

State of progress in THz and broadband spectrum manipulation group

**Takeshi Yasui
(Tokushima University)**

**Minoshima ERATO 3rd group meeting
(June 6, 2015@Tokushima Univ.)**

Group members

Group Leader : Prof. Takeshi Yasui

Sub-Group Leader:

Drs. Yasuhiro Mizutani and Hirotsugu Yamamoto

Senior Member:

Prof. Tetsuo Iwata, Dr. Takeo Minamikawa (July 1~)

Postdoc:

Drs. Yi-Da Hsieh and Dahi Ibrahim

PhD Students (RA):

Eiji Hase and Kyuki Shibuya

MS Students:

Ogura, Ogawa, Miyamoto, Mizuguchi

Secretary:

Yumi Sumino and Natsuko Takeichi

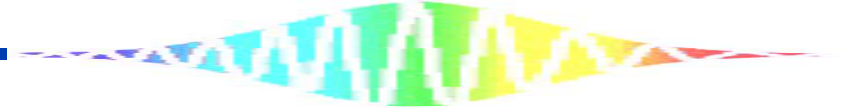
Research topics

(1) Intelligent THz instrumentation and application

- Adaptive sampling, gapless THz-DCS with dual free-running lasers (M1.Mizu)
- THz spectrum analyzer with a single free-running laser (M2.Ogura)
- THz digital holography (M1.Ogawa)

(2) Novel optical comb measurement and application

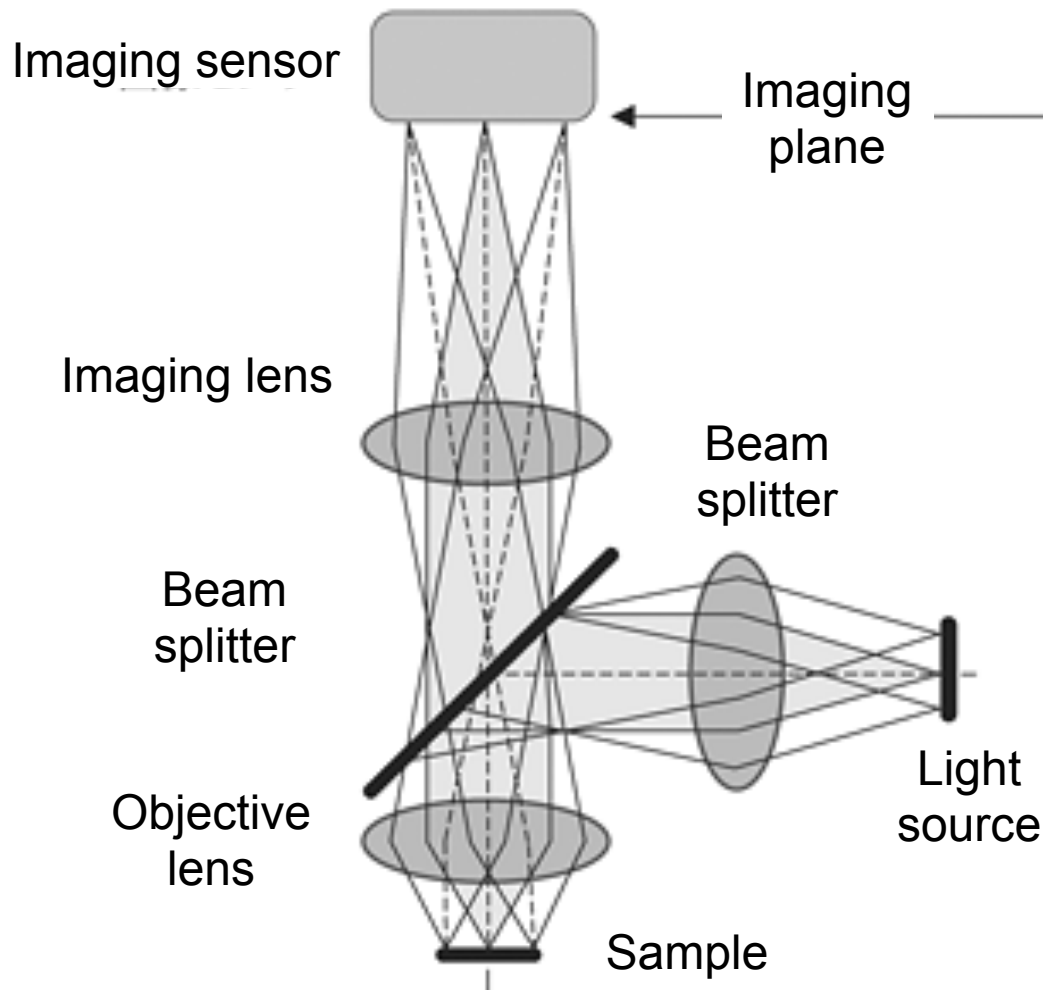
- Scan-less, full-field confocal microscopy (D2.Hase & M1.Miya)
- Ellipsometry (PD.Hsieh)
- Digital holography (PD.Dahi)
- Strain sensing for photoacoustic imaging (M2.Ogura)
- CARS (PD.Harosono & Minamikawa)
- Ghost imaging (D1.Shibuya)



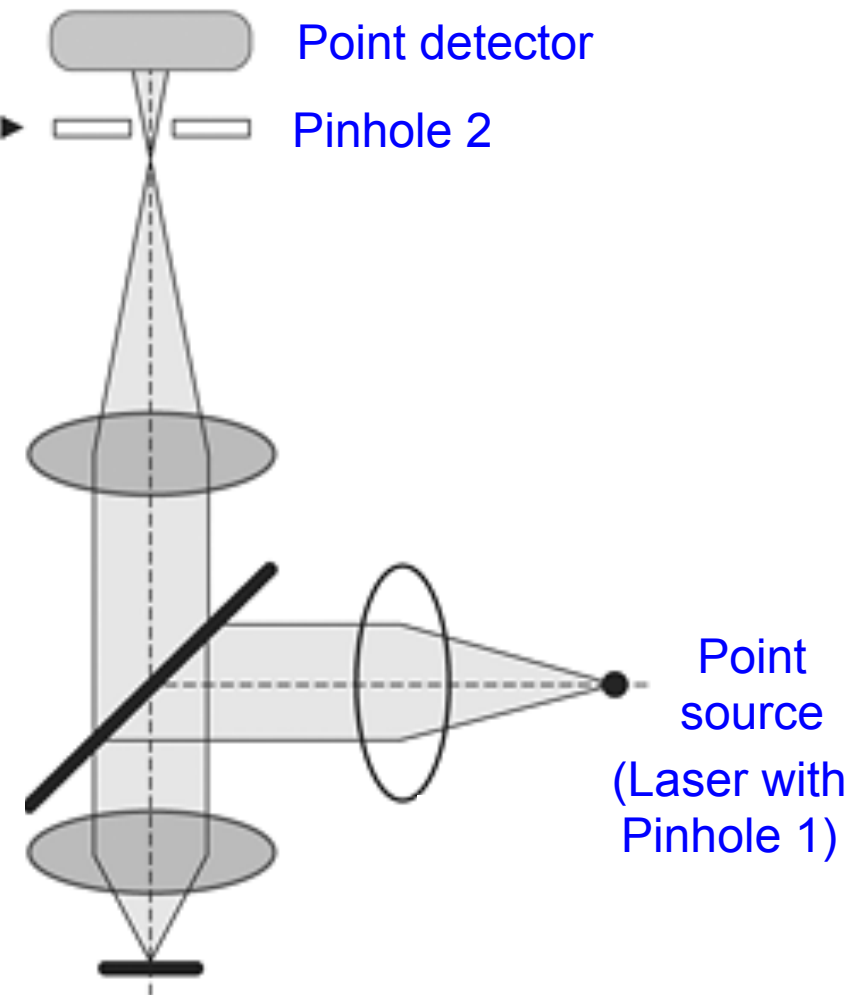
(1) Scan-less, full-field confocal microscopy by use of dual comb technique

Optical microscopy

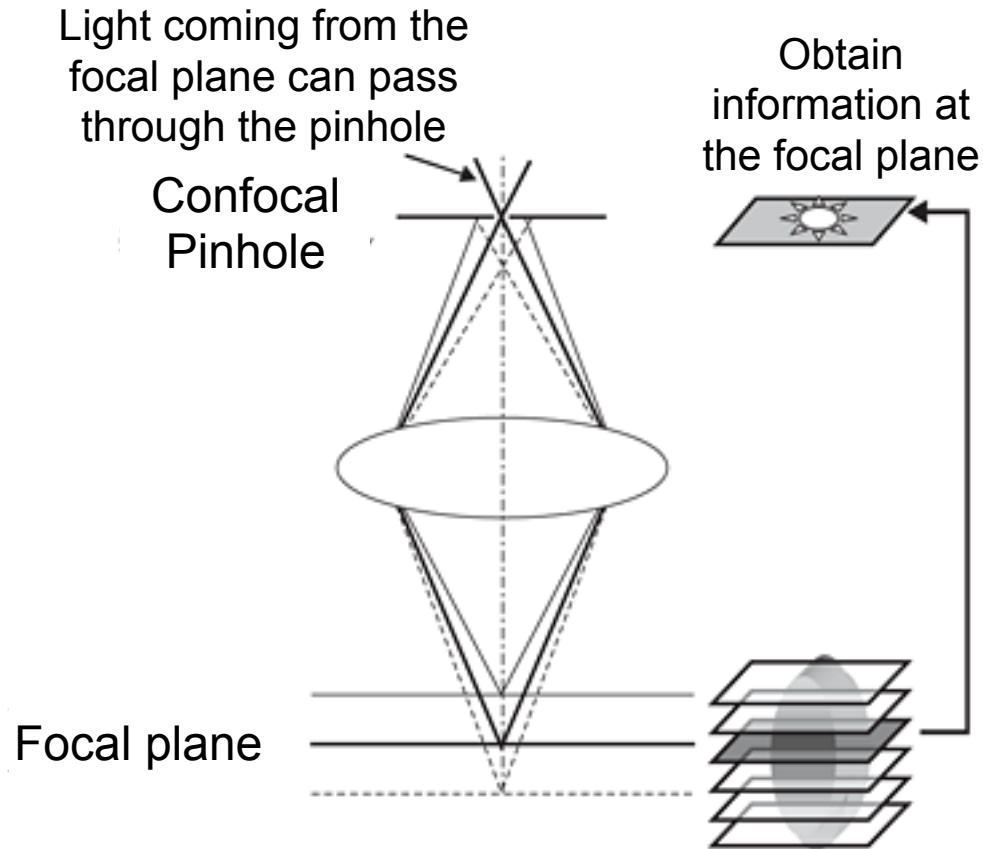
Normal microscopy



Confocal microscopy

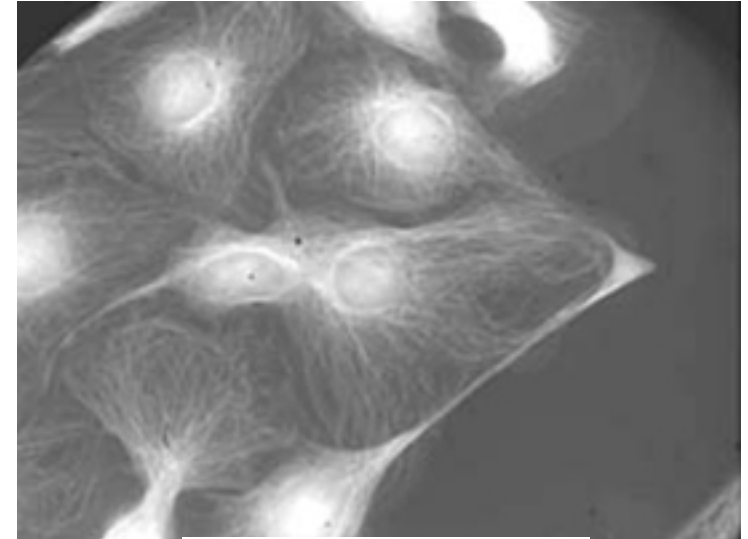


Confocal optical microscopy

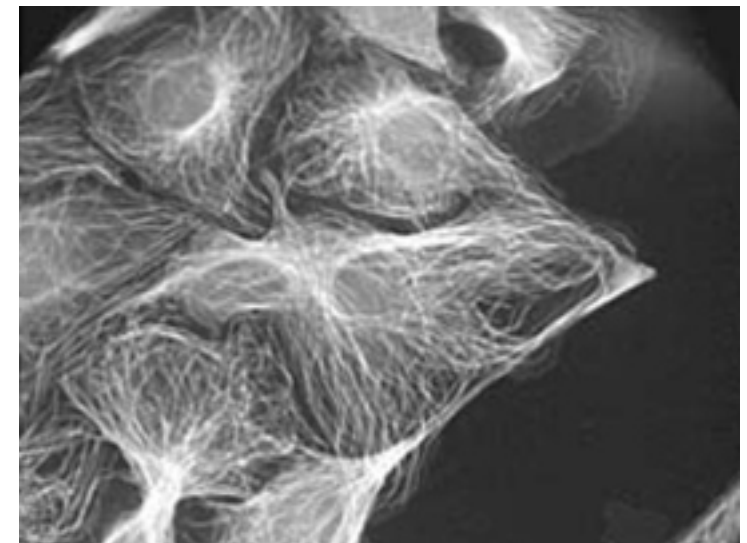


Detect signal at focal plane

- No stray light
- Depth resolution
- Applicable for thick sample

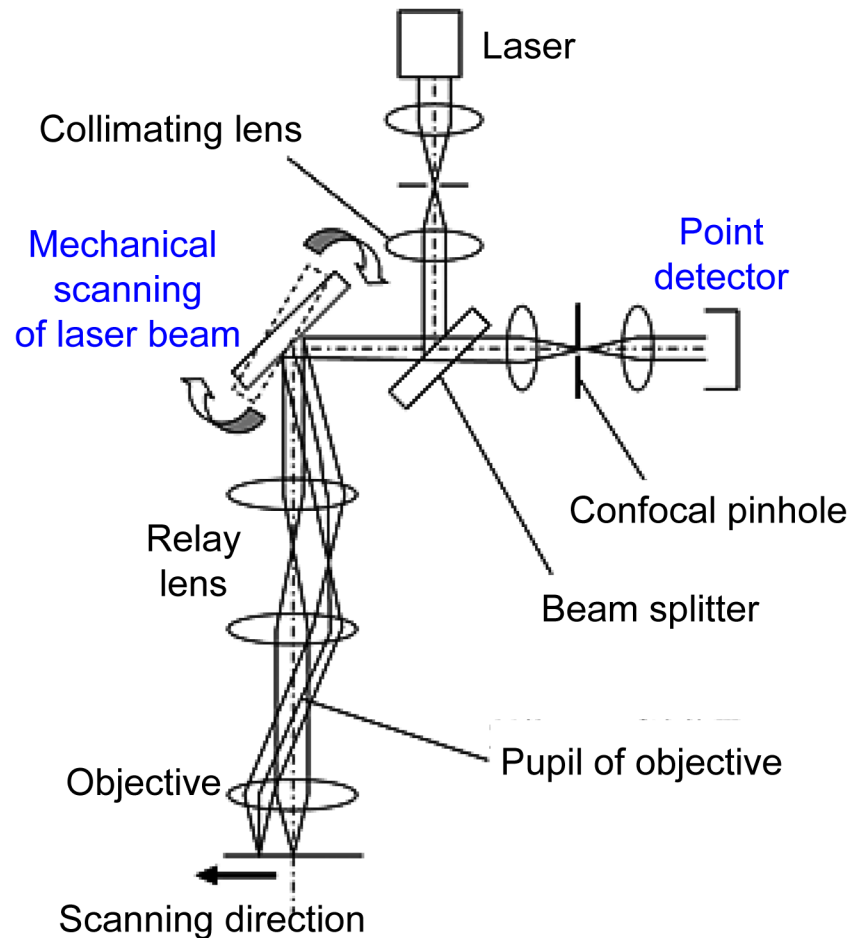


Normal microscopy



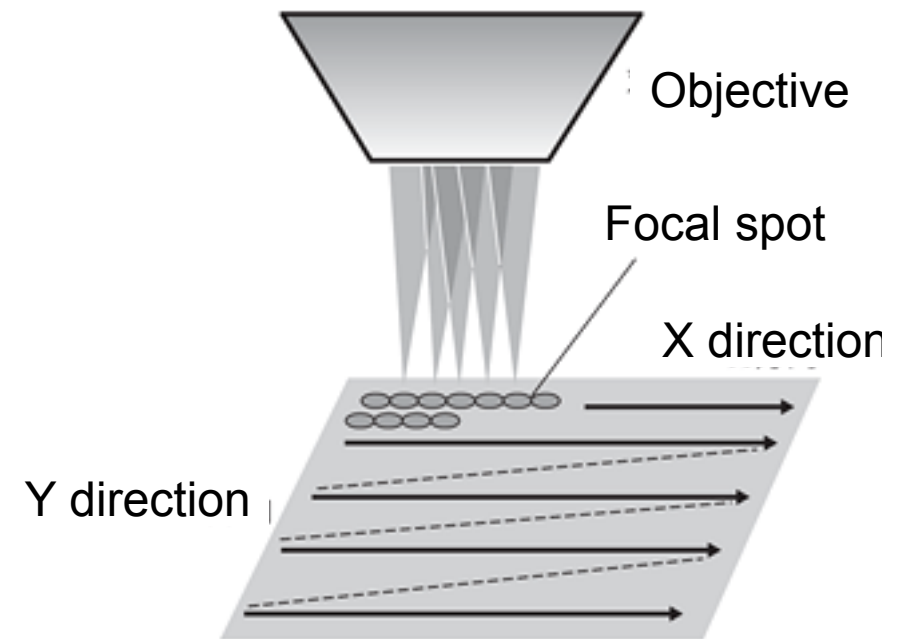
Confocal microscopy

Confocal laser microscopy



Optical configuration

http://bioimaging.jp/learn/023/index_2.html



Raster scanning of a focused laser spot

<http://bioimaging.jp/learn/023/>

Faster image acquisition ! Higher spatial resolution!

Fast confocal microscopy

Conventional

Serial imaging based on mechanical scanning



Optical comb

Proposal

One-shot imaging based on parallel data acquisition

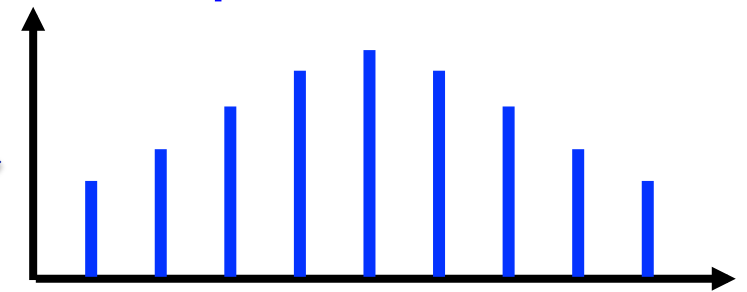


Dimension-converting comb

Temporal
Spatial
Polarization
etc

Convert to
wavelength

Optical comb



Information is superimposed
on each comb mode

Dual comb spectroscopy

Number of comb mode

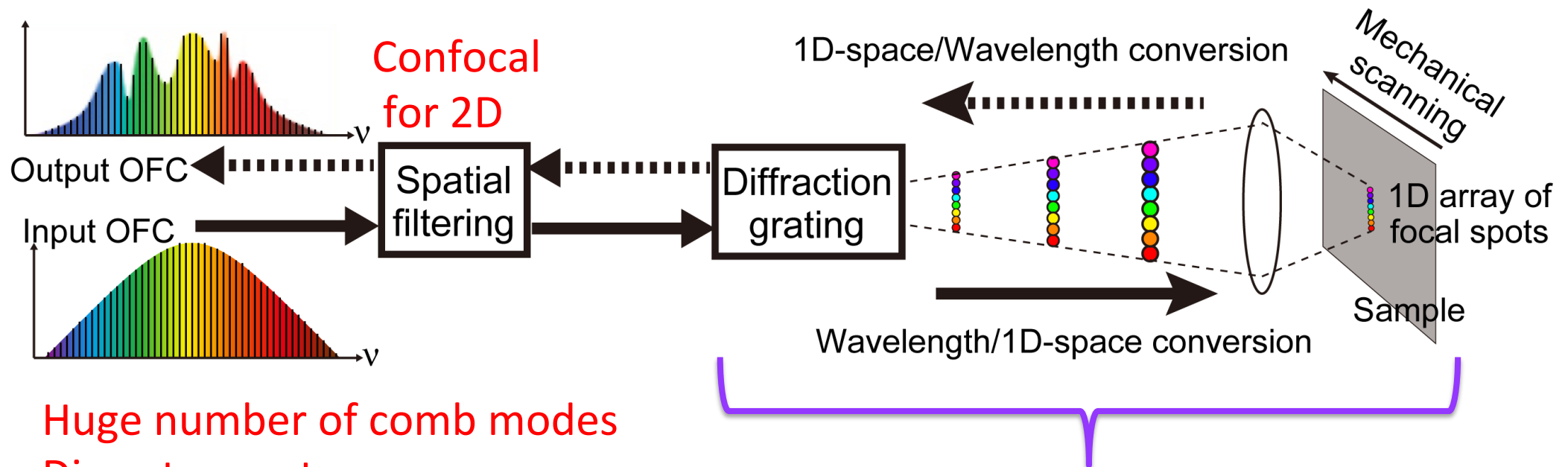
☞ Tremendous channel number

Linewidth of comb mode

☞ Infinitesimal sampling interval

Mode-resolved
comb spectrum

Scan-less line imaging based on bidirectional conversion between wavelength and 1D space

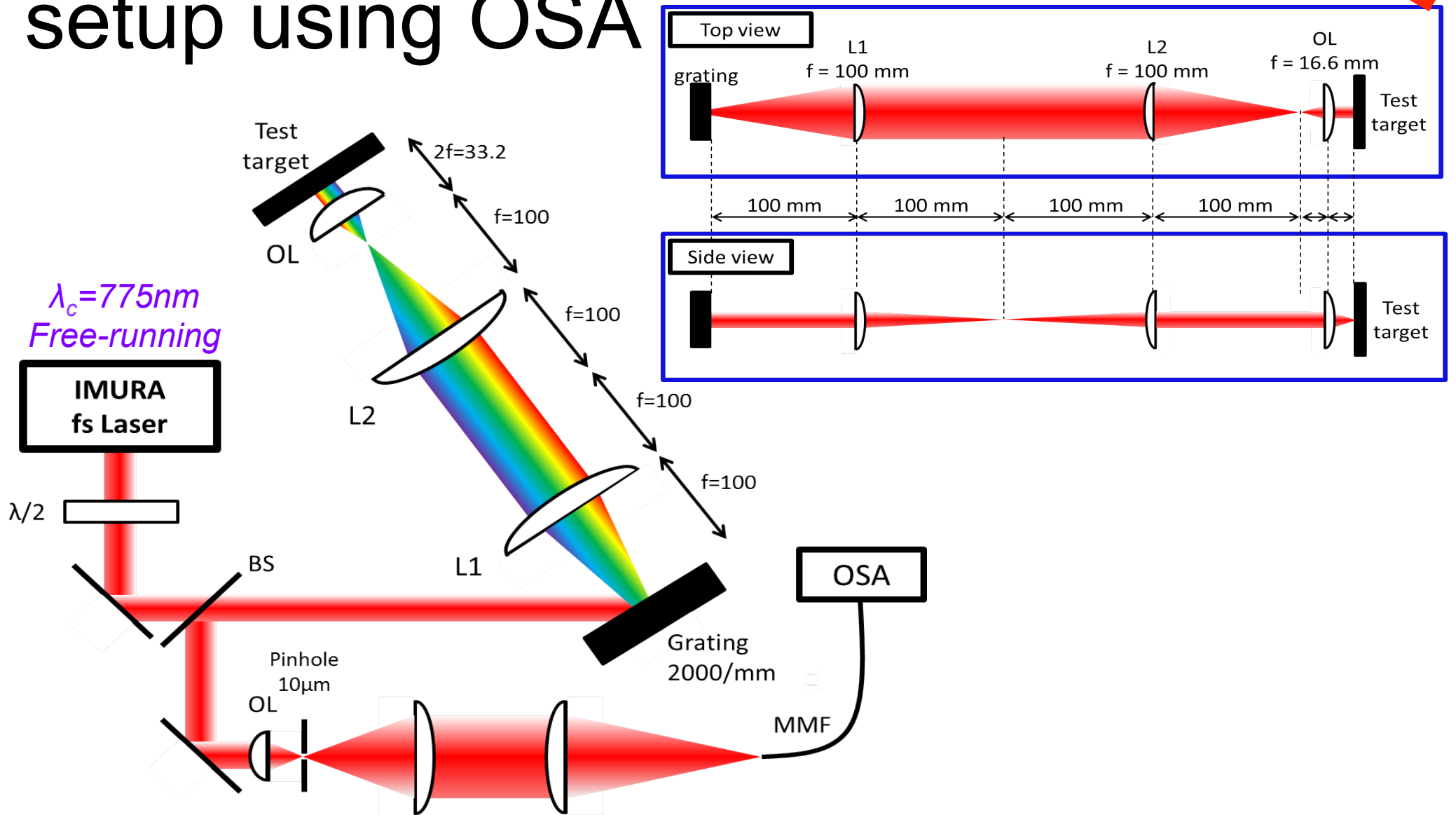


Huge number of comb modes
Discrete spectrum

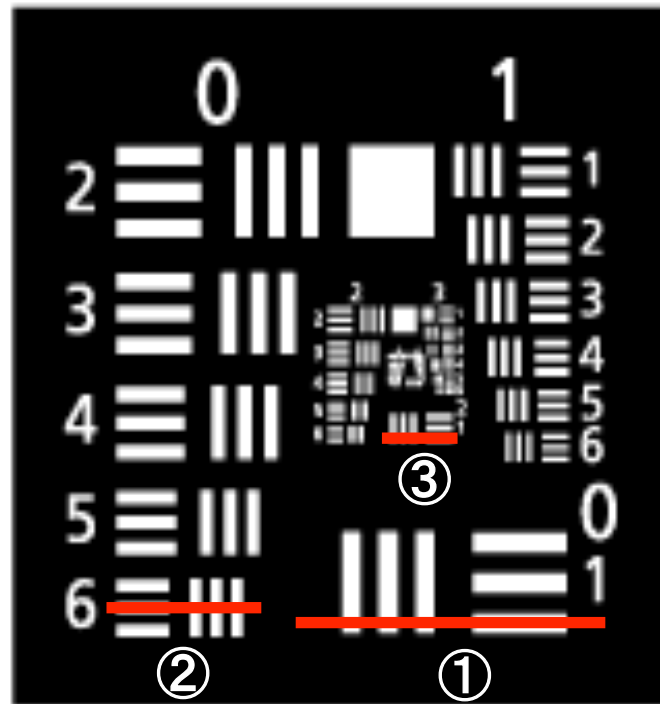
Super-resolution
Ultra-wide DR

Ref) G. J. Tearney, M. Shishkov, and B. E. Bouma,
"Spectrally encoded miniature endoscopy," *Opt. Lett.*
27(6), 412–414 (2002).

Experimental setup using OSA



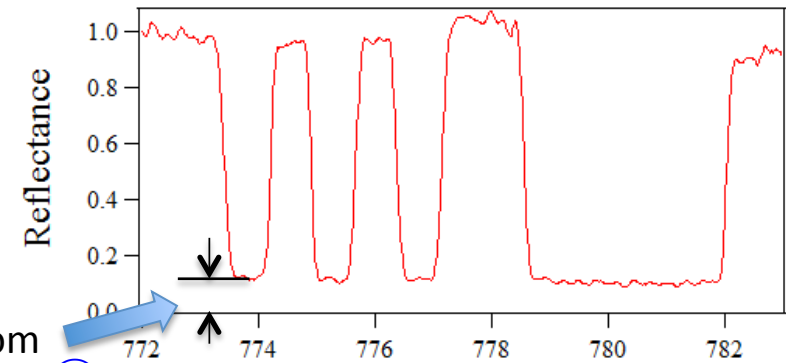
Previous results (spectral profile)



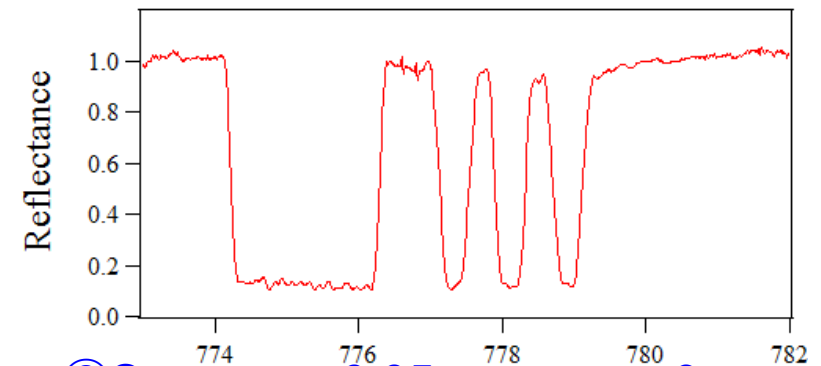
要素番号	0	1	2
1 ①	1.00	2.00	4.00
2	1.12	2.24	4.49
3	1.26	2.52	5.04
4	1.41	2.83	5.66
5	1.59	3.17	6.35
6 ②	1.78	3.56	7.13

③

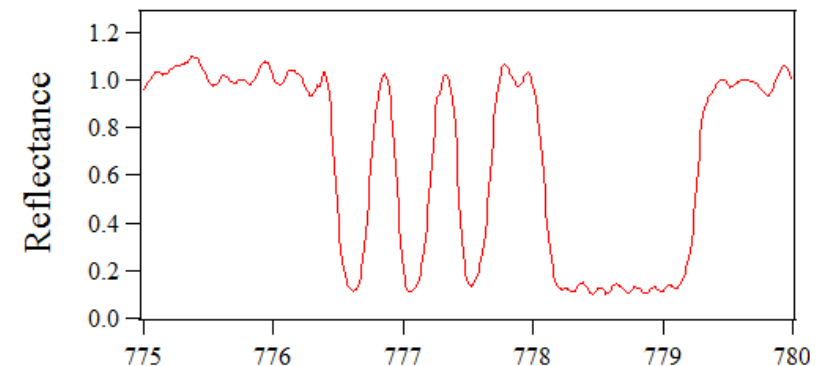
Can not
resolved



① Spec. res=0.1 nm, span=11 nm

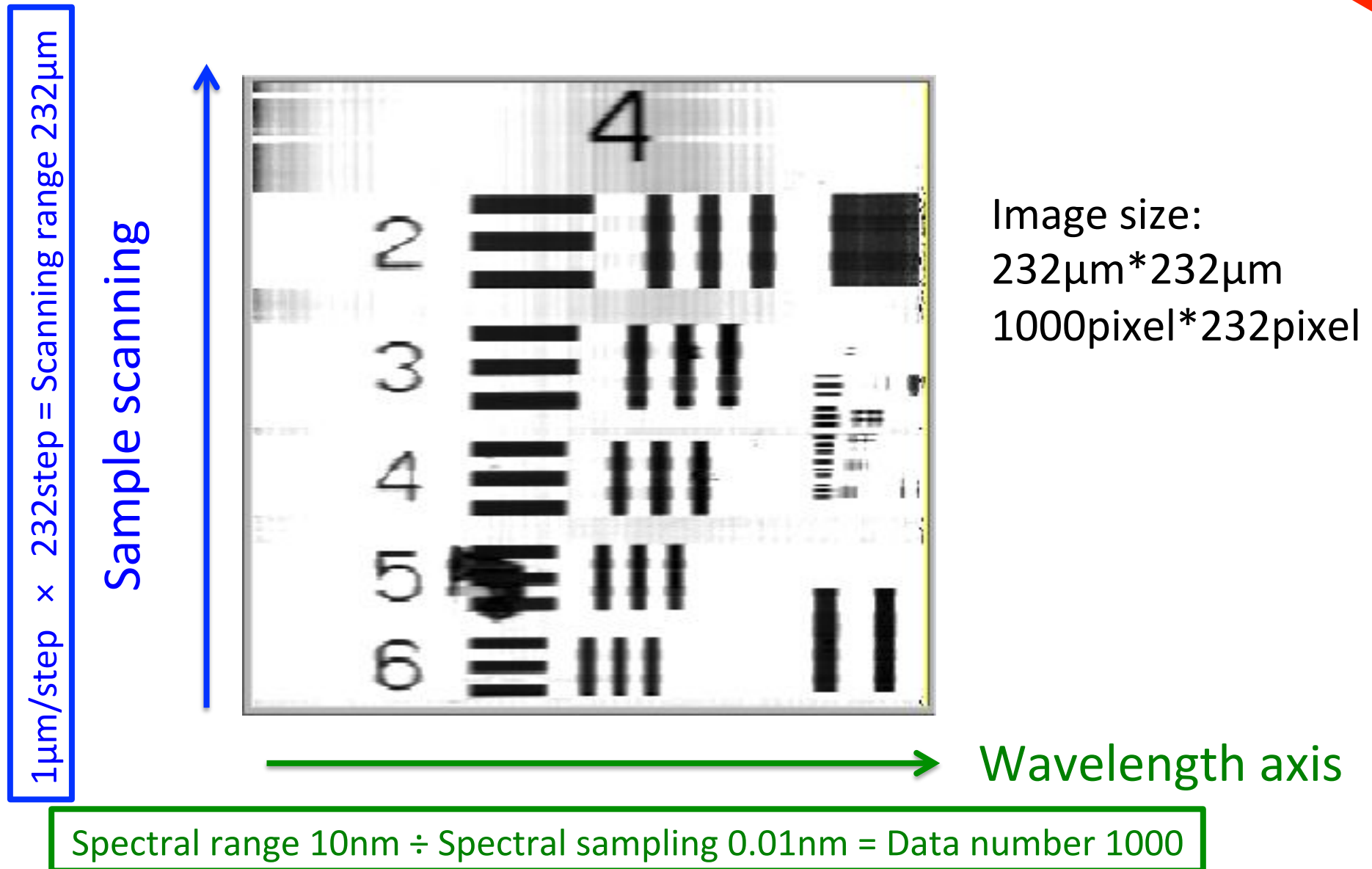


② Spec. res=0.05 nm, span=9 nm

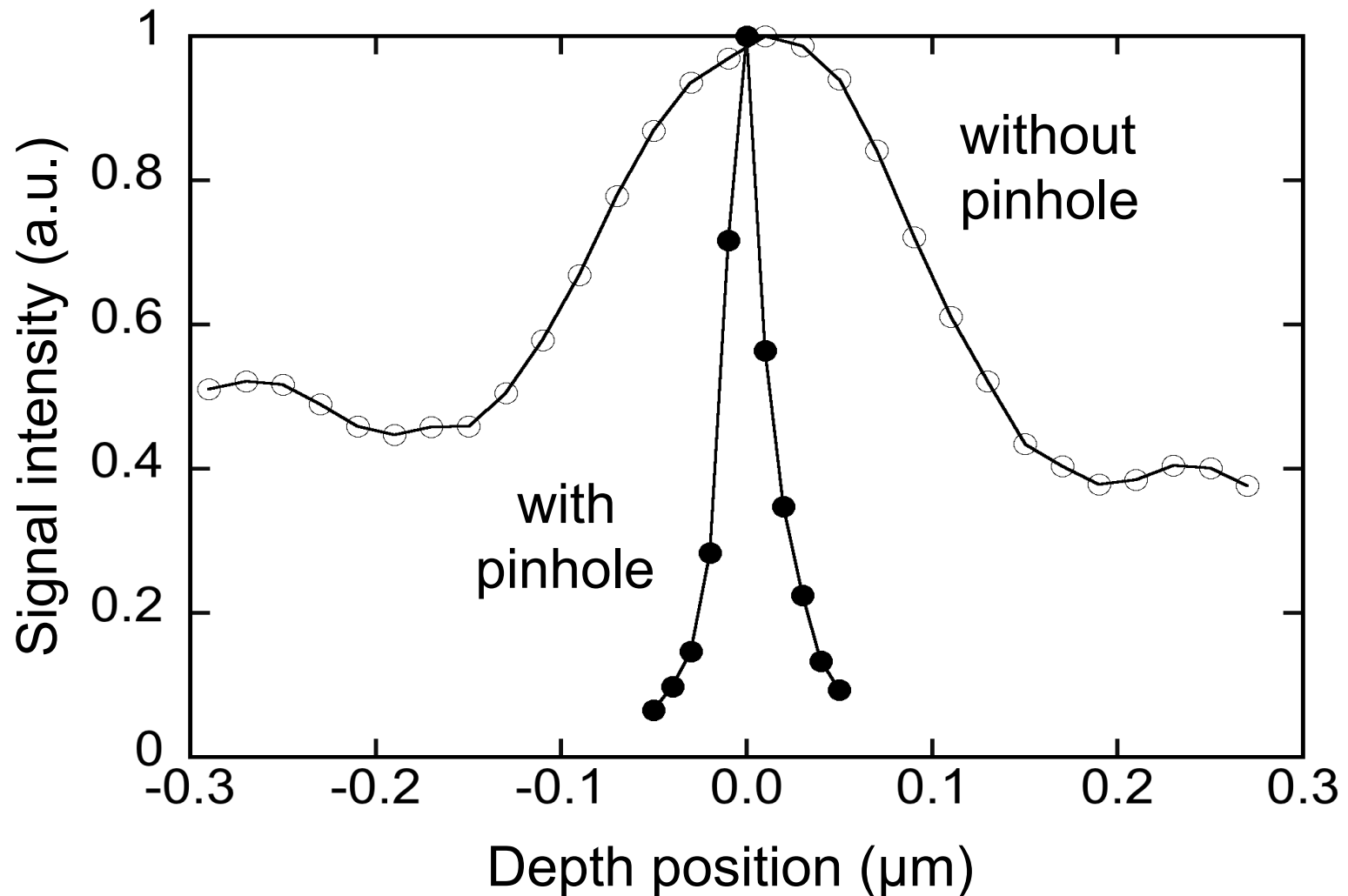


③ Spec. res=0.05 nm, span=5 nm

Reflection image of test chart



Confocal property



Reflection image without pinhole

Confidential

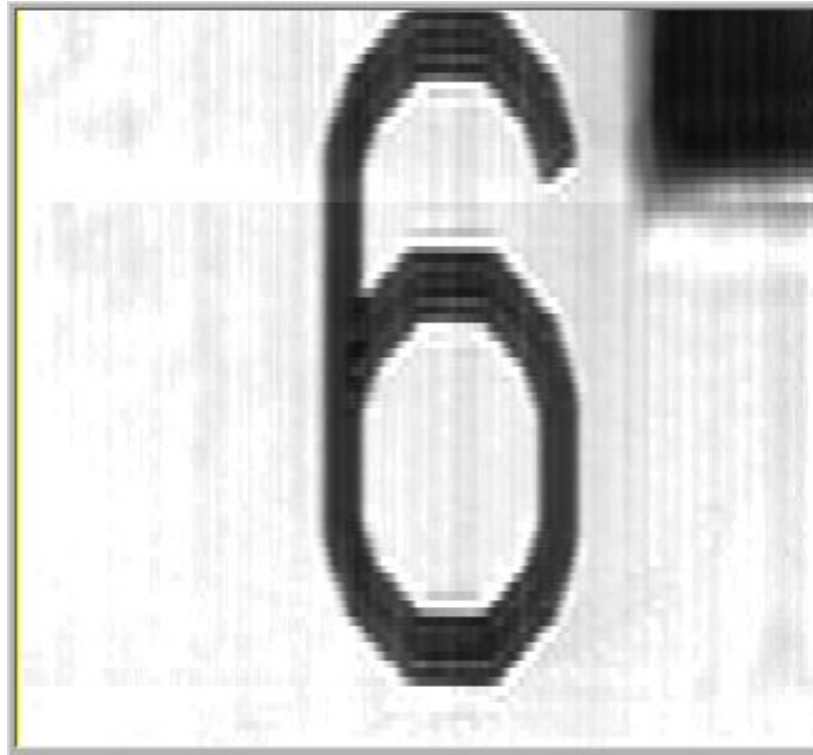
Image size: $100\mu\text{m} \times 100\mu\text{m}$ (1000pixel $\times$ 232pixel)

Depth position = $0\mu\text{m}$

Depth position = $+100\mu\text{m}$

Sample scanning

$1\mu\text{m}/\text{step} \times 100\text{step} = \text{Scanning range } 100\mu\text{m}$



Wavelength axis

Spectral range $10\text{nm} \div$ Spectral sampling $0.01\text{nm} =$ Data number 1000

Reflection image with pinhole

Confidential

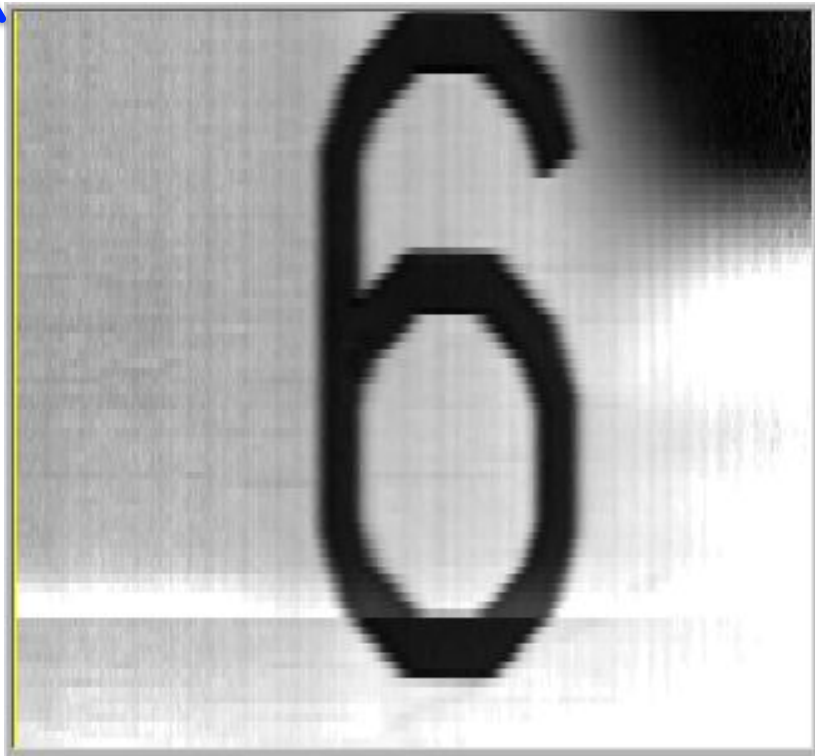
Image size: $100\mu\text{m} \times 100\mu\text{m}$ (1000pixel $\times$ 232pixel)

Depth position = $0\mu\text{m}$

Depth position = $+100\mu\text{m}$

$1\mu\text{m}/\text{step} \times 100\text{step} = \text{Scanning range } 100\mu\text{m}$

Sample scanning

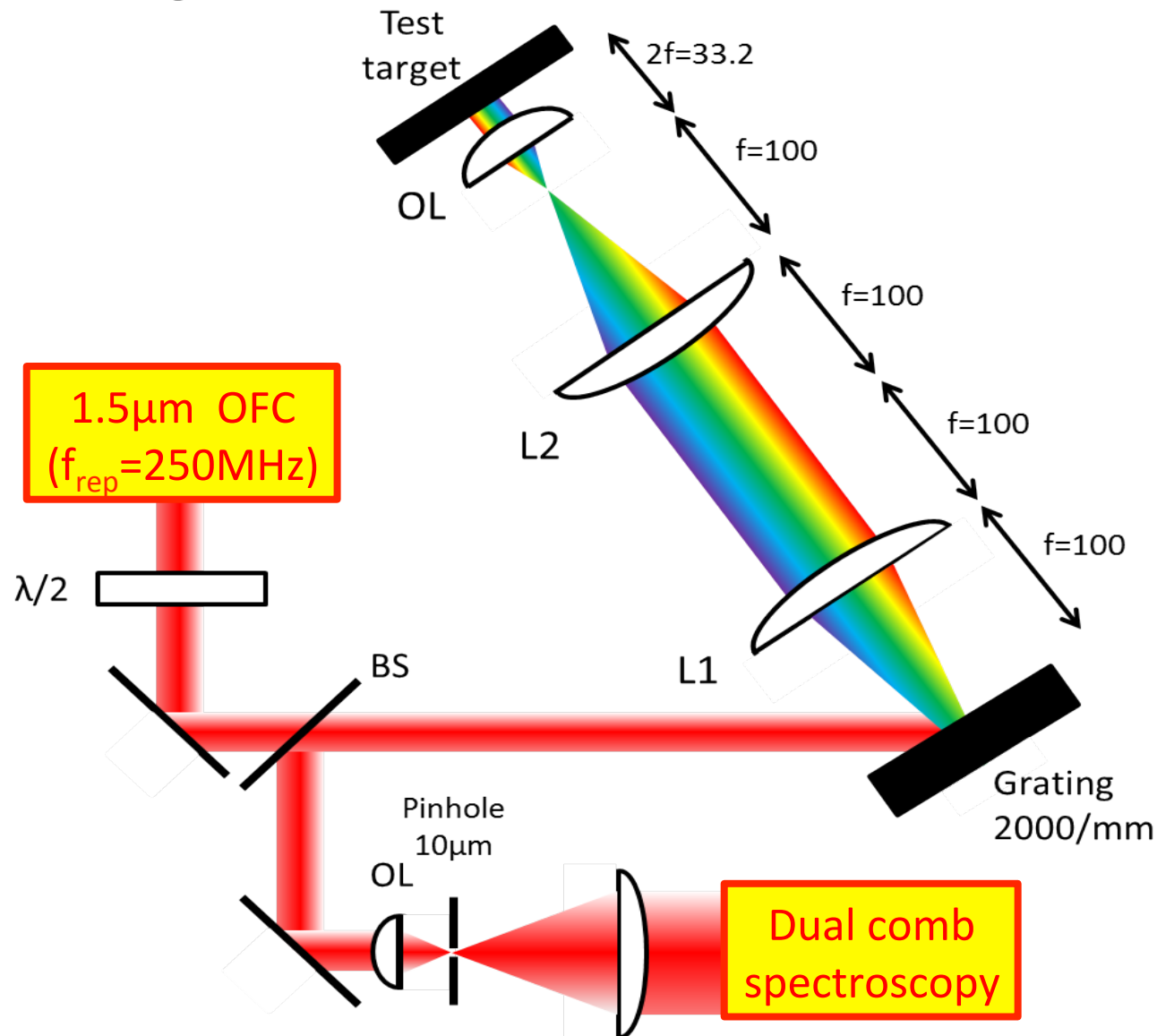


Wavelength axis

Spectral range $10\text{nm} \div$ Spectral sampling $0.01\text{nm} =$ Data number 1000

Experimental setup using dual optical comb

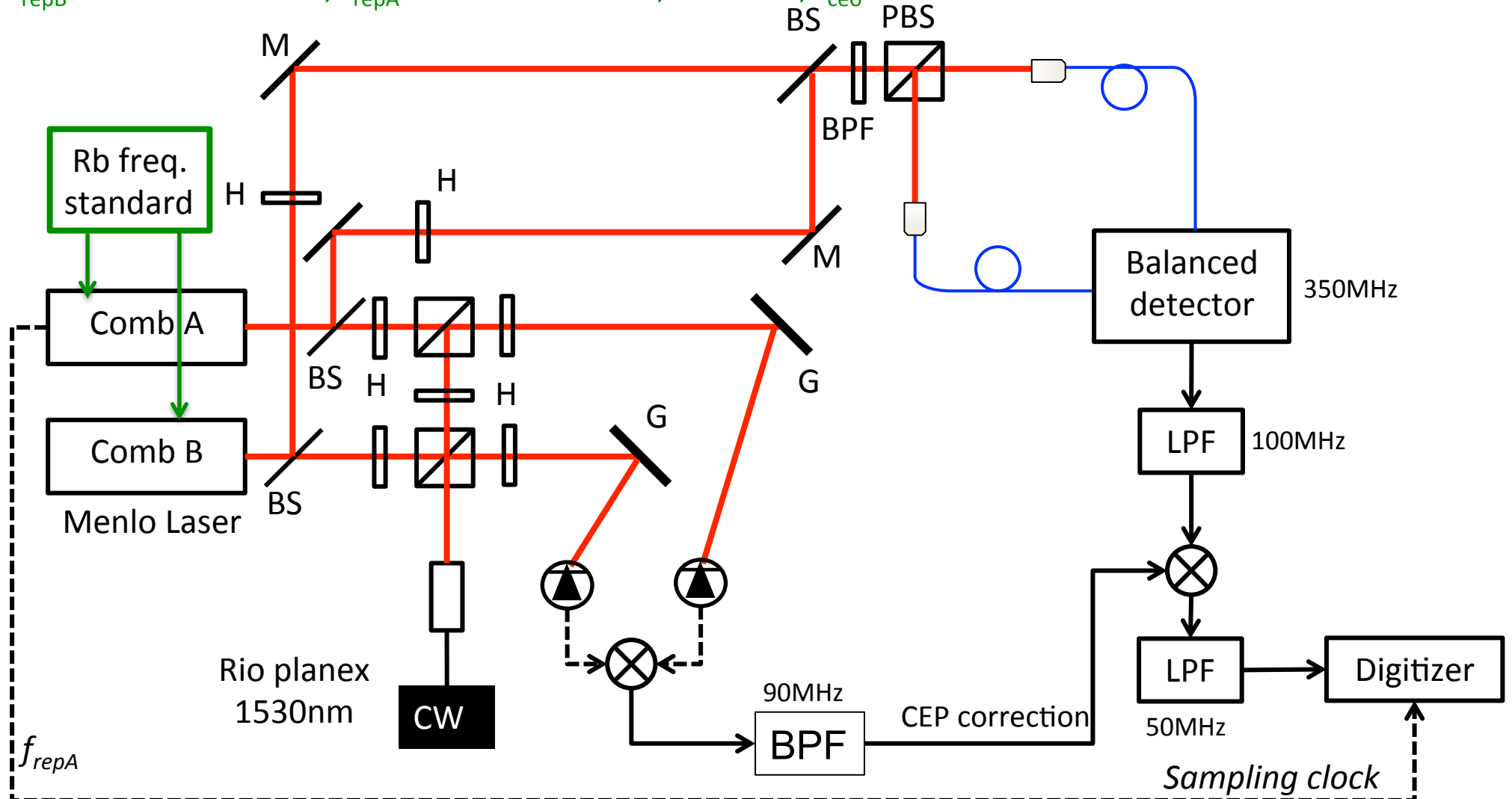
Confidential

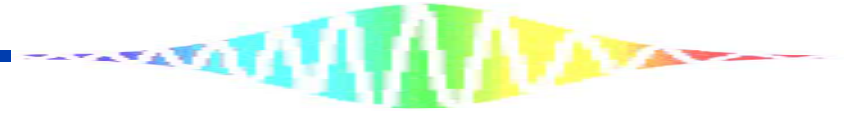


Experimental Setup of dual-comb system

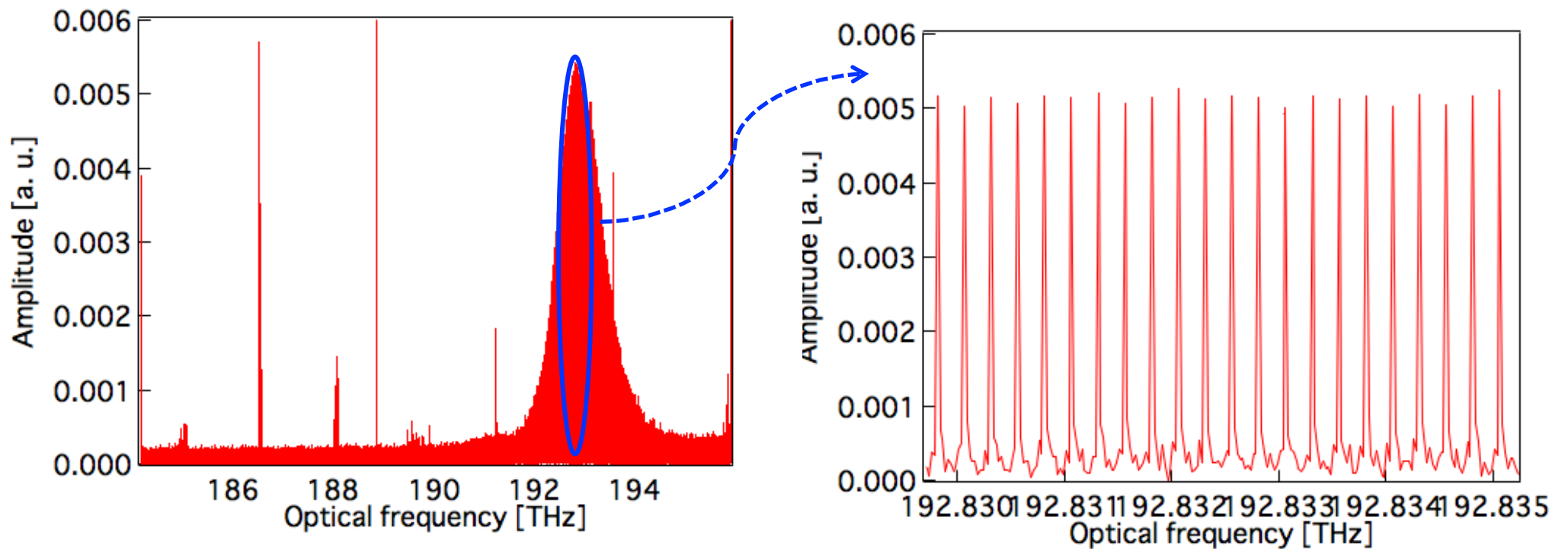
Coherent averaging (Δf_{rep})
Adaptive sampling (Δf_{ceo})

f_{repB} : 250.001484MHz, f_{repA} : 249.998818MHz, $Df=2666$, f_{ceo} : 20MHz





Mode-resolved OFC spectrum



Spatial resolution along λ -axis

Confidential

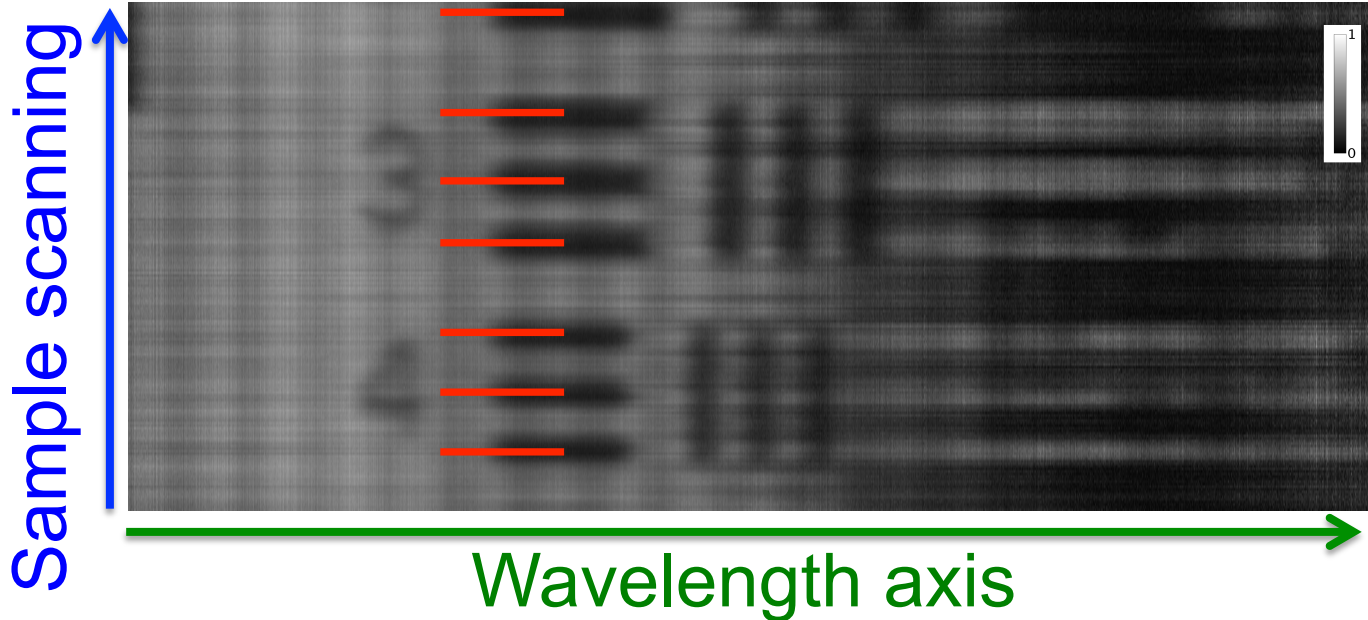
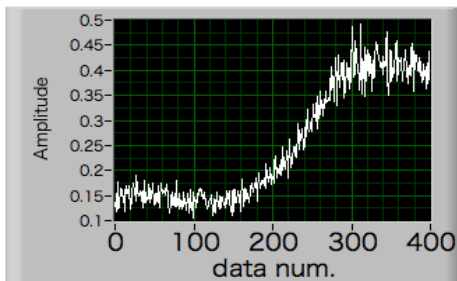


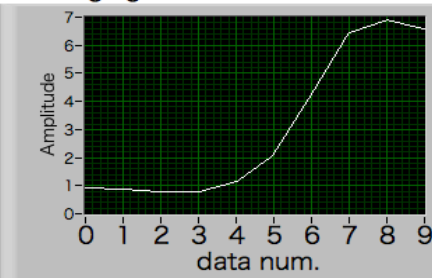
Image size:
200 μm *456 μm
(200 pixel*5000 pixel)

$\delta x^{\text{spatial}}$ = The FWHM of the derivative of the edge response function

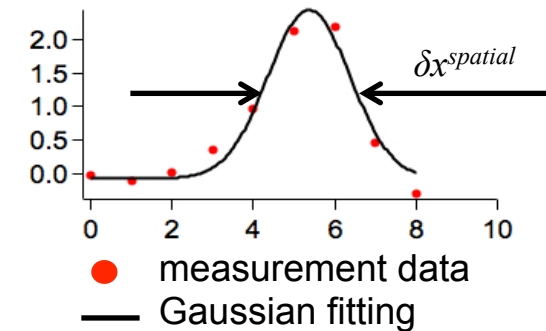
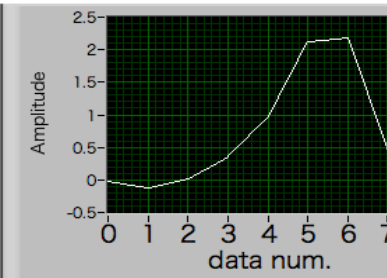
edge response function



Averaging



Differentiation



$$\delta x^{\text{spatial}} = 4.90 \pm 0.19 \mu\text{m}$$

Experimental

$$\delta x^{\text{spatial}} = 3.23 \mu\text{m}$$

Theoretical

Spatial resolution along scanning-axis

Confidential

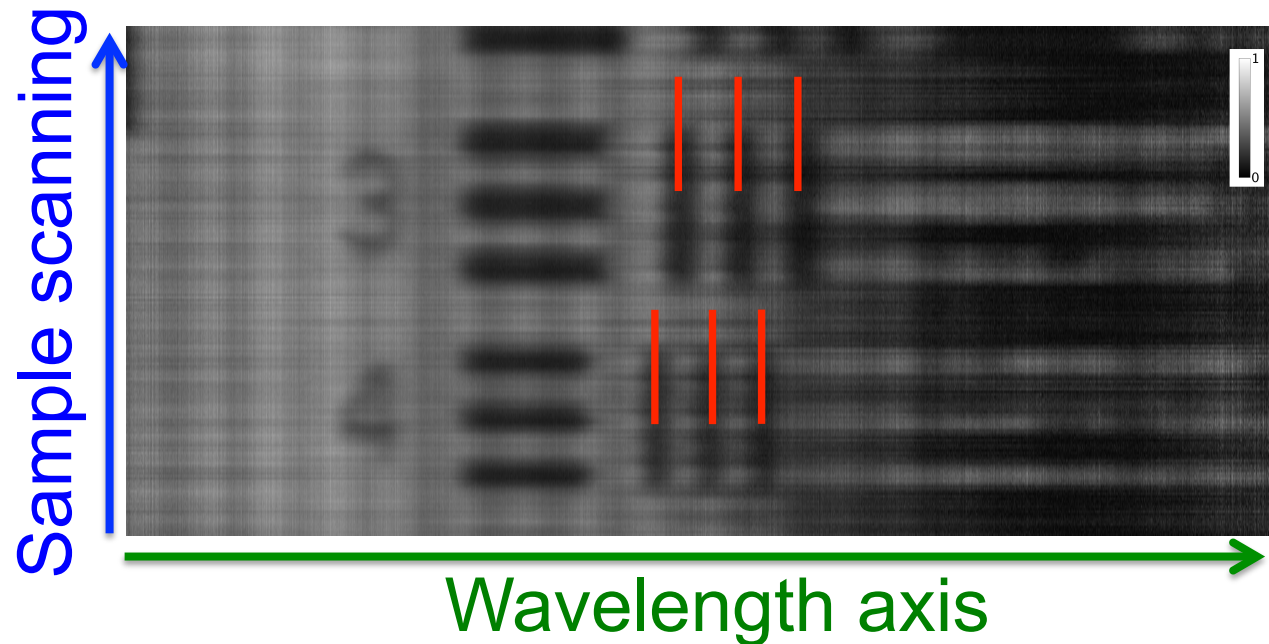


Image size:
200 μm *456 μm
(200 pixel*5000 pixel)

$$\delta y^{spatial} = 10.9 \pm 1.69 \mu\text{m}$$

Experimental

$$\delta y^{spatial} = 3.78 \mu\text{m}$$

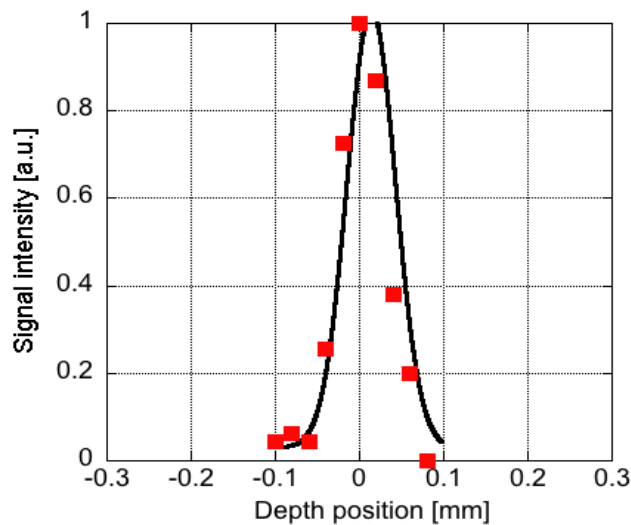
Theoretical

Confocal property

Confidential

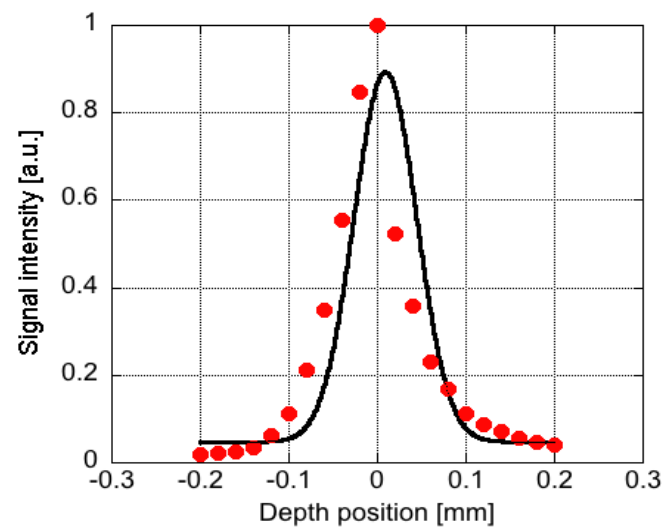
pinhole diameter = 10 μm

DCS



■ measurement data
— Gaussian fitting

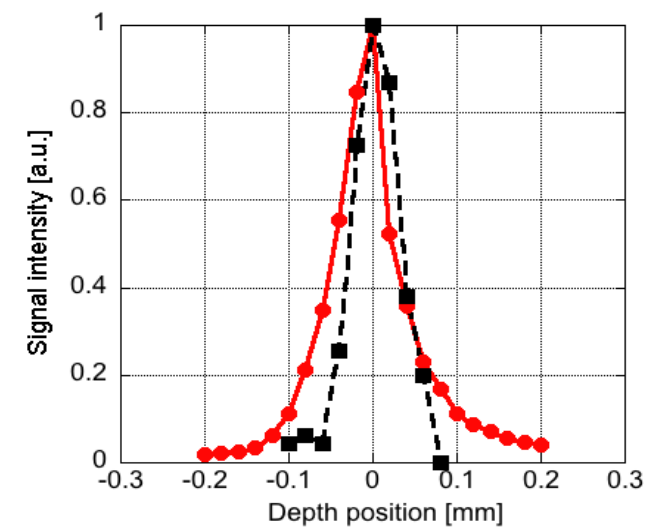
OSA



● measurement data
— Gaussian fitting

FWHM = 50 μm

DCS vs OSA



● OSA
■ DCS

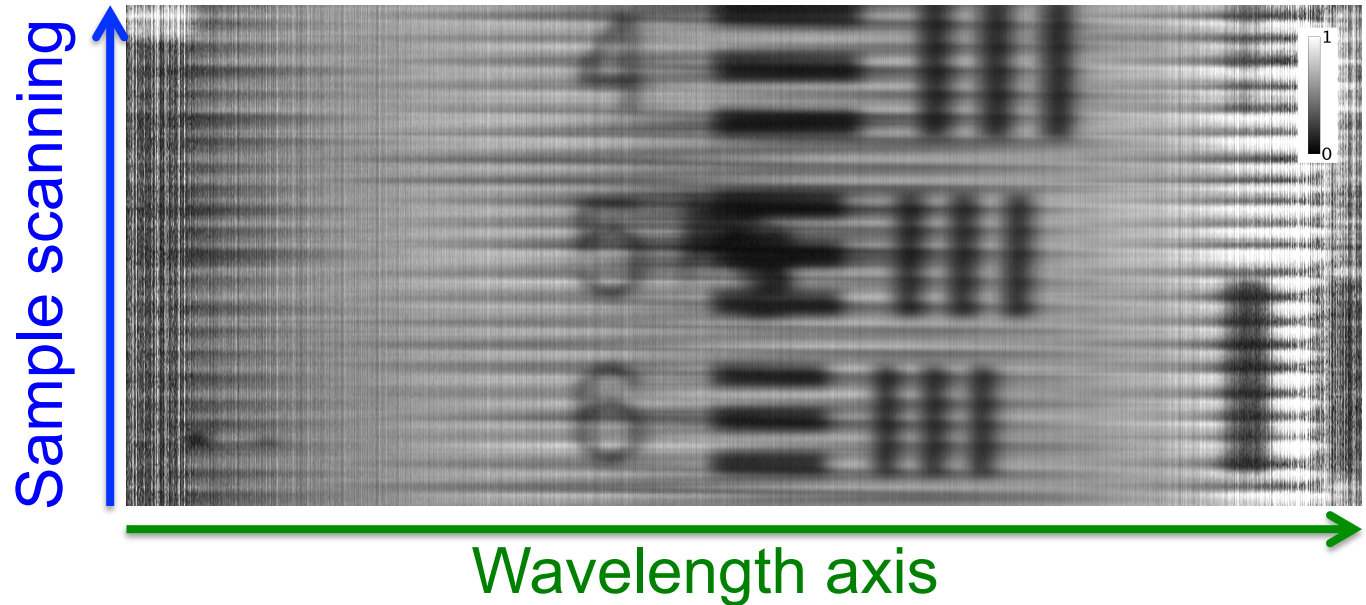
Reflection image with pinhole

Confidential

Image size: $200\text{ }\mu\text{m} \times 456\text{ }\mu\text{m}$ (5000 pixel $\times$ 200 pixel)

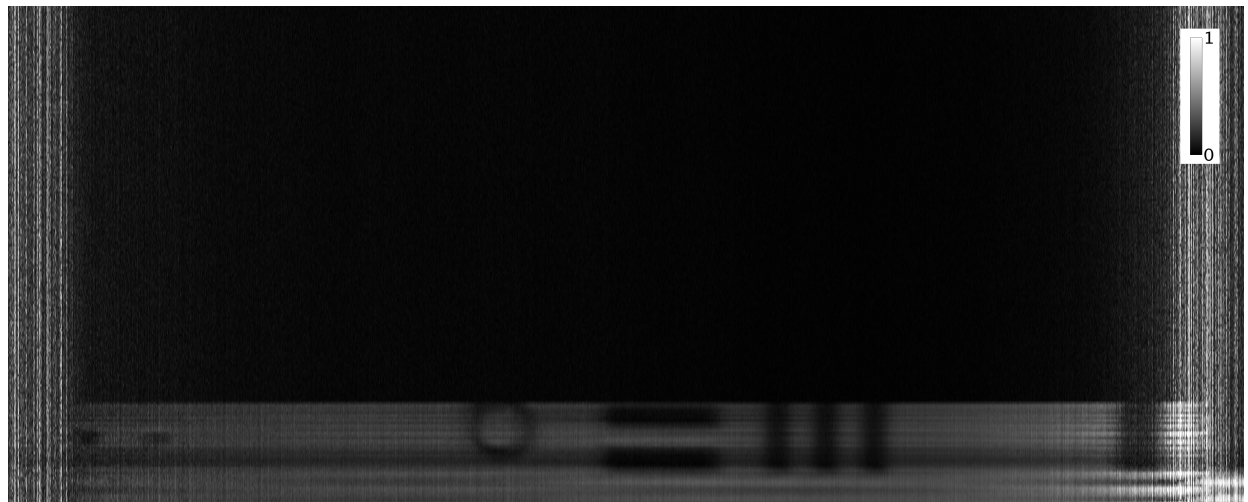
Depth position
= $0\text{ }\mu\text{m}$

At focus



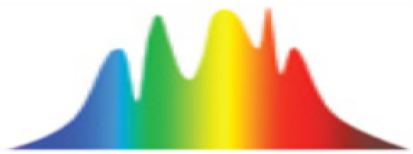
Depth position
= $+120\text{ }\mu\text{m}$

Out of focus



Scan-less full-field imaging based on bidirectional conversion between wavelength and 2D space

Spectral shape reflects 2D image



Output light with broad spectrum

Input light with broad spectrum



Scan-less, full-field image, confocal, Super-resolution, ultra-wide DR

2D-space/Wavelength conversion
(Superimposing 2D image over rainbow spectrum)

2D rainbow spectrum

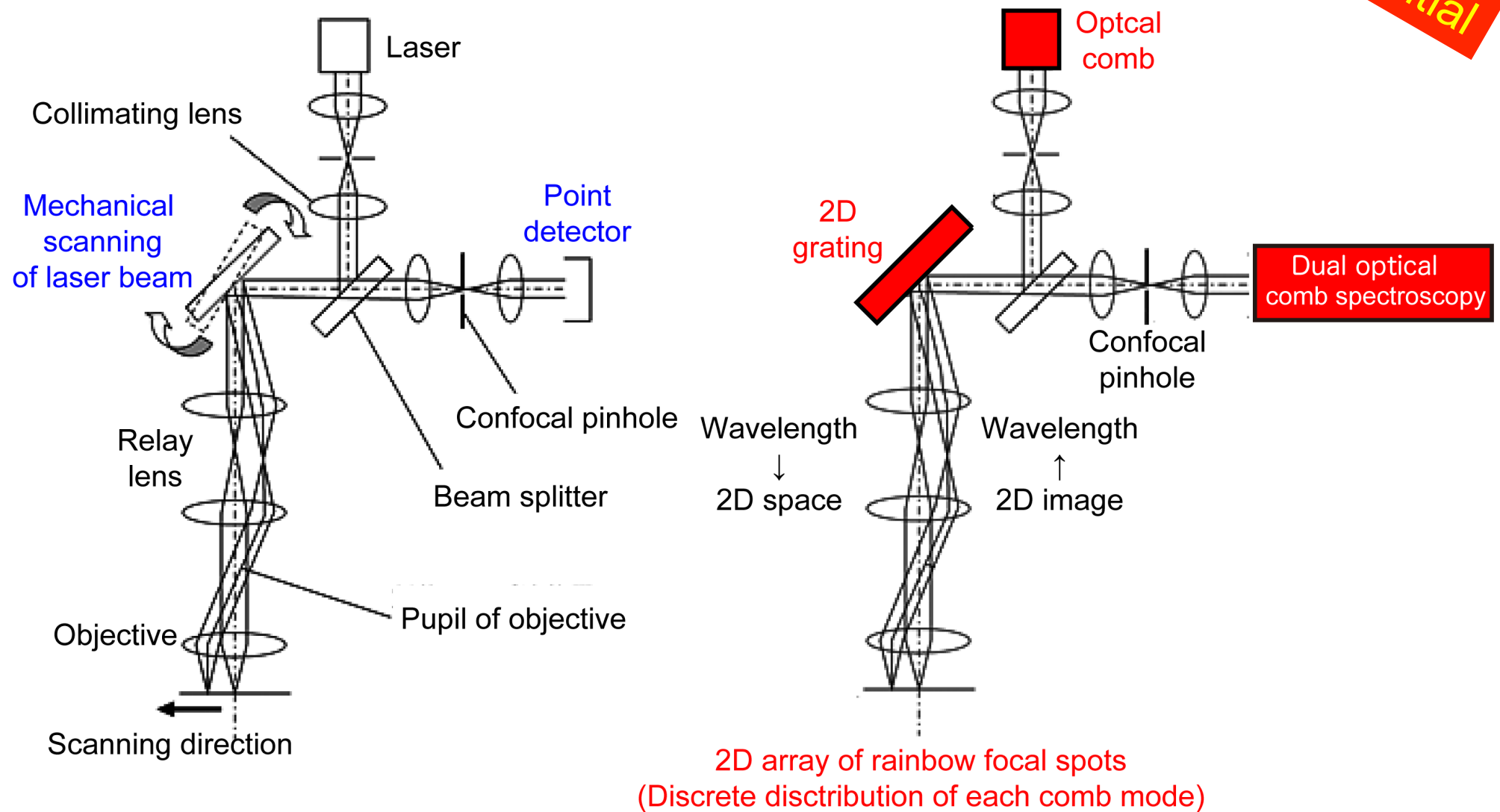
Objective

Wavelength/2D-space conversion
(Mapping rainbow spectrum over 2D space)

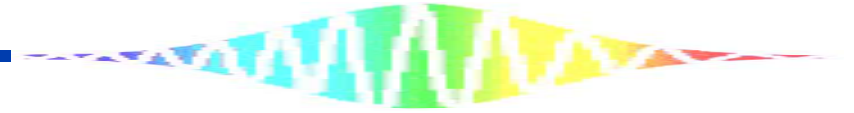
Ref) K. Goda, K. K. Tsia, and B. Jalali, "Serial time-encoded amplified imaging for real-time observation of fast dynamic phenomena," Nature 458(7242), 1145–1149 (2009).

Optical-comb confocal microscopy

Confidential



No mechanical scanning, single-shot imaging, super resolution

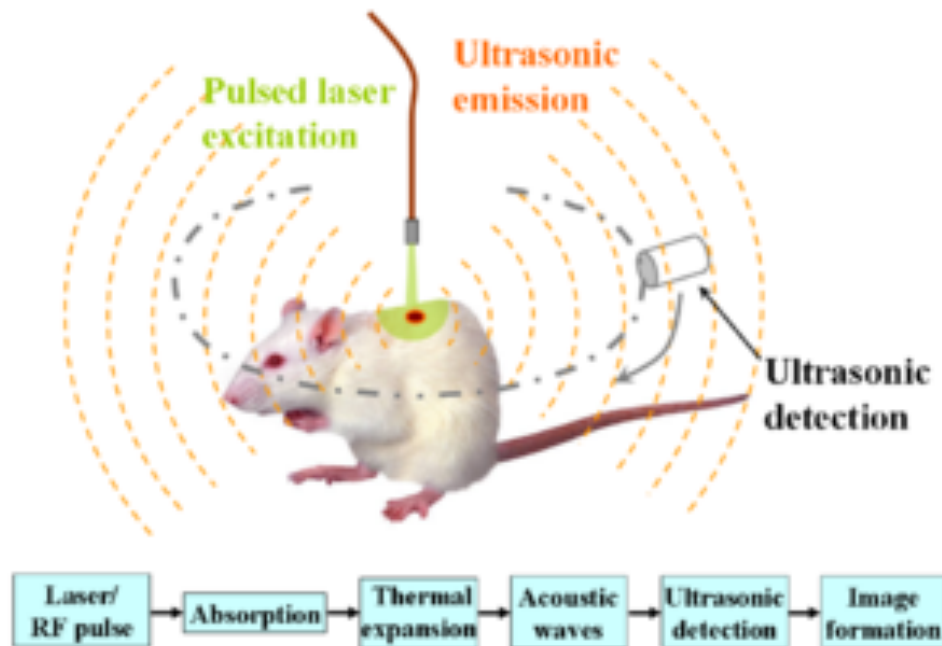


(2) Strain sensing comb for photoacoustic imaging

in collaboration with UEC

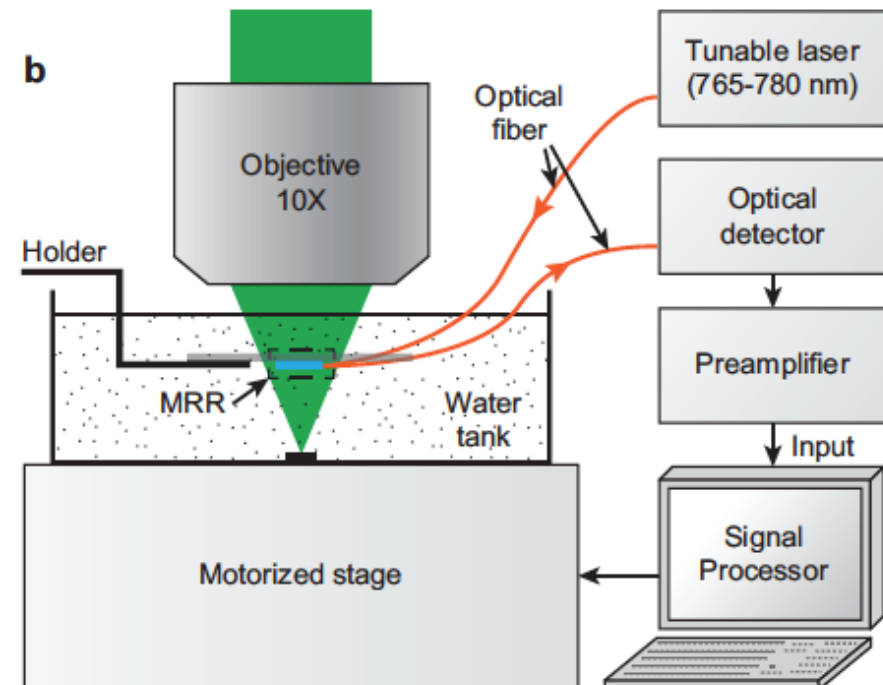
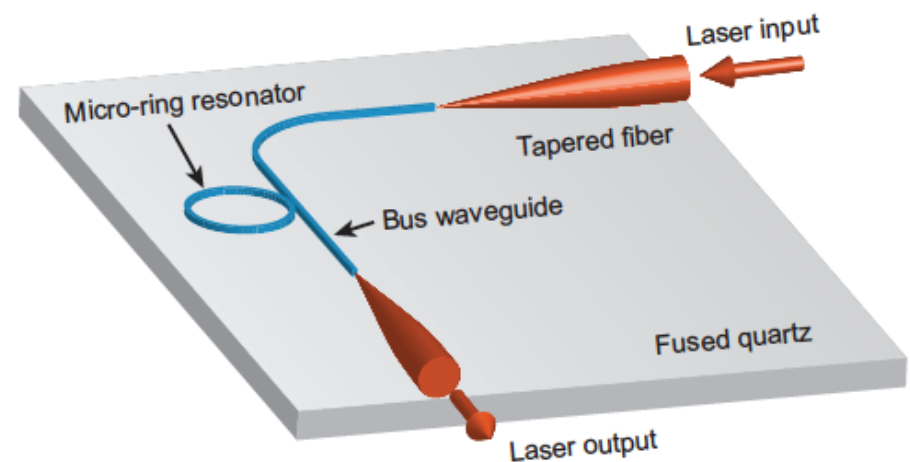
Photoacoustic imaging

Electric transducer



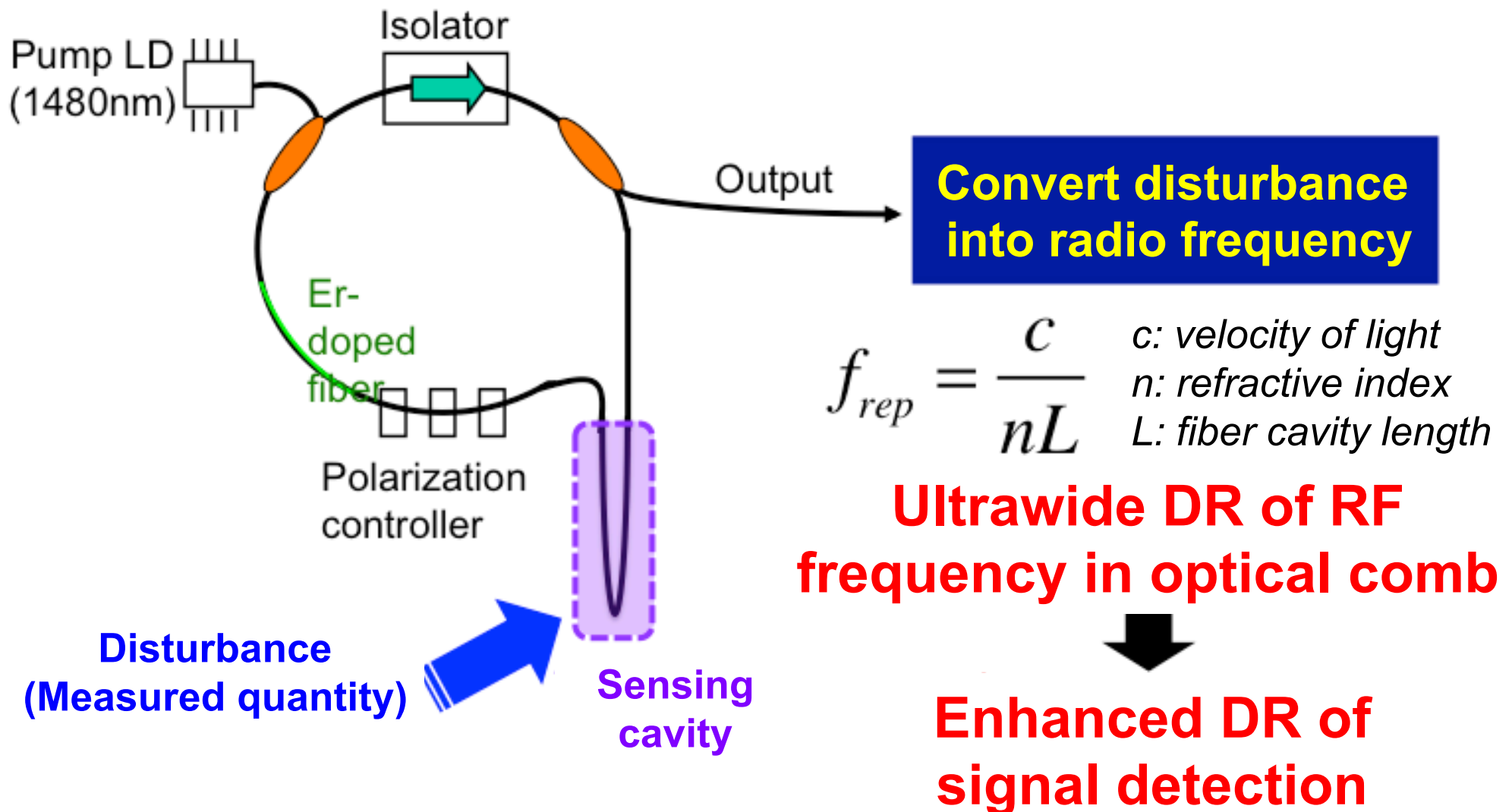
Limitation in frequency response, precision, and DR of signal detection

Microresonator



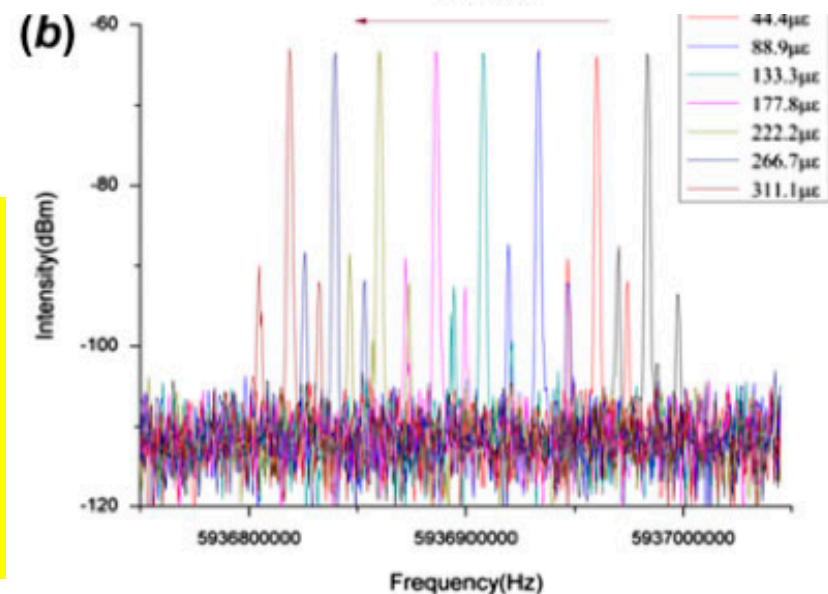
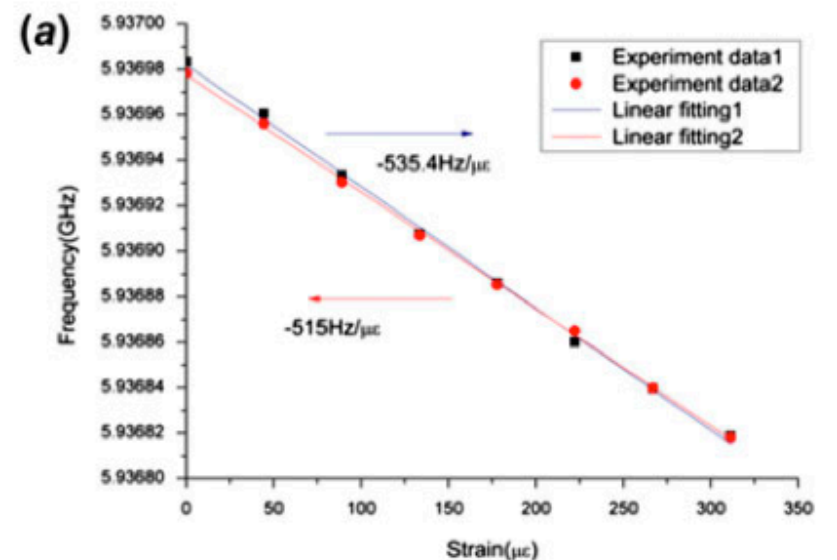
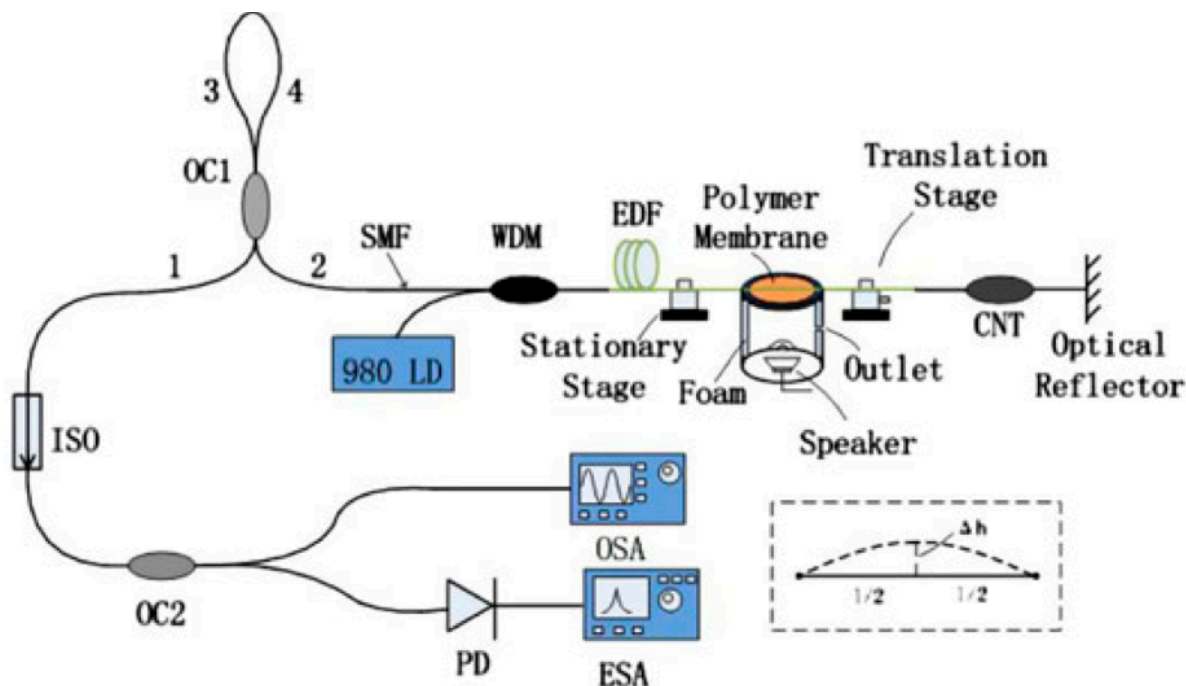
Scientific Reports 4, 4496 (2014).

Disturbance/RF conversion in fiber comb cavity



Previous research

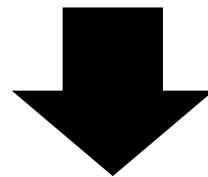
Ref) S. Wang et al., "Passively mode-locked fiber laser sensor for acoustic pressure sensing," *J. Mod. Opt.* **60**, 1892-1897 (2013)



- Measurement of f_{rep} change with RF spectrum analyzer
- Limitation of speed and precision in frequency measurement

Proposed idea

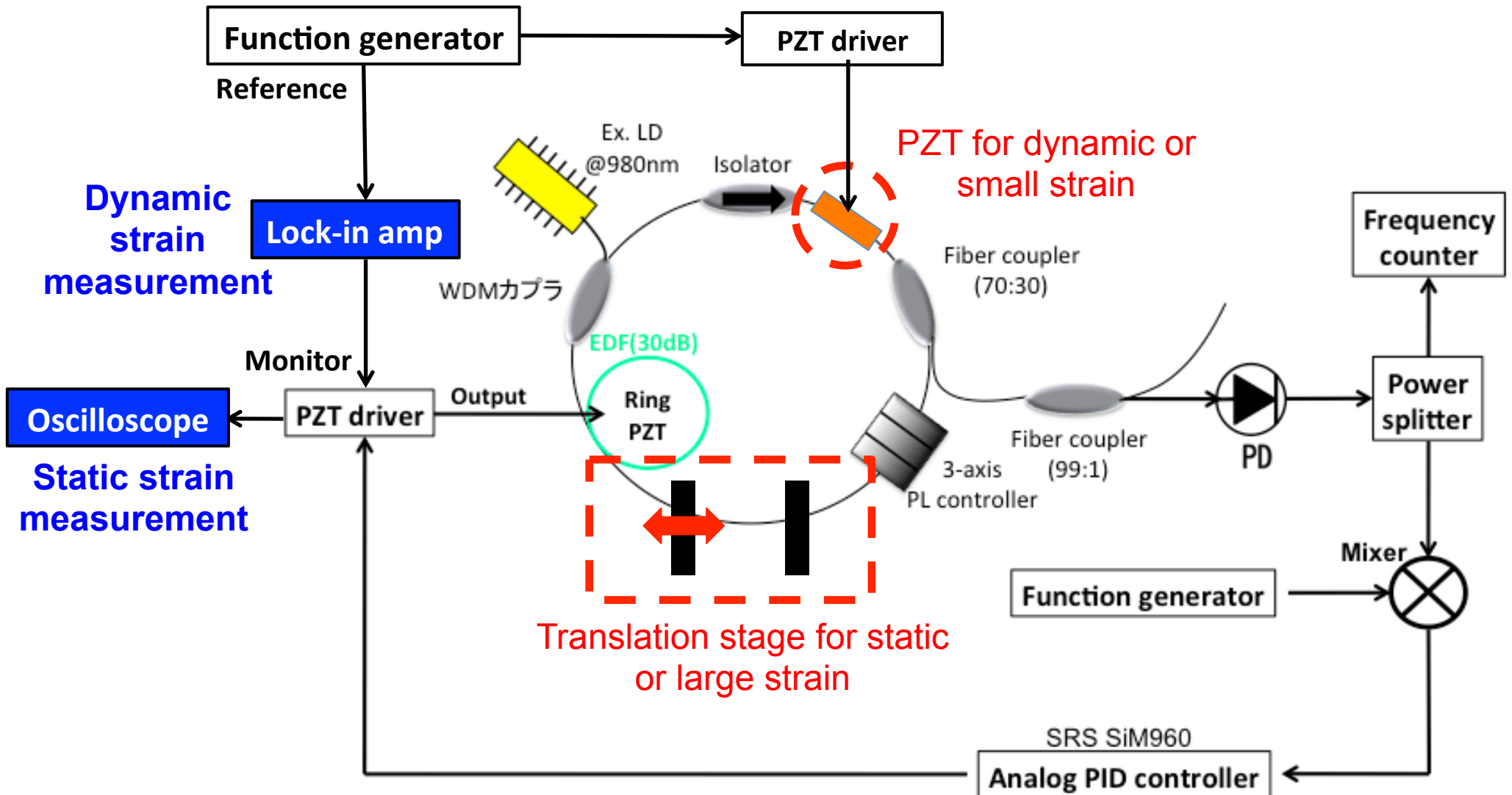
- **Null method** using control voltage signal to stabilize f_{rep} in place of deflection method using frequency signal
- **Precise measurement** by magnifying small strain
- **Rapid measurement** by voltage signal



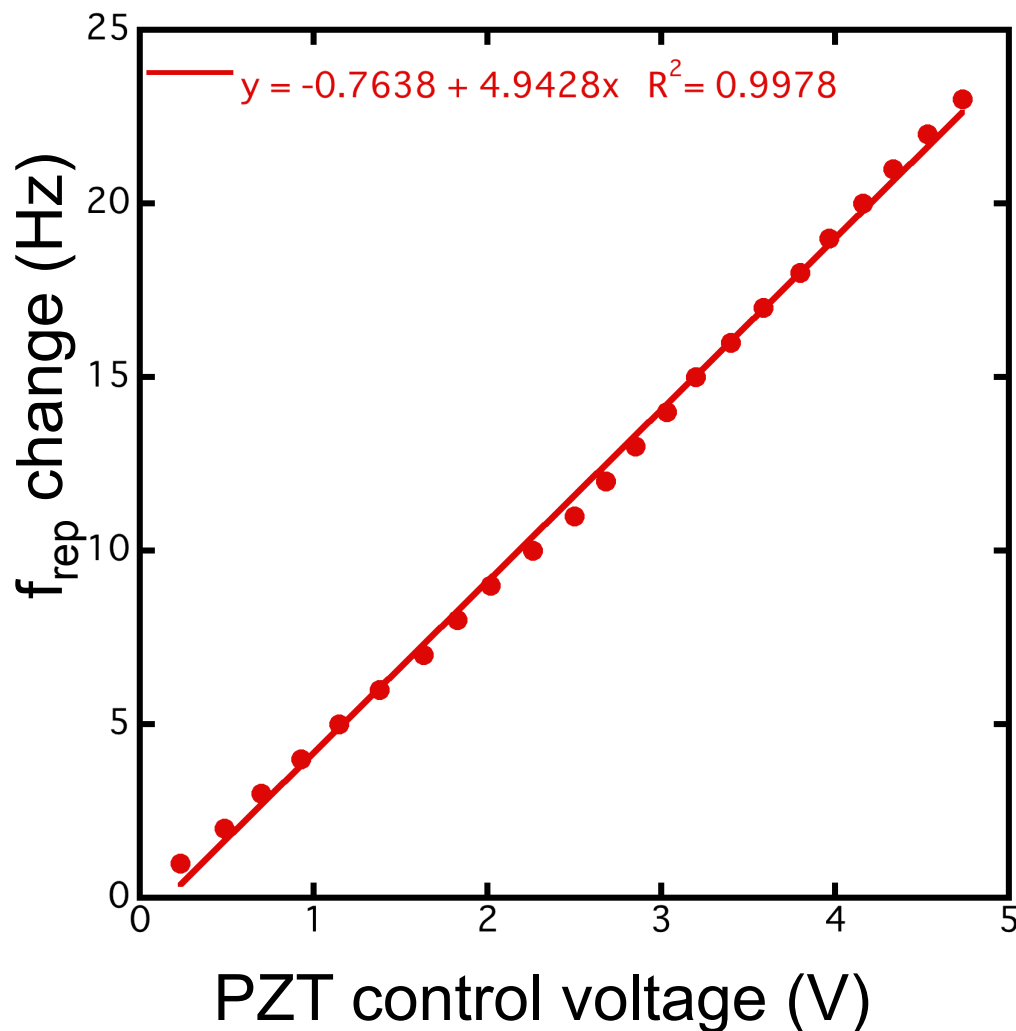
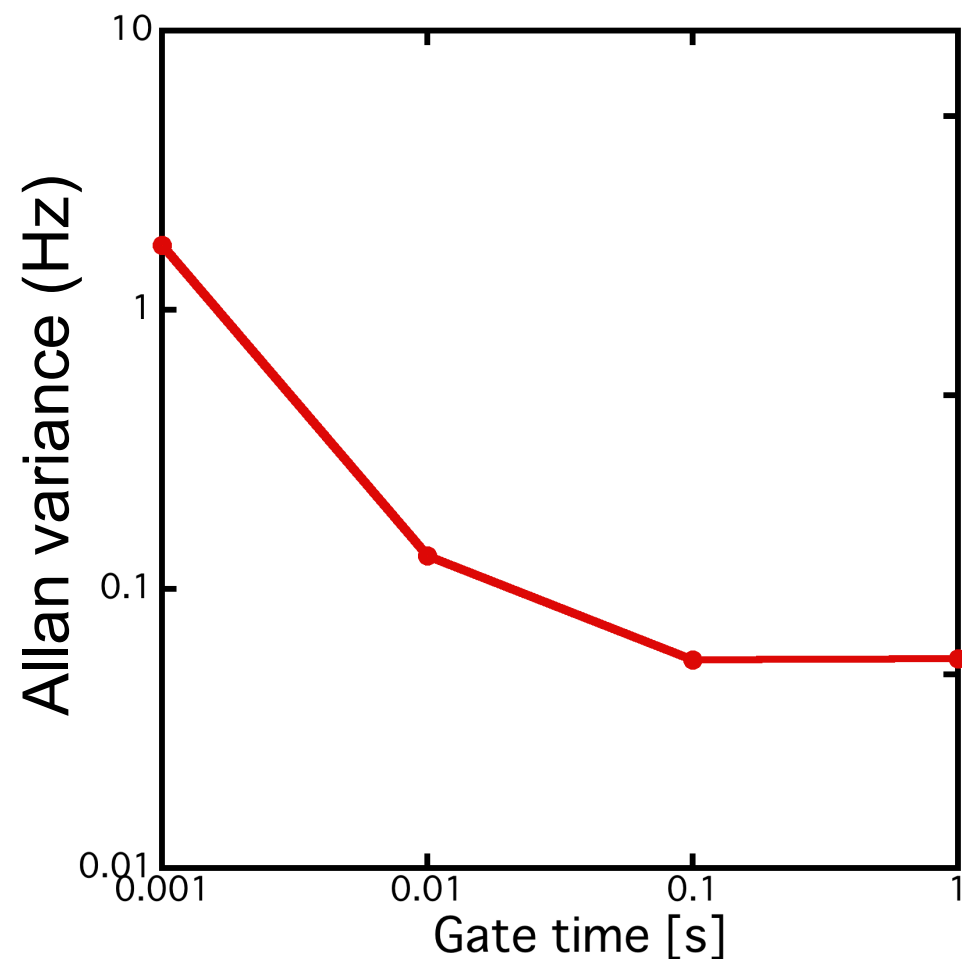
Enhancement of strain measurement and photoacoustic imaging

Strain-sensing fiber comb

(f_{rep} stabilized mode-locked Er:fiber laser)



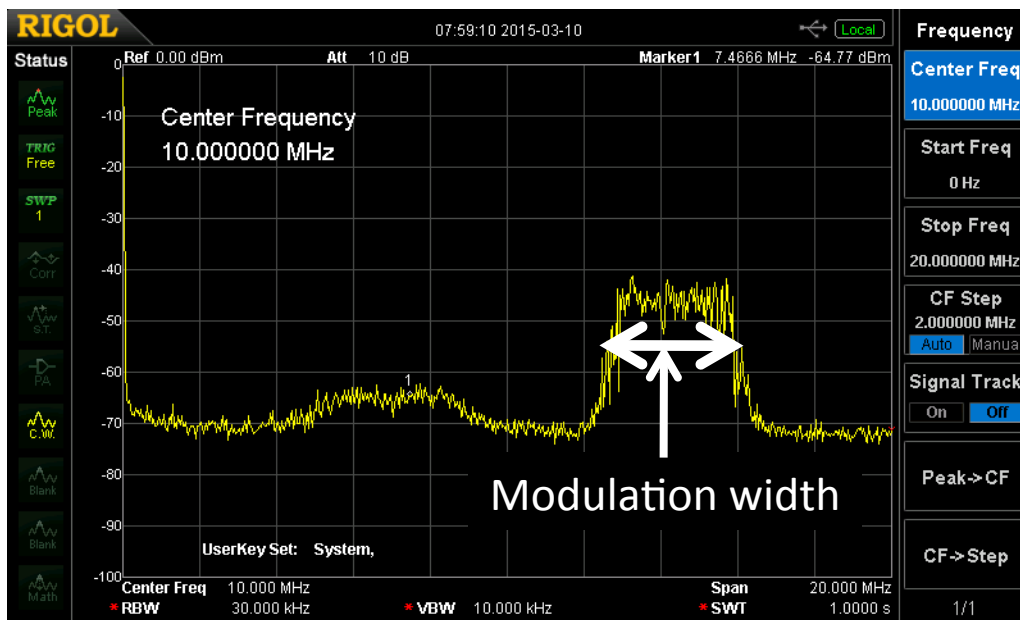
f_{rep} characteristic of fiber comb without strain

Confidential**PZT voltage VS f_{rep}** **Stability of f_{rep}** 

Frequency response of fiber comb without strain (open loop)

Confidential

Optical beat spectrum
between comb mode and
CW laser



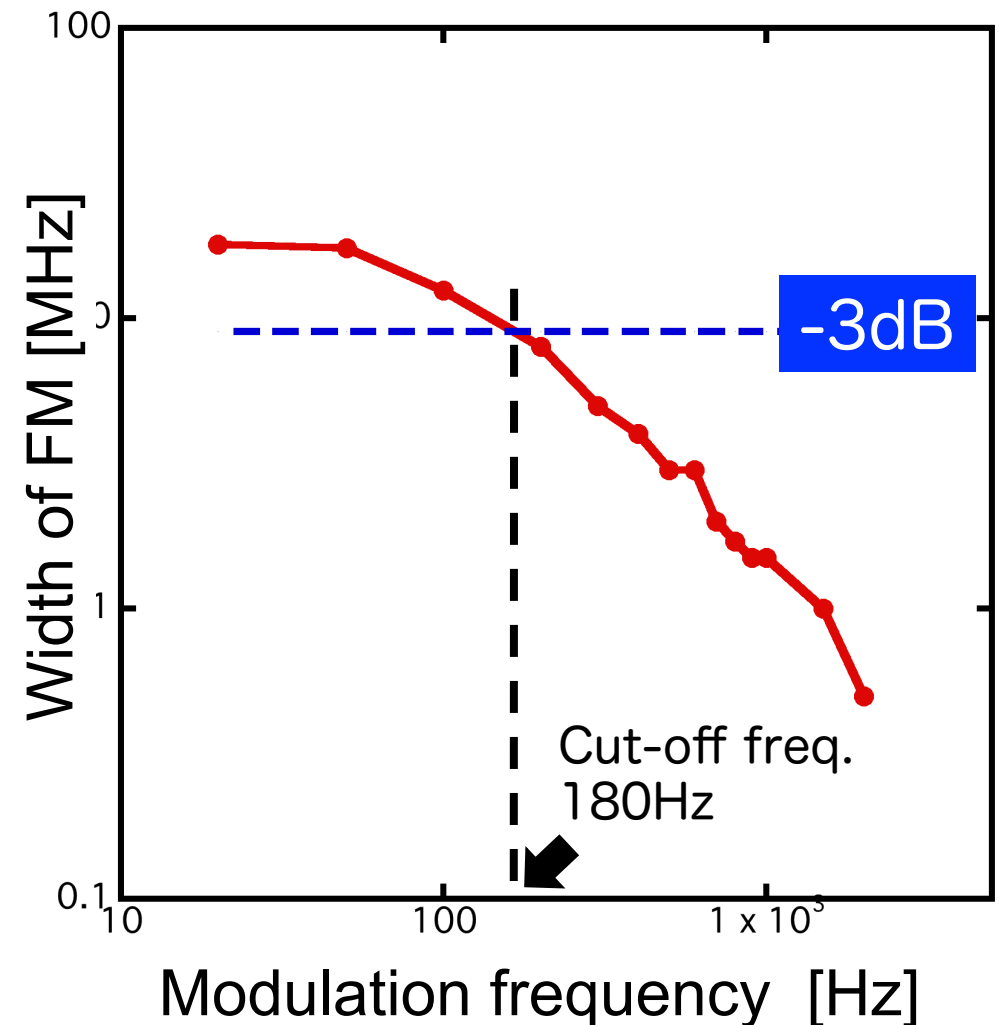
Specification of frequency modulation in f_{rep}

Mod. freq. : 20Hz~2kHz

Center freq. : 21.738,052,60MHz

Modulation width : 1Hz

Frequency response

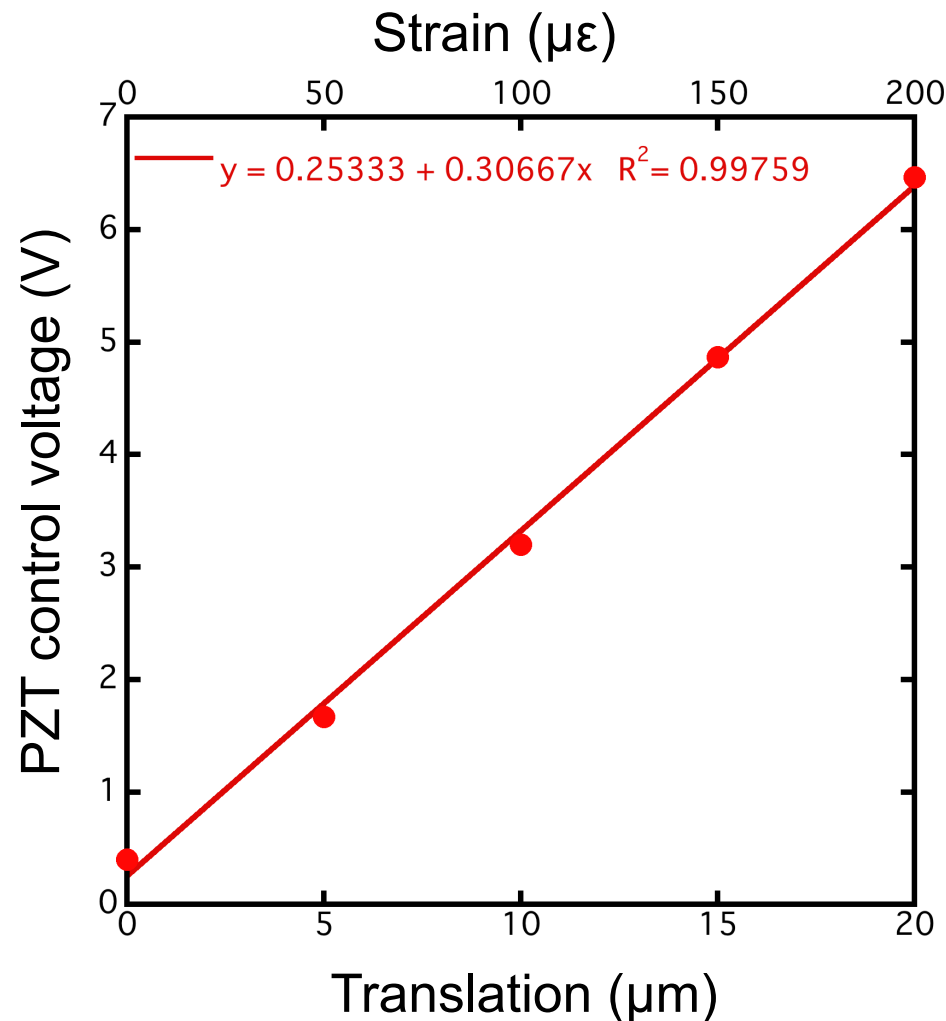


Static strain sensing (1)

Confidential

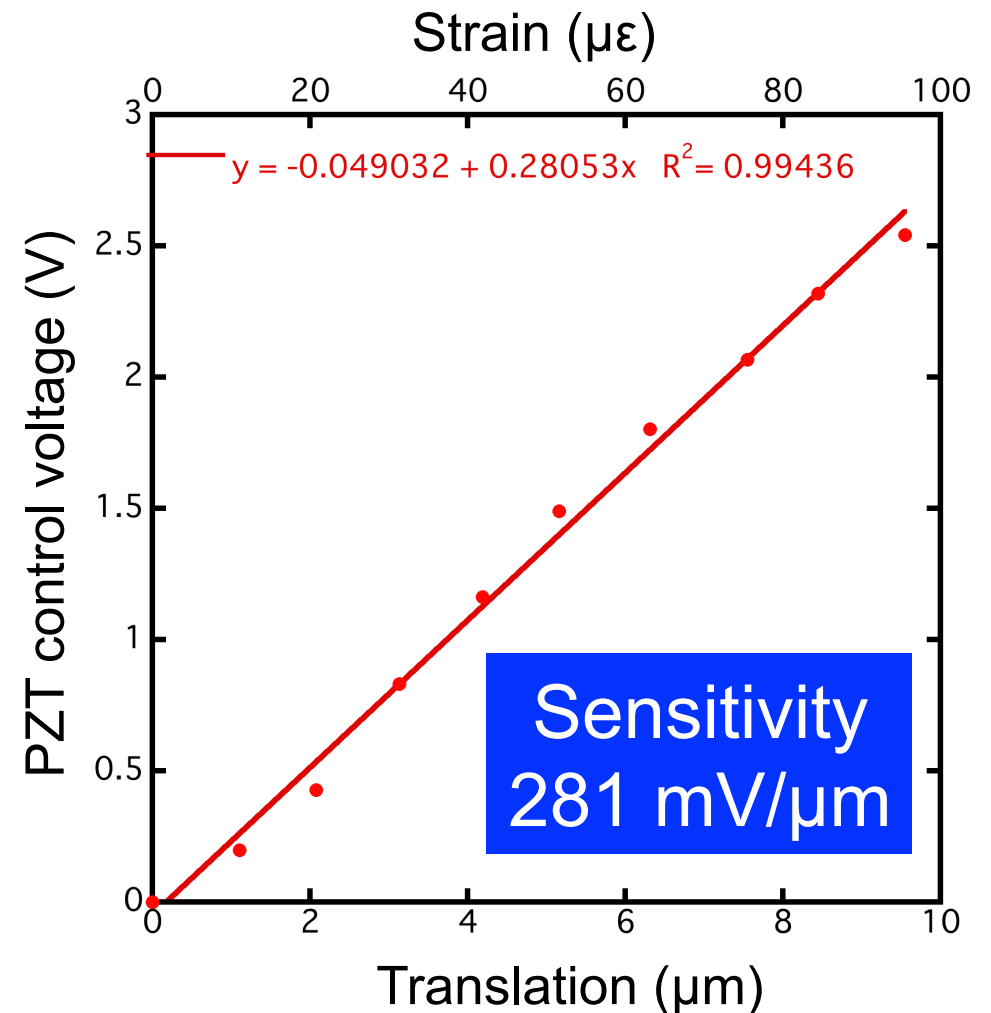
Large strain by translation stage

Strain range=100mm, resolution=10 μ m



Small strain by PZT

Strain range=20mm, resolution=0.1 μ m



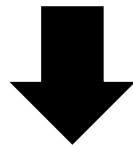
Static strain sensing (2)

Detectable min. translation

Fluctuation of PZT voltage
10mV

÷

Strain sensitivity
281 mV/ μm



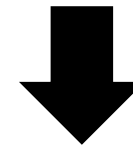
Min. Translation : 0.036 μm

Detectable max. translation

Range of PZT voltage
10V

÷

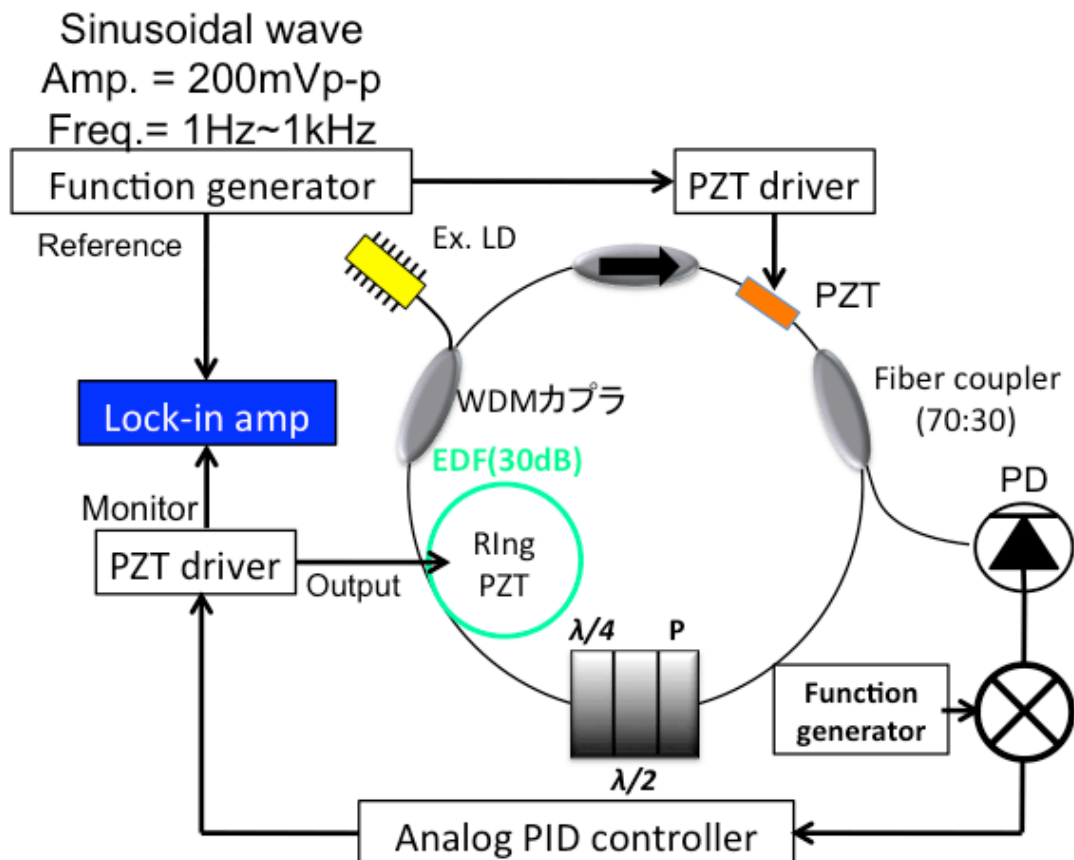
Strain sensitivity
281 mV/ μm



Max. Translation : 36 μm

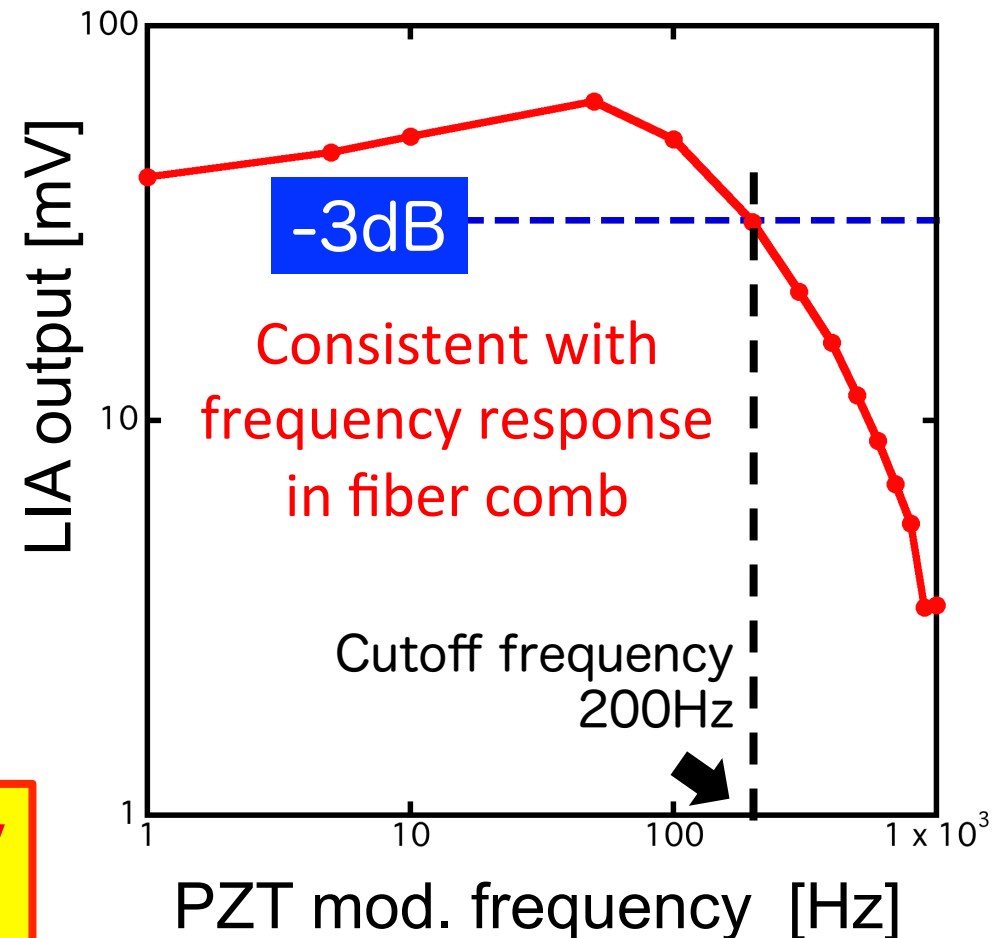
(periodic strain, closed loop)

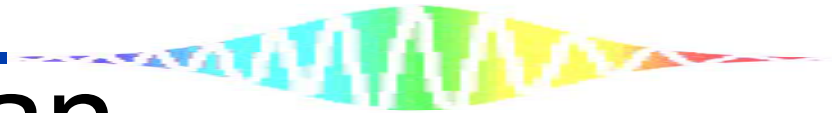
Experimental setup



Further enhancement of frequency response using EOM comb

Freq. response @ LIA





Future plan

(1) Intelligent THz instrumentation and application

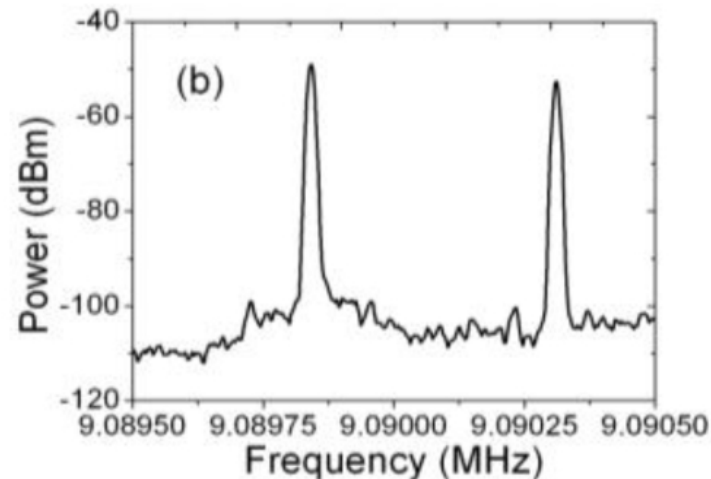
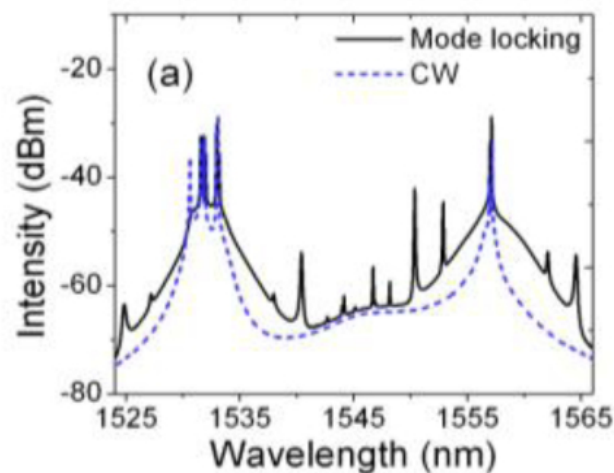
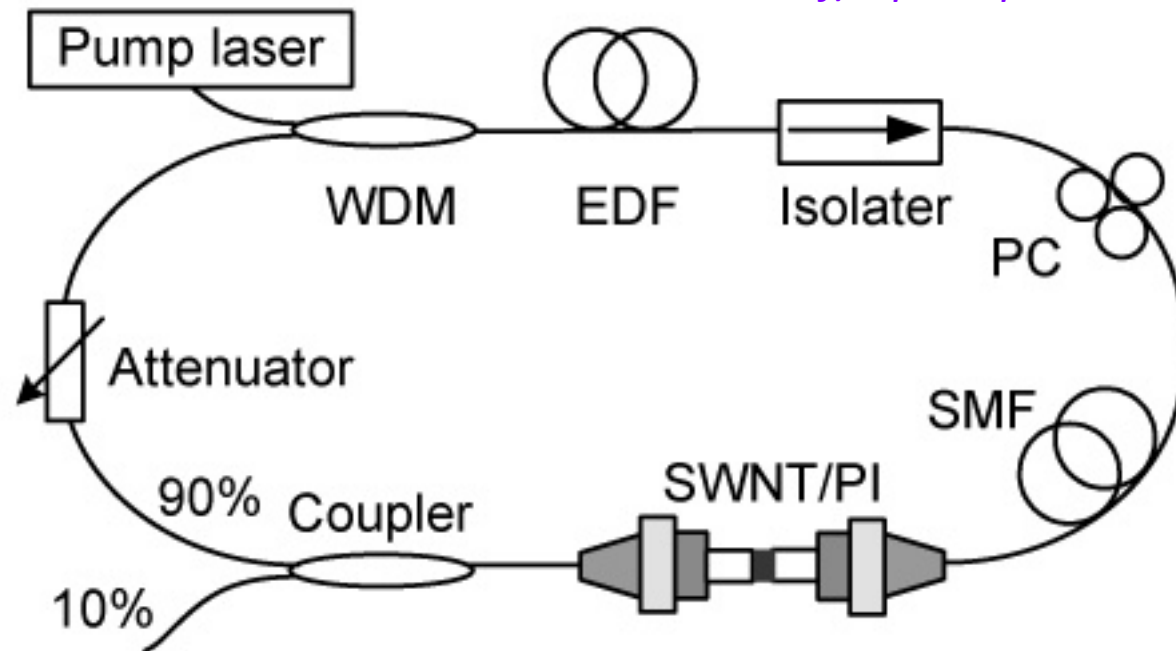
- ✓ **Free-running dual-color comb in single fiber laser**,
in collaboration with Prof. Zheng in Beihang Univ.
 - ☞ Adaptive sampling THz-DCS
 - ☞ THz-comb-referenced spectrum analyzer
- ✓ **Broadband THz synthesizer**, *waiting for good CW laser*
- ✓ **Time-resolved measurement with THz-DCS**

(2) Novel optical comb measurement and application

- ✓ **Spectrally manipulated OFC (non-DCS method)**
 - ☞ Digital holography, Ghost imaging
- ✓ **Lock-in imaging in DCS**
 - ☞ Spectral imaging, DH, CARS imaging

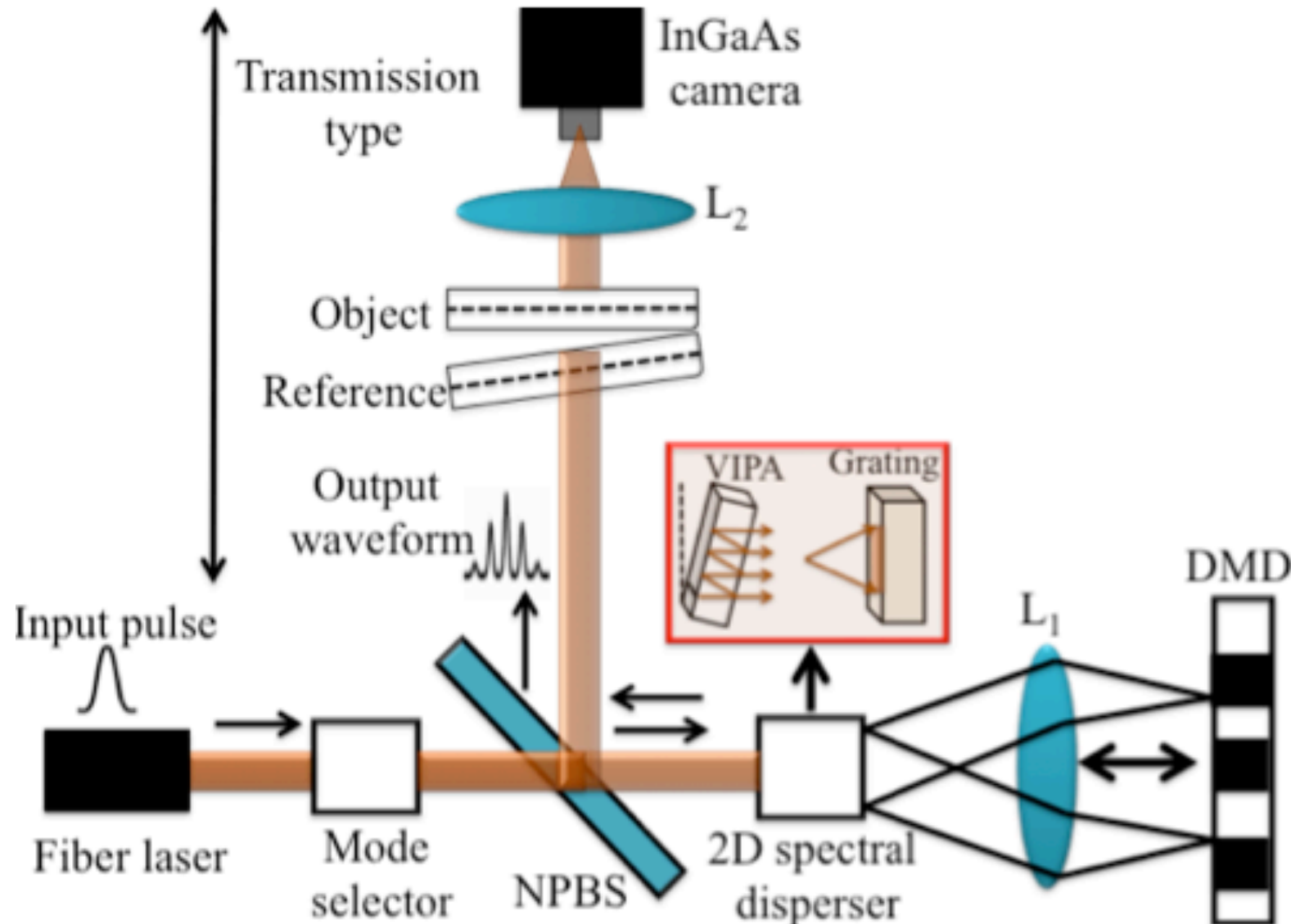
Dual-color comb in single fiber laser

Ref) Opt, Express 19, pp. 1168-1173 (2011).



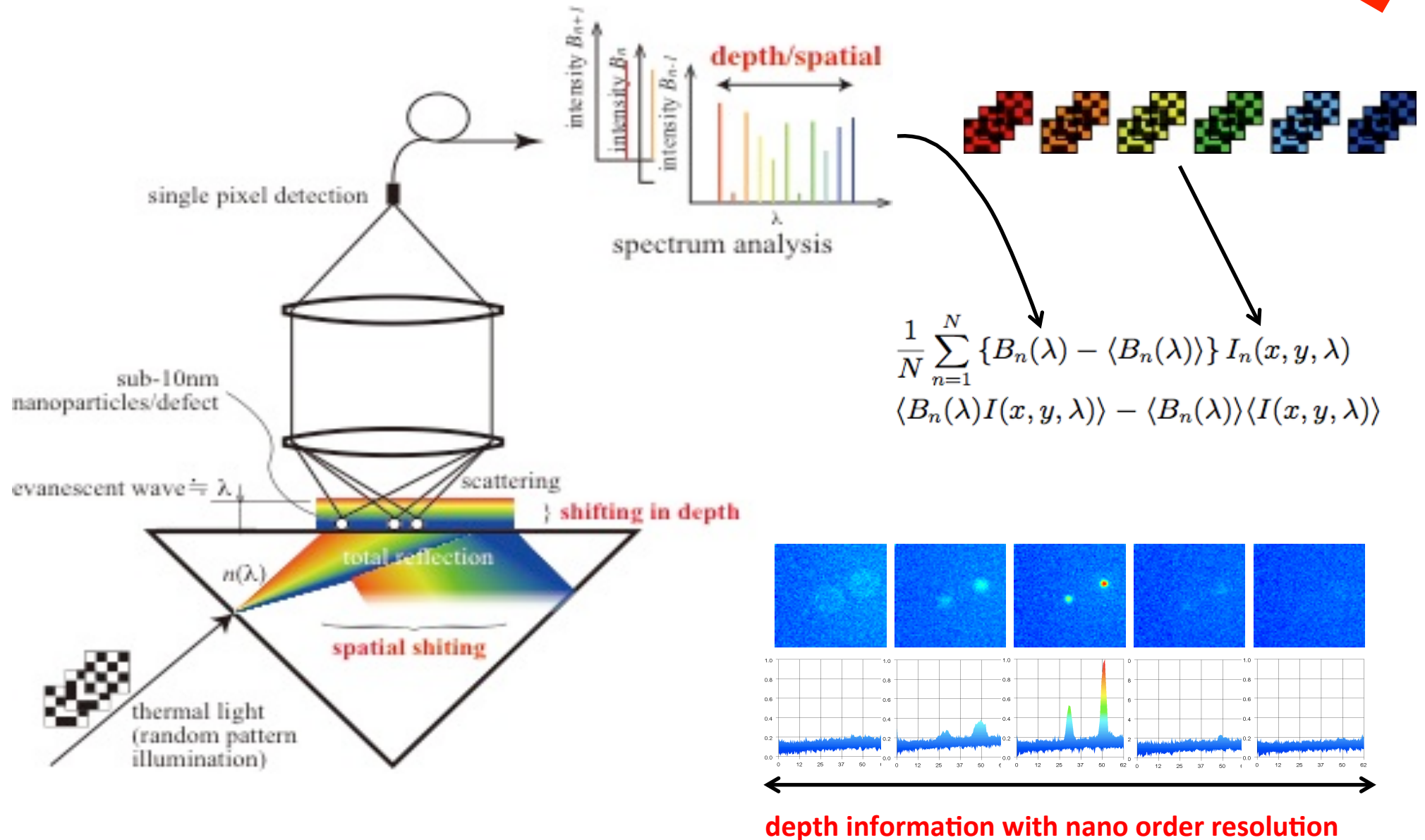
Digital holography with spectrally manipulated OFC (SM-OFC)

Confidential

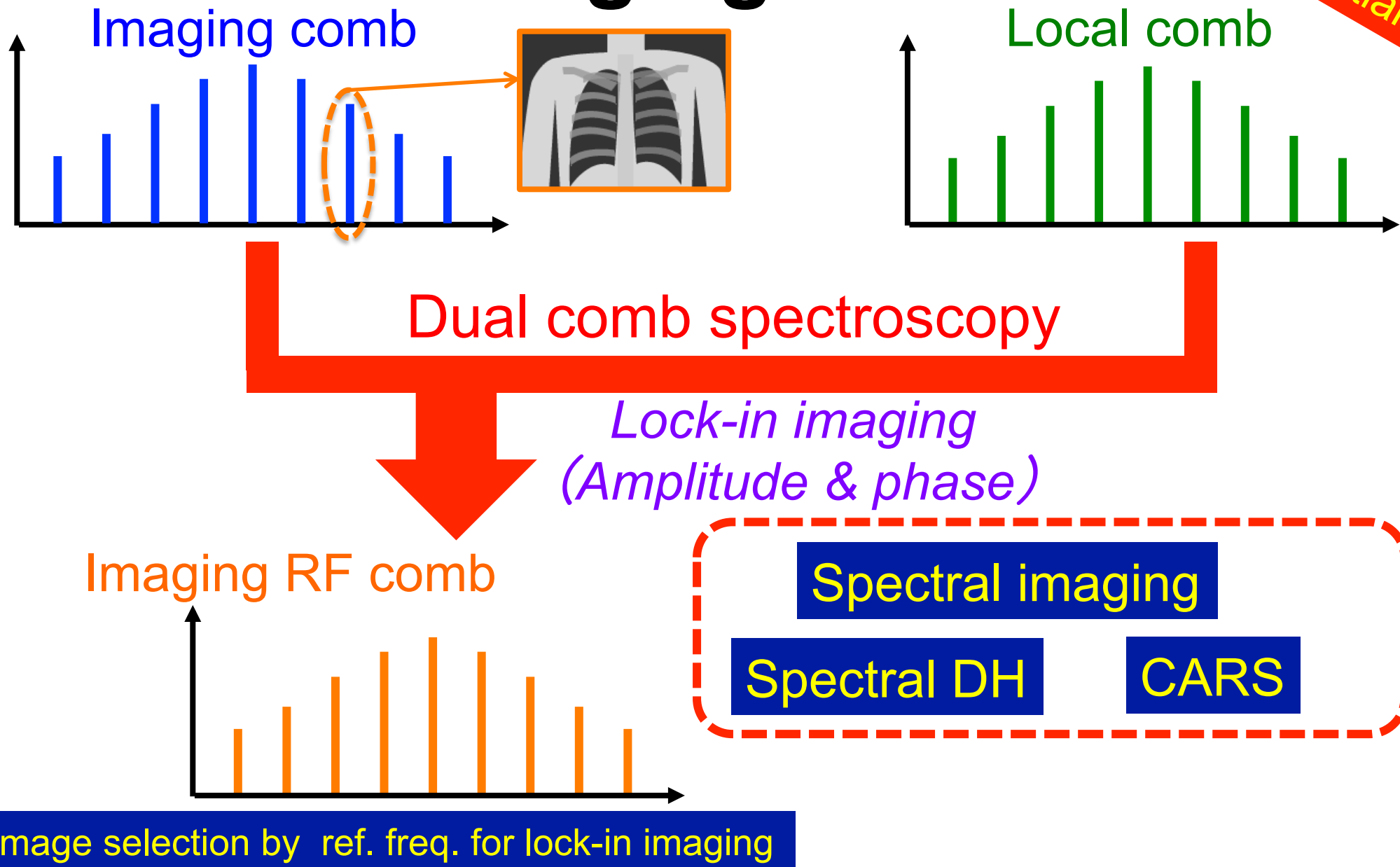


Evanescent, ghost imaging

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Lock-in imaging in DCS



Achievements

Paper

- (1) T. Yasui *et al.*, "Super-resolution discrete Fourier transform spectroscopy beyond time window size limitation using precisely periodic pulsed radiation," *Optica* **2**, 460-467 (2015).
- (2) T. Yasui *et al.*, "Real-time absolute frequency measurement of continuous-wave terahertz radiation based on dual terahertz combs of photocarriers with different frequency spacings," *Opt. Express* **23**, 11367-11377 (2015).
- (3) T. Yasui *et al.*, "Adaptive sampling dual terahertz comb spectroscopy using dual free-running femtosecond lasers," *Sci. Reports*, Vol. 5, art. 10786 (2015).

Patent

- (1) Scan-less, full-field confocal microscopy, *in writing*
- (2) Strain-sensing fiber comb, *in preparation*