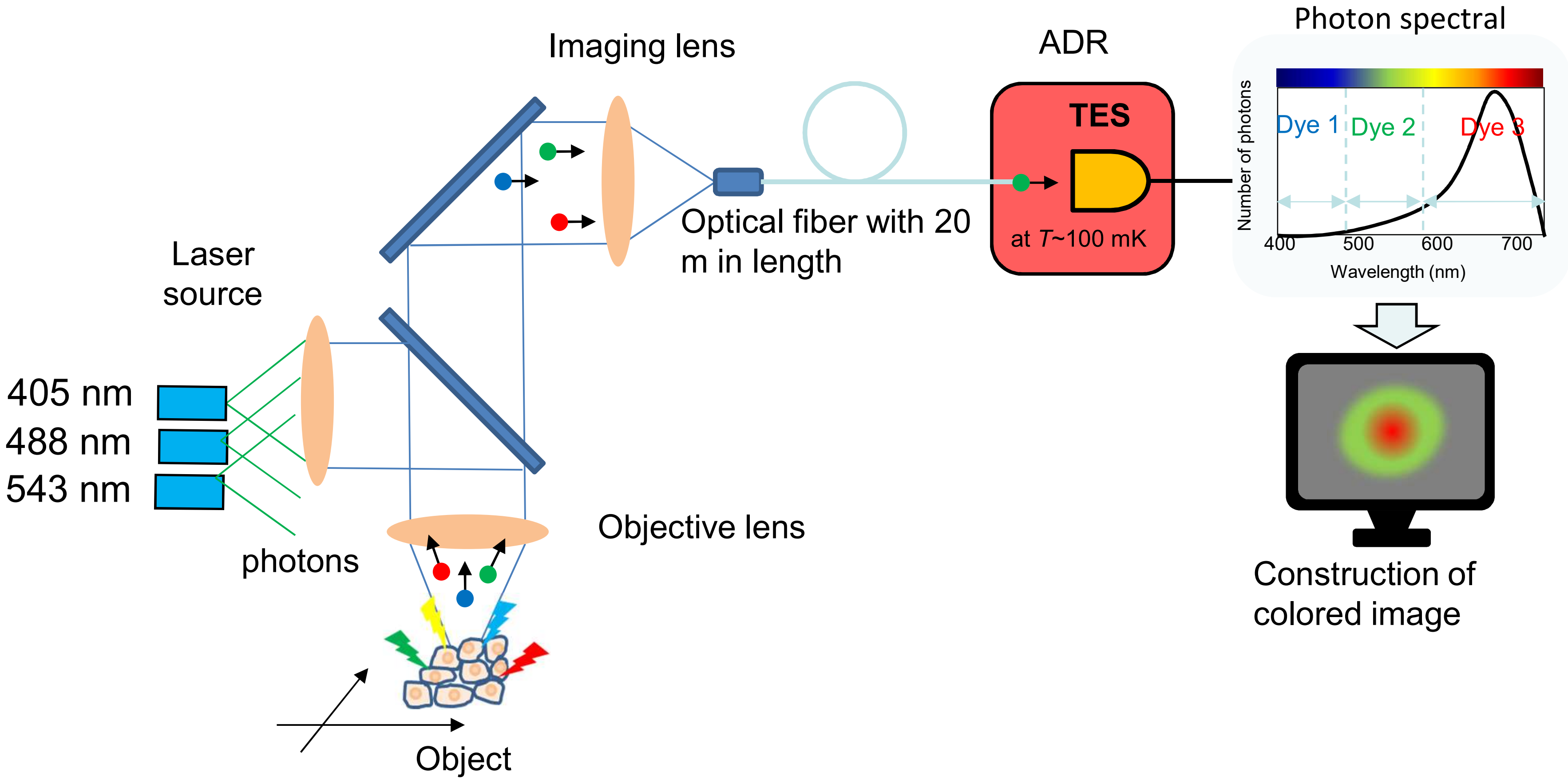
Other related TES characterization by poster #103-106

Single photon spectral imaging with TES

- RGB-color imaging
- Confocal microscope

K. Niwa et al, Sci. Rep. 6, 45660 (2017).

D. Fukuda et al, J. Low Temp. Phys. 193, 1228 (2018).

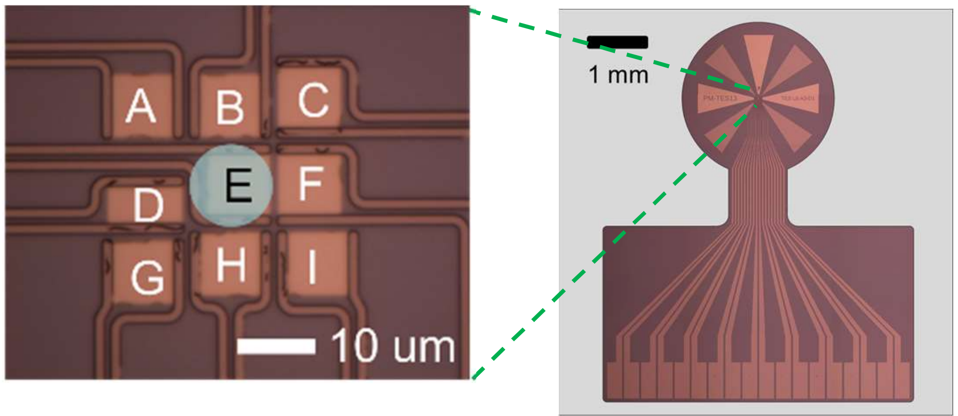


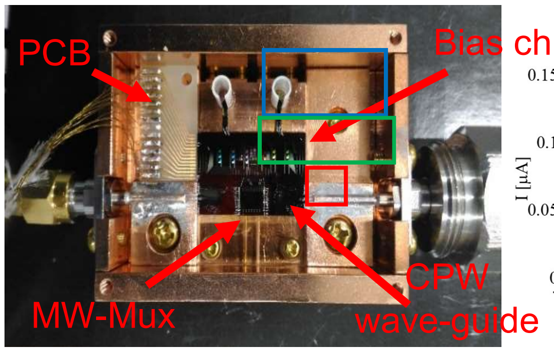
Current & Future outlook

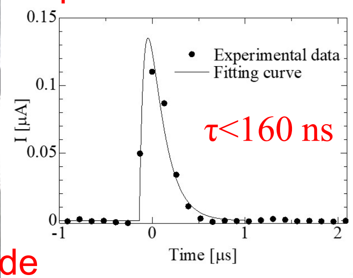
- Challenge to real time single photon imaging
  - Point by point scanning
  - Wide-field by image sensors

Arrayed optical TES by poster #65-75

Readout with MW-Mux by poster #149-109







Cryogenic Module

Summary

- Imaging at extremely low intensity of photons are very beneficial;
  - to allow response of a system at few photons level
  - to make it possible to obtain high resolution below Abbe's DL and high sensitivity beating SNL
- Confocal microscope with TES have shown promising results for single photon spectral imaging at low excitation laser power.

- Future work: TES based imaging sensor