2nd Research Area Meeting of “JST, ERATO MINOSHIMA Intelligent Optical synthesizer Project”
December 22, 2014 at National Institute of Advanced Industrial Science and Technology

Ghost Imaging

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APPLIED OPTICS LAB.

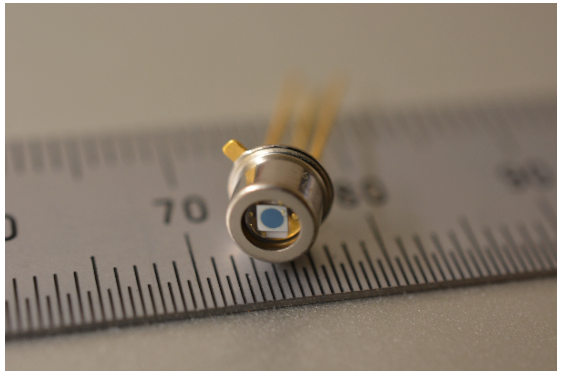
outline

- introduction
  What is the Ghost Imaging (GI)?
- characteristics and advantages
- applications
  - fluorescent GI microscopy
  - 2D GI ellipsometry
- conclusions

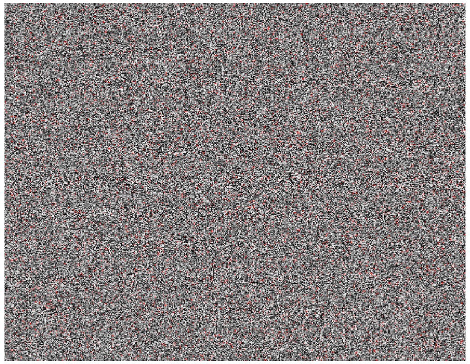
What is the Ghost imaging?

Digital camera with 2D sensor

General imaging



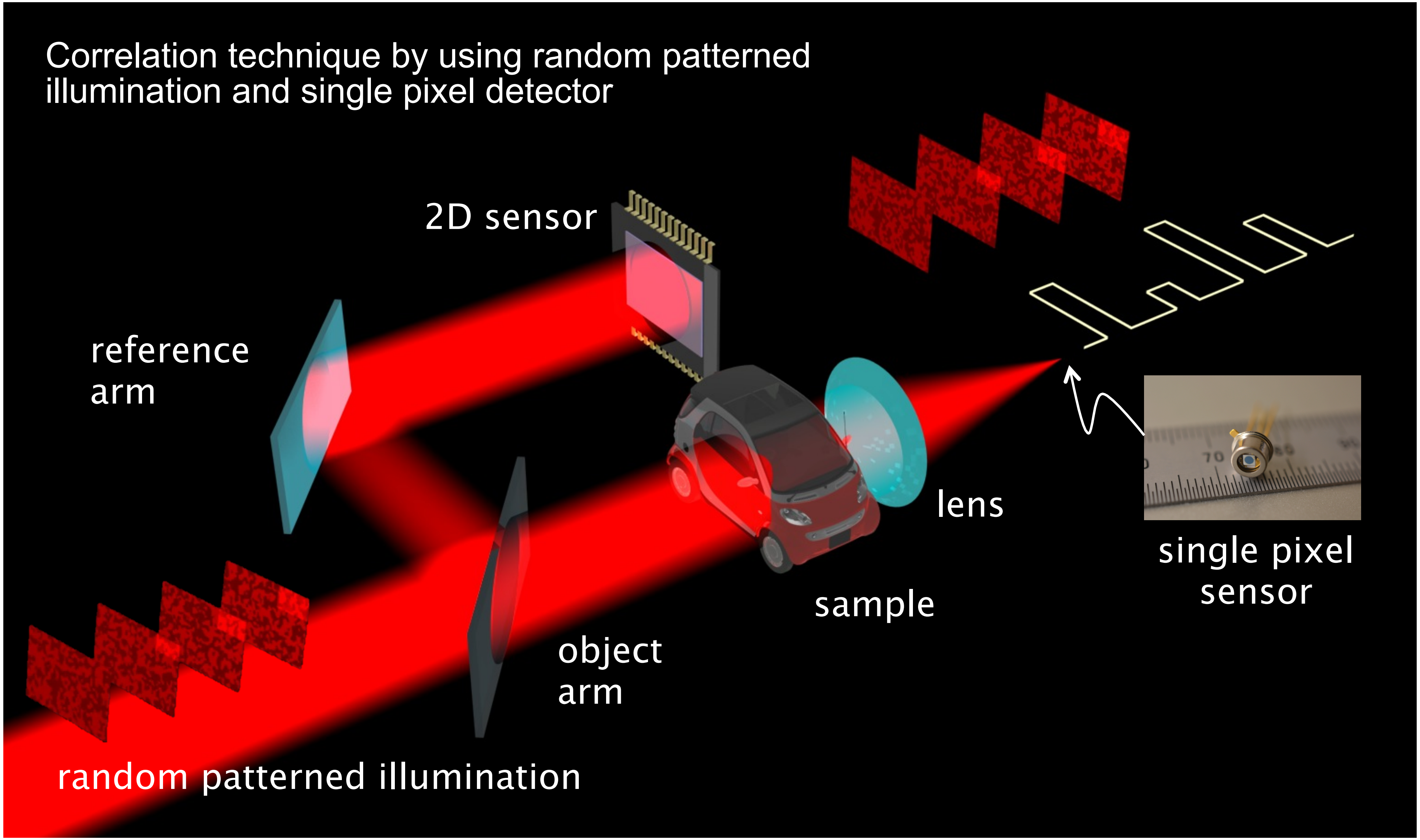
single pixel detector



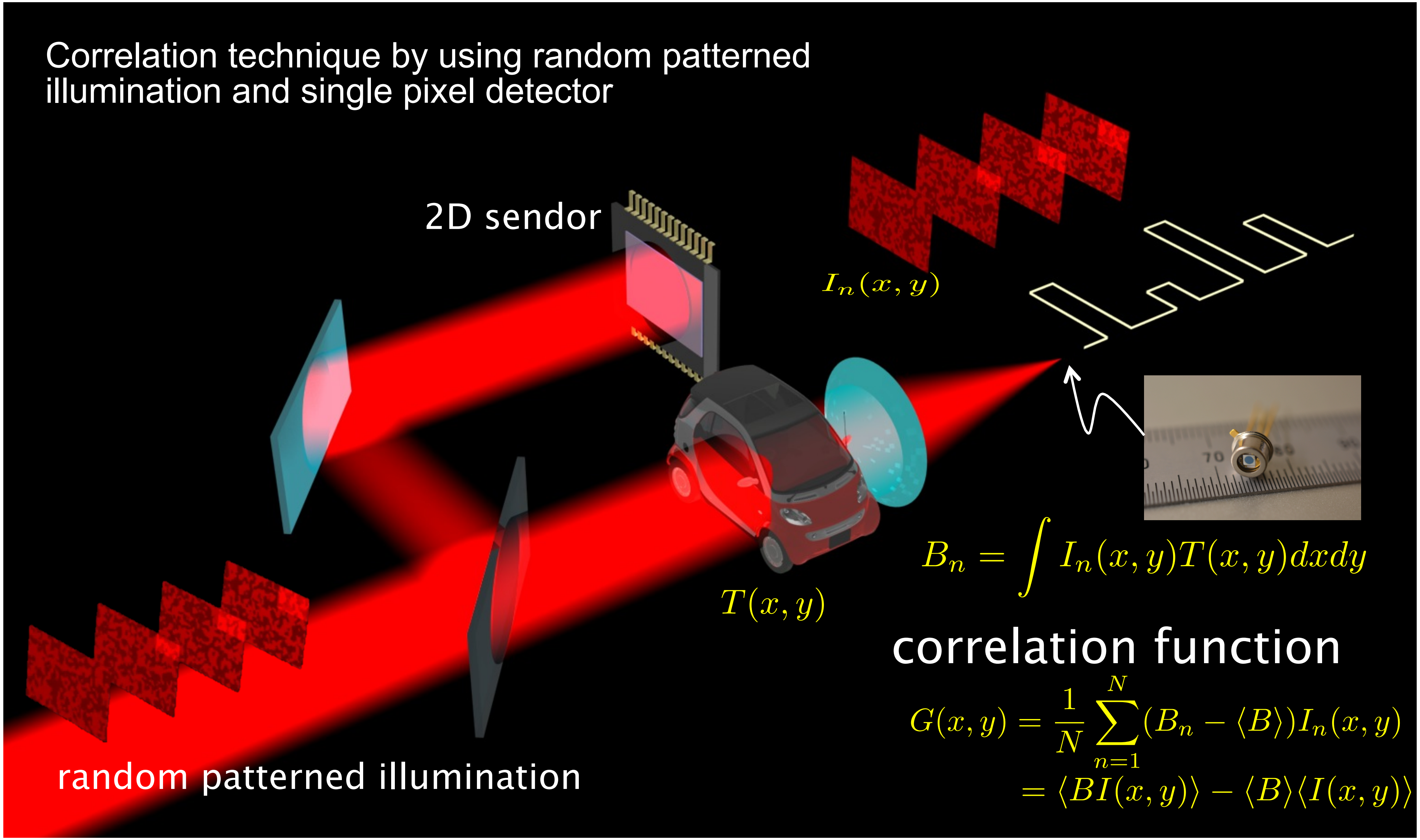
random patterned
Illumination (incoherent)

Ghost imaging

Principle for Ghost imaging



Principle for Ghost imaging



First published paper of the Ghost imaging

measurement for photon pare generation

RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 52, NUMBER 5 NOVEMBER 1995

Optical imaging by means of two-photon quantum entanglement

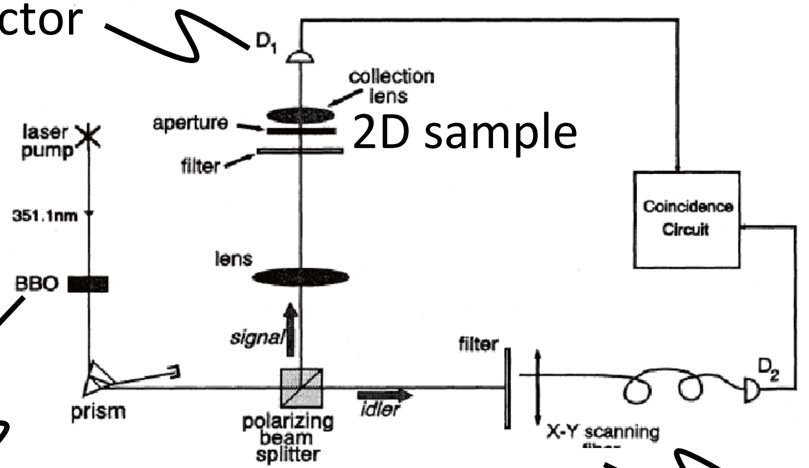
T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko

Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228

(Received 22 December 1994)

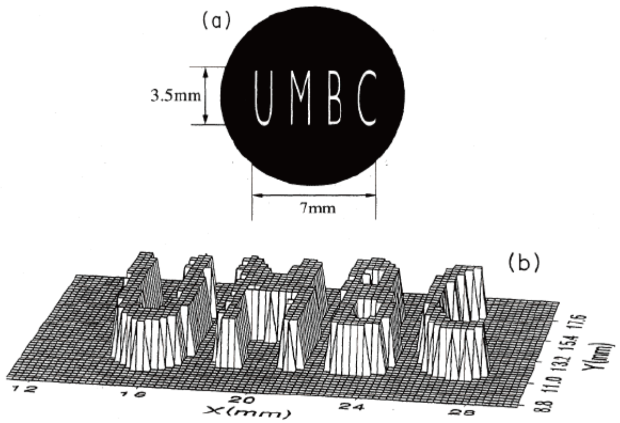
single pixel detector

2D sample



area sensing

nonlinear crystal



VOLUME 74, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 1995

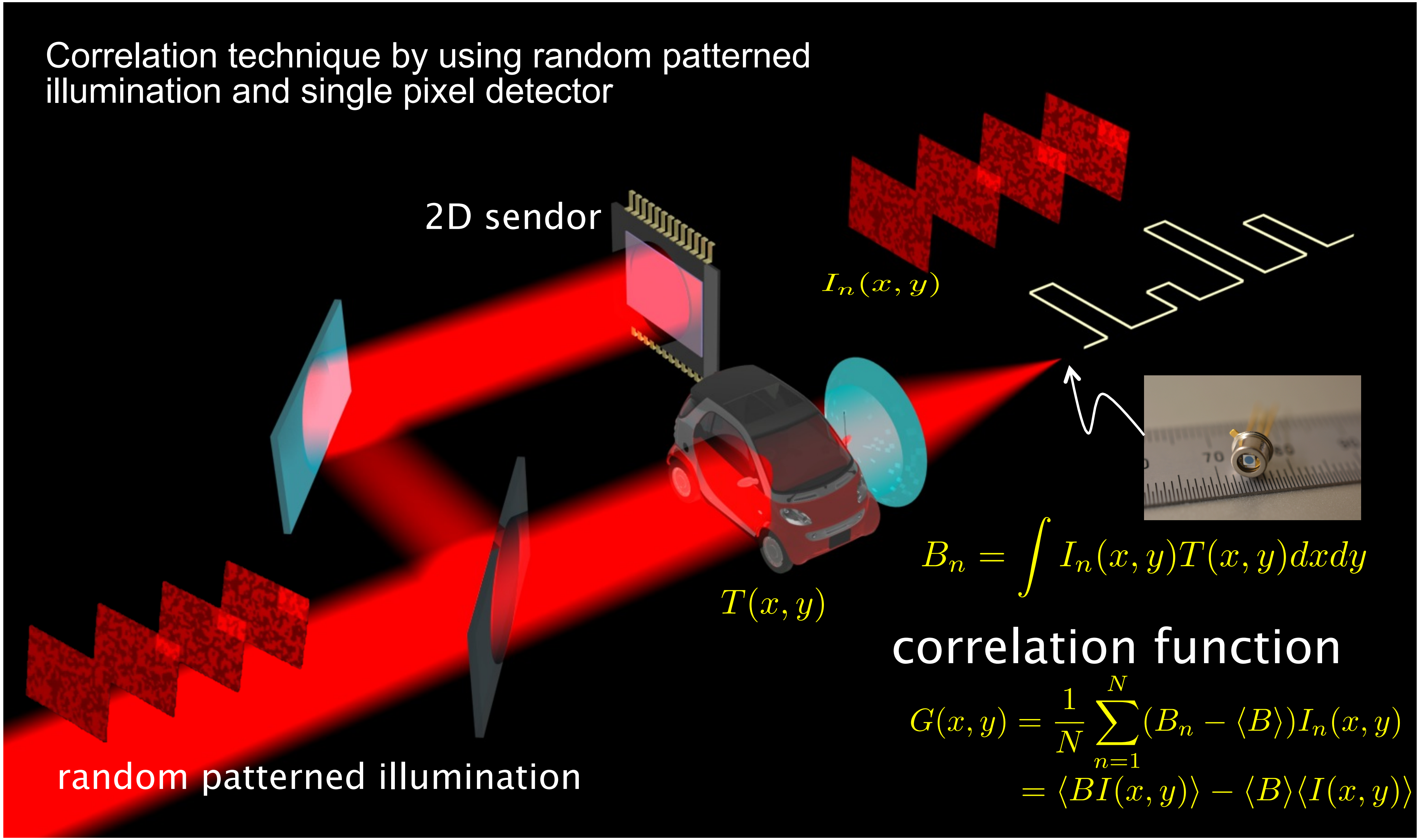
Observation of Two-Photon "Ghost" Interference and Diffraction

D. V. Strekalov, A. V. Sergienko, D. N. Klyshko,* and Y. H. Shih

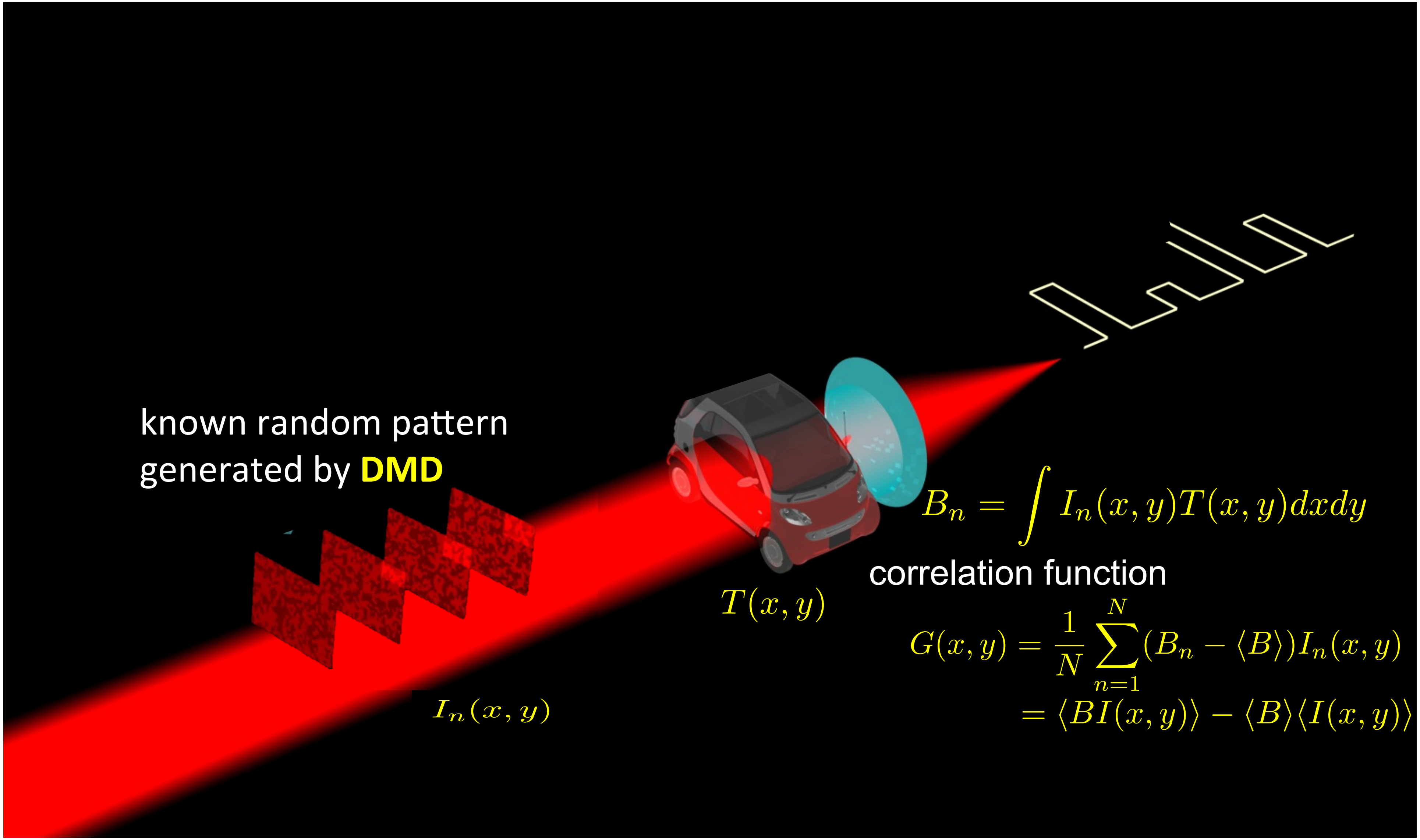
Department of Physics, University of Maryland, Baltimore County, Baltimore, Maryland 21228

(Received 11 August 1994)

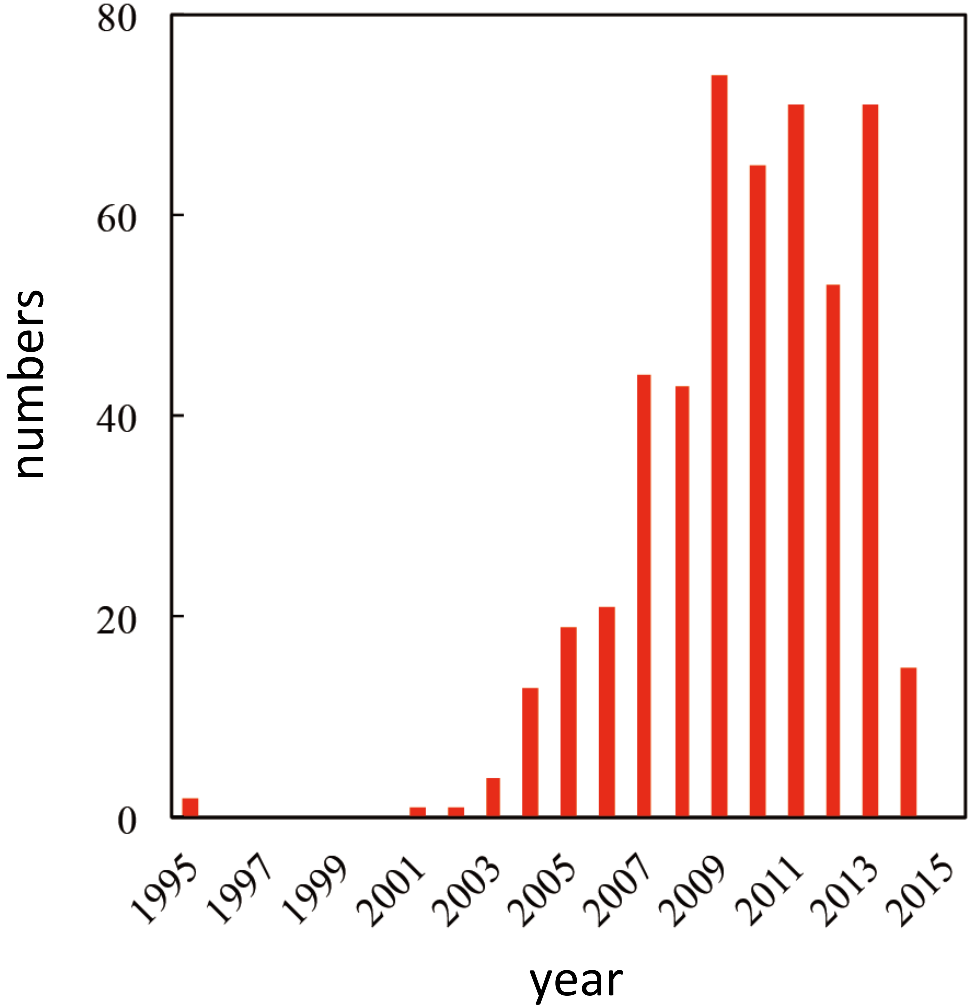
Principle for Ghost imaging



Single axis ghost imaging

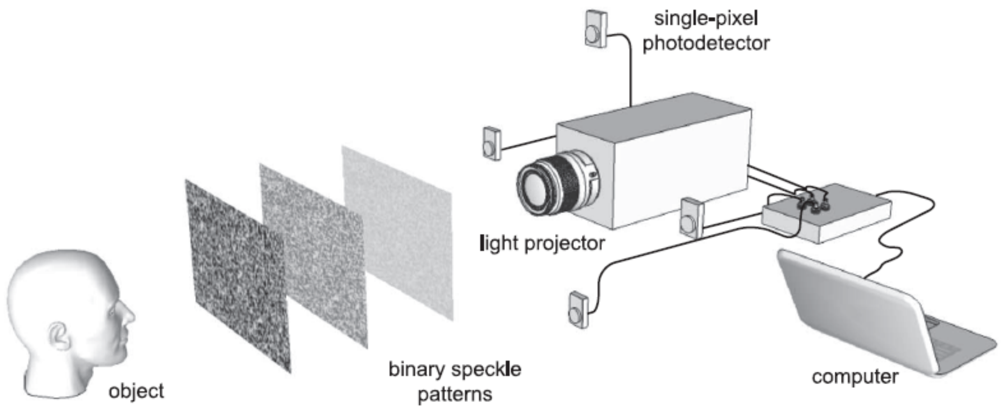


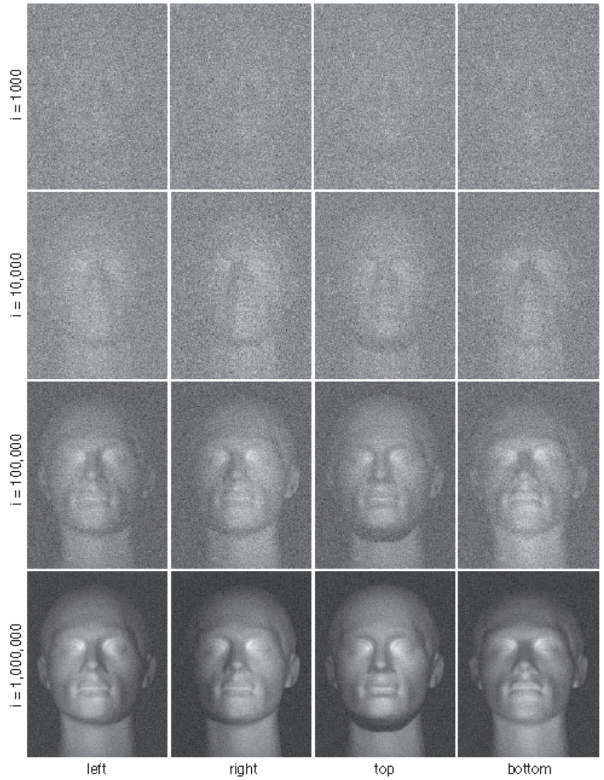
Published papers of Ghost imaging



3D Computational Ghost Imaging

B. Sun *et al*., Science. **340**, 844-847, (2013).

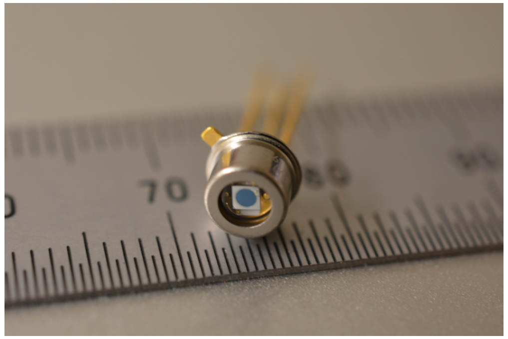




shape from shading by 4 single pixel detectors and projector

accumulated numbers: 50000

Single pixel imaging



general imaging

single pixel imaging

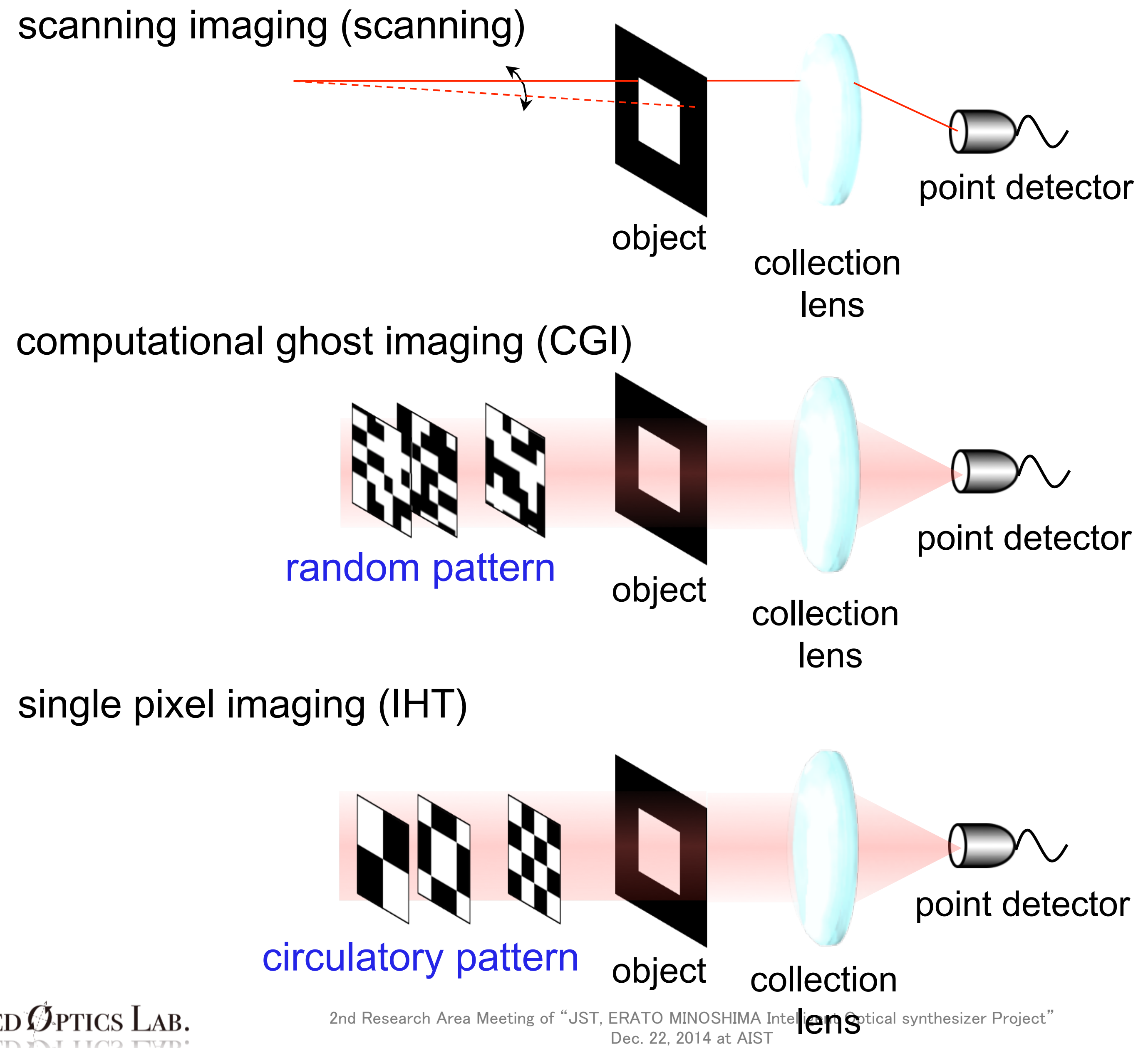
single pixel imaging, compressive sensing

coded pattern illumination
analytic processing
high speed imaging (limited illuminated patterns)

ghost imaging

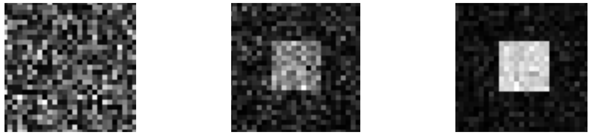
random pattern illumination
correlation based imaging
low speed imaging (many illuminated pattern)
high sensitivity

For comparison of the visibility

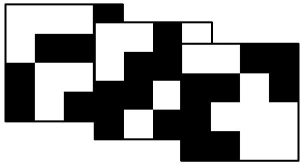


Reduction of accumulated number of computational ghost imaging

reconstructed image



small ← accumulated number → large



random pattern

weak point of ghost imaging

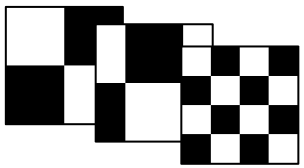
increase of measurement time

low efficiency of object information

- random pattern illumination
- correlation method

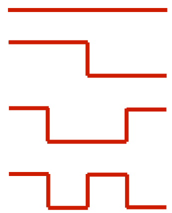
focused on: regularity of illumination pattern

circulatory pattern by Hadamard matrix



circulatory pattern

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix}$$



0
1
2
3

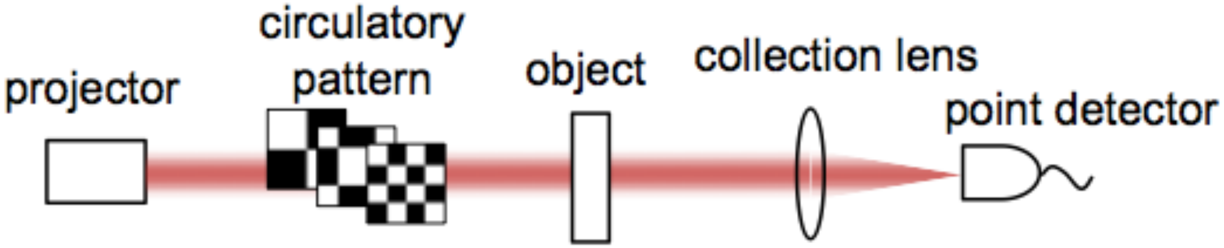
wave number

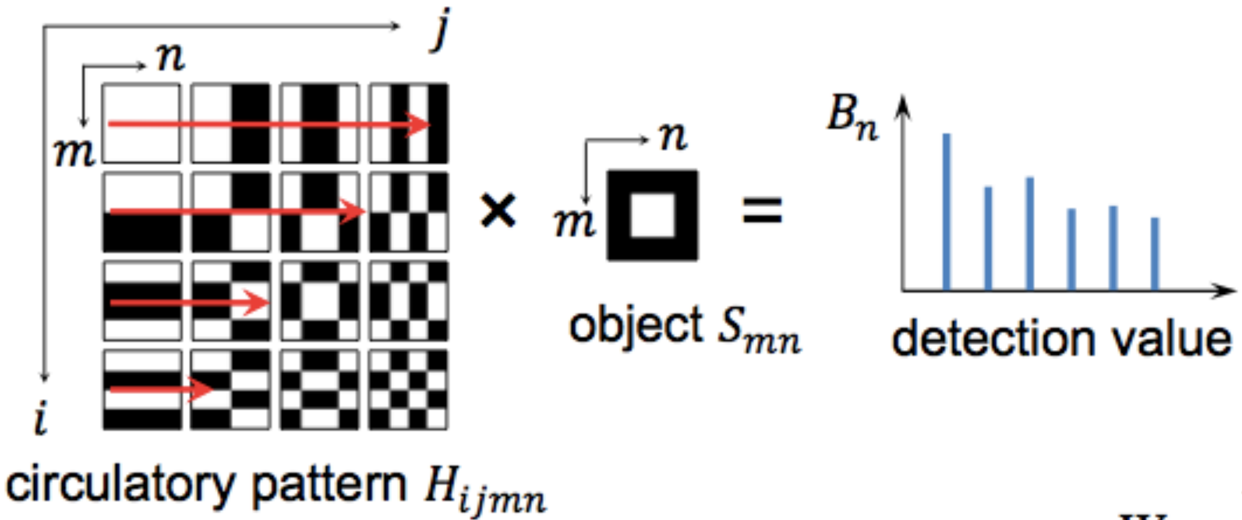
characteristics

- entries +1or -1
- square matrix
- mutually orthogonal rows and columns

high efficiency of the object information by the regularity

Applied for a circulatory pattern to ghost imaging





wavenumber distribution array W_{ij}

$$W_{ij} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} H_{ijmn} S_{mn} = H_M S_{mn} H_N$$

object

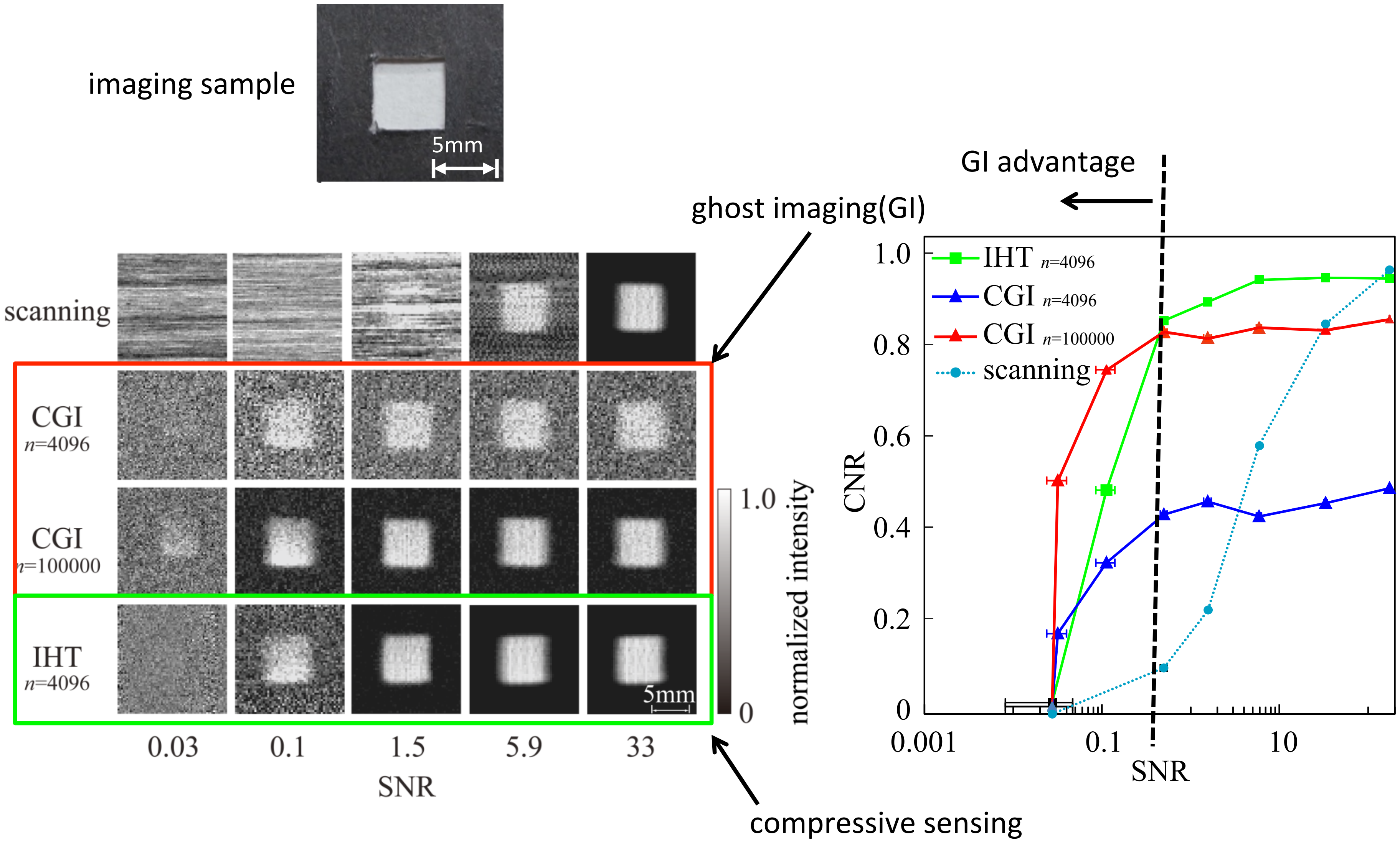
Inverse Hadamard Transform (IHT)

$$S_{mn} = \frac{1}{MN} H_M^{-1} W_{ij} H_N^{-1} \longrightarrow$$

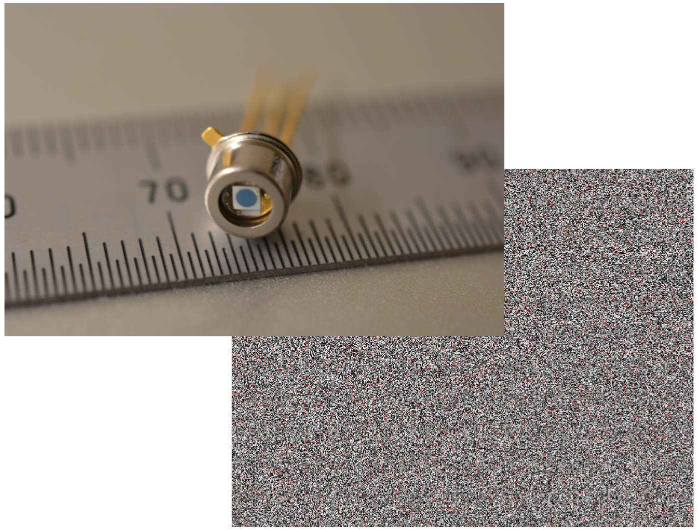
reconstructed image

algebraic reconstruction
of the object image by IHT

Visibility of circulatory pattern ghost imaging



Advantages of Ghost imaging



General imaging | **Ghost imaging**

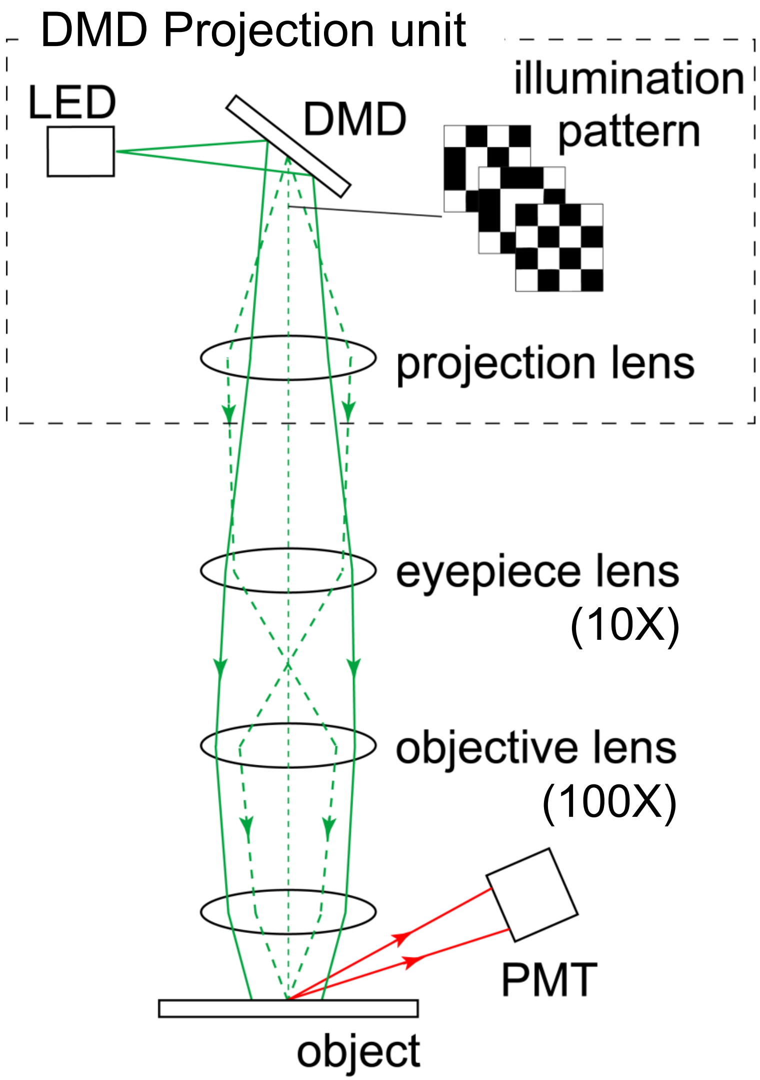
down sizing — Size of a single pixel detector is smaller than 2D sensor. Imaging lens free.

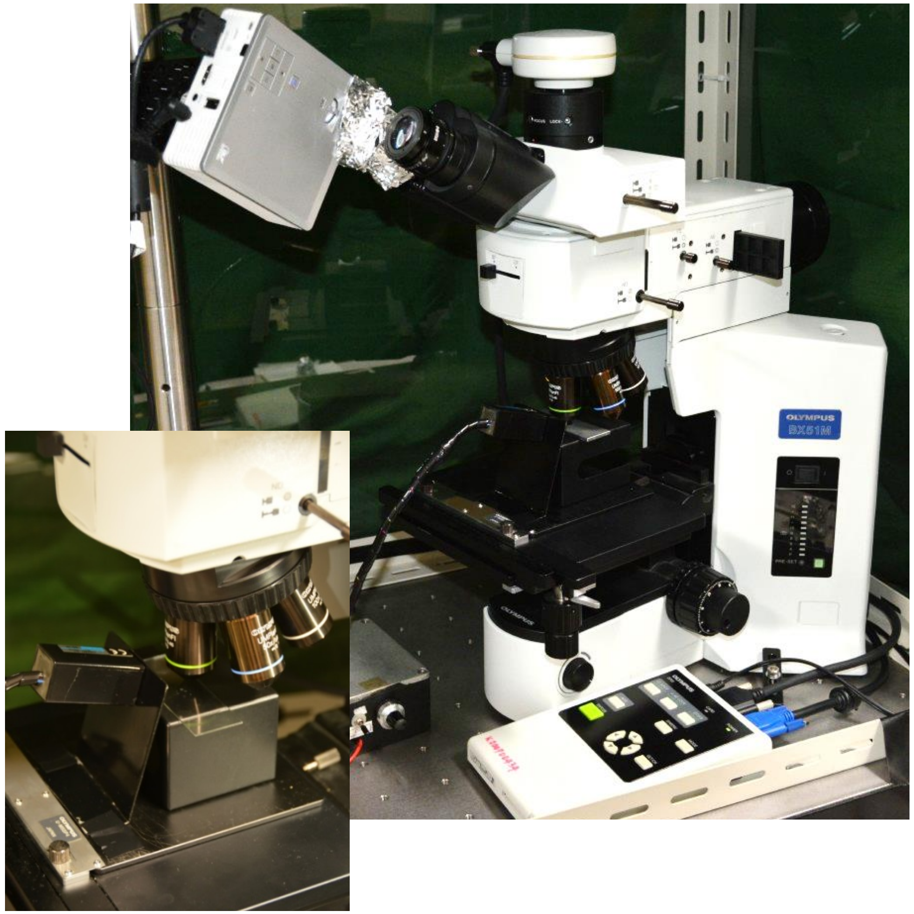
fast detection — High response time about ~ GHz order.

high flexibility for wavelength — Optical sensor for wide range wavelength from gamma ray to mm wave has been already released.

high sensitivity — A correlation technique reduce an influence of light fluctuation.

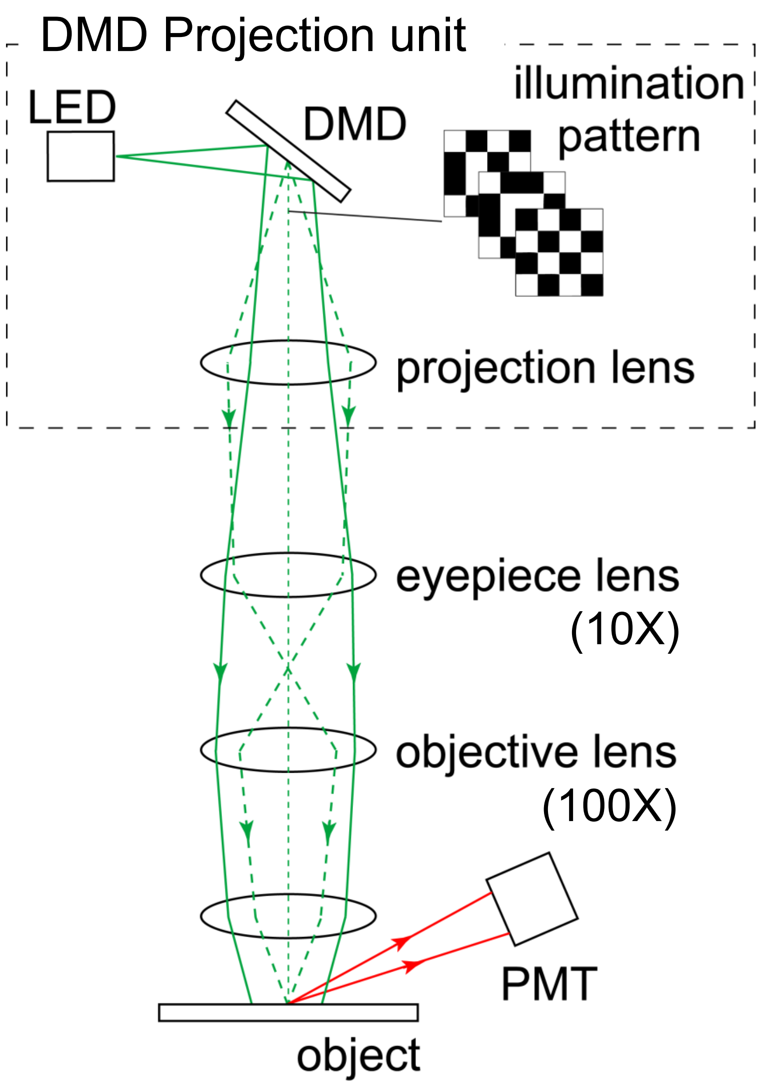
High spatial resolution ghost imaging by microscope



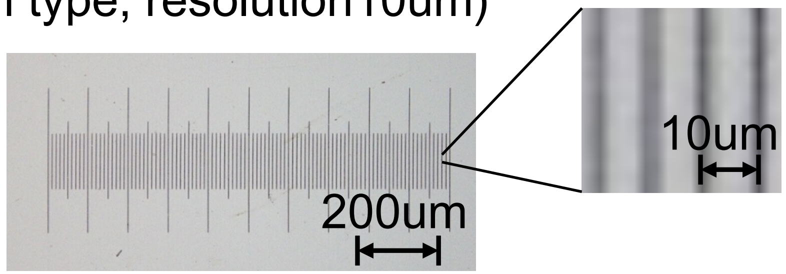


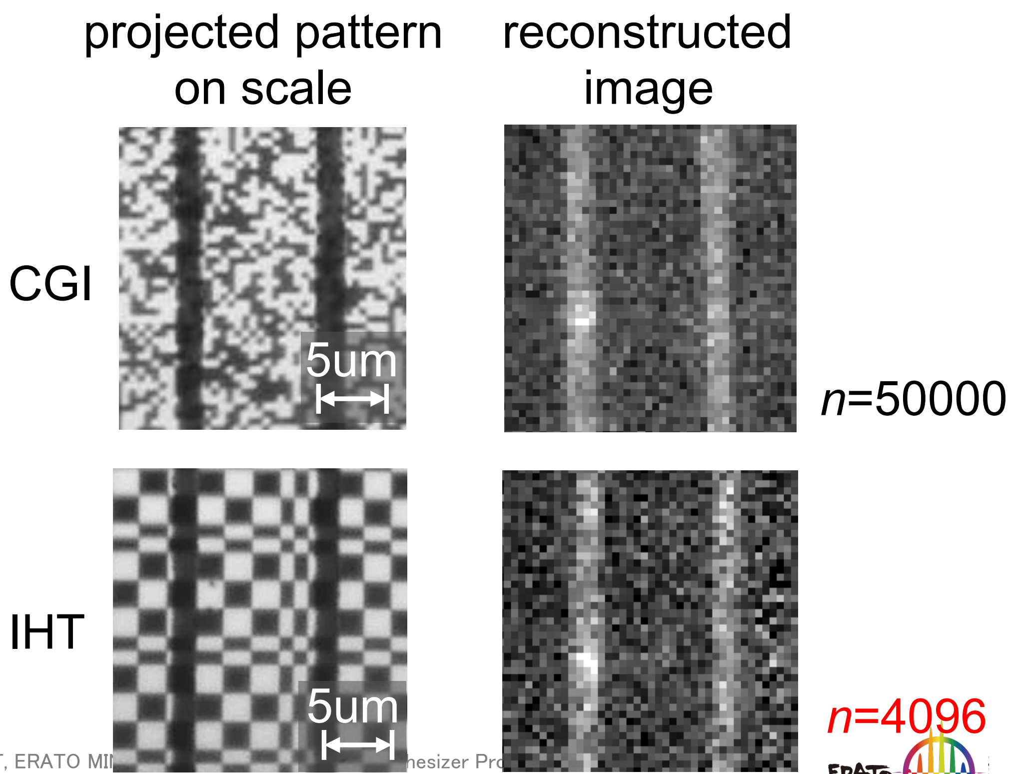
Ghost imaging microscope system

High spatial resolution ghost imaging by microscope

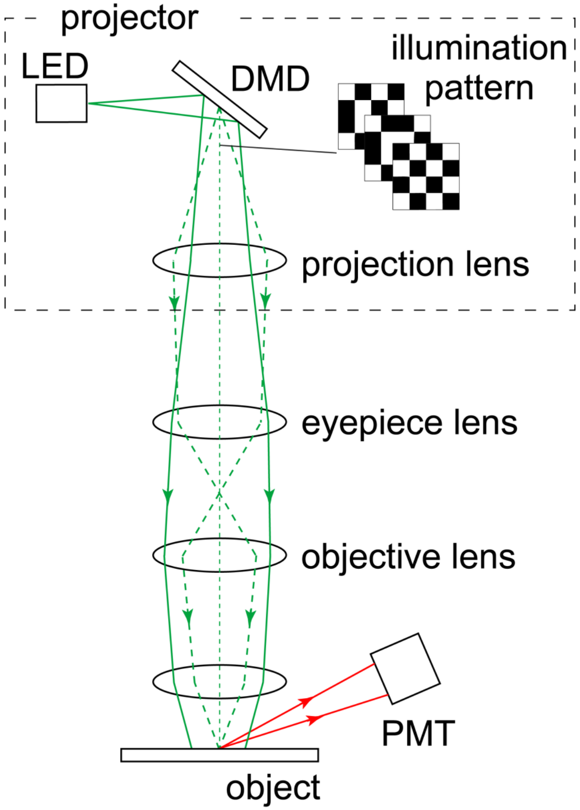


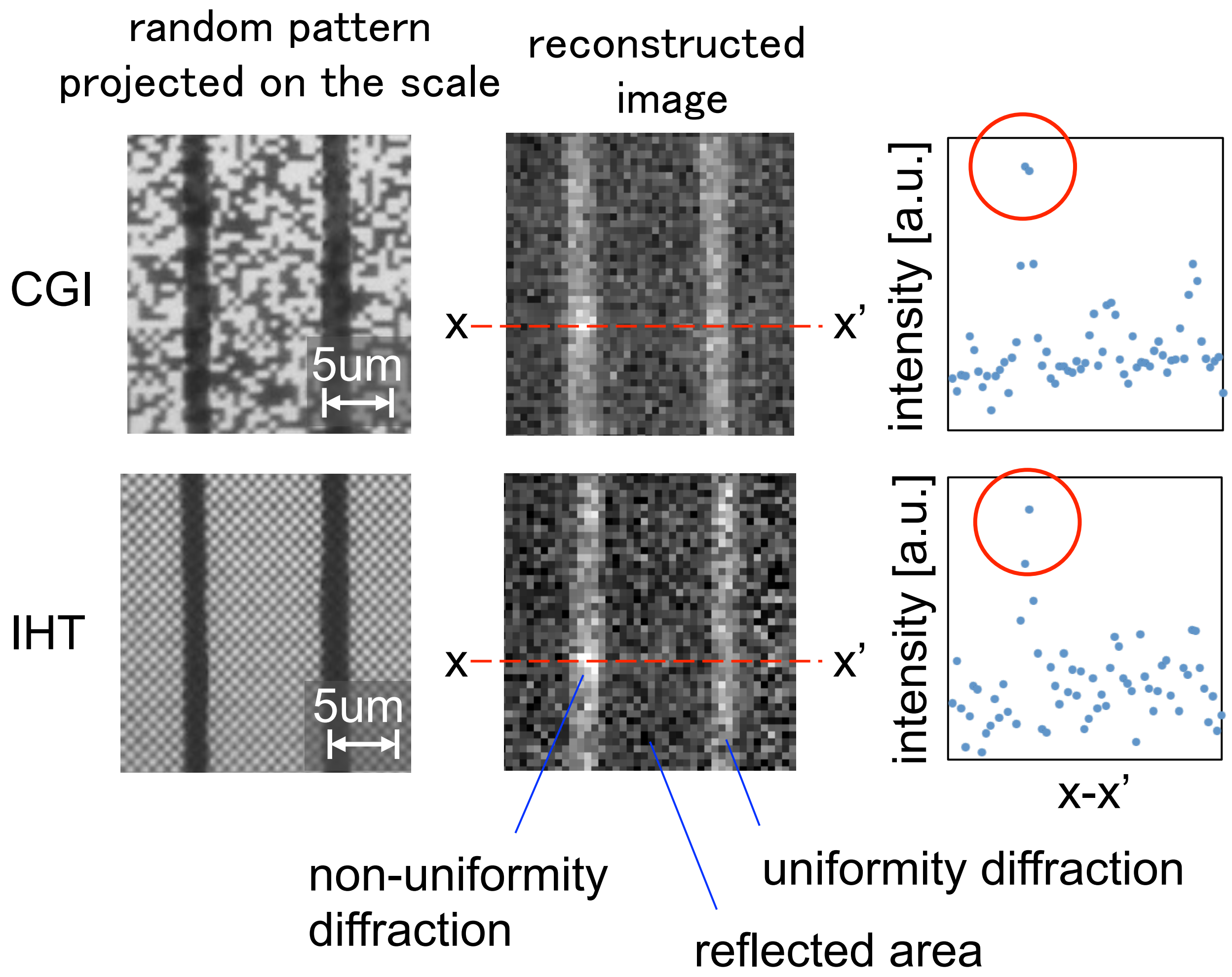
object: objective scale
(reflection type, resolution10um)



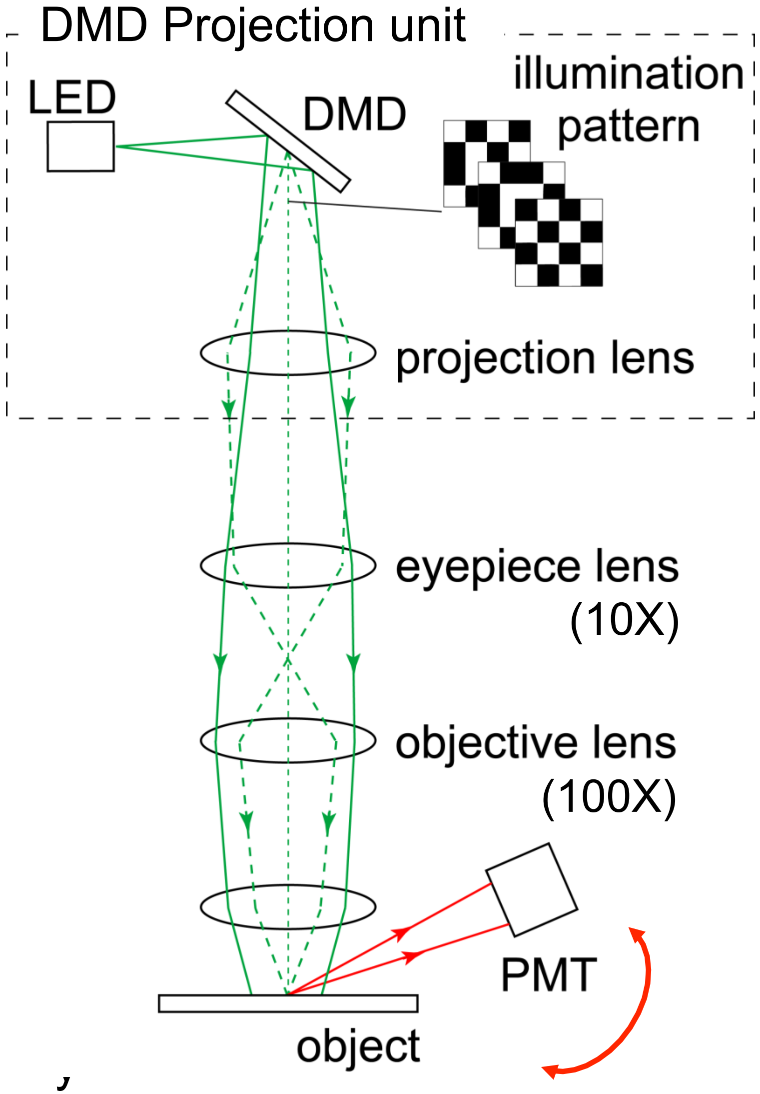


Microscopic imaging detected by GI-based microscope

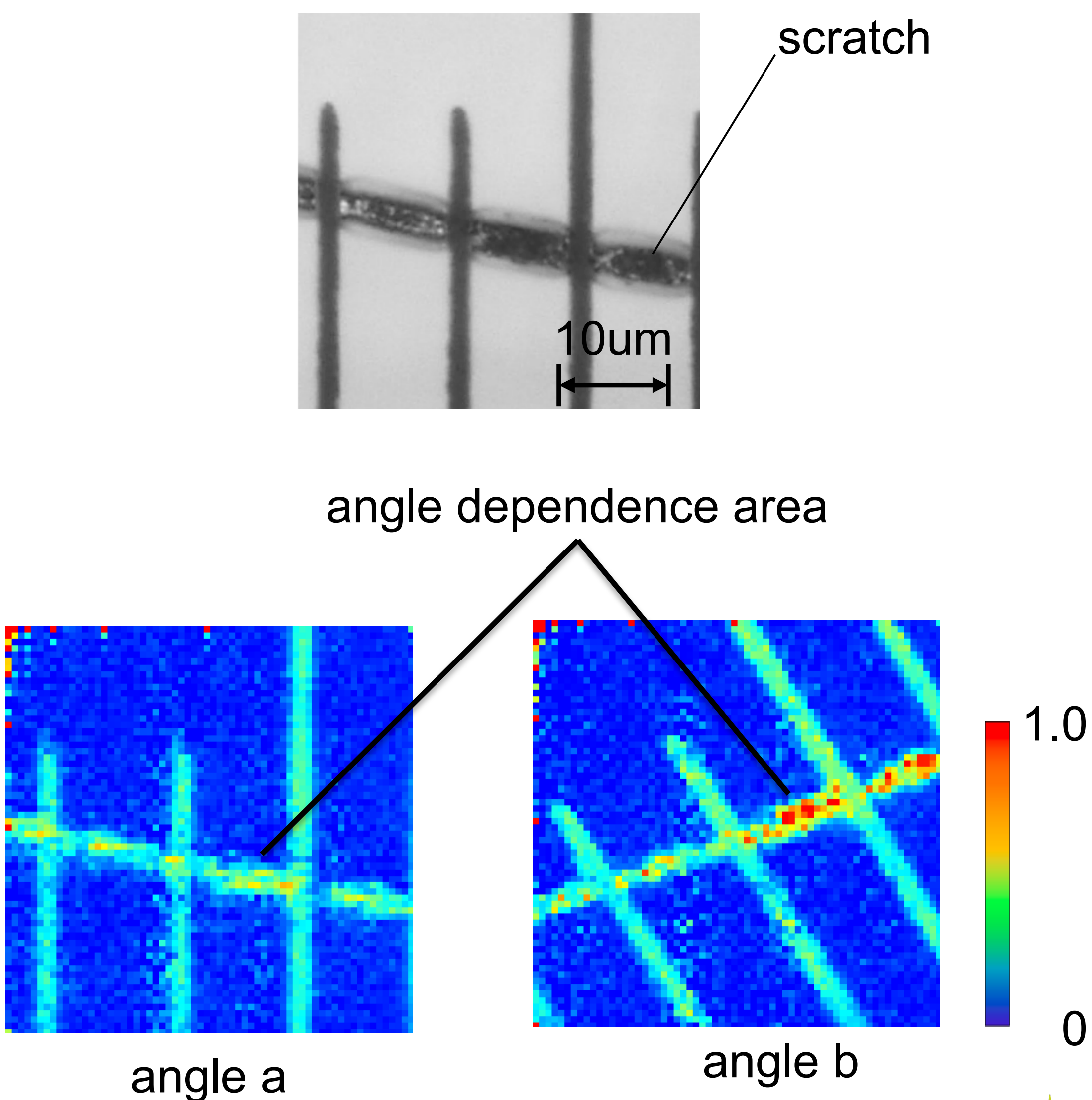




Imaging of non-uniformity diffraction object

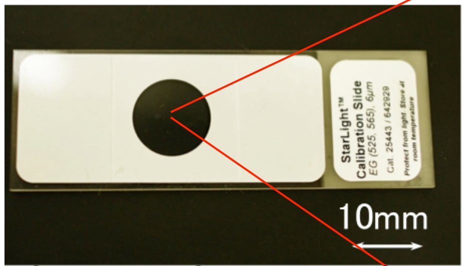


sample: micro scale (CCD image)

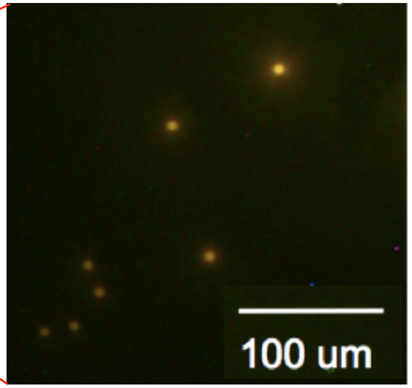


Ghost image

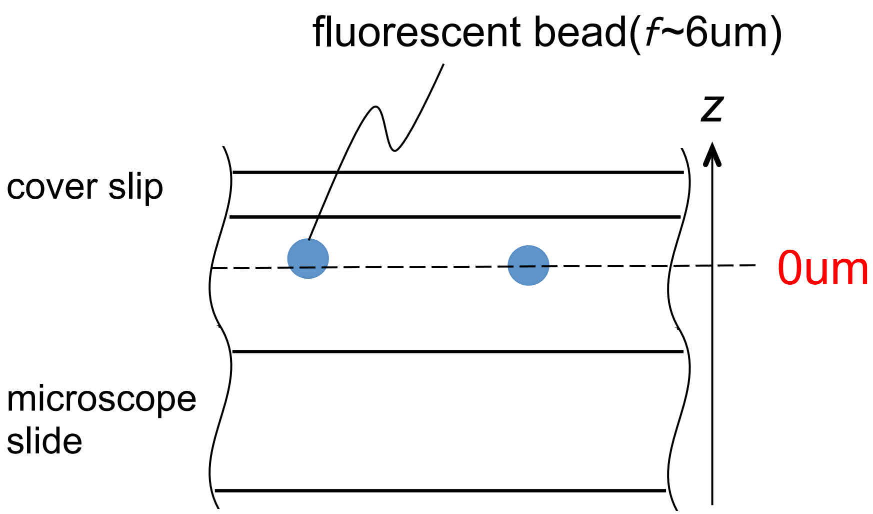
Imaging-position dependency



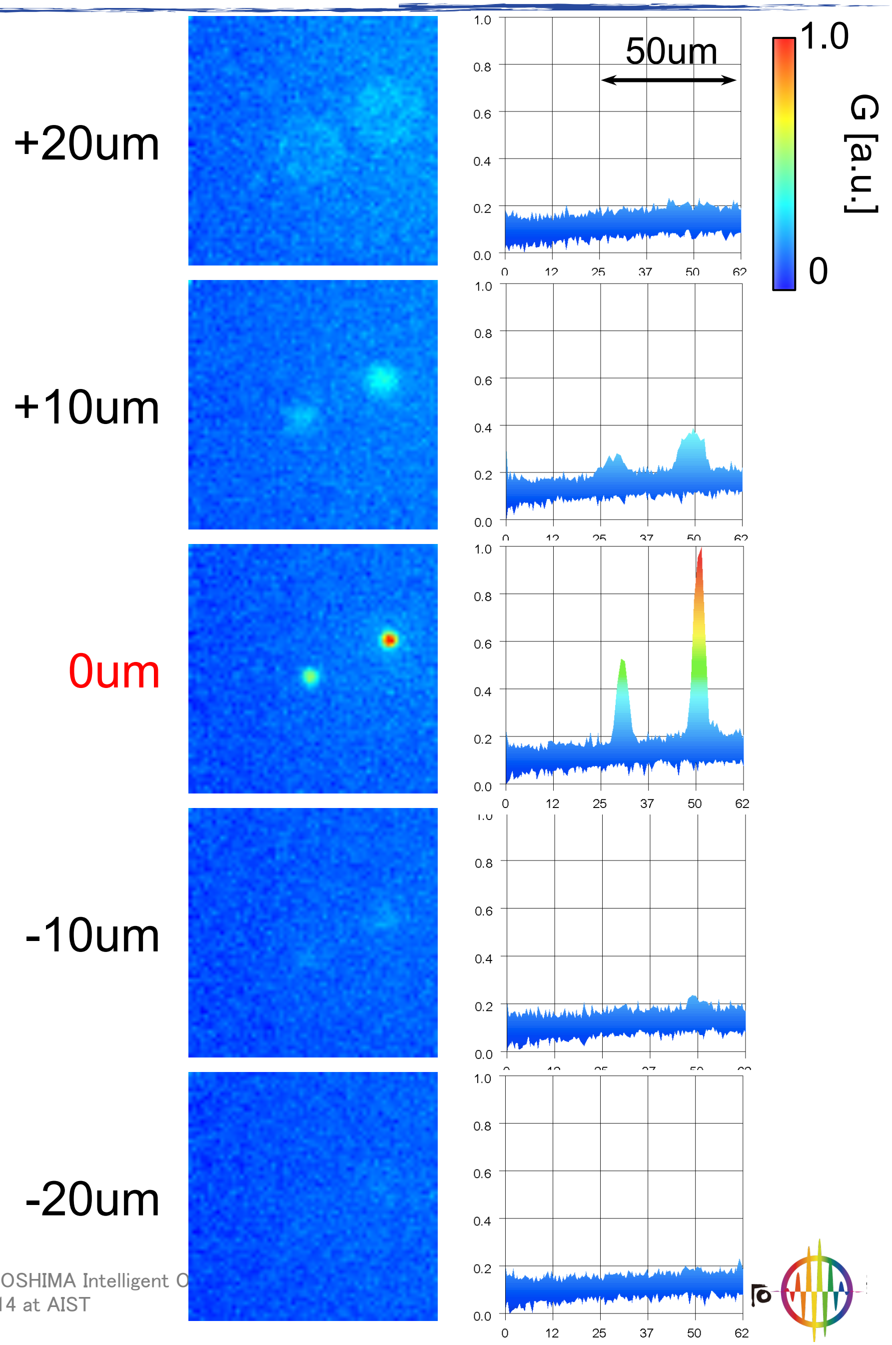
StarLight Calibration Slide
- Envy Green (~6um)



fluorescent microscope



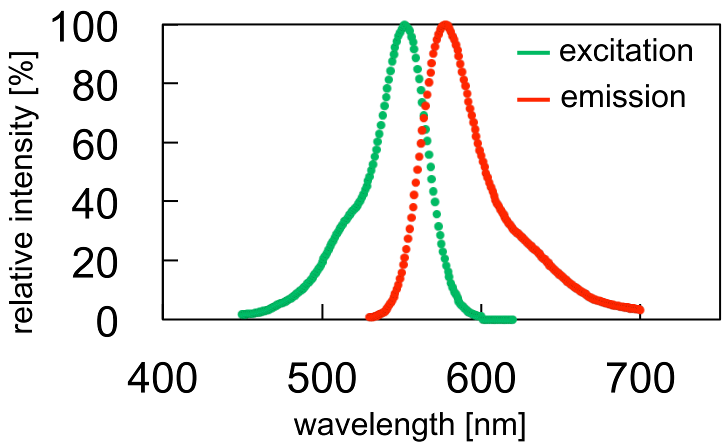
side view



Applied for Biological cell imaging

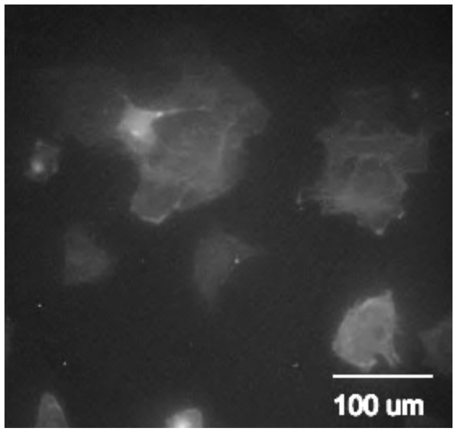
osteoblast cells derived from mouse (MC3T3-E1)
formed born and collagen
after differentiated osteoblast cells

fluorochrome: Rhodamine Phalloidin
- selectively stained with actine (cytoskeleton)

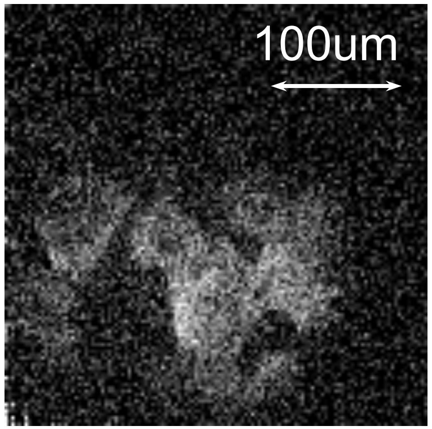


source by Life Technologies Corporation

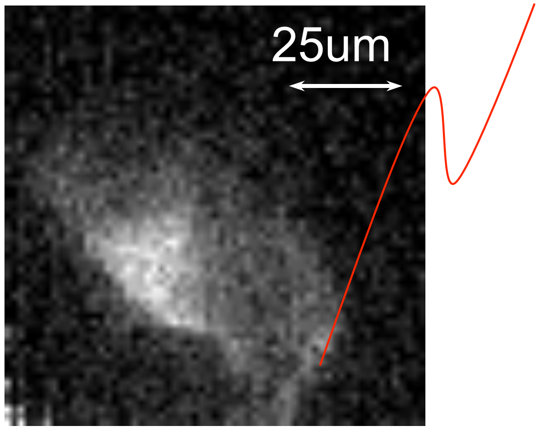
microscope



ghost imaging



cytoskeleton



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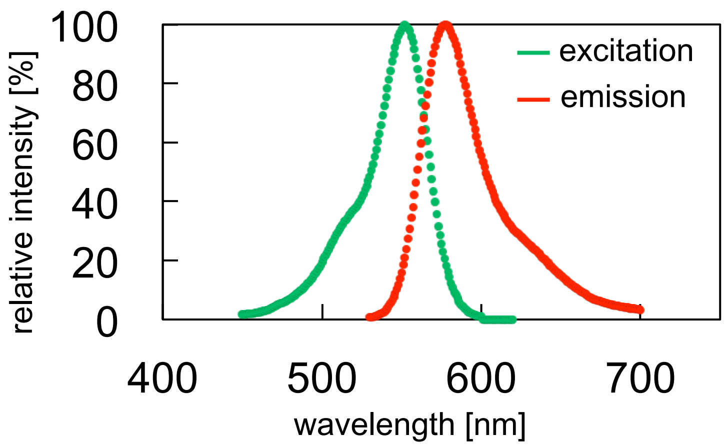
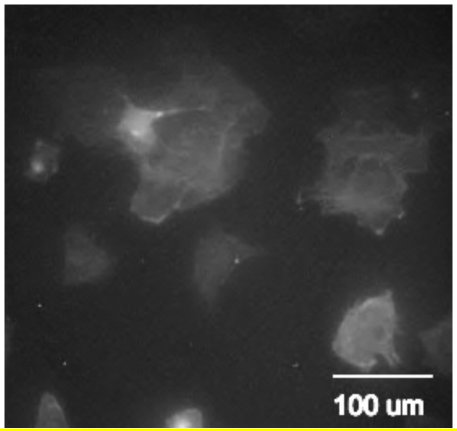
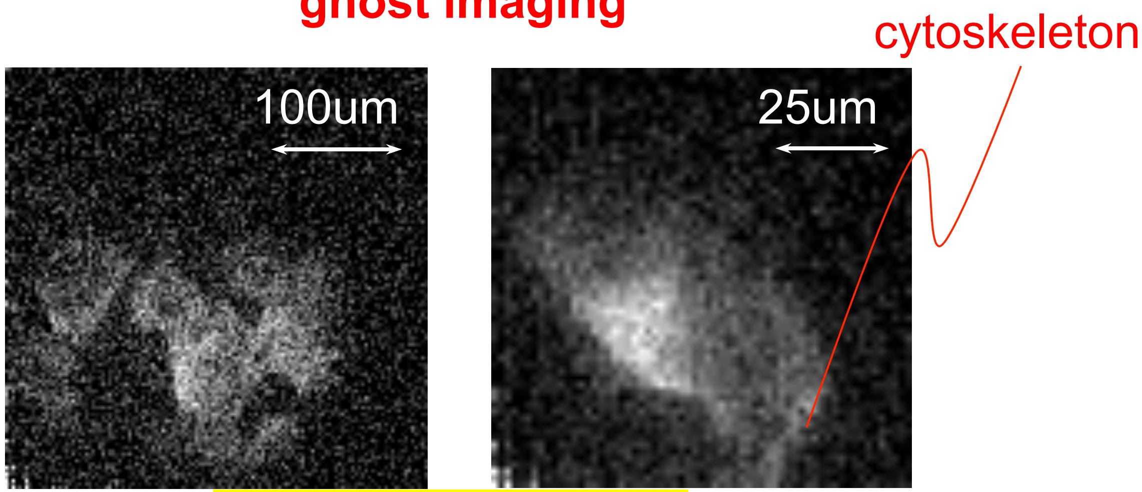


source by Life Technologies Corporation

microscope



ghost imaging

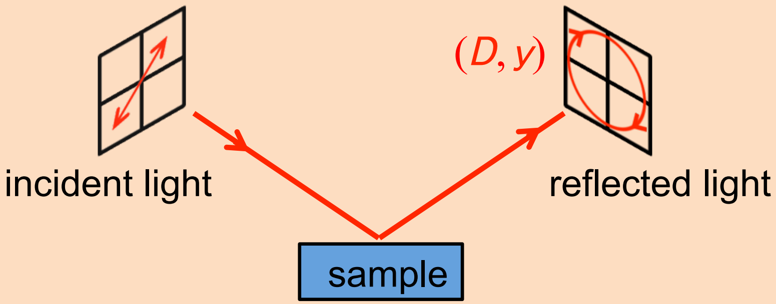


excitation intensity: 87.75uW

> 1/100

excitation intensity: 0.77uW

Ellipsometry



basic configuration of ellipsometry

Measurement of polarization difference between incident and reflected light of sample

D: phase difference between P and S pol. wave
y: amplitude ratio of P and S pol. wave

measured value
D*, *y

- rotating analyzer
- rotating retarder
- phase modulation

- linear fitting
- database

optical model of the sample

- classical modeling (Drude, ･･･)
- rigorous modeling (FDTD, RCWA･･･)

optical properties

refractive index: n, k
dielectric constant: e
absorption coefficient: a

geometrical parameters

thickness (film sample): t
roughness: Ra, ･･･

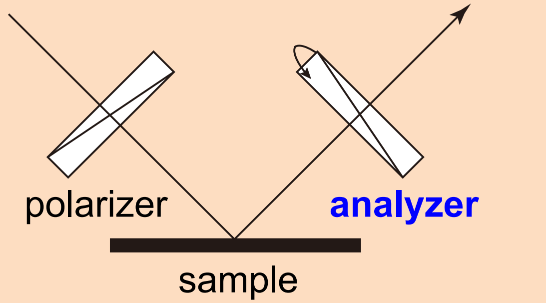
analysis process of ellipsometry

Category of optical setup for ellipsometer

rotating analyzer type

Analyzing ellipso-parameters by rotating analyzer

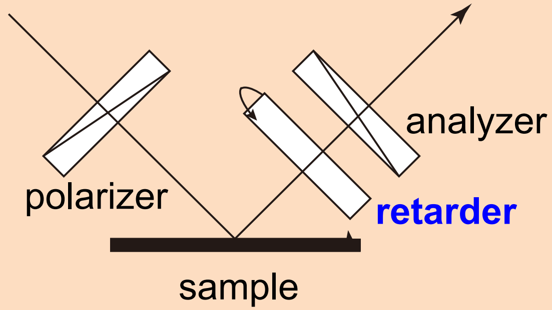
- simple setup
- low speed
- **point measurement**



rotating retarder type

Analyzing ellipso-paramers by rotating retarder

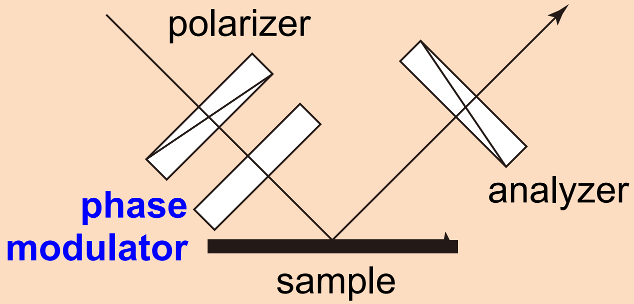
- high accuracy
- low speed
- **point measurement**



phase modulation type

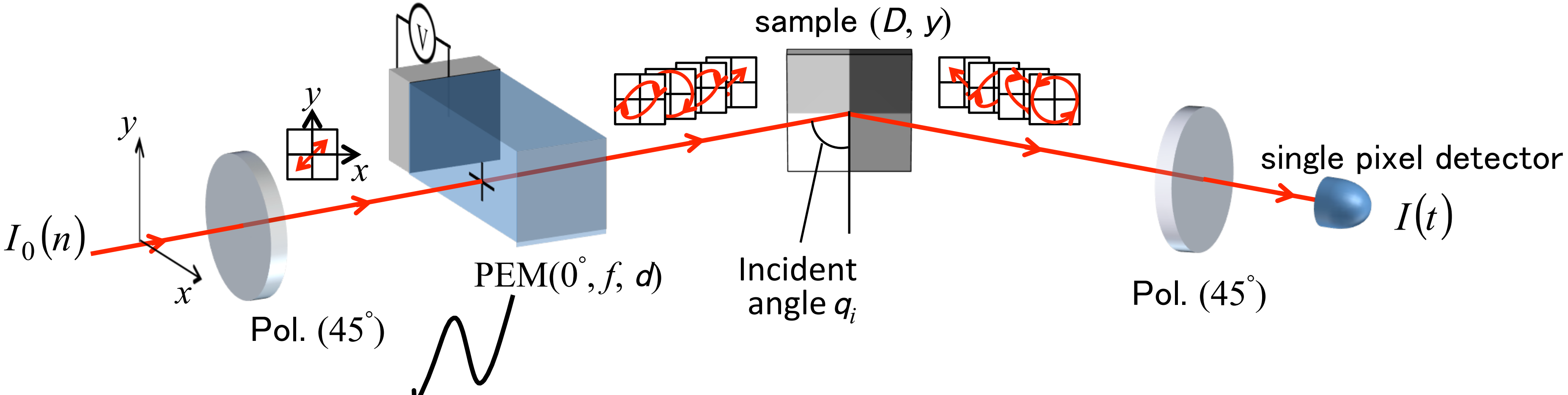
Modulated polarization states by using phase modulator

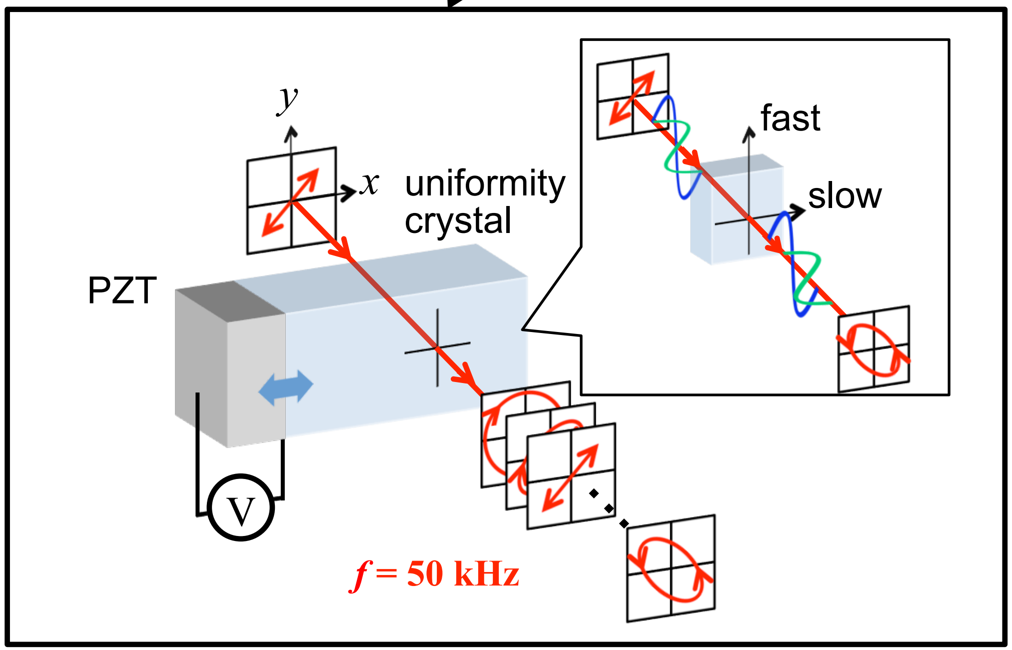
- higher accuracy and sensitivity
- real time measurement
- **point measurement**



(S. N. Jasperson *et al*., Rev. Sci. Instrum. **40**, (1969))

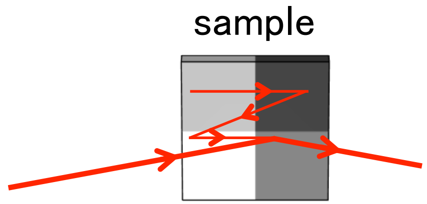
Phase modulation type ellipsometer (S. N. Jasperson *et al.*, Rev. Sci. Instrum. **40**, (1969))

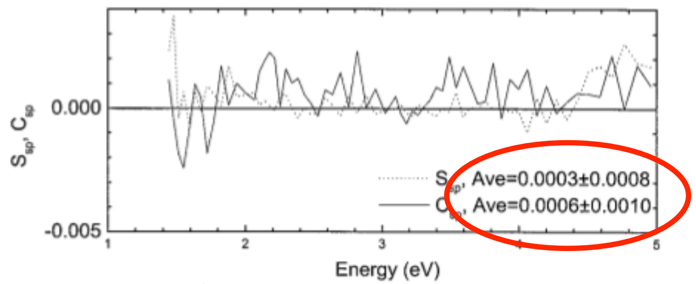




phase modulation by using photo-elastic modulator (PEM)

For 2D detection

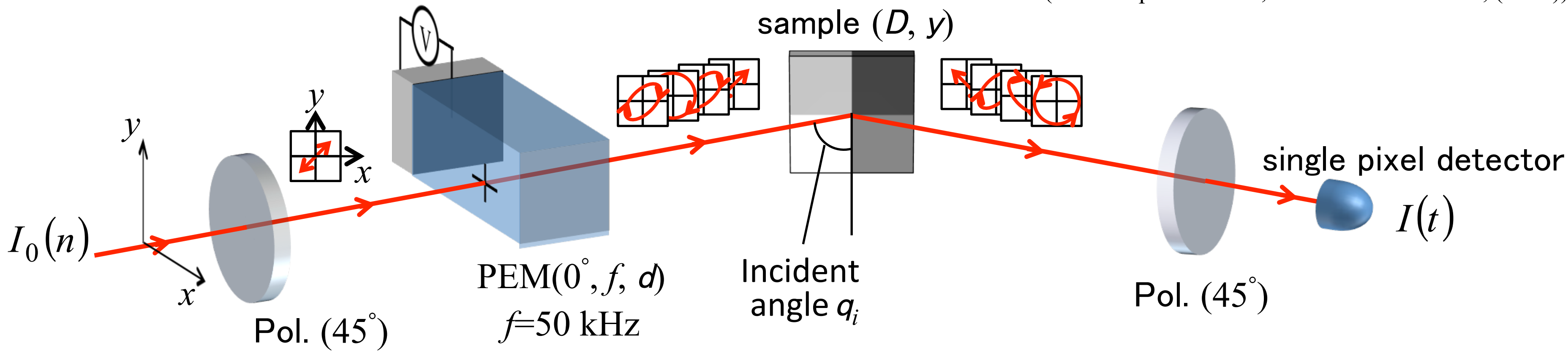




G. E. Jellison, et. Al., Appl. Opt. 36, 8184-8189 (1997)

Principle of phase modulated ellipsometer using PEM

(S. N. Jasperson *et al*., Rev. Sci. Instrum. **40**, (1969))



detected intensity

$$I(t)=\frac{I_0}{4}\{1+\sin 2\psi\sin\Delta[1.038\sin\underbrace{2\pi ft}_{1f}]+\sin 2\psi\cos\Delta[0.864\cos\underbrace{4\pi ft}_{2f}]\}$$

Fourier analysis

$$I_{dc}=\frac{I_0}{4}$$

$$I_{1f}=\frac{I_0}{4}(1.038\sin 2\psi\sin\Delta)$$

$$I_{2f}=\frac{I_0}{4}(0.864\sin 2\psi\cos\Delta)$$

Phase difference

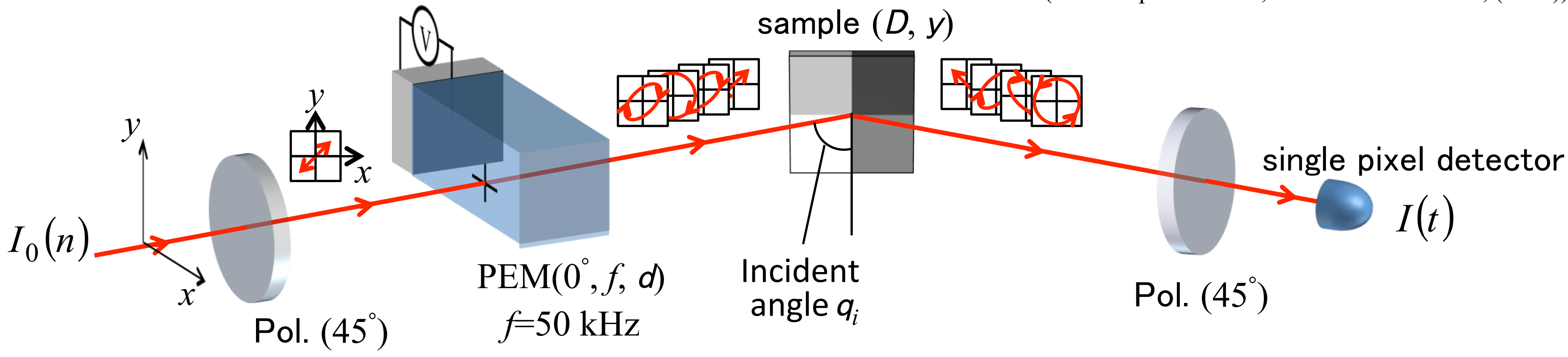
$$\Delta=\tan^{-1}\left(\frac{0.432\,I_{1f}}{0.519\,I_{2f}}\right)$$

Amplitude ratio

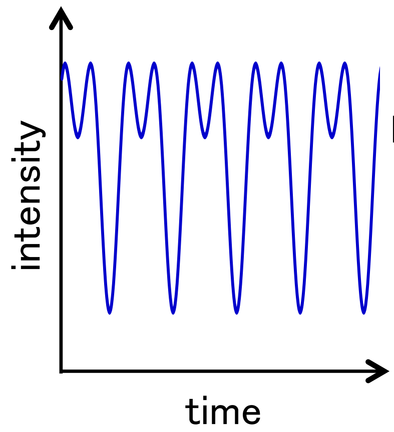
$$\psi=\frac{1}{2}\sin^{-1}\left\{\left(\frac{I_{1f}}{1.038\,I_{dc}}\right)^2+\left(\frac{I_{2f}}{0.864\,I_{dc}}\right)^2\right\}^{\frac{1}{2}}$$

Principle of phase modulated ellipsometer using PEM

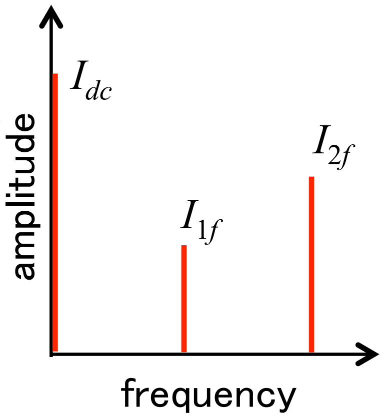
(S. N. Jasperson *et al*., Rev. Sci. Instrum. **40**, (1969))



measurement process



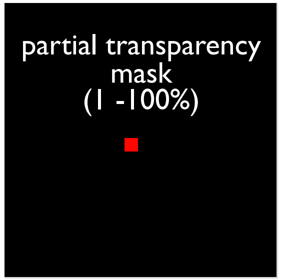
Fourier analysis



$$\Delta = \tan^{-1}\left(\frac{0.432\, I_{1f}}{0.519\, I_{2f}}\right)$$

$$\psi = \frac{1}{2}\sin^{-1}\left\{\left(\frac{I_{1f}}{1.038\, I_{dc}}\right)^2 + \left(\frac{I_{2f}}{0.864\, I_{dc}}\right)^2\right\}^{\frac{1}{2}}$$

Linearity of correlation coefficient

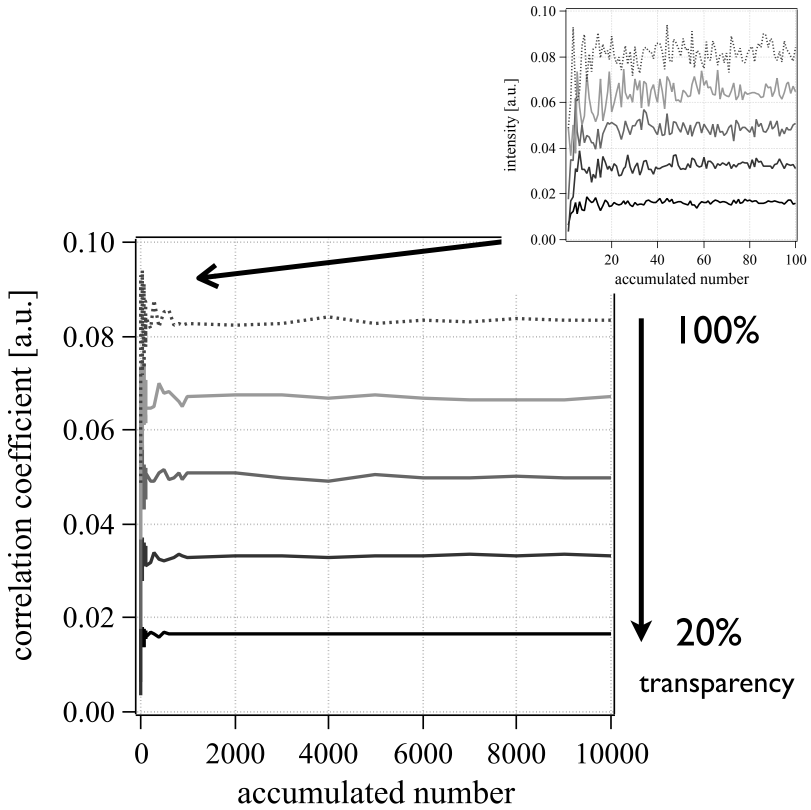


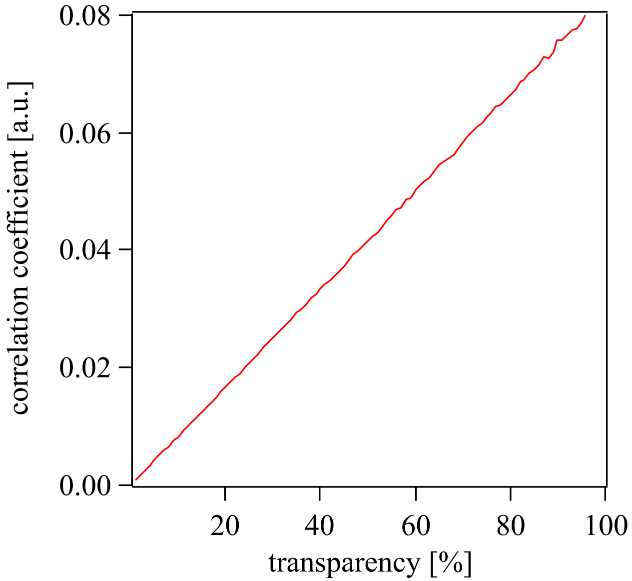
sample

ghost image

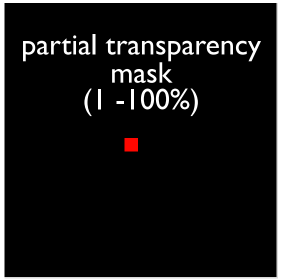
simulation conditions

total size of sample	100 X 100 pixels
aperture size	4 pixels, block pattern
transparency	**1 - 100 %**
total size of random pattern	100 X 100 pixels
random pattern size	1 pixel
accumulated numbers	1 - 10000
ecaluation value	averaged intensity





Linearity of correlation coefficient

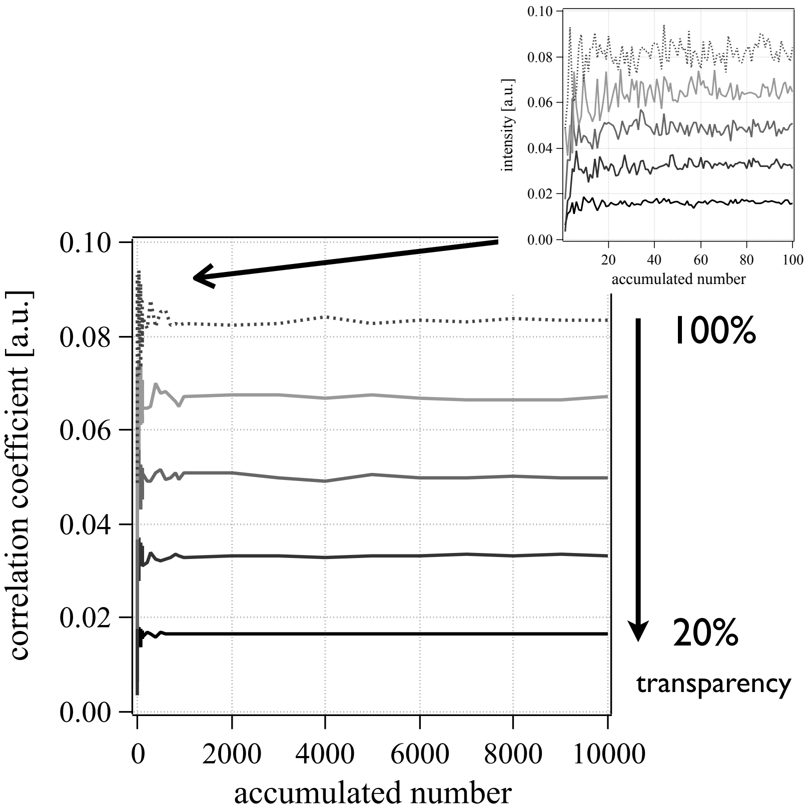


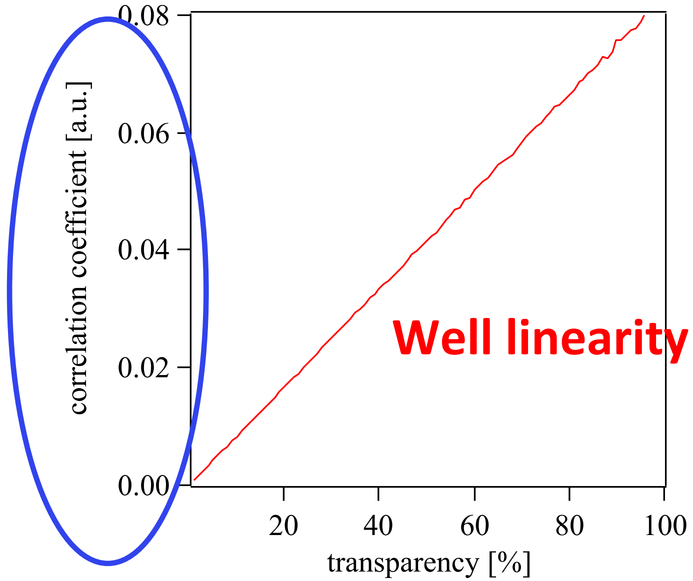
sample

ghost image

simulation conditions

total size of sample	100 X 100 pixels
aperture size	4 pixels, block pattern
transparency	**1 - 100 %**
total size of random pattern	100 X 100 pixels
random pattern size	1 pixel
accumulated numbers	1 - 10000
ecaluation value	averaged intensity

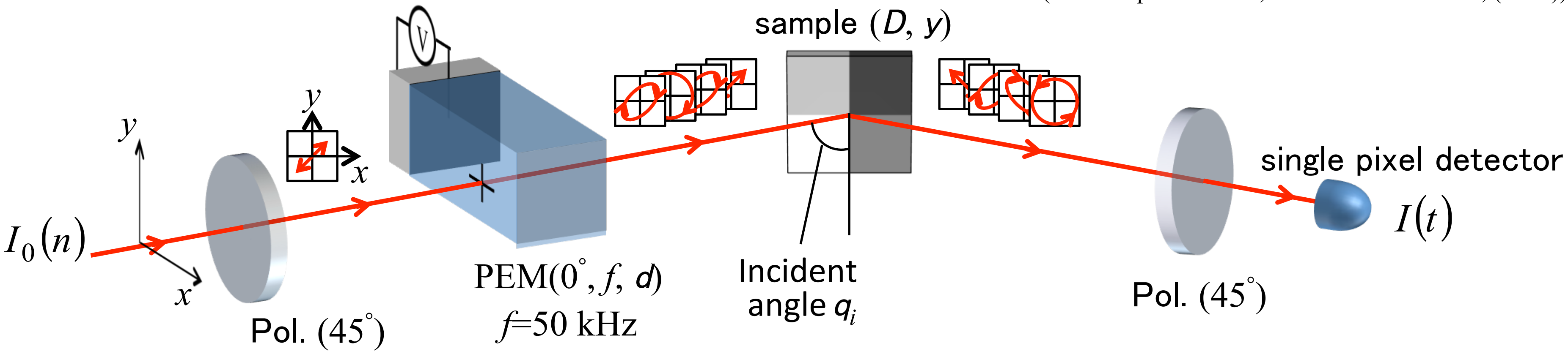




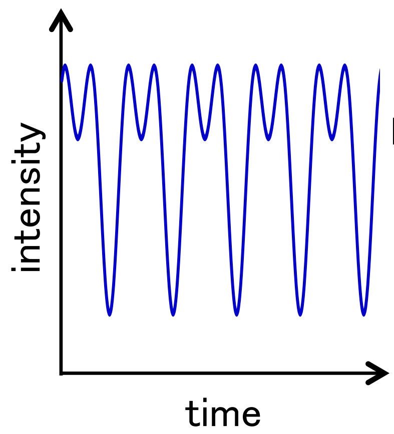
Quantity was not guaranteed

Principle of phase modulated ellipsometer using PEM

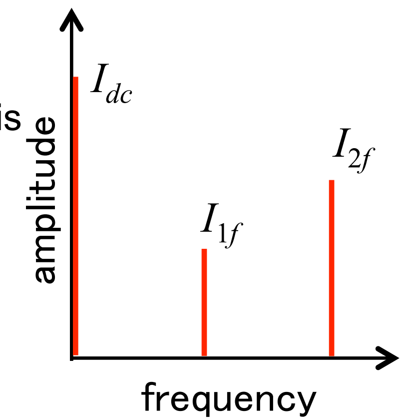
(S. N. Jasperson *et al*., Rev. Sci. Instrum. **40**, (1969))



measurement process



Fourier analysis

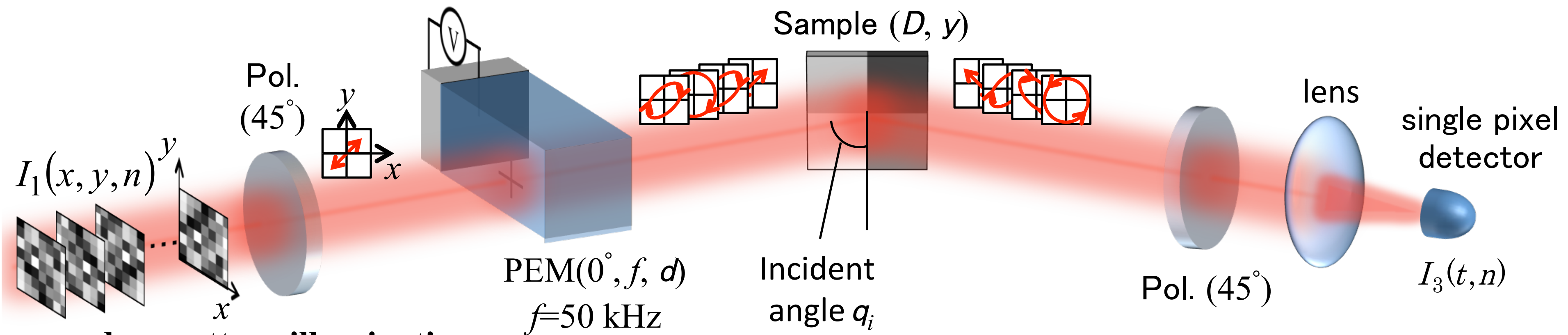


$$\Delta = \tan^{-1}\left(\frac{0.432\, I_{1f}}{0.519\, I_{2f}}\right)$$

$$\psi = \frac{1}{2}\sin^{-1}\left\{\left(\frac{I_{1f}}{1.038\, I_{dc}}\right)^2 + \left(\frac{I_{2f}}{0.864\, I_{dc}}\right)^2\right\}^{\frac{1}{2}}$$

relative components

Principle of Ghost imaging ellipsometry



random pattern illumination

detected intensity

$$I_3(t,n) = \frac{I_1(x,y,n)}{4}\left\{1+\sin 2\psi \sin\Delta\left[1.038\sin \underbrace{2\pi f t}_{1f}\right] + \sin 2\psi \cos\Delta\left[0.864\cos \underbrace{4\pi f t}_{2f}\right]\right\}$$

correction function $G_i(x,y)\ (i = dc, 1f, 2f)$

$$G_i(x,y) = \langle I_1(x,y,n) I_i(n)\rangle - \langle I_1(x,y,n)\rangle\langle I_i(n)\rangle$$

$$\langle I_i(n)\rangle = \frac{1}{n}\sum_{k=1}^{n} I_i(k)$$

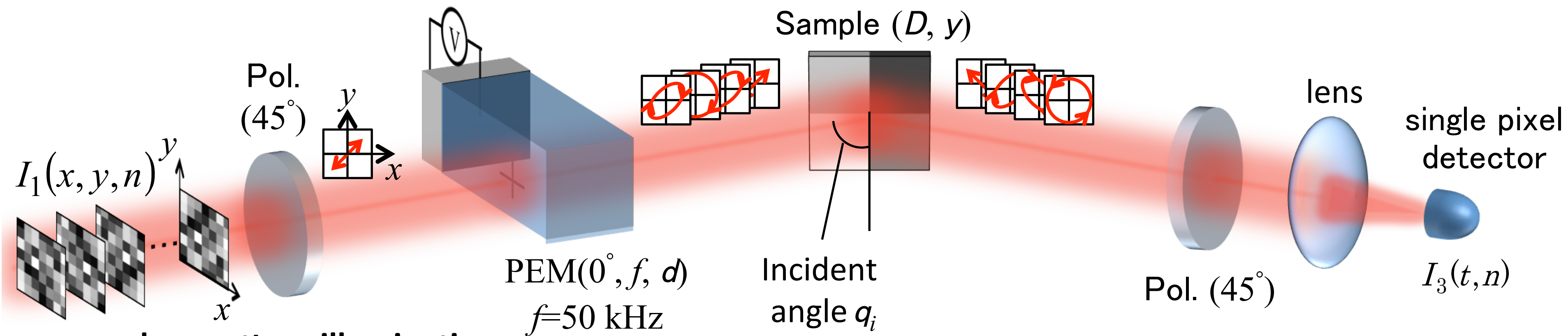
Phase difference

$$\Delta = \tan^{-1}\left(\frac{0.432\, G_{1f}(x,y,n)}{0.519\, G_{2f}(x,y,n)}\right)$$

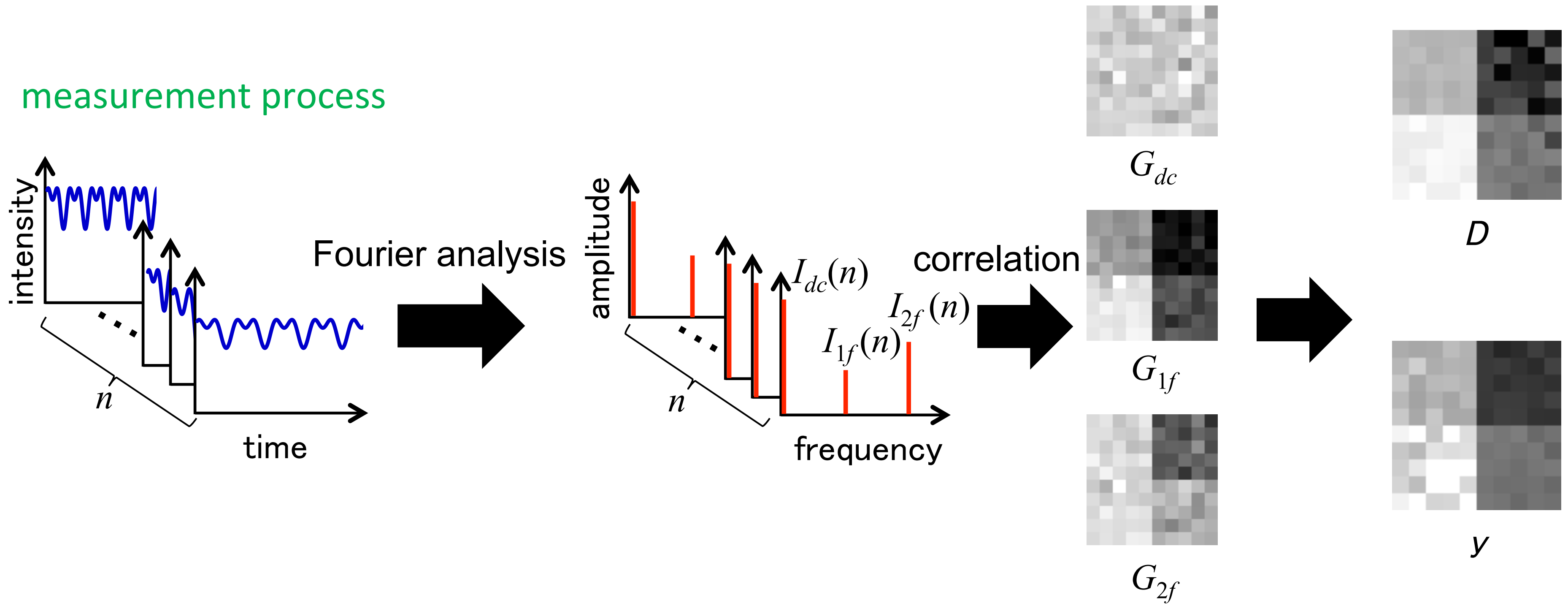
Amplitude ratio

$$\psi = \frac{1}{2}\sin^{-1}\left\{\left(\frac{G_{1f}(x,y,n)}{1.038\, G_{dc}(x,y,n)}\right)^2 + \left(\frac{G_{2f}(x,y,n)}{0.864\, G_{dc}(x,y,n)}\right)^2\right\}^{\frac{1}{2}}$$

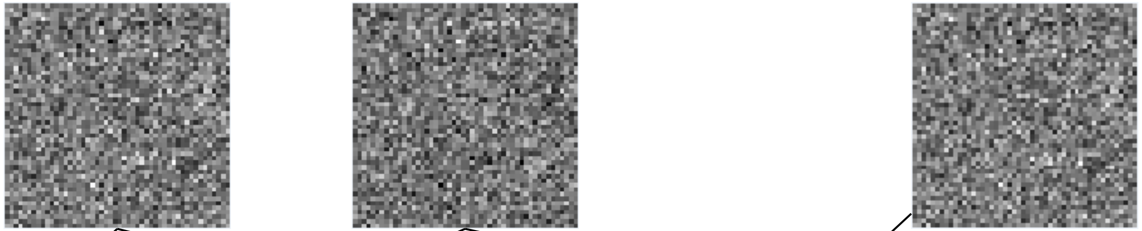
Principle of Ghost imaging ellipsometry



measurement process

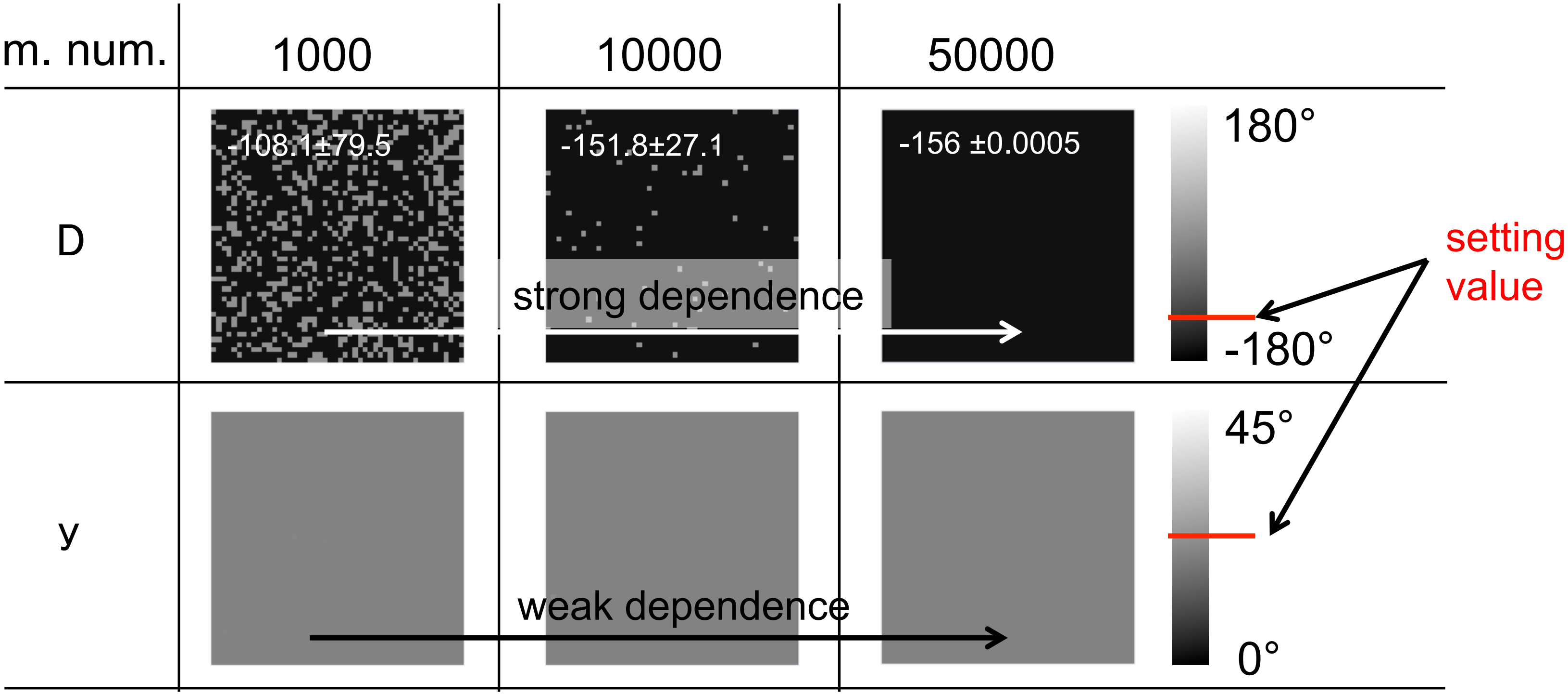


Simulation results of correlation functions (uniformity sample)

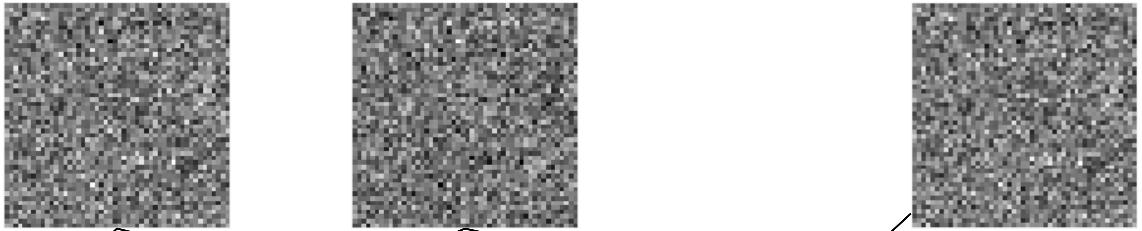


$$\Delta = \tan^{-1}\left(\frac{0.432\, G_{1f}(x,y,n)}{0.519\, G_{2f}(x,y,n)}\right)$$

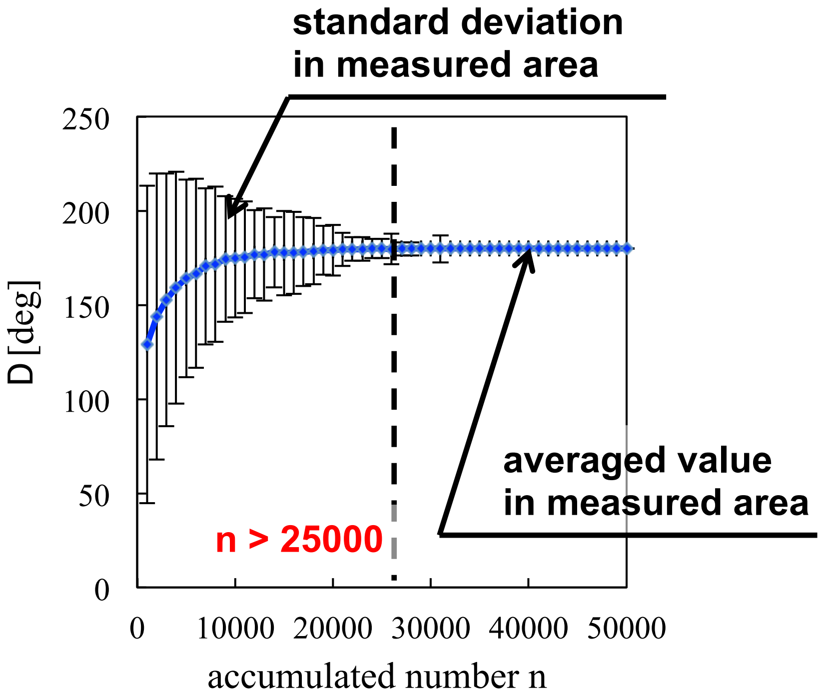
$$\psi = \frac{1}{2}\sin^{-1}\left\{\left(\frac{G_{1f}(x,y,n)}{1.038\, G_{dc}(x,y,n)}\right)^2 + \left(\frac{G_{2f}(x,y,n)}{0.864\, G_{dc}(x,y,n)}\right)^2\right\}^{\frac{1}{2}}$$

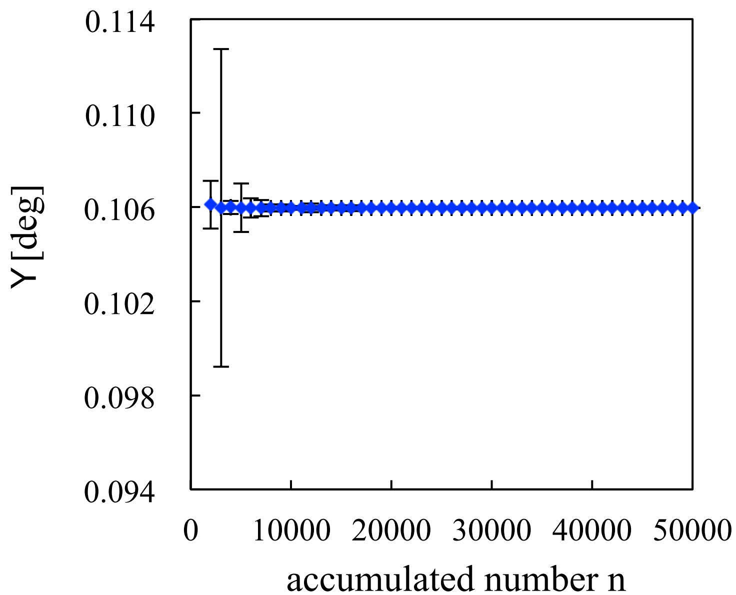


Simulation results of correlation functions (uniformity sample)



$$\Delta = \tan^{-1}\left(\frac{0.432\, G_{1f}(x,y,n)}{0.519\, G_{2f}(x,y,n)}\right) \qquad \psi = \frac{1}{2}\sin^{-1}\left\{\left(\frac{G_{1f}(x,y,n)}{1.038\, G_{dc}(x,y,n)}\right)^2 + \left(\frac{G_{2f}(x,y,n)}{0.864\, G_{dc}(x,y,n)}\right)^2\right\}^{\frac{1}{2}}$$



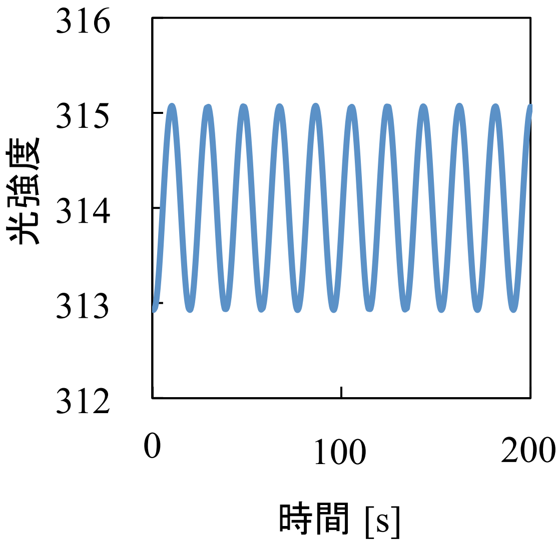


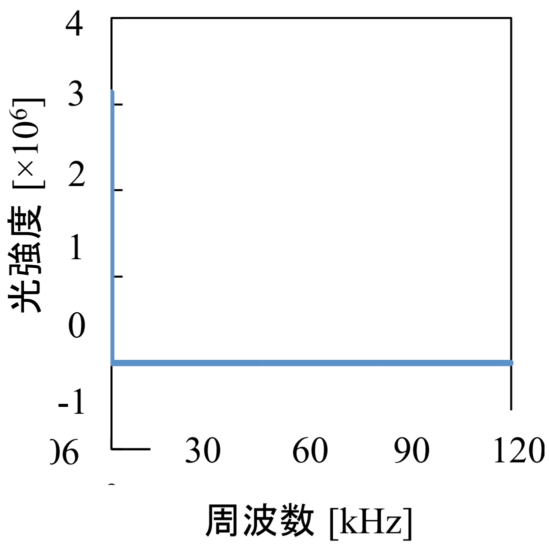
GIEによるBK7の数値計算結果

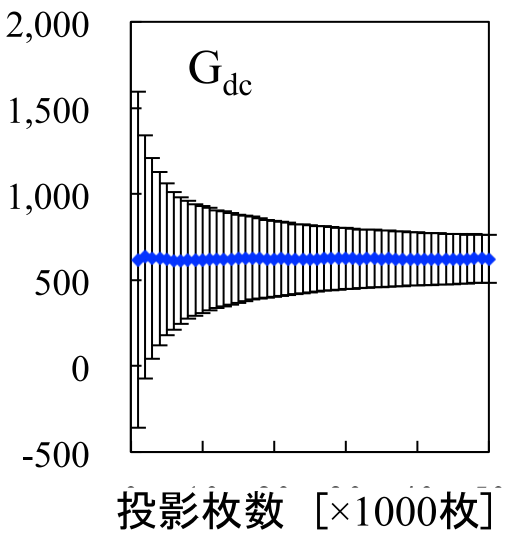
計算条件

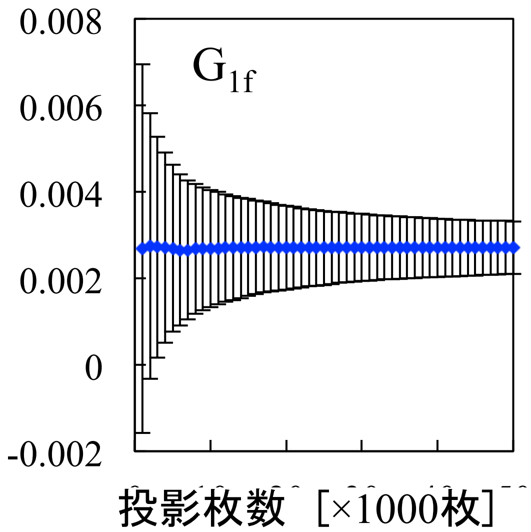
変調周波数	50 [kHz]
入射角	56.5 [deg.]
サンプル	BK7(*D*=180°, *γ*=0.11°)
照明回数	*n*=1000~40000 回
パターンサイズ	50×50 [pixel]

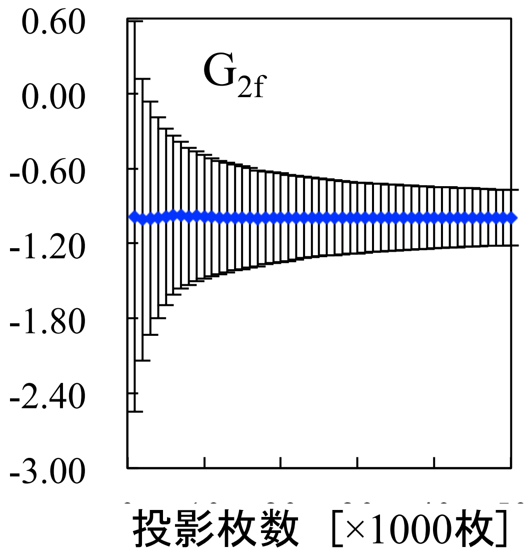
λ=632.8 nmのときの屈折率で計算







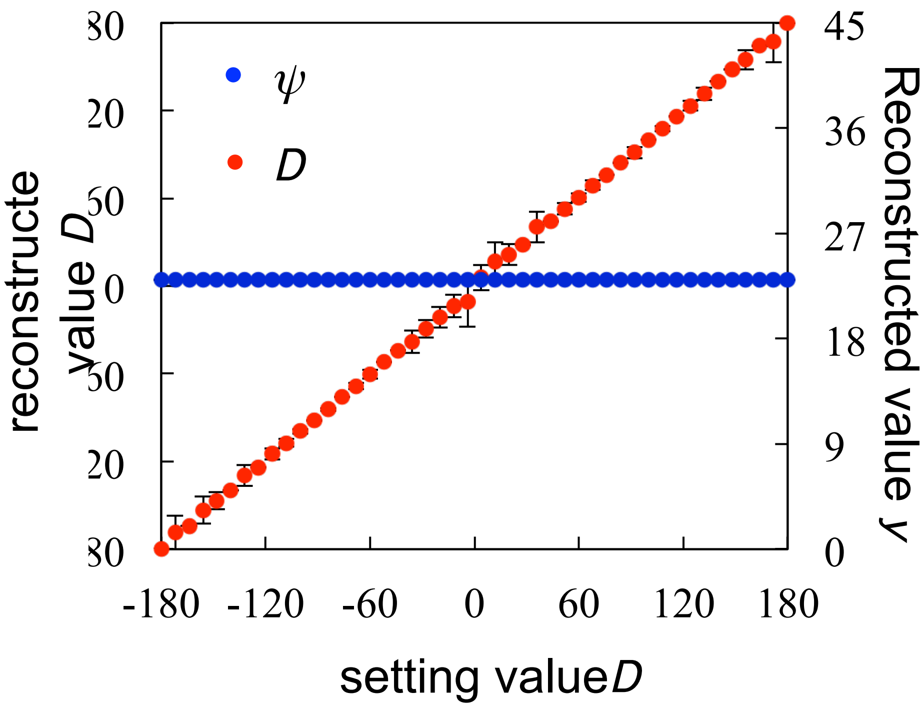


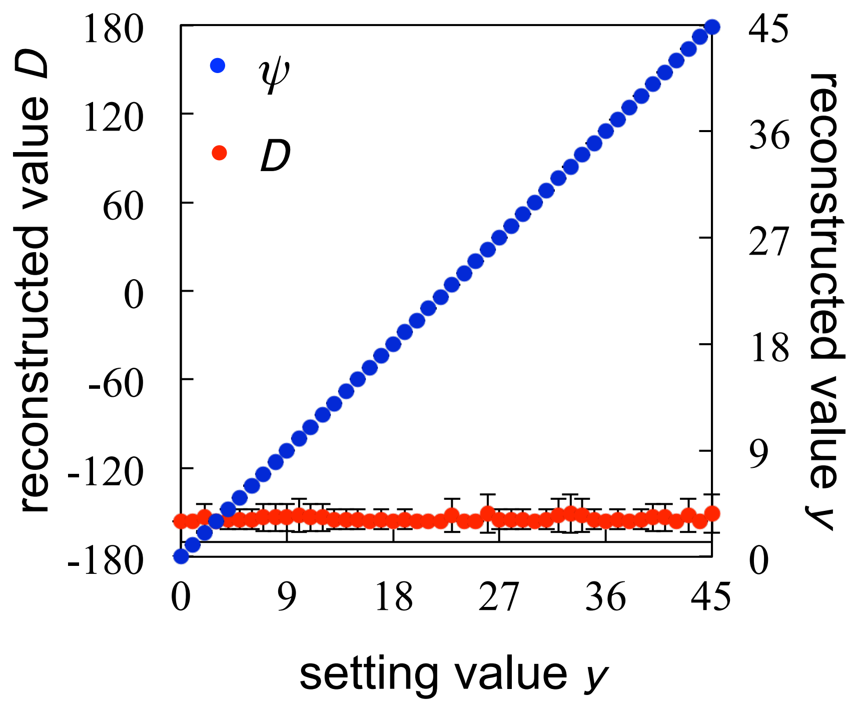


Numerical analysis for accuracy of the GI ellipsometry

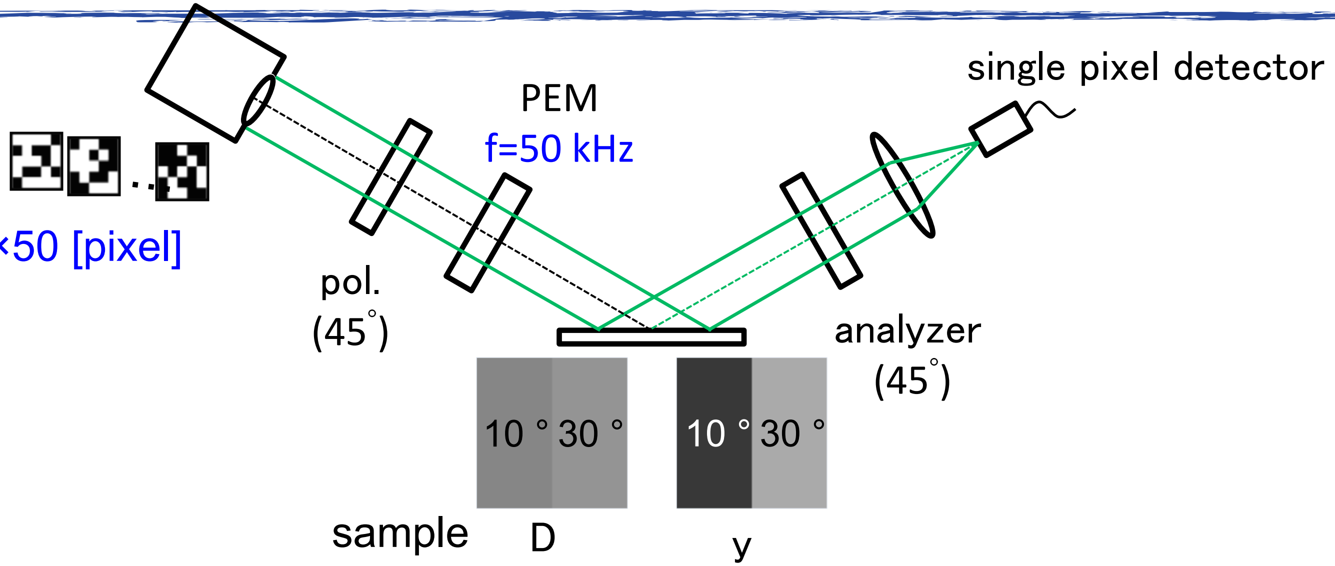
conditions

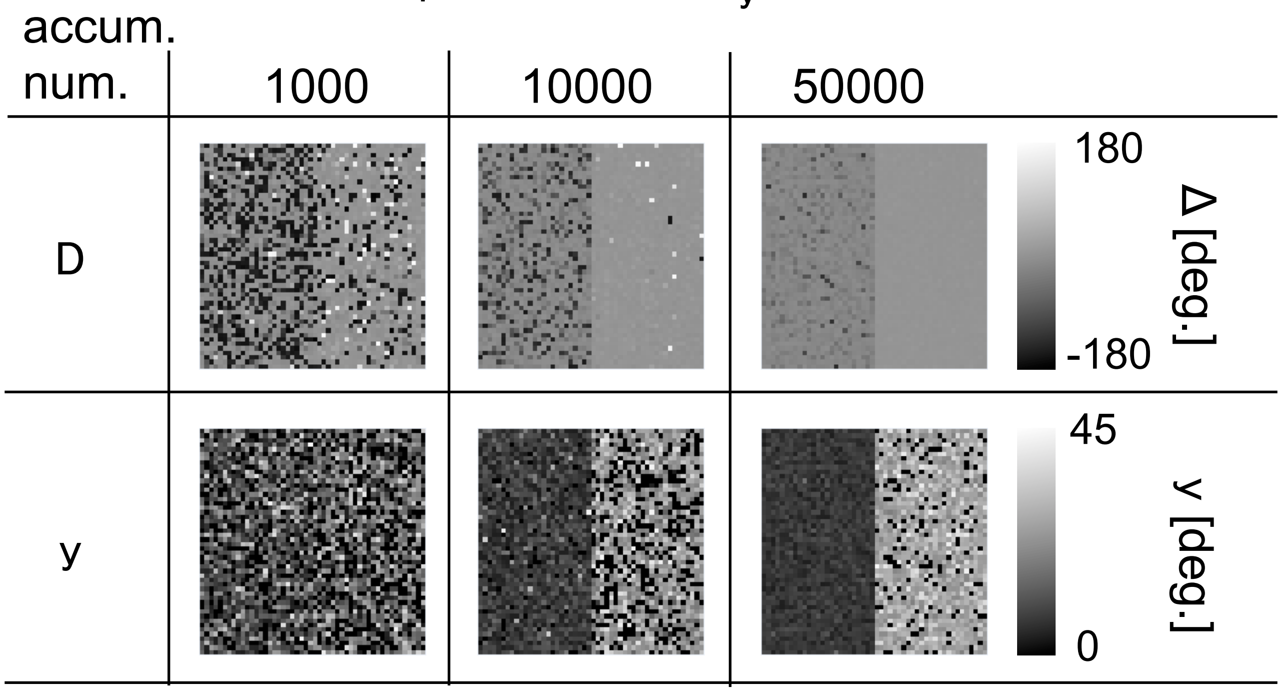
modulation	50 [kHz]
setting value	*D*=-180~180°, *y*=0~45°
accumulated number	*n*=50000 回
pattern size	100×100 [pixel]



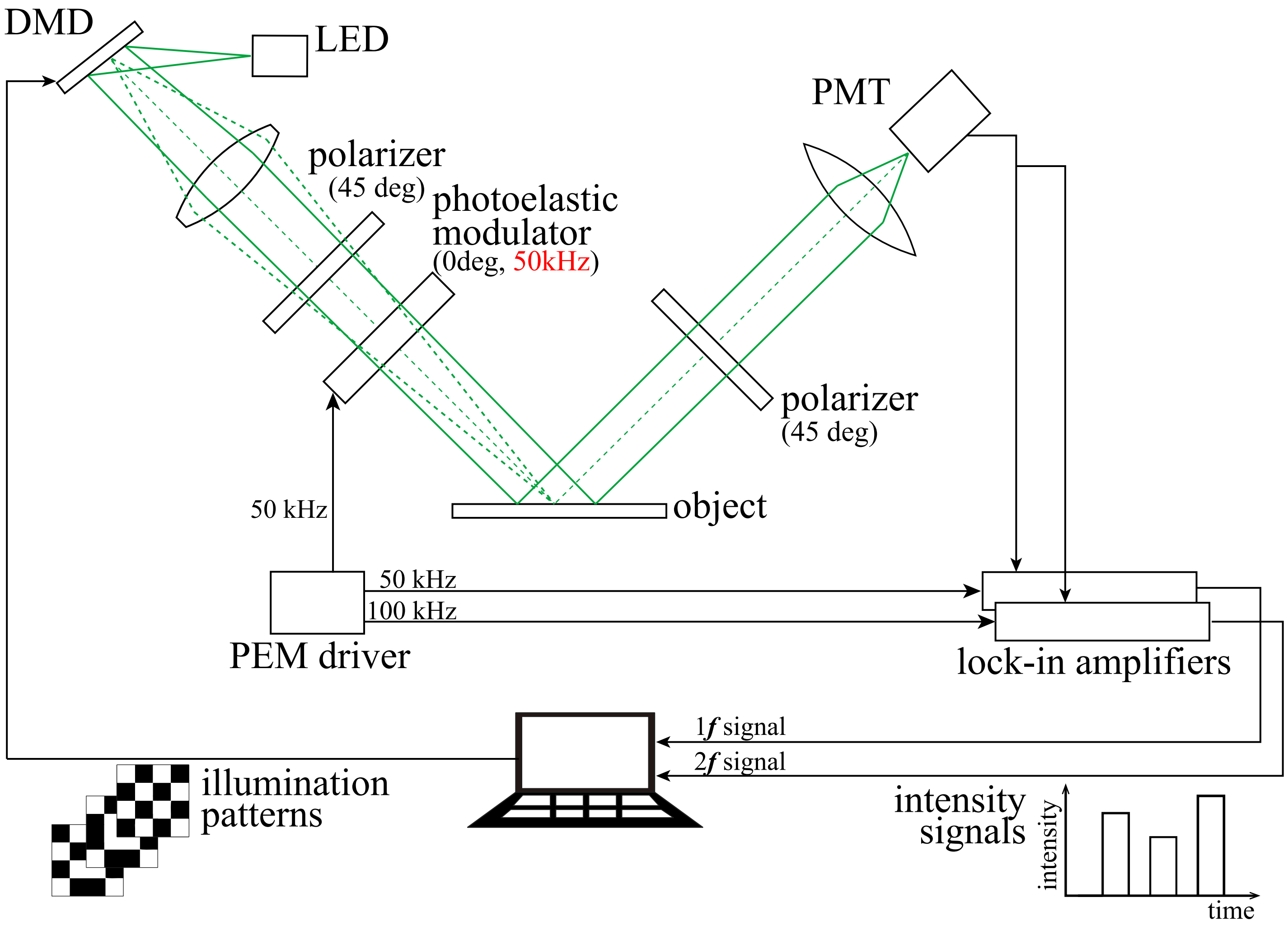


Numerical analysis for patterned sample of the GI ellipsometry

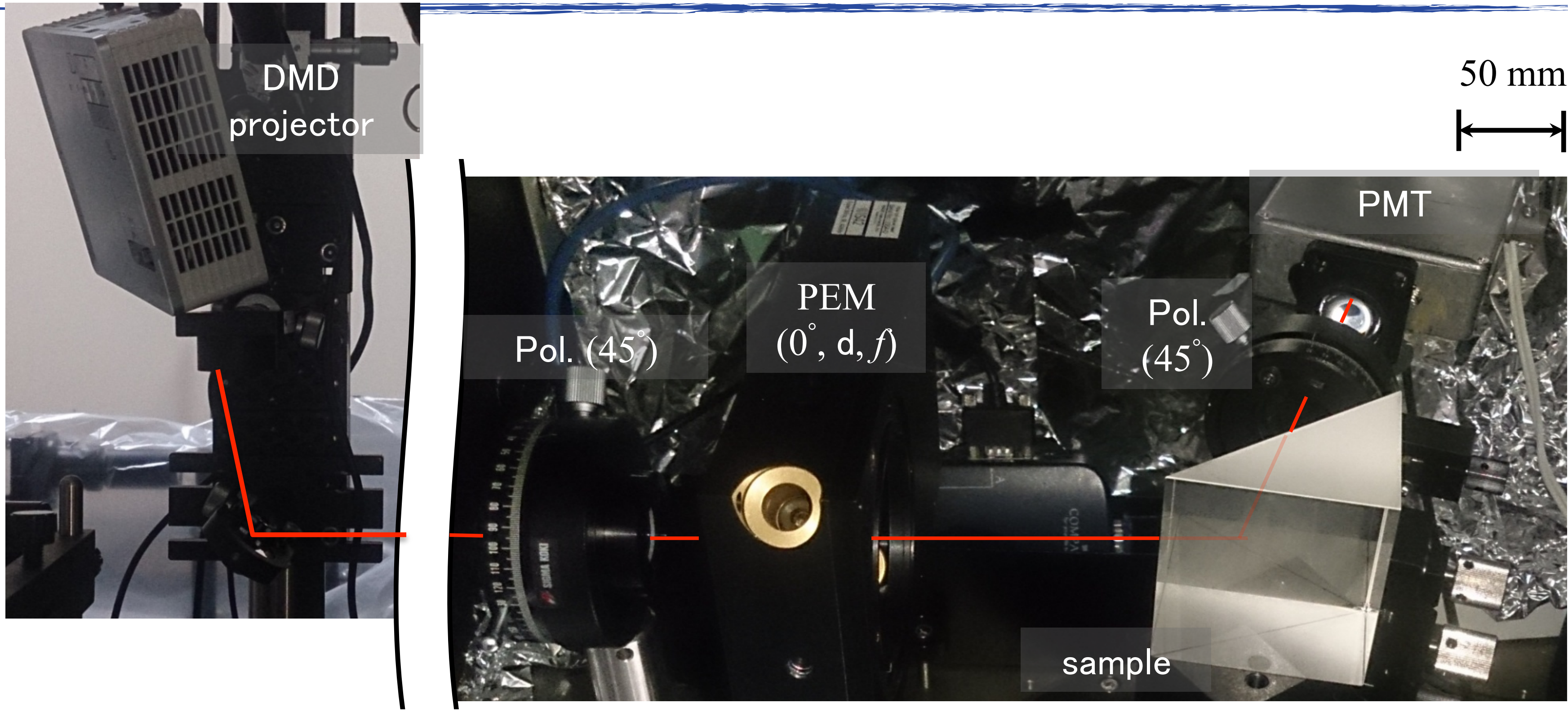




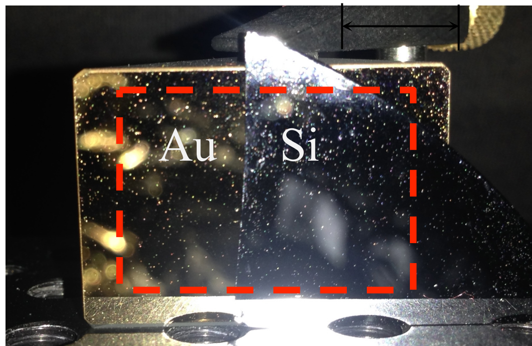
Optical setup of ghost imaging ellipsometry



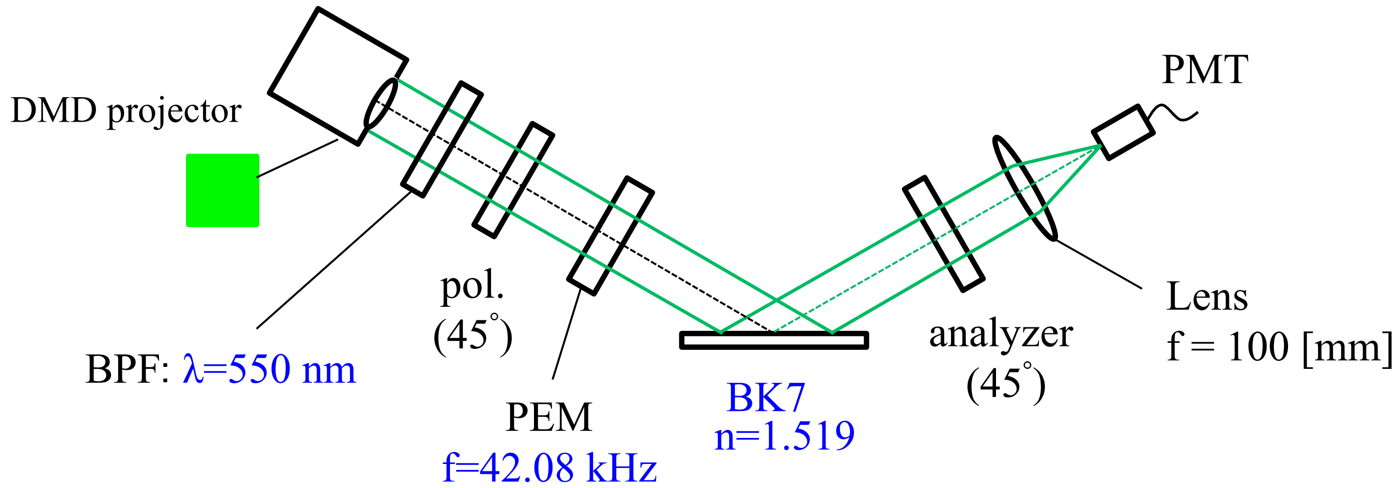
Ghost imaging ellipsometer

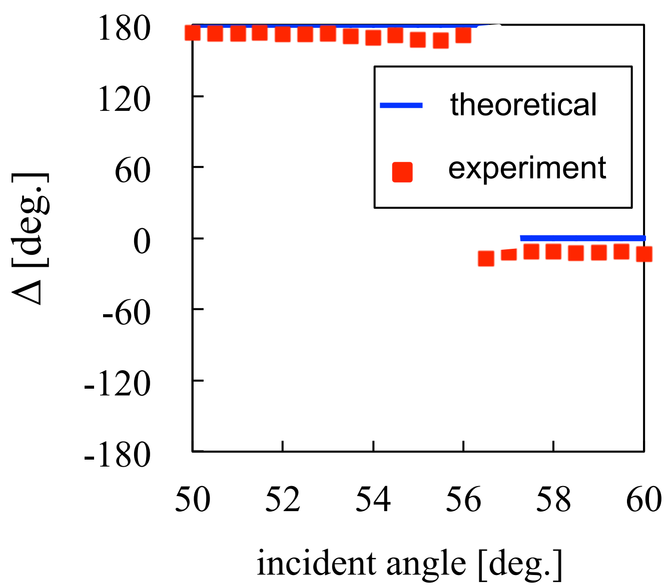


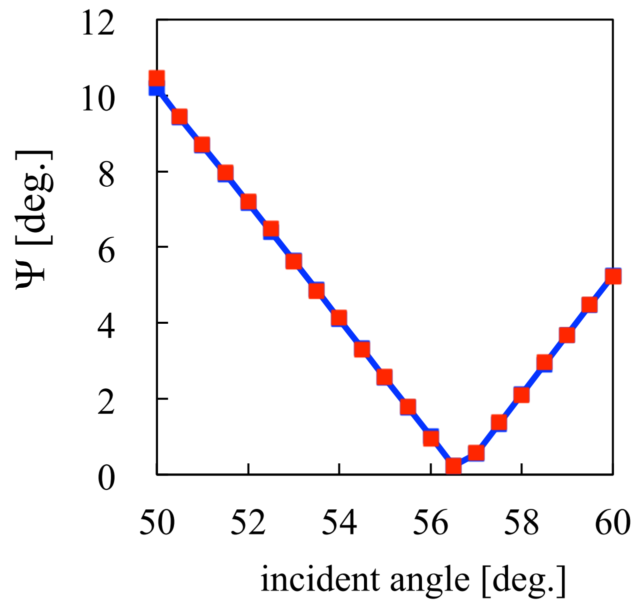
projector	DMD	0.45inch WXGA S450 DMD
	wavelength	550nm
	contrast ratio	10000:1
	size	1280×800 [pixel]
PEM	frequency	42.08 [kHz]
	setting l	550 [nm]



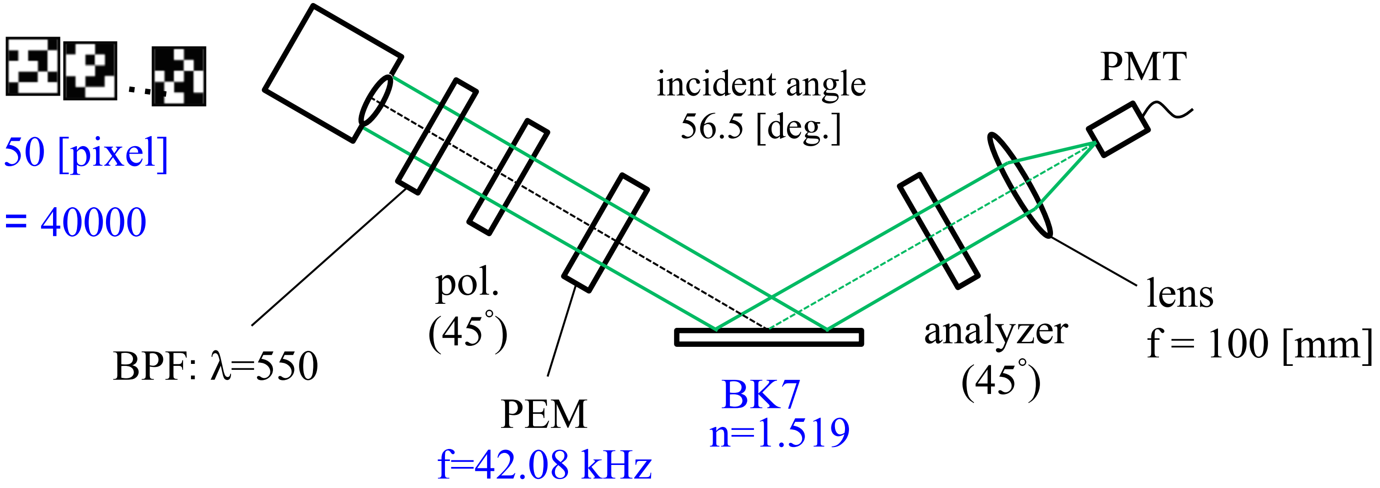
Accuracy measurement of PME without GI



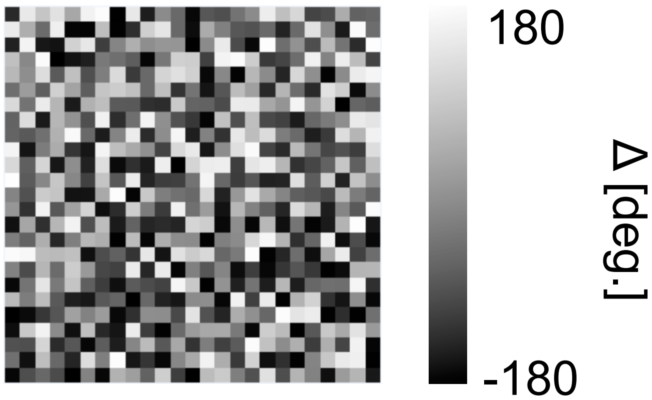




Numerical analysis for accuracy of the GI ellipsometry

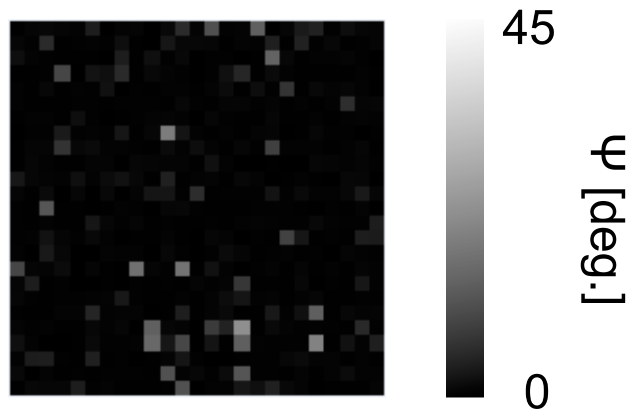


n=40000



D

1.87±102.63



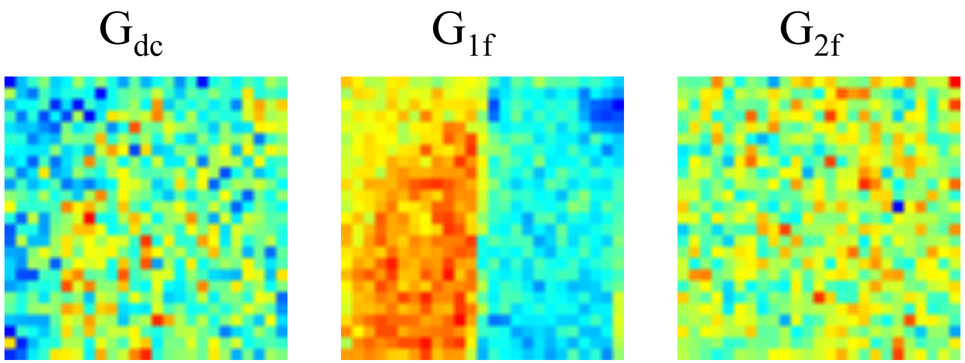
y

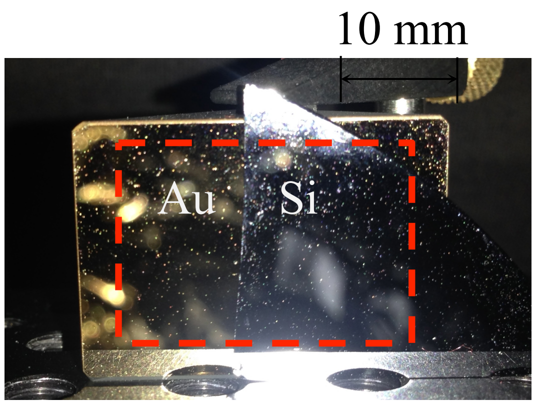
2.34±3.71

Experimental results of Si and Au surface

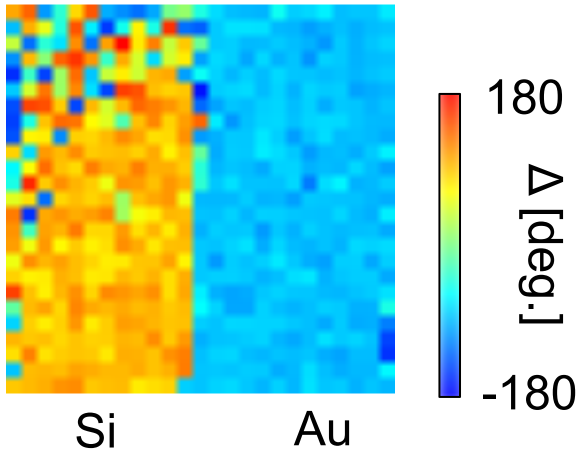
experiment condition

Sample	Si, Au
Accumulated number	46000 (30~hour)
Pattern size	50 x 50 [pixels]
Pattern resolution	25 x 25 [pixels]
Block size	2 [pixel]
Average number	64

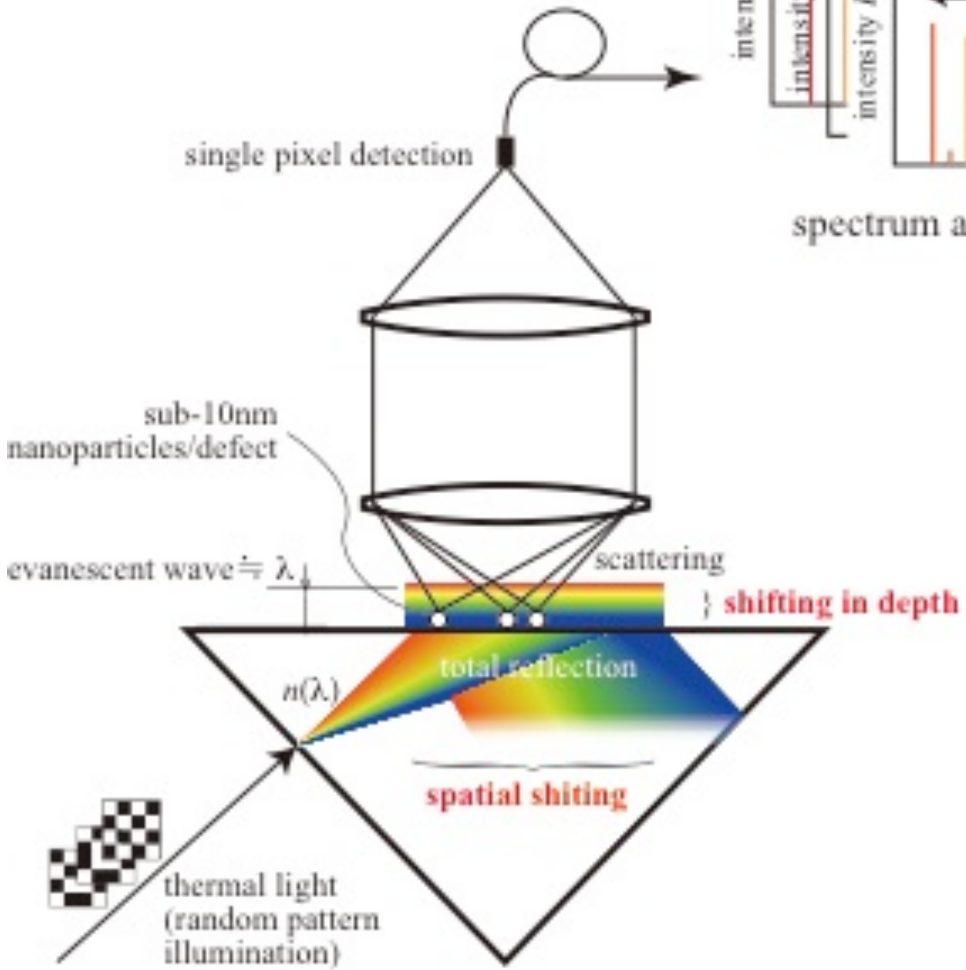


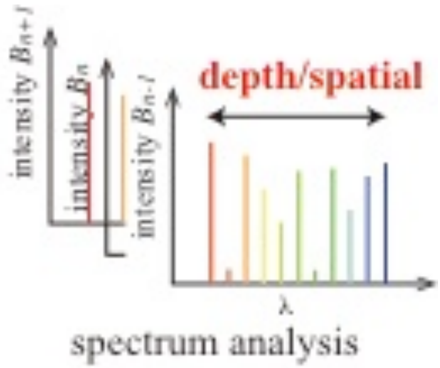


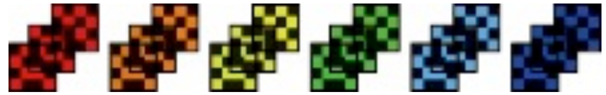
reconstructed image of phase difference



High resolution 3D imaging by optical frequency comb combined with ghost imaging

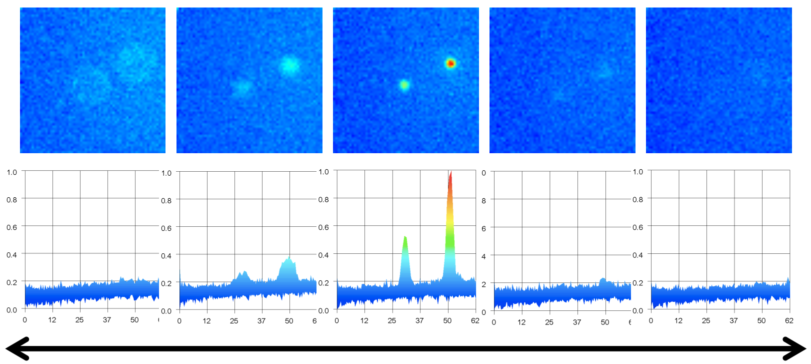






$$\frac{1}{N}\sum_{n=1}^{N}\{B_n(\lambda)-\langle B_n(\lambda)\rangle\}\, I_n(x,y,\lambda)$$

$$\langle B_n(\lambda)I(x,y,\lambda)\rangle - \langle B_n(\lambda)\rangle\langle I(x,y,\lambda)\rangle$$



depth information with nano order resolution

Conclusions

Applications of computational ghost imaging for weak intensity field has been proposed.

- fluorescent microscopy
  - fluorescent cell image detected by 1/100 weak intensity
- ellipsometry
  - 2D ellipsometrical image for phase modulated ellipsometer