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Image Sensors and Spectrometers

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Hamamatsu Corporation

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Agenda

- Spectrometer Introduction
- UV – Visible Image Sensors and Spectrometers
- NIR Spectrometers and InGaAs Image Sensor
- Quest for the “Perfect” Spectrometer
- New and Exciting μ-Spectrometers
- Summary

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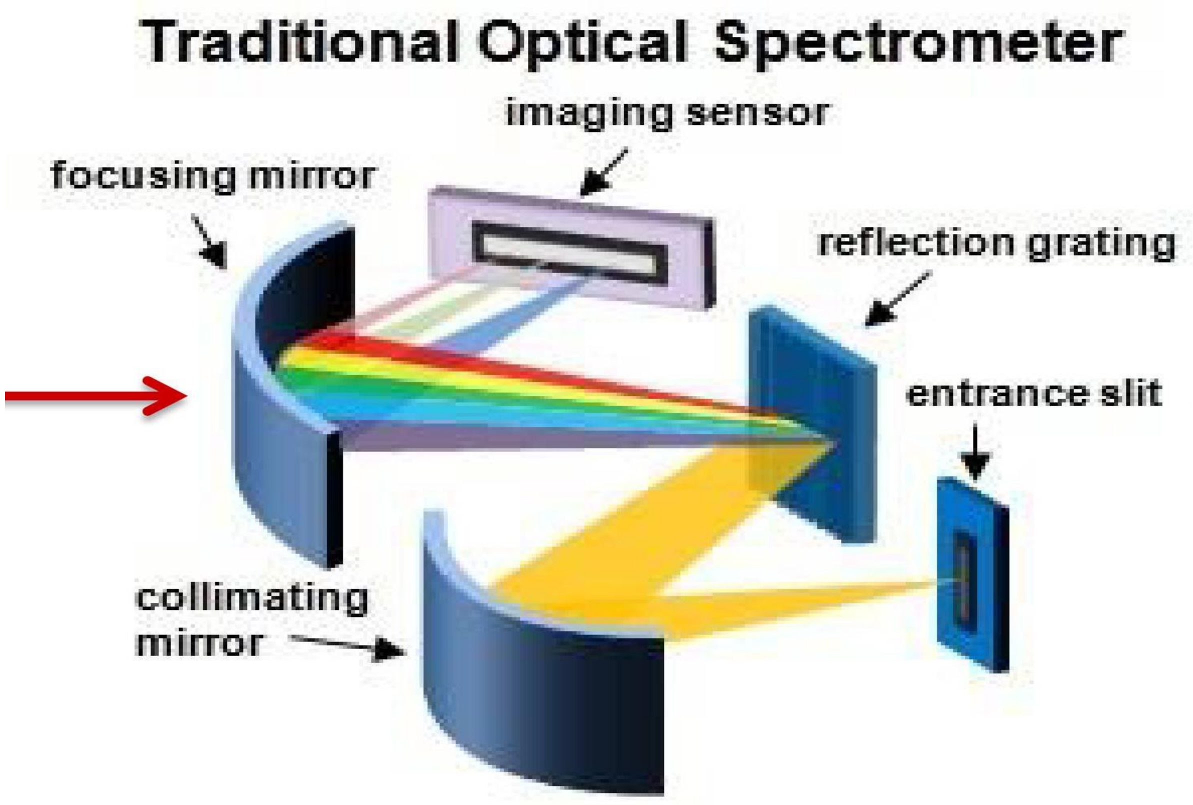
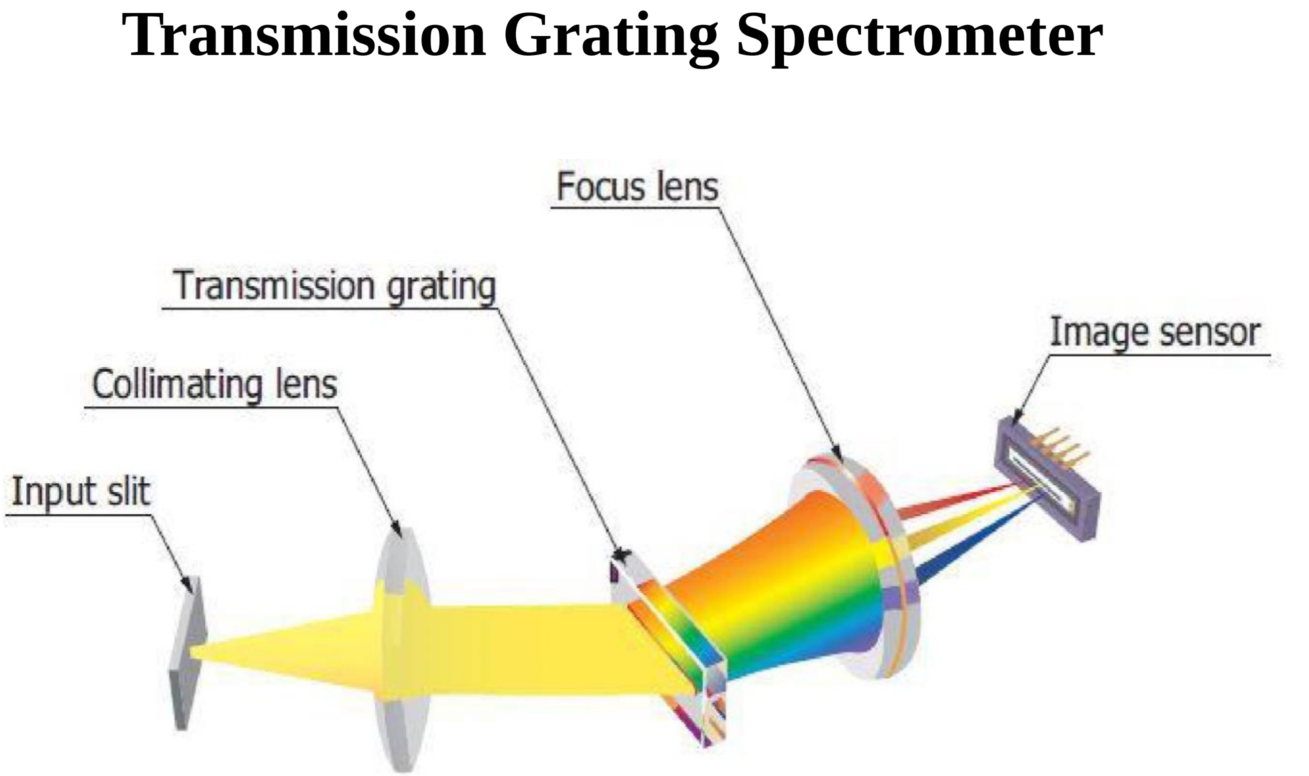
Design of Mini-Spectrometer





Fundamental Building Blocks for Spectrometers

MOEMS Business Promotion

- Semiconductor Technology
- Packaging Technology
- Optical knowledge
- IC and ASIC Technology
- FPGA and Software

M O E M S

M : Micro

O : Opto

E : Electro

M : Mechanical

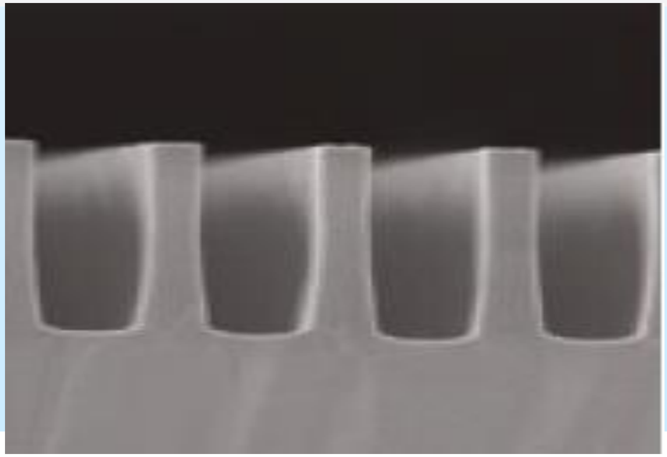
S : System

• MOEMS Technology in Hamamatsu

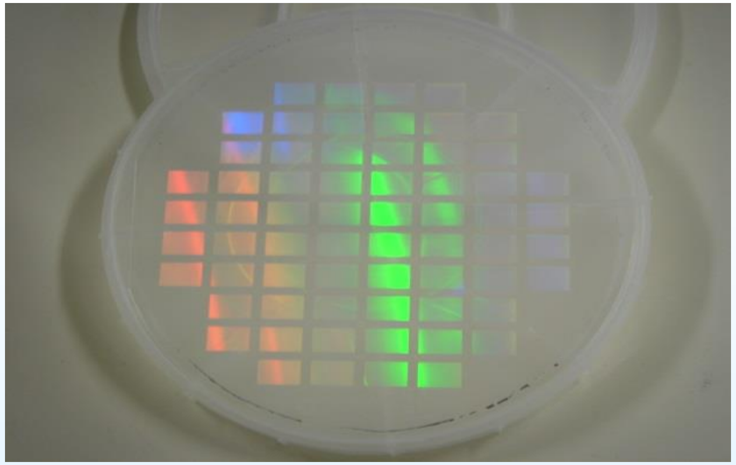
MEMS technologies

Fine processing is used to enhance the functions of optical devices.

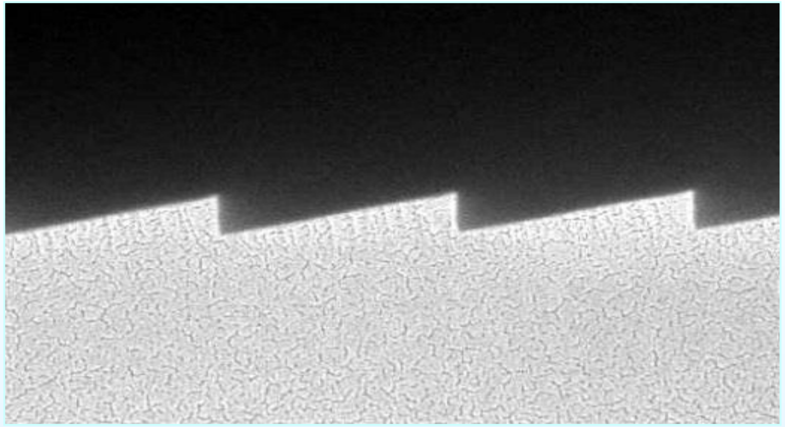
- Etching
- Nanoimprint
- Resist spray coating
- Bonding
- Through-hole electrode



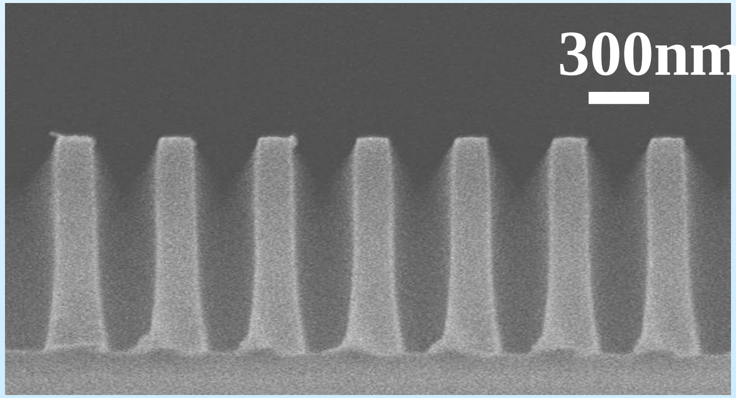
MOEMS for Spectroscopy



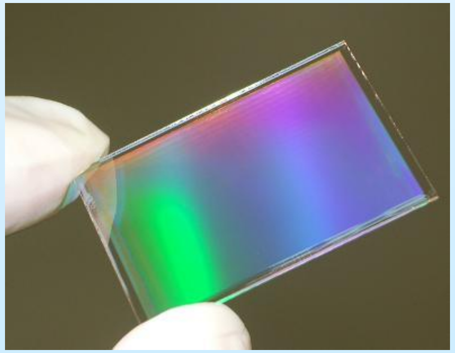
Quartz Grating Wafer

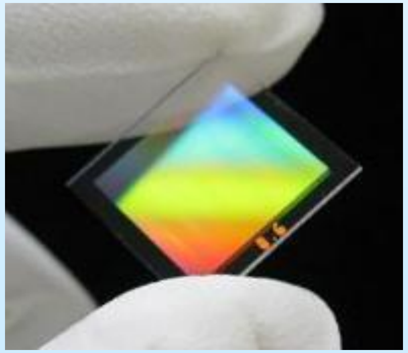


Nanoimprinted Blazed grating



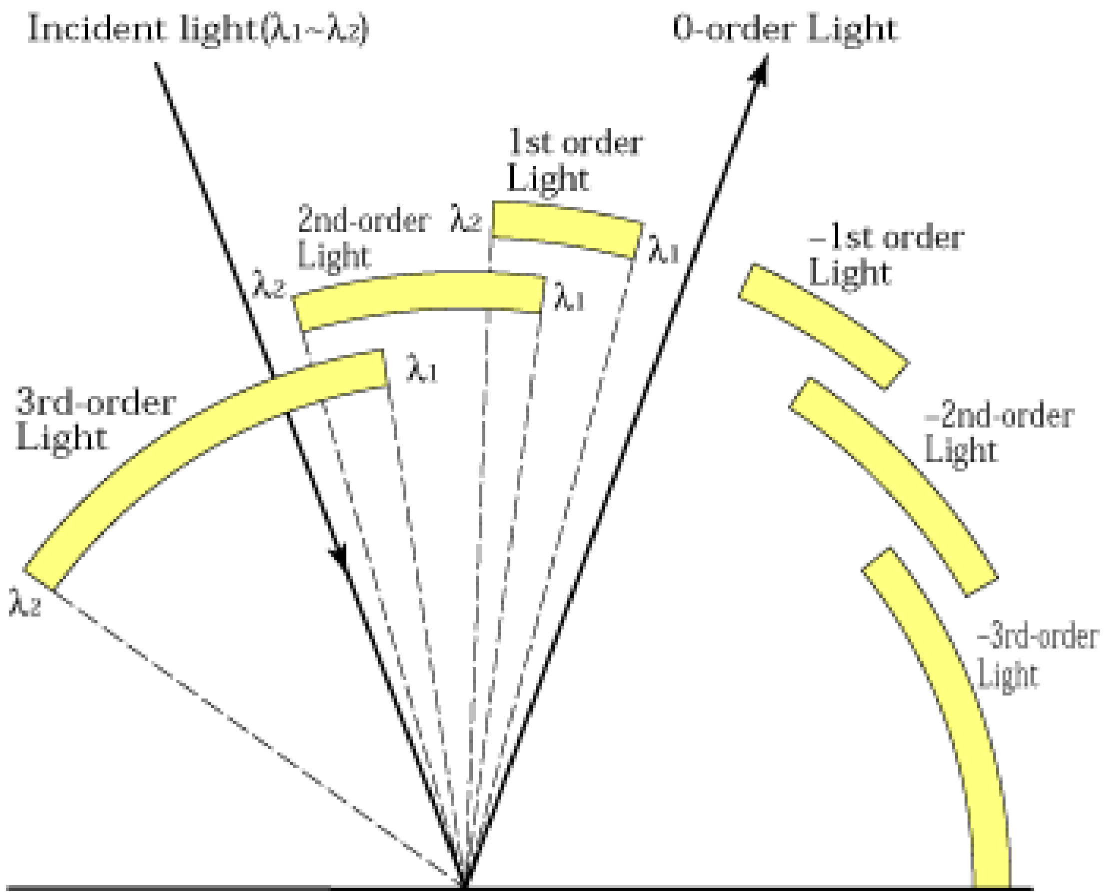
Narrow pitch and High aspect





Example in Grating Spectral Orders

- Multiple emission orders.
- Optical characteristics depend on grating design and fabrication.
  - ✓ Wavelength coverage
  - ✓ Optical resolution
  - ✓ Stray Light
  - ✓ Efficiency



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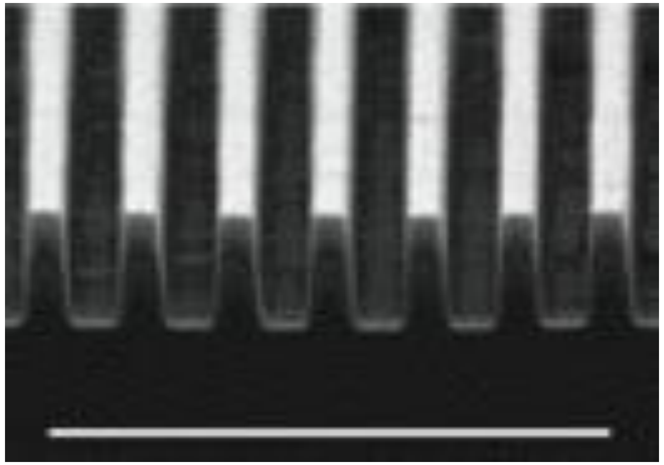
MOEMS & Image Sensor Technologies

MOEMS technology

Gratings for mini-spectrometers (TG/TM series) use a transmission type (made of quartz) fabricated by a HAMAMATSU holographic process.



spectrometer

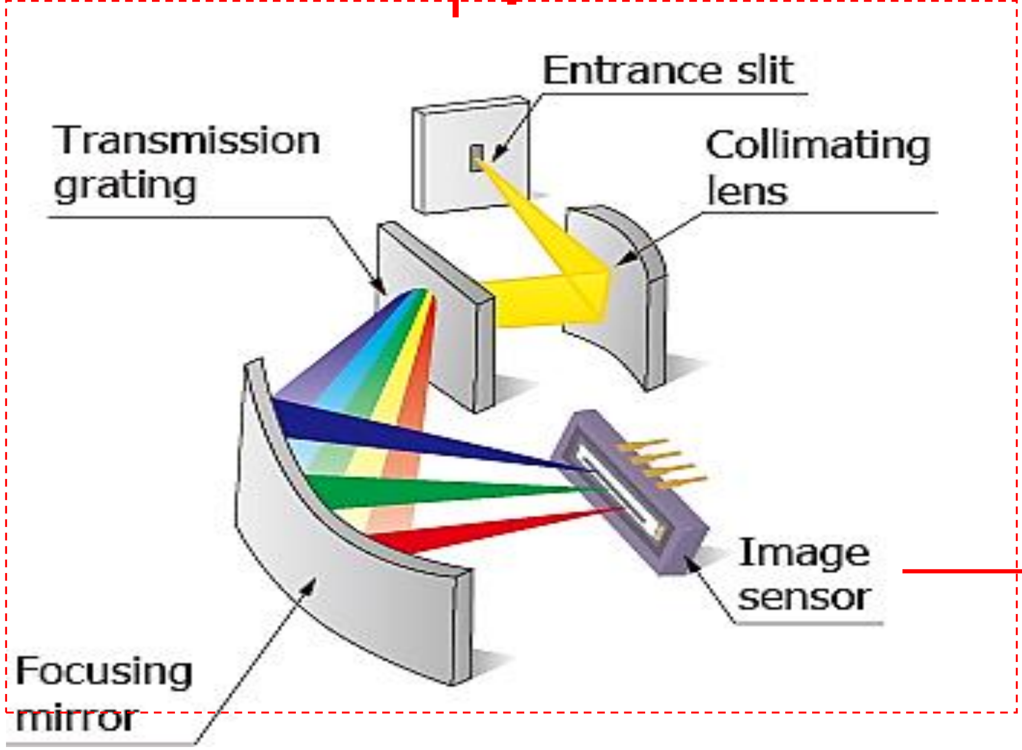
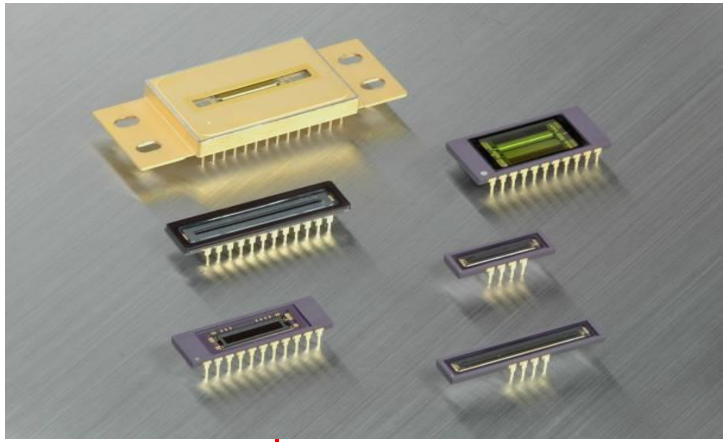


Image sensor technology

The detector that is the heart of the mini-spectrometer is a HAMAMATSU image sensor.



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Mini-spectrometer

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Market Challenges

- **Spectrometers**
  - ✓ **Demands for high precision, scientific instrument.**
    - ➢ **Linearity, stray light, wavelength and repeatability.**
  - ✓ **Moving the instrument to the sample, portability.**
  - ✓ **Broad wavelength coverage, UV – MID IR.**
  - ✓ **Flat response, consistent Signal to Noise ratio.**
  - ✓ **High speed operation, electronic shutter with gating capability.**
  - ✓ **UV hardness, reliability and lifetime.**

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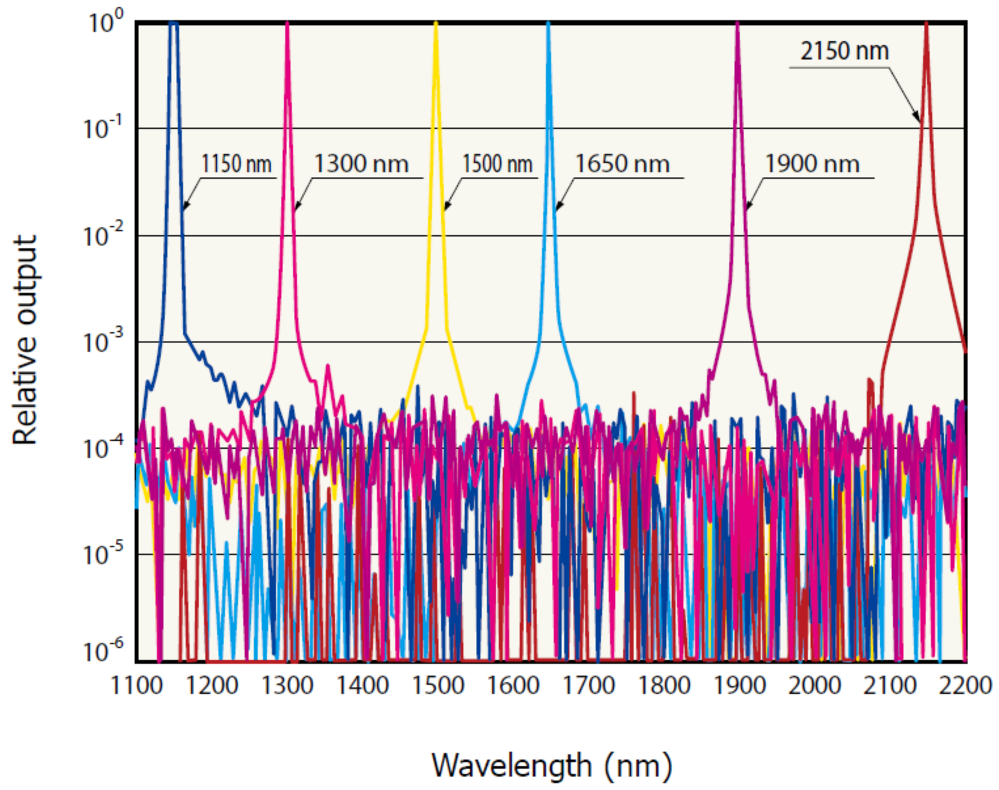
Spectrometers for Spectroscopy Applications

- High sensitivity
- Rectangular active area
- Low noise, for low light applications
- Large saturation charge, wide dynamic range.
- Optical resolution.
- Stray light performance.



Example of NIR Spectrometer Stray Light

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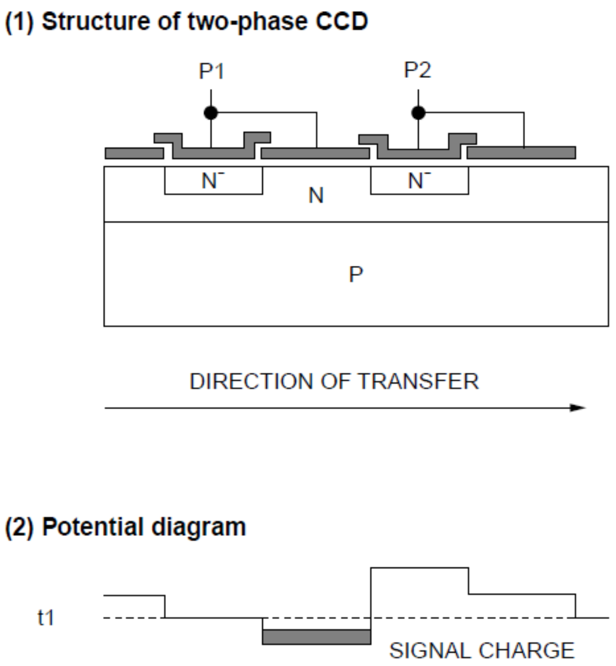
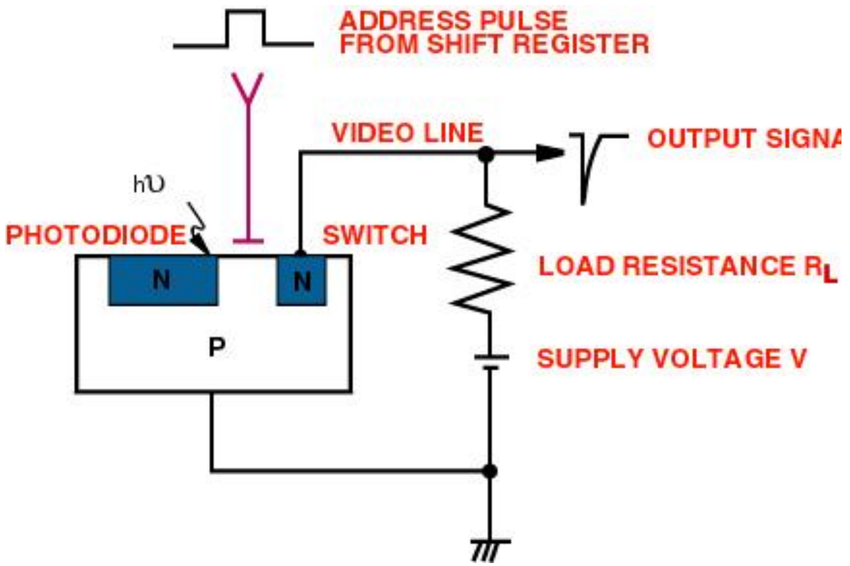
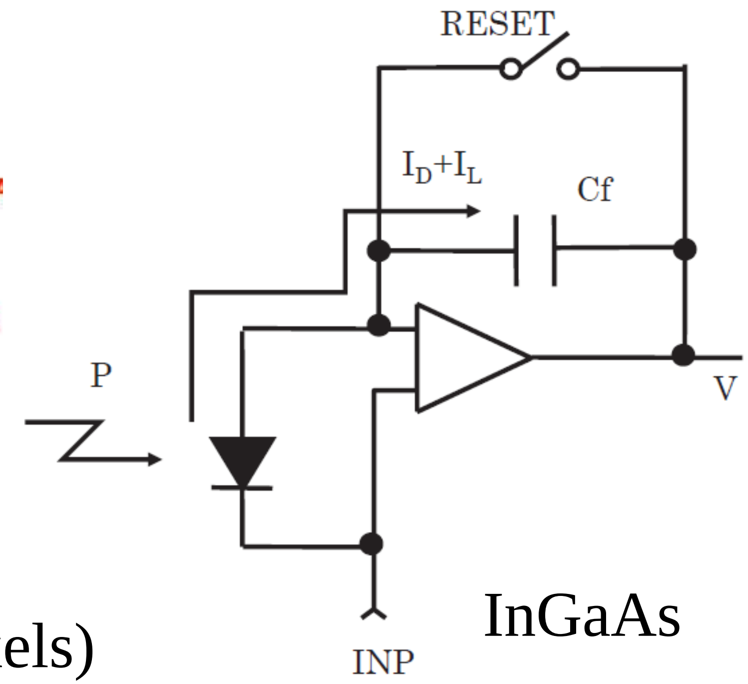
Image Sensor Operating Principle



Charged Coupled Device (CCD)



CMOS (Passive & Active Pixels)



InGaAs

$$Q = CV = \int_{t0}^{t1} I(t)dt$$

$$\mathbf{Q = CV = I * \Delta t}$$

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Consumer and Scientific image sensors

- **Consumer image sensors**

  Digital camera, Mobile phone’s camera

  > small pixel size, narrow dynamic range
  > high sensitivity in visible
  > low price and mass production efficiency

- **Scientific image sensors**

  Analytical and measuring equipment, Industrial camera

  > larger pixel size, wider dynamic range
  > high sensitivity from UV to NIR
  > high accuracy and good linearity

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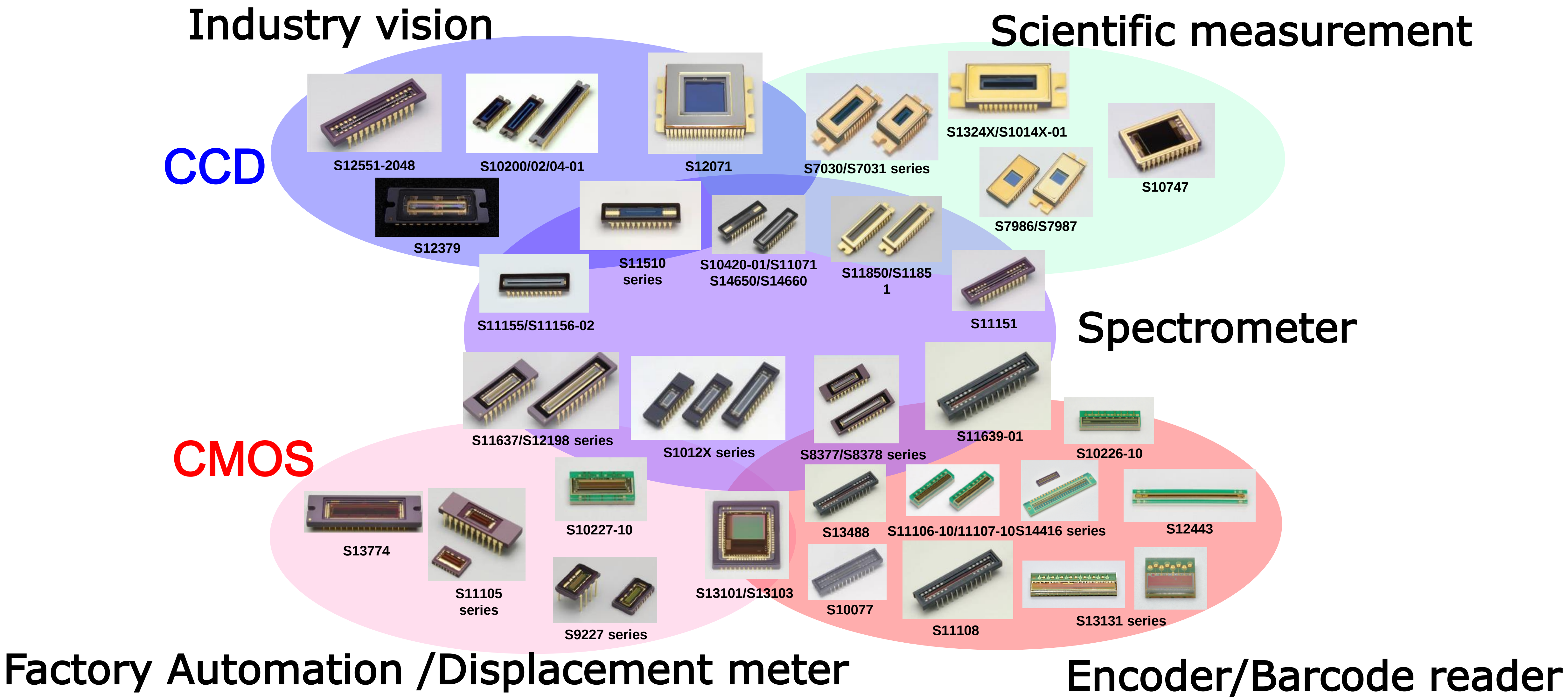
CCD / CMOS image sensors



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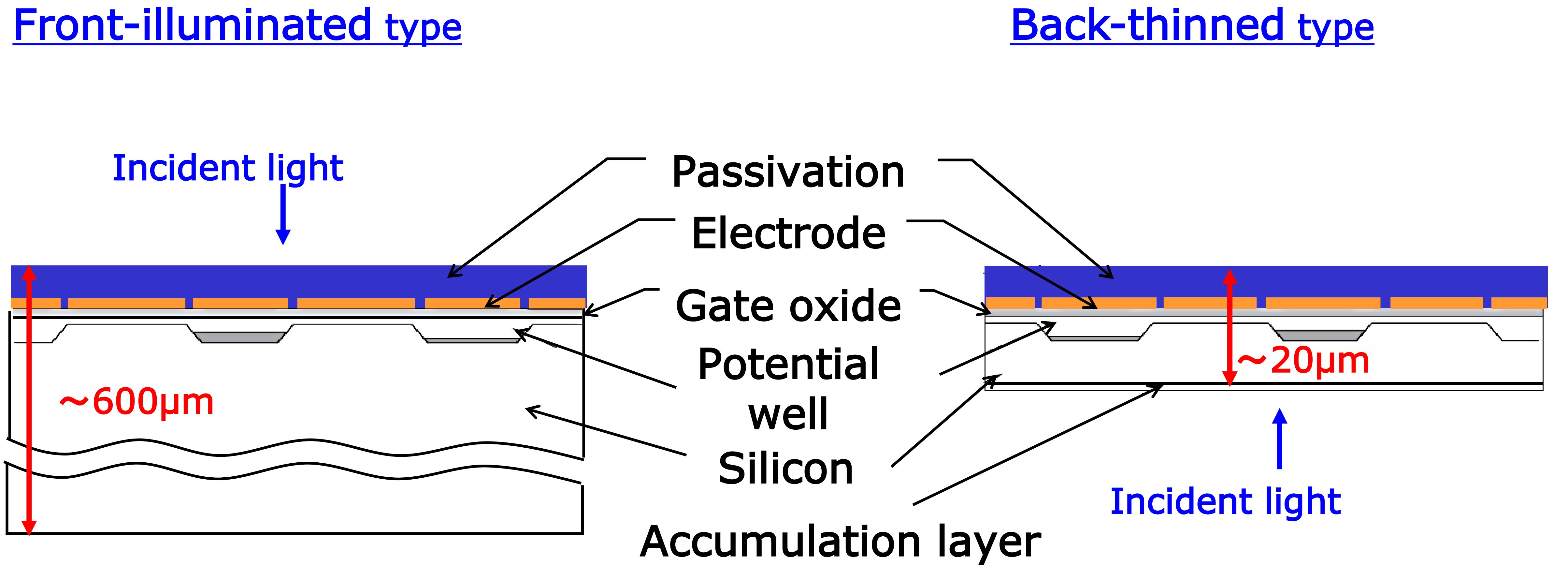
Market Demand ~ High Sensitivity (QE X Gain)



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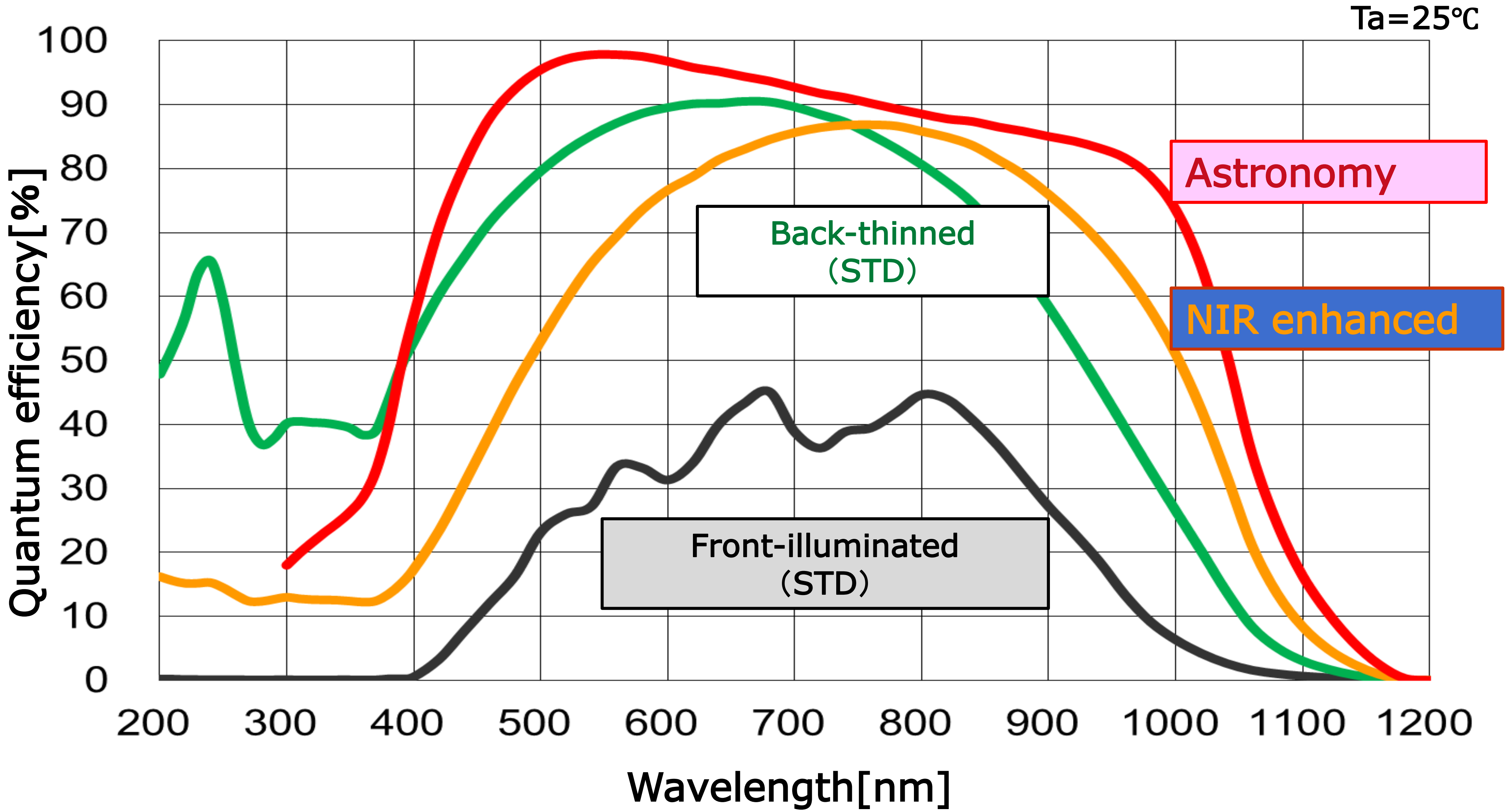
Visible - NIR Sensitivity Enhanced CCD



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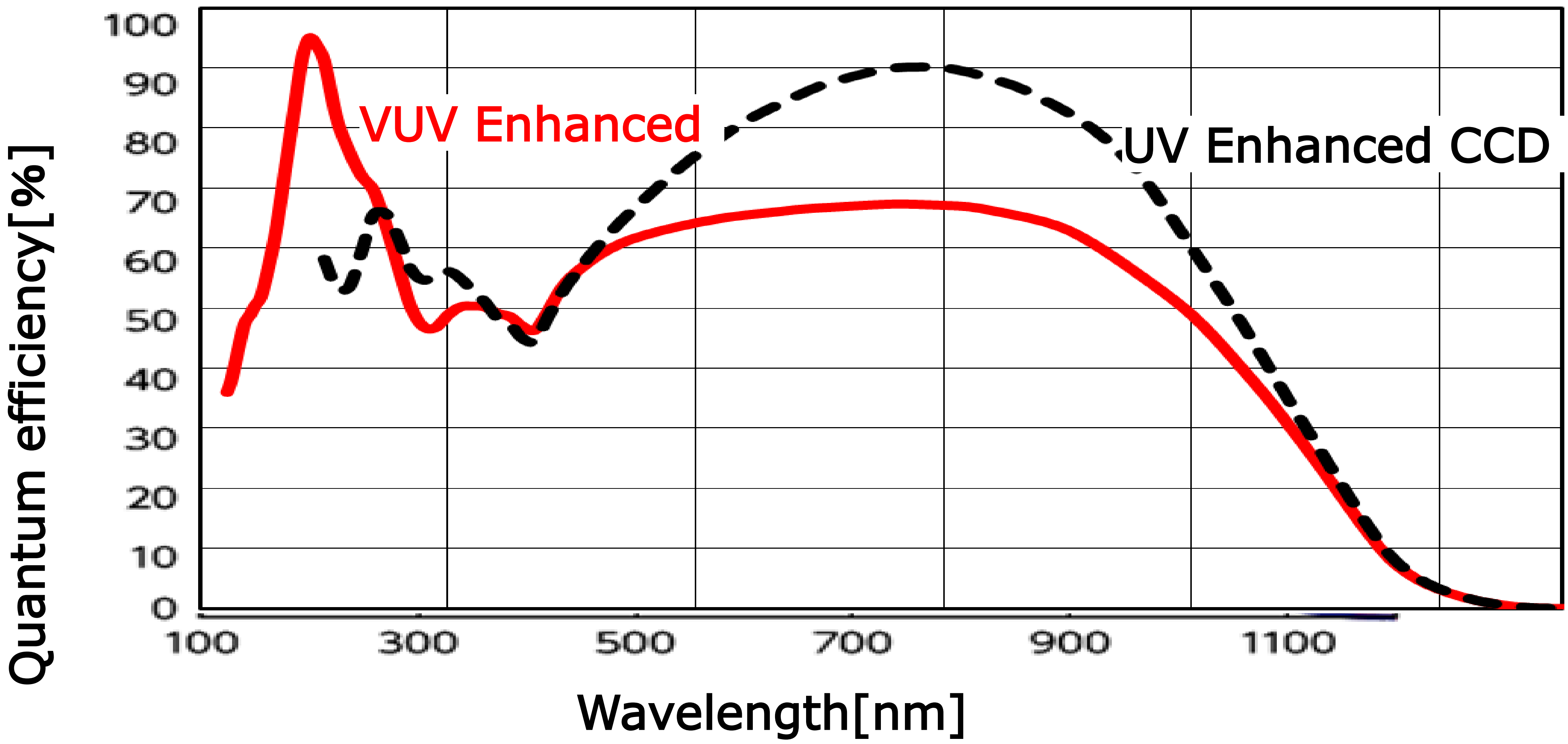
High VUV sensitivity CCD



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Market Demand ~ Reliability and Lifetime

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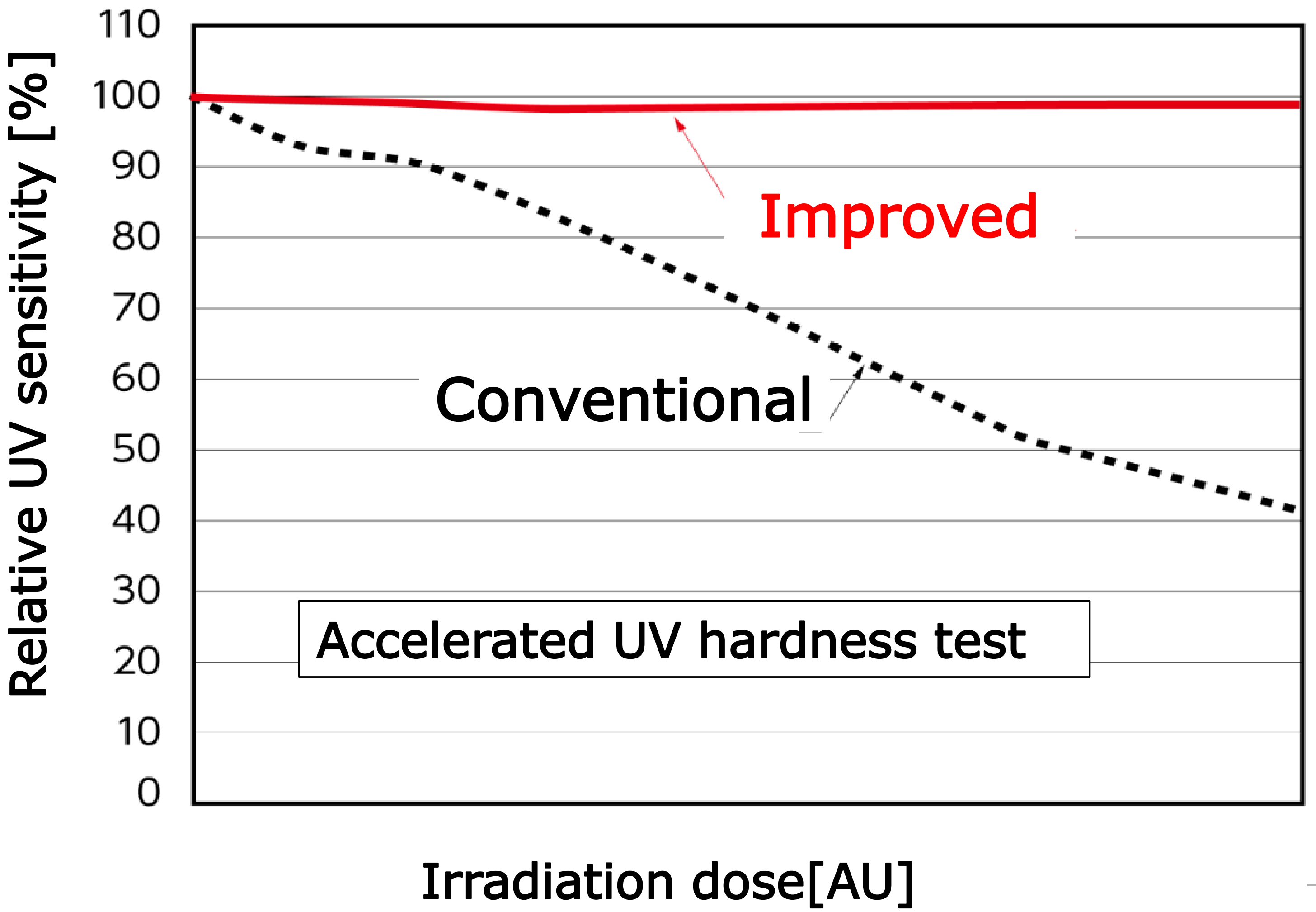
High VUV sensitivity and reduced sensitivity deterioration by UV irradiation



Application (example)

- Water Analysis
- Excimer wavelength monitor
- Semiconductor
- Film Properties
- Spectroscopic measurement (liquid chromatography)

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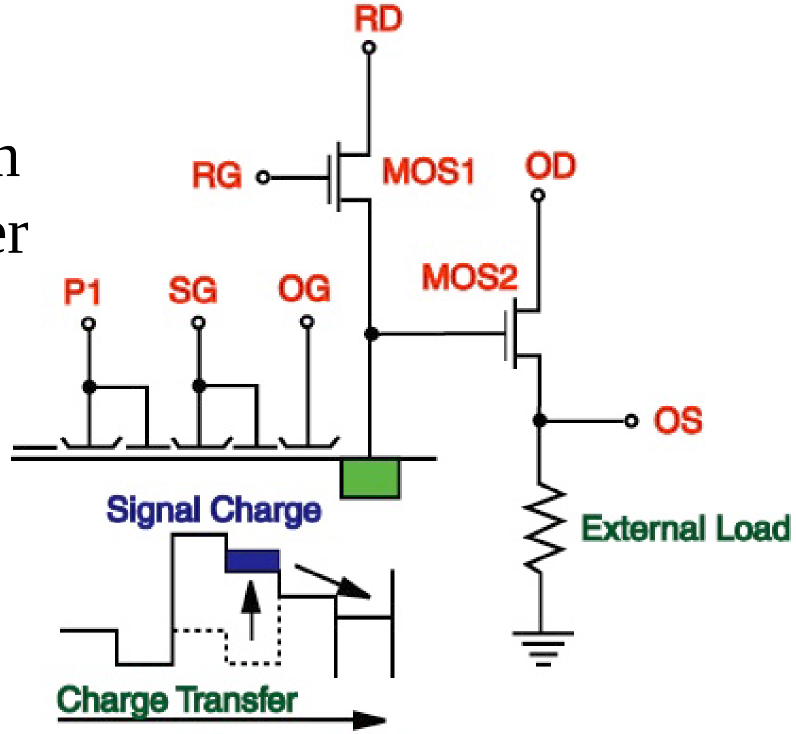
Why are CCD's low light champions? Three reasons - #1 Amplifier Noise

Floating Diffusion Amplifier (FDA)



Output Voltage

$$\Delta V_o = \frac{(A_v \times q)}{C_{fd}}$$

CCD Node Sensitivity

$$S_v = 1.6\times10^{-19}\left[\frac{\Delta V_o}{A_v}\right]\ \mathrm{V/e}$$

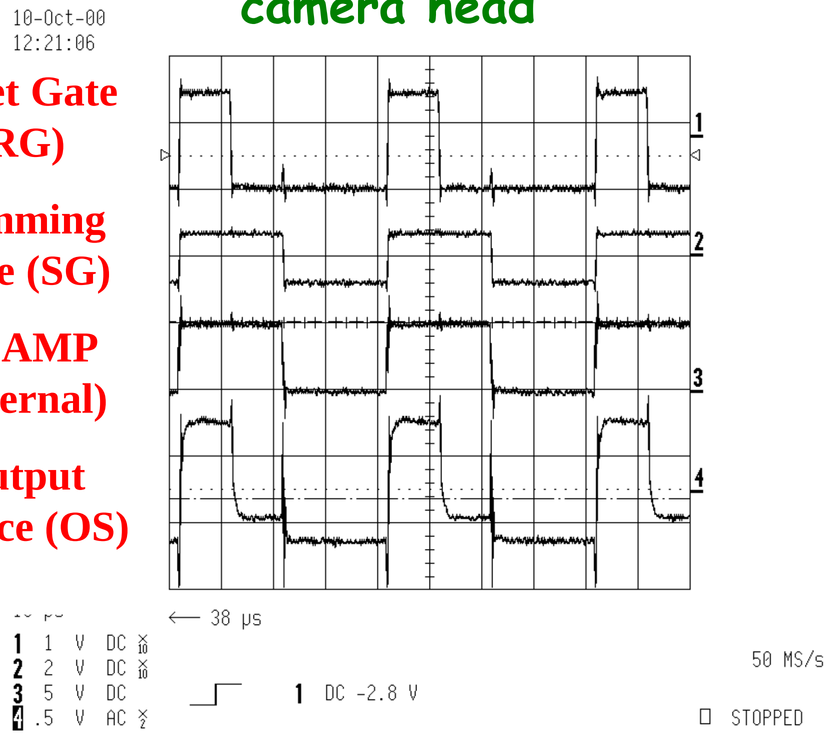
Output Waveforms using camera head

Reset Gate (RG)

Summing Gate (SG)

CLAMP (external)

Output Source (OS)



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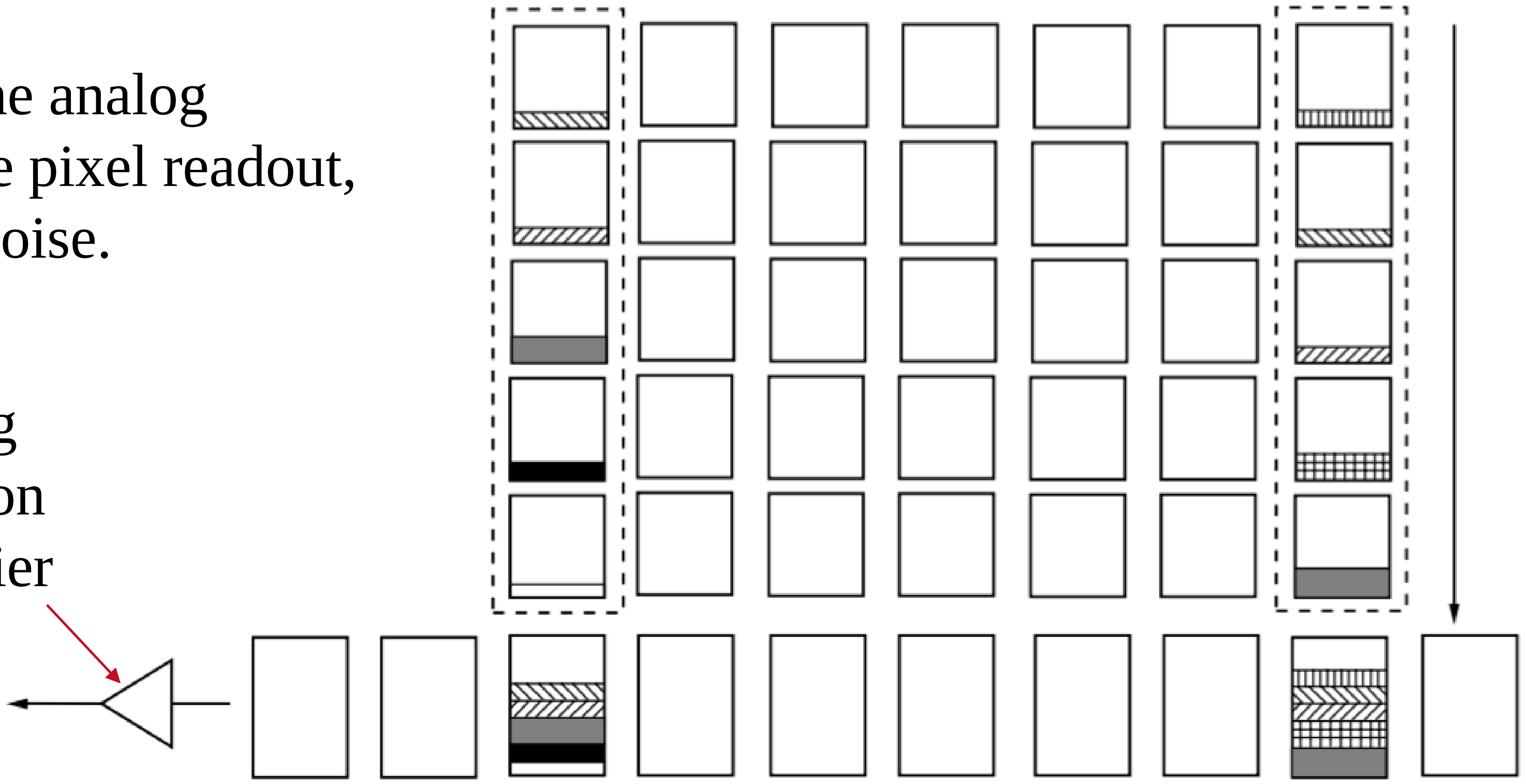
Reason #2 - CCD Vertical Line Binning Operation

(1) Signal flow

Summing in the analog domain, before pixel readout, reduces total noise.

Floating Diffusion Amplifier (FDA)



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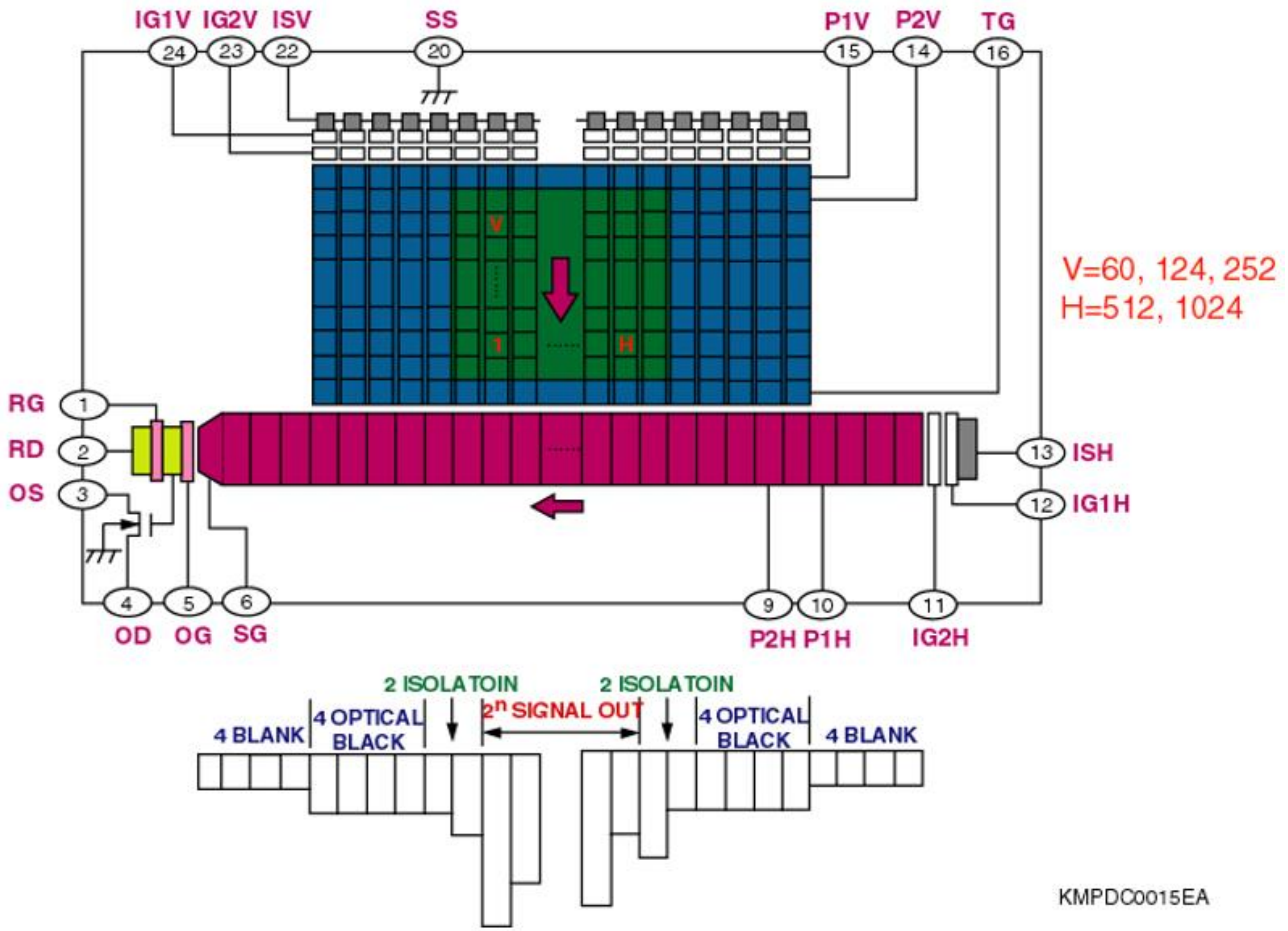
CCD Device Structure

- Full Frame Transfer (FFT-CCD).
- Readout on the order of mSec (1-10mSec).



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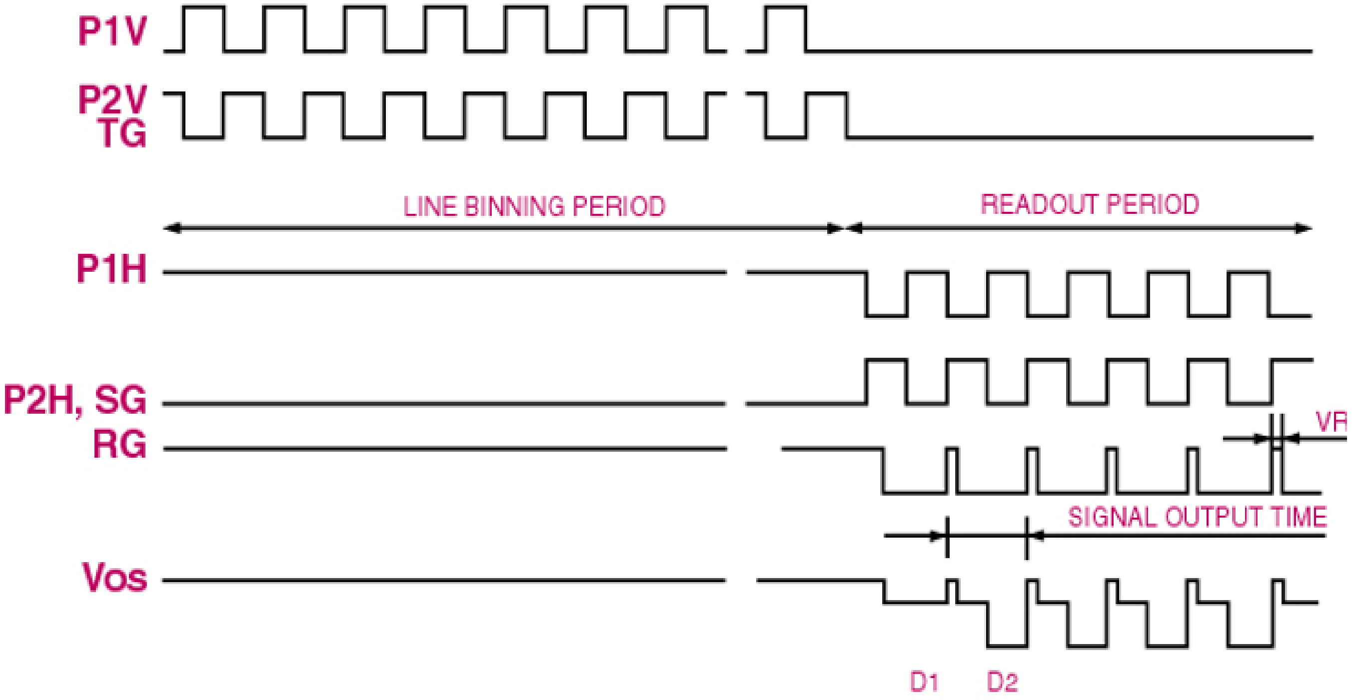
CCD Line Binning Timing Chart

- Readout time determines spectrometers minimum exposure time.



Reason #3 – High QE and high conversion gain.

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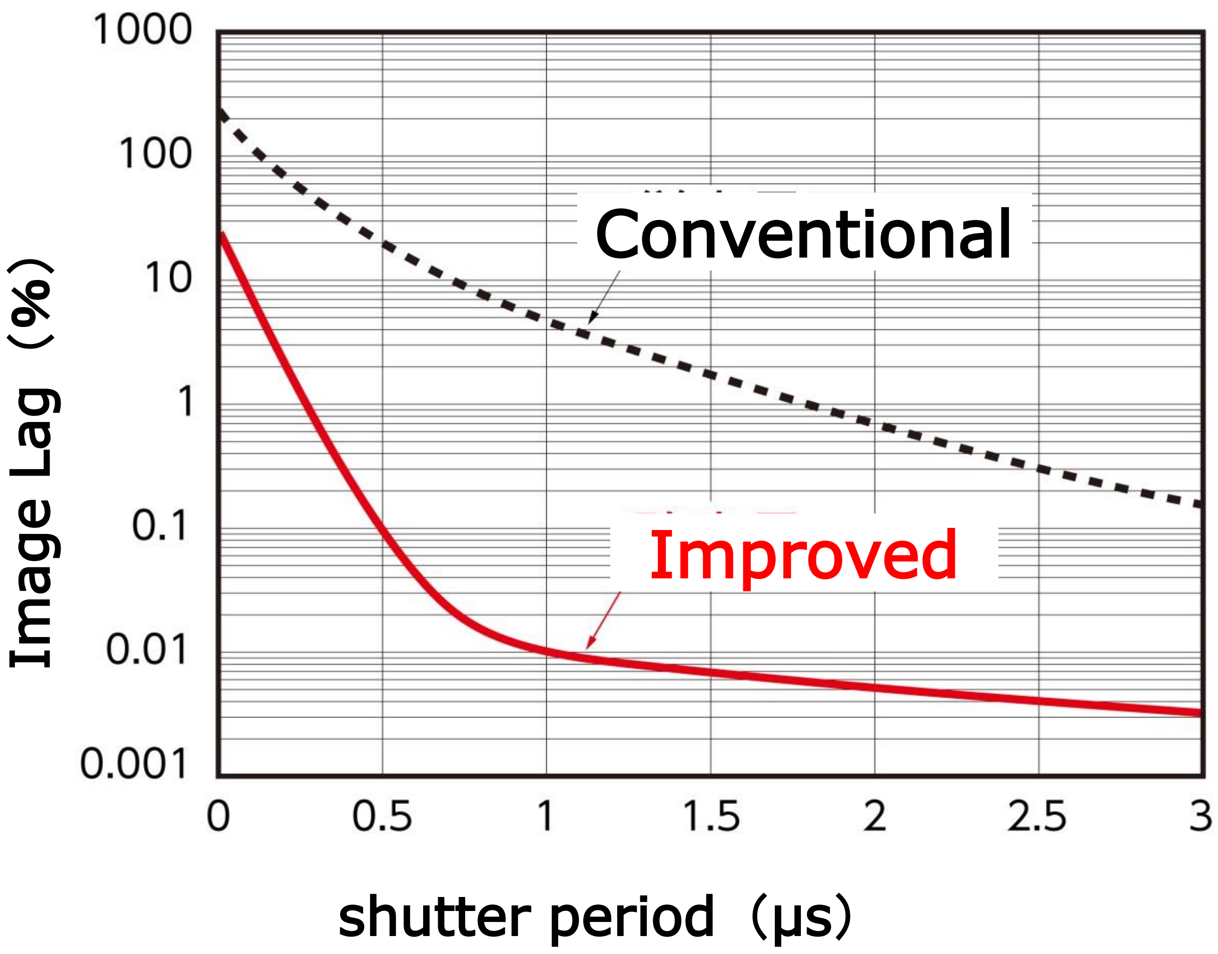
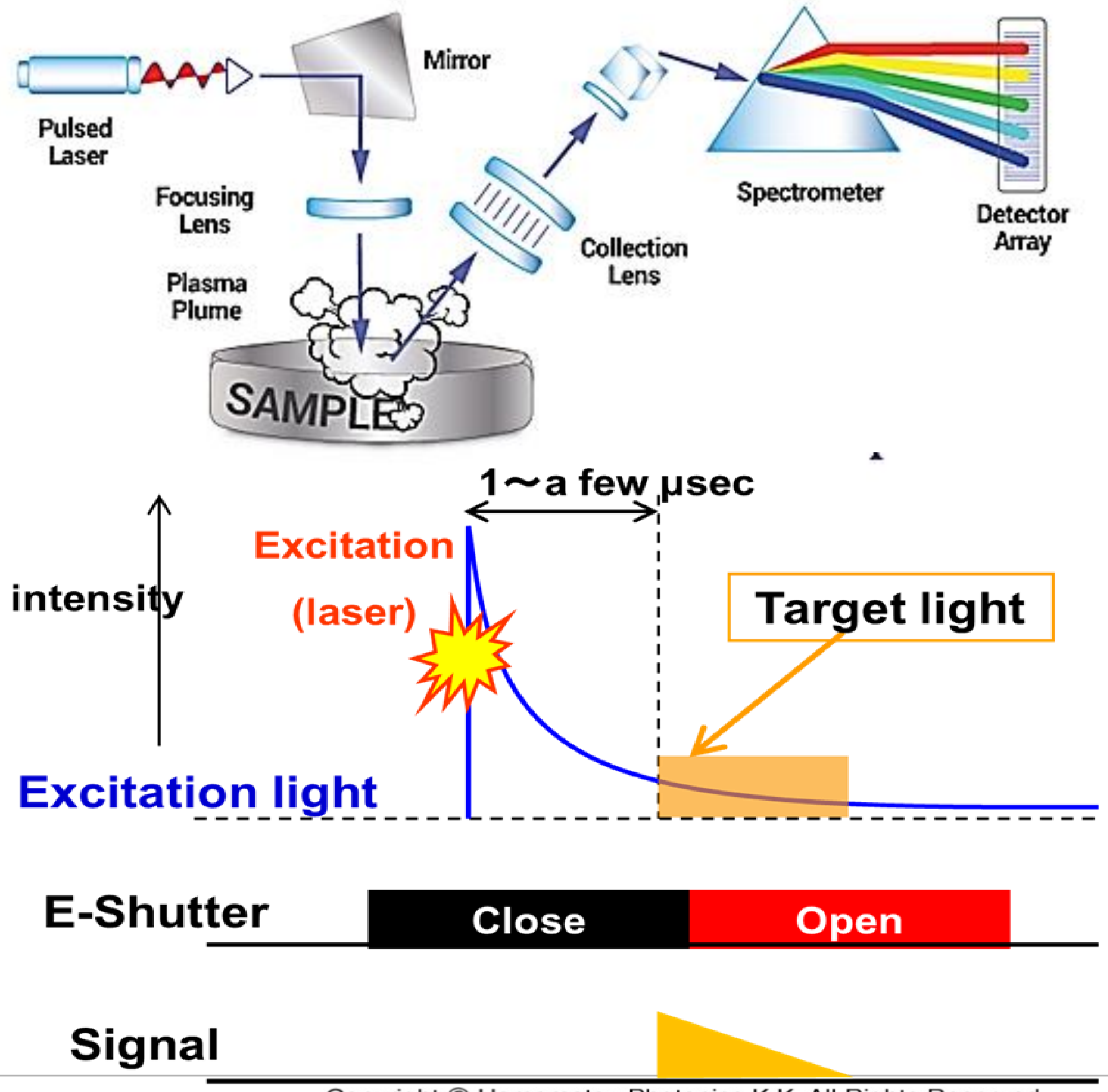
Market Demand High-speed electronic shutter

low afterimage of 0.01%
Short shutter period of 1 μsec.





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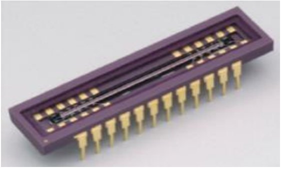
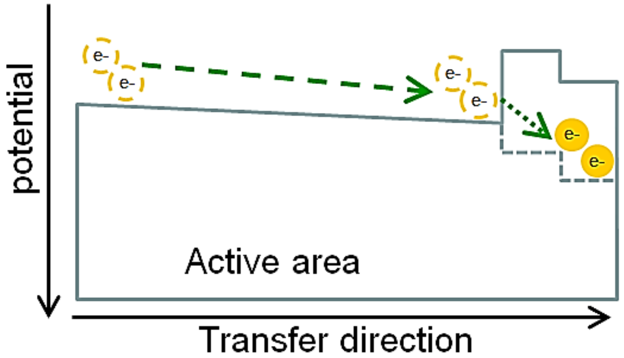
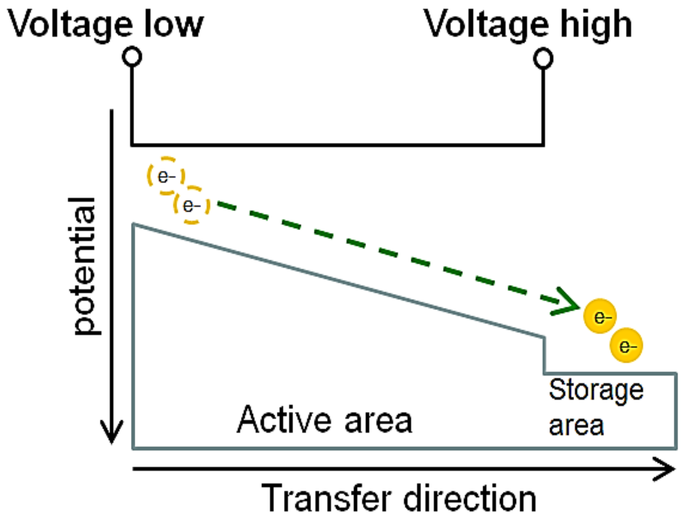
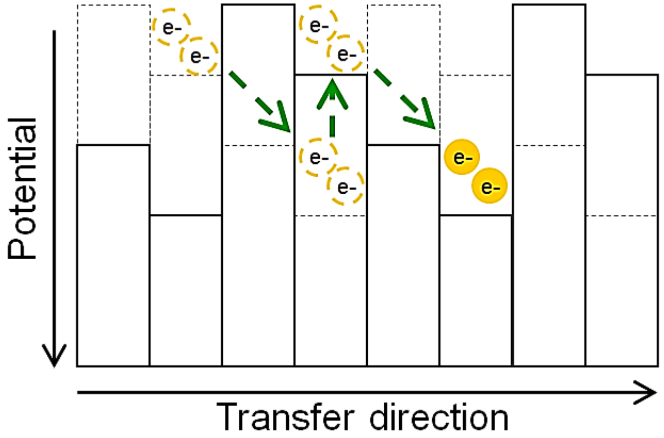
CCD with different charge transfer

<table>
<tr><td></td><td>Interline CCD</td><td>Resistive gate CCD
Back thinned type</td><td>Binning readout
Back thinned type</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Product</td><td>S15351(New)</td><td>S15254(New)</td><td>S703x, S10420,S11071</td></tr>
<tr><td>Charge transfer</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Feature</td><td>General application</td><td>High sensitivity
E-shutter function</td><td>High sensitivity
Wide dynamic range</td></tr>
</table>

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High-speed electronic shutter

■ Basic concept

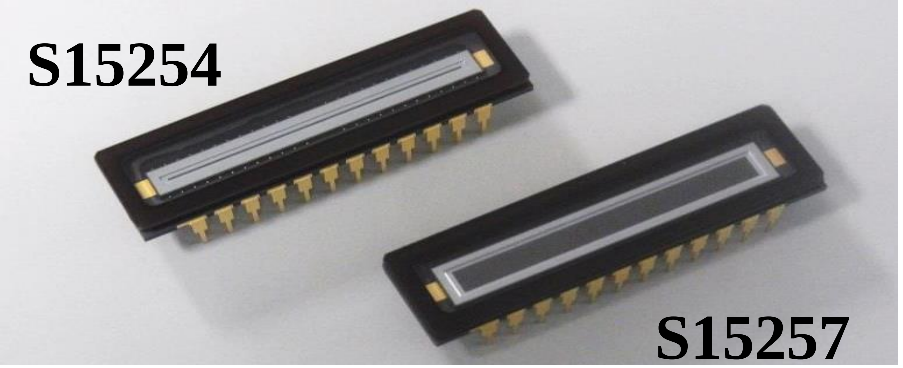
- ➢ Long pixel height
- ➢ Back illuminated type linear CCD
- ➢ High speed e-shutter function

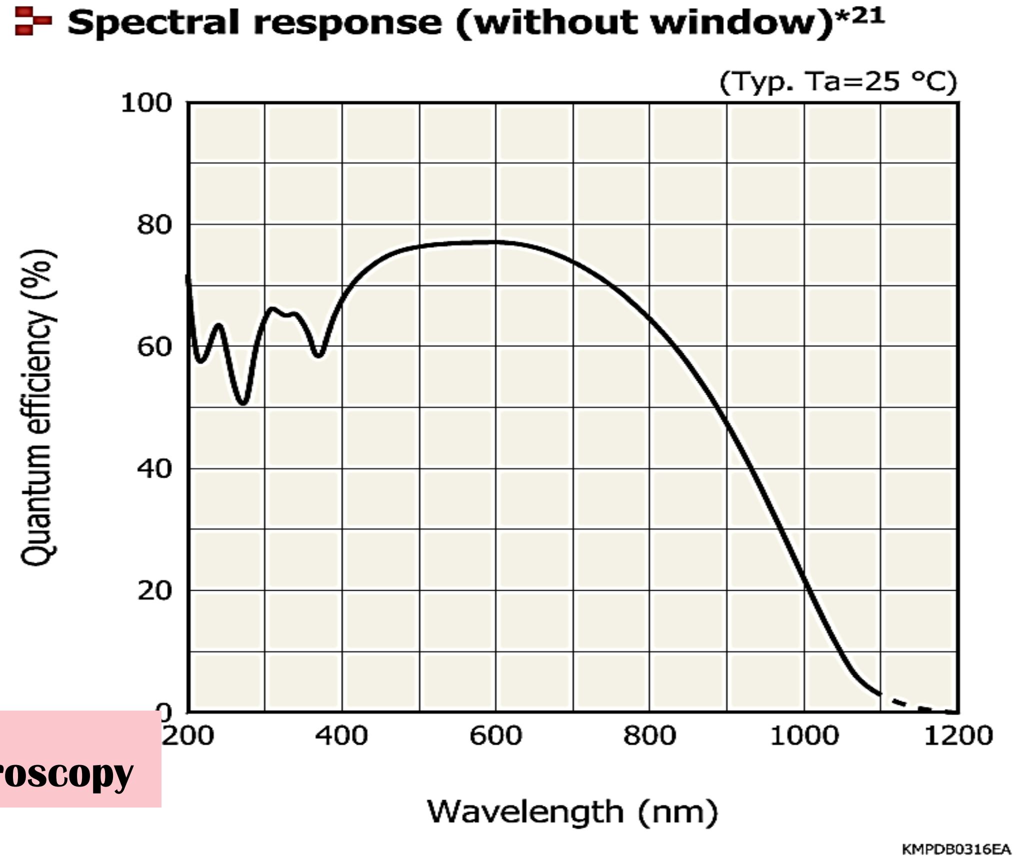
■ Specification

- ➢ Pixel pitch 14um
- ➢ Pixel height S15254 : 200um, S15257 : 2500um
- ➢ Shutter speed S15254 : < 1us , S15257 : 50us
- ➢ Readout Speed 5MHz(Typ), 10MHz(Max)
- ➢ Full Well Capacity 200ke-
- ➢ Dynamic range 6660
- ➢ Low image lag

■ Application

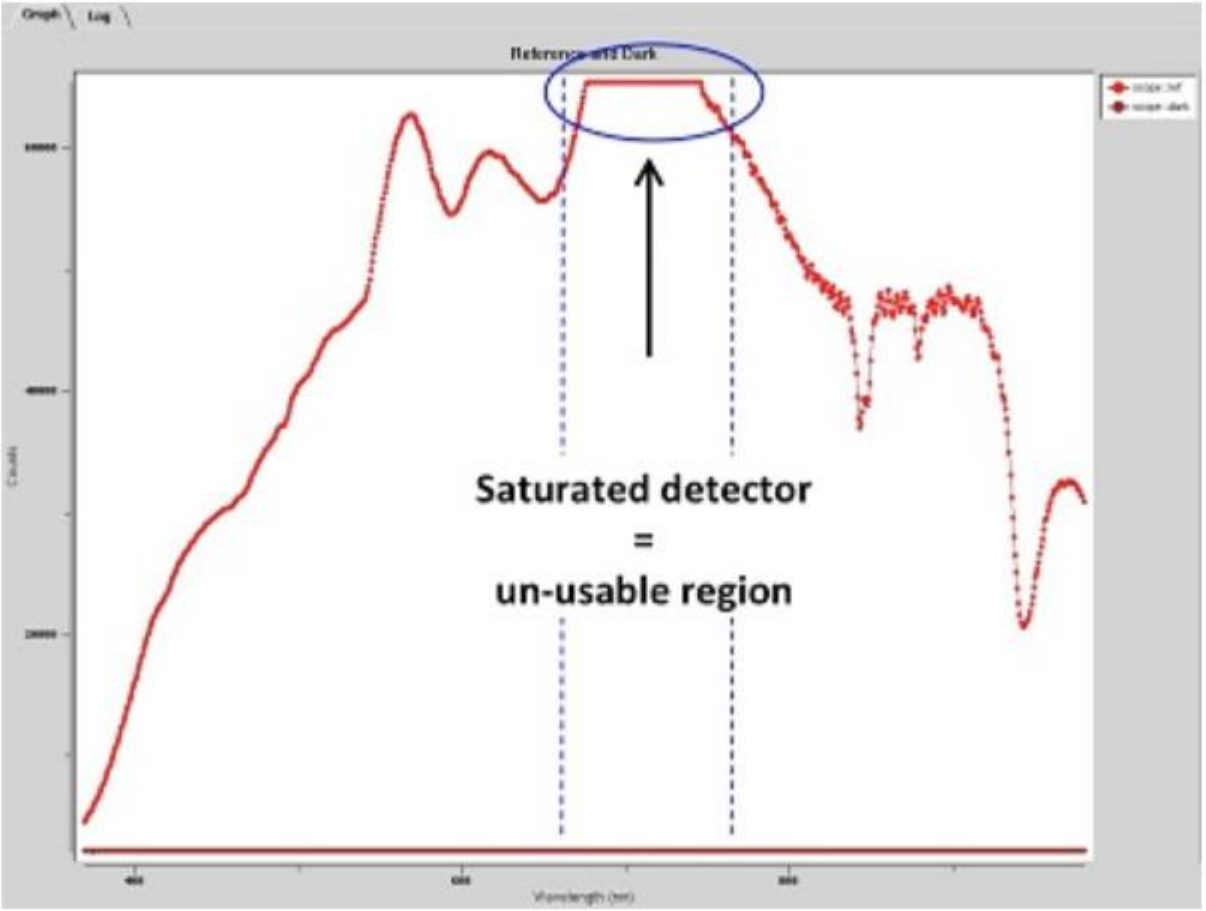
- ➢ LIBS
- ➢ Gating operation

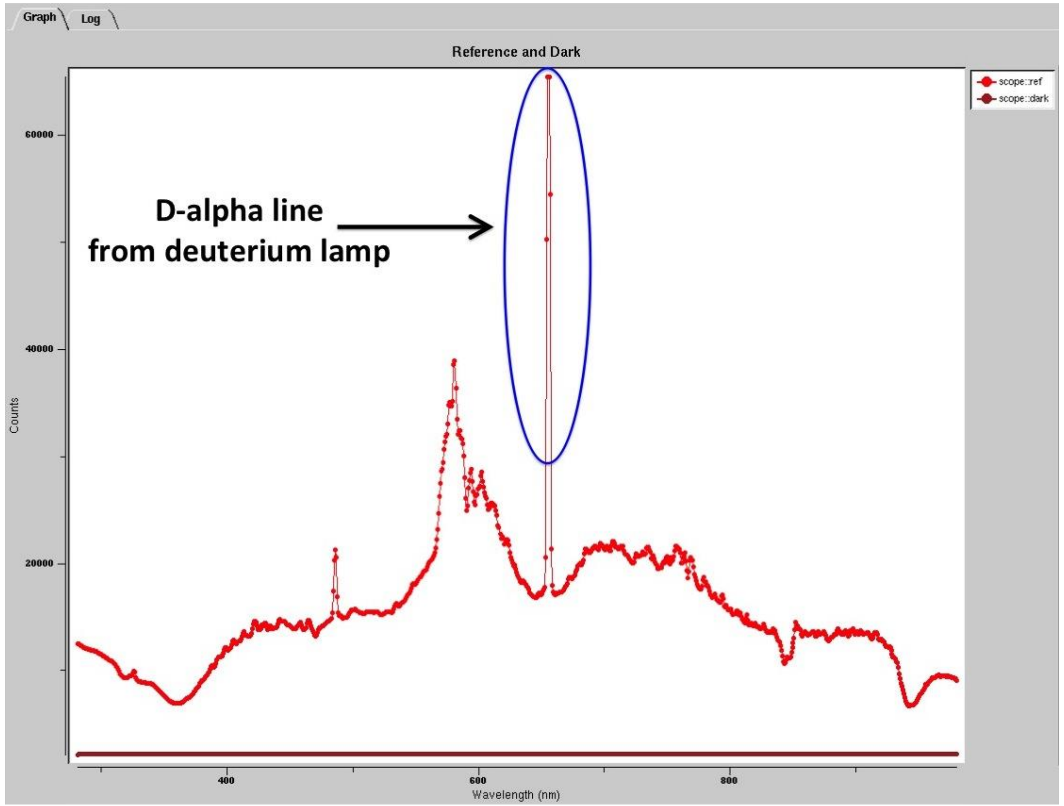




＊ LIBS : Laser Induced Breakdown spectroscopy

Market Demand Spectrometers with Flat Response





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Solutions for Spectrometer Saturation

•Application

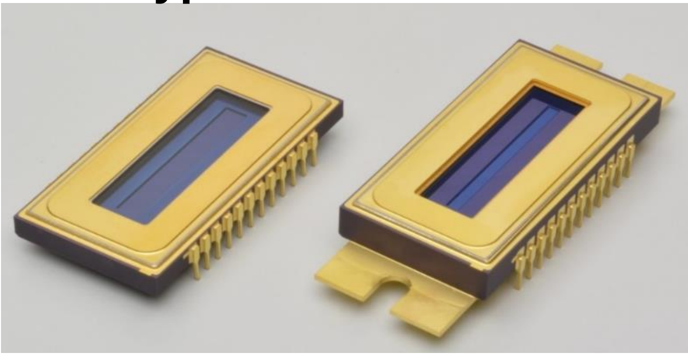
- Spectrometer

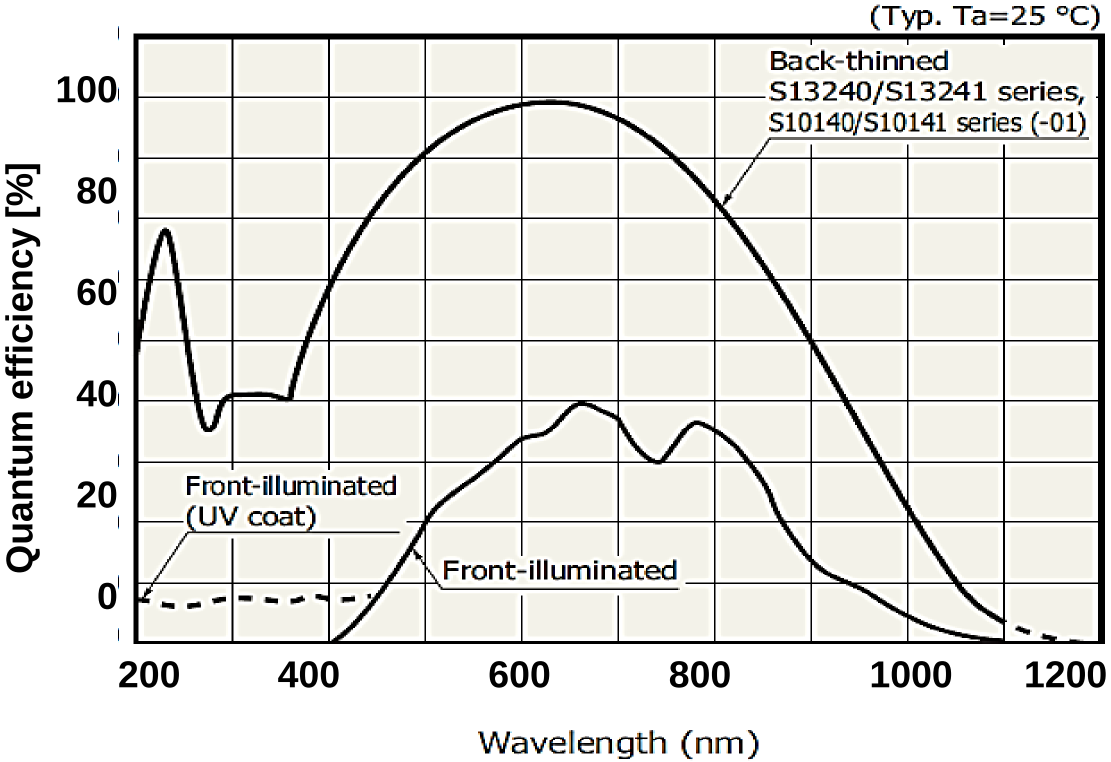
•Features

- Anti-blooming (saturation control)
- Horizontal pixels: 2048
- Vertical pixels :128, 256, 512
- Low noise type :S1014x-01
- High speed type : S1324x
- Large full well : 500ke-

(3 times larger than conventional)

Non-cooled type TE-cooled type





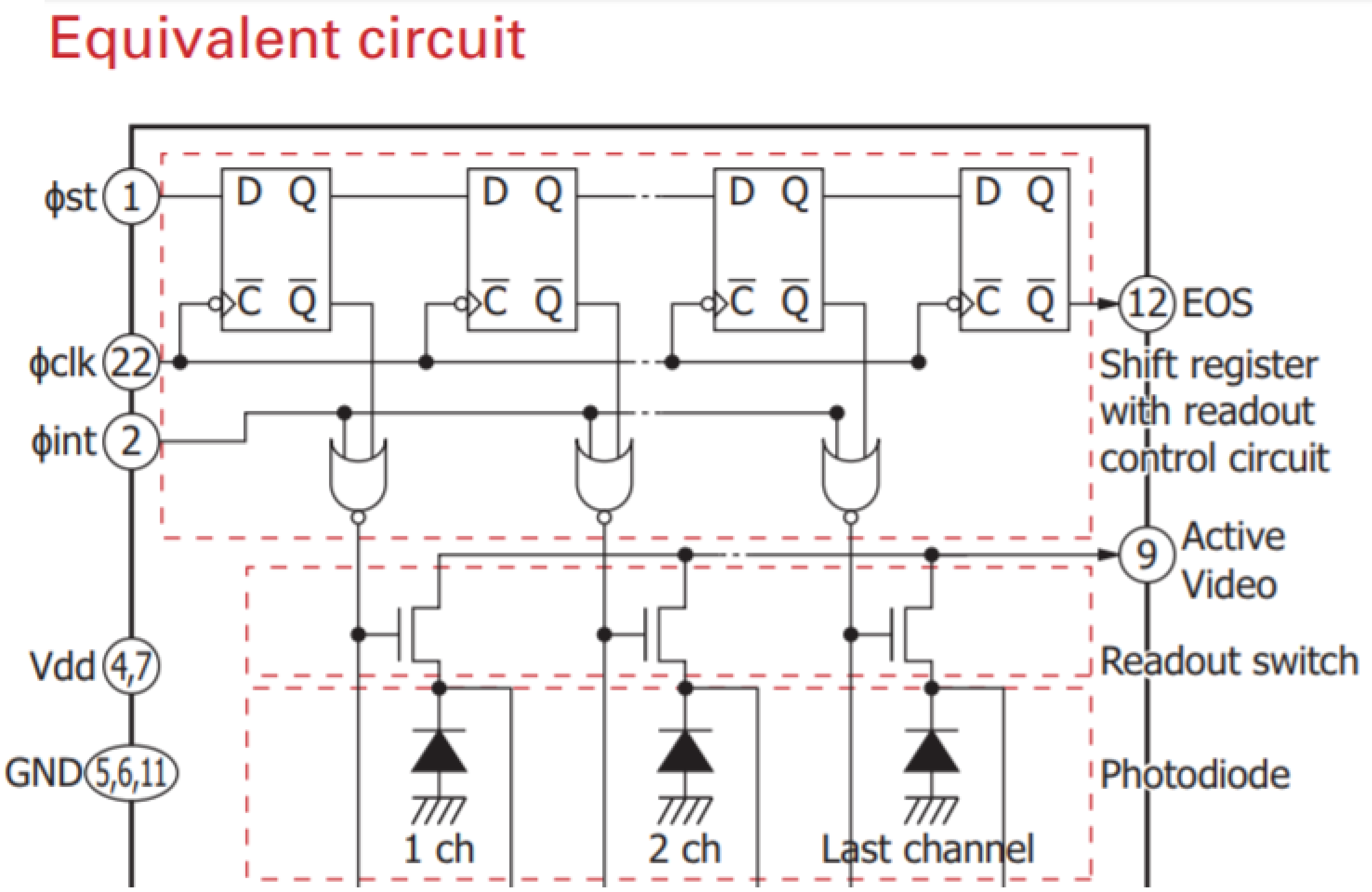
Solutions for Saturation Control and Flat Response

•Application

•**Spectrometer**

•Benefits

- Readout bright portions of the spectrum, while allowing weaker signal to accumulate longer.
- Saturation Charge ~ 180pC



CMOS image sensor with variable integration capabilities

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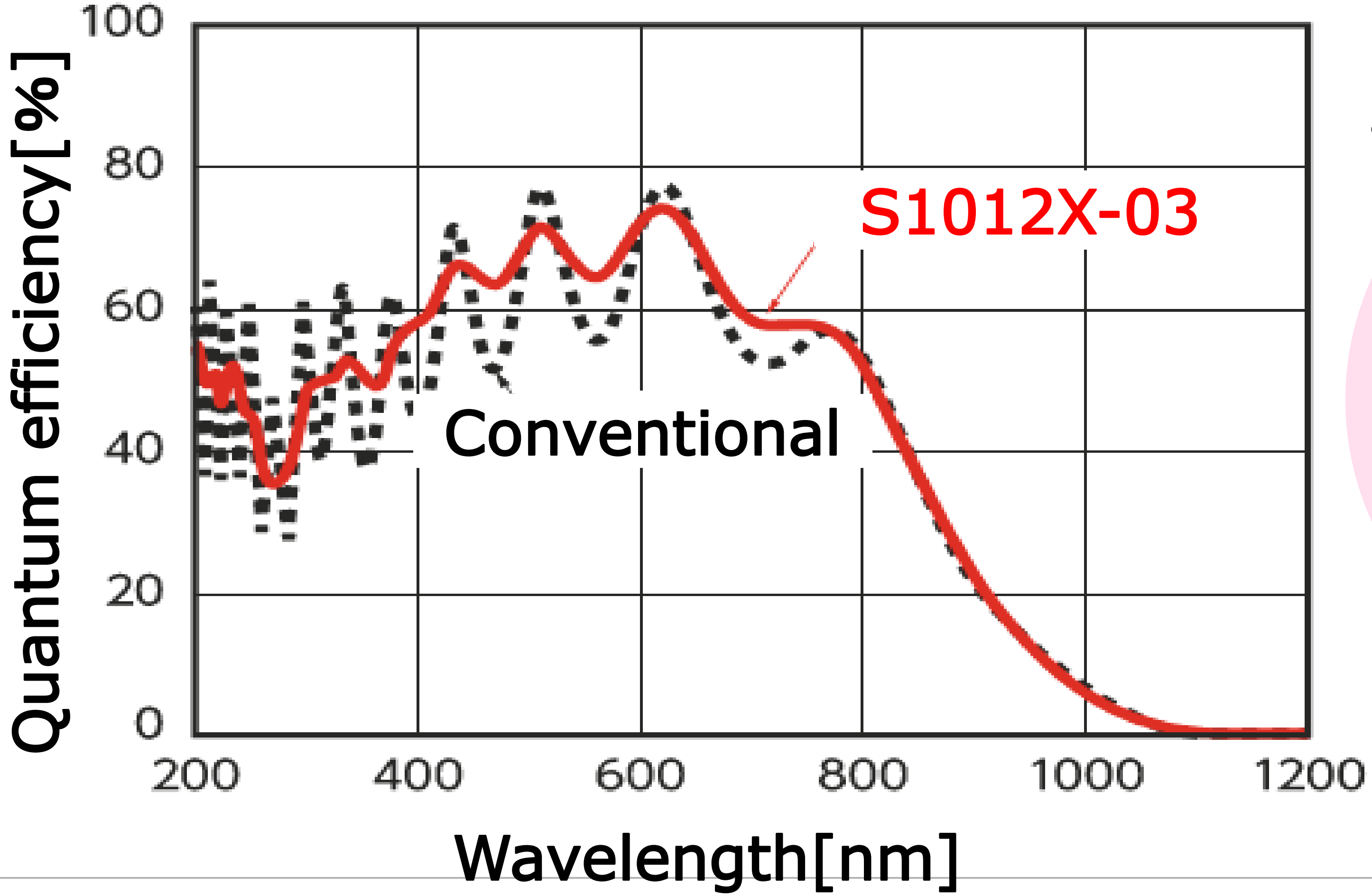
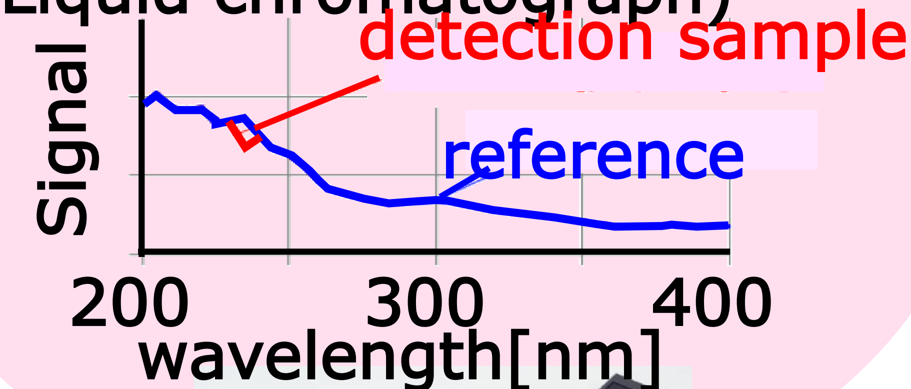
Suppressed fringe of spectral sensitivity

Suppressed the fringe of spectral sensitivity curve over a wide wavelength range.



Application (example)

- Absorption spectroscopic measurement (Liquid chromatograph)



NEW S1012X-03

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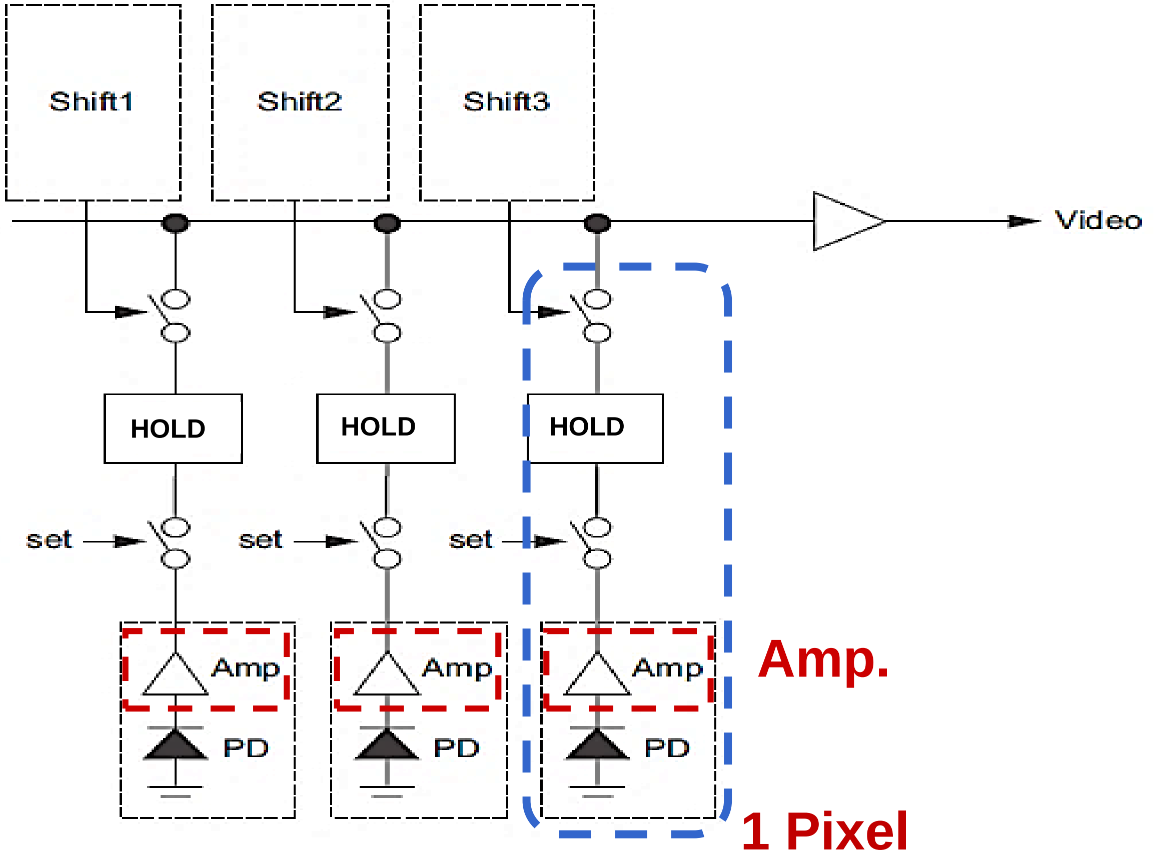
CMOS ~ Difference between PPS and APS

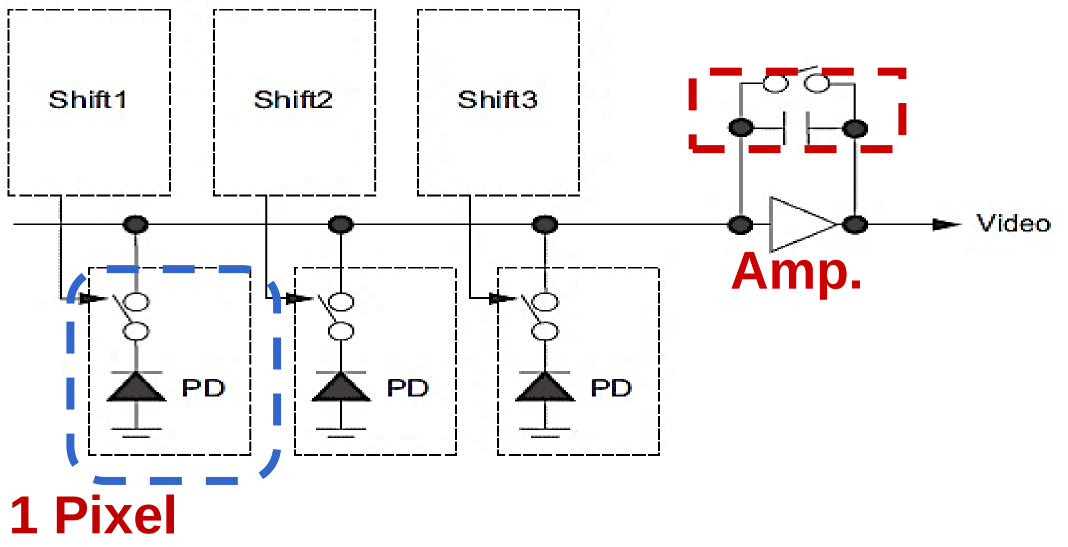
Active Pixel Sensor

The APS is a method with the amplifier in each pixel.



Passive Pixel Sensor

The PPS is a method with only one amplifier at the end of video line.



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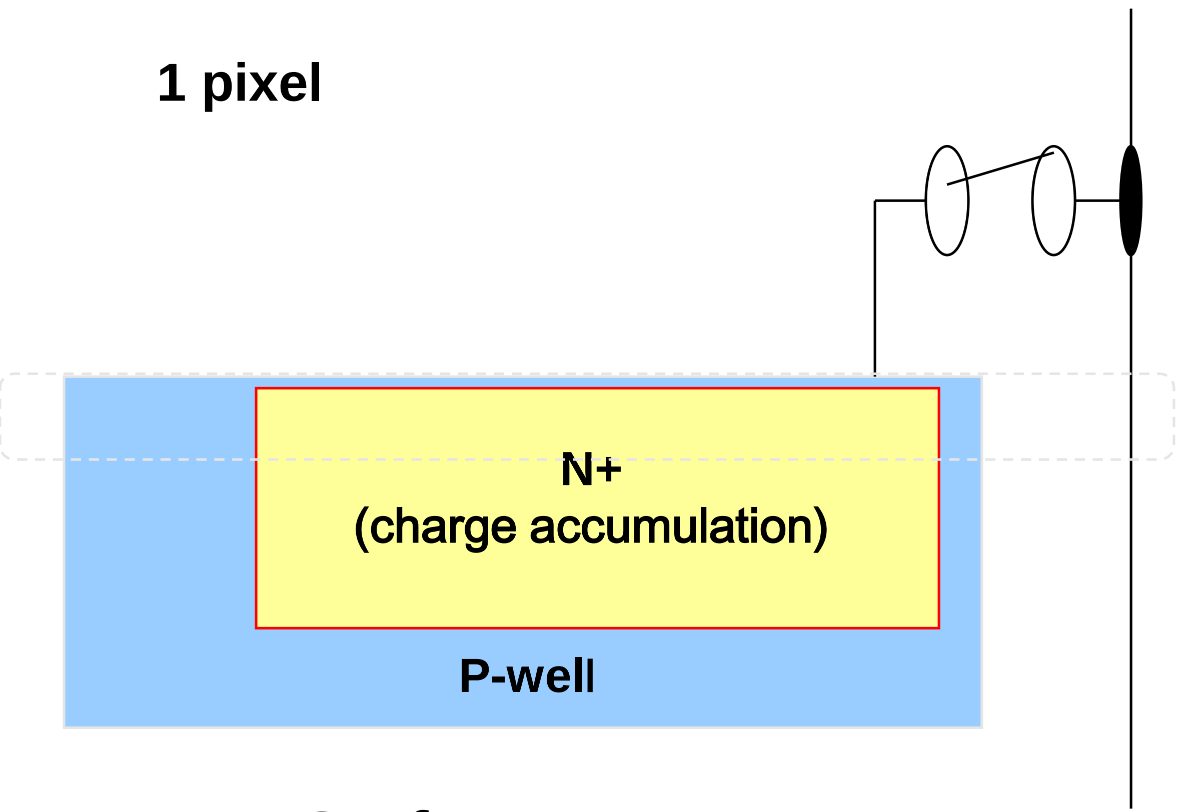
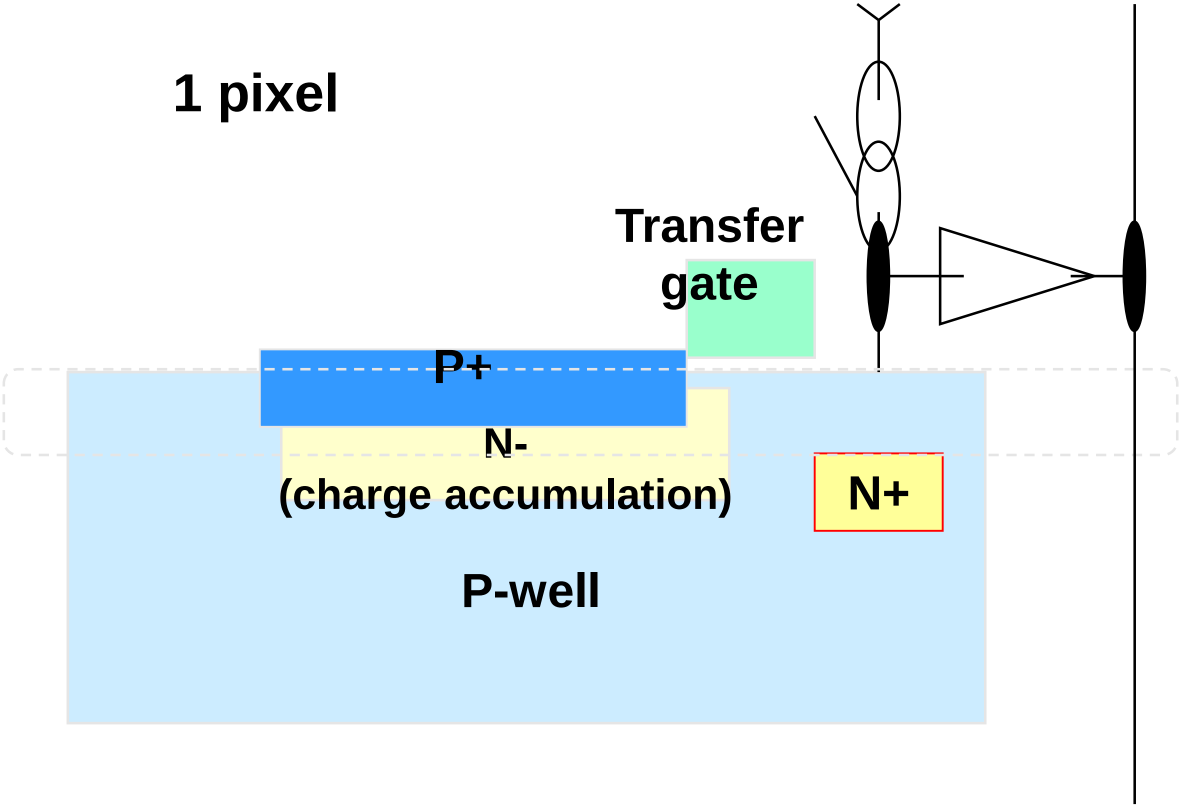
Buried Photodiode technologies



Surface PD structure



Buried PD structure

Enhanced sensitivity by minimizing capacitance of charge integration area

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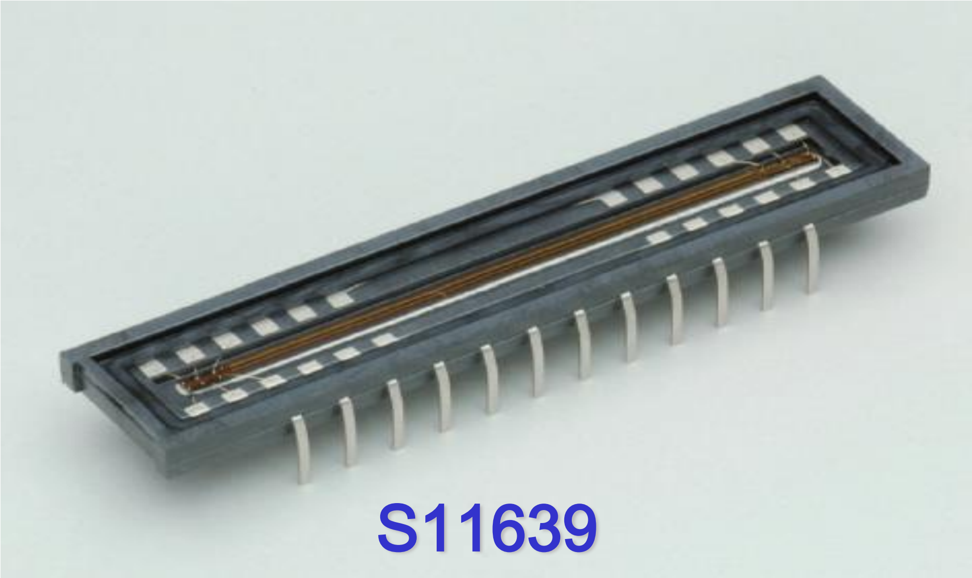
Higher sensitivity CMOS-APS with Buried PD

- Features
  - Higher pixel in size(14x200um)
  - Higher sensitivity with buried PD
  - APS (Active Pixel Sensor)
  - Sensitivity 1300V/lx s
    （8 times higher than conventional type)
  - Electronic shutter
- Application
  - Spectrometer
- Specification
  - 14um x 200um, 2048ch



Almost same as CCD

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CCD vs CMOS Image sensors

	CCD	CMOS
Output (pixel)	charge	voltage
Amplifier	1-amp for multi pixels	1-amp for single pixel
Output(chip)	voltage (analog)	digital/analog
Charge transfer	from pixel to pixel	inside of pixel
Fabrication	specialized process for CCD	common LSI process
Input bias	multiple, high, voltage clocking	single, low,DC
Onchip circuit	Very difficult	possible
External circuit	complicated	simple

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CCD vs CMOS image sensors

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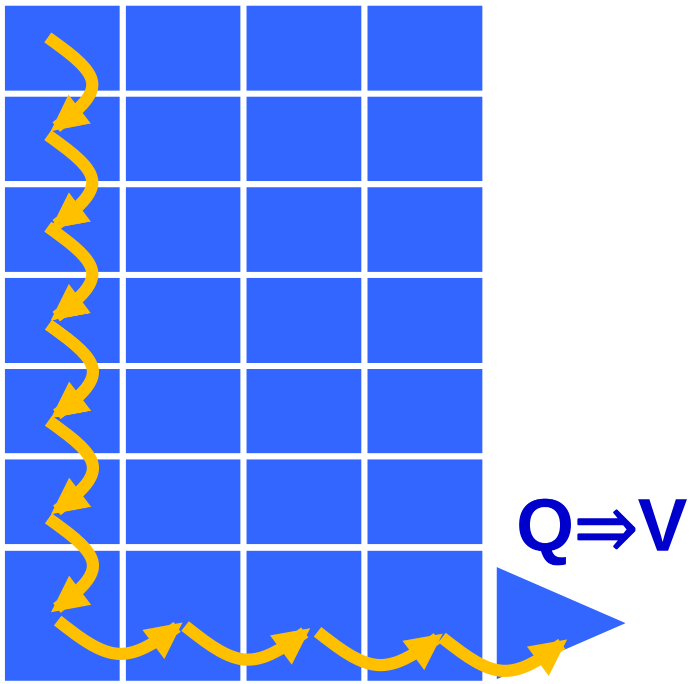
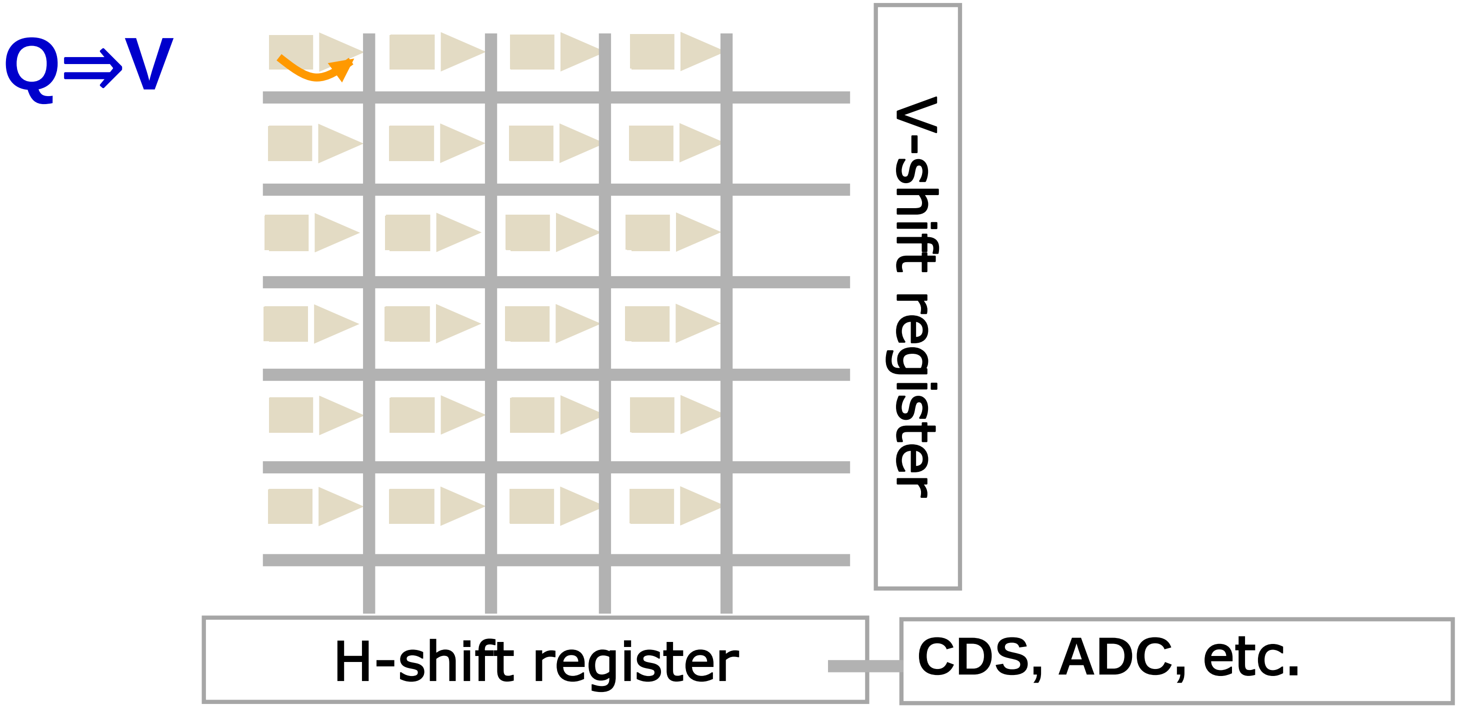
CCD image sensor

- Signal charges are transferred in Si.
- Charges are converted to voltage "after" transferring.



CMOS image sensor

- Signal voltage is transferred in the metal.
- Charges are converted to voltage "before" transferring.



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UV – Visible (SWIR) Summary (190nm-1100nm)

- Spectrometers & Image Sensors
  - ✓ CCD based solutions excellent for low light levels.
  - ✓ CMOS-APS spectrometers, portable implementations for middle range.
  - ✓ CMOS-PDA spectrometers with variable integration time and huge dynamic range. Absorption applications with bright light, detecting small changes.

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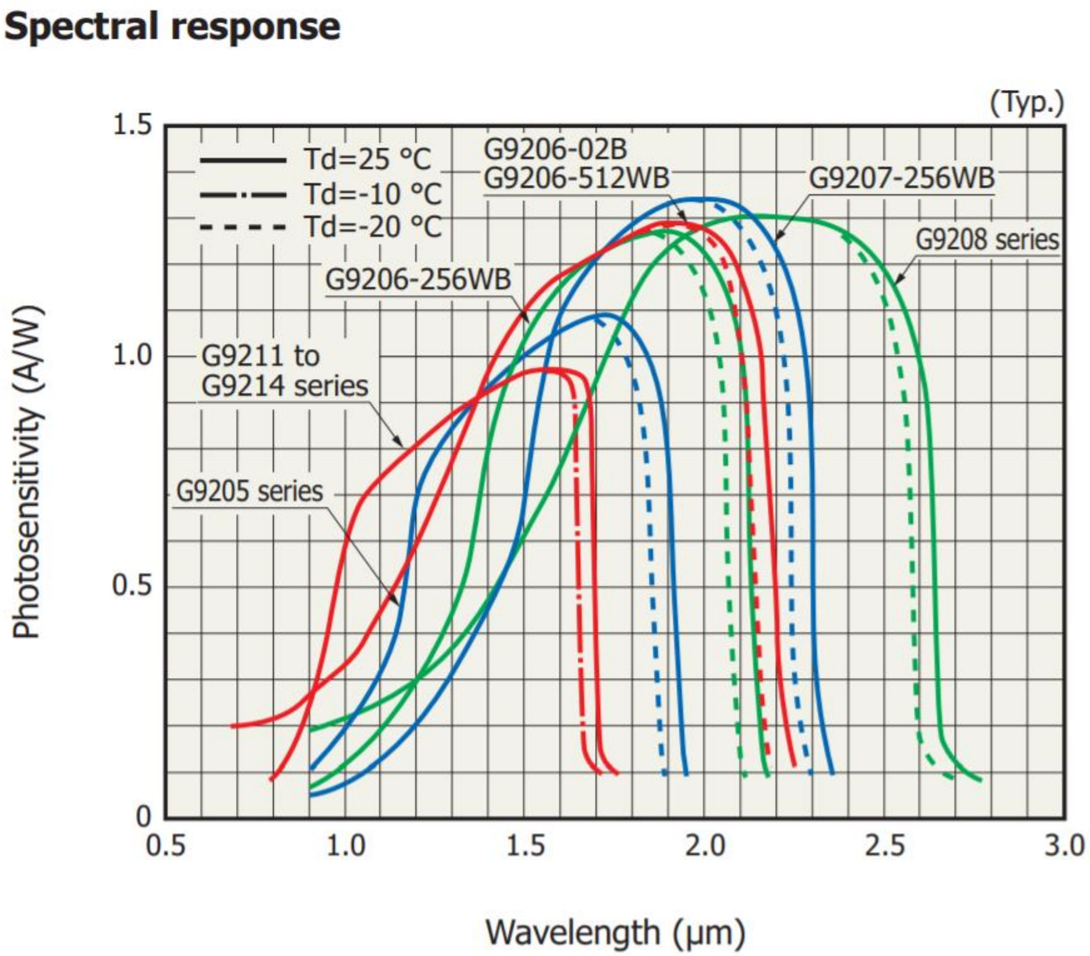
NIR Image Sensors and Spectrometers (900-2500nm)



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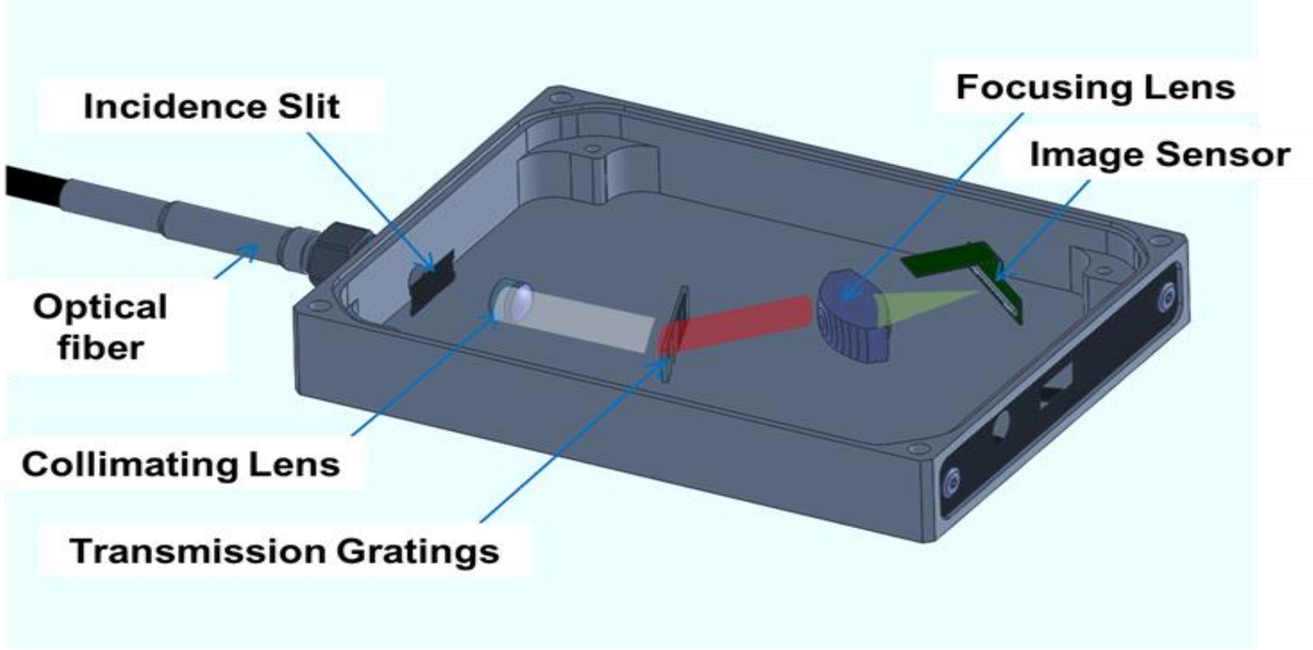
NIR Spectrometers

	C14486GA
Photo	
Spectral range [nm]	950 to 1700 (NIR)
Resolution[nm]	5.0 typ
Image sensor	InGaAs
N of pixel	256
W x D x H [mm]	80 x 60 x 12
Weight [g]	88



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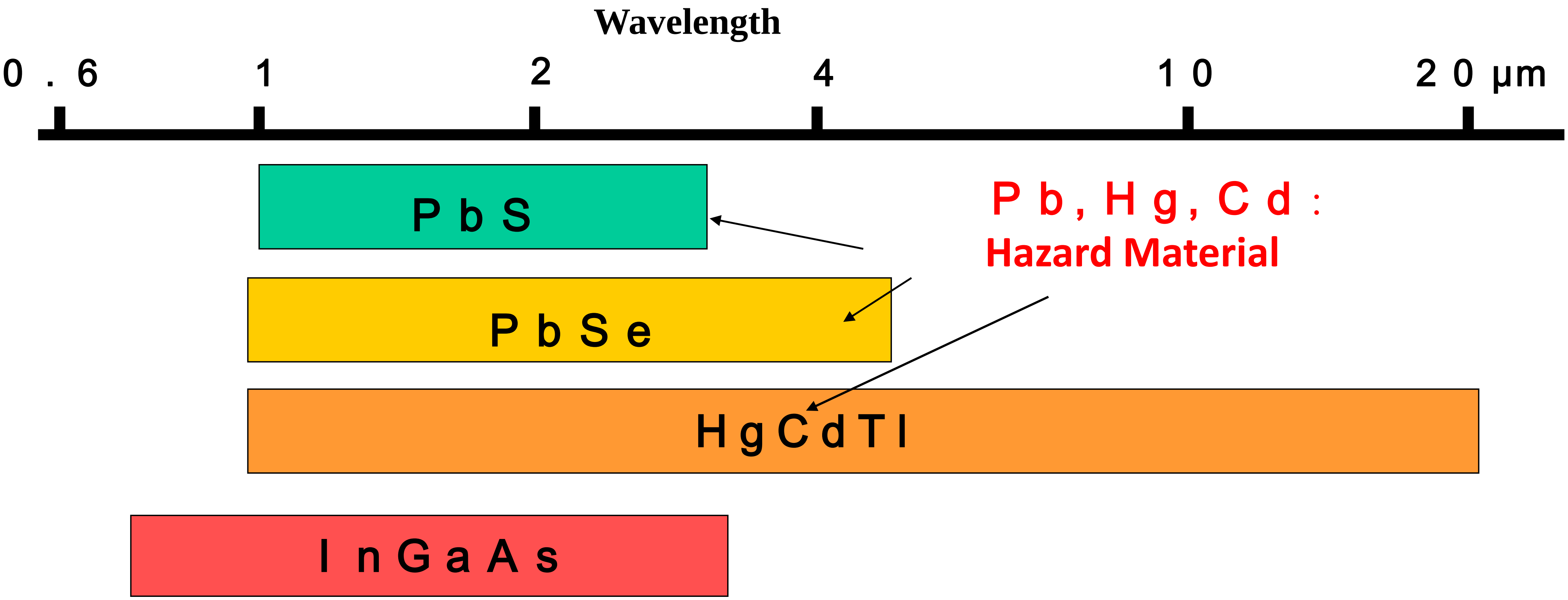
Compound Semiconductors for IR sensors



Good candidate to replace

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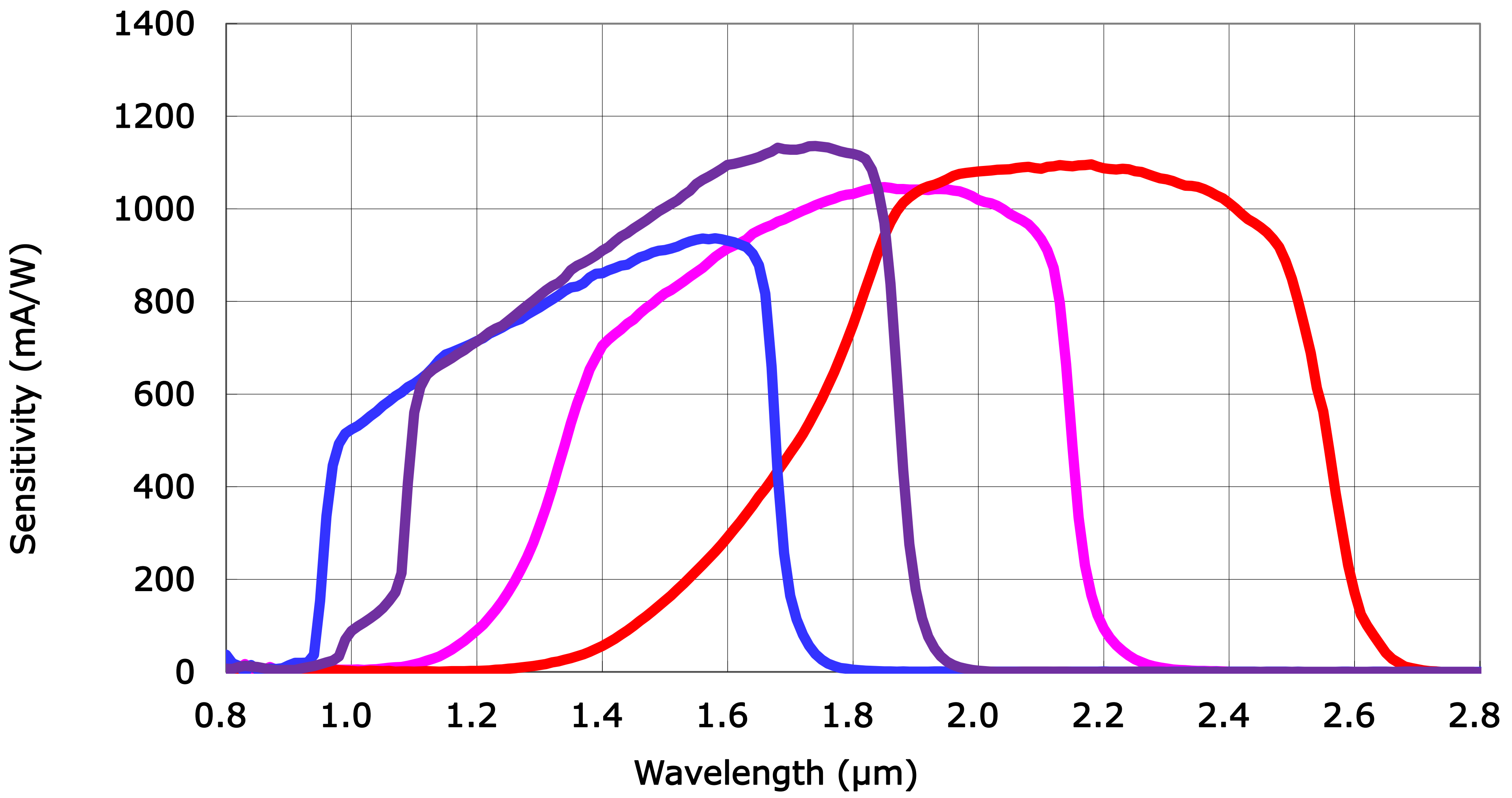
InGaAs image sensor spectral response



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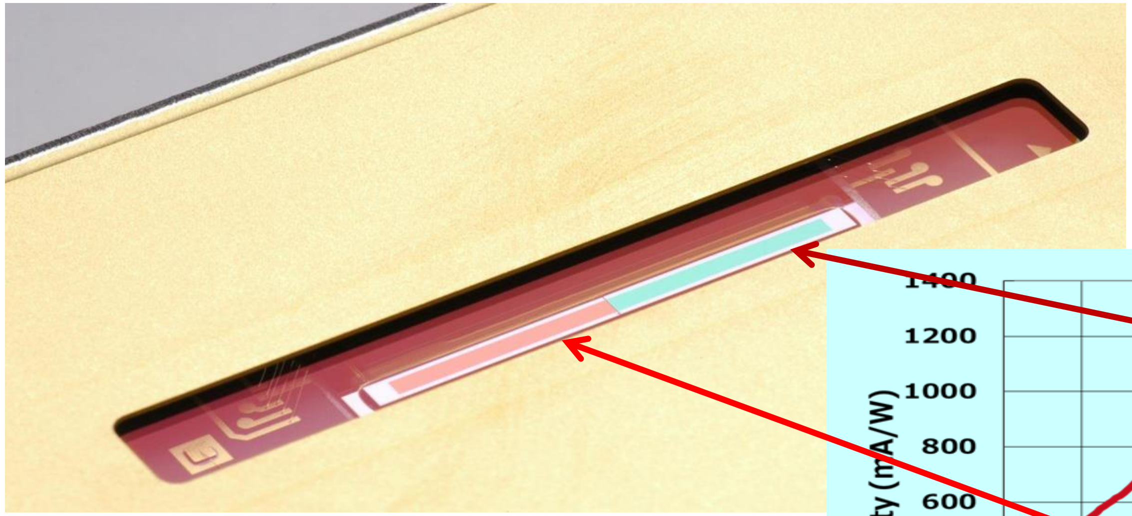
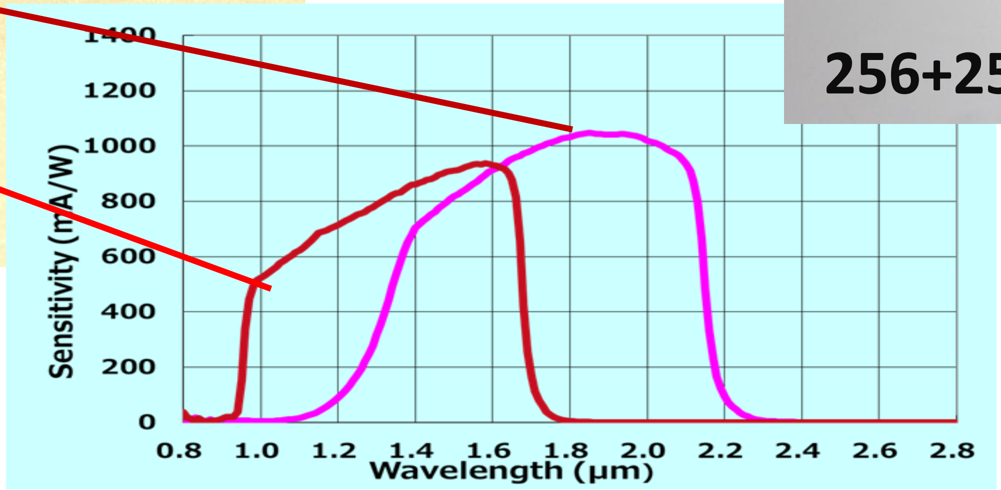
For wide wavelength spectrometer

2 types InGaAs in 1PKG





InGaAs Hybrid Linear image sensors (Back Illuminated Type)

- Single video line 512ch
- High speed readout 5MHz max.
- 255ch(0.95-1.7um)&255ch(1.4-2.2um)

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Market Demand ~ "Perfect" Spectrometer

- Stray Light Corrections

Simple spectral stray light correction method for array spectroradiometers

Yuqin Zong, Steven W. Brown, B. Carol Johnson, Keith R. Lykke, and Yoshi Ohno

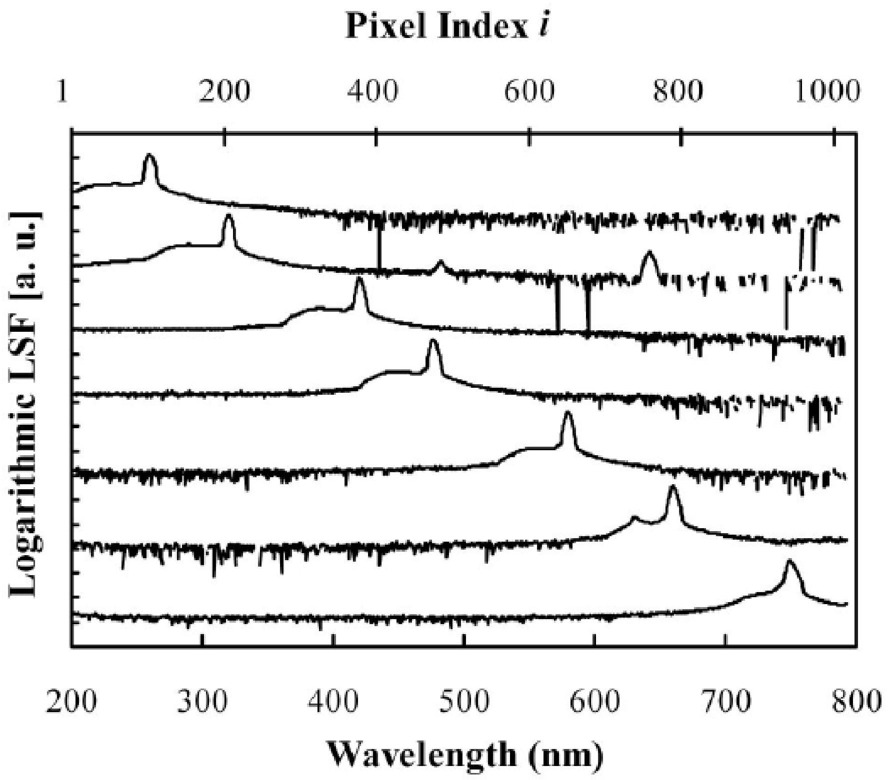
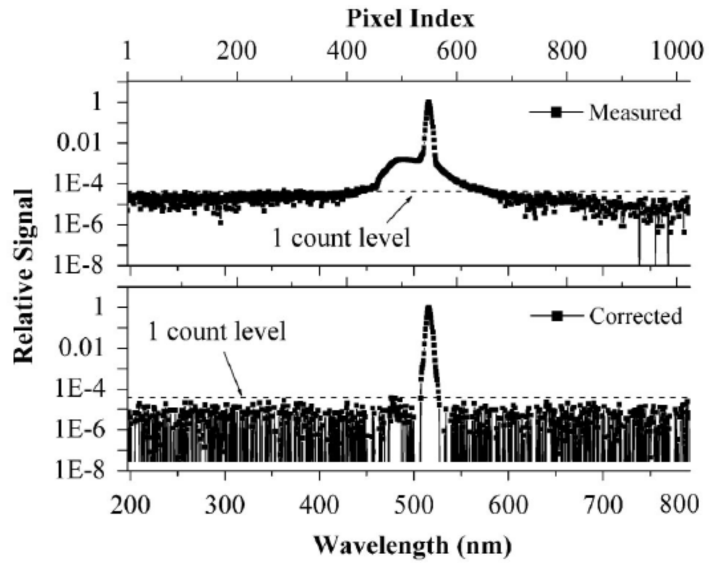
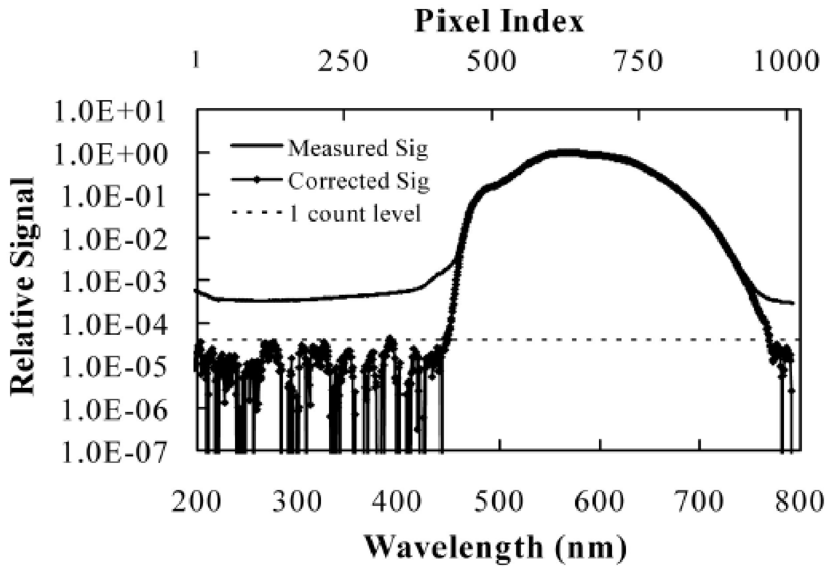


Fig. 3. Representative LSFs spanning the test spectrograph's detector array.





Market Demand ~ “Perfect” Spectrometer

- Linearity Corrections

Article

Improving Optical Measurements: Non-Linearity Compensation of Compact Charge-Coupled Device (CCD) Spectrometers

Münevver Nehir [1], Carsten Frank [2,3], Steffen Aßmann [3,4] and Eric P. Achterberg [1,*]

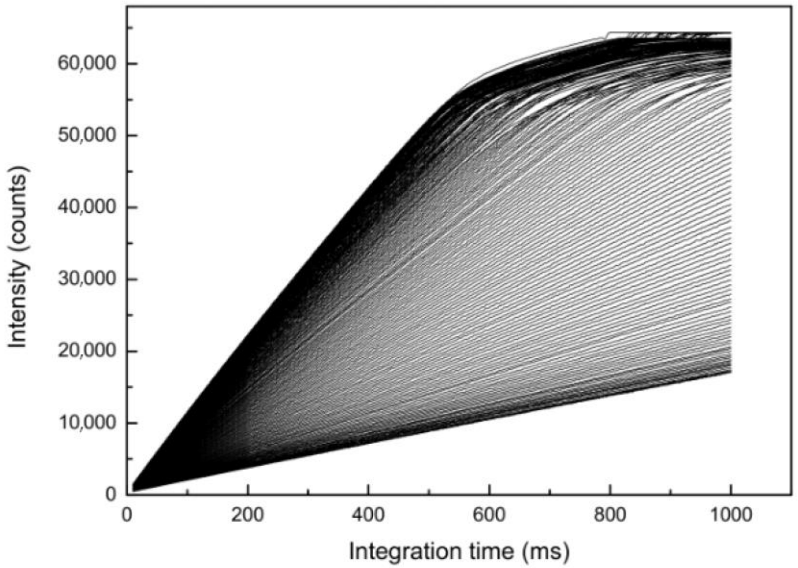
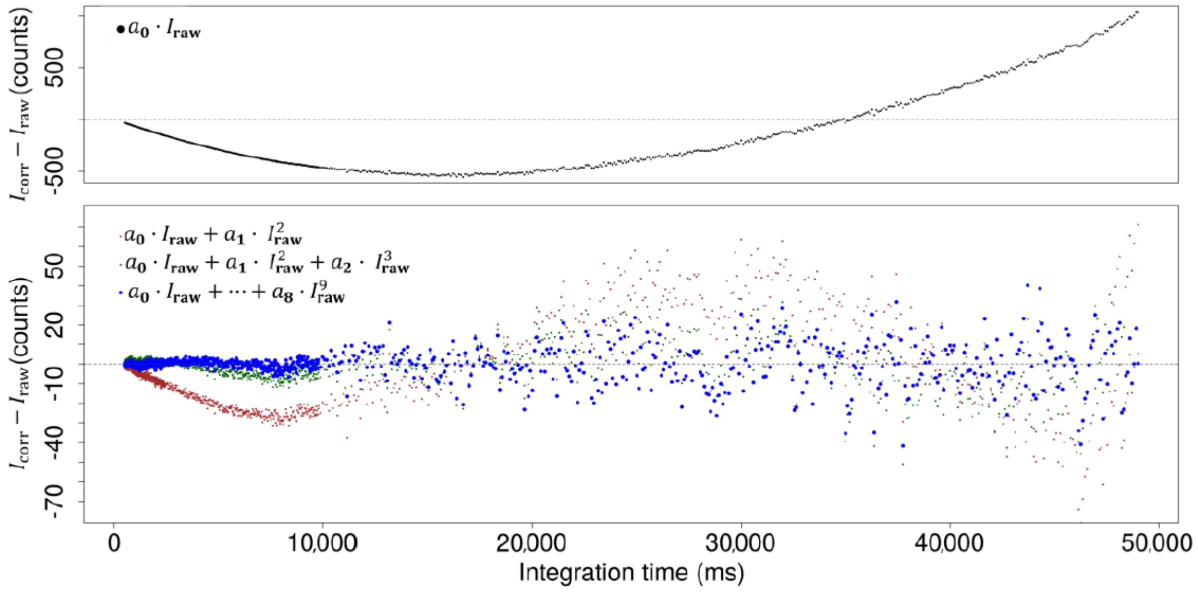


Figure 7. Pixel intensities (counts) versus integration time (ms). A single line represents data from one pixel. Data from 200 representative pixels (equally spaced between 400–800 nm) are shown. All data lines appear to be linear up to 50,000 counts and then deviate strongly from the ideal line.



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MOEMS Technologies

New Technology creates new solutions …..

Micro-Spectrometers

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New development for NIR Mini-Spectrometer

Grating design has some limitation to make smaller and cheaper

- **Have to use a very expensive Image sensor**
- **Very difficult to get higher resolution in limited so pace**
- **Difficult to design wide wavelength spectrometer**

How to realize small and cheap NIR spectrometers ?

Not Grating type but

“ Interference Spectrometer using Actuator “

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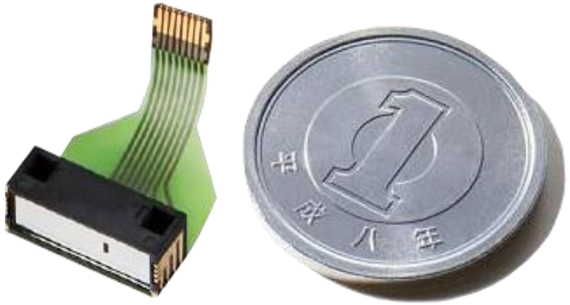
Focusing on Portable Implementations

- Mini-spectrometer SMD series (640 to 1050 nm)



- MEMS-FPI spectrum sensor (e.g.,1550 to 1850 nm)

- Compact FTIR engine (1100 to 2500 nm)

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Hamamatsu Contributions to Industry

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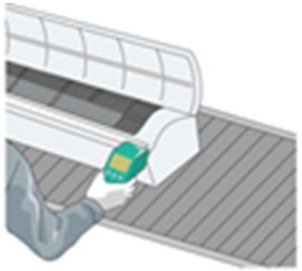
Industry

- incoming test
- Process control
- Wet process analysis

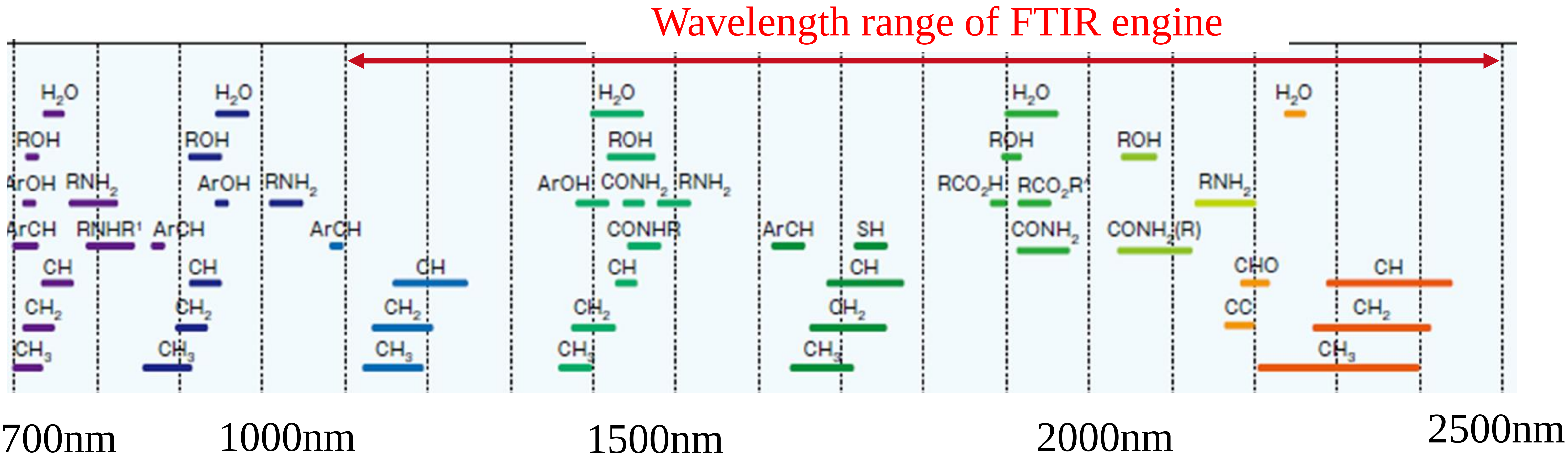
Agriculture

Recycle



Infrastructure

Functional group of Near infrared region



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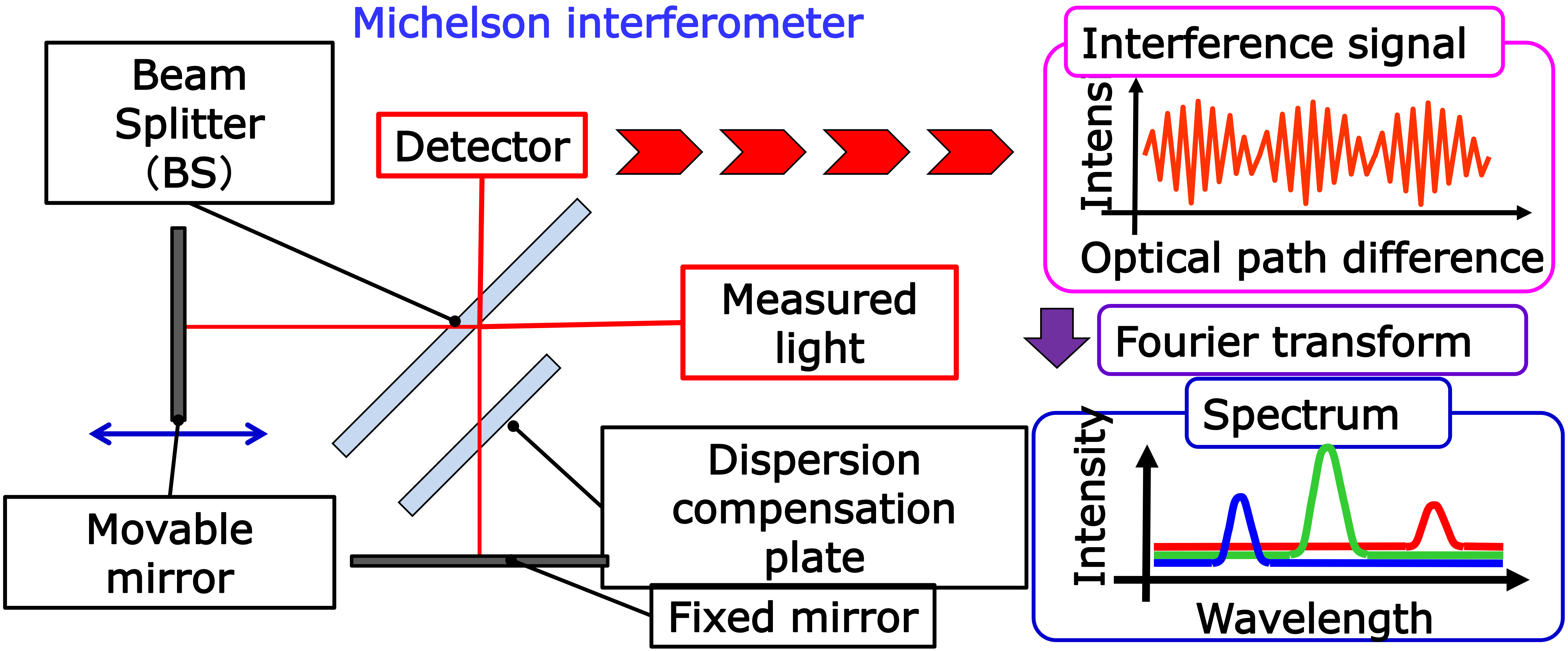
FTIR（Fourier transform infrared spectrometer）ーPrinciple ー



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Optical configuration for the interferometer

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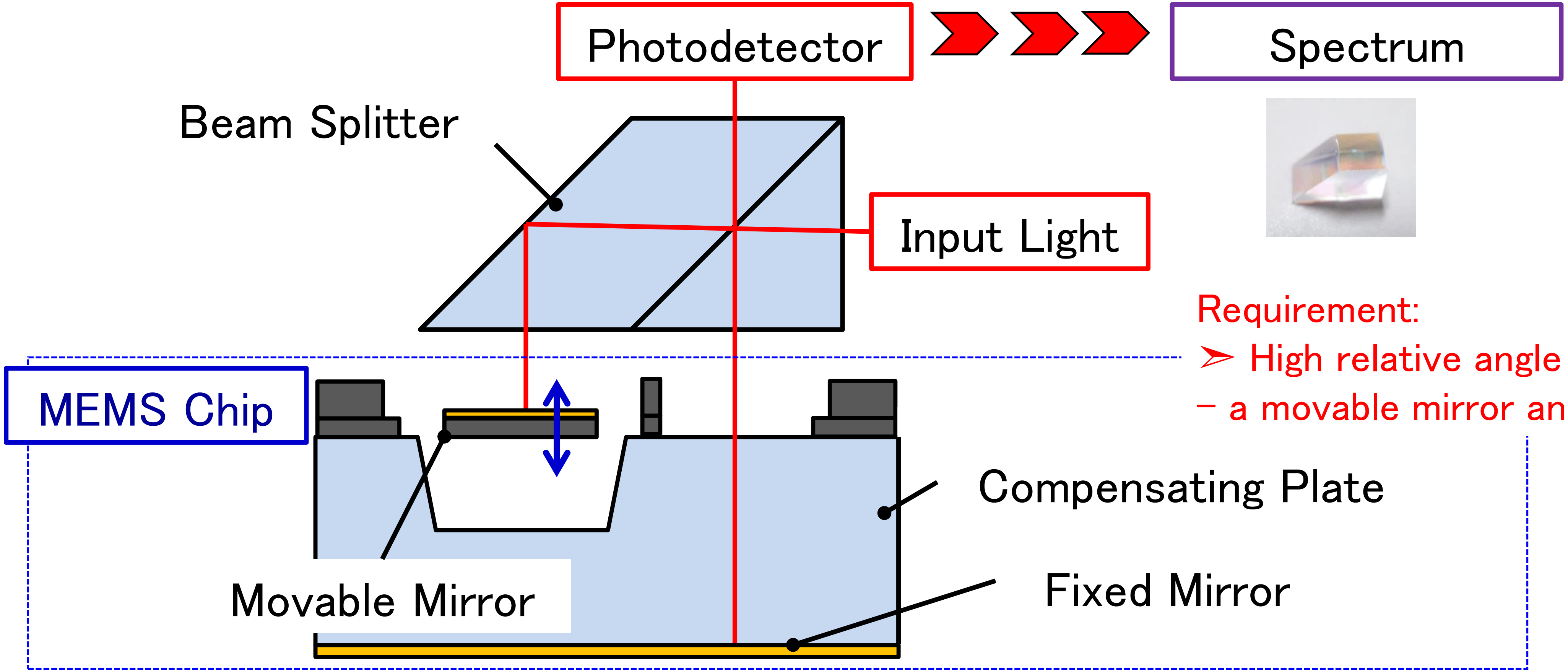
Features:

- ➢ Integrated MEMS chip and beam splitter prism
- ➢ Manufactured with less optical adjustment



Requirement:

➢ High relative angle accuracy

– a movable mirror and a fixed mirror

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• SNR improvement by NEW FTIR Engine (vs old model)

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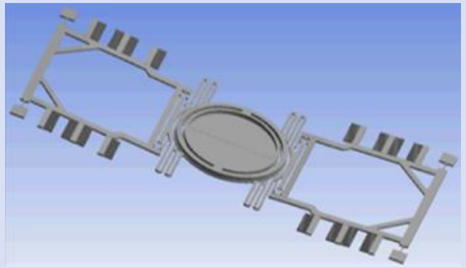
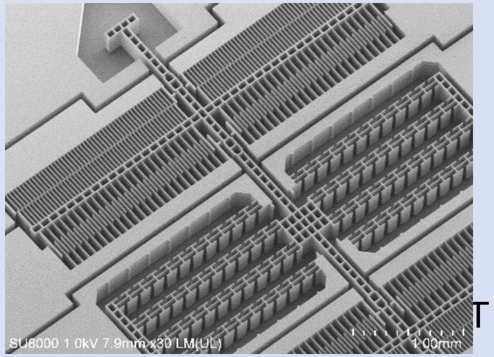
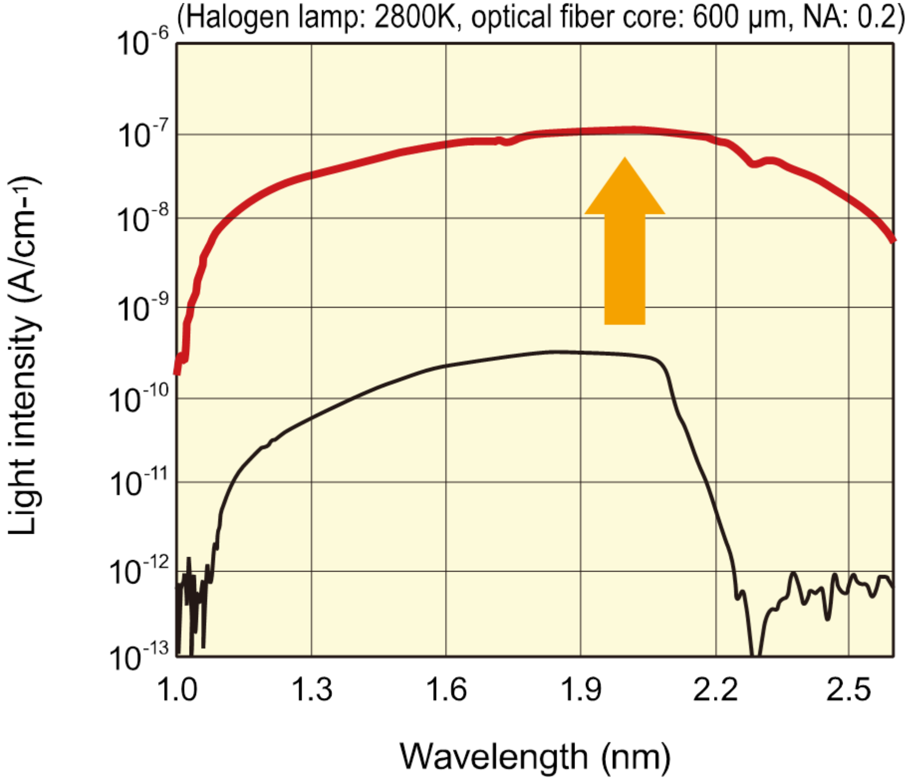
	New FTIR Engine C15511-01	Old MEMS-FTIR C12606-02
	 * Mirror size : 3mm dia.	*  T
Spectral range	1100 to 2500 nm	1150 to 2050 nm
SNR *1	10,000 : 1 (40dB)	1,000 : 1 (30dB)
Resolution	25cm-1 = 5.7 nm (1533nm)	29cm-1 = 6.8nm (1533nm)
Size	57 x 49 x 76 mm ($212,000mm^3$)	100 x 75 x 27 mm ($202,500mm^3$)

- Expanded spectral range up to 2500 nm
- Improved sensitivity about 100 times (*2)



*1 : The SNR values are on conditions optimized to each type.
*2: The graph on the right shows the sensitivity improvement by 100 times, whose measurements are on conditions optimized to C15511-01. (i.e. too weak light for C12606-02)

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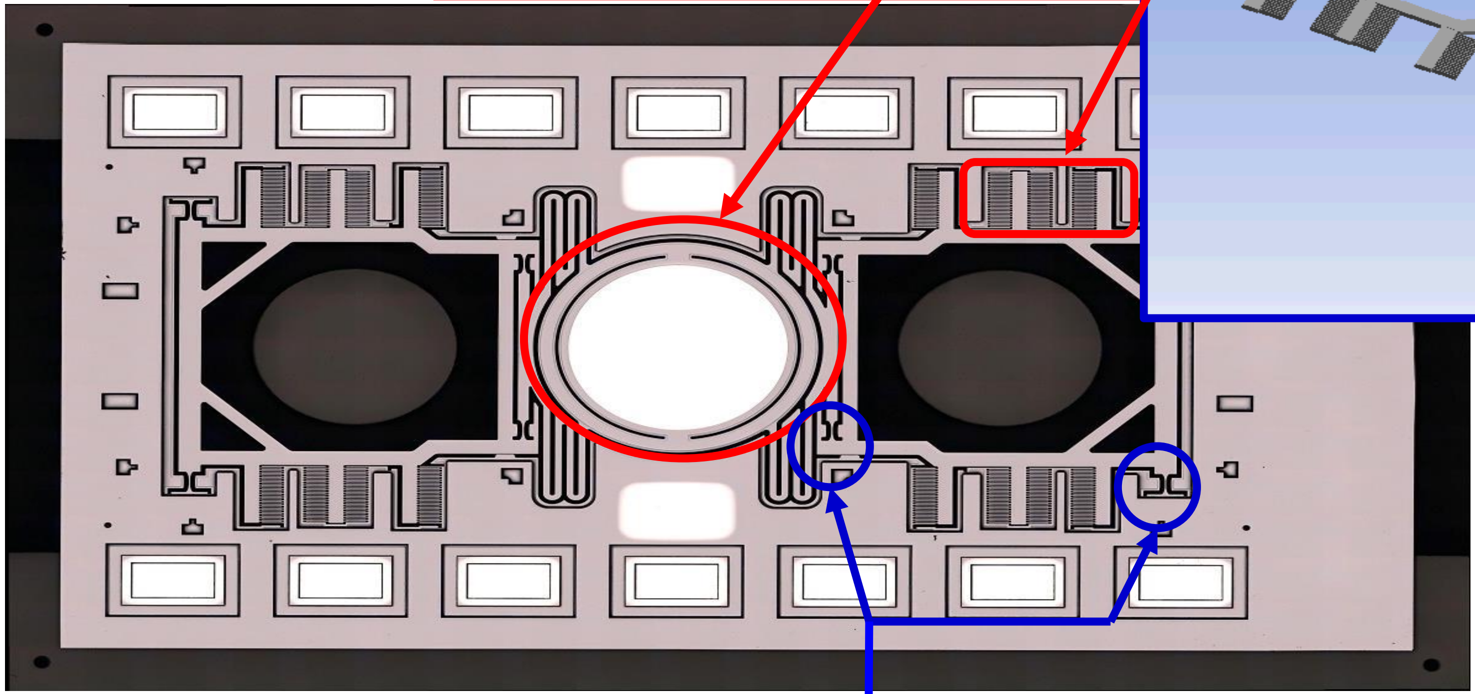
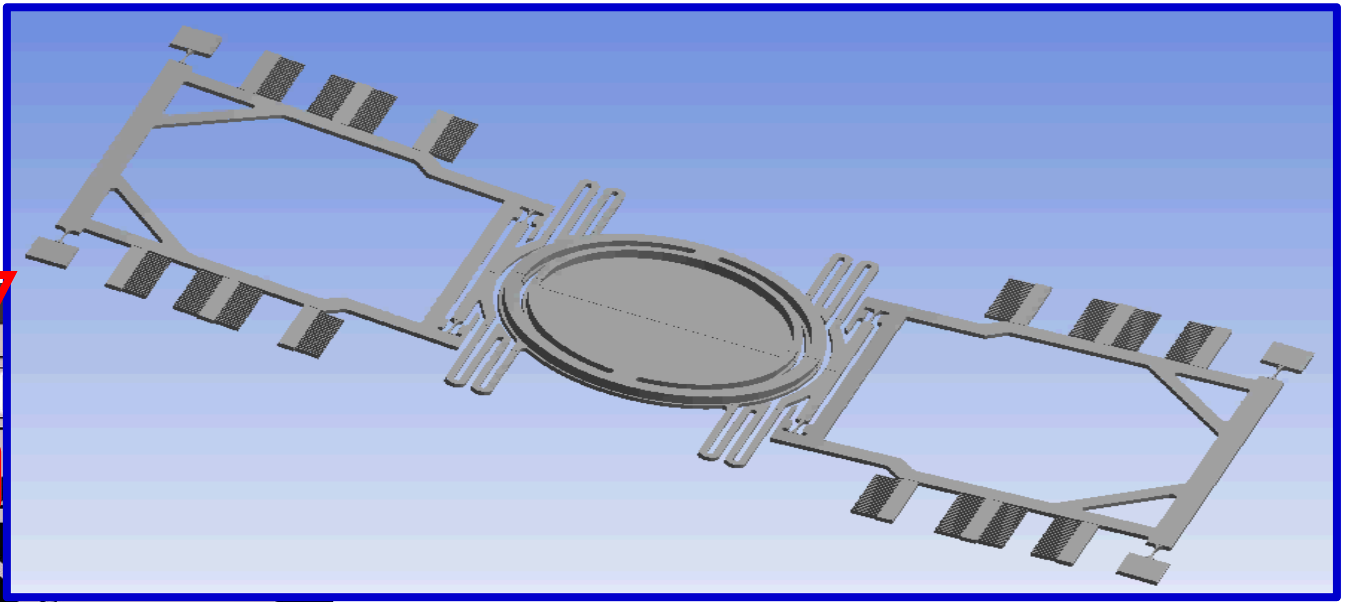
Compact FTIR engine - design concept

φ3.0 mm movable mirror
（Flat/Large diameter）

Comb tooth electrode





Torsion spring

- High SNR
  (by large mirror size)
- High resolution
  (by flat optical surface)

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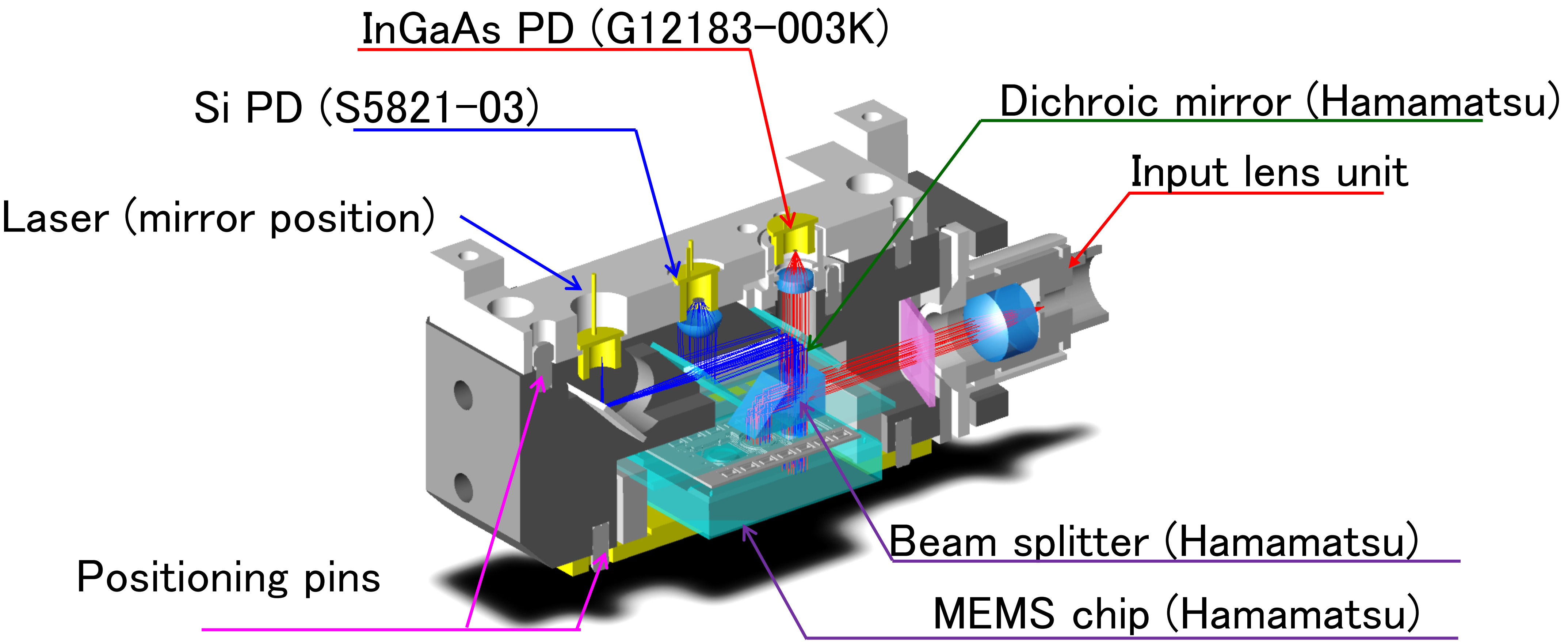
- Optical system of FTIR engine (cross-sectional view)

➢ Two interferometers separated by a dichroic mirror
➢ Passive alignments are applied with positioning pins



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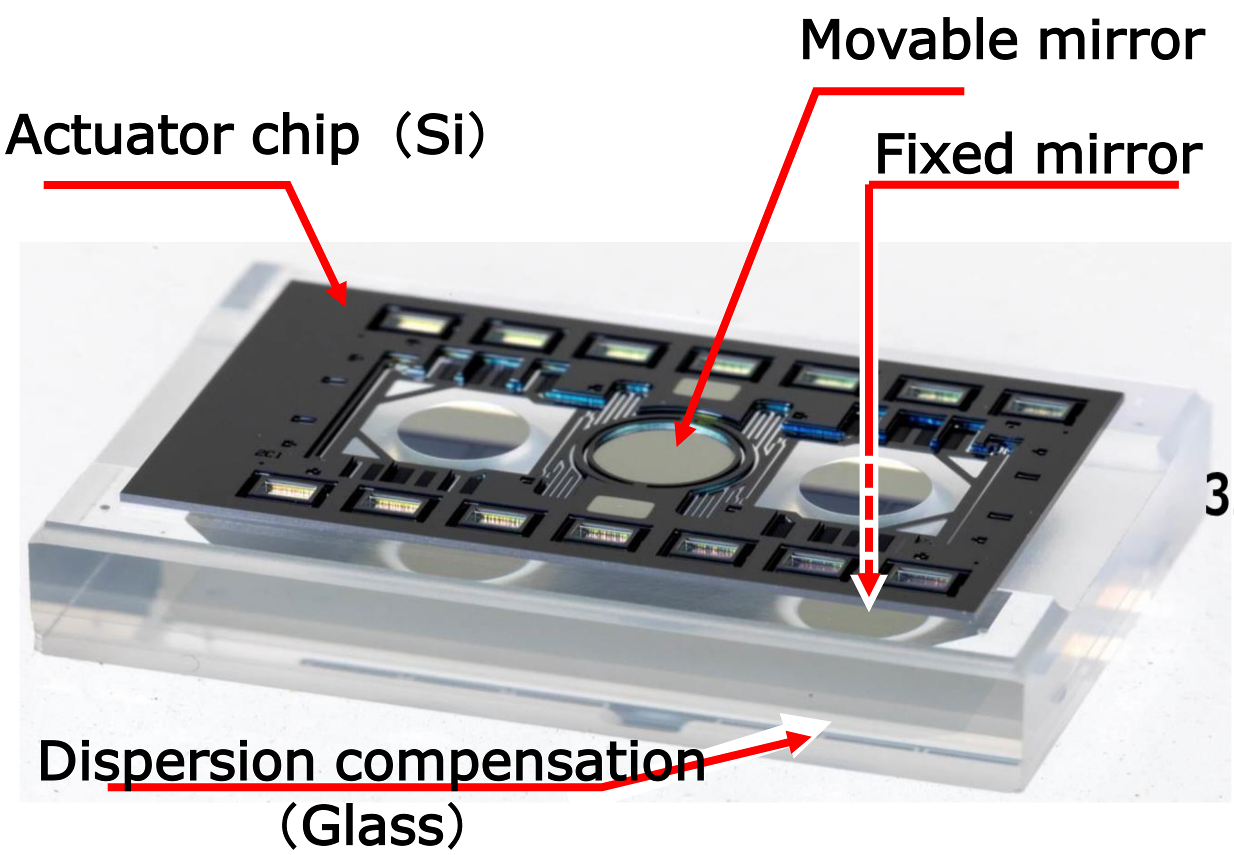
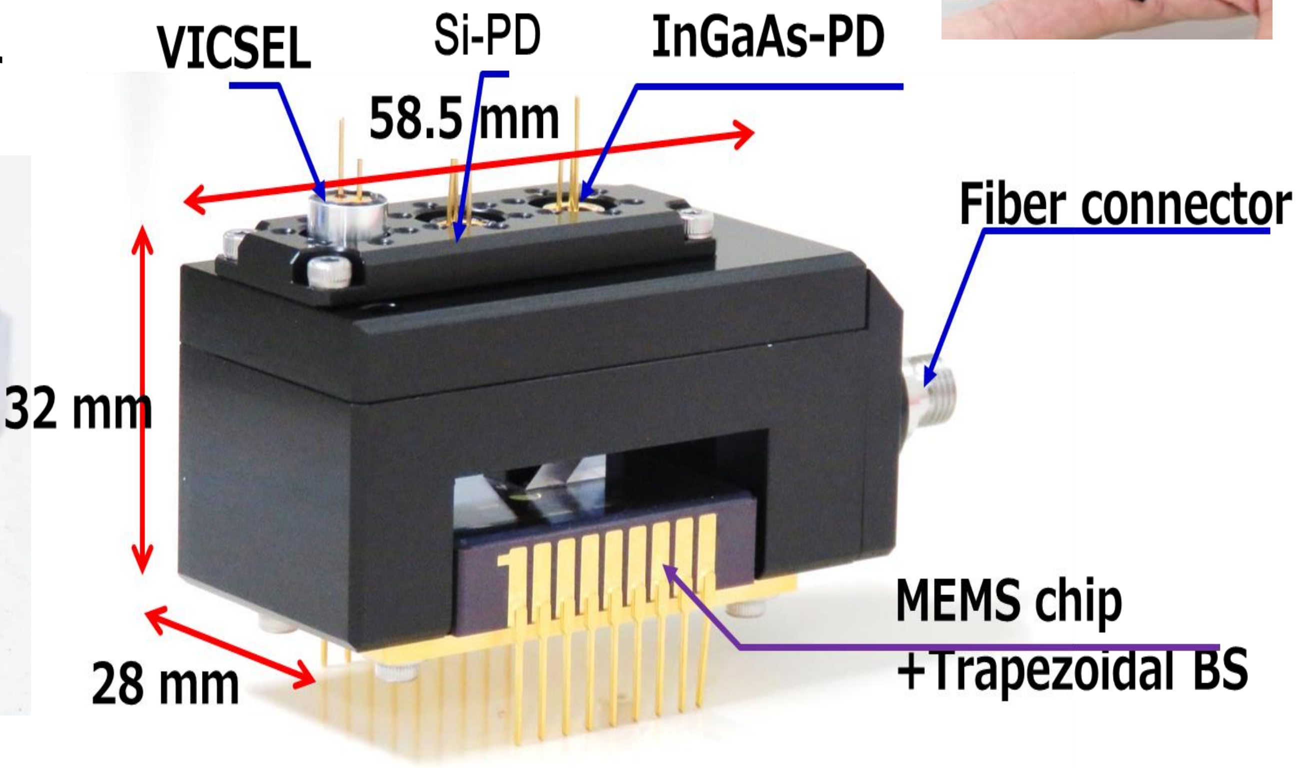
Compact FTIR engine –Test sample－



【MEMS chip】



【Compact FTIR engine】

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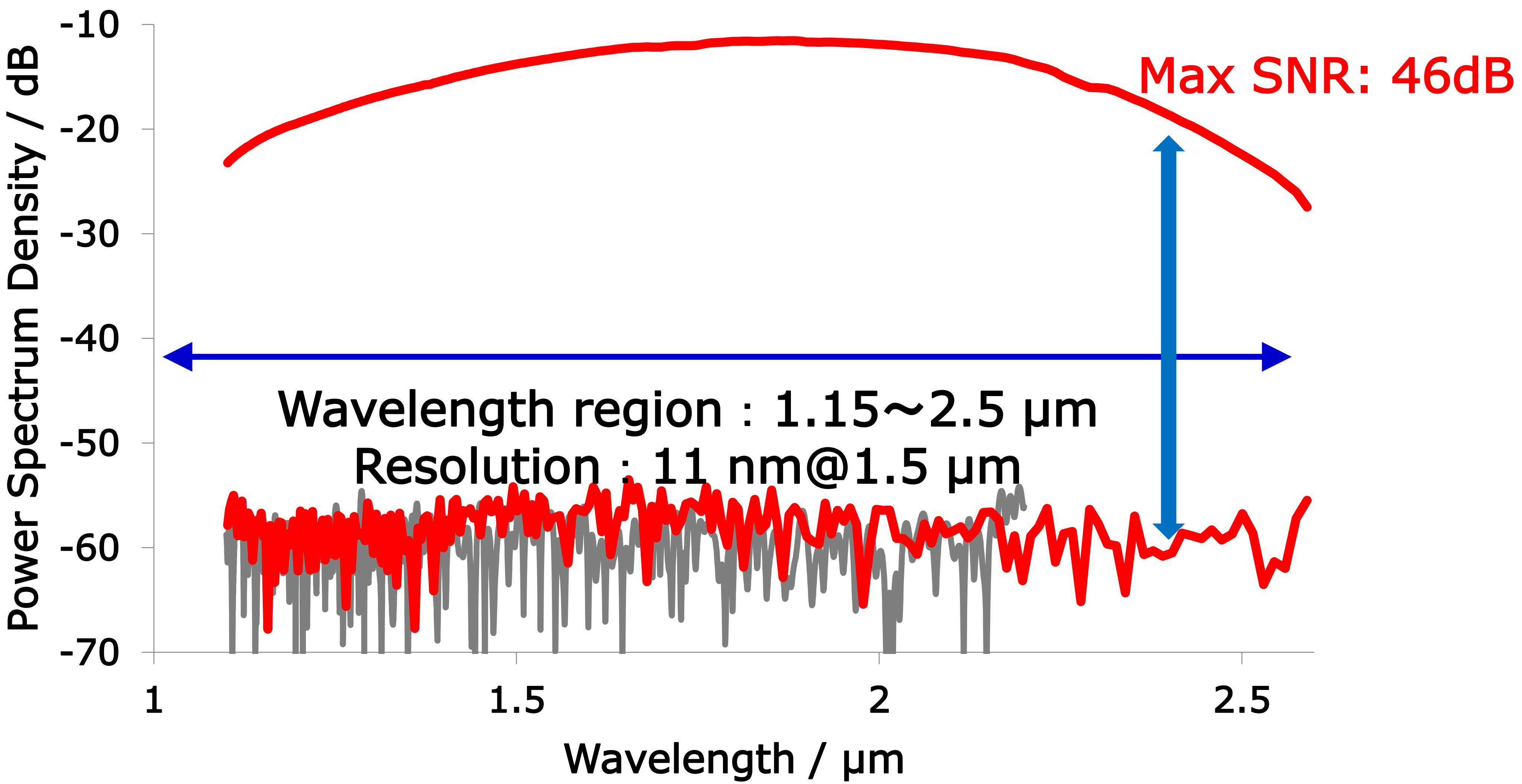
Compact FTIR engine –Evaluation result－



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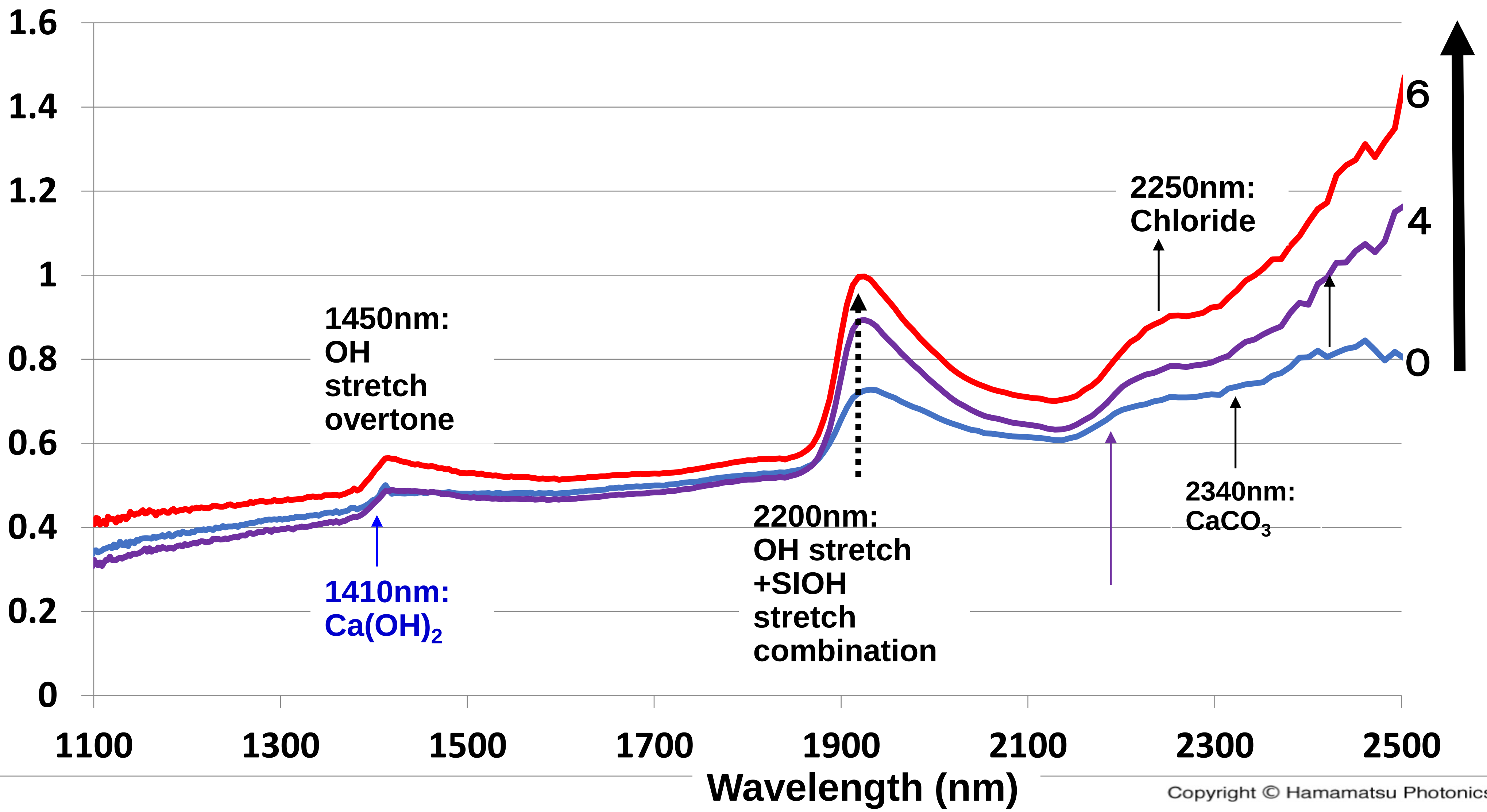
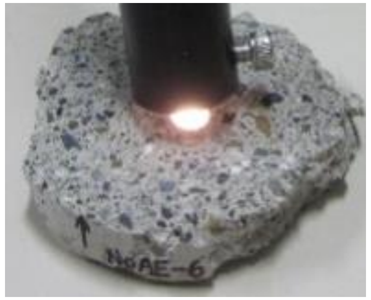
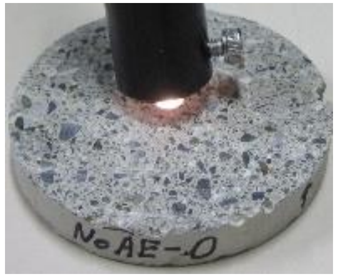
Compact FTIR engine application : degradation of mortal



Freeze-melt cycles



Degradation



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Compact FTIR engine – application : alcoholic beverage

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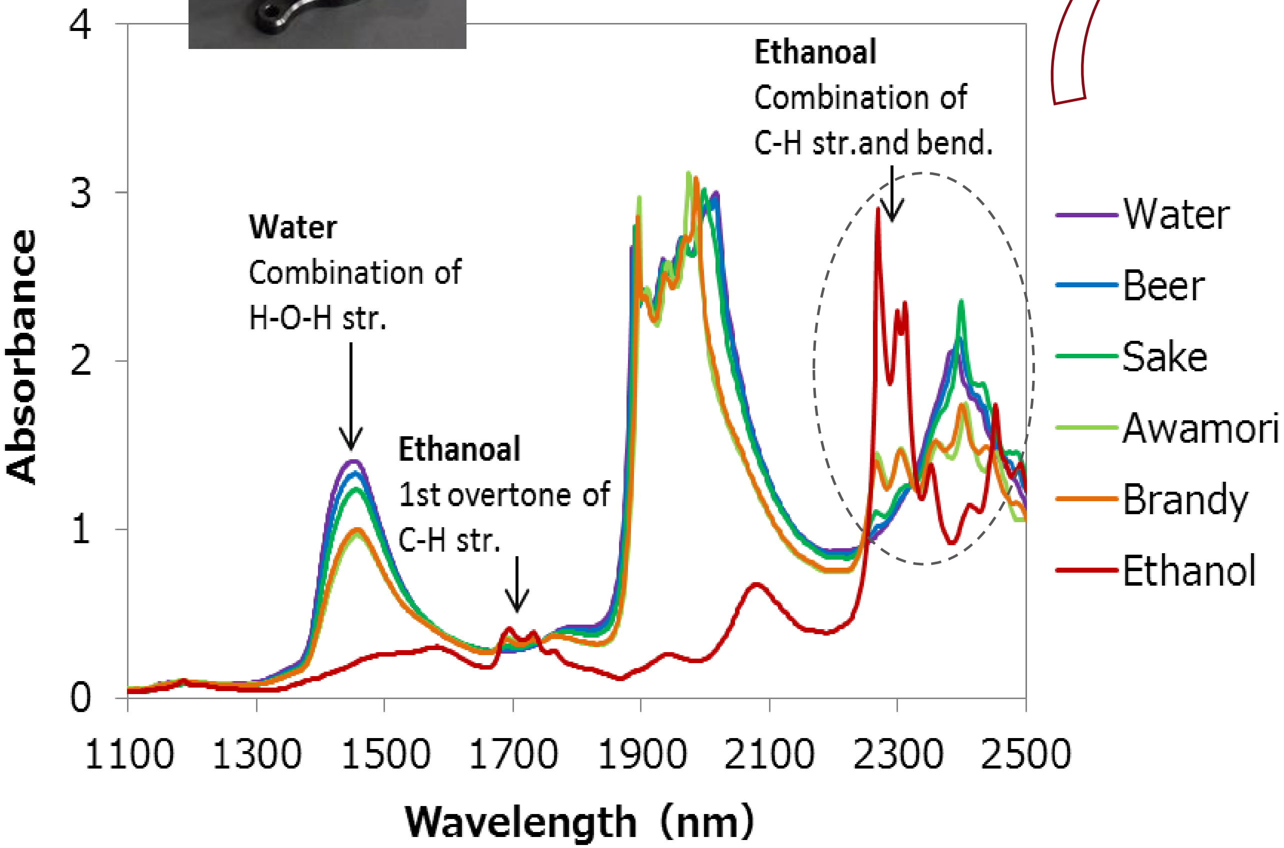
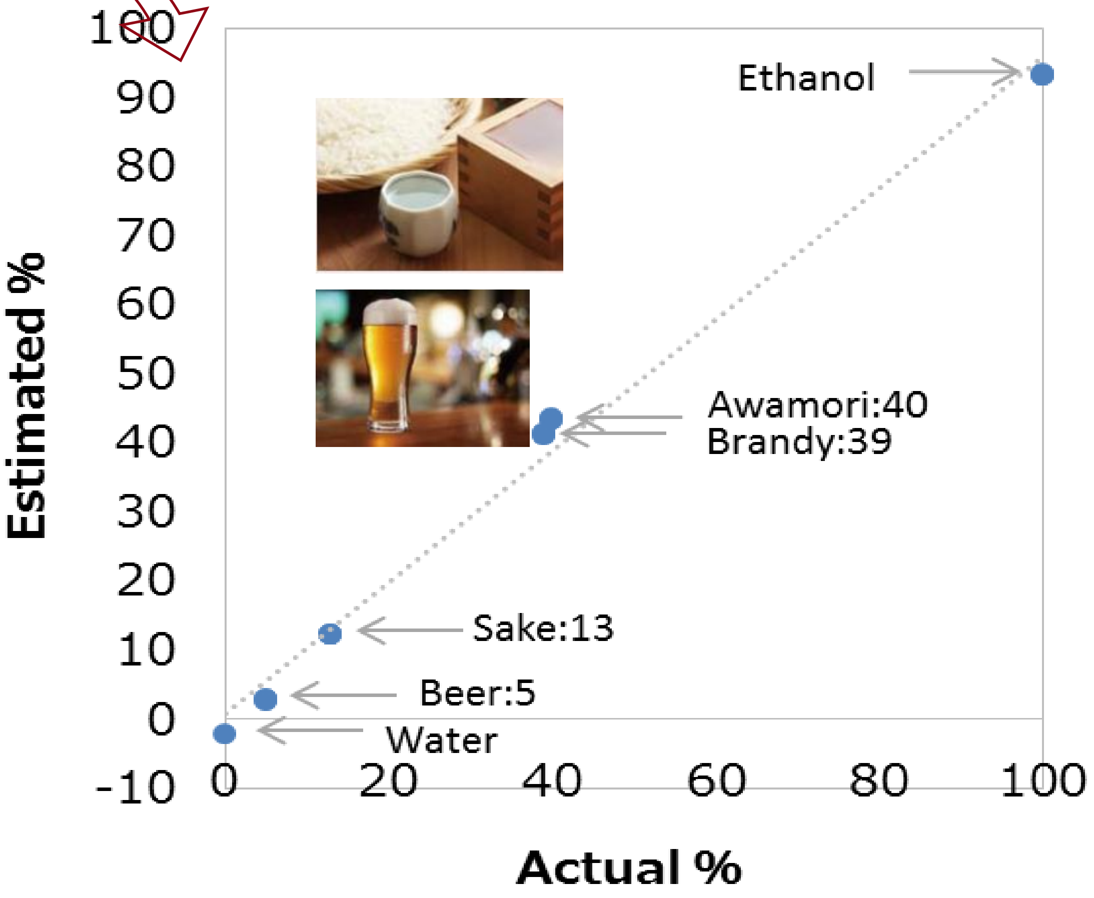
Near infrared alcohol absorption spectrum

- Transmission measurement
- 1mm quartz cell
- Light source = Halogen



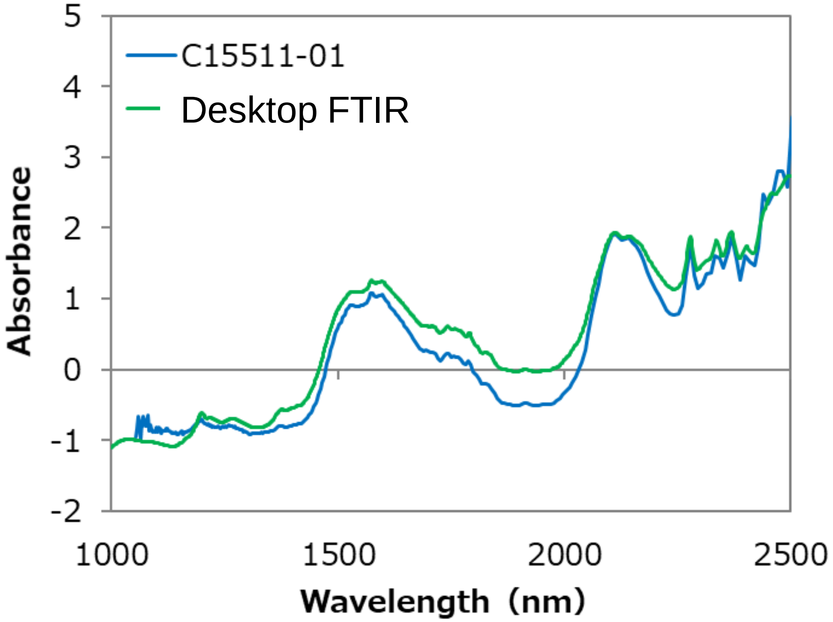
Estimation of alcohol concentration using information in a region of 2300 nm



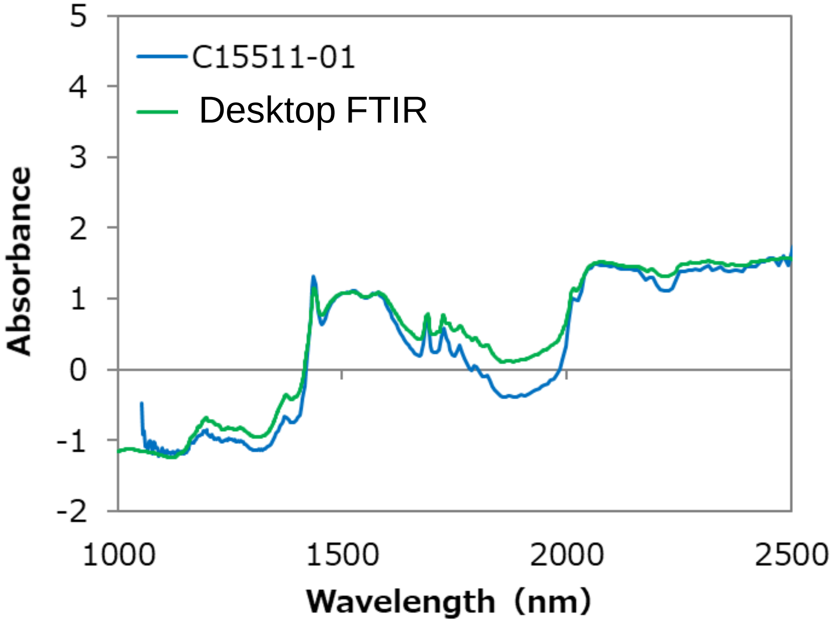
• Comparison with desktop FTIR instrument

The absorption peaks of glucose, sucrose and fructose can be found by the FTIR engine C15511-01, which is correspondent with the data by the desktop FTIR instrument

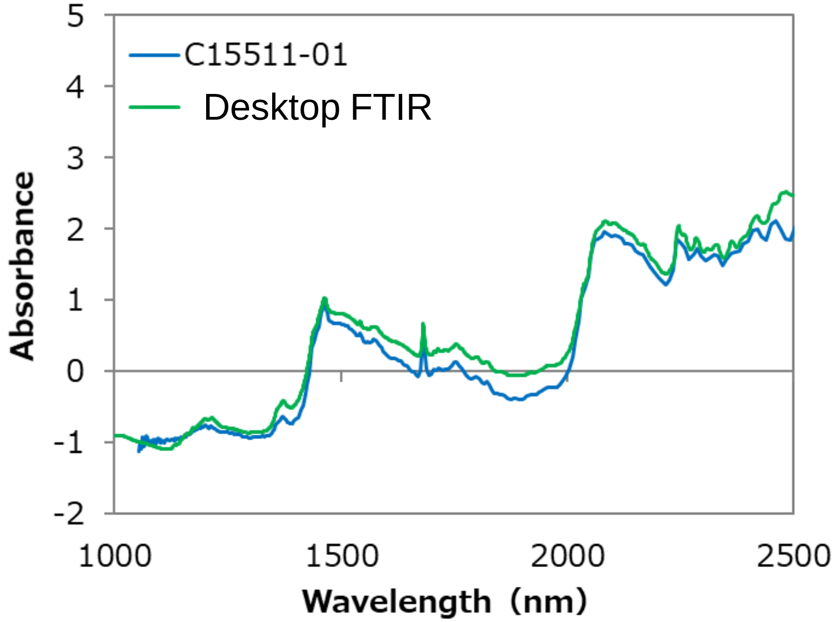
glucose



sucrose



fructose



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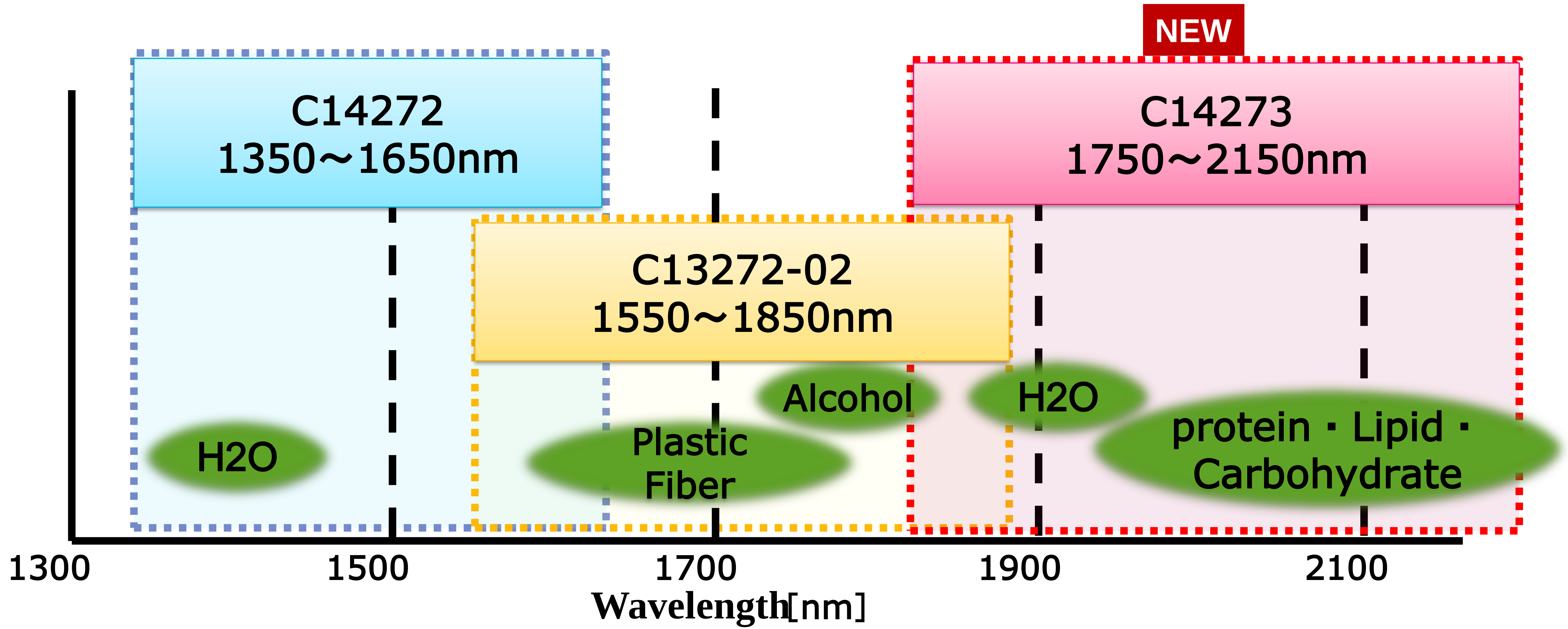
MEMS-FPI Spectral sensor –Lineup－



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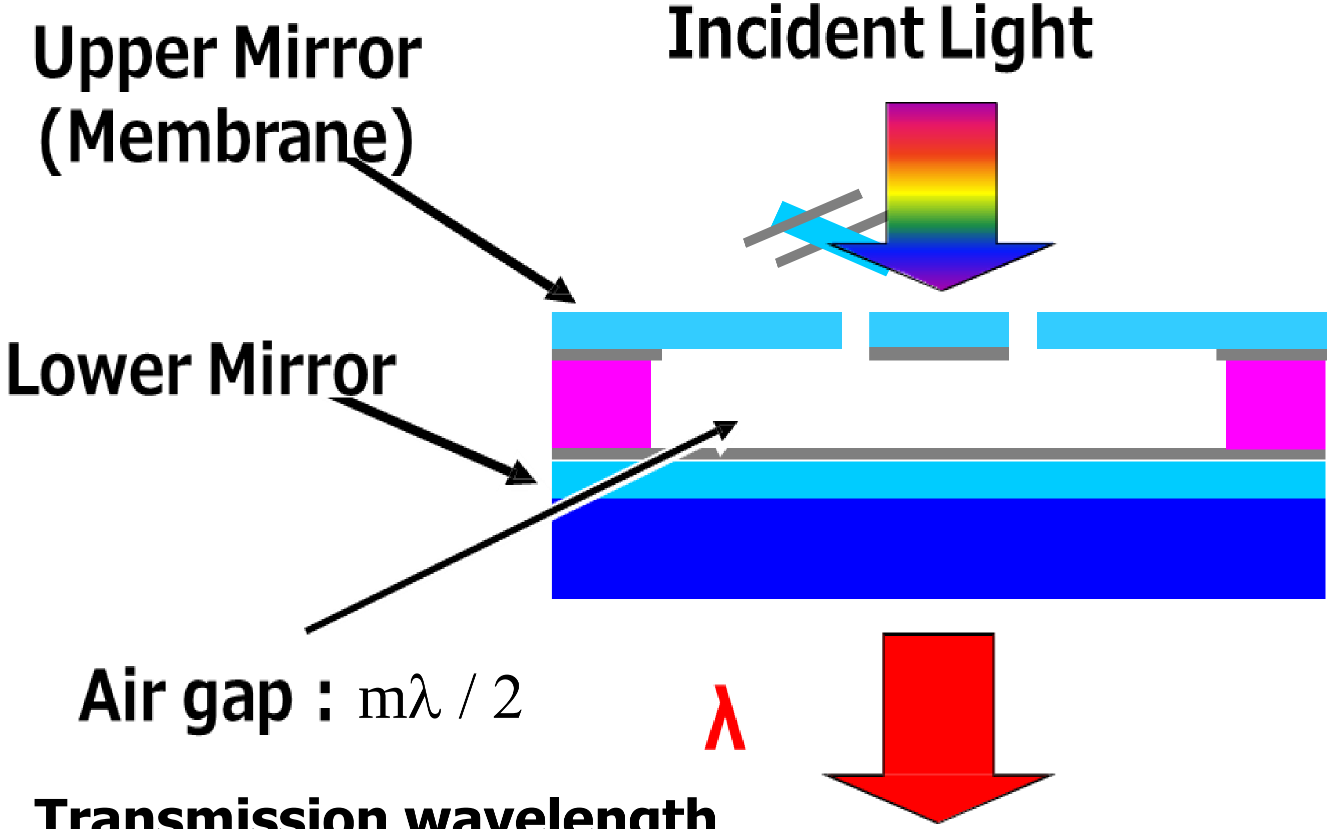
Non-Grating IR Spectrometer

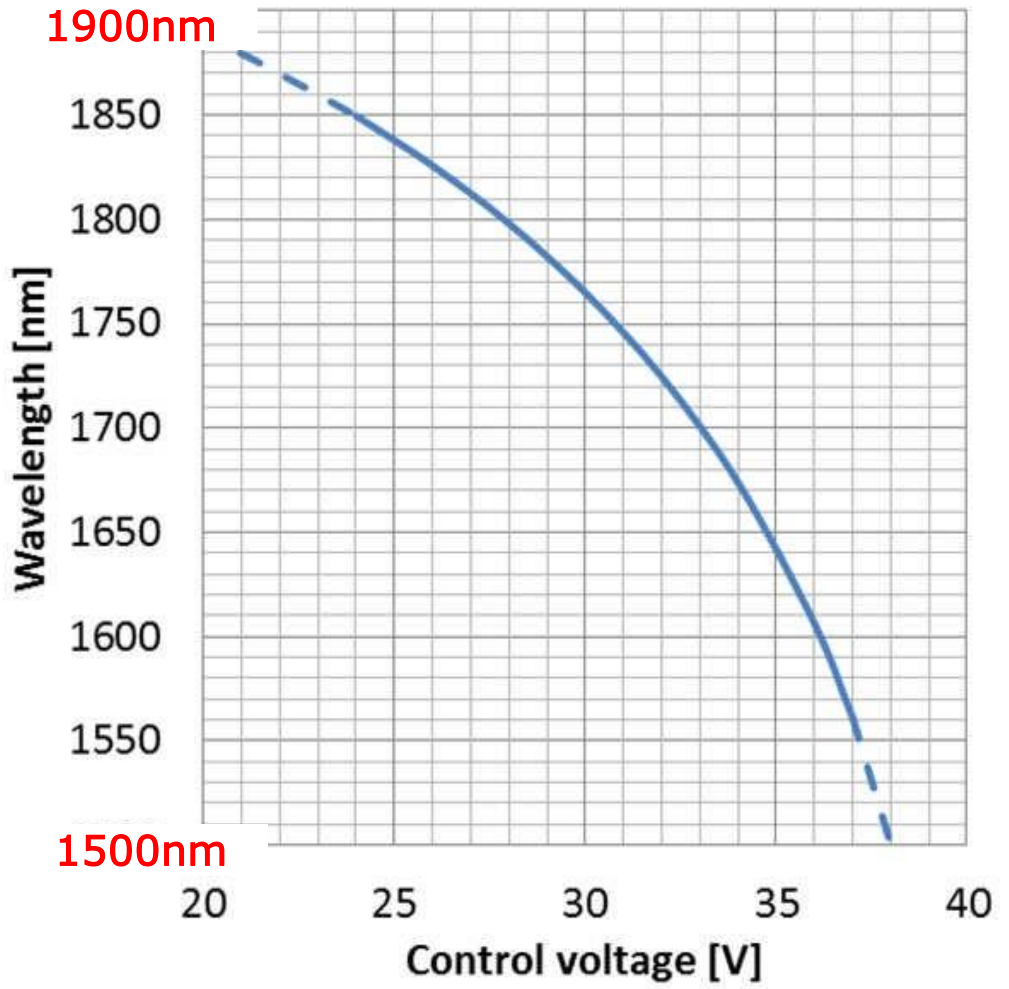
MEMS-FPI

FPI (Fabray-Perot Interferometer)

A tunable filter that adjust transmission wavelength by controlling the applied voltage



Transmission wavelength to be tuned by this air gap



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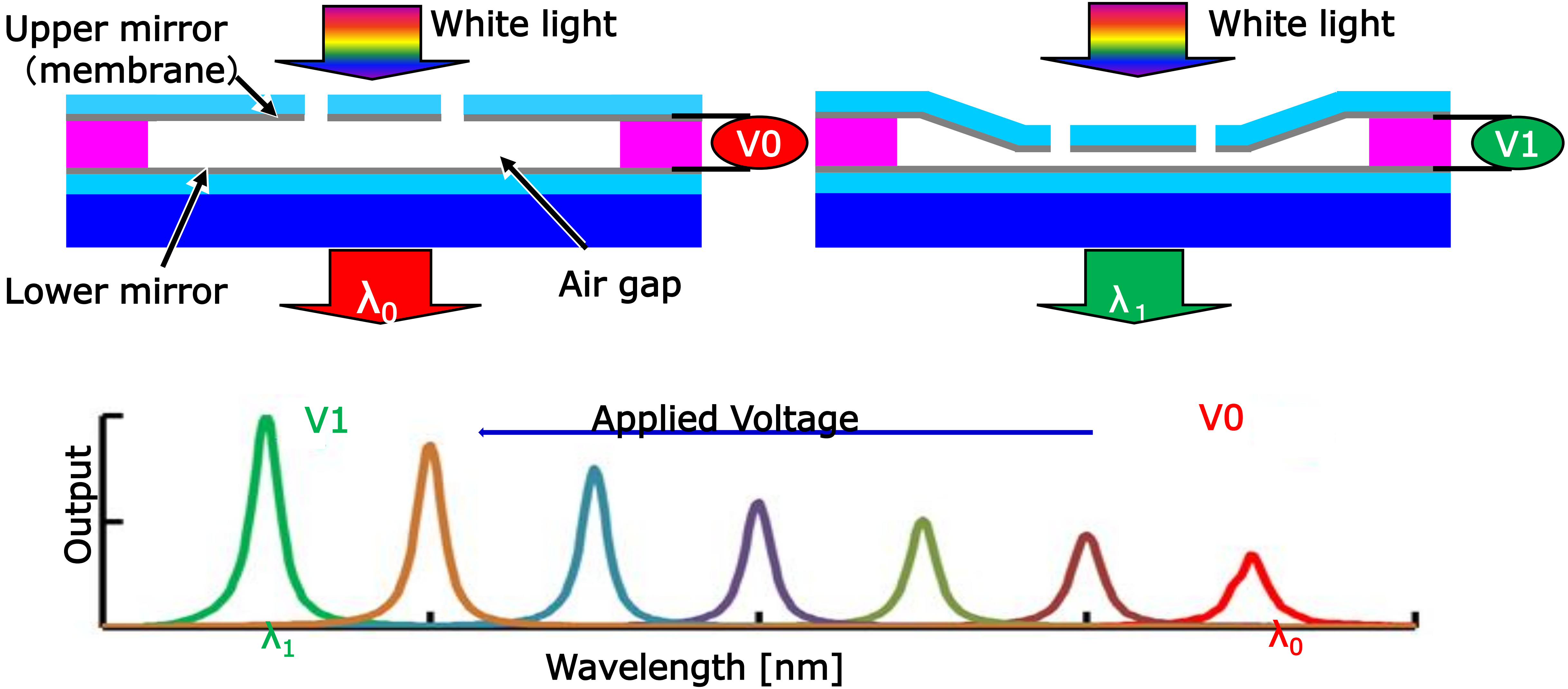
MEMS-FPI Spectral sensor –Tunable filter－

A tunable filter that adjust transmission wavelength by the applied voltage



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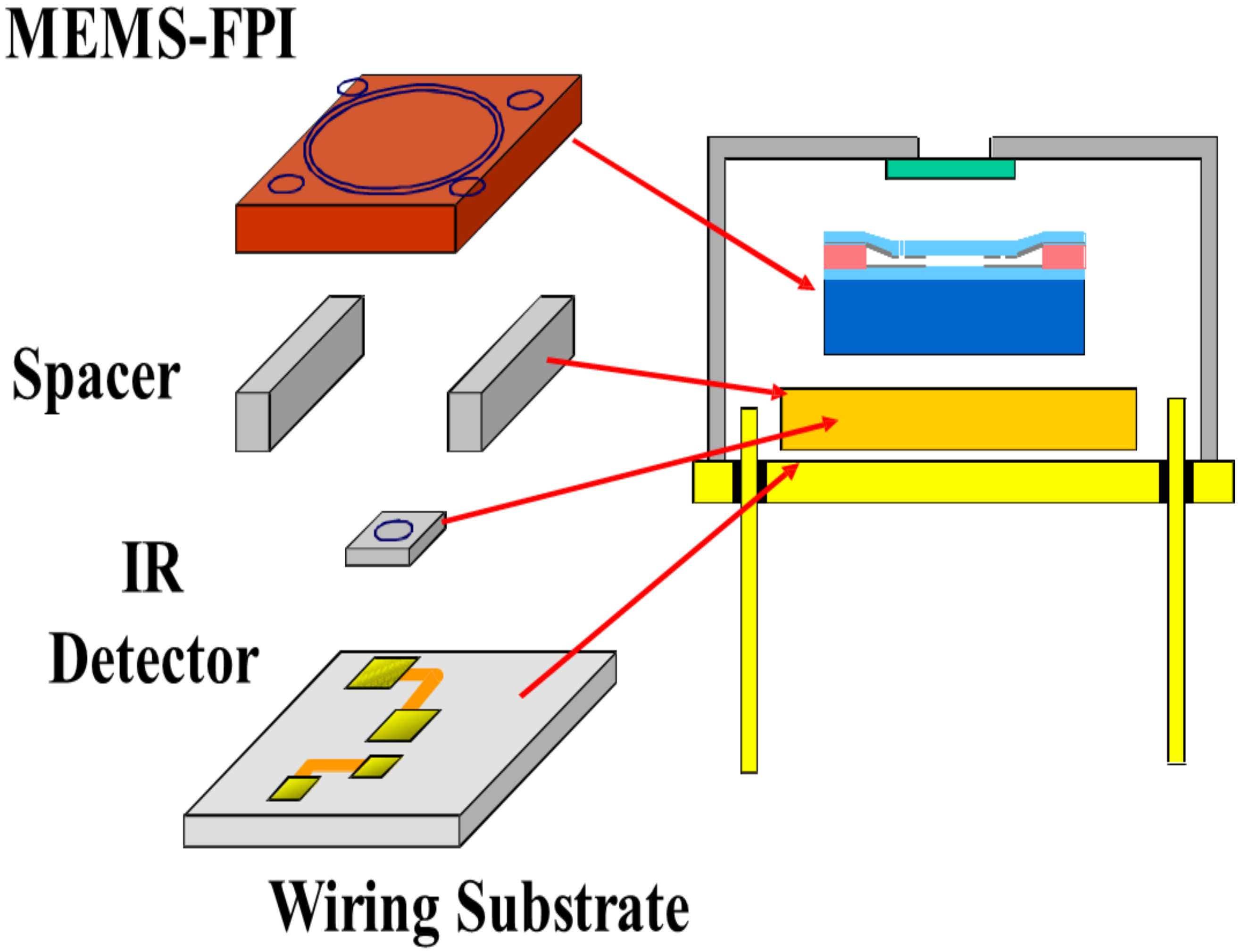
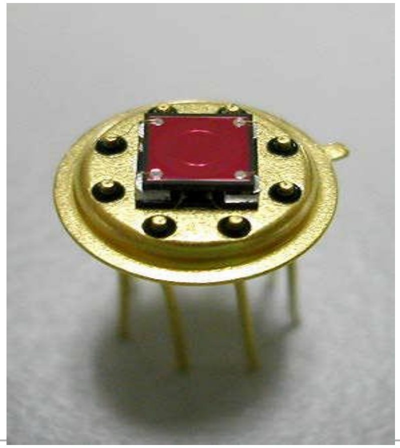
Structure of MEMS-FPI



Feature

- Small PKG : TO-5
- Super lightweight : 1g
- Hermetic PKG
- Single InGaAs-PD included
- Thermistor included
- Band pass filter included



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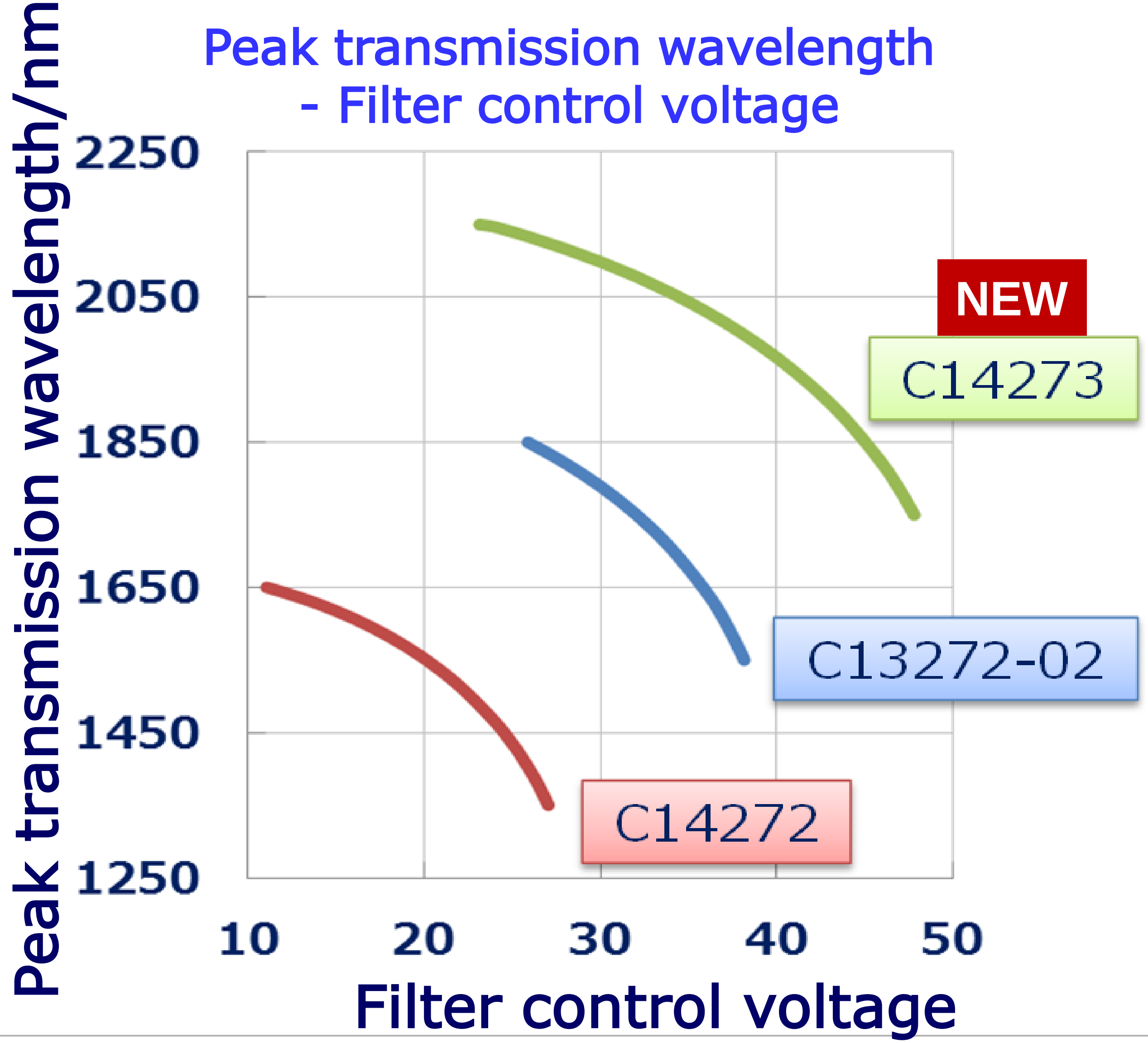
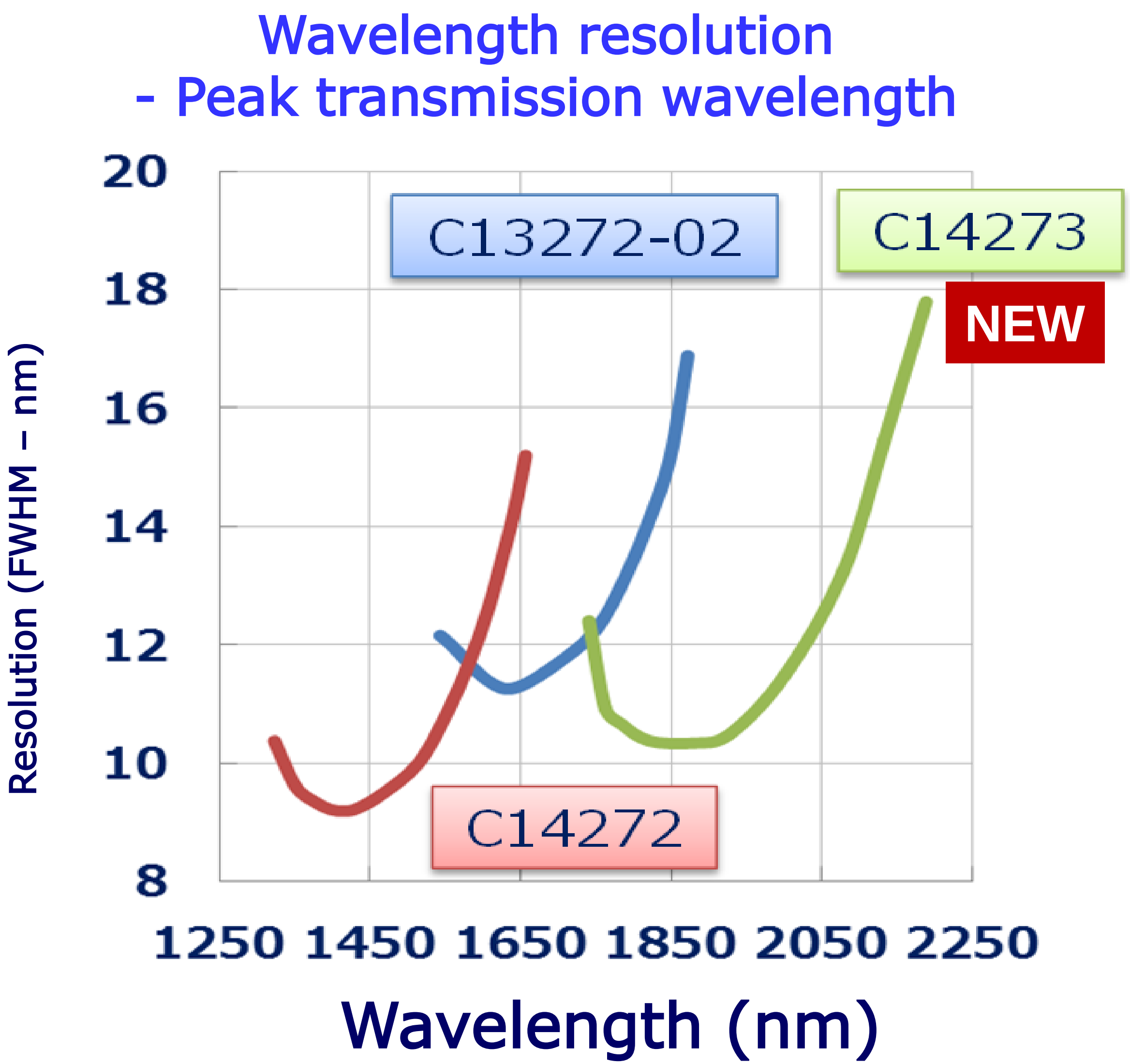
MEMS-FPI spectral sensor –Characteristics－





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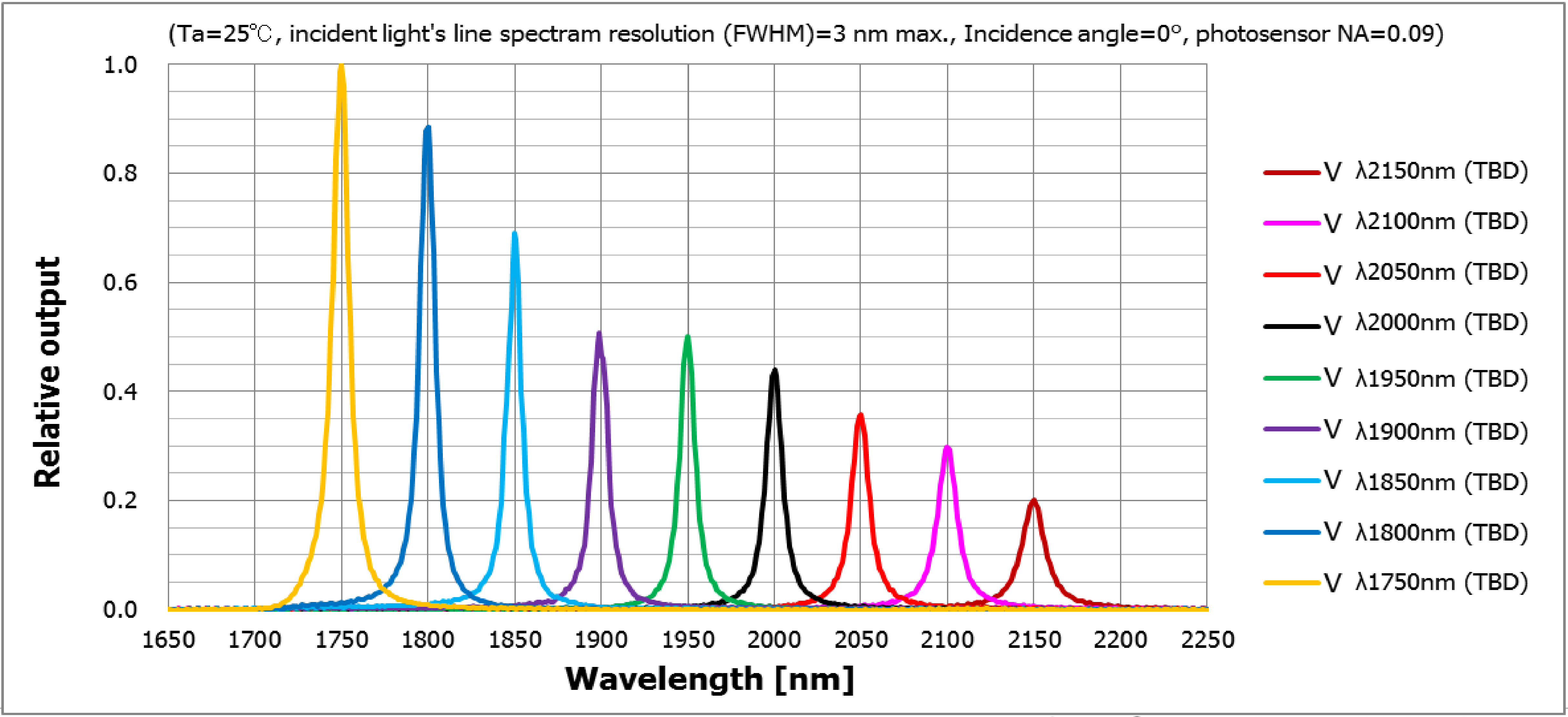
MEMS FPI : Wavelength transmission response

FPI Type : C14273 (1750～2150nm)



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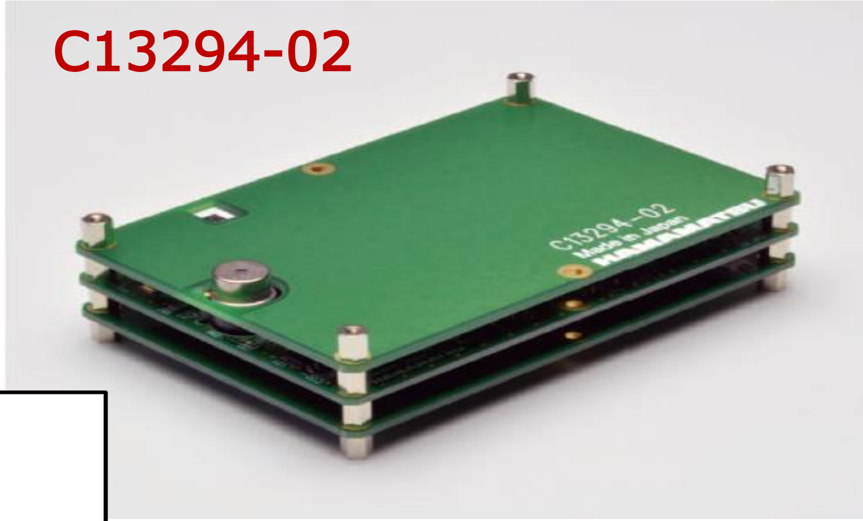
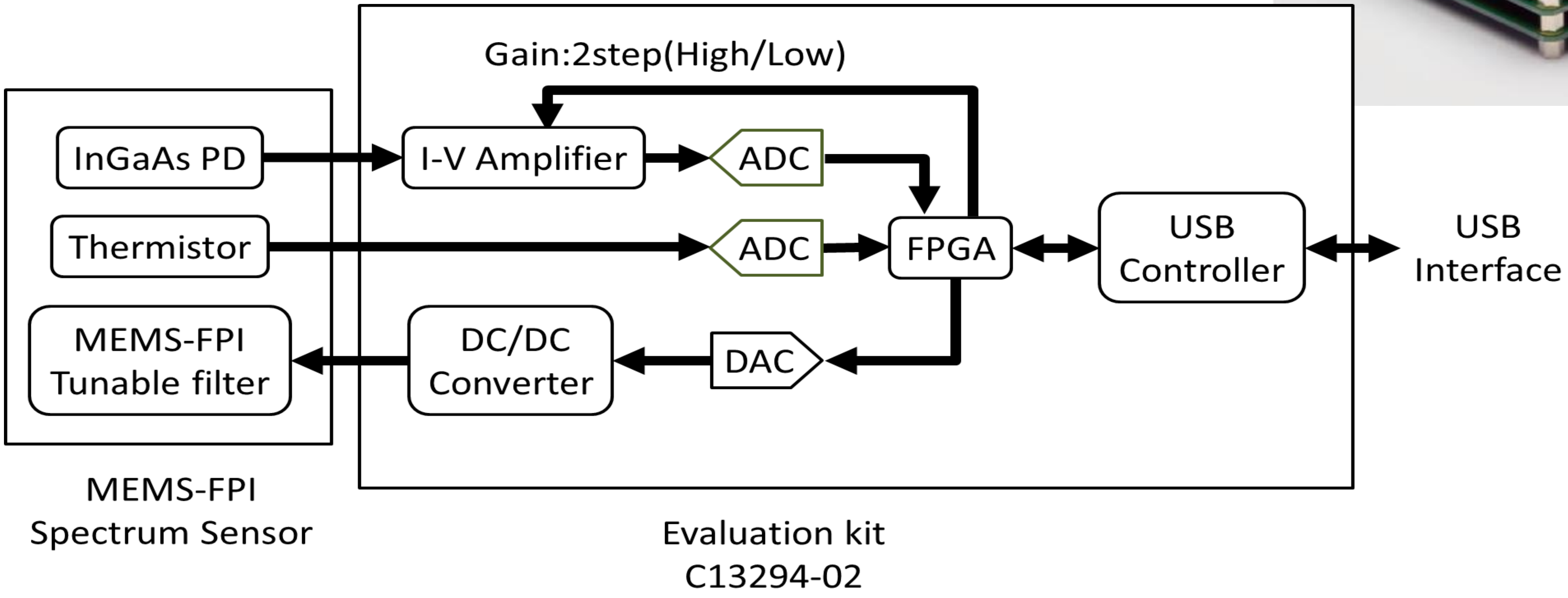
MEMS-FPI Spectral sensor –Evaluation kit－

- USB connection
- 16 bit ADC
- Gain: Low / High
- Evaluation software banddled





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MEMS-FPI spectrum module　features

UNDER DEVELOPMENT

It will be released on Spring, 2020

- **Compact・Thin**
  - Size : 74×32×16mm
- **MEMS-FPI spectrum sensor built-in**
  - 3 types C15712, C15713, C15714 are available
- **USB2.0 bus-power operation**
- **Transmission wavelength compensation**
  - Transmission wavelength shift by ambient temperature (Max.0.9nm/℃) can be compensated by circuit
- **High speed measurement**
  - <1 sec/scan is possible (at 1 nm step between 300 or 400nm wavelength range)
- **Built-in lamp**
  - Reflection measurement is available
  - Transmission measurement is also available with Lamp OFF
- **Software**
  - In addition to evaluation software, DLL can be provided soon
- **Option**
  - SMA fiber attachment (option) is available.

Operating temperature : -5~+50℃

Spectral resolution (FWHM)

C15712 : 18nm
C15713 : 20nm
C15714 : 22nm

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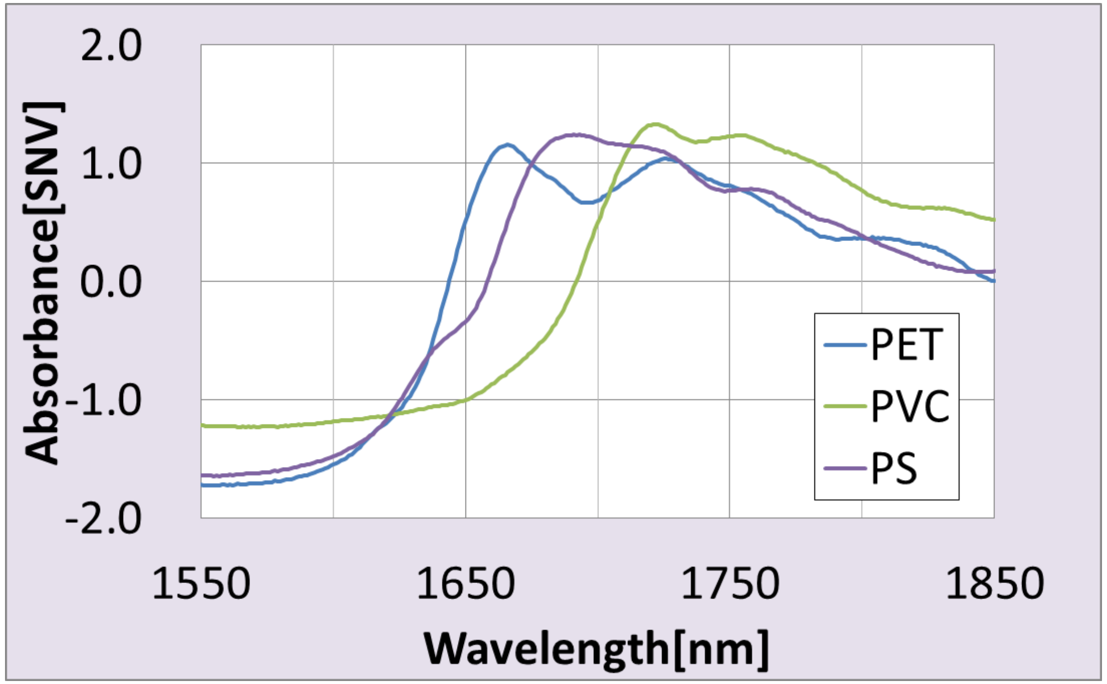
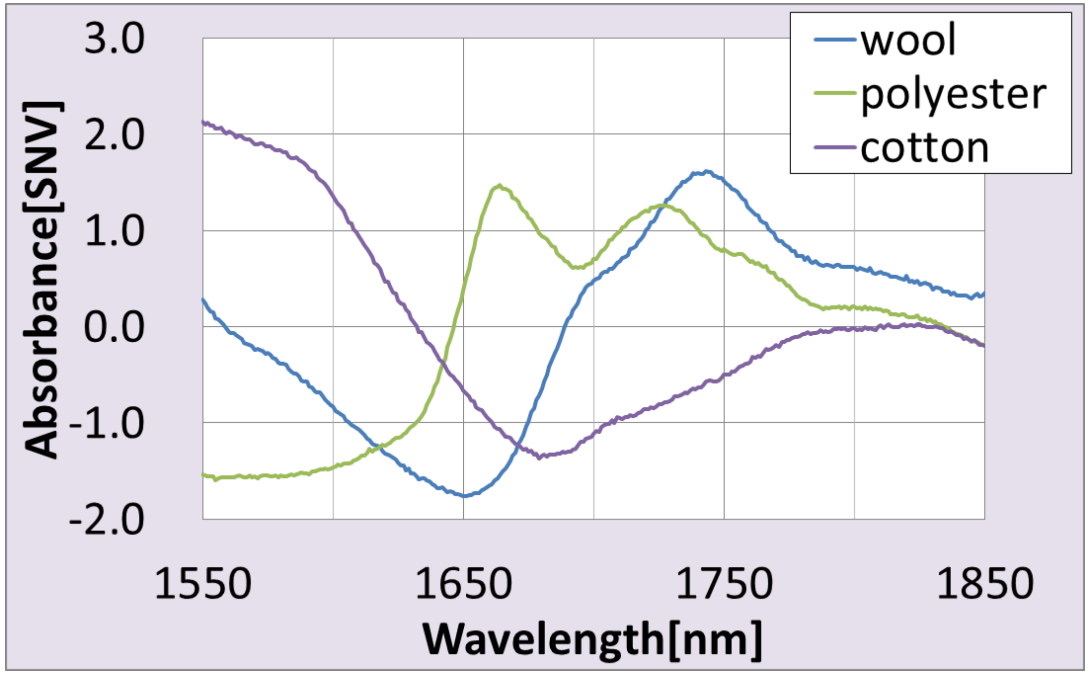
MEMS-FPI spectrum module　application example

■Plastics

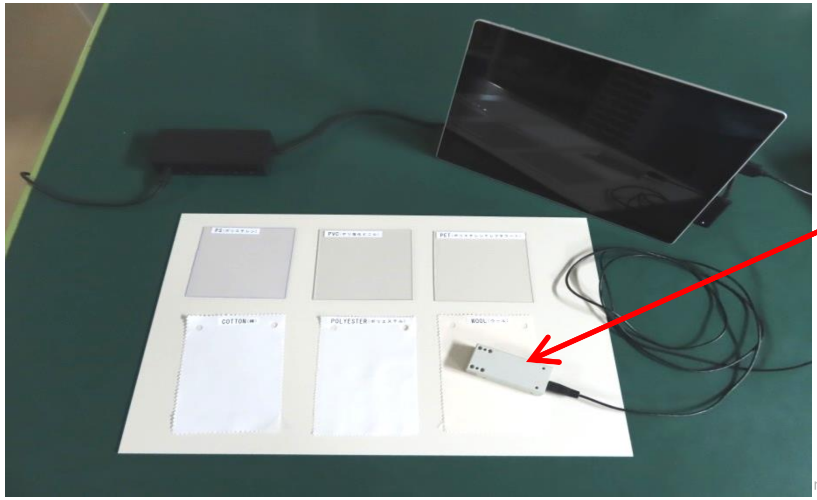


■Fabrics



Measured by reflection

Material identification by spectrum differences



MEMS-FPI module

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FPI & FTIR Summary Table

Item	MEMS-FPI spectral sensor	Compact FTIR
Method	Fabry-Perot interferometer Tunable filter	Michelson interferometer FTIR
Wavelength length region	1.35-1.65μm, 1.55-1.85μm, 1.75-2.15μm	1.15-2.5μm
Wavelength resolution	18nm@1.65μm, 20nm@1.85μm, 22nm@2.15μm	11nm@1.5μm
Detector	InGaAs PIN PD single element	InGaAs PIN PD
Light incident method	Window	Optical fiber (SMA)
Product form	Sensor component or module Module – Temperature Compensation Component – User calibrate	Module

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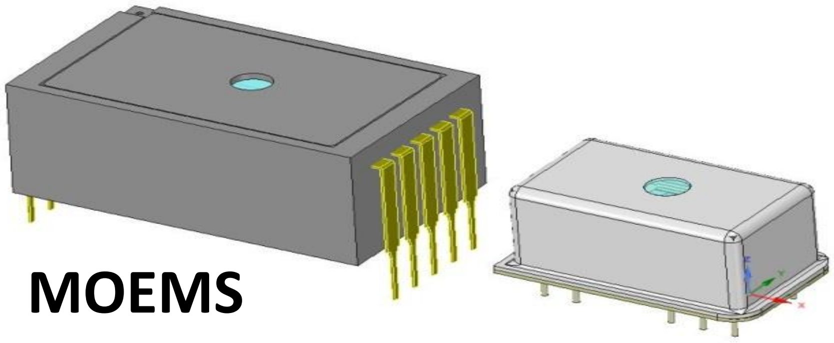
Market Demand – Move the instrument to the sample



MOEMS spectrometer

Micro spectrometer

27x17x13mm

Pocket Spectrometer for Color Analysis

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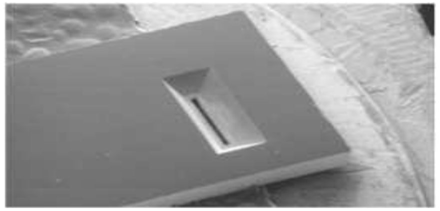
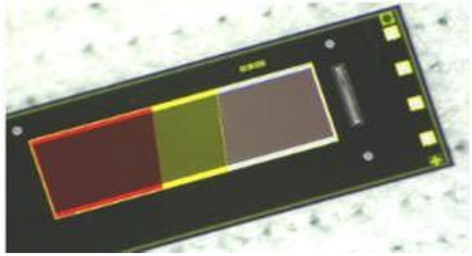
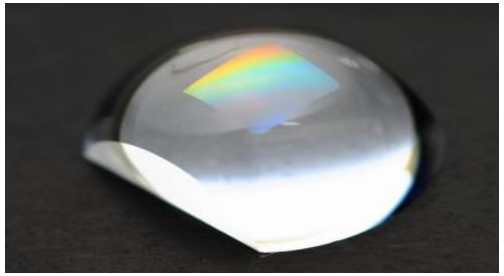
Components for Mini& Micro-Spectrometers



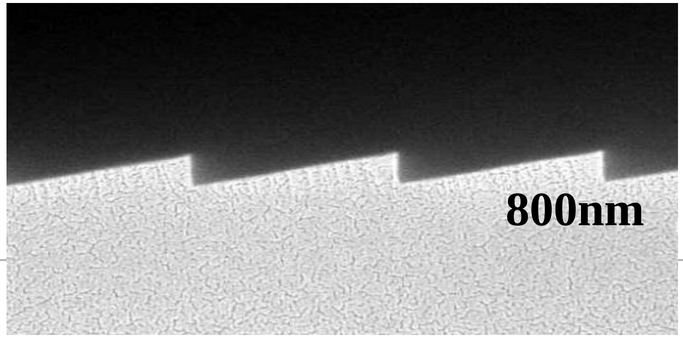
Optical slit on the same CMOS image sub.



Color Filter on CMOS image sensor

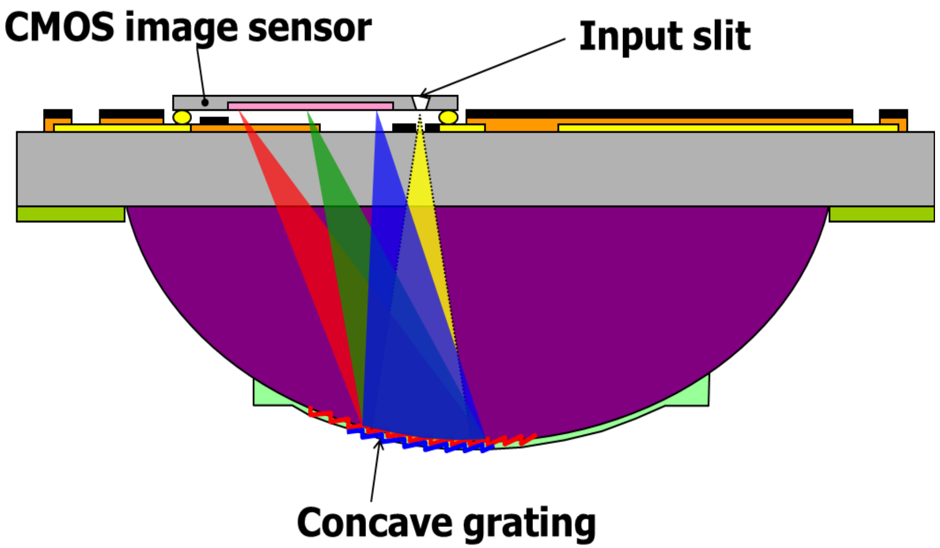


Master Lens for Replication

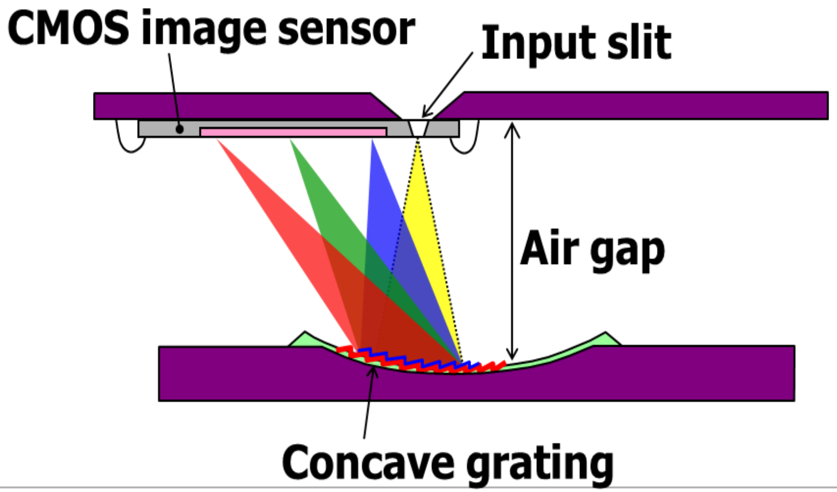


Blazed Grating by Nanoimprint

1st Gen. Mini-Spectrometer



2nd Gen. Micro Spectrometer



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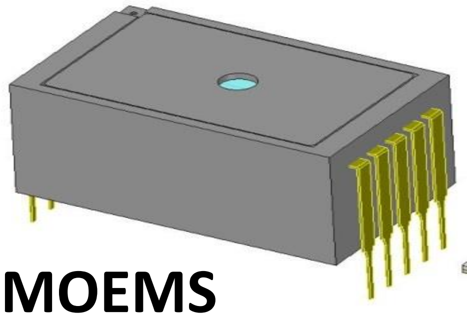
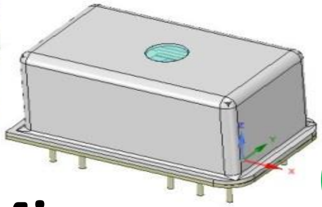
Strategy for much smaller Spectrometer



MOEMS spectrometer



Micro spectrometer

?

Spectrometer inside smartphone!

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Optical design

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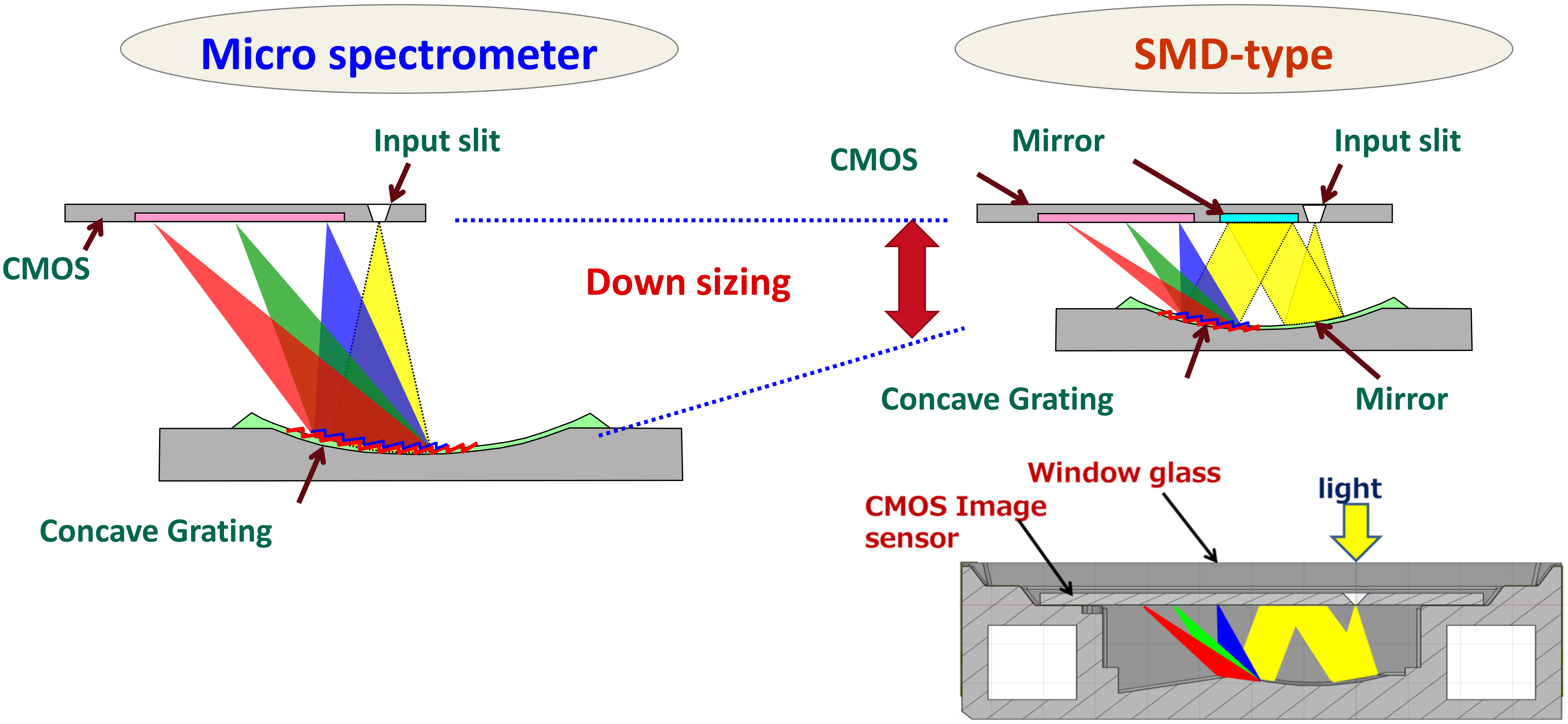

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Components of MOEMS Spectrometer

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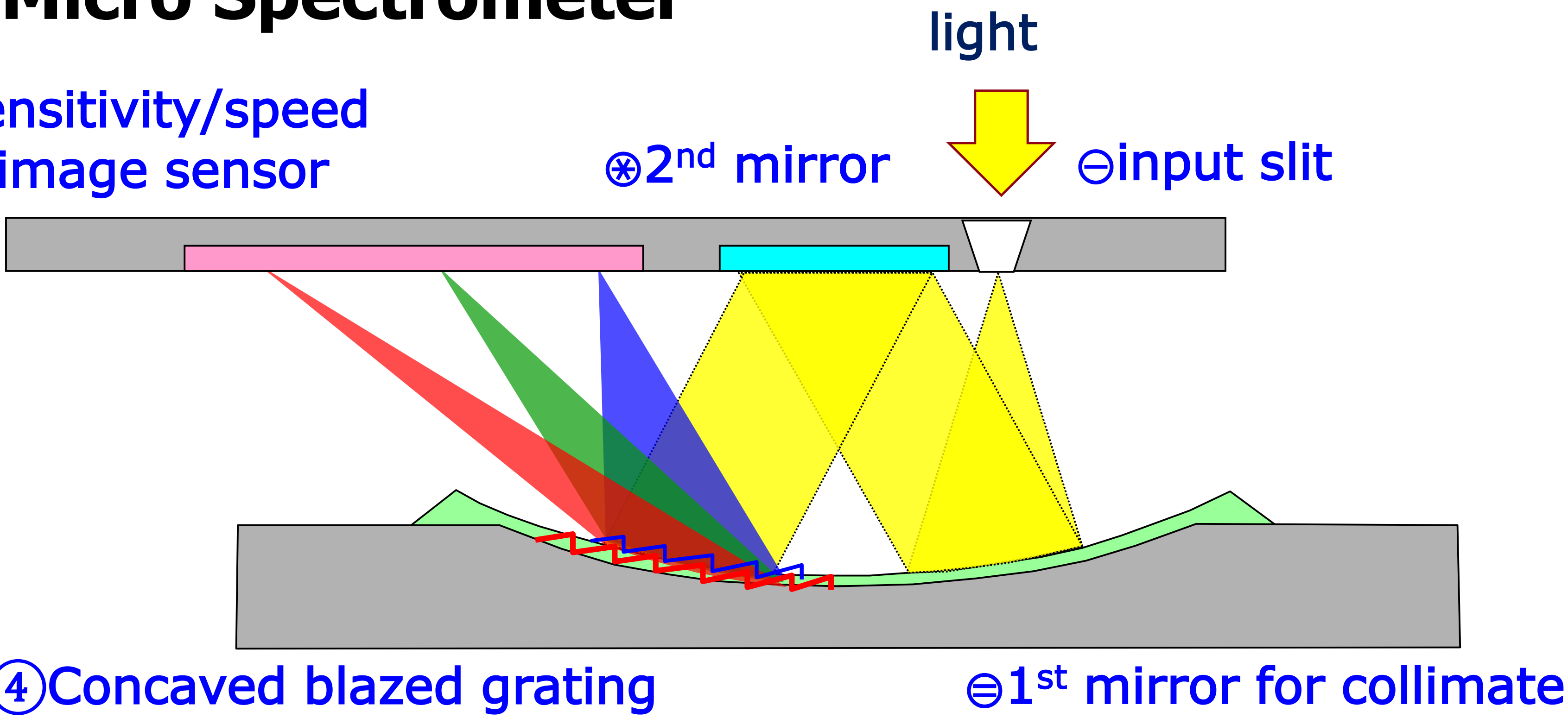
3rd Gen. Micro Spectrometer



- ✓ Integrated slit and mirror to CMOS
- ✓ Formed grating and mirror on concave

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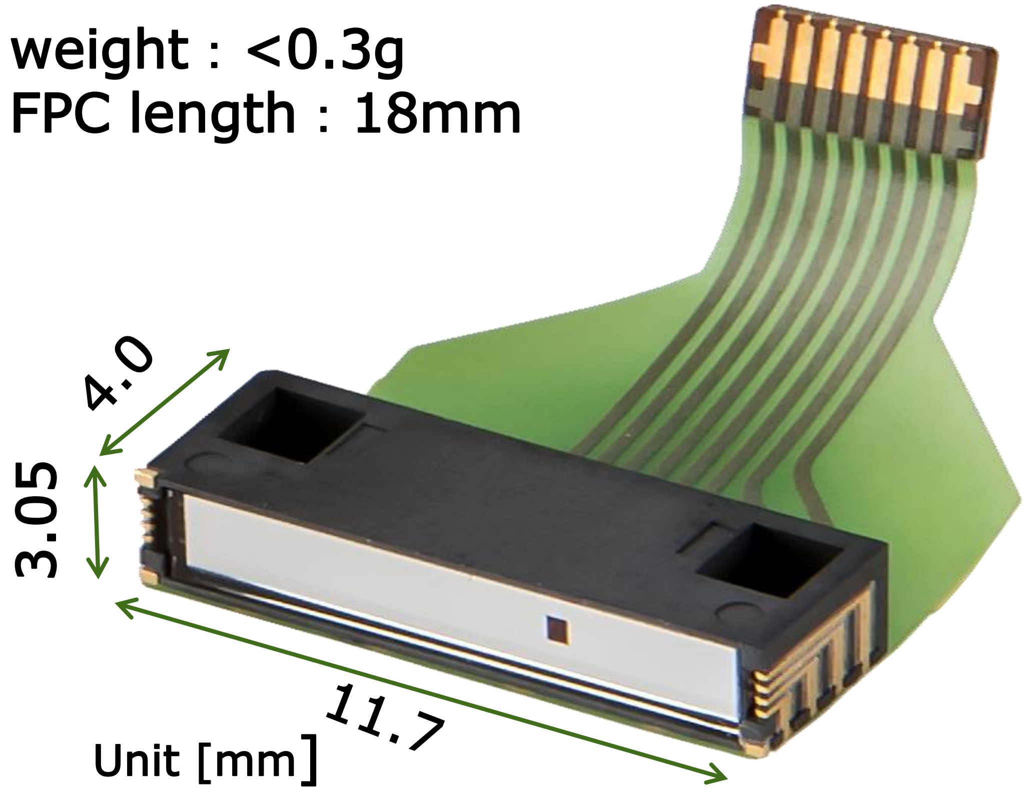
Micro -spectrometer SMD type－C14384MA－

weight：<0.3g
FPC length：18mm



➢ Feature

- Grating type
- Ultra compact, light weigt
- Thin type, Side looker
- Wavelength：640～1050nm
- High sensitivity, high speed
- Flexible cable connection

➢ Target market

- food, agriculture, environment monitor

The smallest size as a grating type spectrometer !

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NEW

Mini-spectrometer SMD series - Characteristics -

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Construction / Optical characteristic

Item	C14384MA	Unit
Spectral response range	640-1050	nm
Number of pixels	256	pixels
Clock pulse frequency	5	MHz
Slit size	15×300	μm
NA	0.22	-
Spectral resolution (FWHM)	20(Max.)	nm
Wavelength temperature dependence	±0.1	nm/℃
Wavelength reproducibility	±0.5	nm
Spectral stray light	-23	dB

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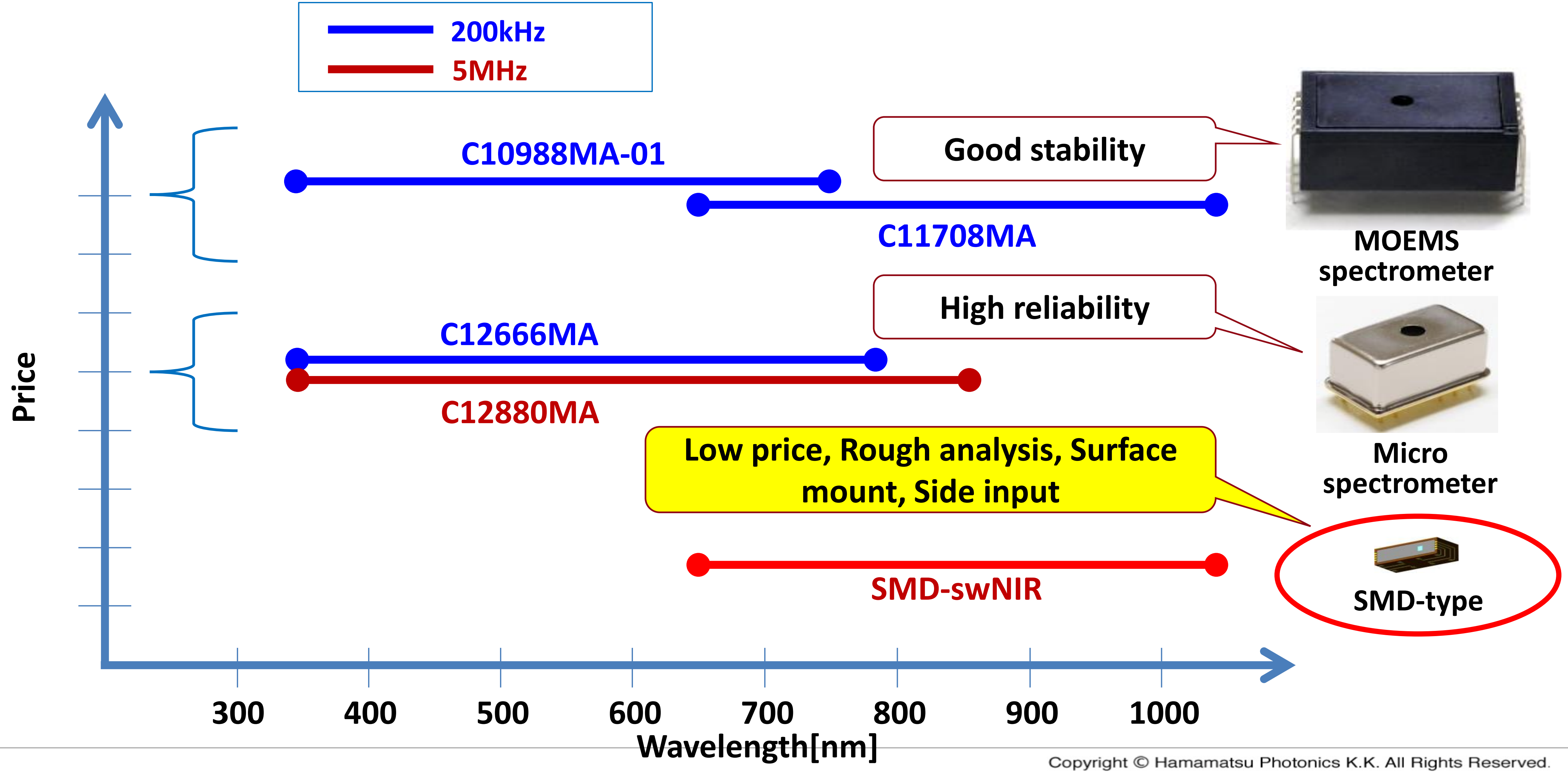
Line-up of spectrometers using MOEMS grating



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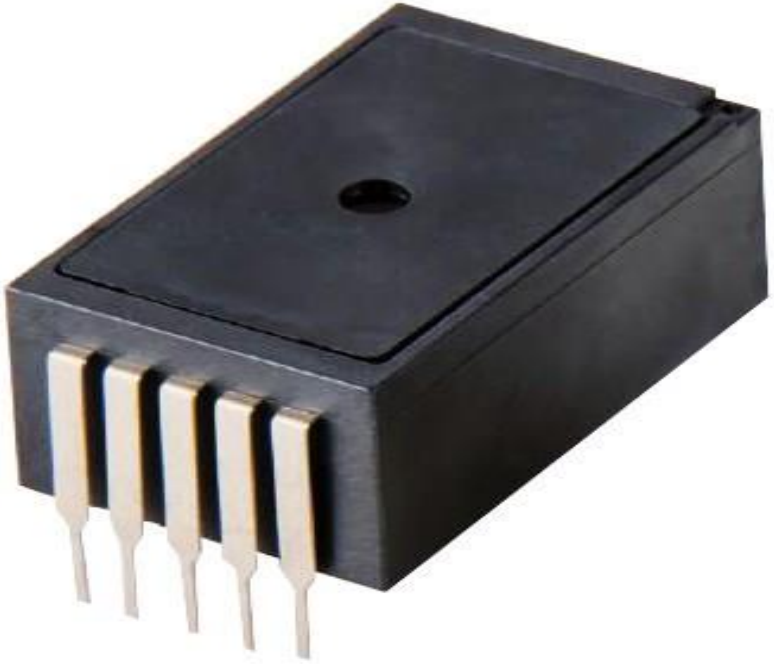
Grating type compact spectrometer series

MS series
weight : 9g
C10988MA(340～750nm)
C11708MA(640～1050nm)



Micro series
weight : 5g
C12666MA(340～780nm)
C12880MA(340～850nm)

SMD series
weight : <0.3g
C14384MA(640～1050nm)

\1 Coin

volume:1/40

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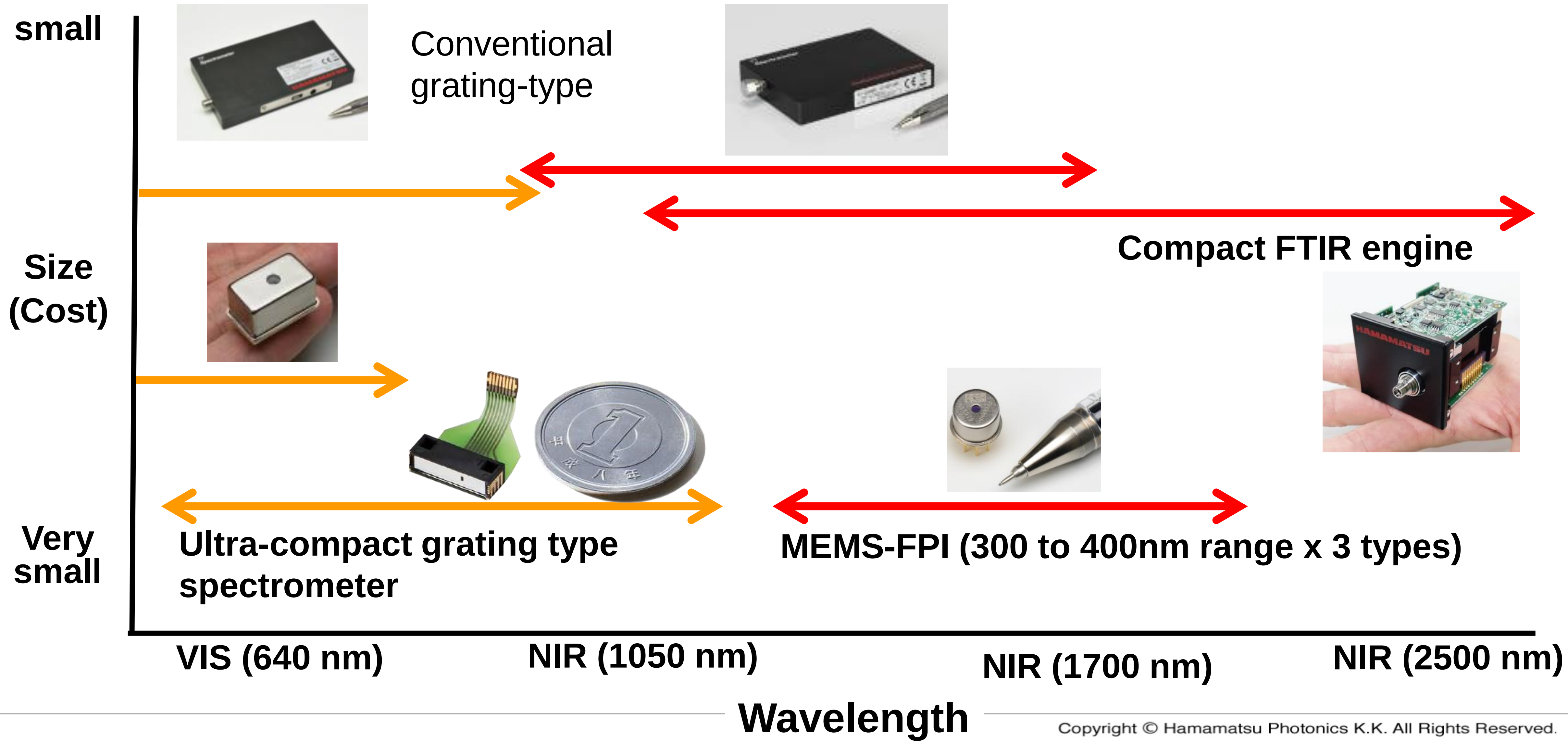
MOEMS Spectrometers



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Summary

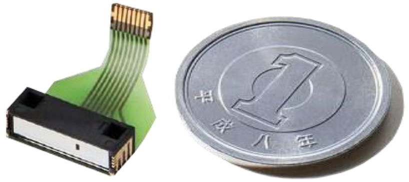
- Optical MEMS (MOEMS) devices to enrich sensor information remarkably, which will make "real-time, on-site measurements in various fields" possible.

- Downsizing, cost reduction of the devices

→ to be utilized in more and more handy products

→ to be utilized in more and more production lines

→ to be utilized in our daily lives more and more

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Week #	Weekly Topics	# of Talks	Talk #1 Date	Talk #2 Date
1	Introduction to Photodetectors	2	26-May-20	28-May-20
2	Emerging Applications - LiDAR & Flow Cytometry	2	2-Jun-20	4-Jun-20
3	Understanding Spectrometer	2	9-Jun-20	11-Jun-20
1 Weeks Break				
4	Specialty Products – Introduction to Light Sources & X-Ray	2	23-Jun-20	25-Jun-20
5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
1 Weeks Break				
6	Specialty Products – Laser Driven Light Sources	2	14-Jul-20	16-Jul-20
7	Image Sensor Circuits and Scientific Camera	2	21-Jul-20	23-Jul-20
8	Mid-Infrared (MIR) Technologies & Applications	2	28-Jul-20	30-Jul-20
1 Weeks Break				
9	Photon Counting Detectors – SiPM and SPAD	1	11-Aug-20	
10	Using SNR Simulation to Select a Photodetector	1	18-Aug-20	

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https://www.mdpi.com/1424-8220/19/12/2833/htm

https://www.nist.gov/publications/simple-spectral-stray-light-correction-method-array-spectroradiometers

http://smb.slac.stanford.edu/facilities/software/blu-ice/microspec_tab.html#Hardware_tab

https://www.shimadzu.com/opt/guide/diffraction/06.html

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78