第７回可視赤外線観測装置技術ワークショップ
２０１７年１１月１７日（金）１３：００〜１３：４０
京都大学　北部キャンパス　益川ホール（北部総合教育研究棟）

ＭＥＭＳ光制御技術の研究動向

（静電マイクロアクチュエータの光学応用）

年吉　洋
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Center for International Research on Micronano Mechatronics
Institute of Industrial Science
The University of Tokyo

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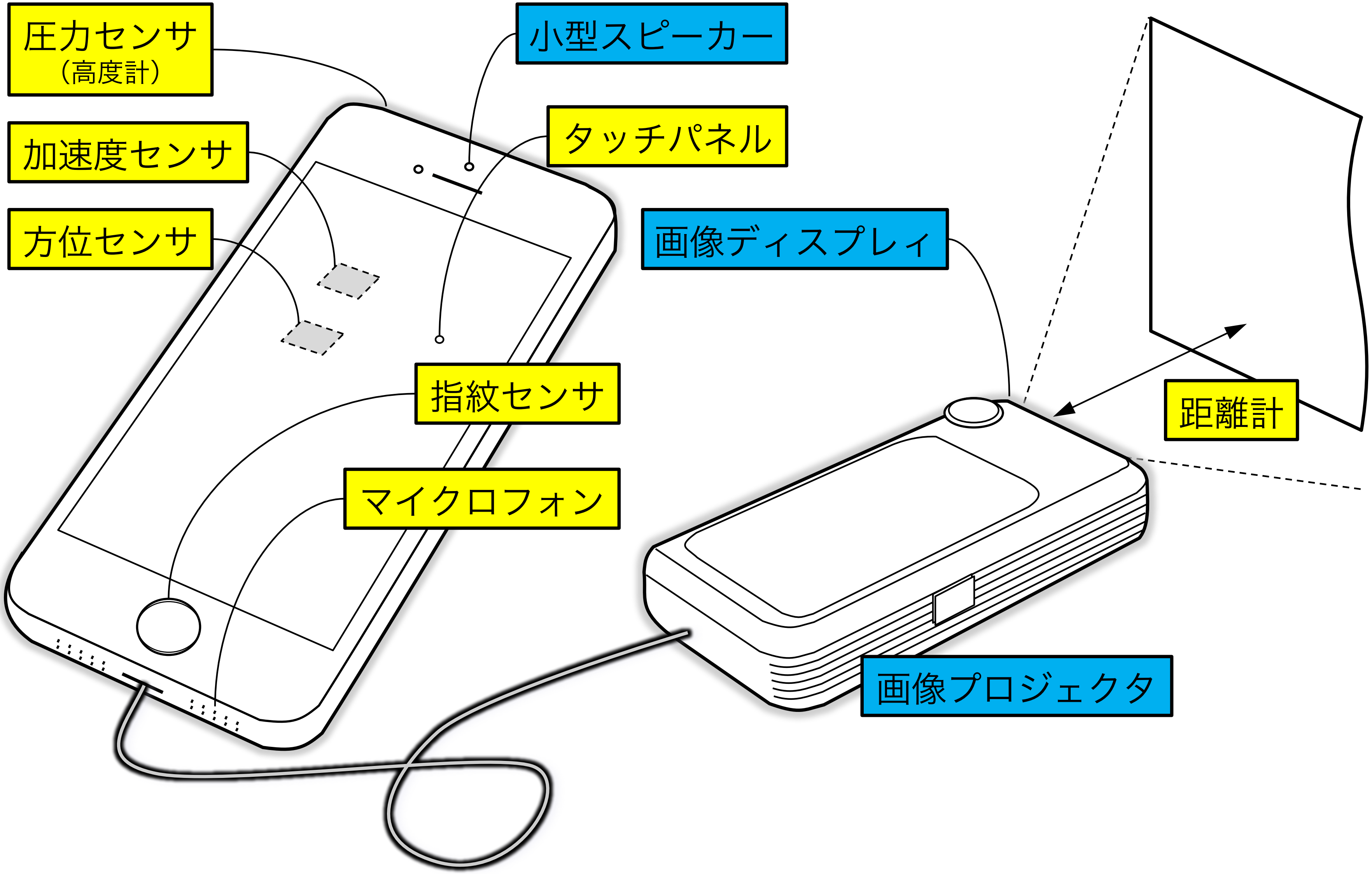
4. Theory of Electrostatic Force
5. More Added Values
6. Summary

ケータイ／スマホの部品、実世界とのＩ／ＯはＭＥＭＳ

センサ　アクチュエータ



圧力センサ
（高度計）

加速度センサ

方位センサ

小型スピーカー

タッチパネル

画像ディスプレィ

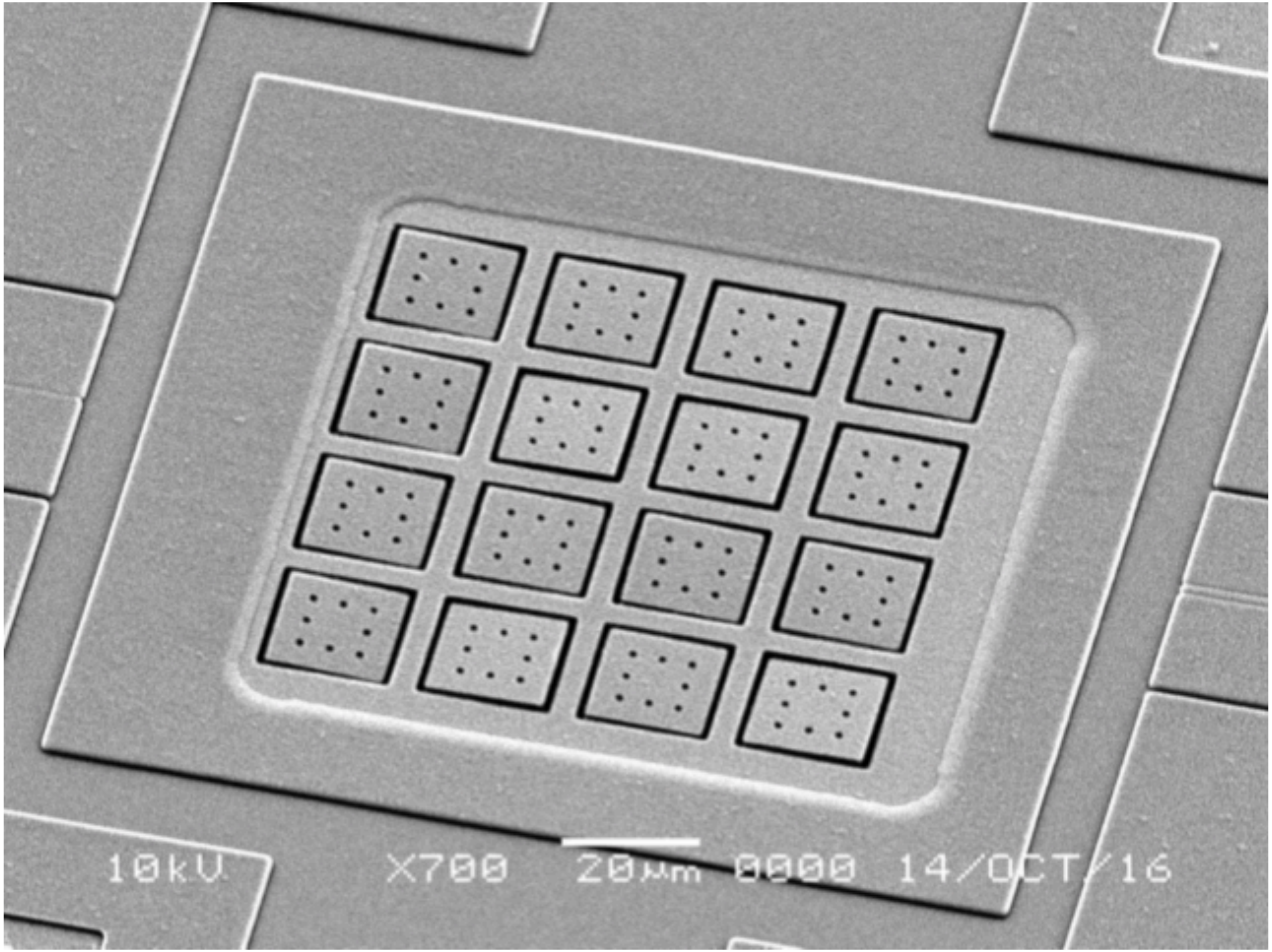
指紋センサ

マイクロフォン

距離計

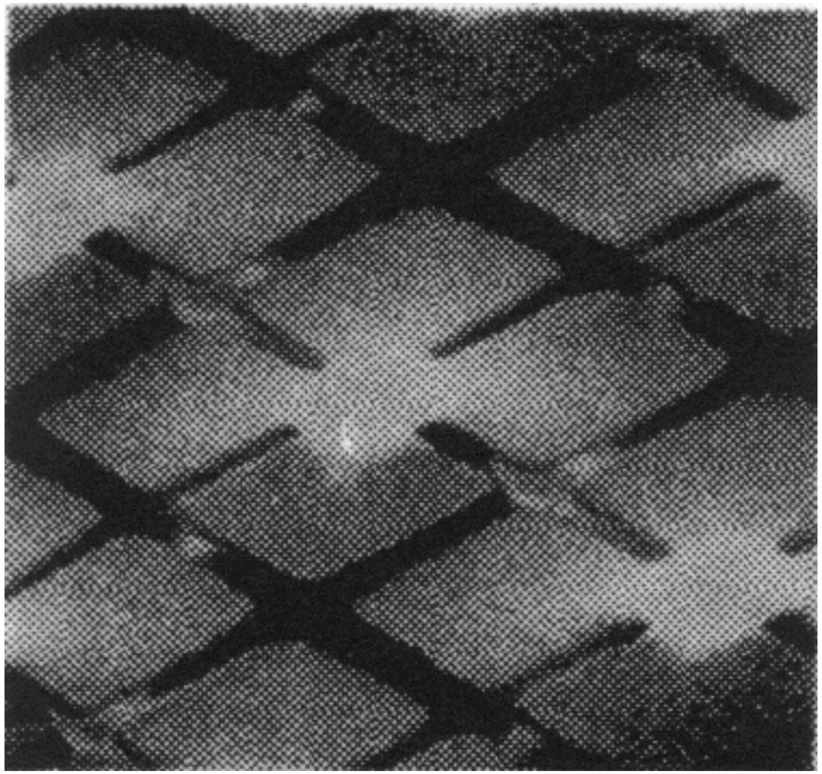
画像プロジェクタ

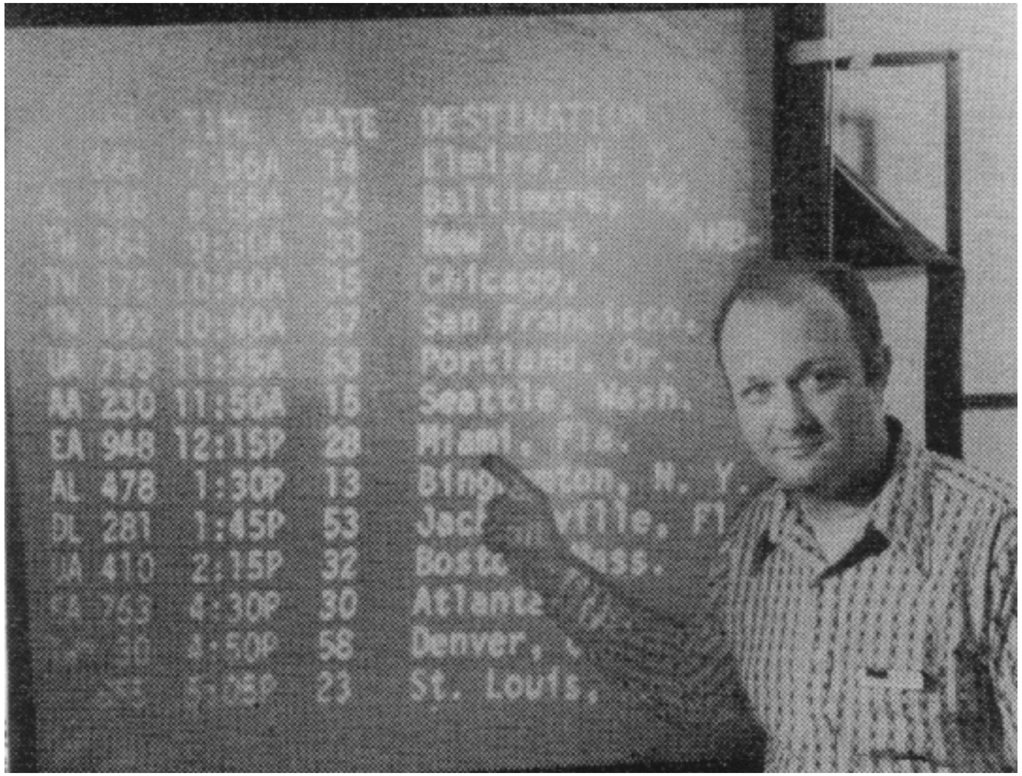
CMOS-MEMSマイクロミラーはじめました

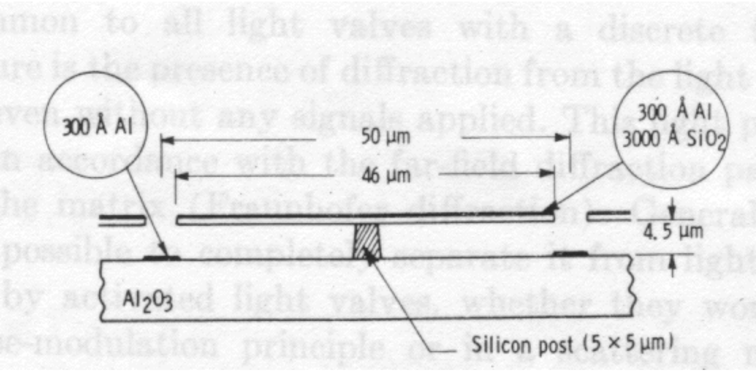


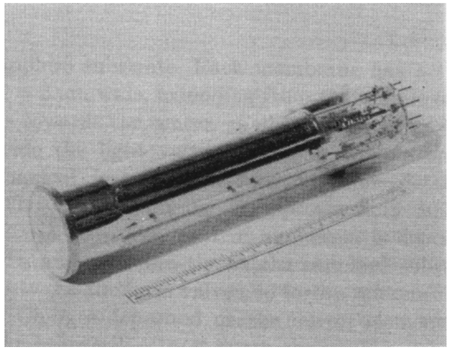
Projection Display in 1975

R. N. Thomas, J. Guldberg, H. C. Nathanson, P. R. Malmberg, IEEE Trans. ED vol. 22, 1975, Westinghouse Research Labs & Philips

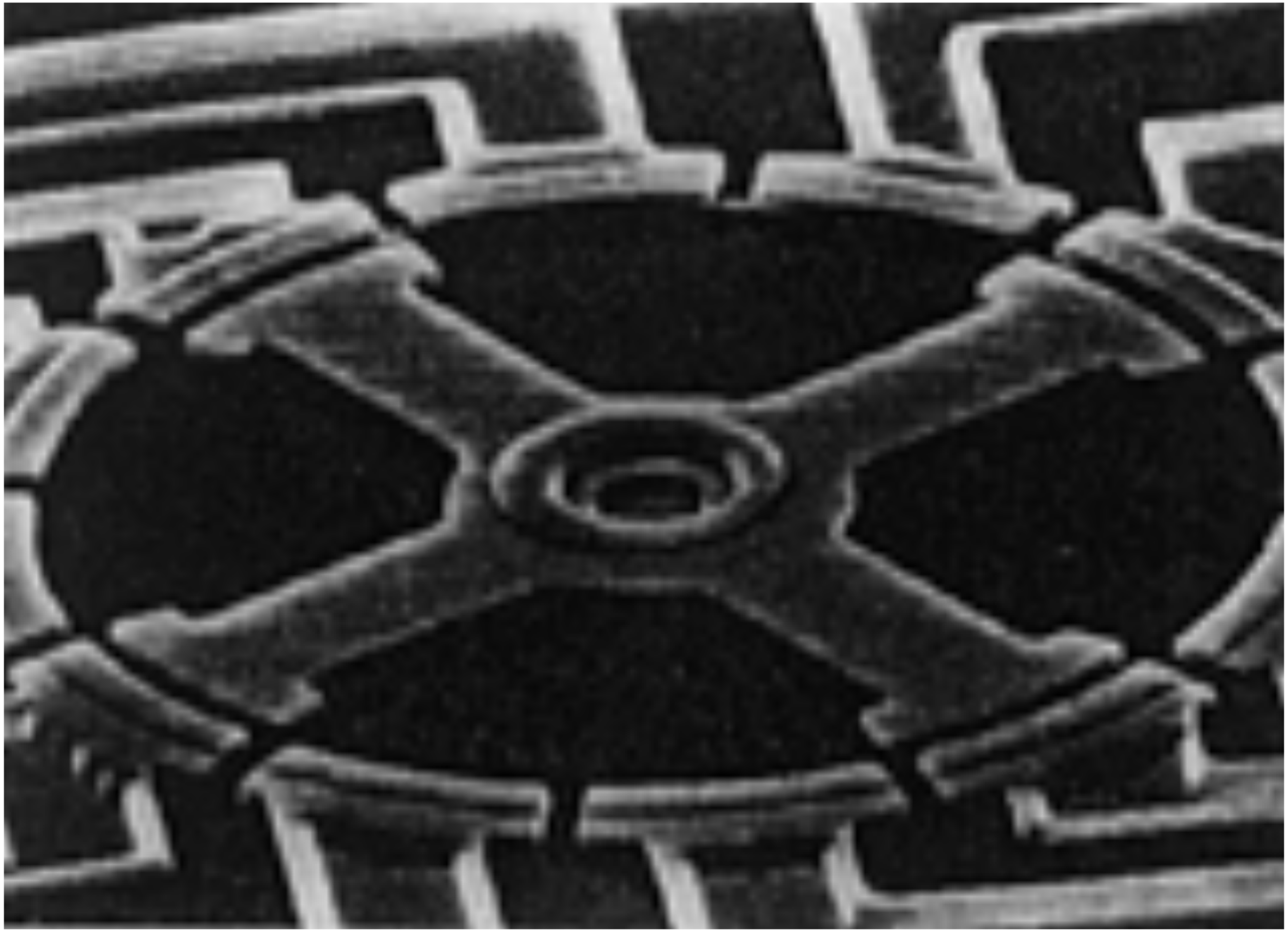




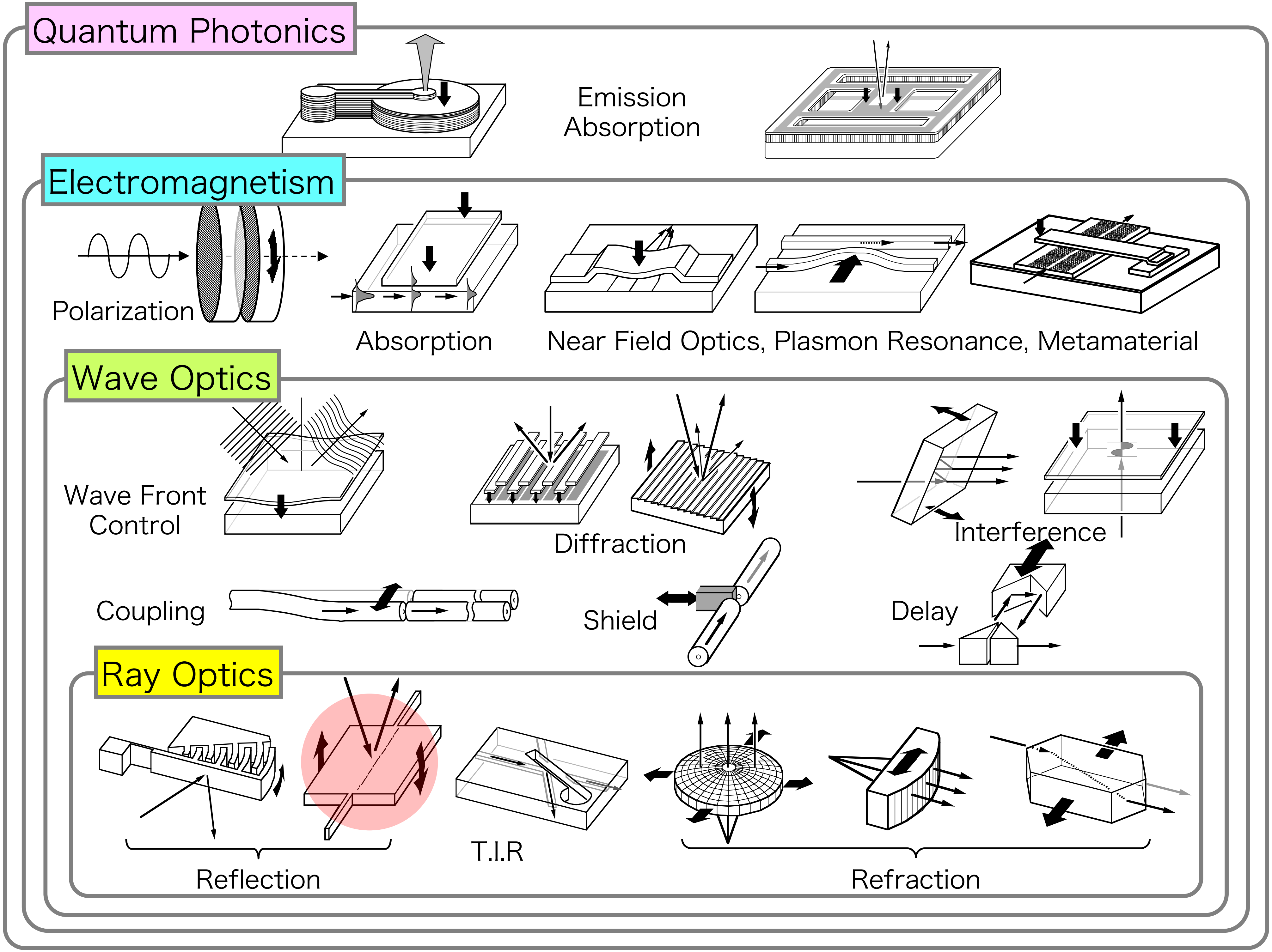




A True Micro Motor, Diameter 120 microns

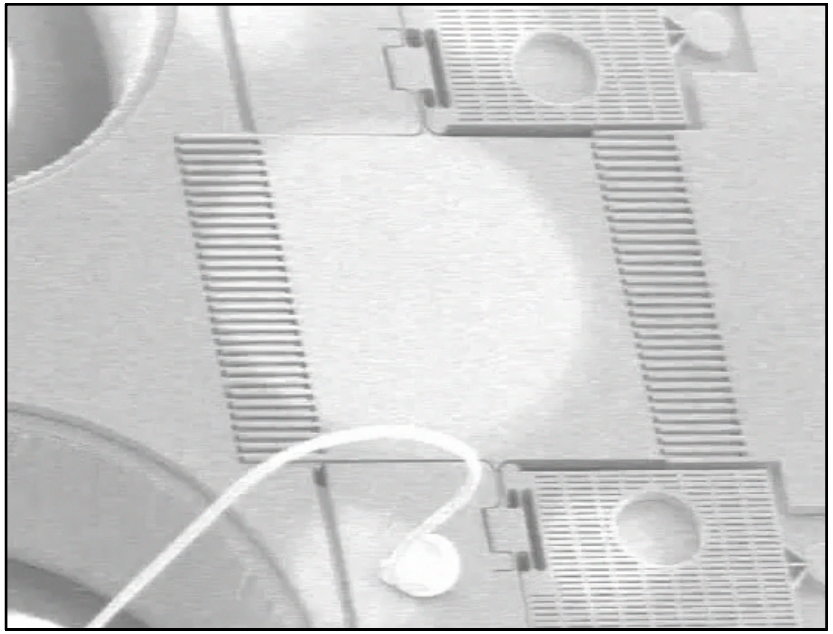


Y.Tai et al. Sensors & Actuators 1989

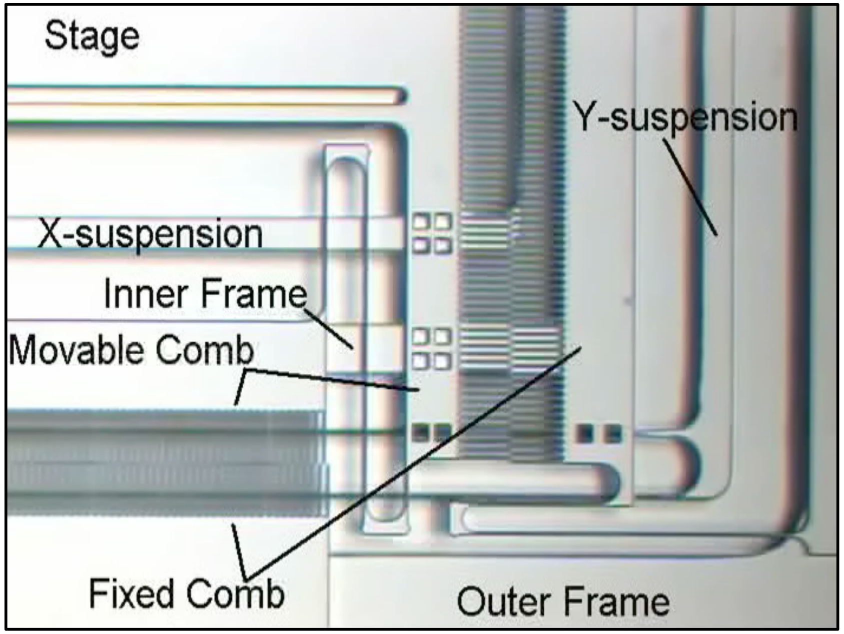

Quantum Photonics
Emission
Absorption
Electromagnetism
Polarization
Absorption
Near Field Optics, Plasmon Resonance, Metamaterial
Wave Optics
Wave Front
Control
Diffraction
Interference
Coupling
Shield
Delay
Ray Optics
Reflection
T.I.R
Refraction

MEMS Micro Actuators

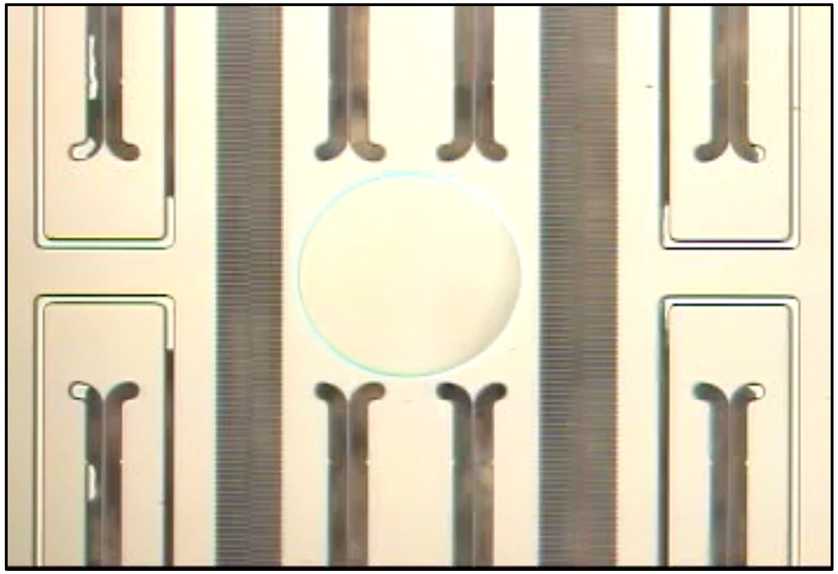
MEMS = Micro Electro Mechanical Systems



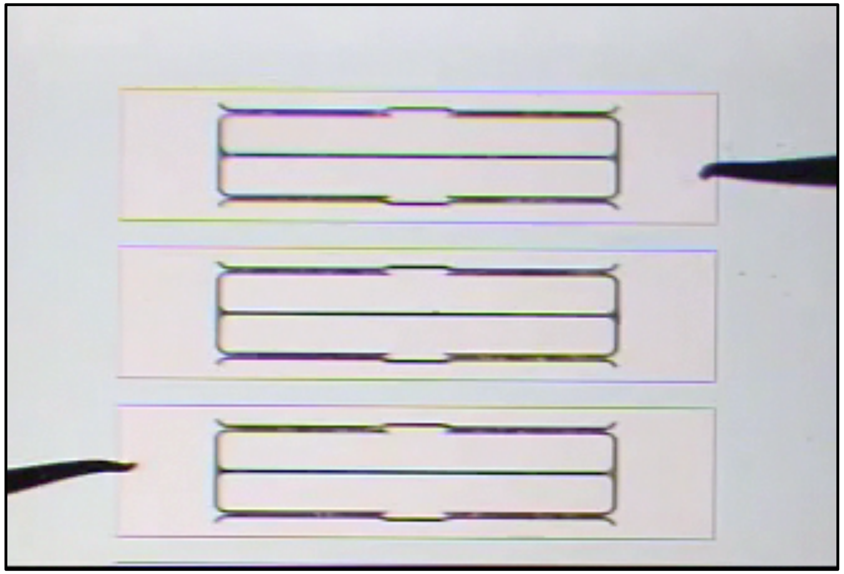
K. Isamoto, Santec Corp.,



K. Takahashi, 2007



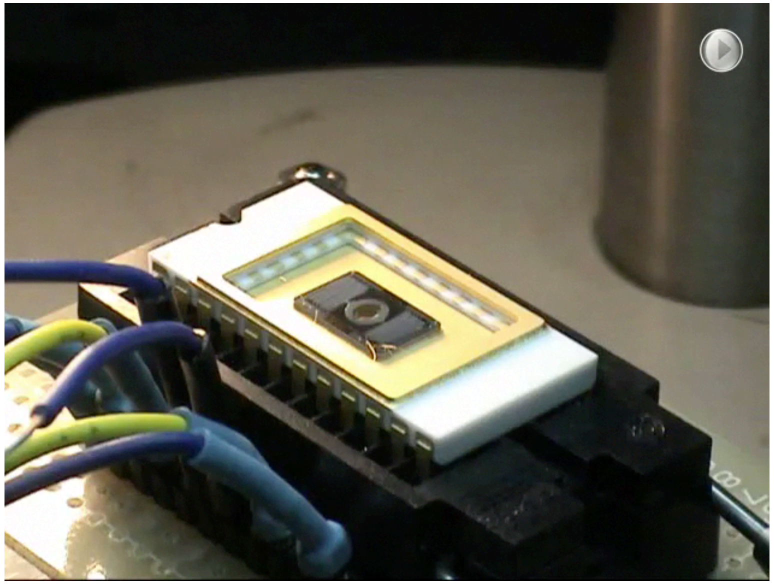
K. Takahashi, IIS, Univ. of Tokyo 2005

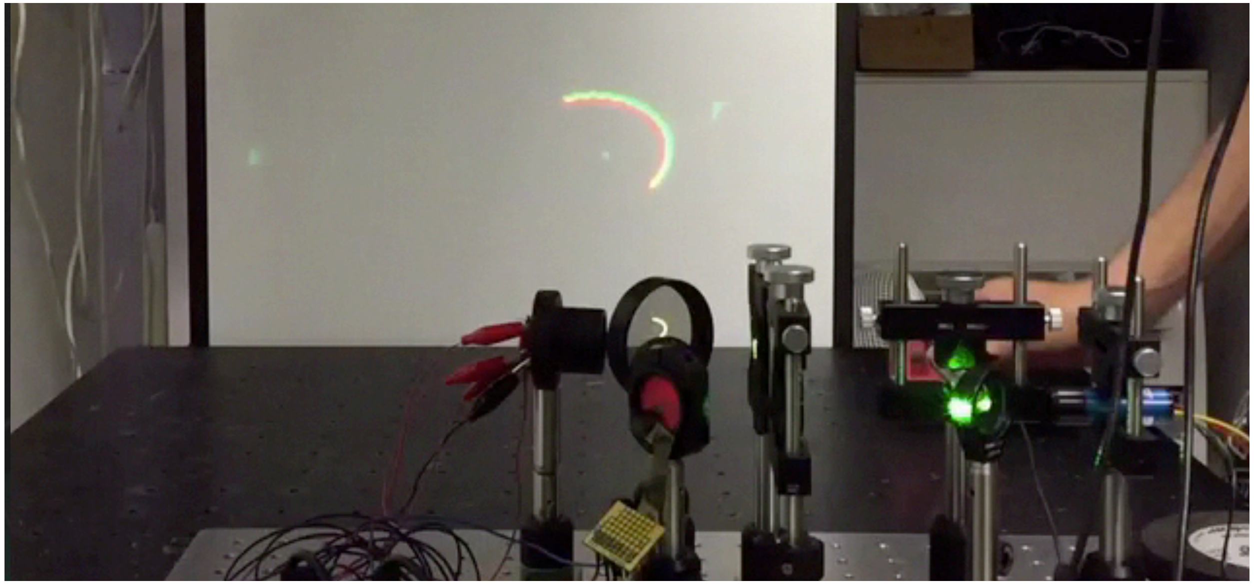


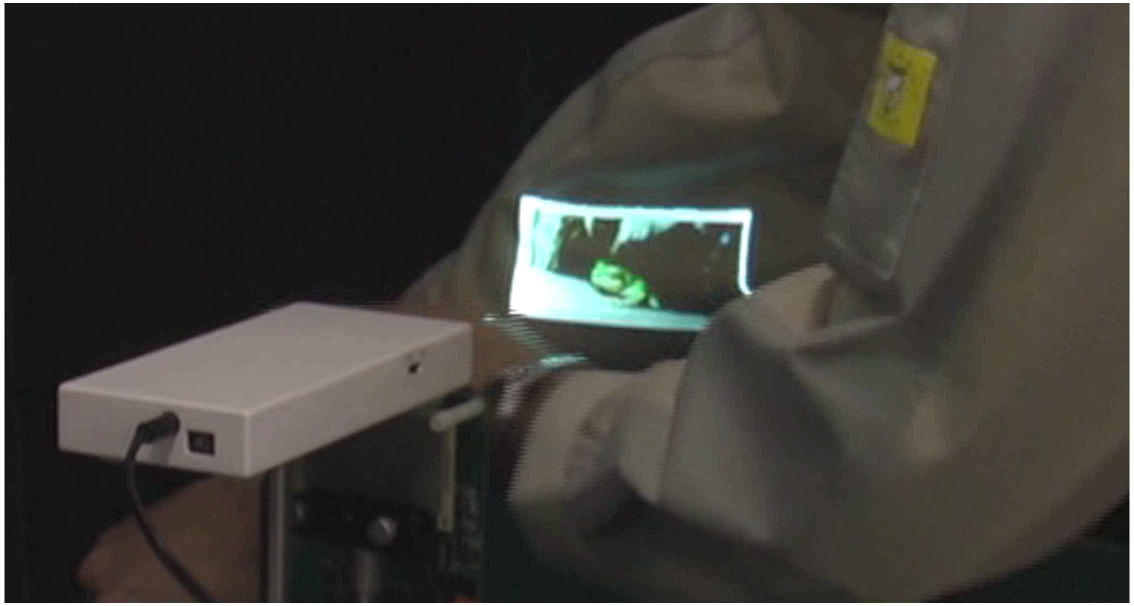
T. Takahashi, IIS, Univ. of Tokyo 2006

MEMS Actuators for Optical Applications

Interactive Image Displays







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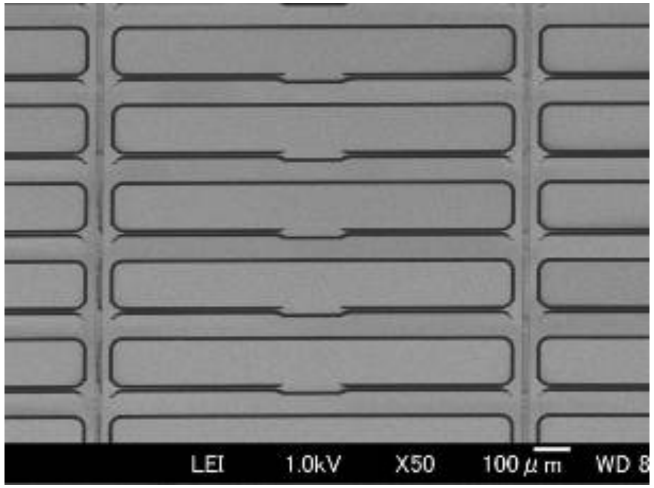
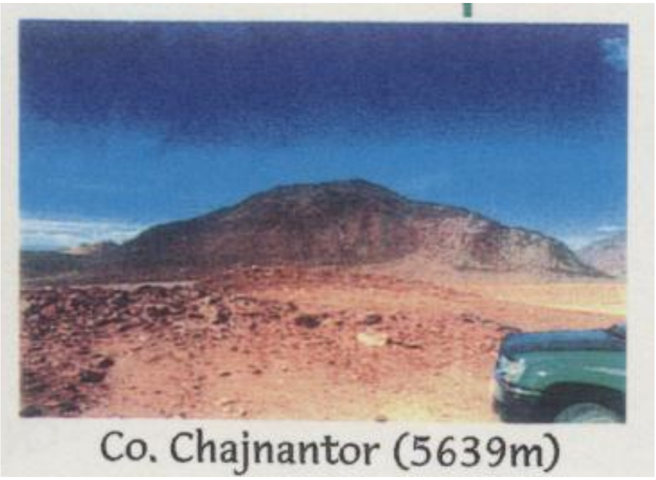
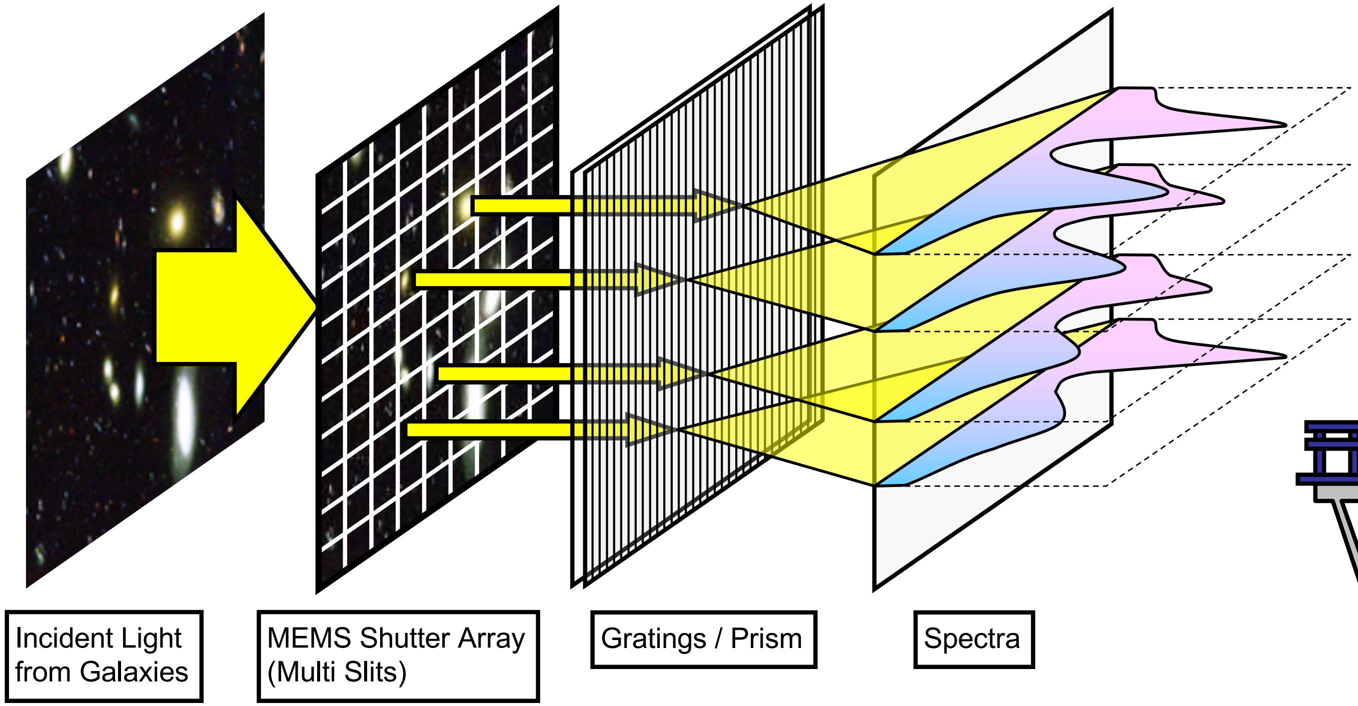
Multi-Slit Array for Observatory

TAO in Atacama（5639 m）





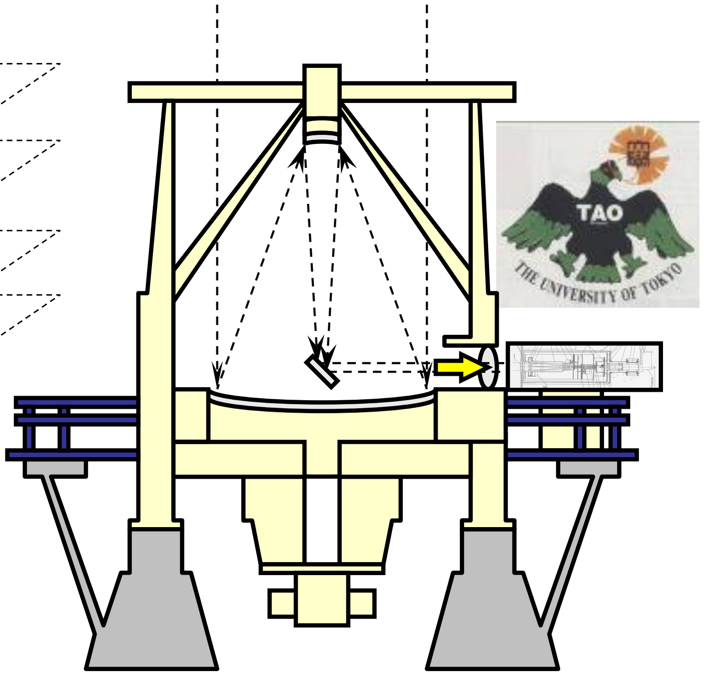


Incident Light from Galaxies

MEMS Shutter Array (Multi Slits)

Gratings / Prism

Spectra



HIGH CONTRAST, CRYOGENIC, LARGE MICROMIRROR ARRAY FOR MULTI-OBJECT SPECTROSCOPY

Frederic Zamkotsian[1], Michael Canonica[2,3], Patrick Lanzoni[1], Wilfried Noell[2]

[1] Laboratoire d'Astrophysique de Marseille - CNRS, Marseille, France
[2] Ecole Polytechnique Fédérale de Lausanne, Neuchâtel, Switzerland
[3] MIT, Cambridge, USA

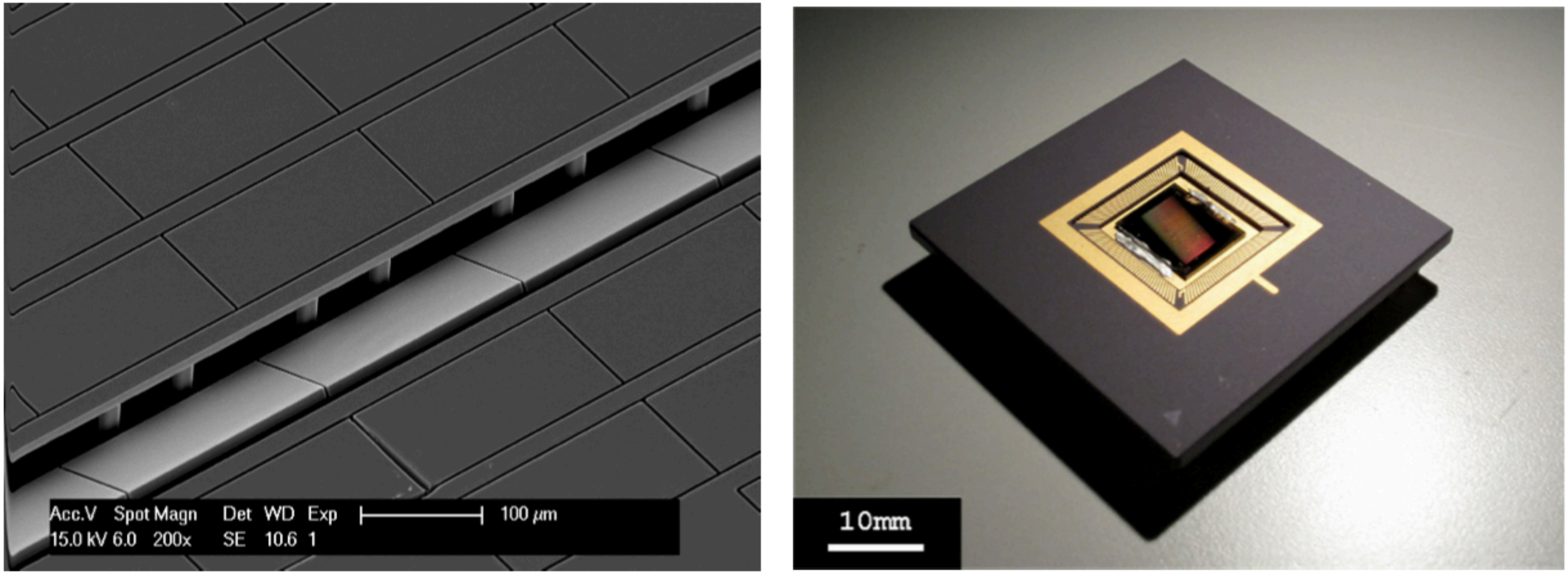
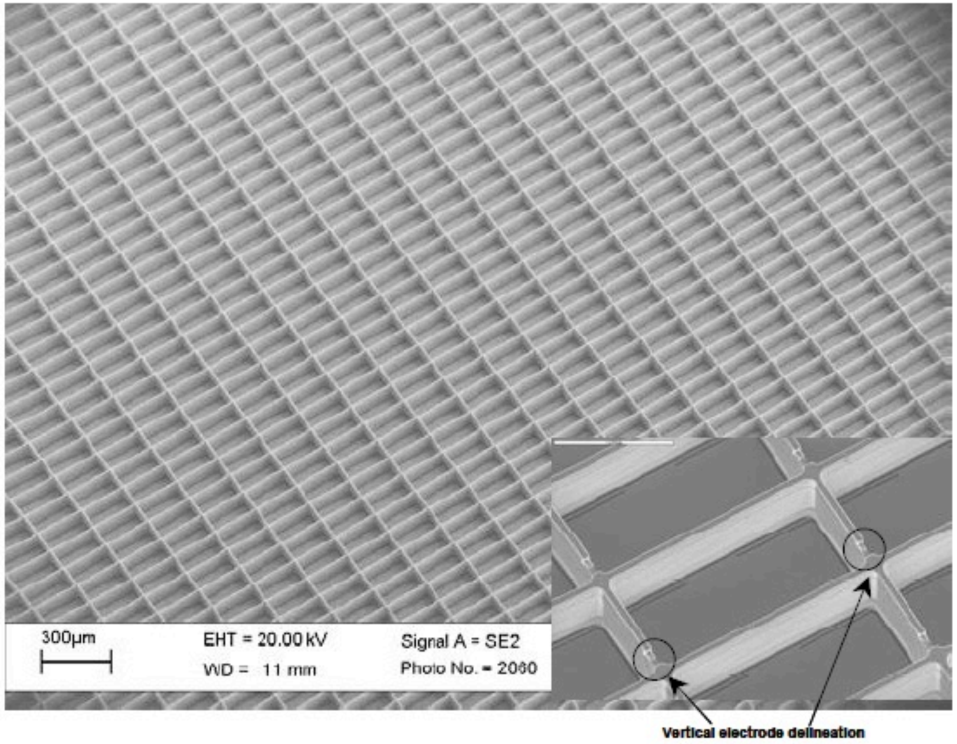


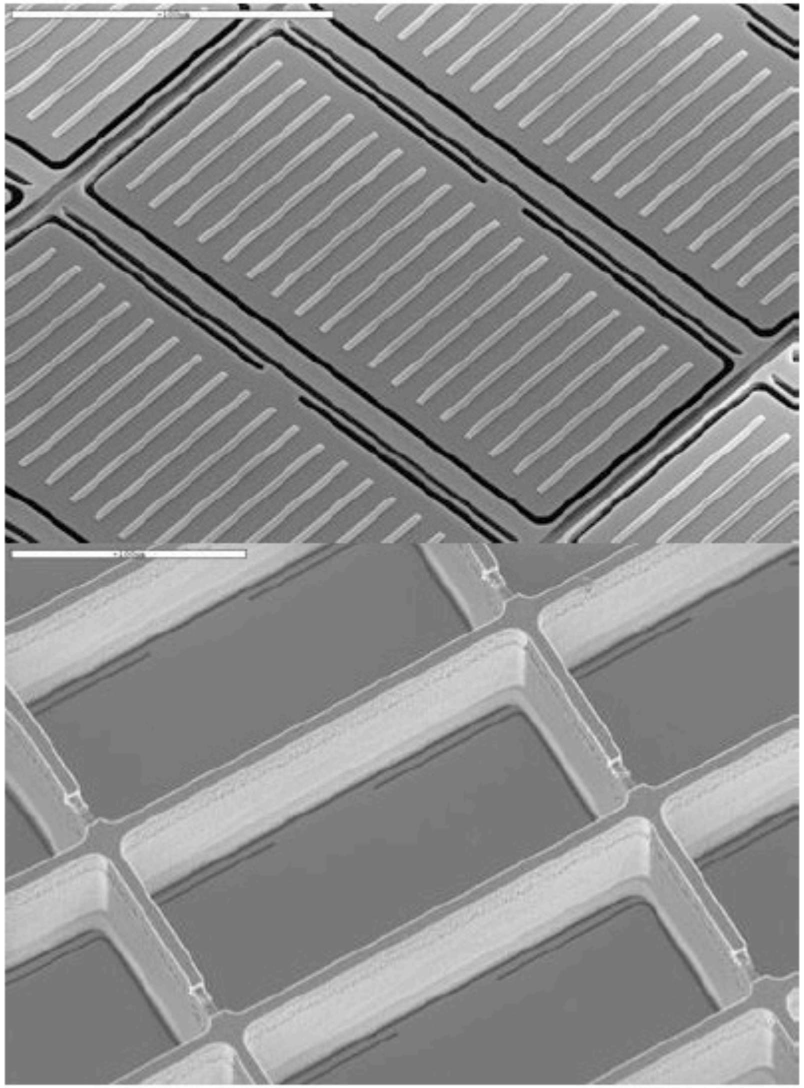
Figure 1. 64 x 32 micromirror array with high fill factor in one direction, providing long slits. Each mirror measures 200 x 100 µm^2. Array surface picture and packaged device.

Electromagnetic MEMS Shutter for NASA JWST

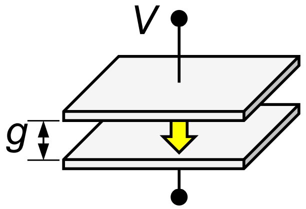
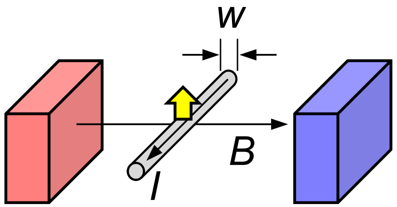
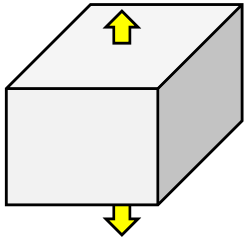
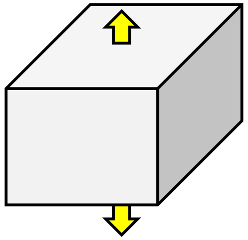
Li et al., "Microshutter array development for the James Webb space telescope," (2005) SPIE 5650 9

- For satellite mount
- Open Electromagnetically
- Latch Electrostatically
- Matrix 64 × 128
- Size 100 µm × 200 µm



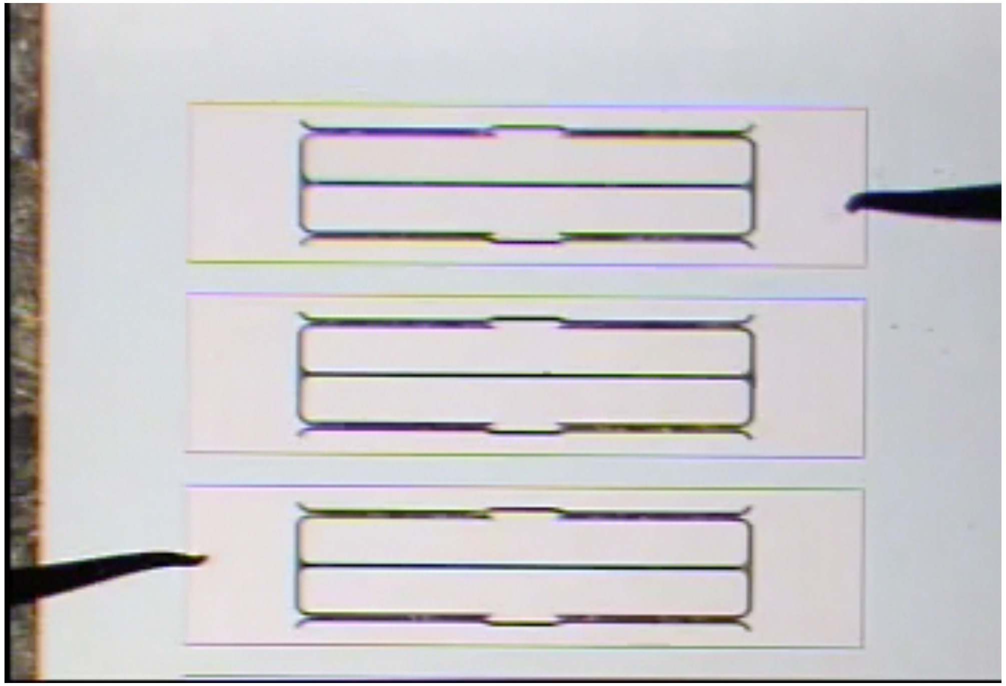


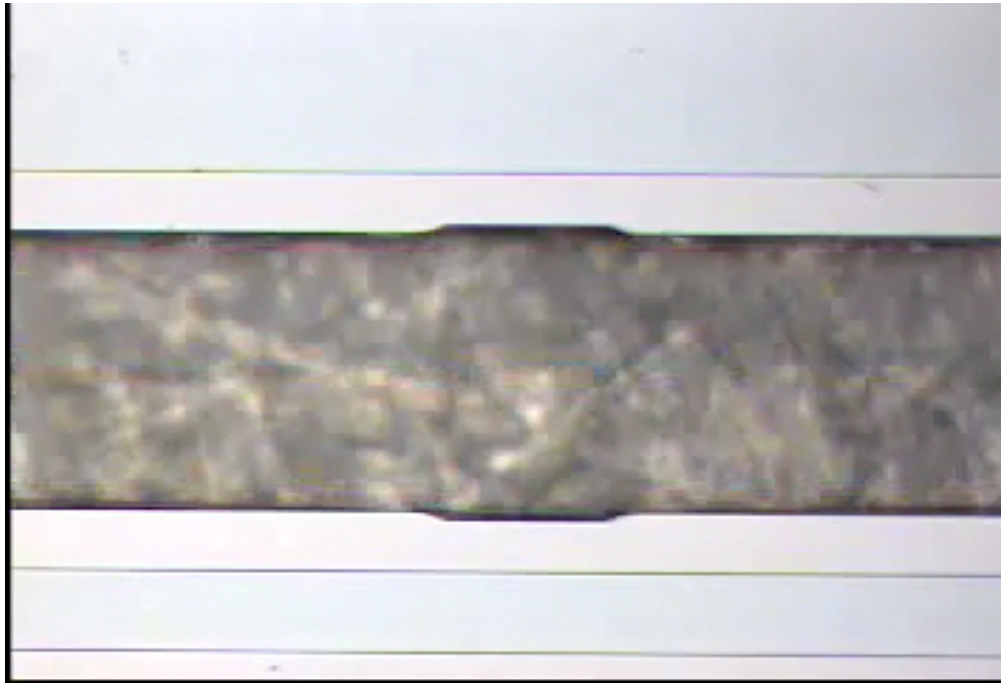
単位面積あたり発生力

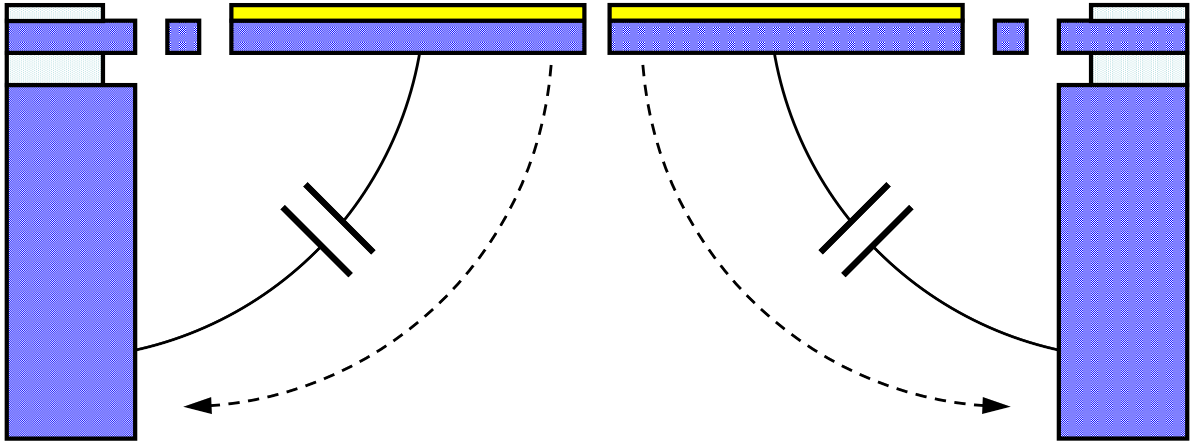
	静電駆動	電磁駆動	圧電駆動（磁歪・電歪駆動）	熱膨張（通電加熱）
原理図				
単位面積あたりの発生力 (N/m^2)	$(1/2)\,\varepsilon_0 E^2$ E : 電場 ε_0 : 誘電率	$I B / w$ I : 駆動電流 B : 磁束密度 w : 線幅	$E \varepsilon$ E : ヤング率 ε : 歪	$E \alpha \Delta T$ E : ヤング率 α : 線膨張系数 ΔT : 温度変化
	10^1～10^4 N/m^2	10^1～10^3 N/m^2	圧電 10^7～10^8 N/m^2 電歪 10^7～10^9 N/m^2	10^6～10^8 N/m^2
代表的設計値	静電ギャップ $g = 1 \sim 10\ \mu\mathrm{m}$ 駆動電圧 $V = 1 \sim 100$ V	永久磁石 $H_c \sim 10$ kOe 駆動電流 $I = 1$ mA ~ 1 A 配線幅 $w \sim 10\ \mu\mathrm{m}$	ヤング率 $E \sim 100$ GPa 圧電の機械歪 $\varepsilon = 0.01 \sim 0.1$ % 磁歪、電歪の機械歪 $\varepsilon = 0.01 \sim 1$ %	ヤング率 $E \sim 100$ GPa 線膨張係数 $\alpha \sim 10$ ppm 温度変化 $\Delta T = 1 \sim 100$ ℃

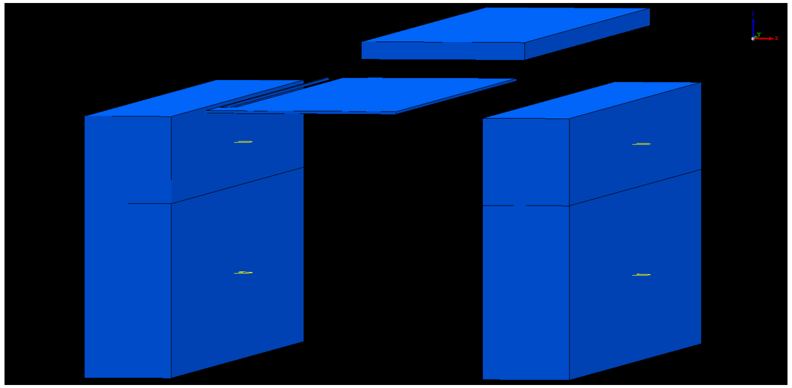
Optical MEMS Shutter Array at UTokyo

W 100 um x L 1000 um









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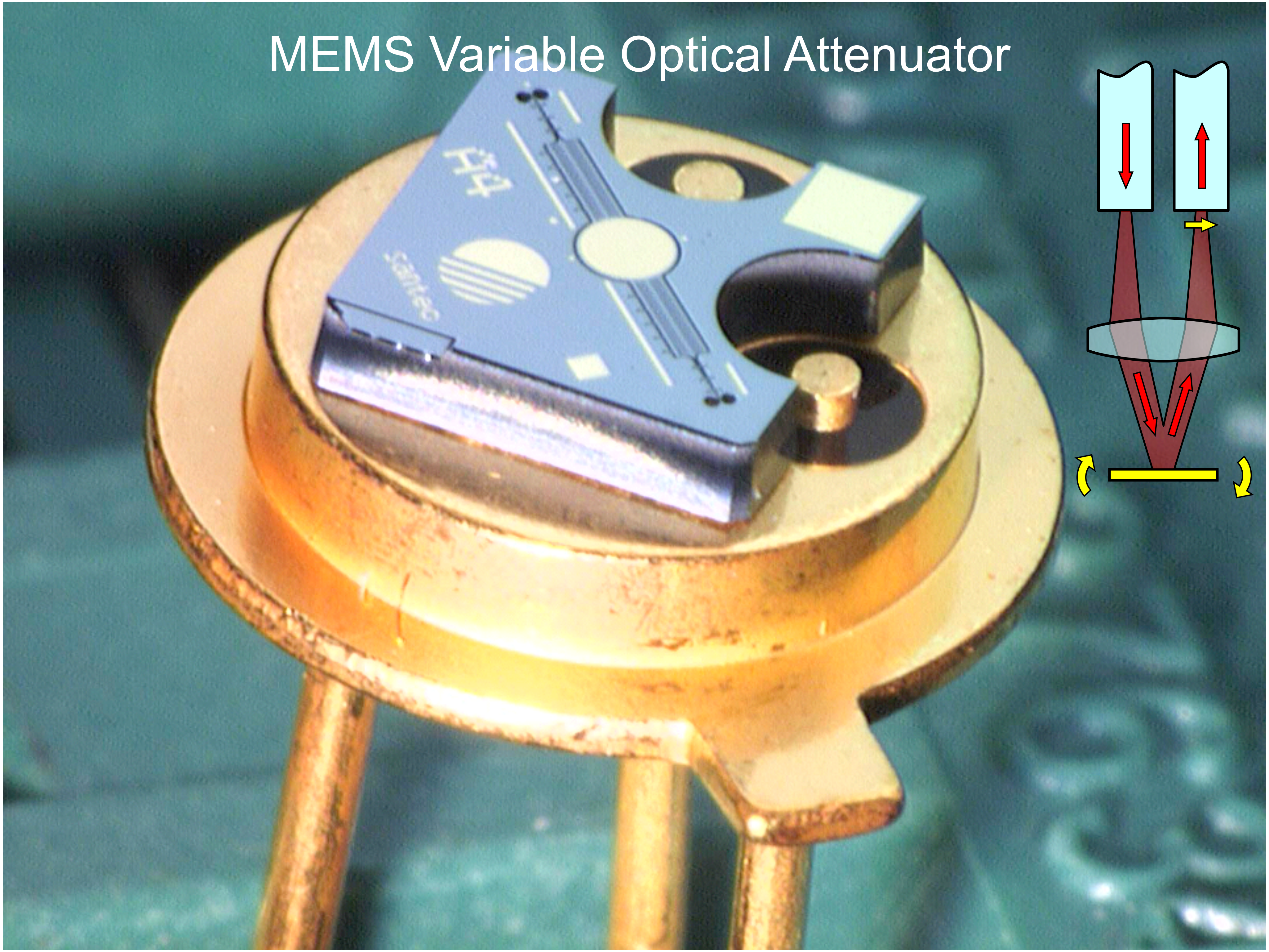
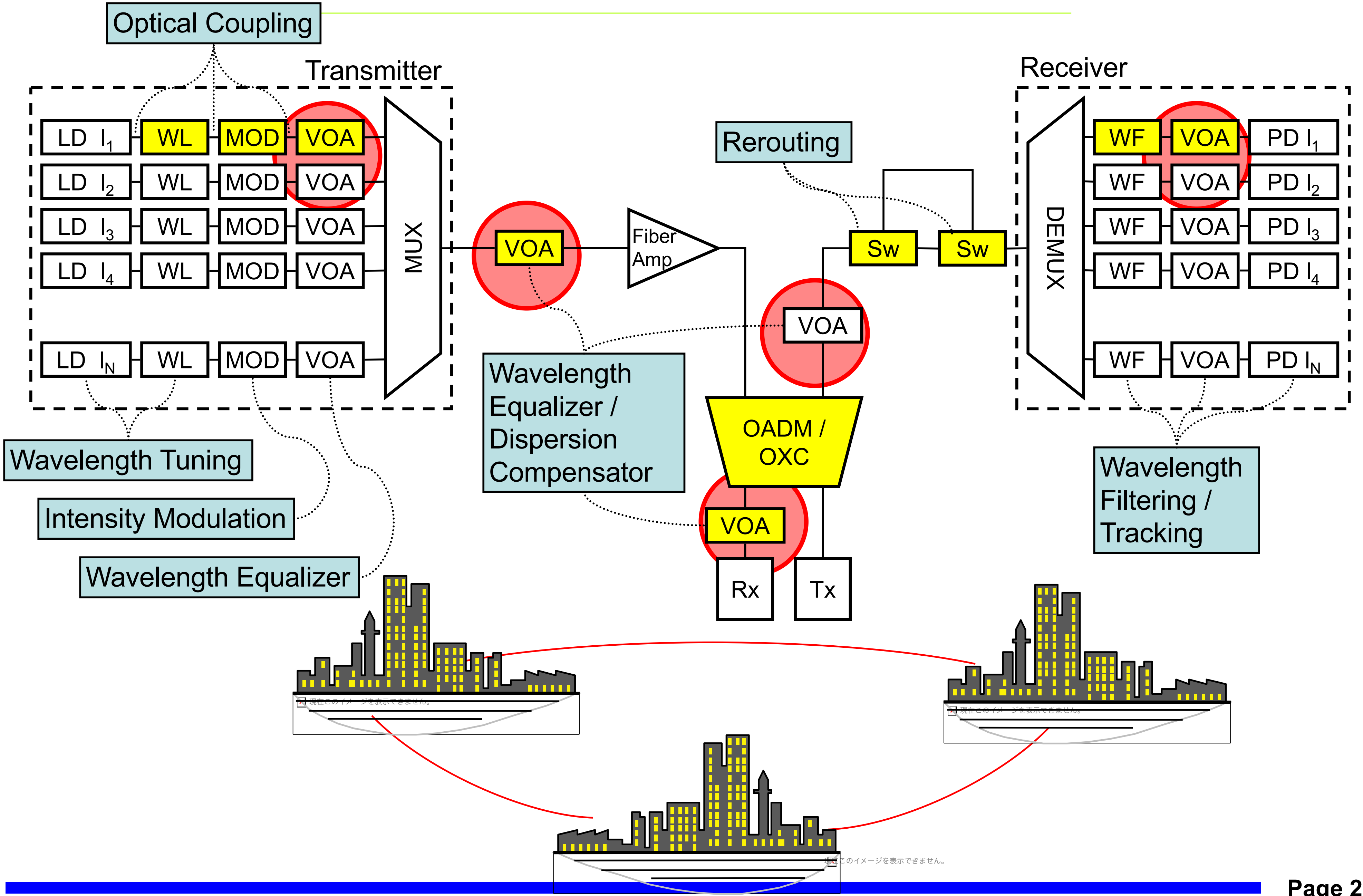
MEMS Variable Optical Attenuator



MEMS VOA Application in Fiber Telecom Network



Optical Coupling

Transmitter

LD l_1 WL MOD VOA

LD l_2 WL MOD VOA

LD l_3 WL MOD VOA

LD l_4 WL MOD VOA

LD l_N WL MOD VOA

MUX

VOA

Fiber Amp

Rerouting

Sw Sw

VOA

OADM / OXC

VOA

Rx Tx

Receiver

DEMUX

WF VOA PD l_1

WF VOA PD l_2

WF VOA PD l_3

WF VOA PD l_4

WF VOA PD l_N

Wavelength Tuning

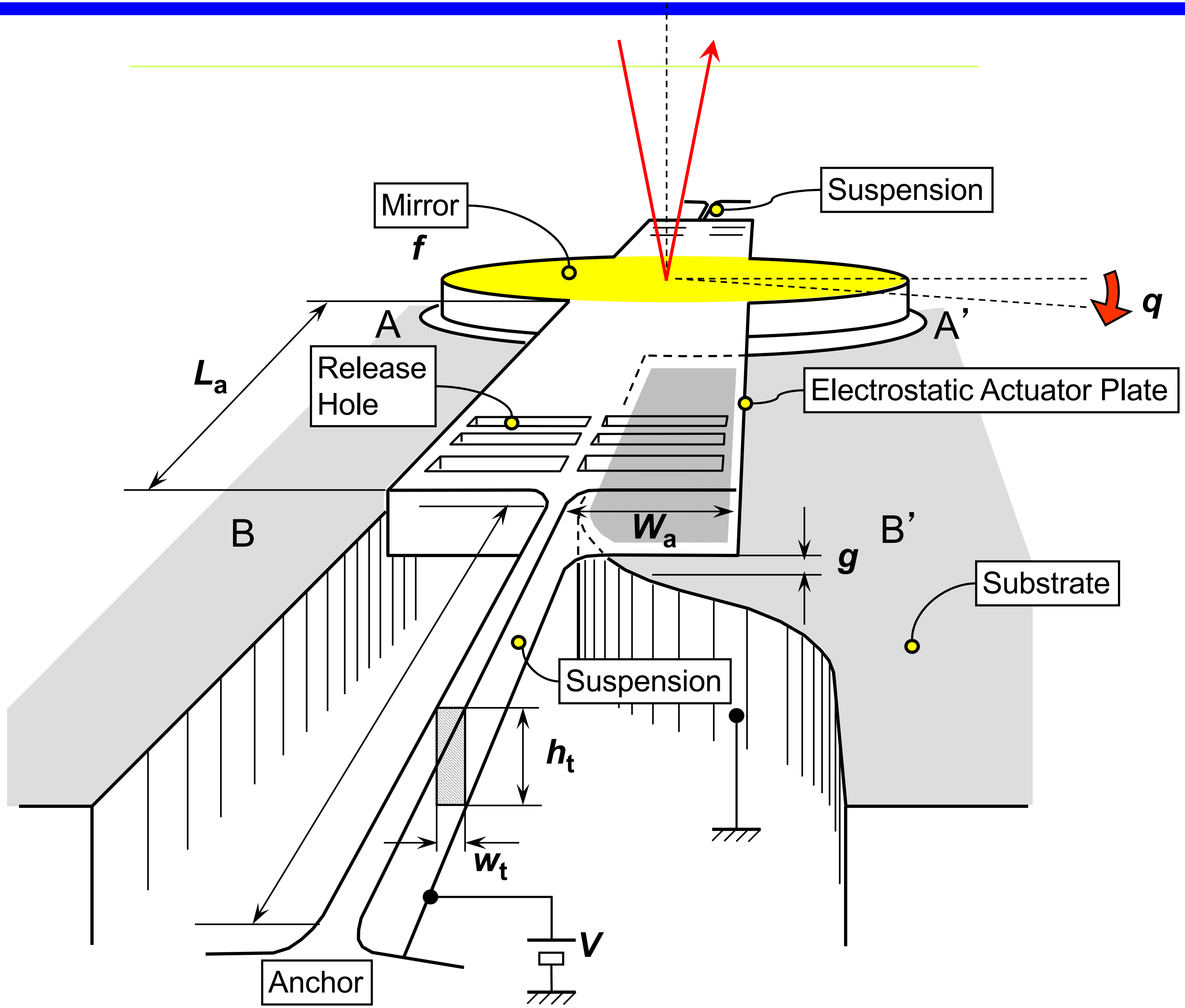
Intensity Modulation

Wavelength Equalizer

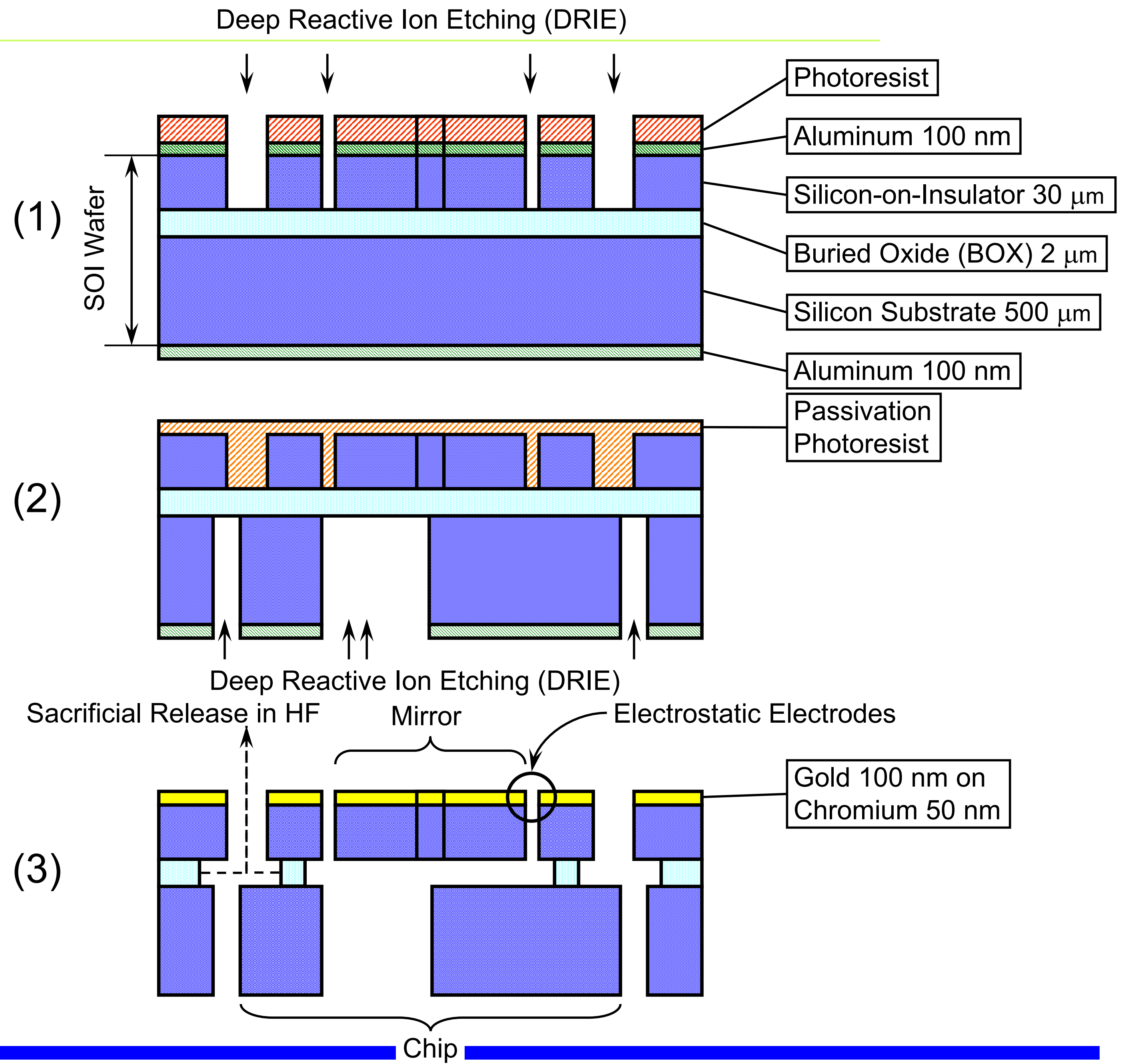
Wavelength Equalizer / Dispersion Compensator

Wavelength Filtering / Tracking

Simple Structures and Process for VOA

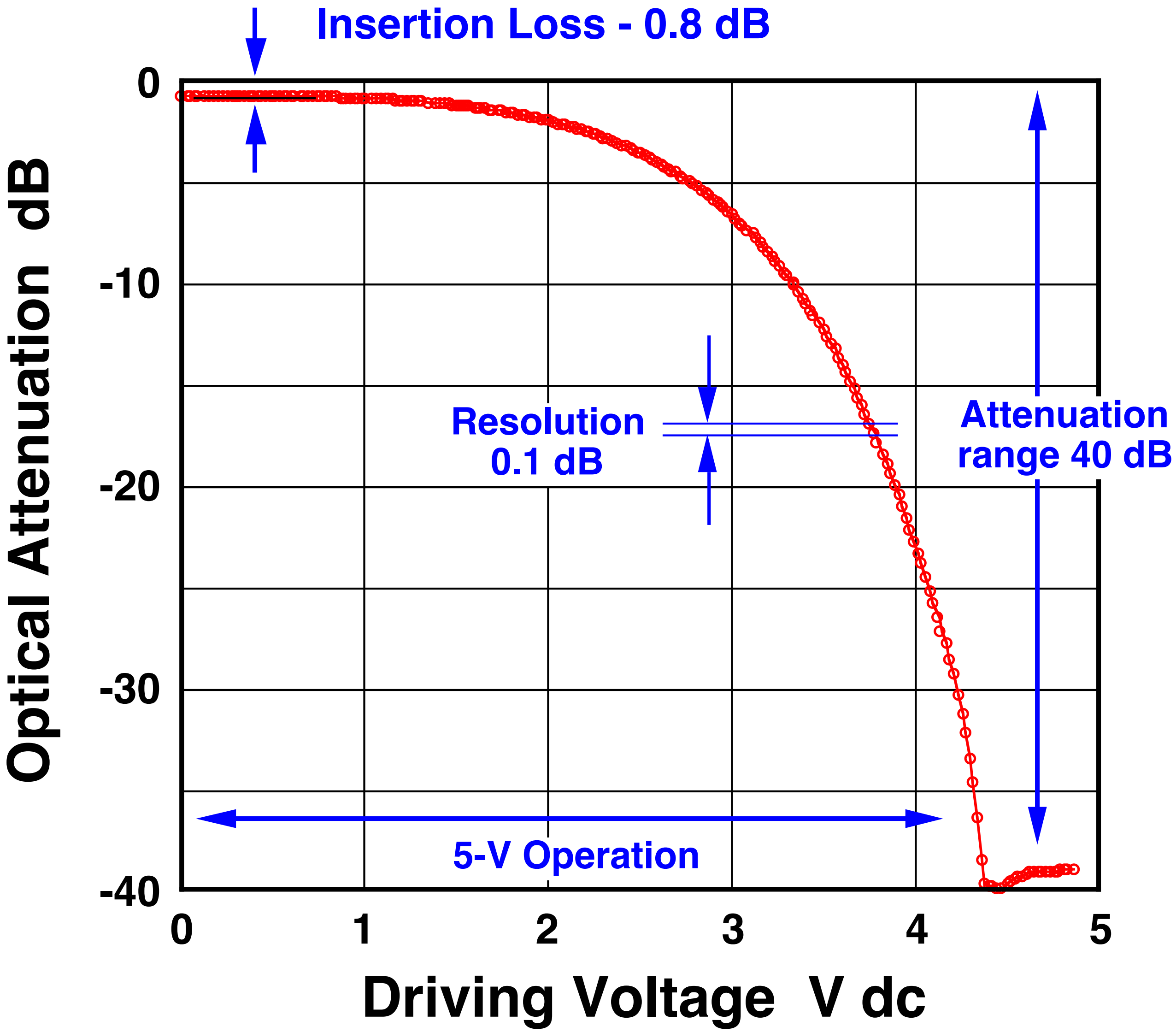


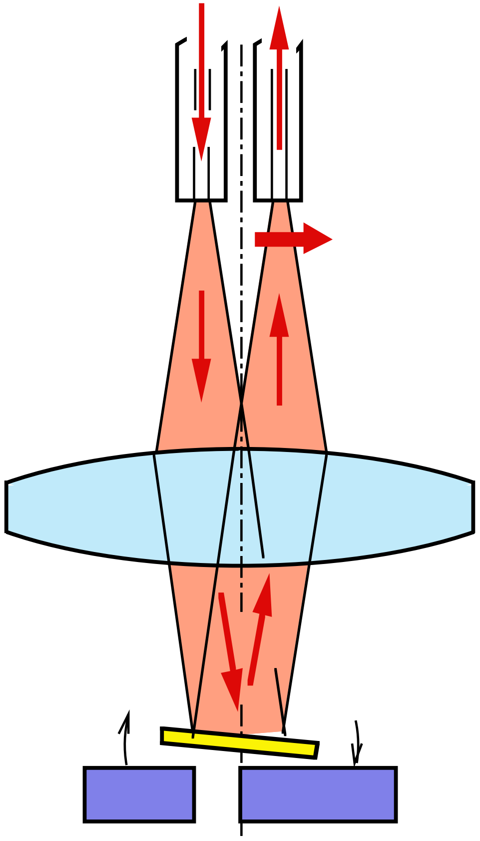
SOI Bulk Micromachining by DRIE



Attenuation Control and Complete Block-out

Normally-Bright Mode





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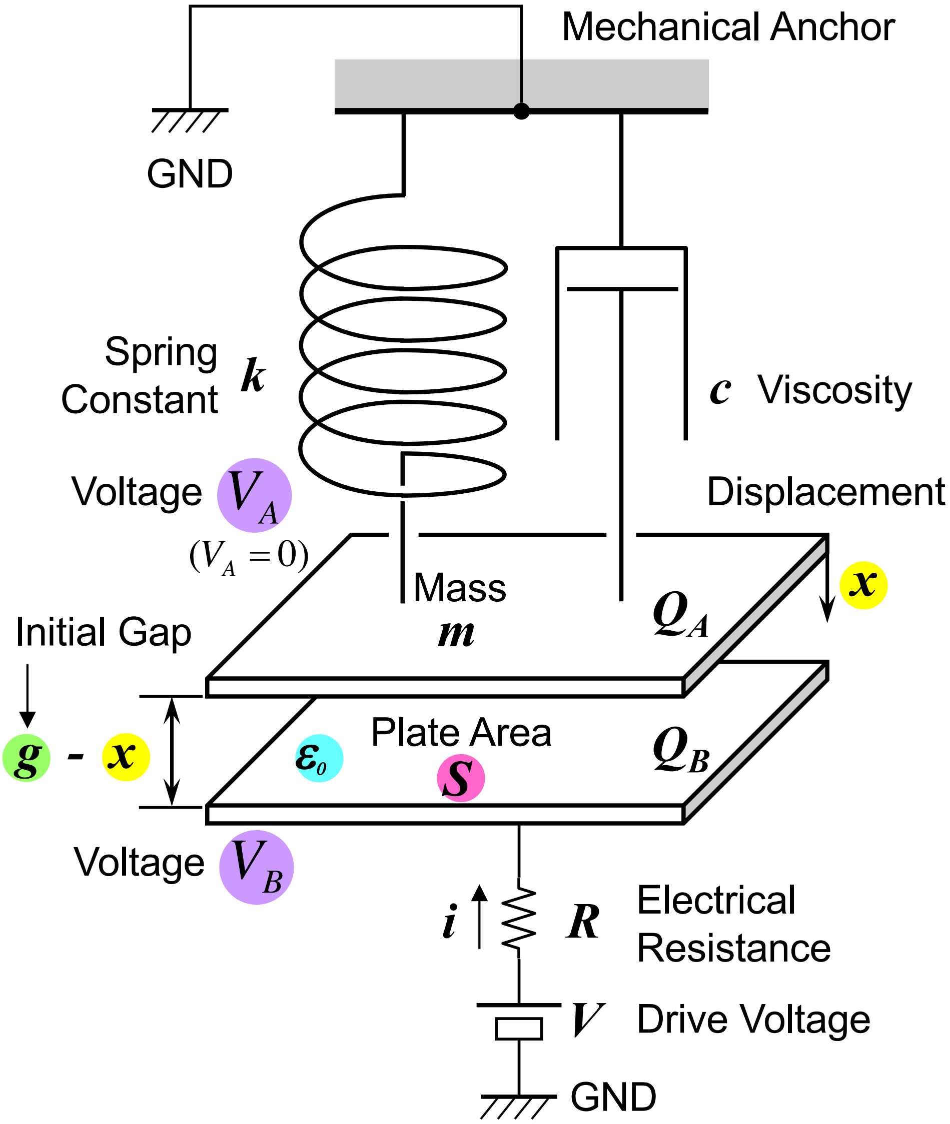
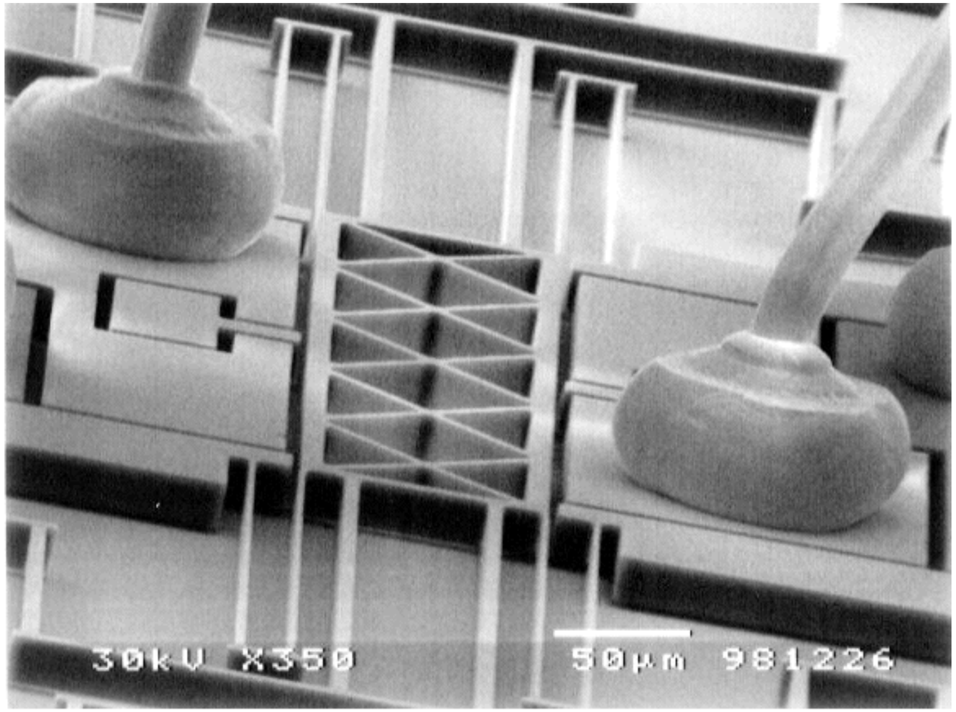
静電駆動マイクロアクチュエータ

電圧印加 → 静電引力 → 機械的変形

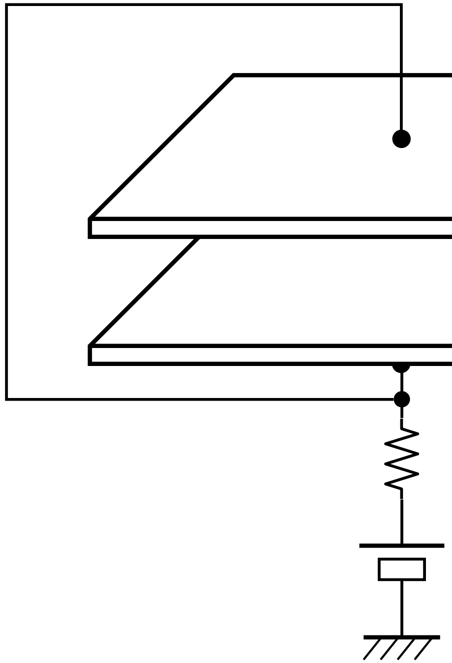




Electrostatic micro actuator (bi-directional)

$$F=\frac{1}{2}\varepsilon_0\frac{S}{(g-x)^2}(V_A-V_B)^2$$

第１問　電極間を接続するとどうなるでしょう？



$$F = \frac{1}{2}\varepsilon_0 \frac{S}{(g-x)^2}(V_A - V_B)^2$$

A
動く

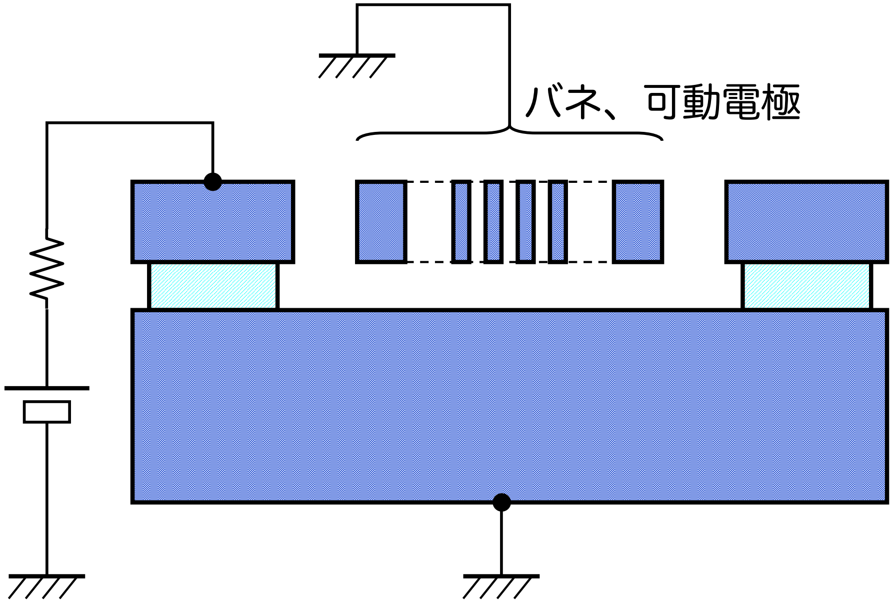
B
動かない

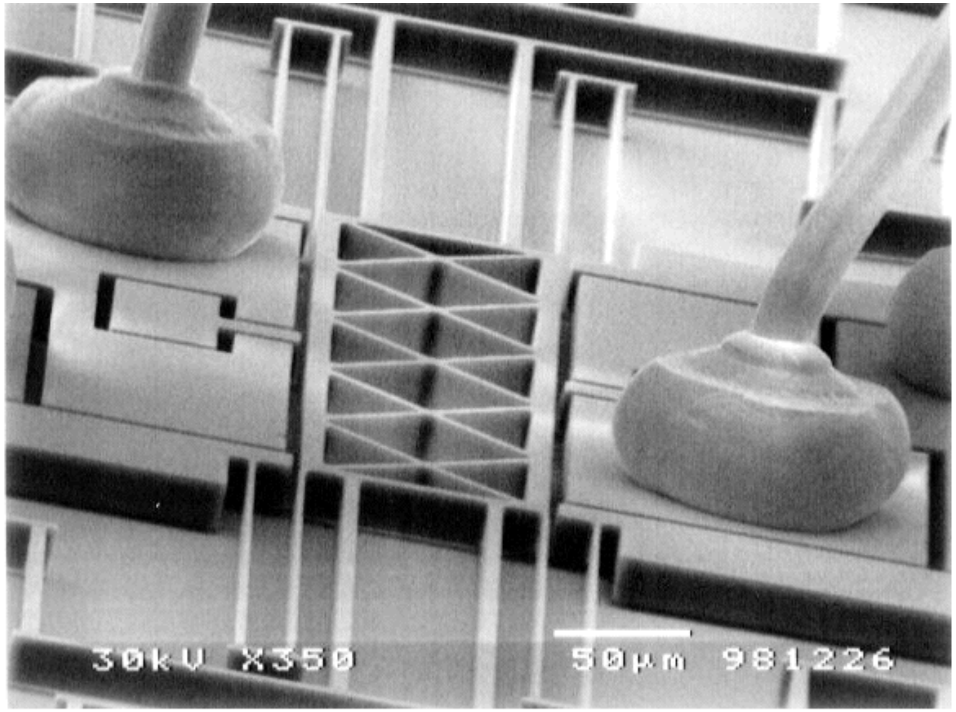
正解と解説

B
動かない

電極間が等電位であれば、静電引力は発生しない。
→よって、等電位の電極どうしは動かない。

この原理の応用例：
可動構造と基板を等電位に接地して、下向きの動きを防止。

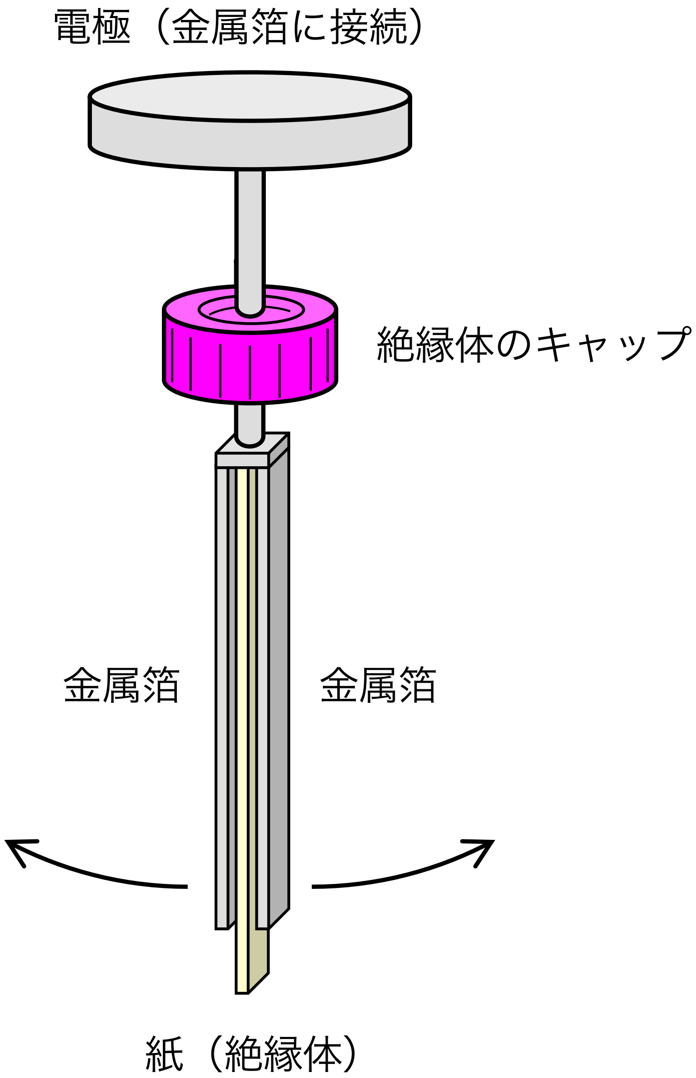




第２問　等電位なのに、なぜ動くのでしょうか？

箔（はく）検電器

http://www.kenis.co.jp/

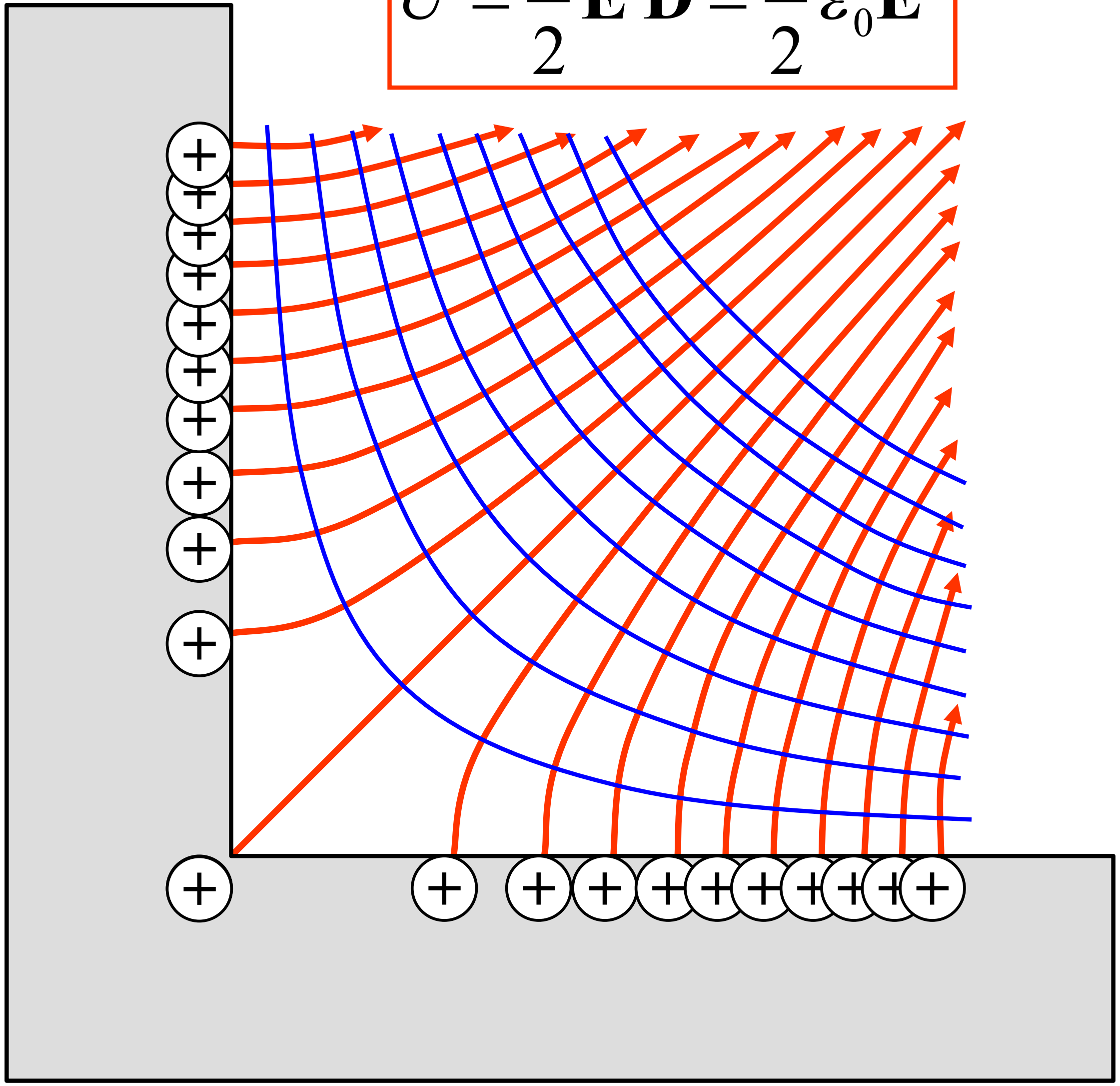


解説

等電位であっても、クーロン反発力は働きます

$$U = \frac{1}{2}\mathbf{E}\,\mathbf{D} = \frac{1}{2}\varepsilon_0\mathbf{E}^2$$

http://www.kenis.co.jp/

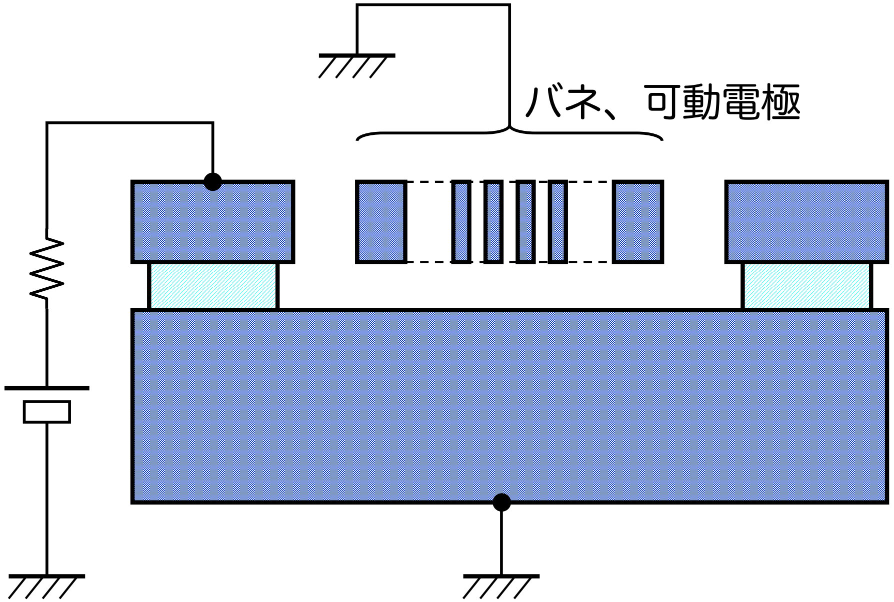


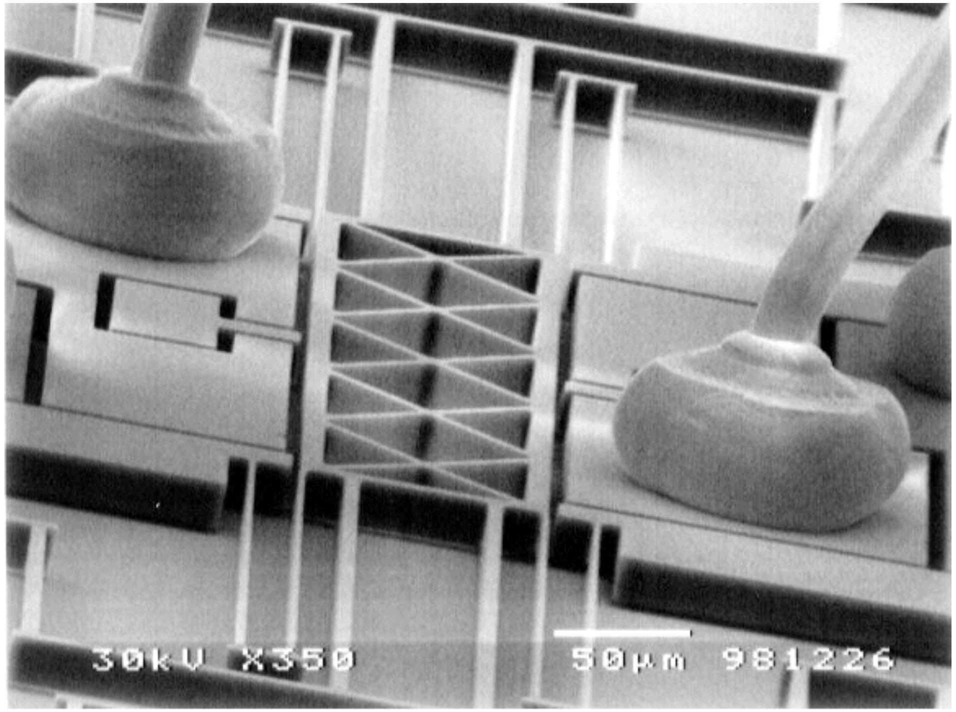
だまされてませんでしたか？

B
動かない

電極間が等電位であれば、静電引力は発生しない。
→よって、等電位の電極どうしは動かない。

ただし、等電位であっても静電反発力は働く。

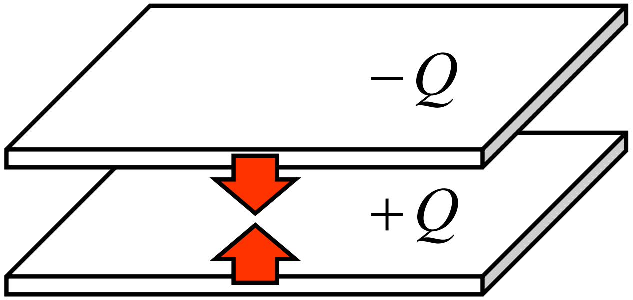




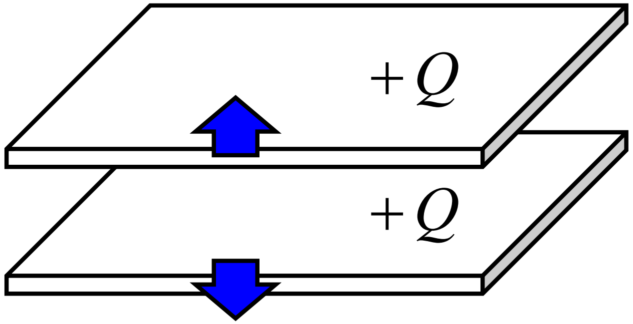
第３問　静電反発力を使わない理由は？

どっちもクーロン力、電荷の量は同じ、符号が違うだけ

$$F = \frac{1}{4\,\pi\,\varepsilon_0} \cdot \frac{Q_1 \cdot Q_2}{r^2}$$



静電引力アクチュエータ

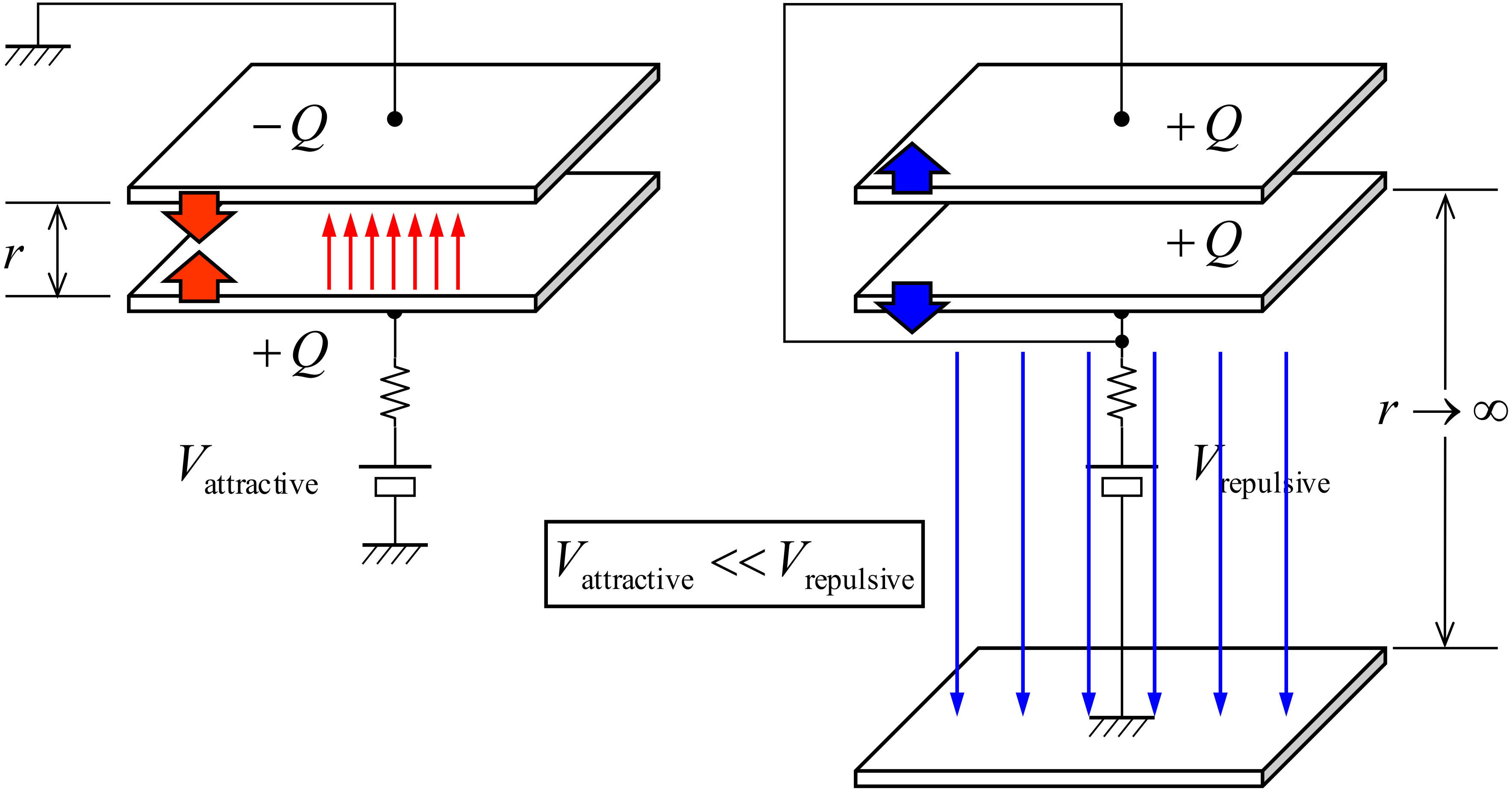


静電反発力アクチュエータ

解説　駆動電圧が高いのは損

電場に逆らって電荷を移動した仕事が「電位」

$$V = E_n \cdot r = \frac{\sigma}{2\,\varepsilon_0} \cdot r$$



$$\boxed{V_{\text{attractive}} << V_{\text{repulsive}}}$$

静電引力アクチュエータ　　**静電反発力アクチュエータ**

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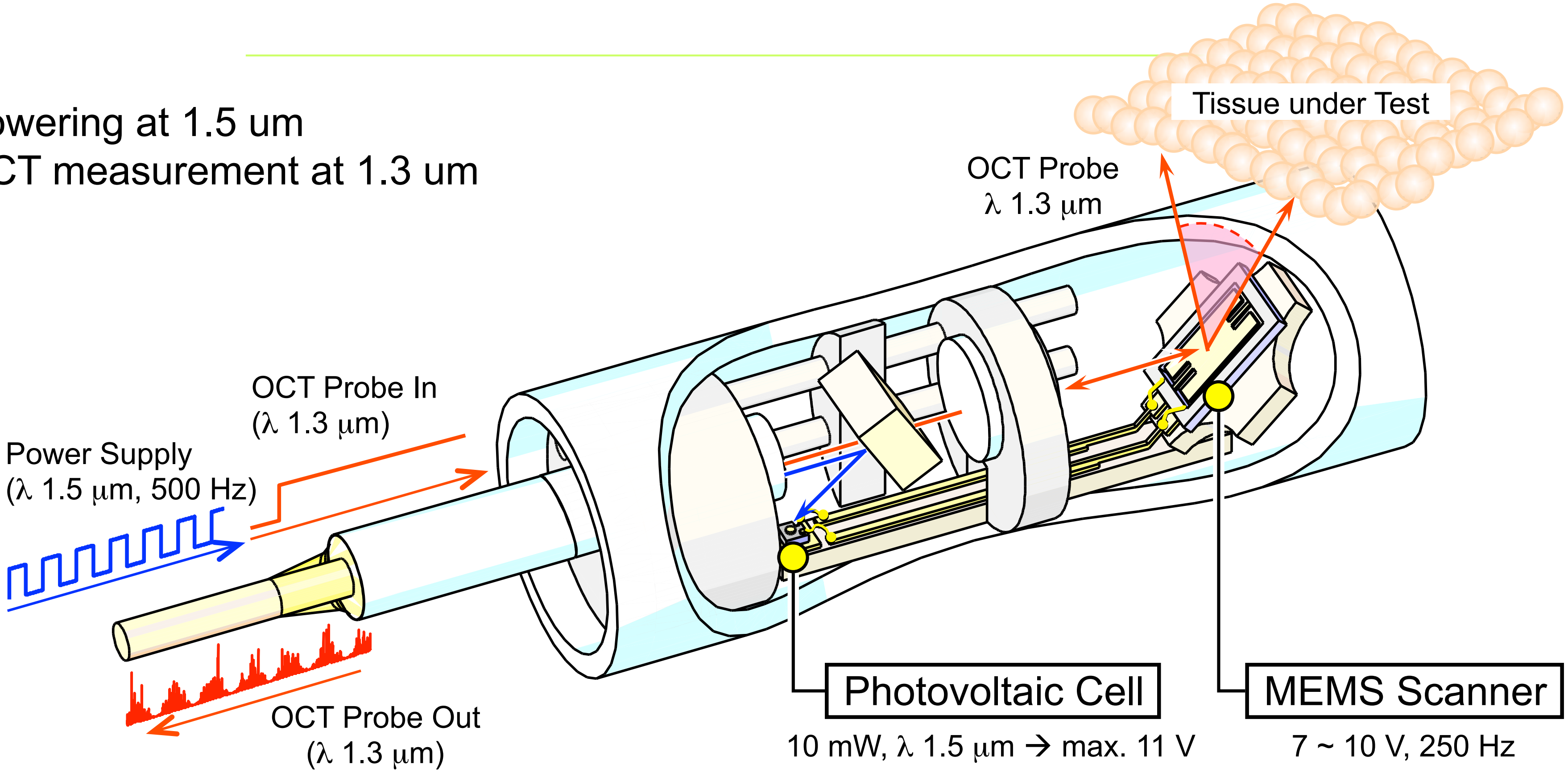
Optically Powered Fiber Endoscope

- 🟦 Powering at 1.5 um
- 🟥 OCT measurement at 1.3 um



Tissue under Test

OCT Probe
λ 1.3 μm

OCT Probe In
(λ 1.3 μm)

Power Supply
(λ 1.5 μm, 500 Hz)

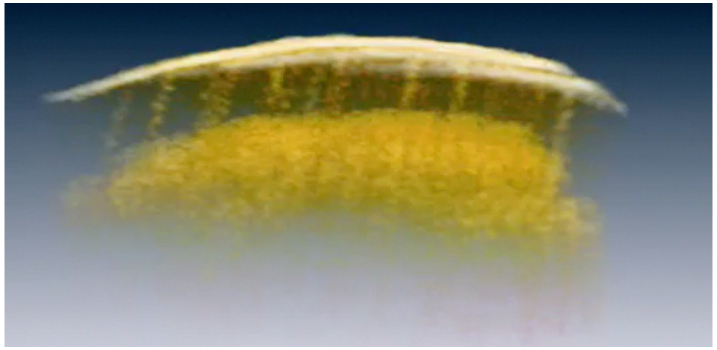
OCT Probe Out
(λ 1.3 μm)

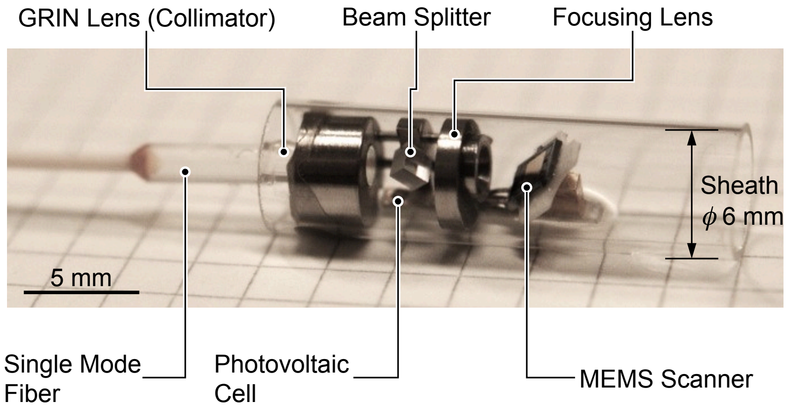
Photovoltaic Cell

10 mW, λ 1.5 μm → max. 11 V

MEMS Scanner

7 ~ 10 V, 250 Hz

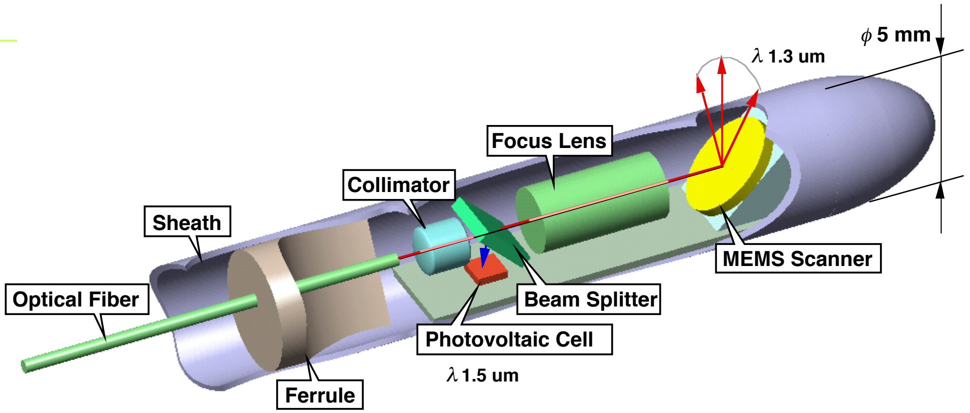


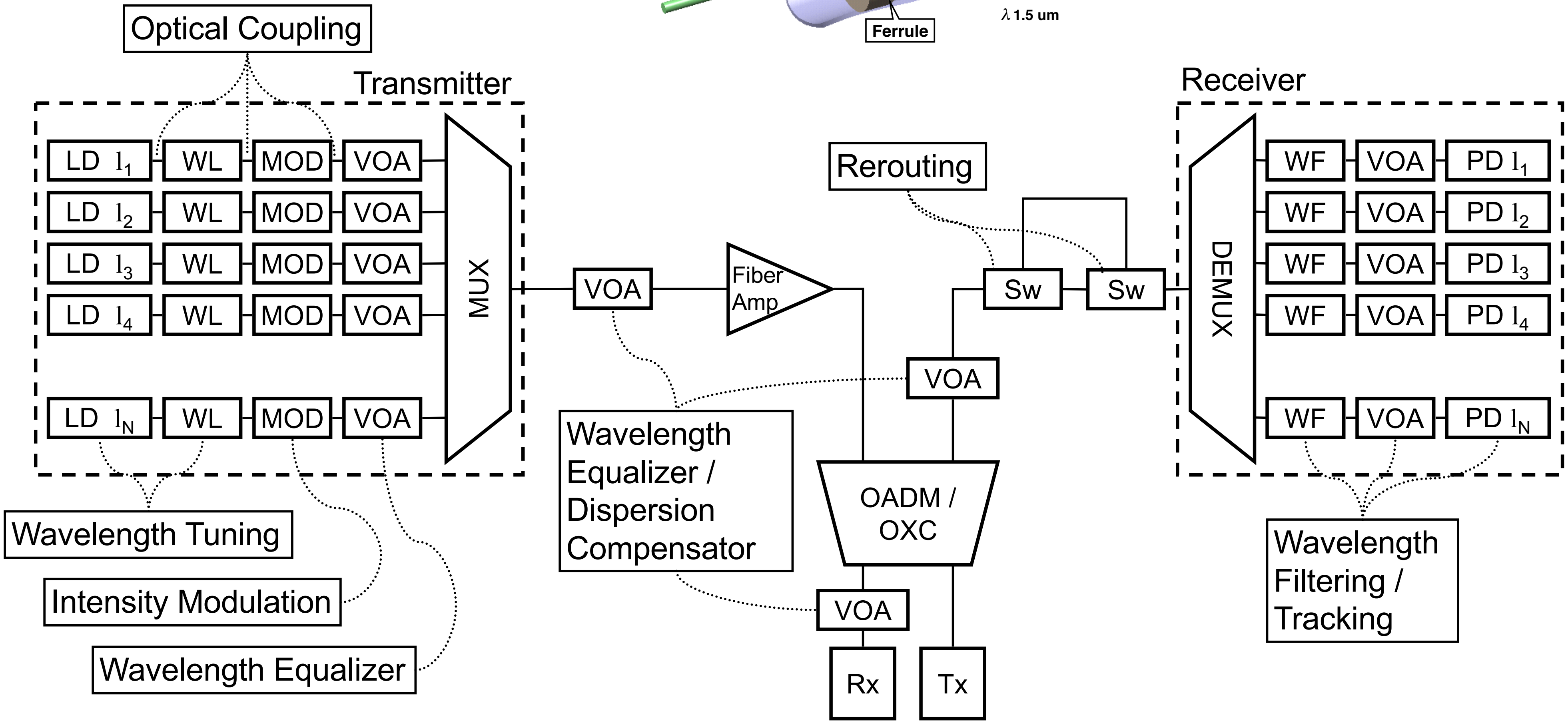


Application of WDM Technology

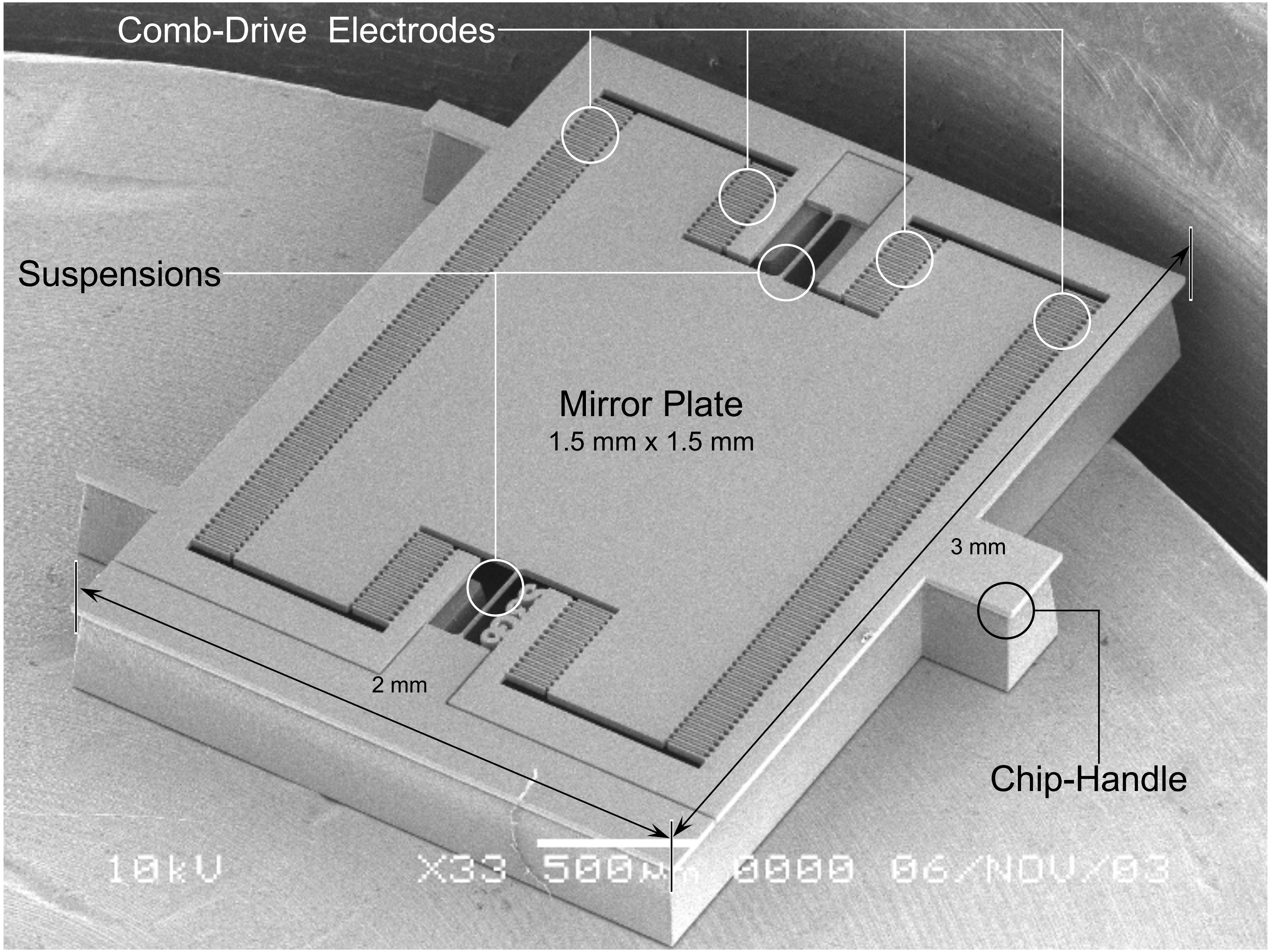
🟦 Power 1.5 μm

🟥 OCT Probe 1.3 μm

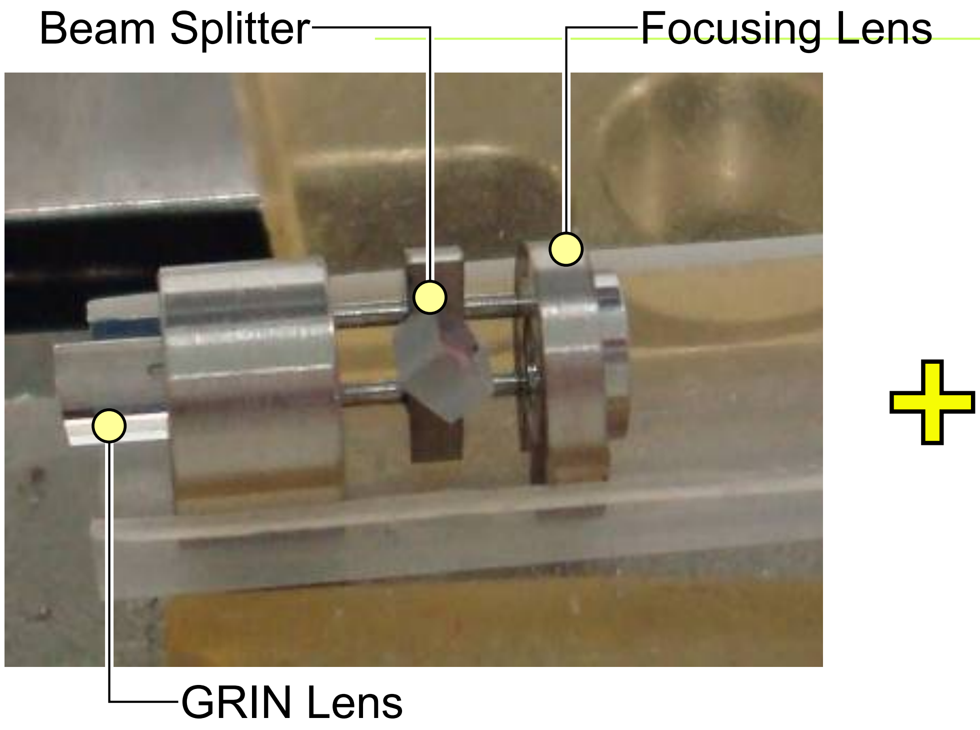




Electrostatic MEMS Optical Scanner 2 mm x 3 mm



Assembly of MEMS Endoscope Head



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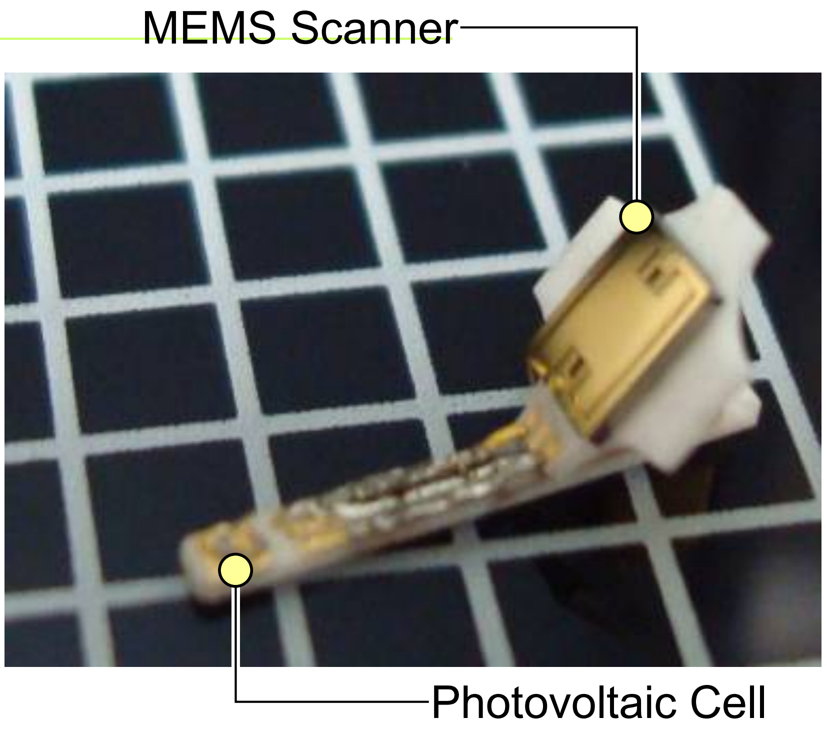
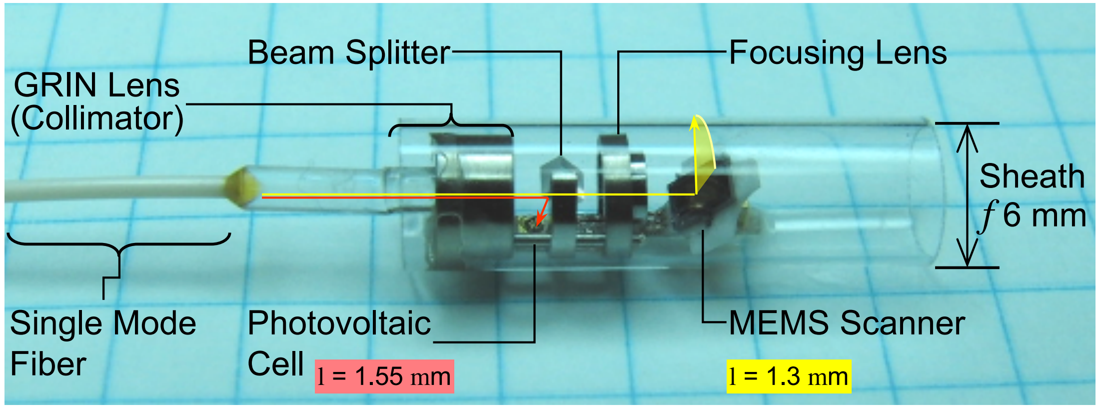
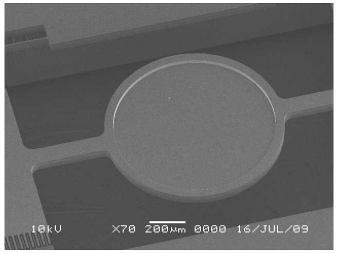


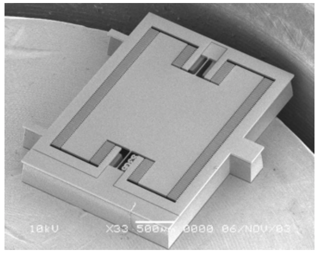


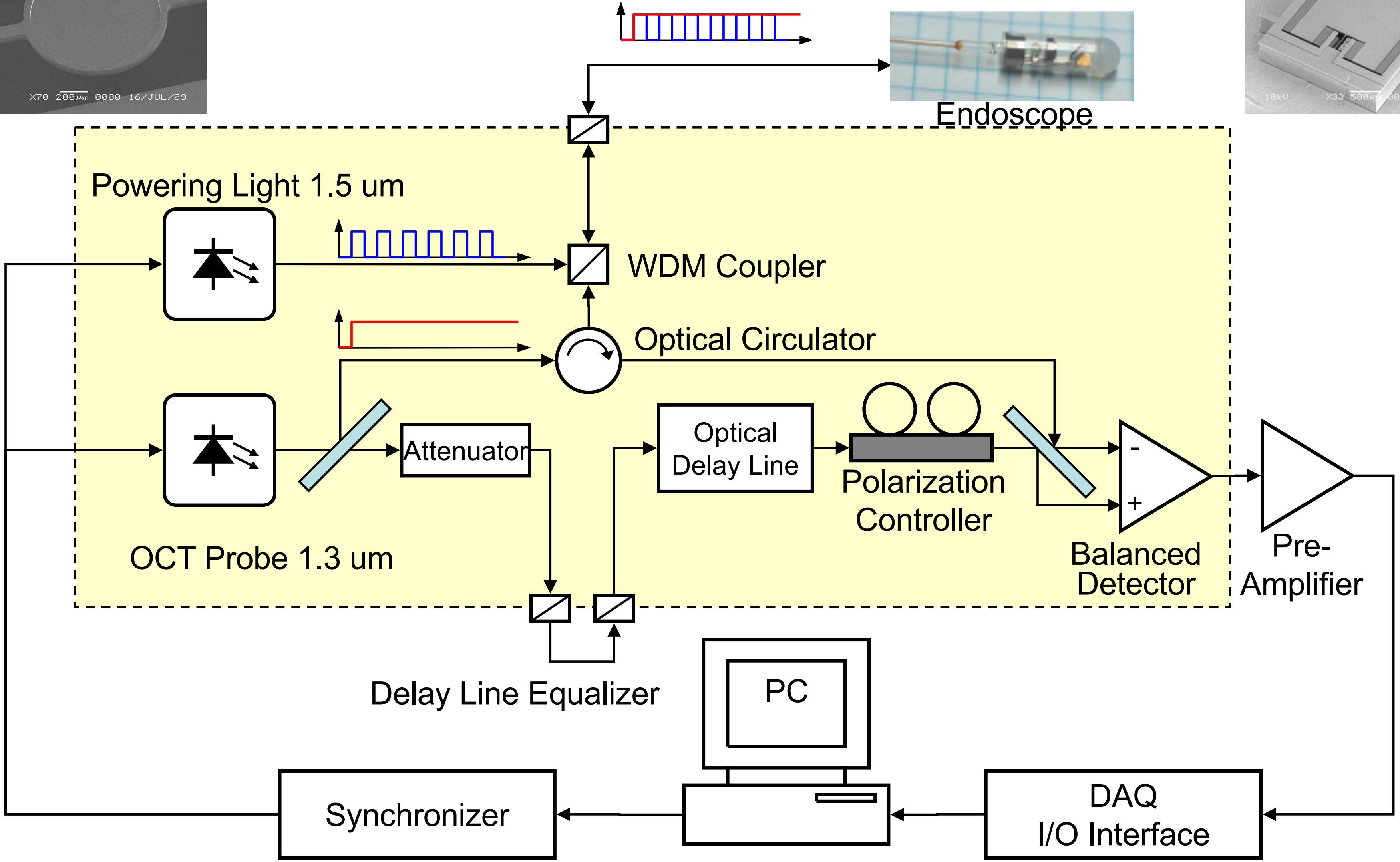
Detail View of Optically Powered OCT



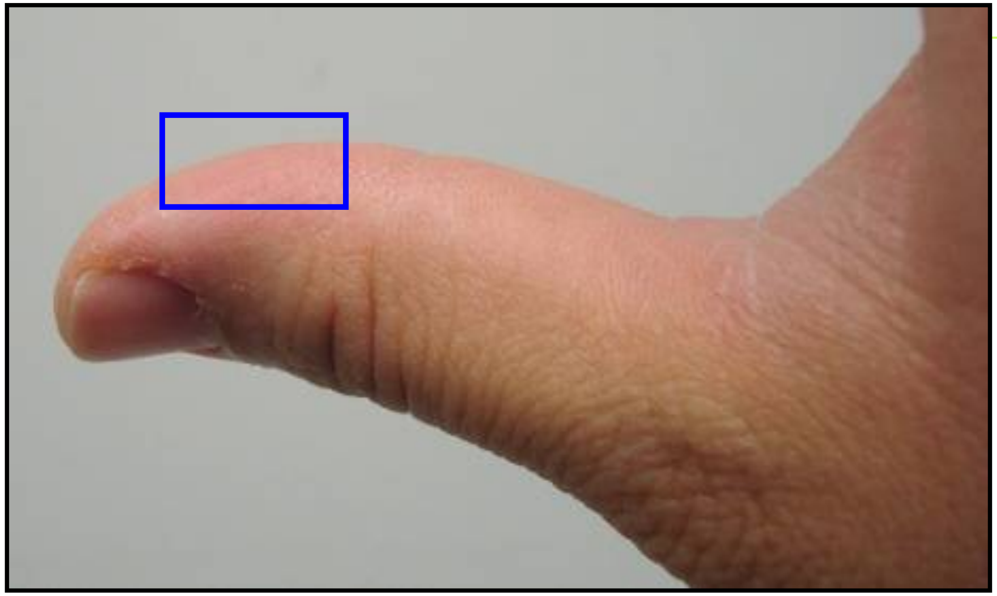
← Fast Scanner

Slow Scanner →



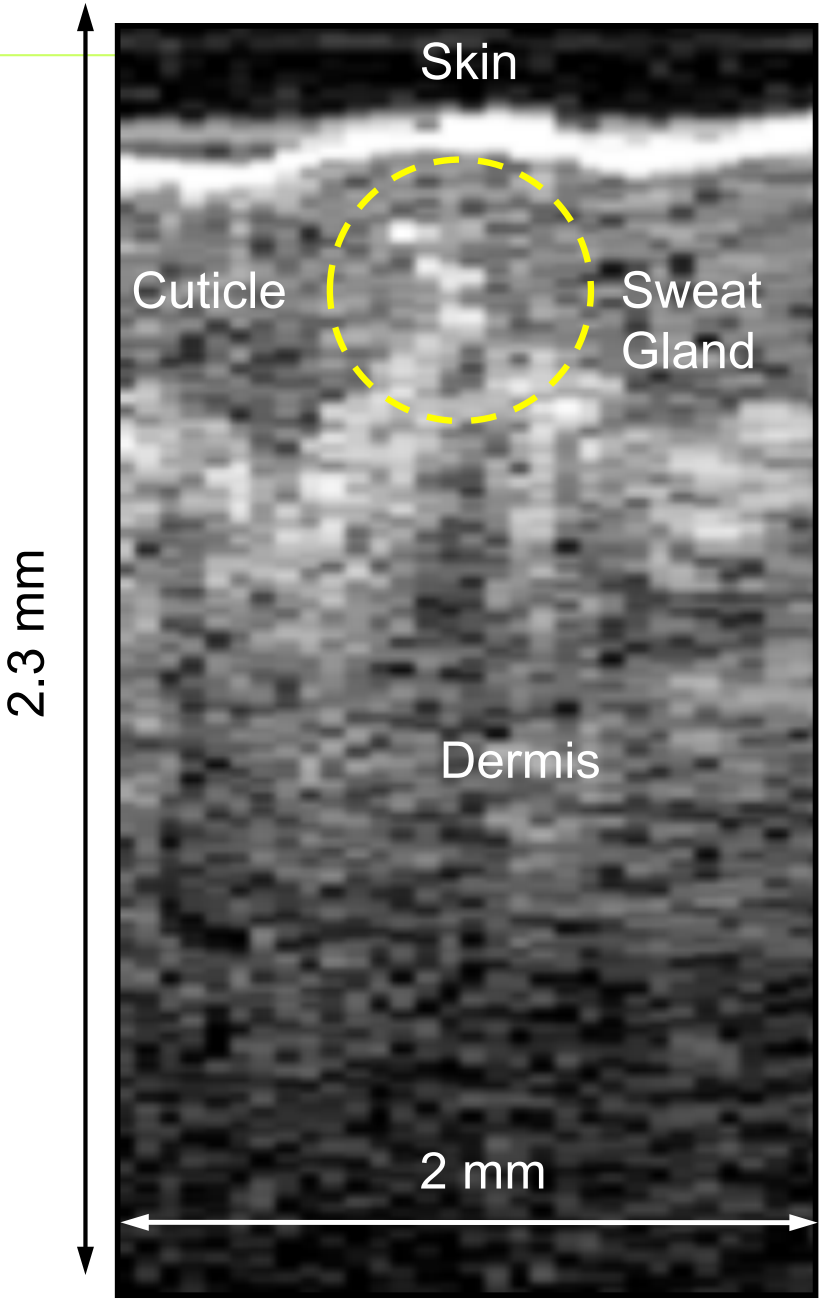


OCT (Optical Coherence Tomography) Image



M. Nakada, et al., "Optical Coherence Tomography based on Power-over-fiber MEMS Scanner," *APCOT 2008,* Jun. 22-25 2008.

	Scan Range (mm)	Resolution (um)
Lateral	1.6	40
Depth	1.0 ~ 2.5	8



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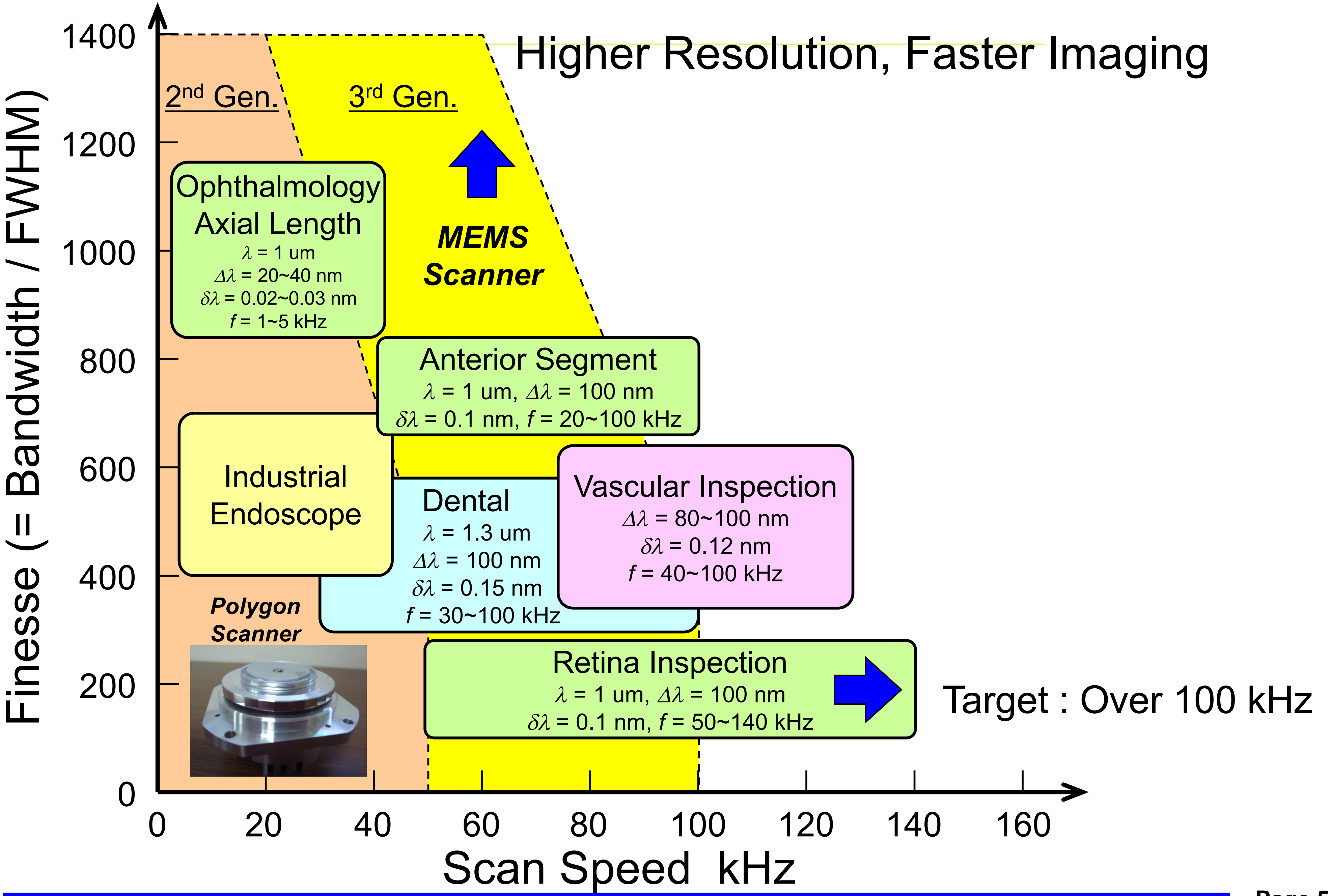
Wavelength-Tunable Laser for OT



Higher Resolution, Faster Imaging

Ophthalmology Axial Length
λ = 1 um
$\Delta\lambda$ = 20~40 nm
$\delta\lambda$ = 0.02~0.03 nm
f = 1~5 kHz

Anterior Segment
λ = 1 um, $\Delta\lambda$ = 100 nm
$\delta\lambda$ = 0.1 nm, f = 20~100 kHz

Industrial Endoscope

Dental
λ = 1.3 um
$\Delta\lambda$ = 100 nm
$\delta\lambda$ = 0.15 nm
f = 30~100 kHz

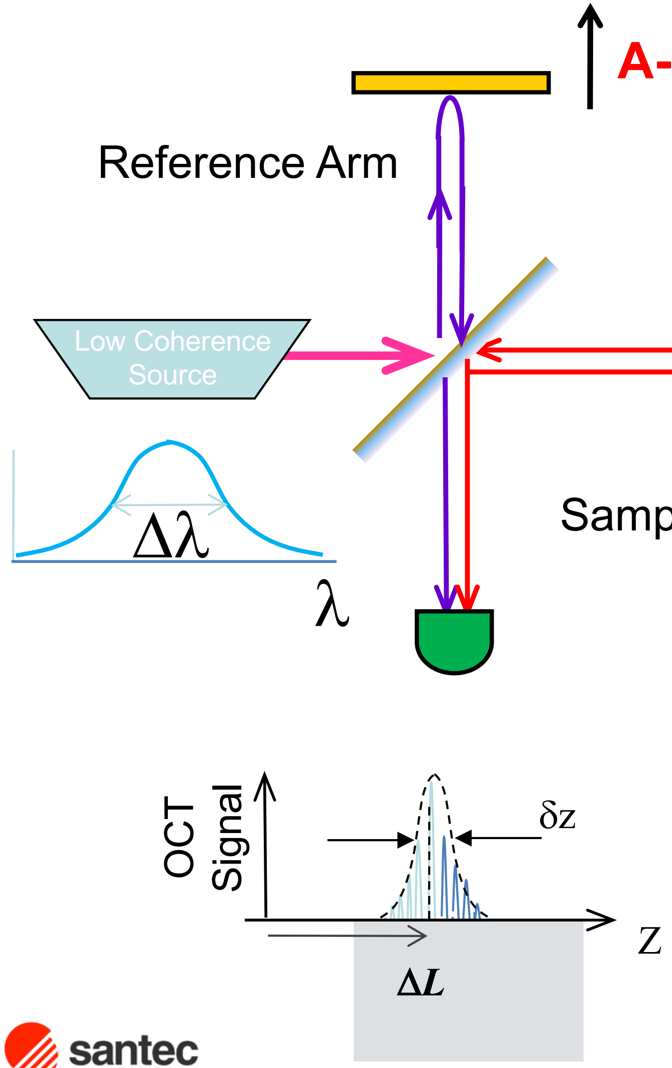
Vascular Inspection
$\Delta\lambda$ = 80~100 nm
$\delta\lambda$ = 0.12 nm
f = 40~100 kHz

Retina Inspection
λ = 1 um, $\Delta\lambda$ = 100 nm
$\delta\lambda$ = 0.1 nm, f = 50~140 kHz

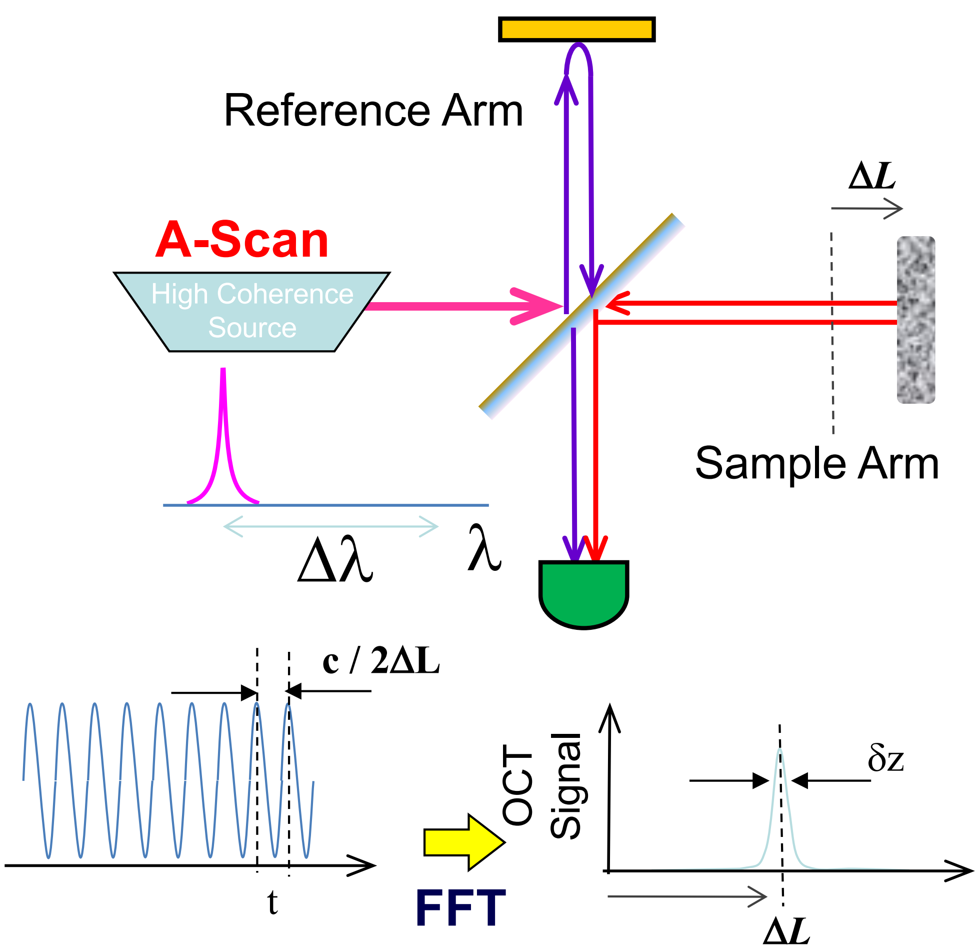
Target : Over 100 kHz

Two OCT Operation Principles

Time-Domain OCT (TD-OCT)



Swept-Source OCT (SS-OCT)



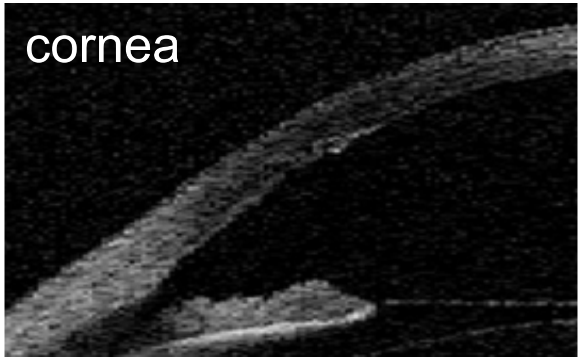
Advantages of SS-OCT

Time-Domain OCT (TD-OCT)

Time-Domain Zeiss Visante OCT

Swept-Source OCT (SS-OCT)

This work



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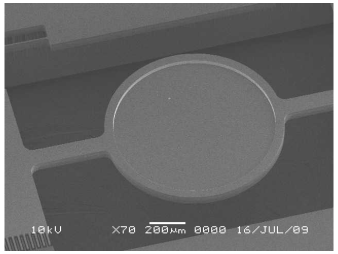

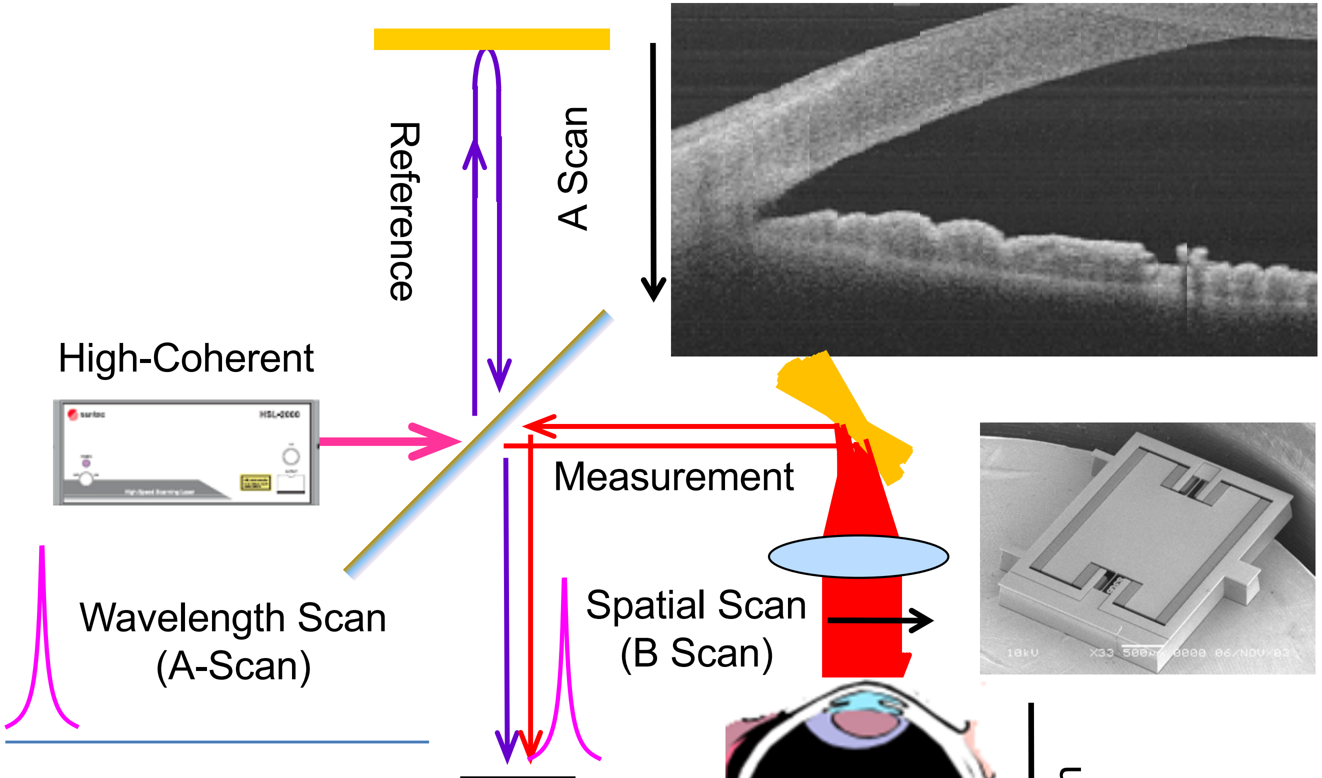

	TD-OCT	SS-OCT
Sensitivity dB	~ 90 dB	~ 110
Frame Rate fps	1	54
Resolution µm	10~15	5~10

Keiji Isamoto, Kohki Totsuka, Tooru Sakai, Takuya Suzuki, Atsushi Morosawa, Changho Chong, Hiroyuki Fujita, Hiroshi Toshiyoshi, "A High Speed MEMS Scanner for 140-kHz SS-OCT," IEEE Int. Conf. on Optical MEMS and Nanophotonics, Istanbul, Turkey, Aug. 8-11, 2011.

MEMS Scanner to Replace Polygon Mirrors

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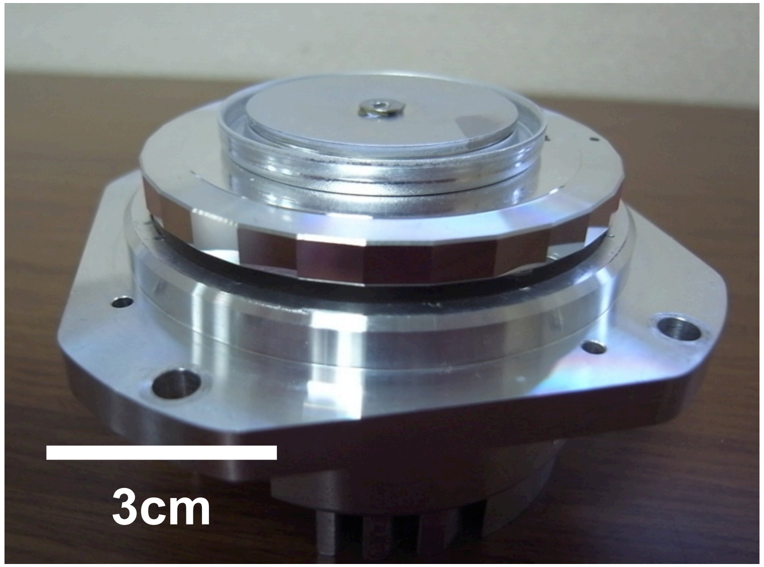
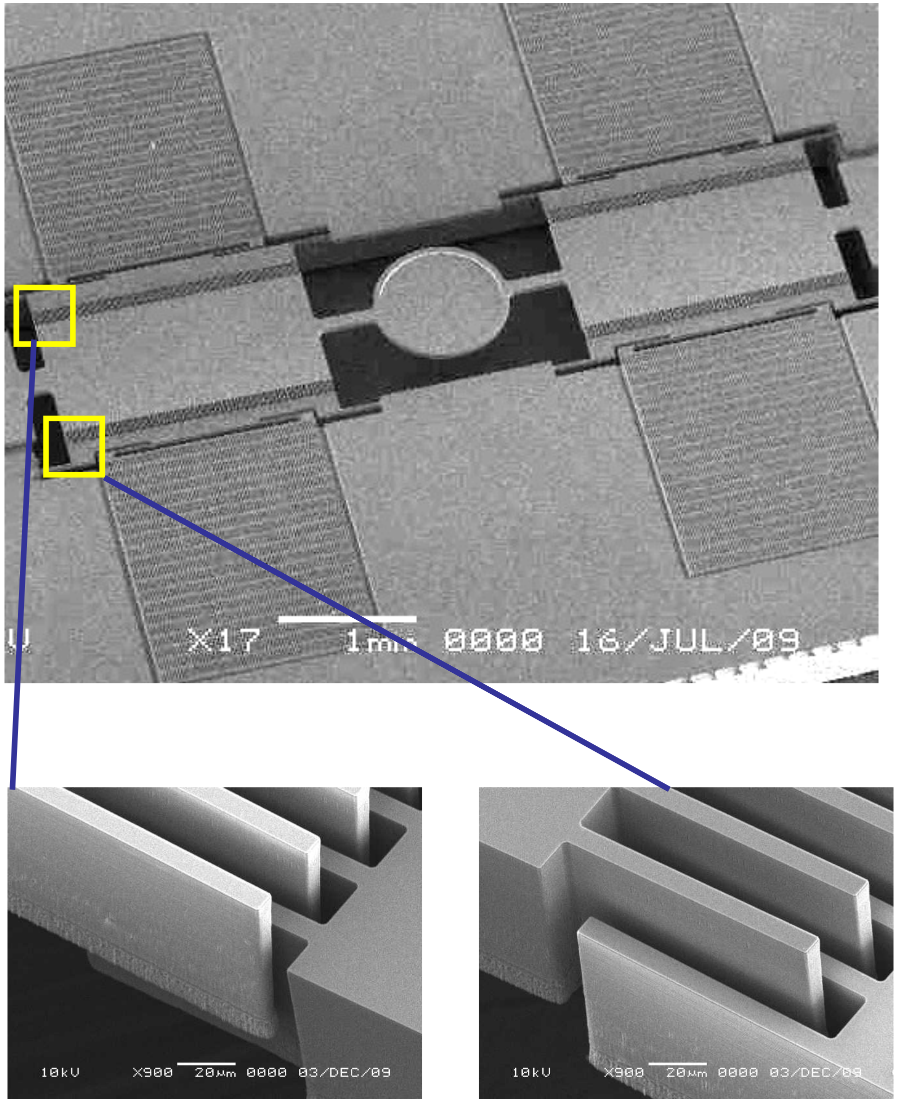
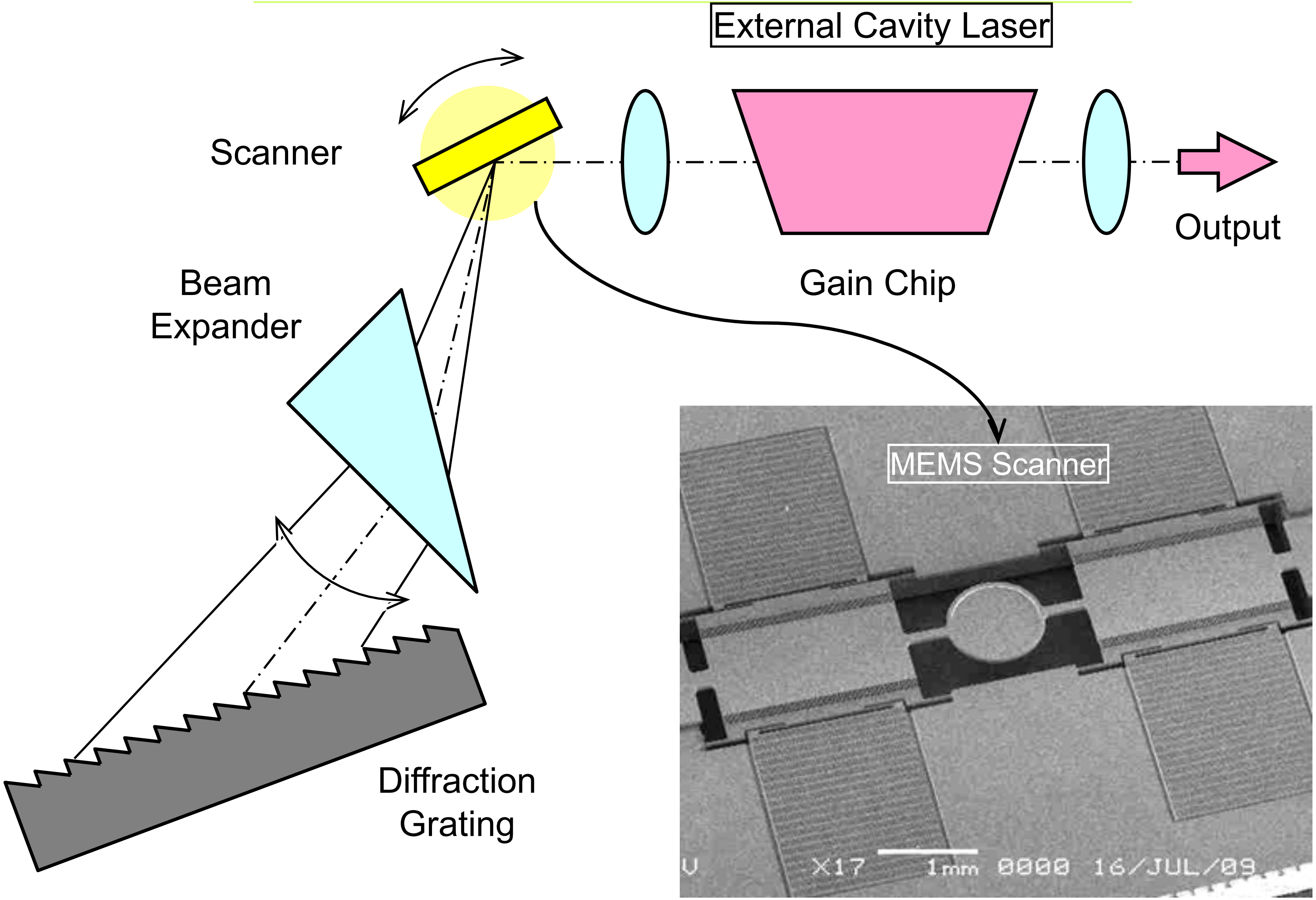
Fast Operation Speed at 70 kHz





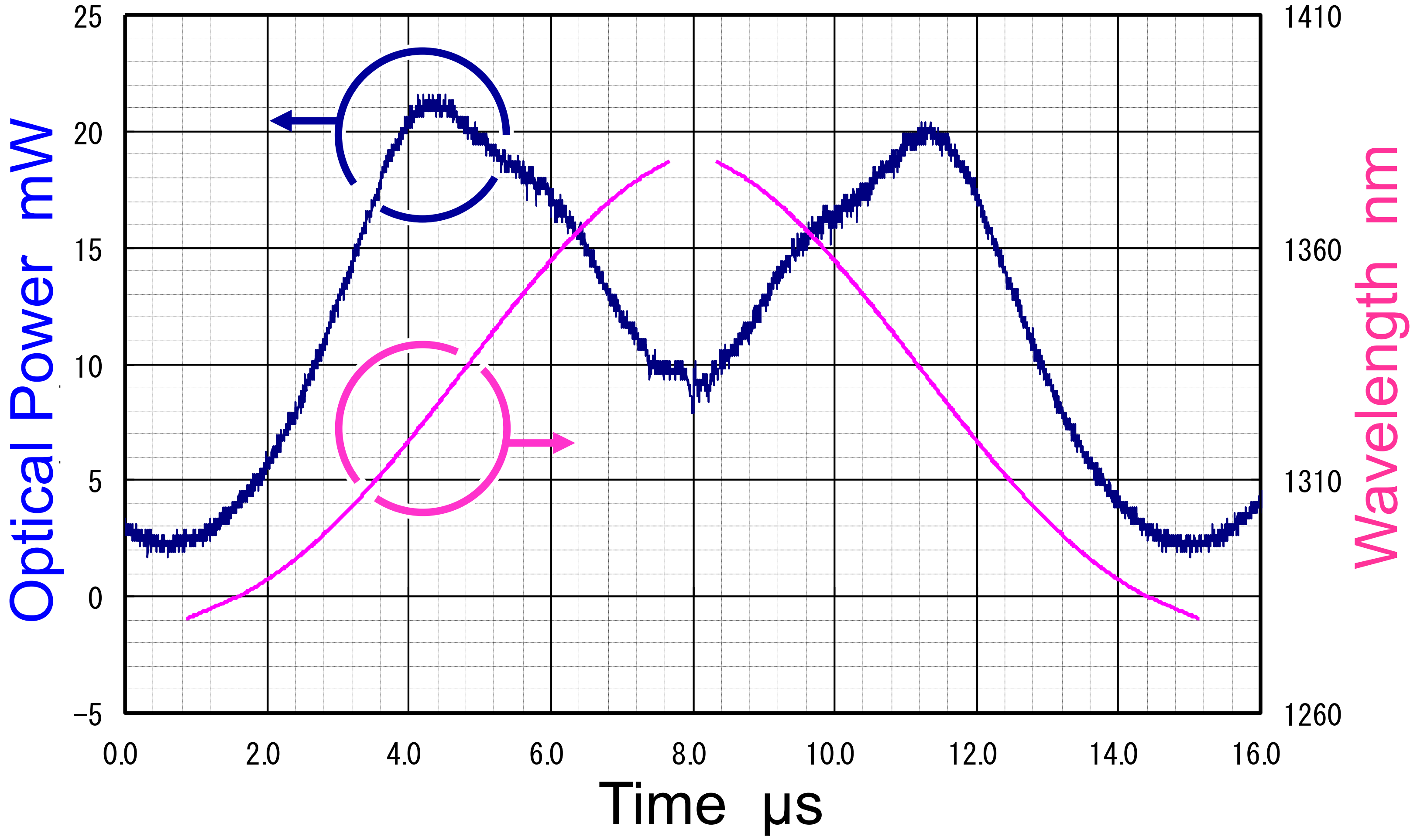
External Cavity Laser for Wavelength Tuning



Wavelength Scan Performance

Mechanical 70 kHz x round-trip scan → 140 kHz Sweep

Band Width ~ 100 nm



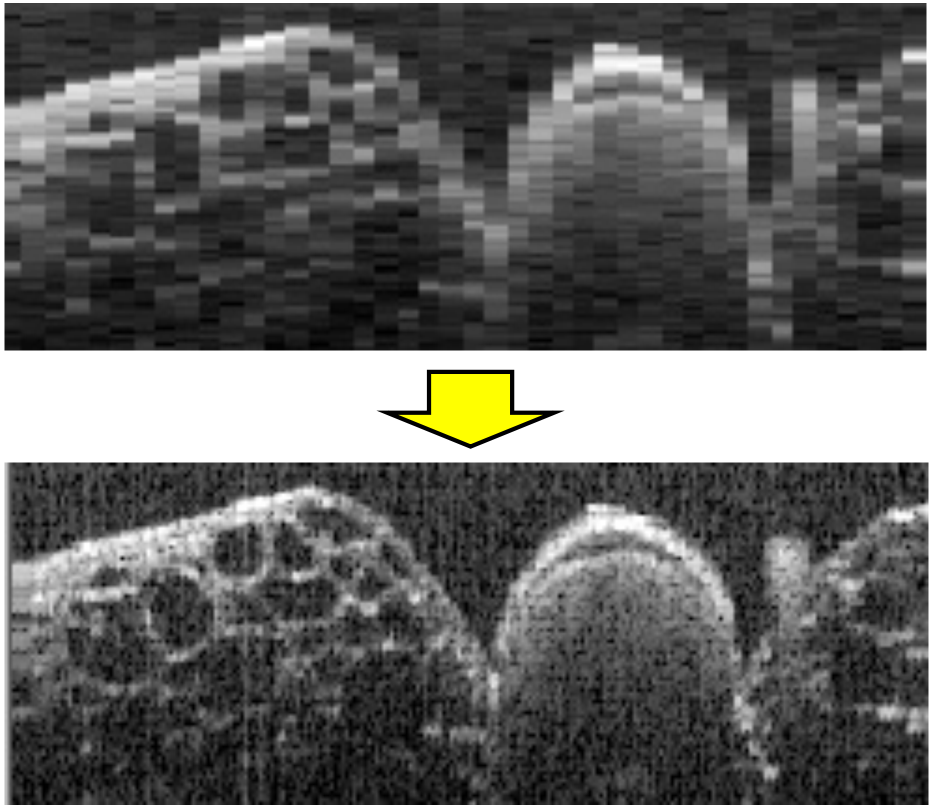
Intensity calibration required for OCT imaging

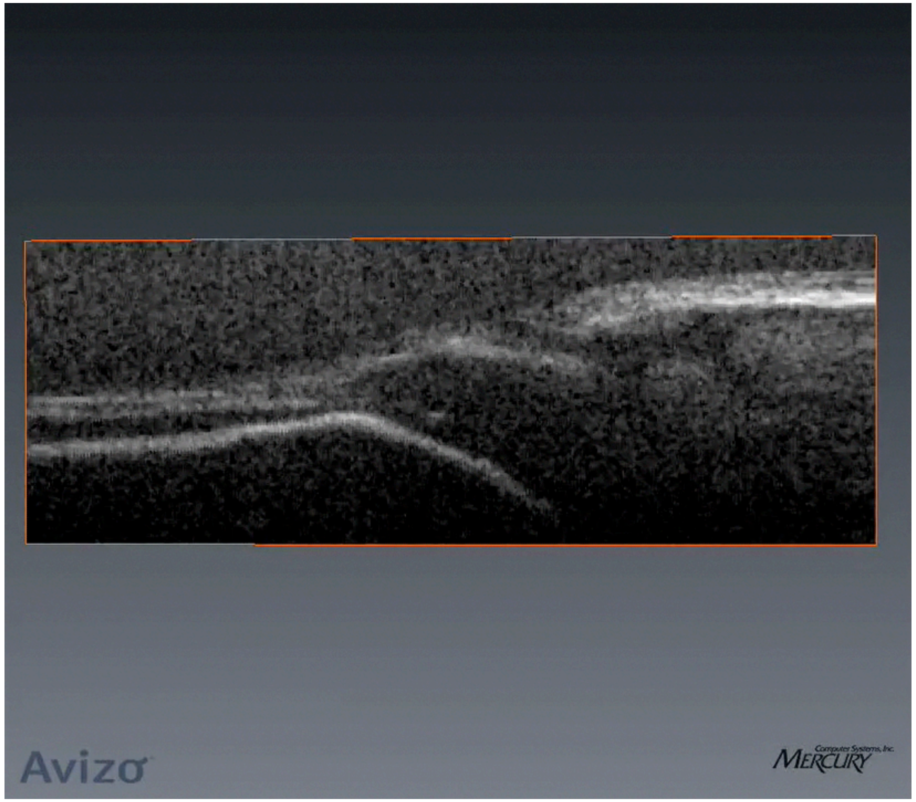
Virtually Slicing Alive

Higher resolution, less invasive, and less expensive than X-ray CT or Ultrasonic Imagers

Benefits of Fast OCT Scan

Higher Resolution & Faster Frame Rate





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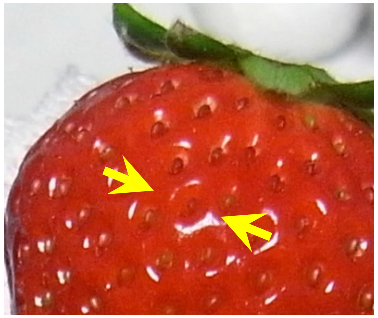
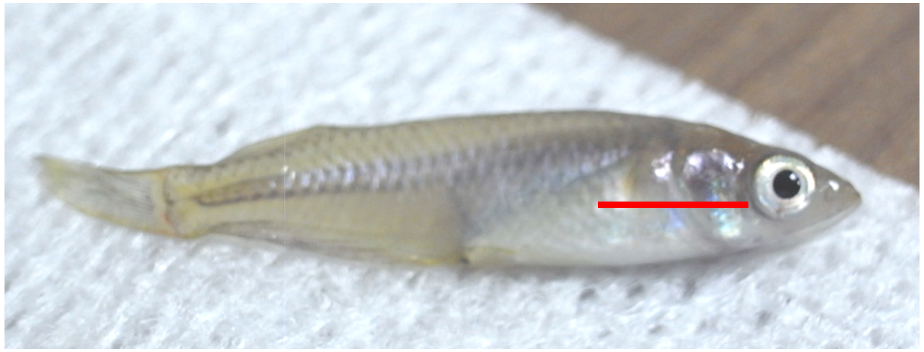
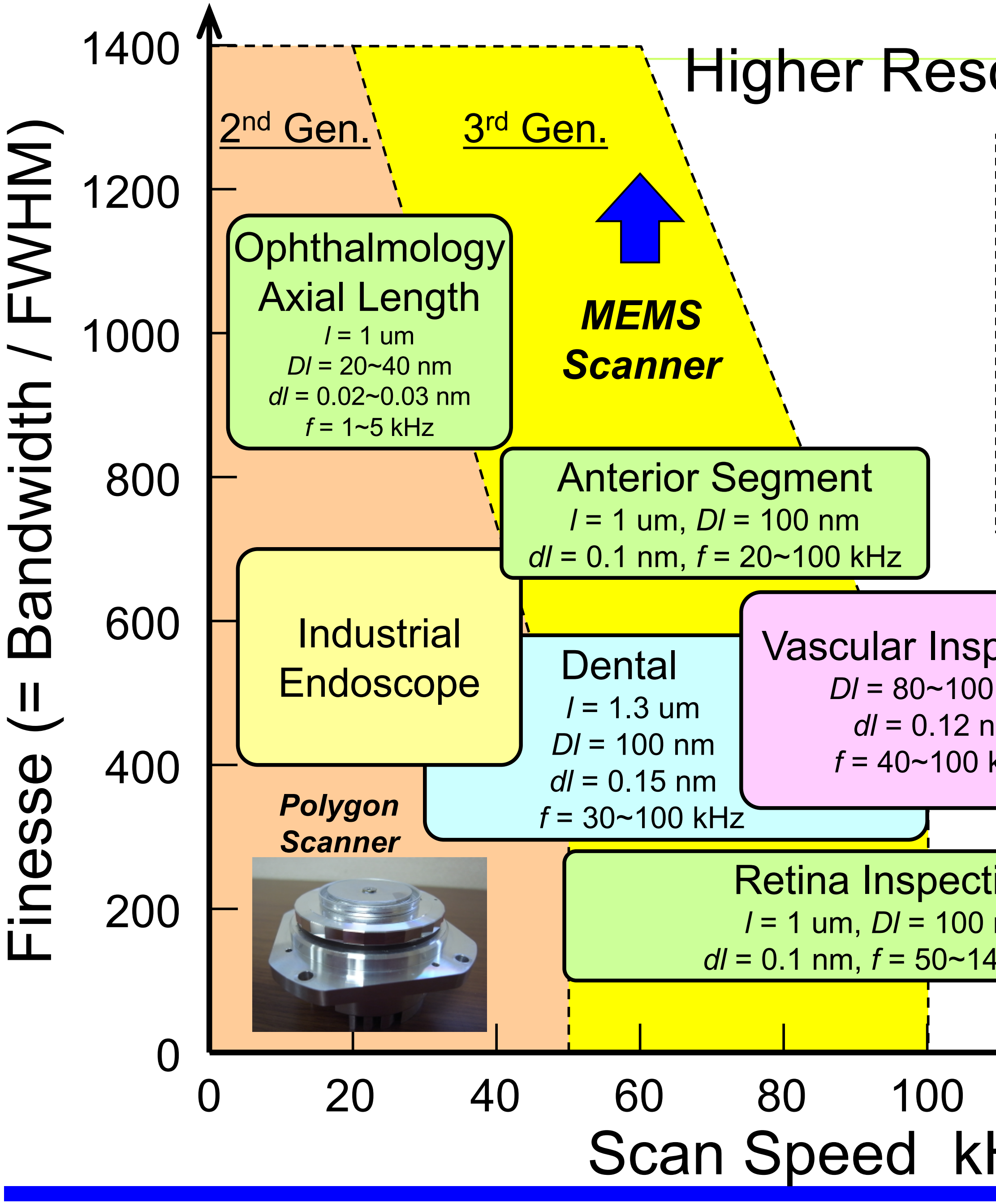




This research is supported by Optoelectronic Industry and Technology Development Association (OITDA), subsidized by JKA through its Promotion funds from KEIRIN RACE.

Wavelength-Tunable Laser for OT



Ophthalmology Axial Length
l = 1 um
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dl = 0.02~0.03 nm
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Industrial Endoscope

Dental
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Dl = 100 nm
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dl = 0.12 nm
f = 40~100 kHz

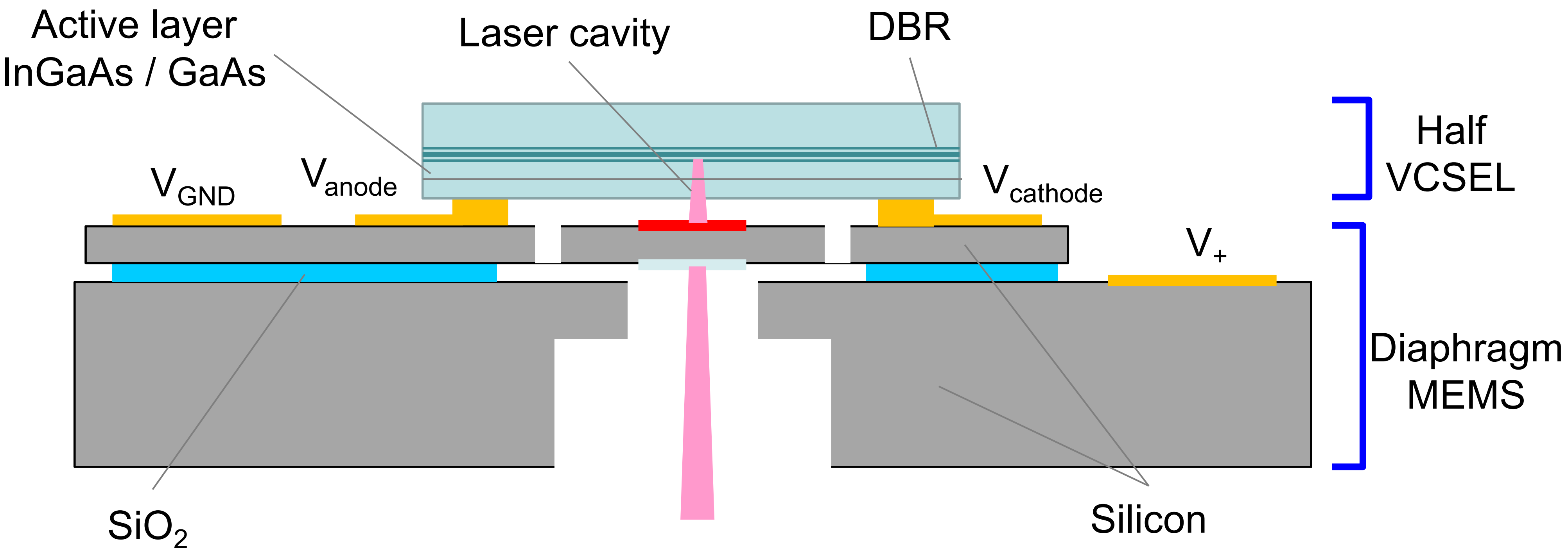
Retina Inspection
l = 1 um, Dl = 100 nm
dl = 0.1 nm, f = 50~140 kHz

Higher Resolution, Faster Imaging

Target : Over 100 kHz

MEMS-based Tunable VCSEL

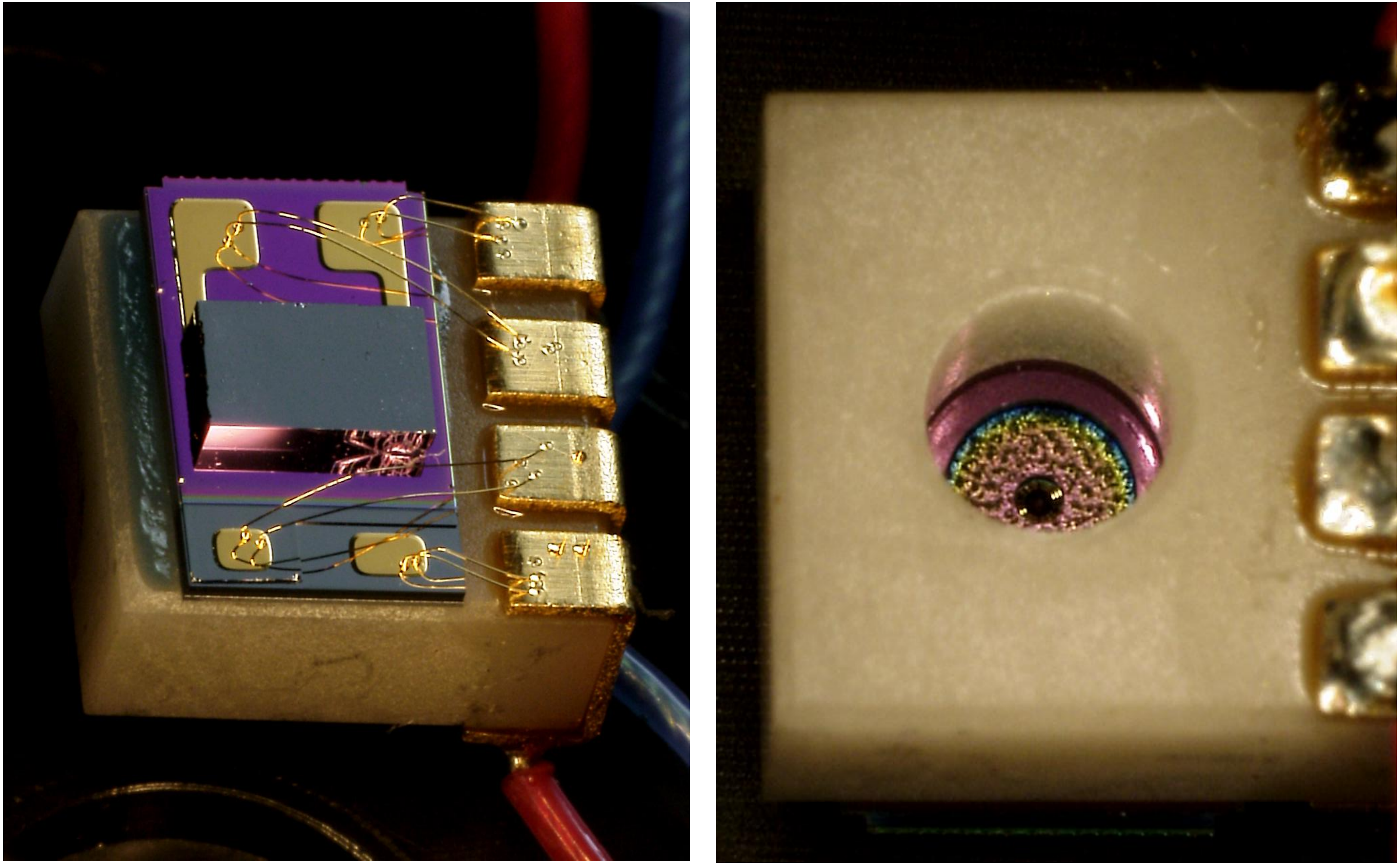
1060 nm wavelength range with InGaAs/GaAs



Keiji Isamoto, Kiyotaka Yamashita, Mohammed Saad Khan, Nicolas Lafitte, Kouki Totsuka, Changho Chong, Nobuhiko Nishiyama, and Hiroshi Toshiyoshi, "A MEMS based electrically pumped tunable VCSEL operating at 1060nm for SS-OCT," SPIE Photonics West 2015 -- MOEMS and Miniaturized Systems XIV --, Feb. 9-12, 2015, The Moscone Center, San Francisco, CA.

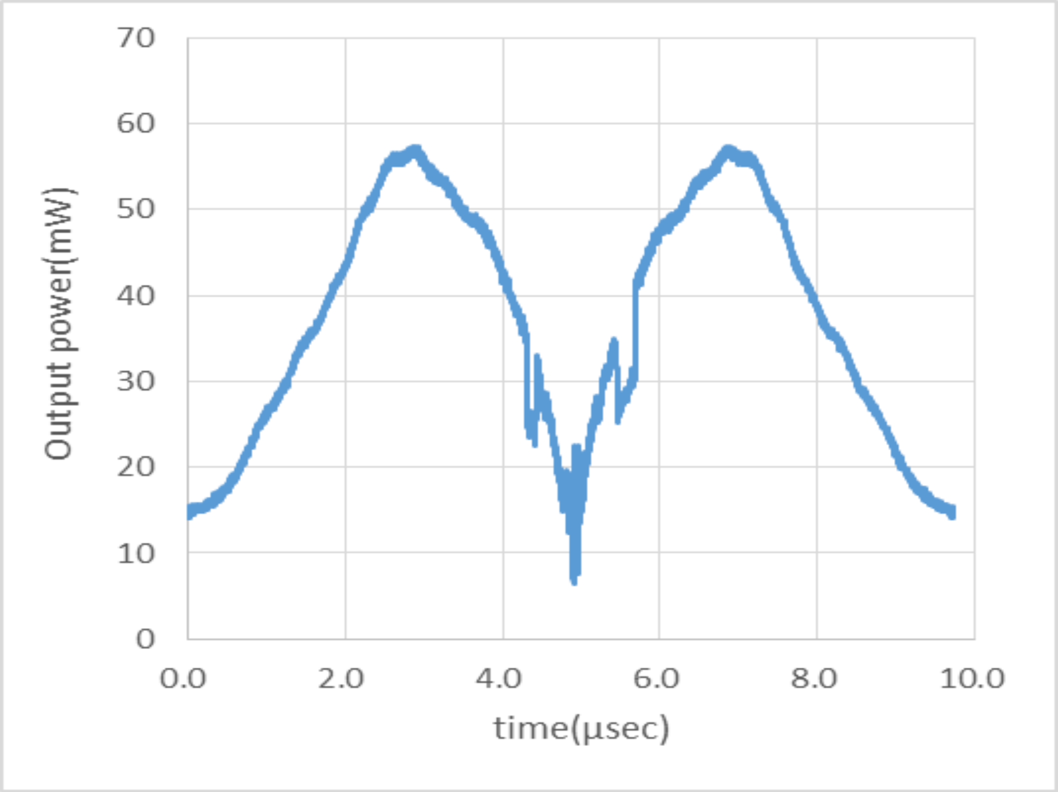
MEMS-based Tunable VCSEL

Device Package (Front / Rear)



Wavelength Tuning Performance

Coherence Length > 100 nm to probe deep inside

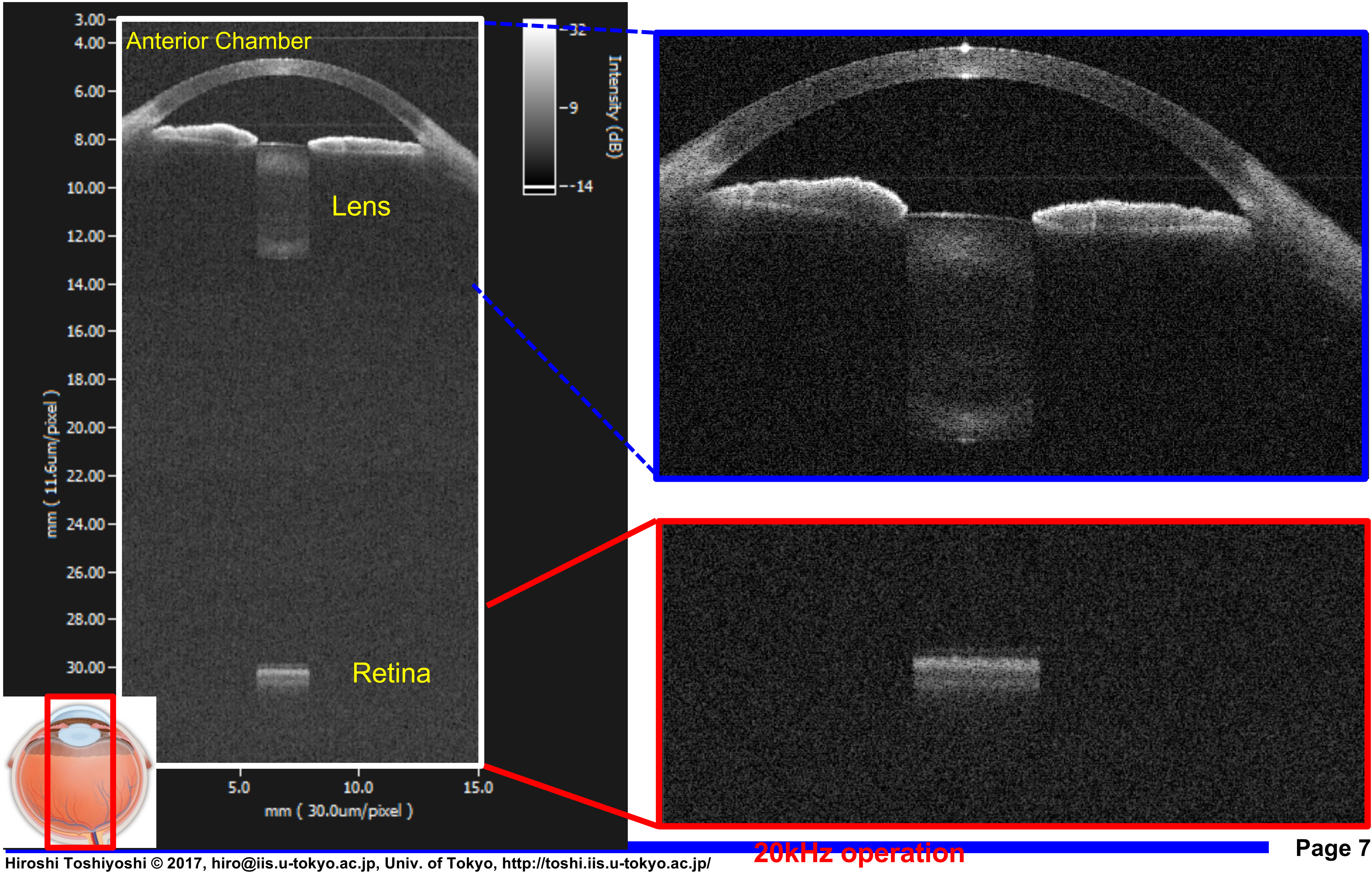


Output Intensity
(Time = Wavelength)

Spec.	Typical
Scan Speed	10 - 200 kHz
Coherence Length	>100 mm
Output Power	40 mW average (2 mW w/o amp)
Wavelength Range	80 nm

Benefits of Long Coherence Length

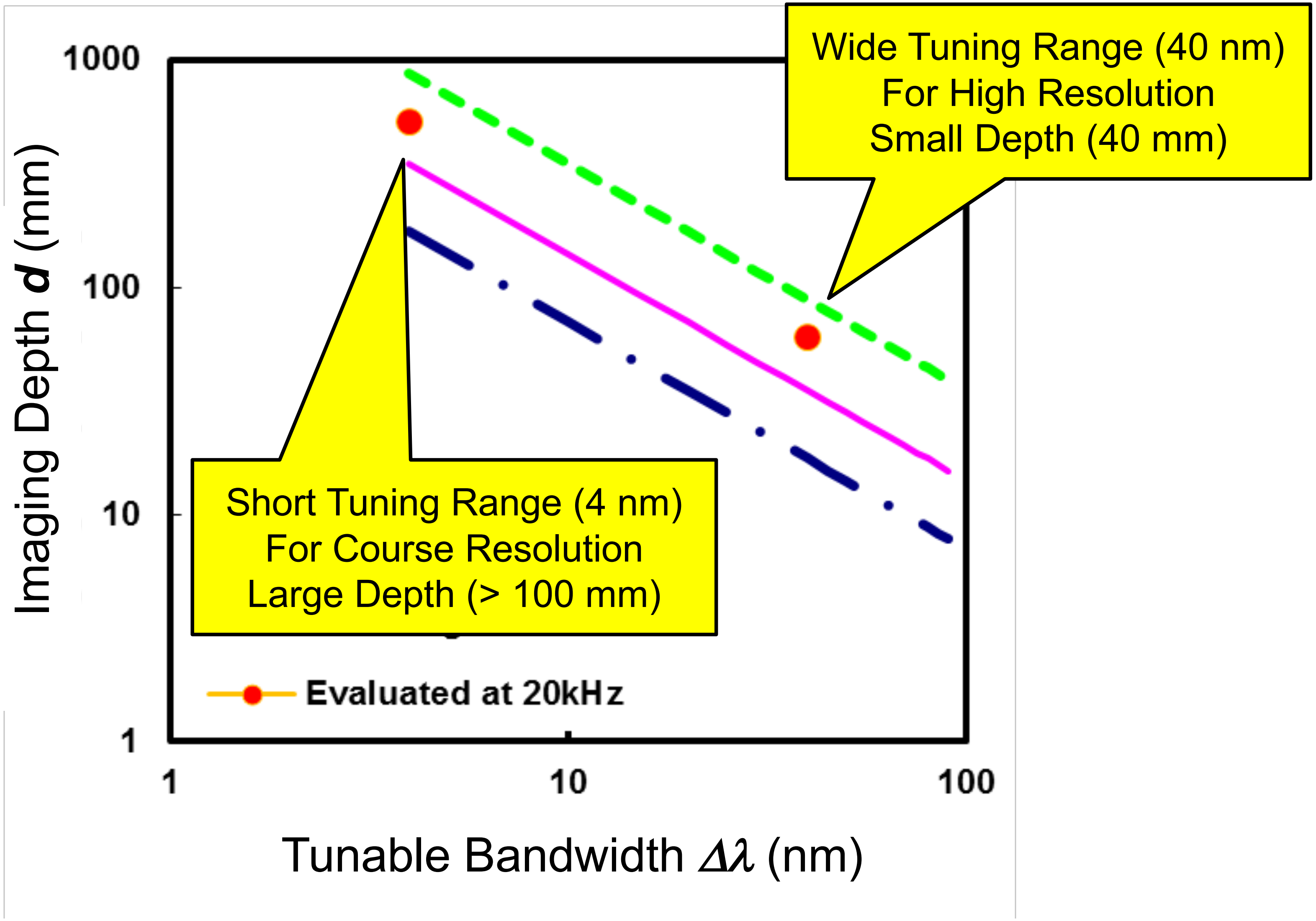
Visualizing Long Distance … in particular for ophthalmologic examination



20kHz operation

Imaging Depth Scaling

At 500 MHz data sampling with a 50% duty cycle

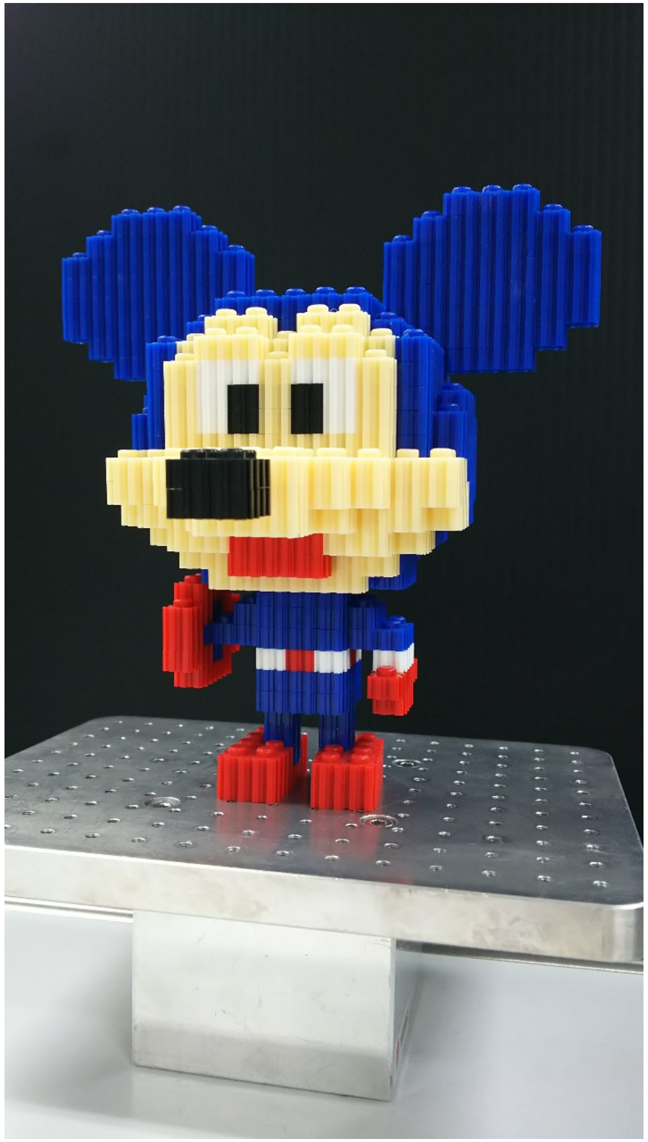


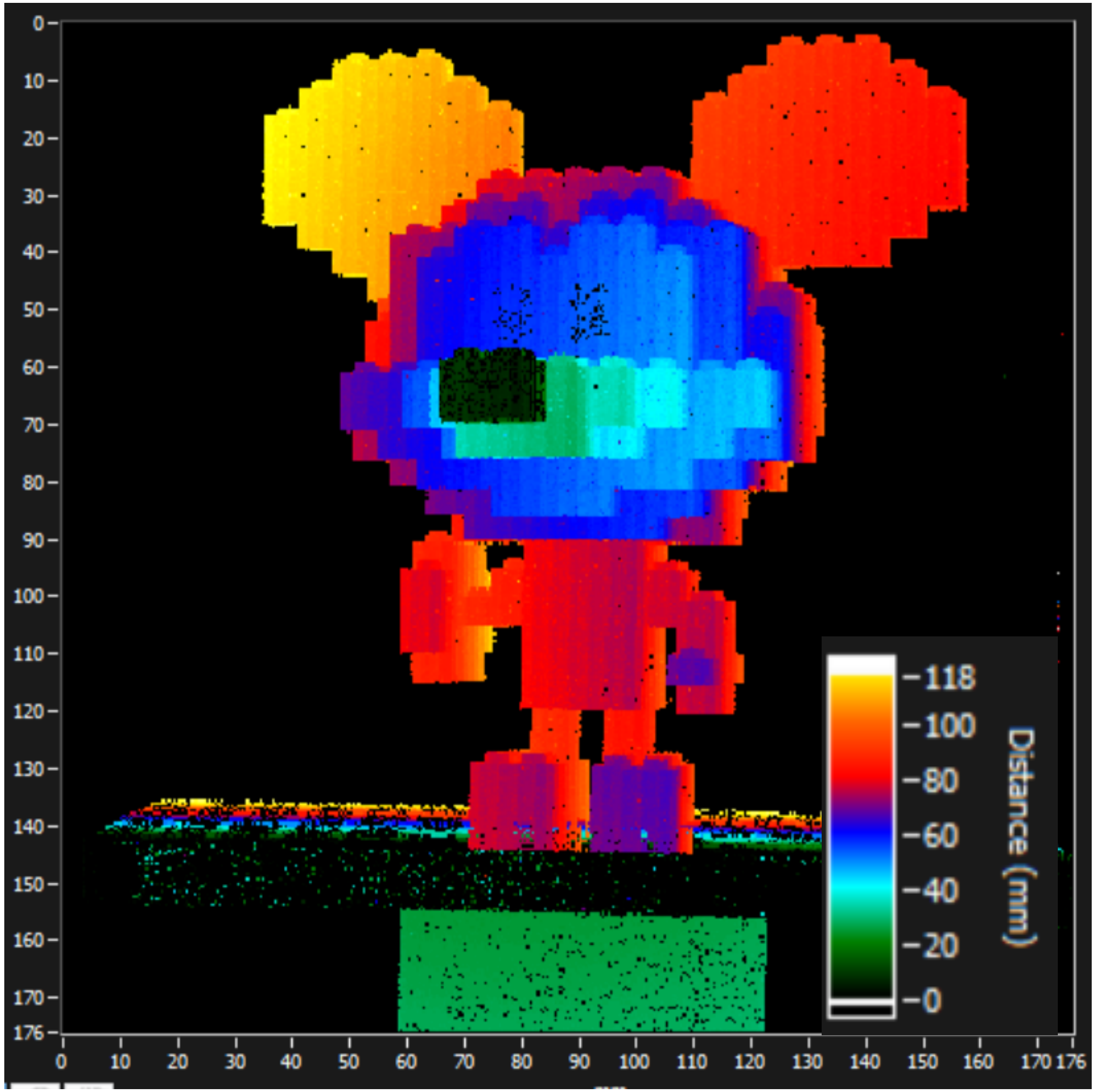
Wide Tuning Range (40 nm)
For High Resolution
Small Depth (40 mm)

Short Tuning Range (4 nm)
For Course Resolution
Large Depth (> 100 mm)

OCT over a Distance (~ 1 m)

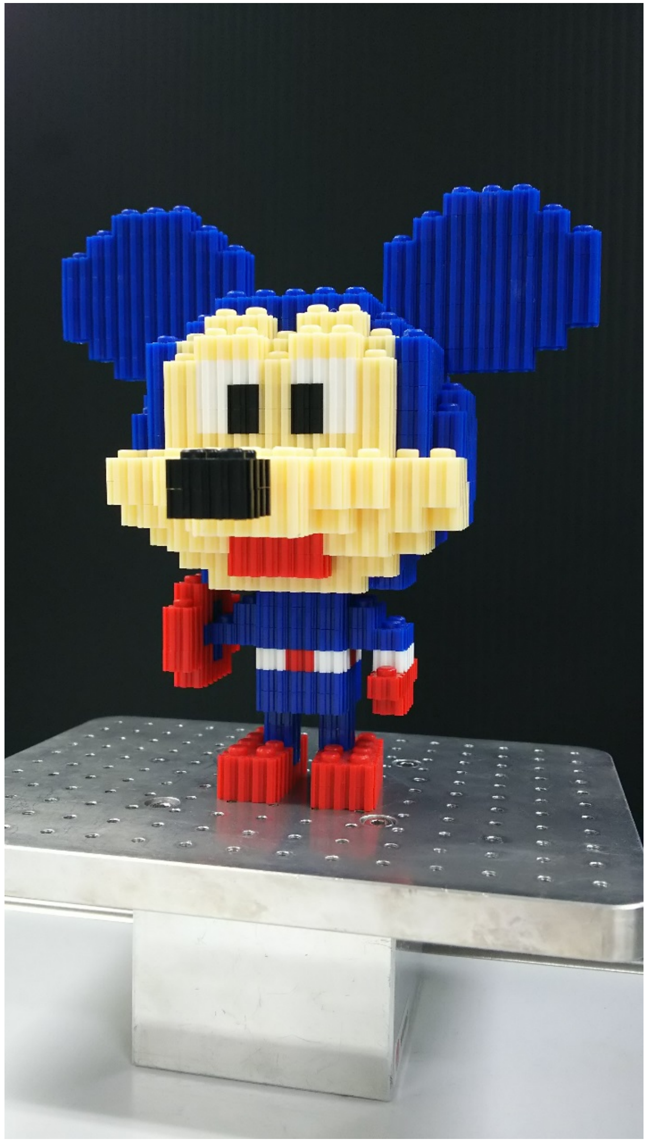
$\Delta\lambda = 4$ nm → ***d*** ~ 10 cm

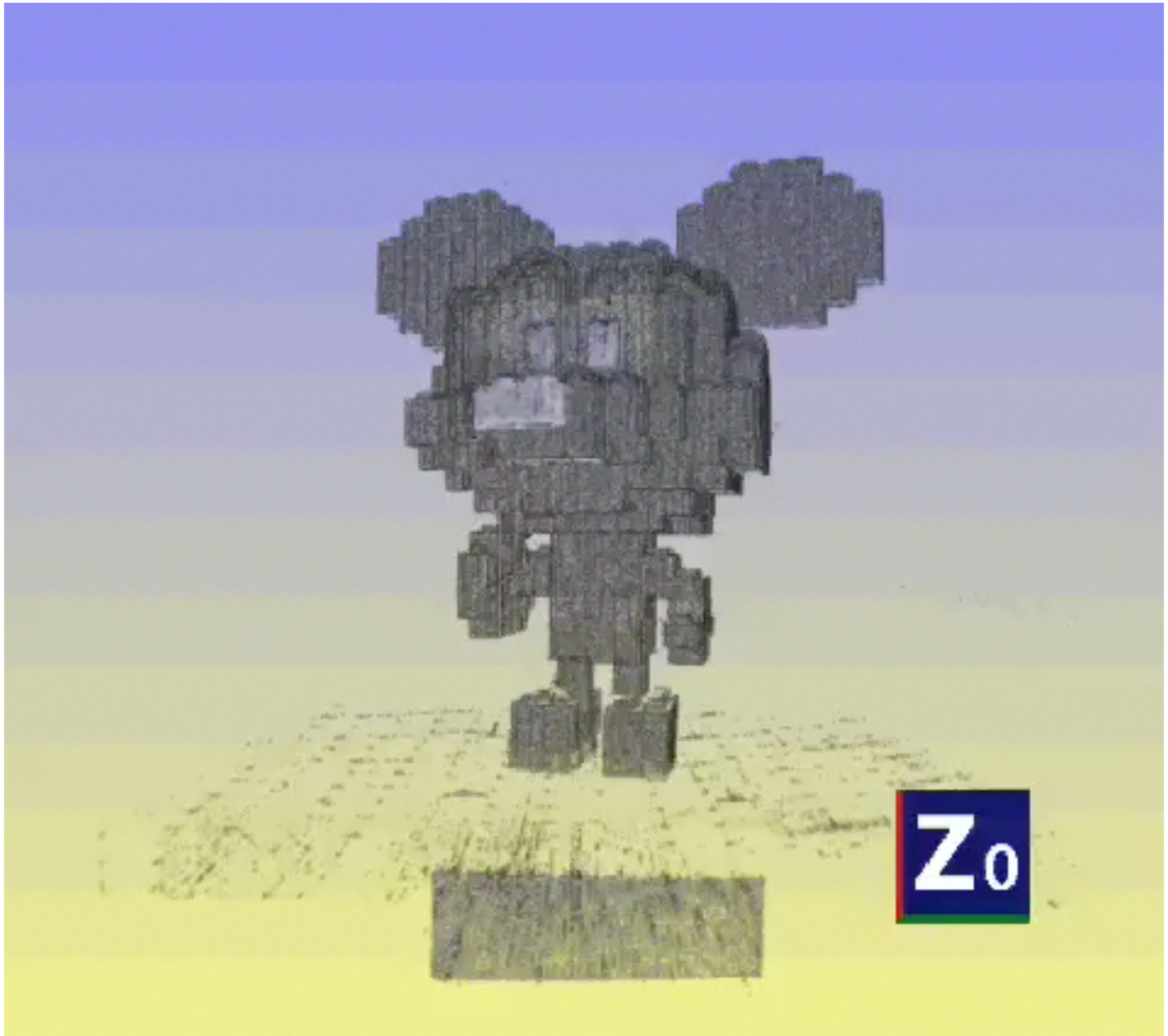




OCT over a Distance (~ 1 m)

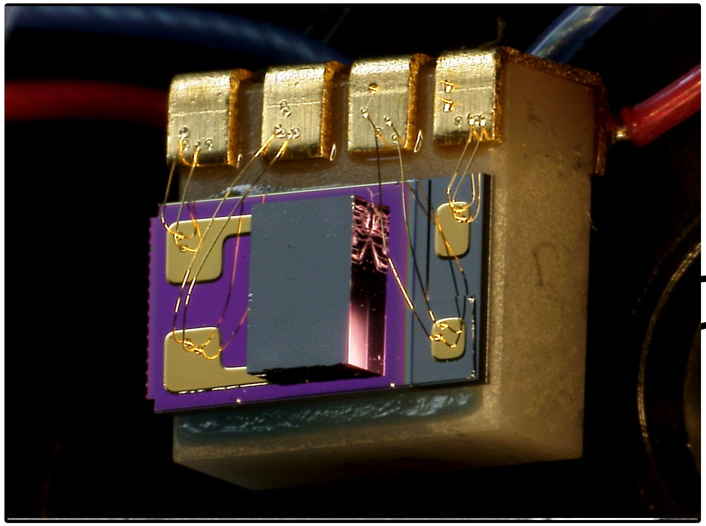
$\Delta\lambda = 4$ nm → $\boldsymbol{d} \sim 10$ cm

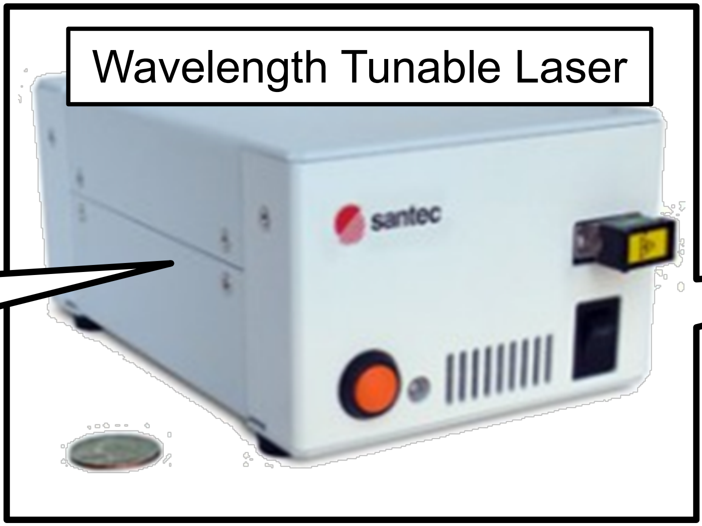




Overall OCT System Performance

	Experimental Results	Note
Scan Speed	140 kHz	Round-Trip Scan
Band Width	100 nm	1310 nm (in Air)
OCT Resolution	9 µm	
Spectrum Width	0.25 nm	
Coherence Length	3 mm	
Maximum Power	20 mW	
Dynamic Range	60 dB	





Wavelength Tunable Laser

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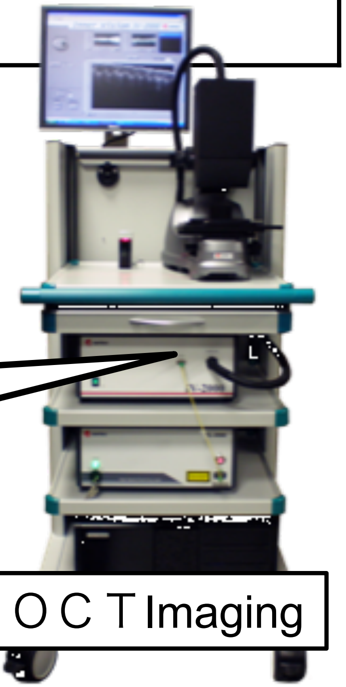
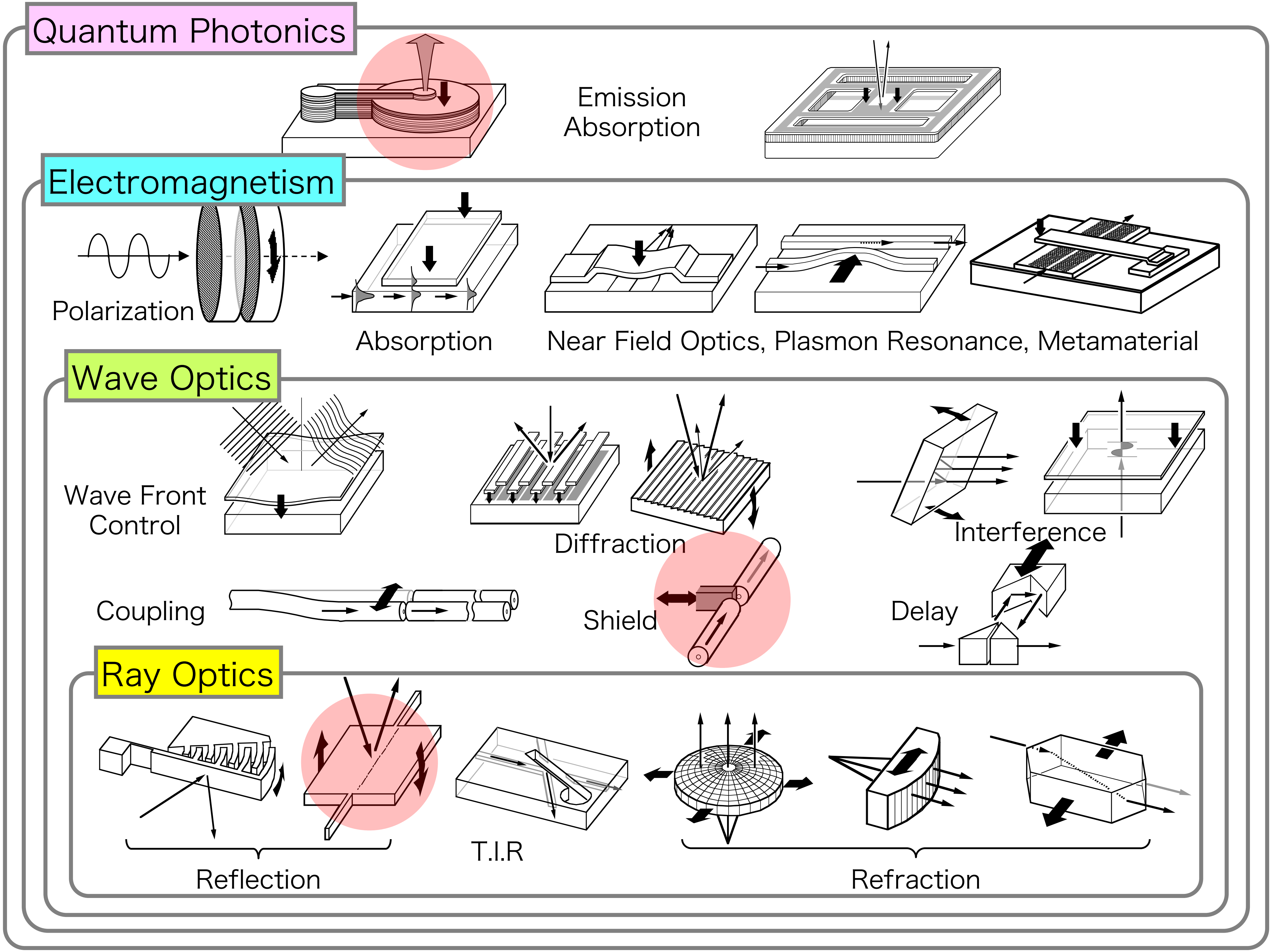


O C T Imaging

Contents Today

1. MEMS = Micro Electro Mechanical Systems
2. µ-Actuator for Astronomy
3. MEMS at the Beginning = Fiber Telecom
4. Theory of Electrostatic Force
5. More Added Values
6. ▶ Summary



Quantum Photonics

Emission
Absorption

Electromagnetism

Polarization

Absorption

Near Field Optics, Plasmon Resonance, Metamaterial

Wave Optics

Wave Front
Control

Diffraction

Interference

Coupling

Shield

Delay

Ray Optics

Reflection

T.I.R

Refraction