量測

2022基礎實驗技術訓練

雷射光電支援中心
陳蔚然

量測

- 偵測儀器
  - 光電類偵測器：雷射功率計、 Photodiode、 PMT、 Channeltron、MCP、CCD、CMOS
  - 其他種類偵測器：溫度、壓力、位移、速度、磁場、真空
- 原理規格
  - 各種偵測器的特性(偏壓、飽和、噪音、阻抗)與使用方法
- 訊號處理
  - 訊號擷取：同步觸發、雜訊控制、DAQ
  - 前置處理：帶通濾波器、前置放大器、鎖相放大器、Boxcar積分平均器、類比訊號處理器、A/D轉換

實驗量測

- 物理訊號→電子訊號→擷取與數位化→儲存→分析處理
  - 光譜、影像、質譜、電性、磁性、聲、溫度、壓力、能量、作用力、形變、運動、酸鹼、氧化還原、離子……
- 偵測儀器
  - 光偵測器：雷射功率計、 Photodiode、 PMT、Channeltron、MCP
  - 光譜：光譜儀（Raman, PL）、干涉儀
  - 影像：CCD、CMOS 、IR viewer 、Beam viewer、光學顯微鏡、共軛焦顯微鏡、近場光學顯微鏡、掃瞄探針顯微鏡(STM、AFM)、電子顯微鏡(TEM、SEM、STEM)
  - 各種偵測器的特性(如何提供偏壓、飽和、噪音、阻抗)和應用

測量與單位

- 電性、磁性
- 聲、光
- 溫度、溼度
- 壓力
- 硬度、形變
- 質量
- 酸鹼、氧化還原
- 離子
- 流量、黏度

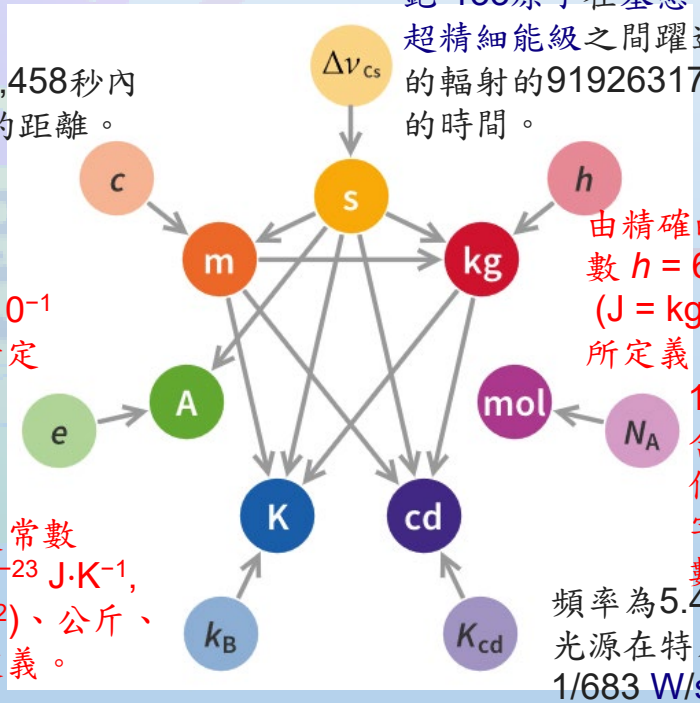
……

- 單位制
  - 長度
  - 質量
  - 時間
  - 電流
  - 溫標
  - 照度
  - 數量
- 基本常數

國際單位制(基本單位)

光在1/299,792,458秒內在真空中行進的距離。

銫-133原子在基態下的兩個超精細能級之間躍遷所對應的輻射的9192631770個週期的時間。



由新的元電荷 $e = 1.602176634\times10^{-19}$ C (C = A·s)和秒所定義。

由精確的普朗克常數 $h = 6.62607015\times10^{-34}$ J.s (J = kg·m^2·s^{-2})、公尺和秒所定義。

1莫耳包含 6.02214076×10^{23} 個基本實體，這一數字是新的亞佛加厥常數。

由新的波茲曼常數 1.380649×10^{-23} J·K^{-1}, (J = kg·m^2·s^{-2})、公斤、公尺和秒所定義。

頻率為5.4×10^{14}赫茲的單色光源在特定方向輻射強度為1/683 W/sr時的發光強度。

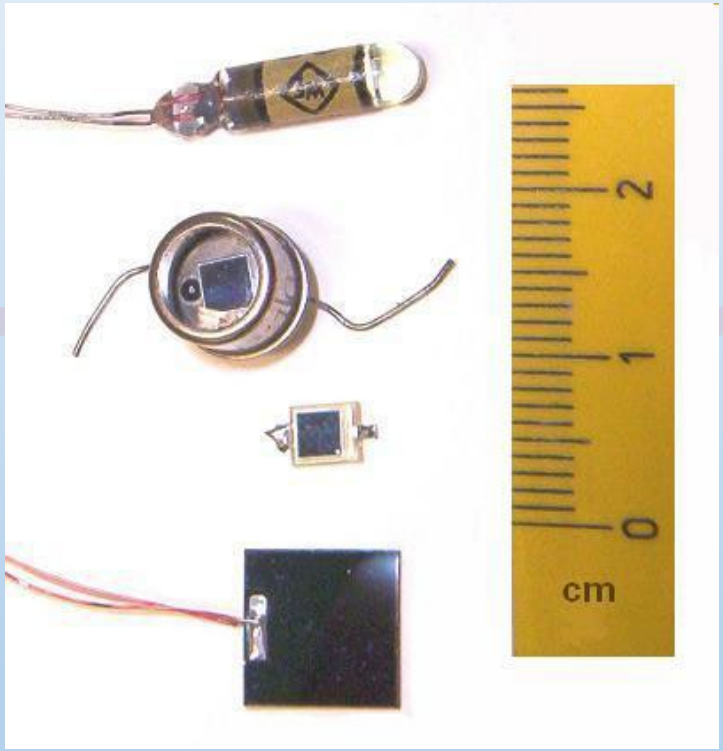
圖片來源：維基百科https://commons.wikimedia.org/w/index.php?curid=40278935

從國際單位制導出的已命名單位

名稱	符號	物理量	以其他SI單位表達	以基本單位表達
弧度	rad	角		$m \cdot m^{-1}$
立弧度	sr	立體角		$m^2 \cdot m^{-2}$
赫茲	Hz	頻率		s^{-1}
牛頓	N	力、重量		$kg \cdot m \cdot s^{-2}$
帕斯卡	Pa	壓力、應力	N/m^2	$kg \cdot m^{-1} \cdot s^{-2}$
焦耳	J	能量、功、熱量	$N \cdot m$	$kg \cdot m^2 \cdot s^{-2}$
瓦特	W	功率、輻射通量	J/s	$kg \cdot m^2 \cdot s^{-3}$
庫侖	C	電荷		$s \cdot A$
伏特	V	電壓（電位差）、電動勢	W/A	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-1}$
法拉	F	電容	C/V	$kg^{-1} \cdot m^{-2} \cdot s^4 \cdot A^2$
歐姆	Ω	電阻、阻抗、電抗	V/A	$kg \cdot m^2 \cdot s^{-3} \cdot A^{-2}$
西門子	S	電導	A/V	$kg^{-1} \cdot m^{-2} \cdot s^3 \cdot A^2$
韋伯	Wb	磁通量	$V \cdot s$	$kg \cdot m^2 \cdot s^{-2} \cdot A^{-1}$
特士拉	T	磁通量密度（磁場）	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
亨利	H	電感	Wb/A	$kg \cdot m^2 \cdot s^{-2} \cdot A^{-2}$
攝氏度	˚C	溫度（相對於273.15 K）		K
流明	lm	光通量	$cd \cdot sr$	cd
勒克斯	lx	照度	lm/m^2	$m^{-2} \cdot cd$
貝克勒	Bq	放射性活度		s^{-1}
戈雷	Gy	致游離輻射的吸收劑量	J/kg	$m^2 \cdot s^{-2}$
西弗	Sv	致游離輻射等效劑量	J/kg	$m^2 \cdot s^{-2}$
開特	kat	催化活度		$mol \cdot s^{-1}$

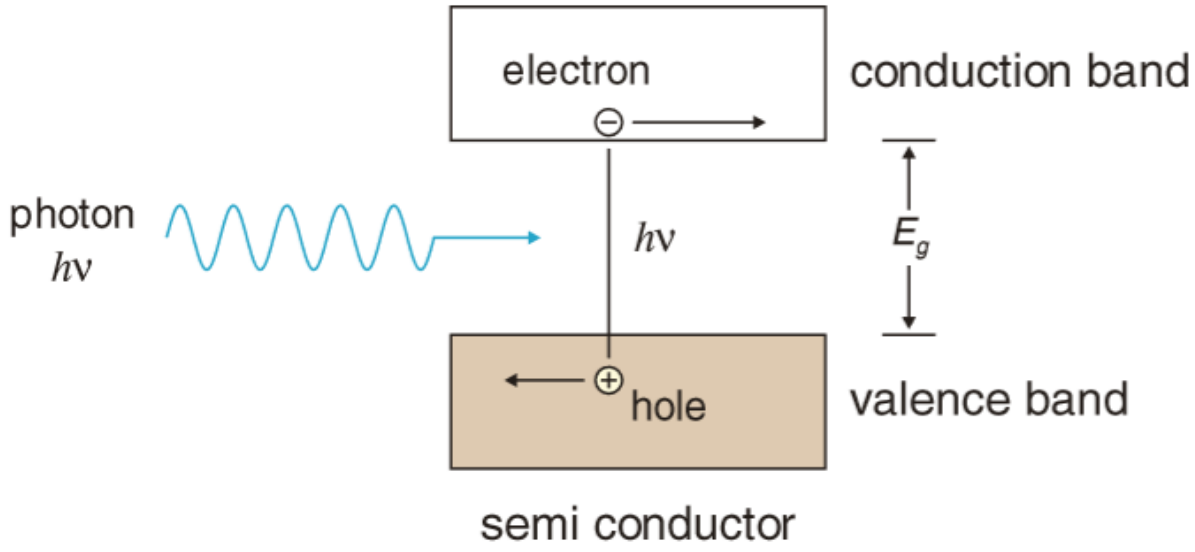
•備註弧和立弧曾經是具有特殊地位的單位，但現在只當做無因次導出單位看待。
•上表的排序方法是，表中所有單位都只建立在位置更前的單位以及基本單位上。

光偵測器



Introduction to photodetectors

1. thermal detectors
2. photoelectric detectors
   a. internal photoeffect (photoconductivity)



Power meter

1. head:
   - surface absorber
   - volume absorber
2. monitor:
   - analog monitor
   - digital monitor
   - interface (RS-232, GPIB)
3. calibration

Laser power meter

Laser Power Sensors

Laser Energy Sensors

BeamTrack Sensors

High Power Sensors

Temporal Sensors

Terahertz Sensors

IPL Sensors

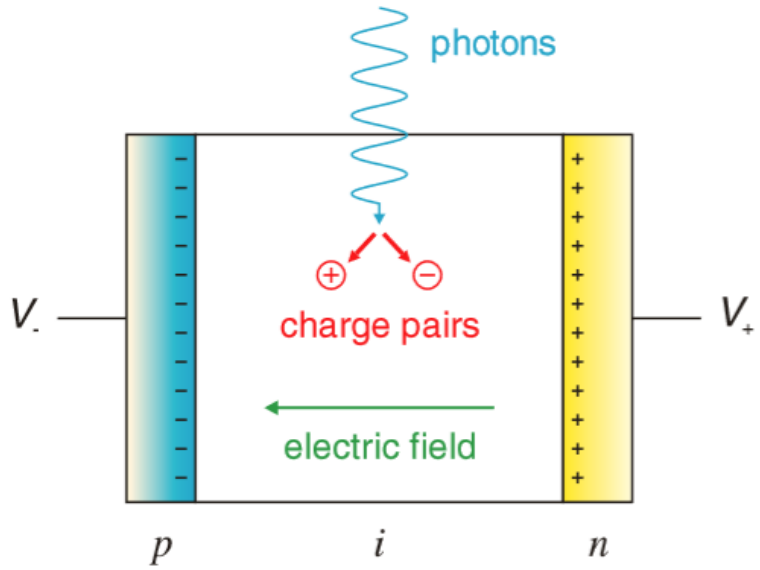
Pulsed Power sensors

種類	特性
Thermopile Pyroelectric Photodiode	Power level, Spectral region, Beam size

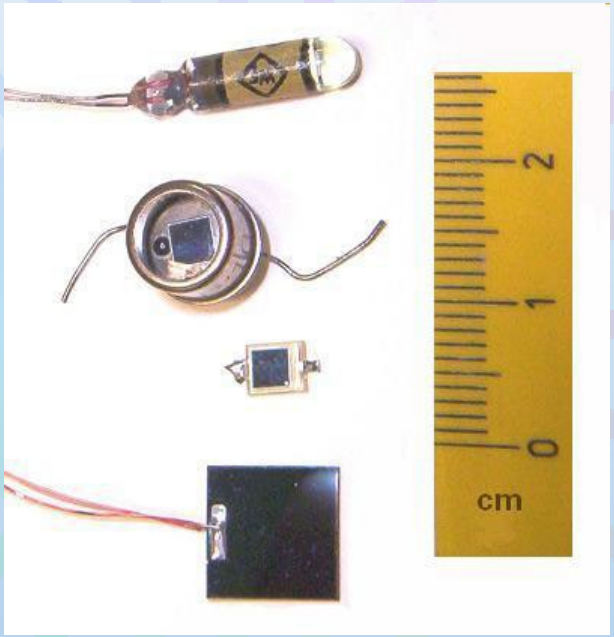
https://www.ophiropt.com/laser--measurement/laser-power-energy-meters

Photodiode

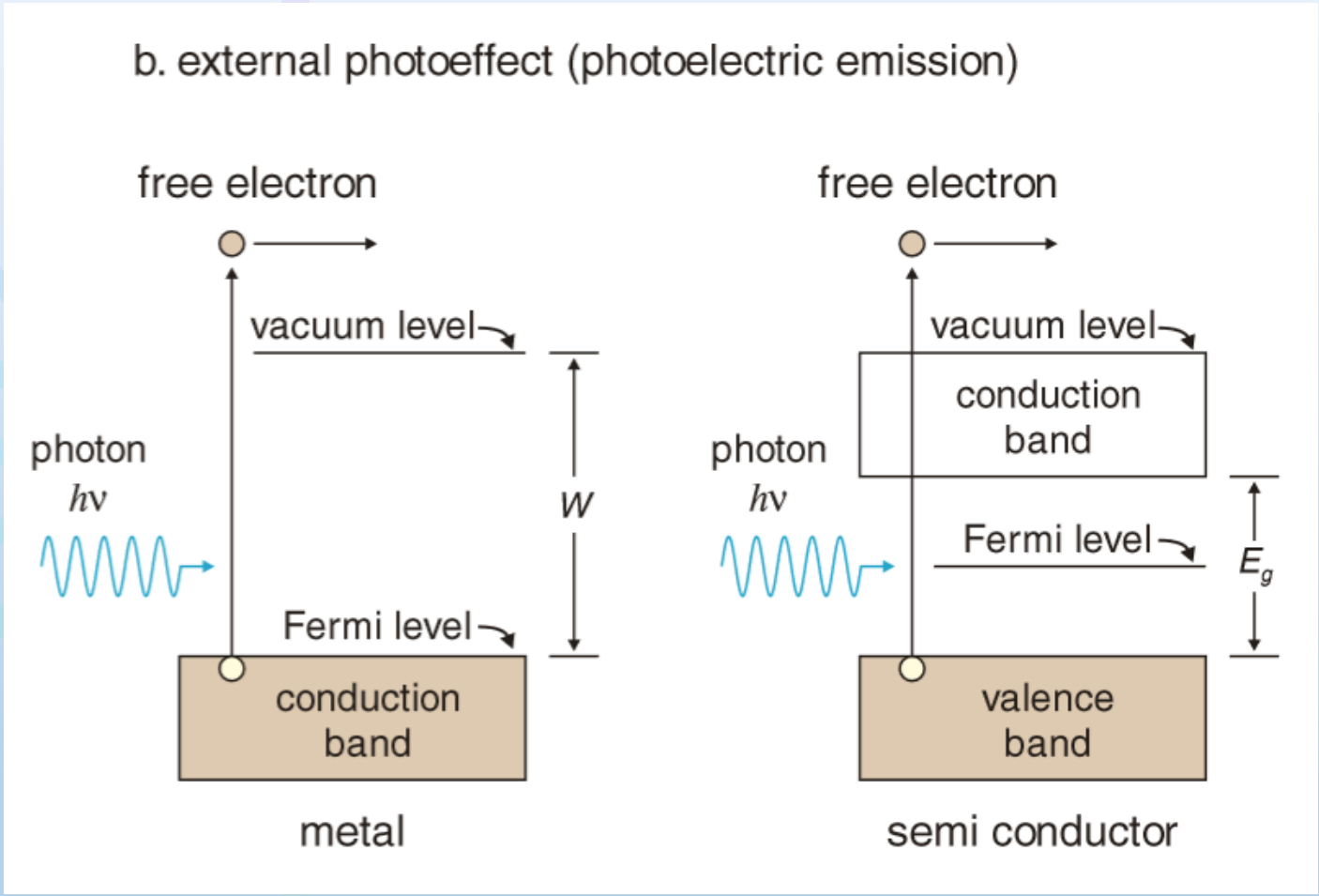
p-i-n photodiode, reverse bias, electron-hole production



https://www.eotech.com/cart/category44/photodetectors

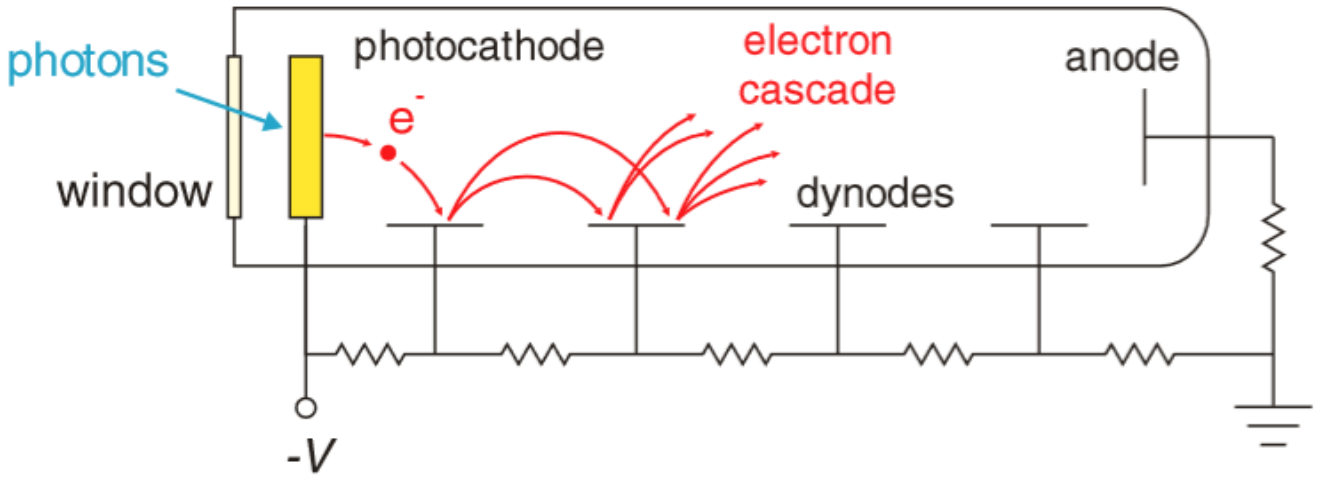


https://zh.wikipedia.org/wiki/%E5%85%89%E7%94%B5%E4%BA%8C%E6%9E%81%E7%AE%A1


b. external photoeffect (photoelectric emission)
free electron
vacuum level
photon
hν
W
Fermi level
conduction band
metal
free electron
vacuum level
conduction band
photon
hν
Fermi level
E_g
valence band
semi conductor

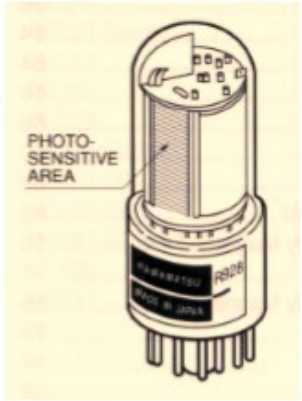
Photon-multiplier tube (PMT)

1. principle

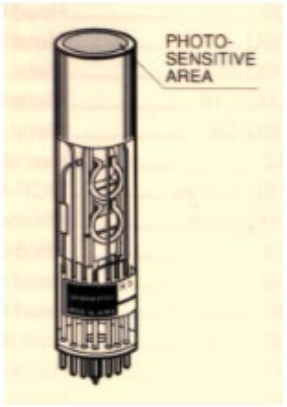


2. structure

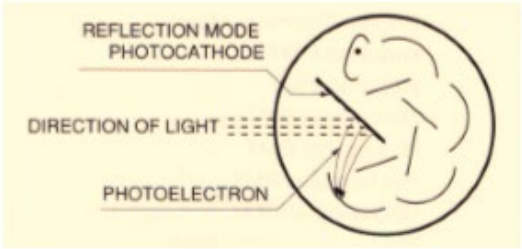
side-on type



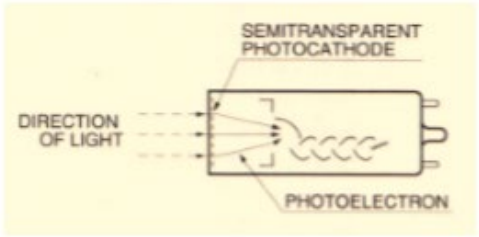
head-on type



reflection mode

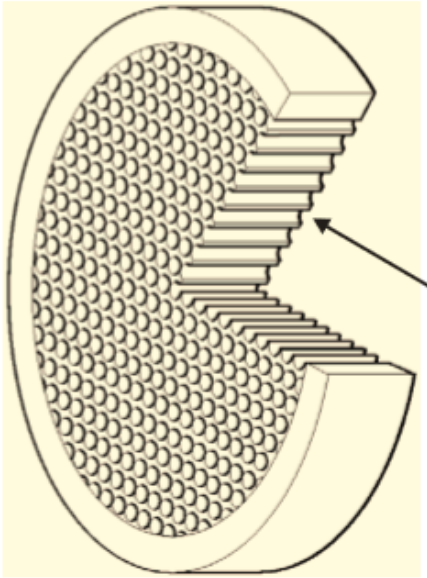


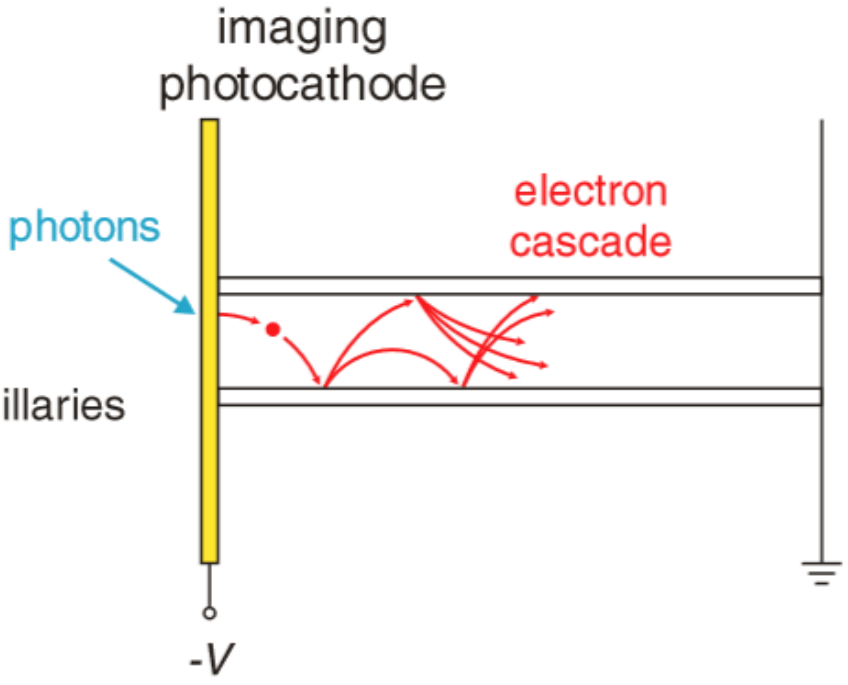
transmission mode



3. micro-channel plate (MCP)

channel diameter: 2~20 μm





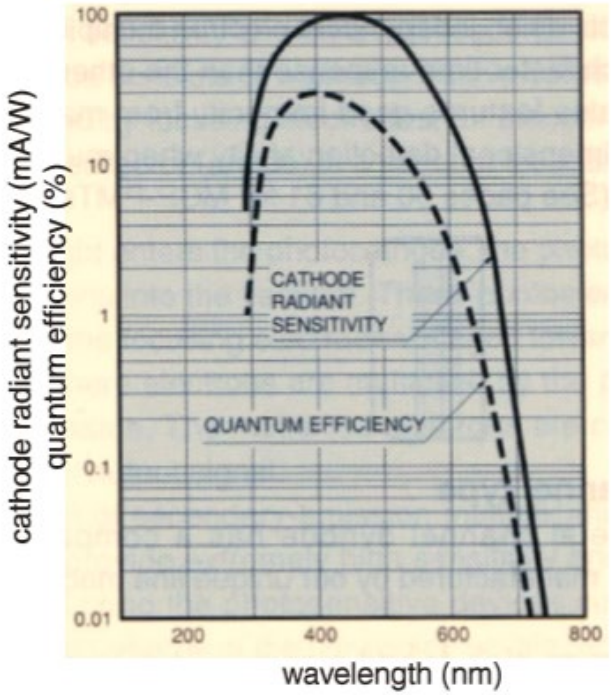
4. photocathode material

Ag-O-Cs, GaAs(Cs),
InGaAs(Cs), Sb-Cs,
Cs-Te, Cs-I,
bialkali (Sb-Rb-Cs, Sb-K-Cs),
multialkali (Na-K-Sb-Cs)

spectral response

$$quantum\ efficiency = \frac{excited\ electron\ numbers}{incident\ photon\ numbers}\ (\%)$$

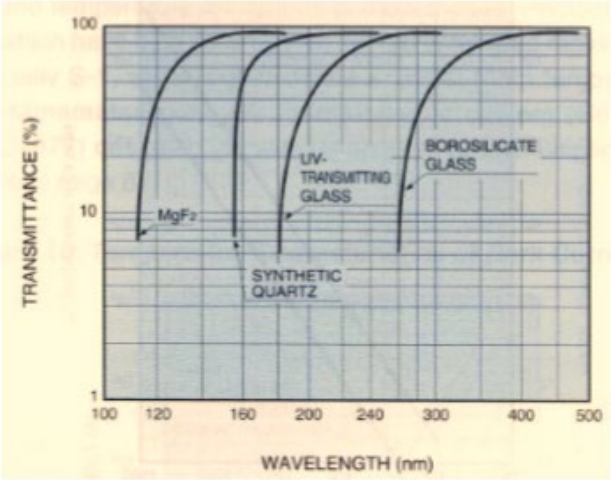
$$radiant\ sensitivity = \frac{output\ current}{incident\ power}\ (A/W)$$



typical spectral response
of head-on,
bialkali photocathode

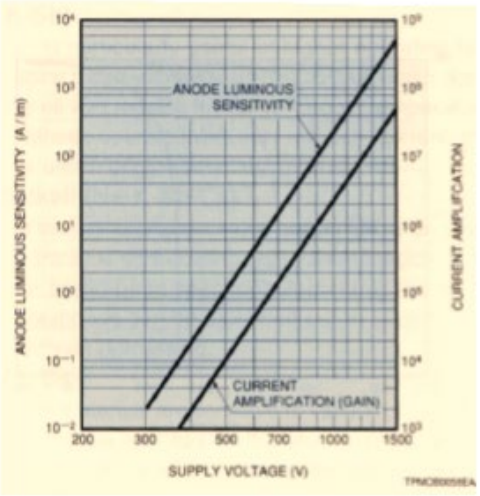
3. window material

borosilicate glass
UV glass
synthetic silica
MgF_2



transmittance v.s. wavelength

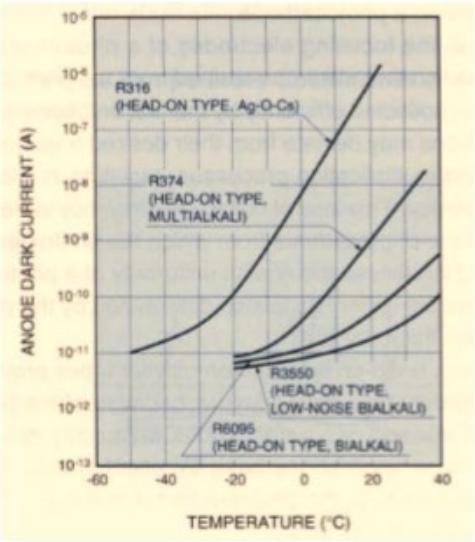
4. current amplification



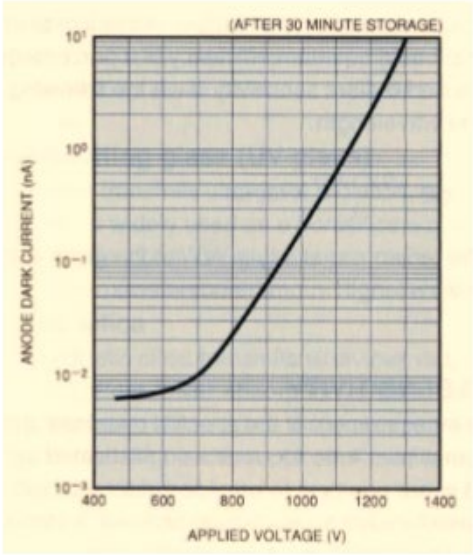
typical current amplification
v.s. supply voltage

5. dark current

thermonic emission of electrons
ionization of residual gase
glass scintillation
leakage current
field emission



temperature characteristics of dark current



typical dark current vs. supply voltage

Channeltron

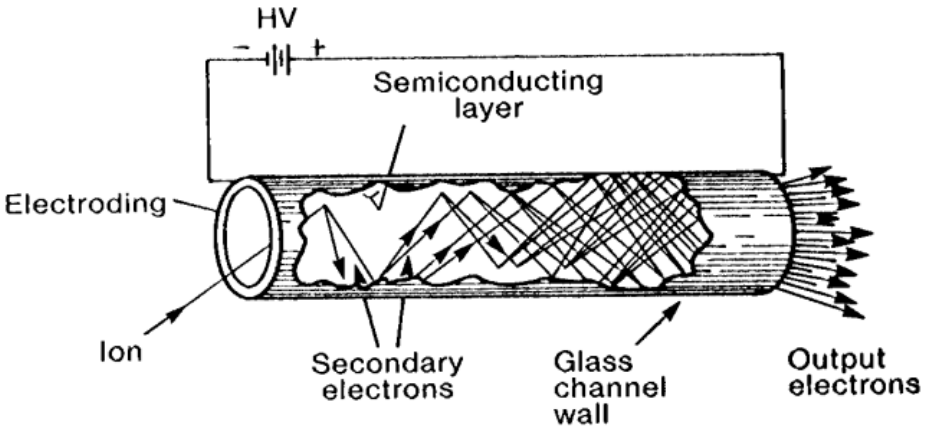
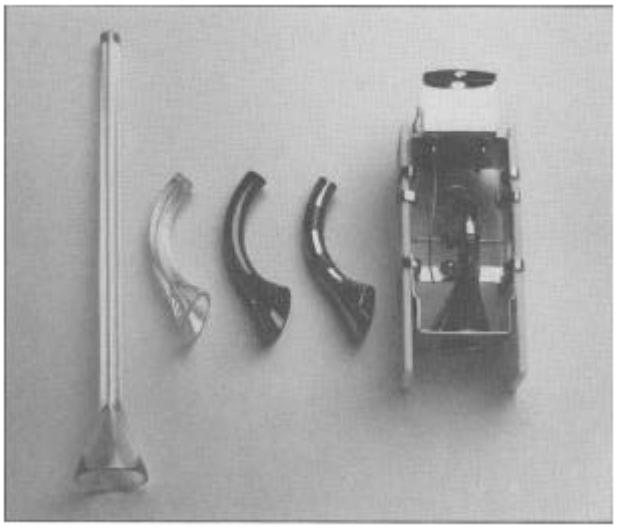
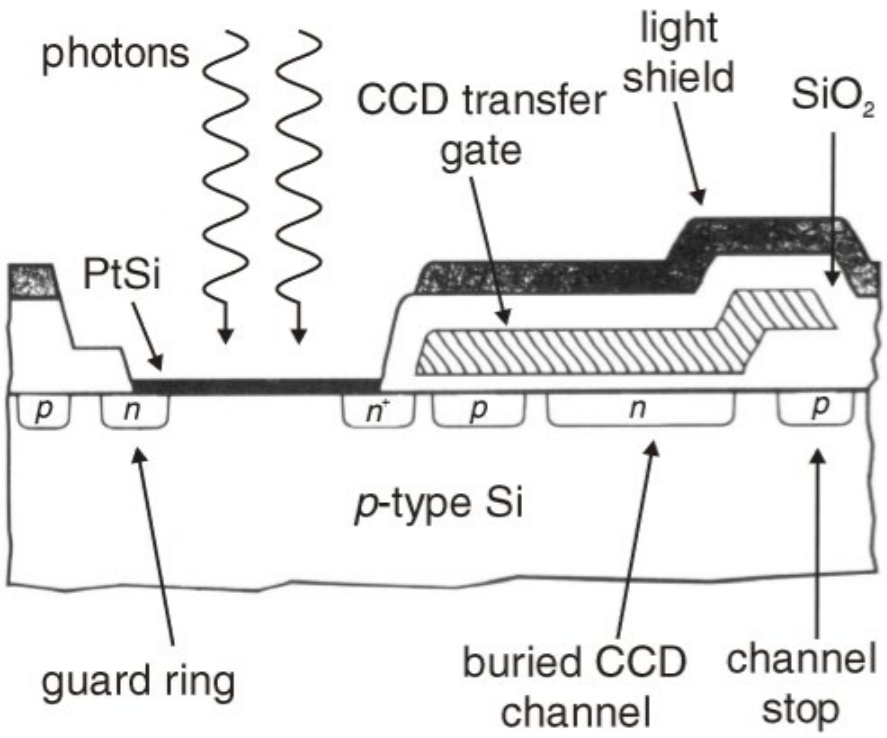


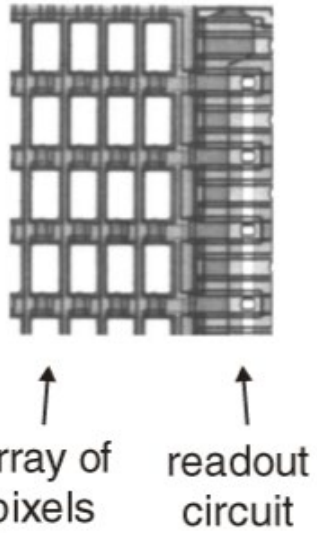
Figure 2-4 Basic Operation



CCD camera

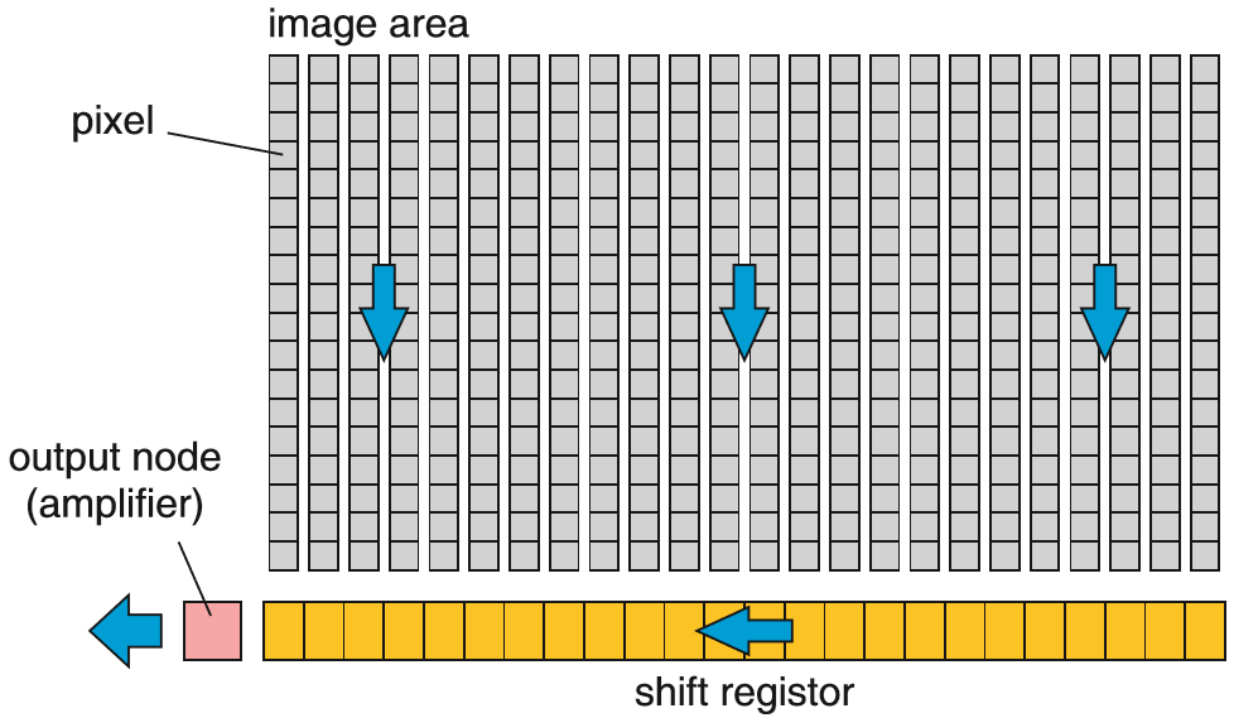
1. charge coupled devices (CCD)





2. CCD camera

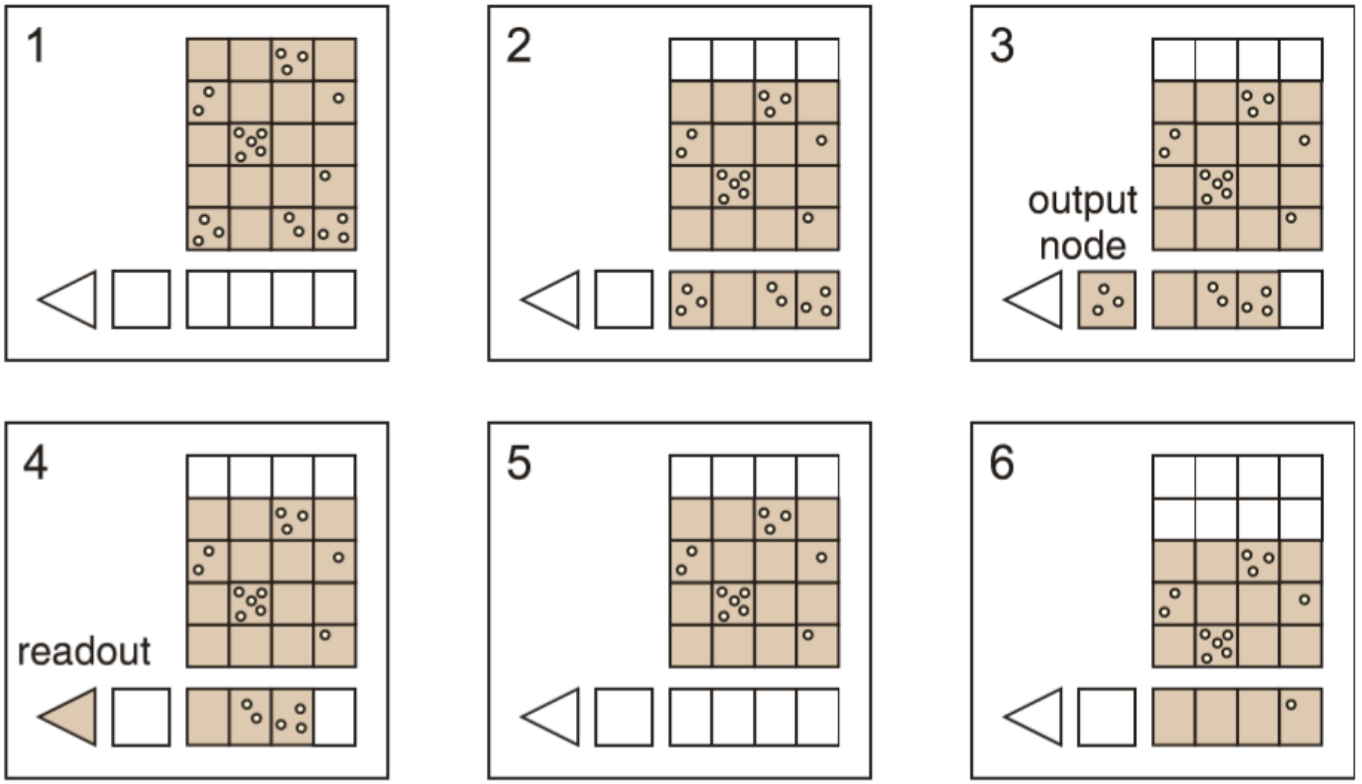
exposure, readout, ADC resolution, dynamic range, and spatial resolution



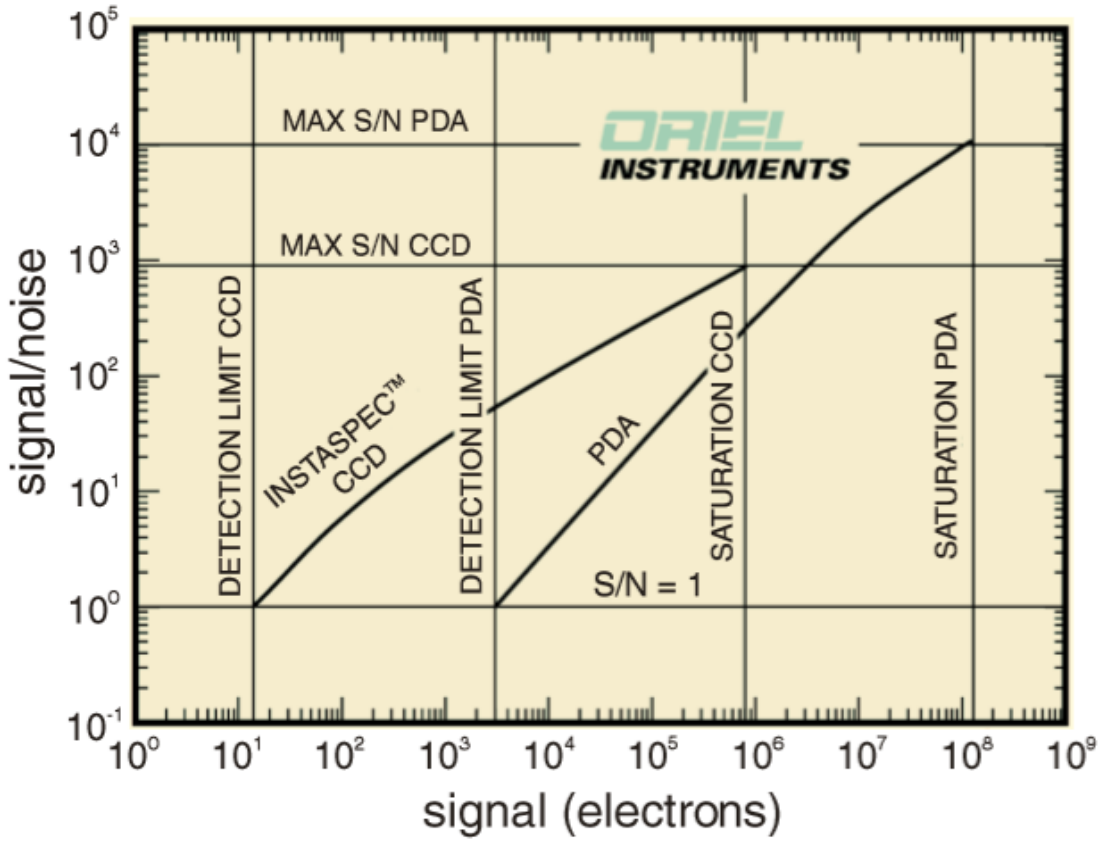
3. readout

"Progressive Scan"

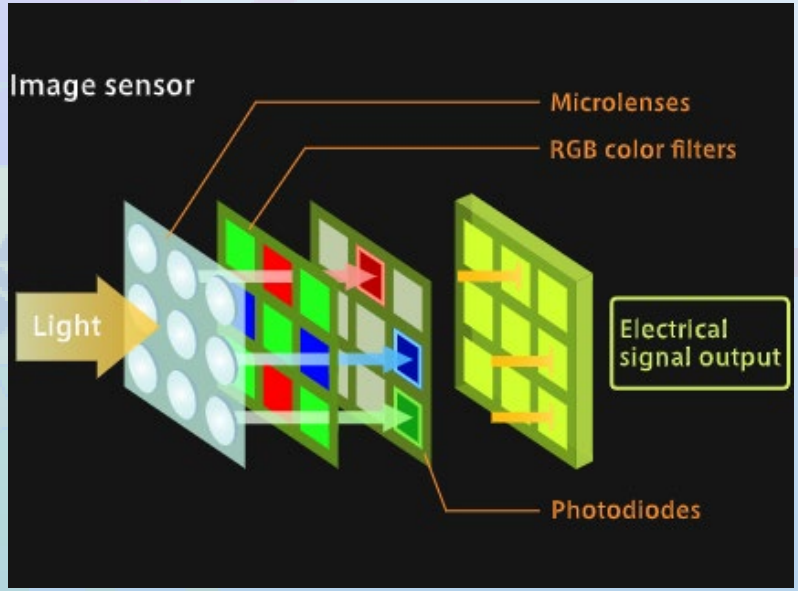
CCD chip readout sequence



Comparison of photodiode and CCD

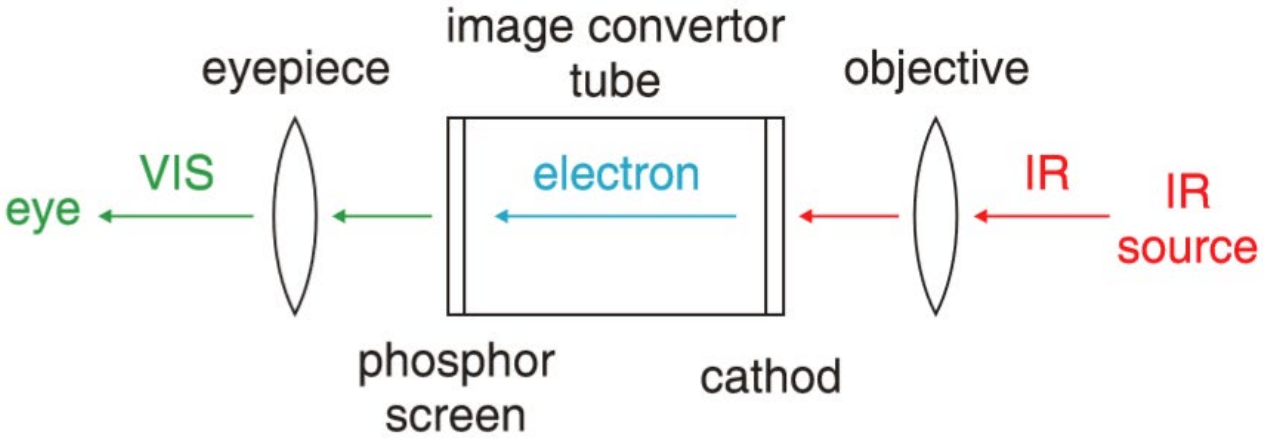


CMOS vs CCD



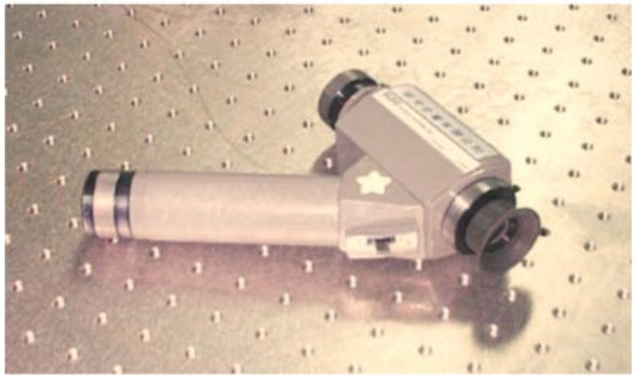
https://www.tel.com/museum/exhibition/principle/cmos.html

IR viewer



FJW Find-R-Scope 84499

standard sensitivity: 350~1350 nm
peak sensitivity: 800 nm
magnification: 1:1
focal range: 4-inch to infinity
field of view: 40°



訊號處理(擷取與數位化)

- 同步觸發、負載與失真、雜訊控制、阻抗匹配
- 帶通濾波器、射頻放大器、前置放大器、鎖相放大器、Boxcar積分平均器、類比訊號處理器、A/D轉換 、頻譜分析儀。

同步觸發

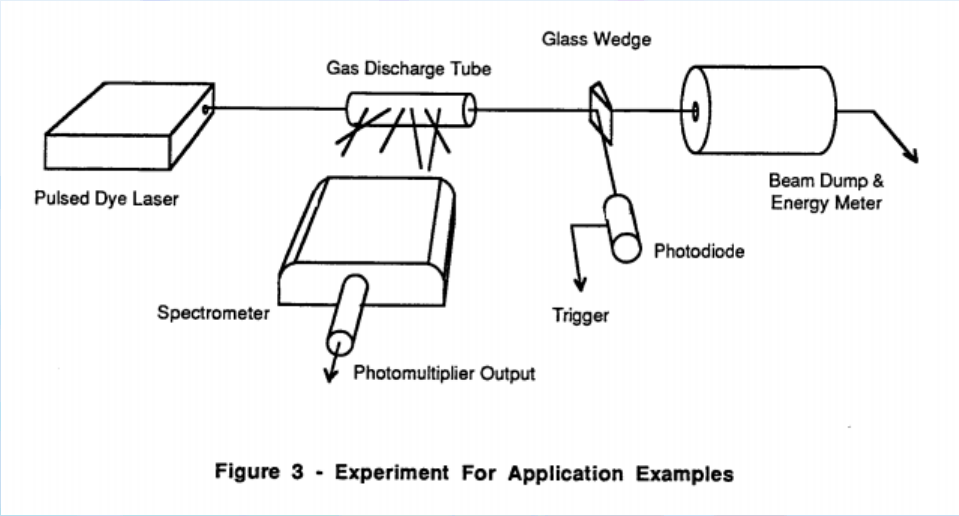
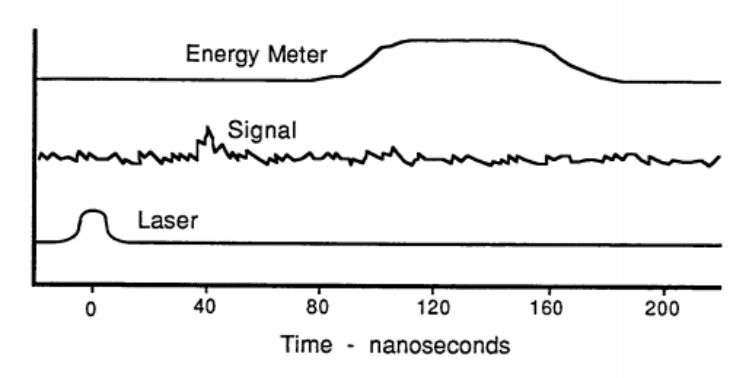


Figure 3 - Experiment For Application Examples

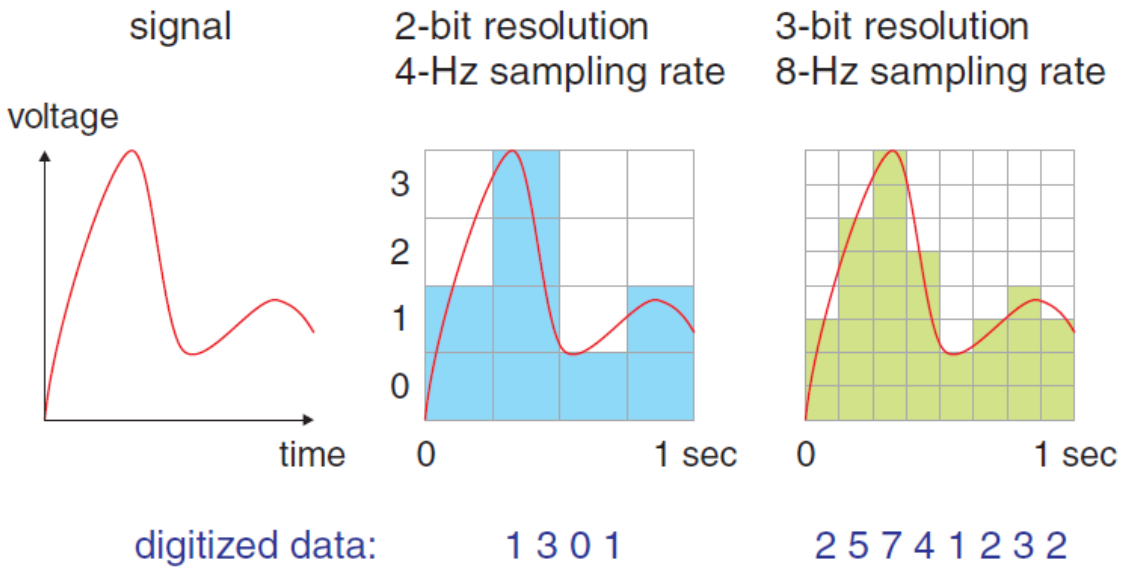


https://www.thinksrs.com/downloads/pdfs/manuals/Boxcarm.pdf

訊號數位化

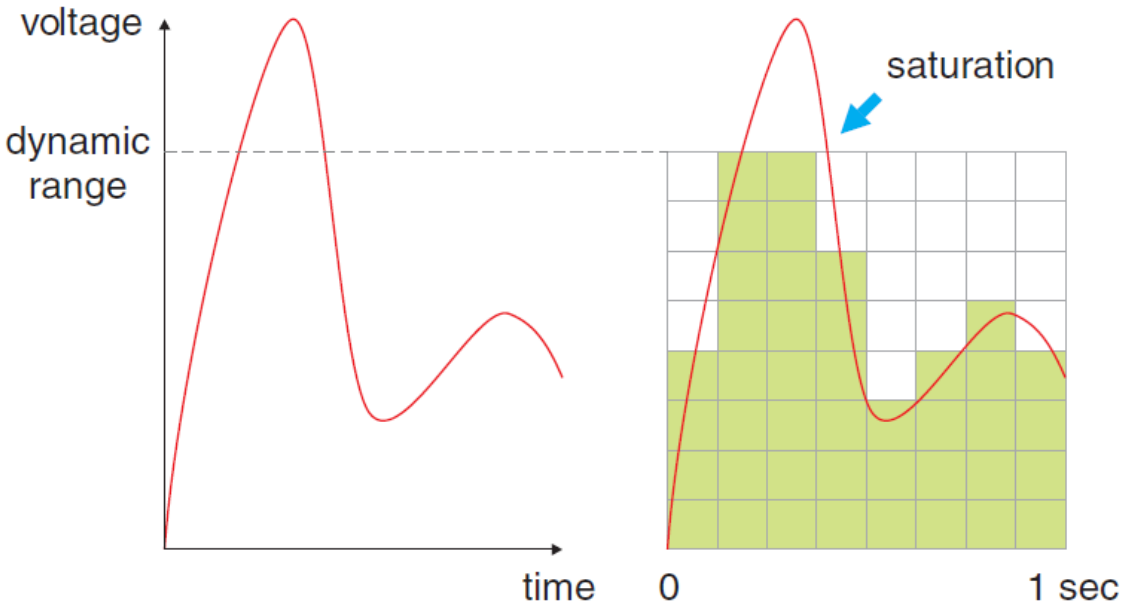
Introduction to signal digitization

- resolution and sampling rate



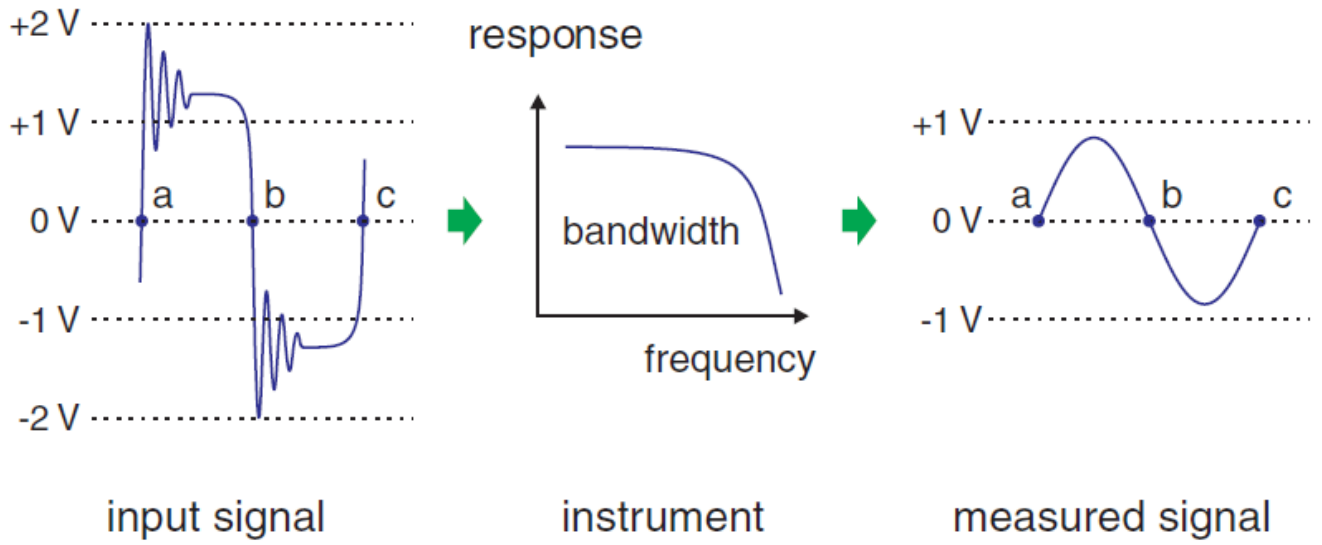
動態範圍

- dynamic range



類比頻寬

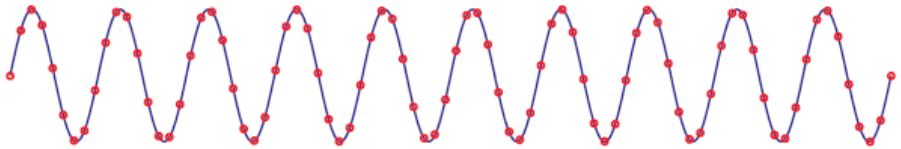
- analog bandwidth



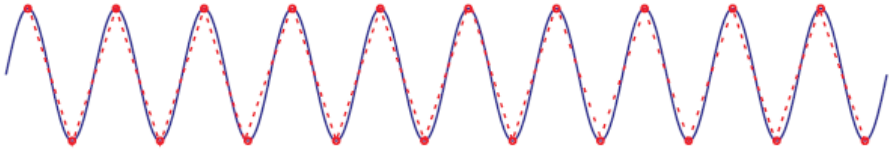
Nyquist理論

3. Nyquist theorem

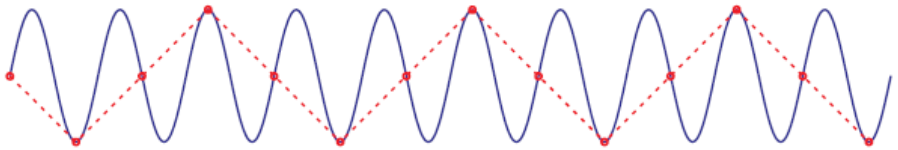
sampling rate >= 2 (highest frequency component in the signal)



adequate sampling



sampling at Nyquist frequency

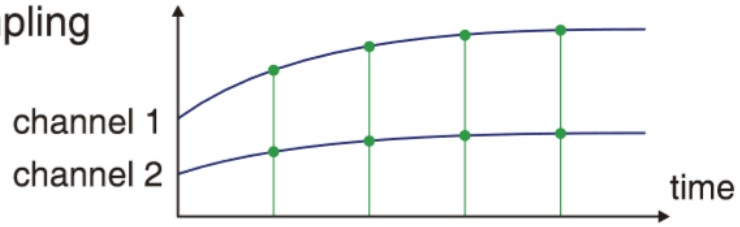


improper sampling

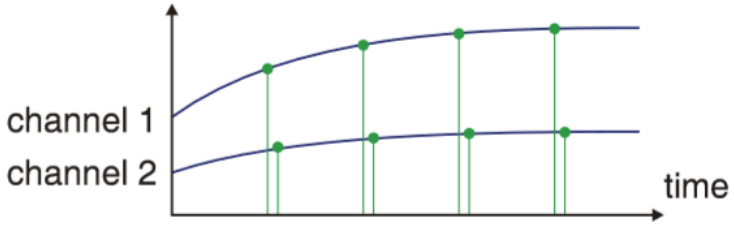
取樣方法

5. sampling method

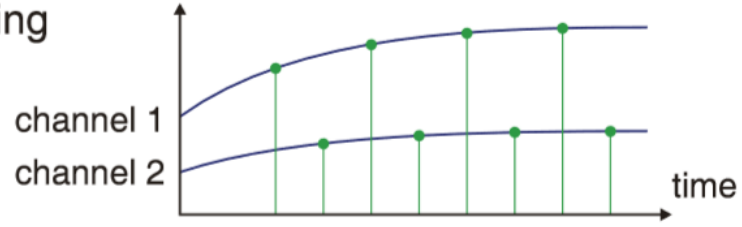
(1) simultaneous sampling



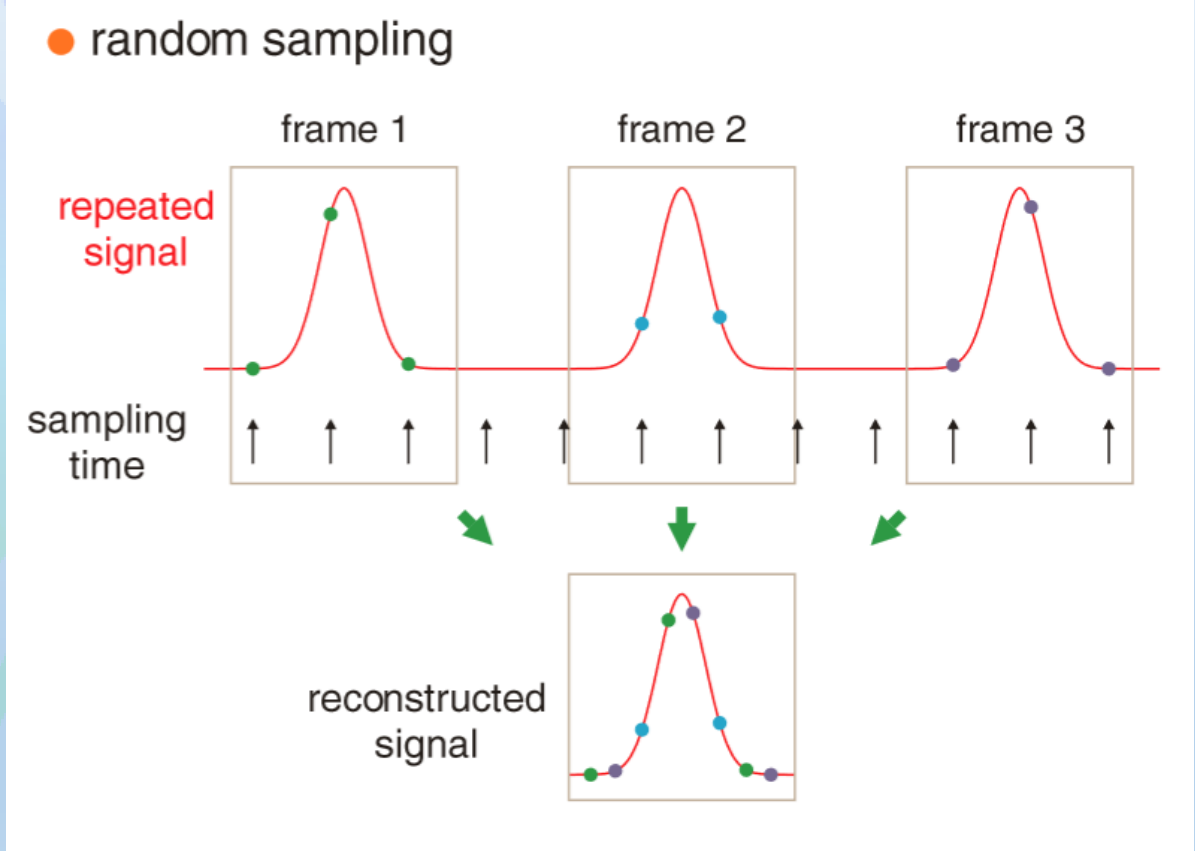
(2) interval scanning



(3) continuous scanning



隨機取樣


random sampling
frame 1
frame 2
frame 3
repeated signal
sampling time
reconstructed signal

訊號型態

- signal type

(1) grounded signal source:

power supply, function generator...

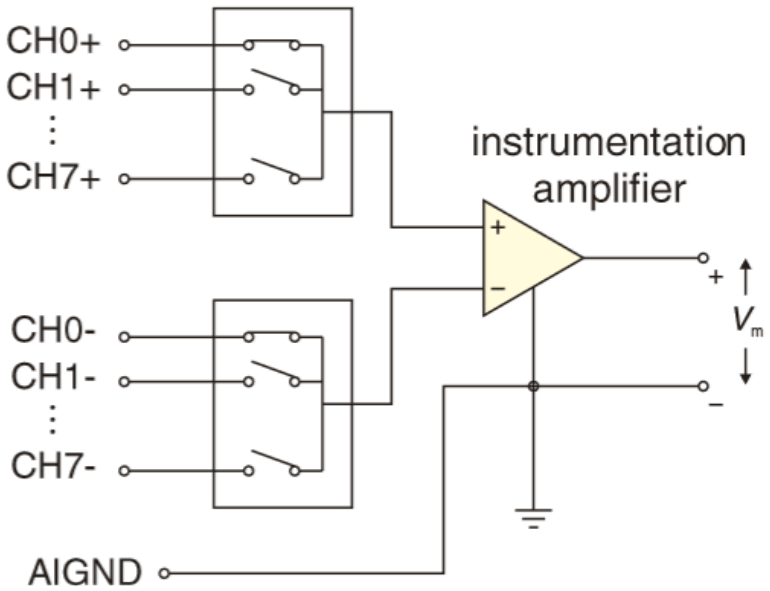
(2) floating signal source:

battery, thermal couple...

測量架構

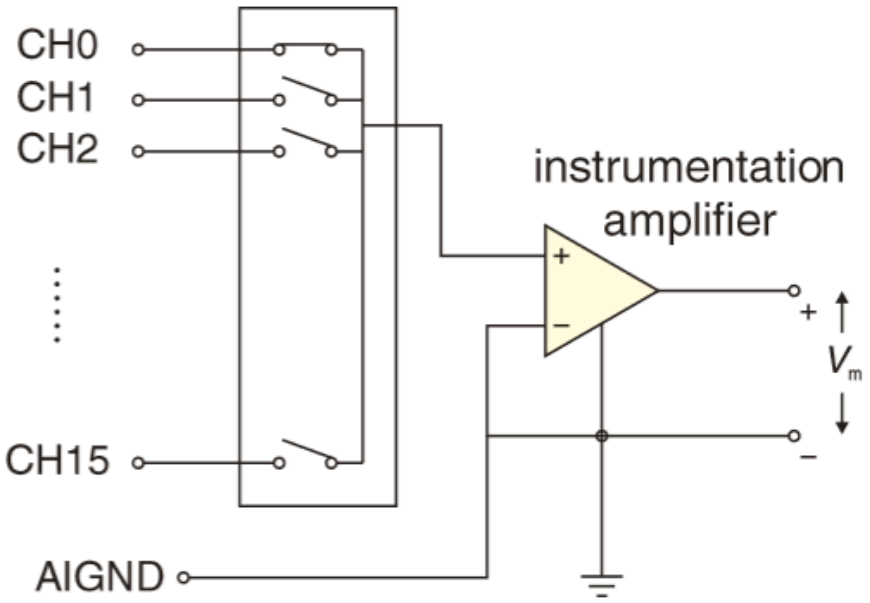
- measurement configuration

(1) differential measurement system



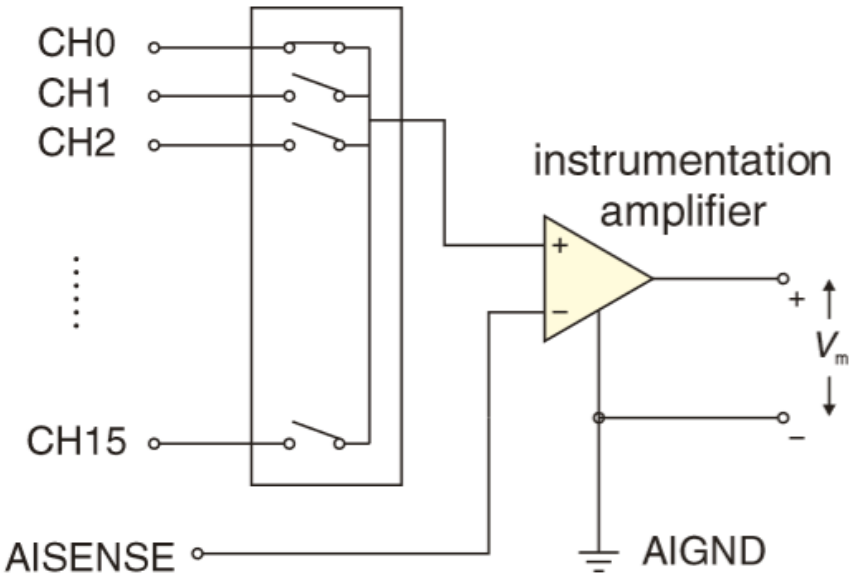
測量架構

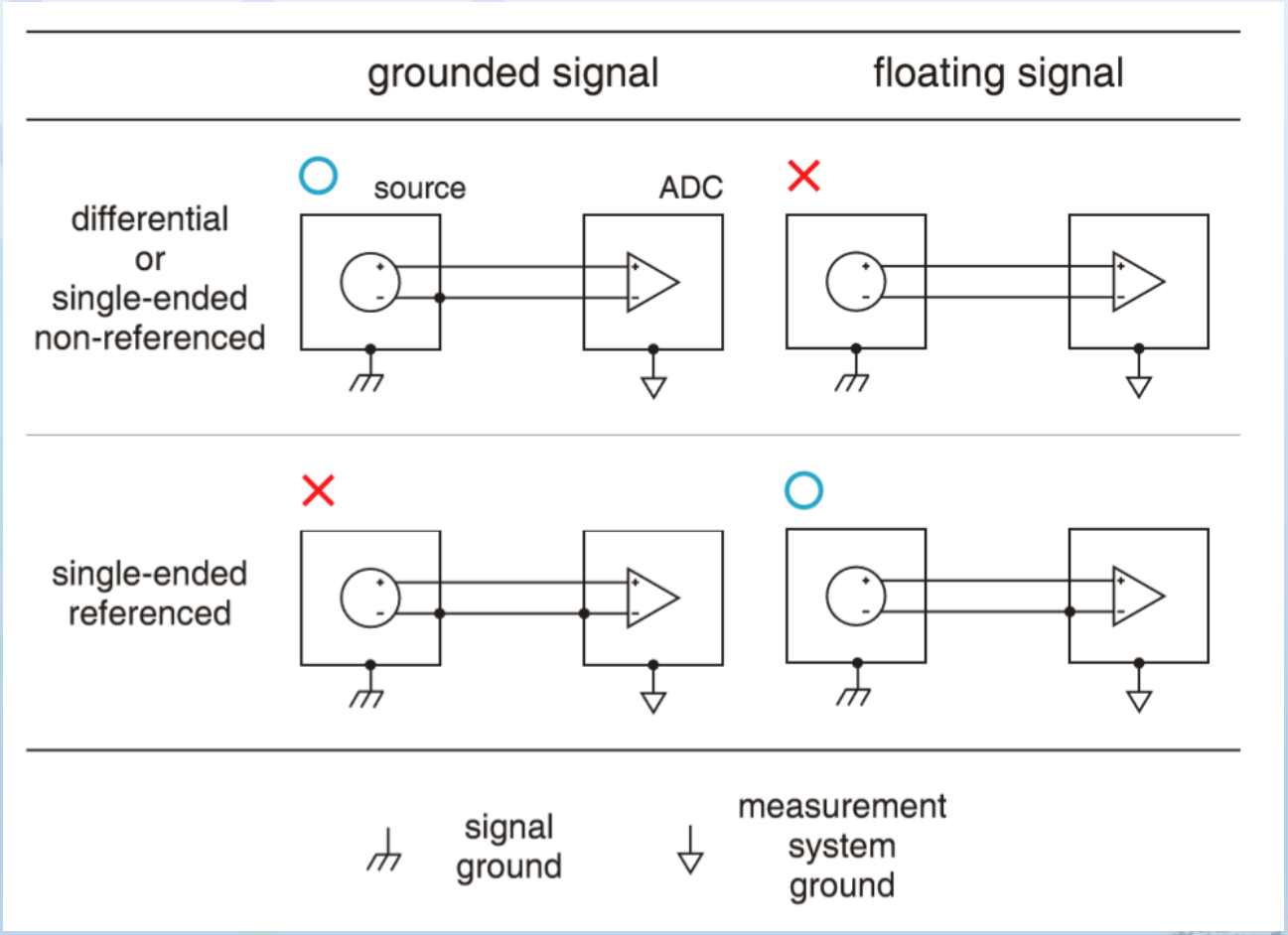
(2) referenced single-ended measurement system



測量架構

(3) non-referenced single-ended measurement system




grounded signal
floating signal
differential
or
single-ended
non-referenced
source
ADC
single-ended
referenced
signal
ground
measurement
system
ground

Major specification of an A/D convertor

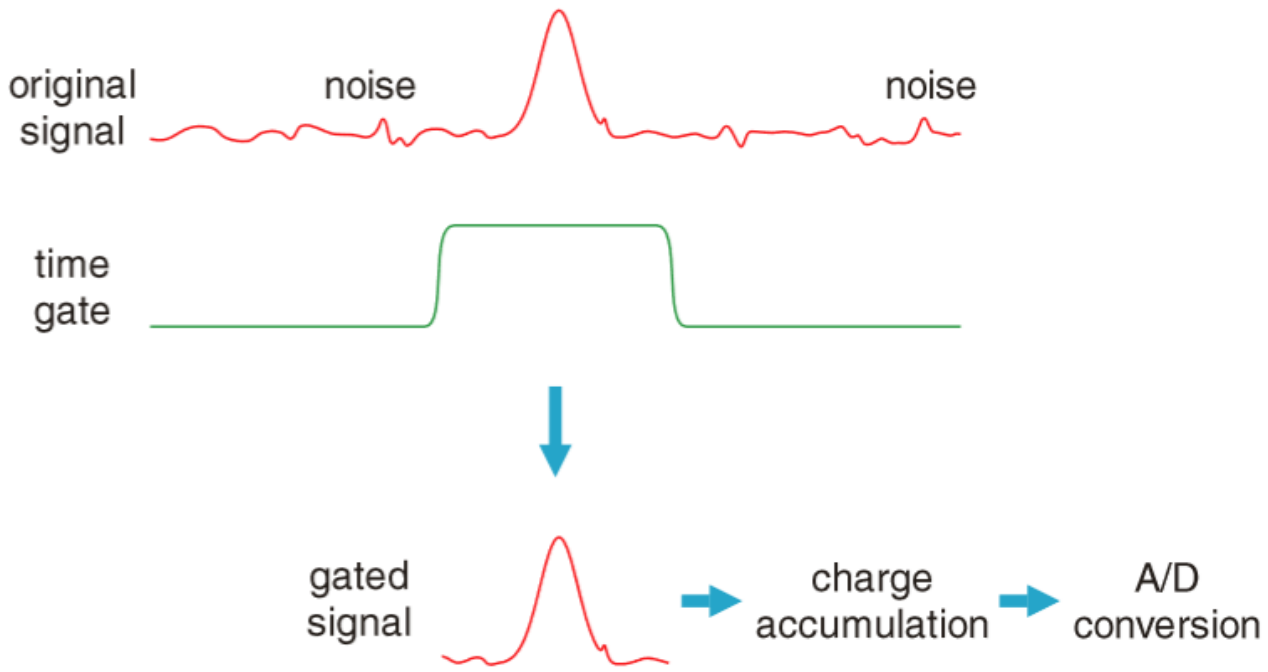
1. resolution and sampling rate

2. dynamic range

3. differential nonlinearity (DNL) and relative accuracy

4. noise

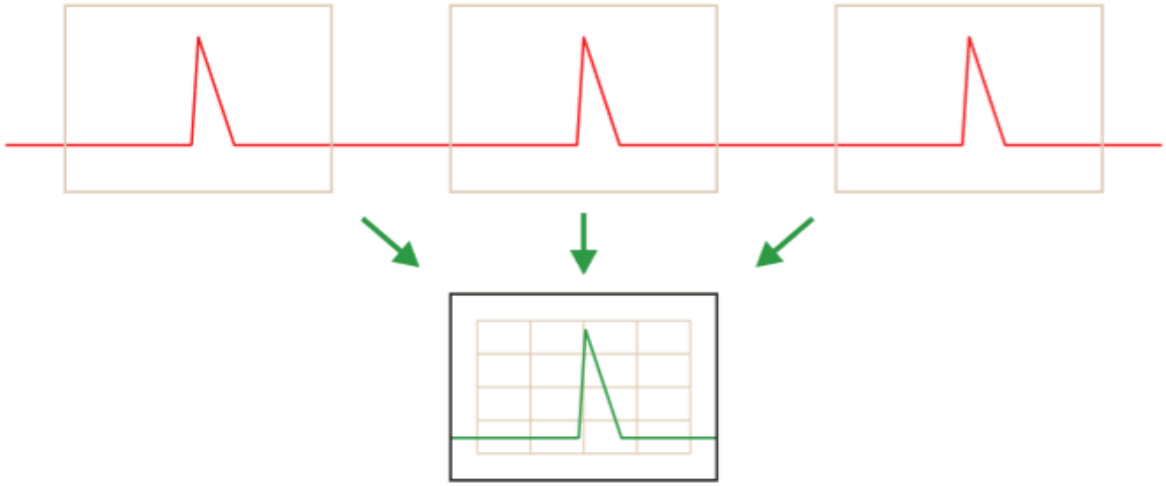
Charge-accumulating A/D convertor (QDC)



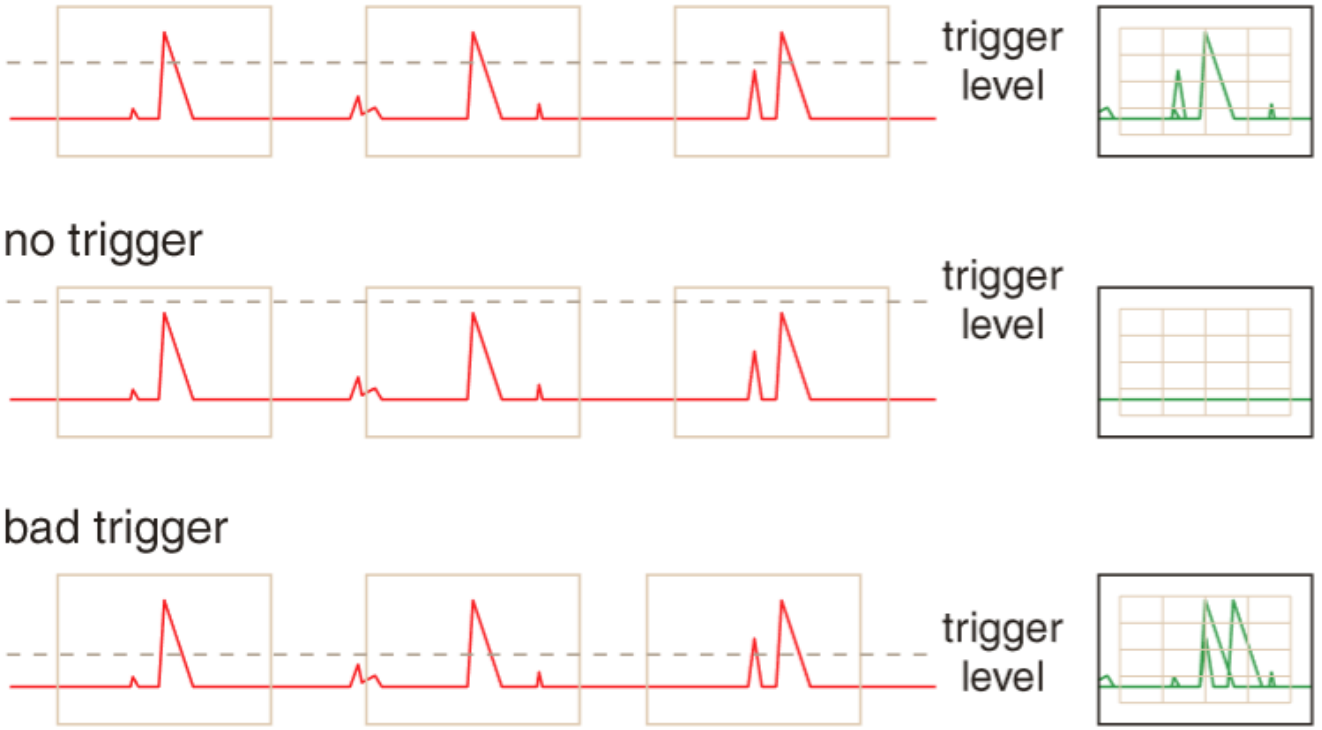
數位示波器

Oscilloscope

1. analog and digital oscilloscope



2. trigger (normal, auto, auto level)


good trigger
trigger level
no trigger
trigger level
bad trigger
trigger level

3. important specification

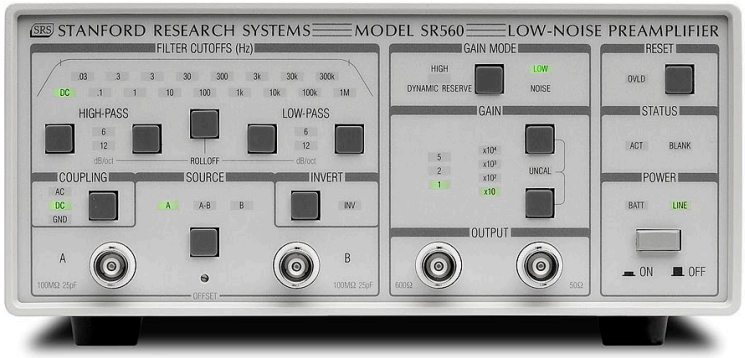
response time, bandwidth, sweep speed, sampling rate, resolution, damage threshold

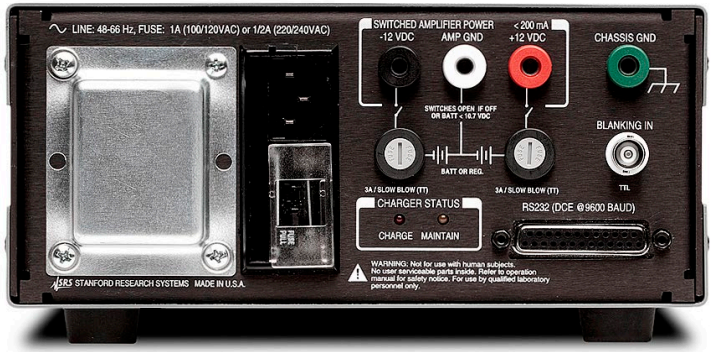
4. input coupling

AC, DC high impedance (1MΩ), DC 50 Ω, GND

Digital Storage Oscilloscope vs. Sampling Oscilloscope

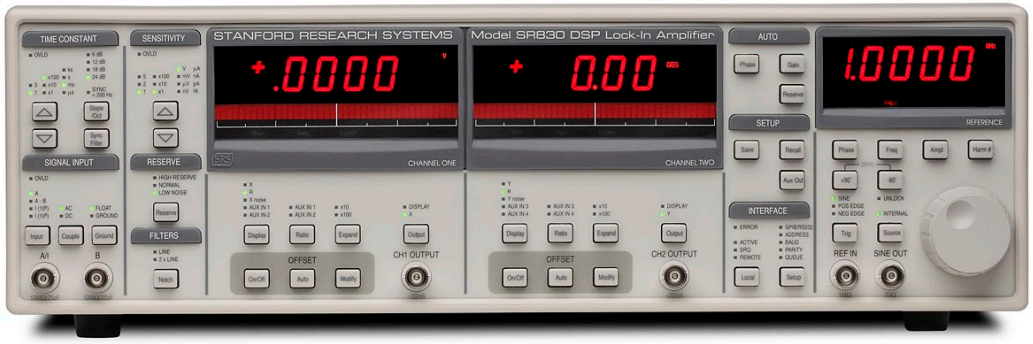
前置放大器





https://www.thinksrs.com/products/sr560.html

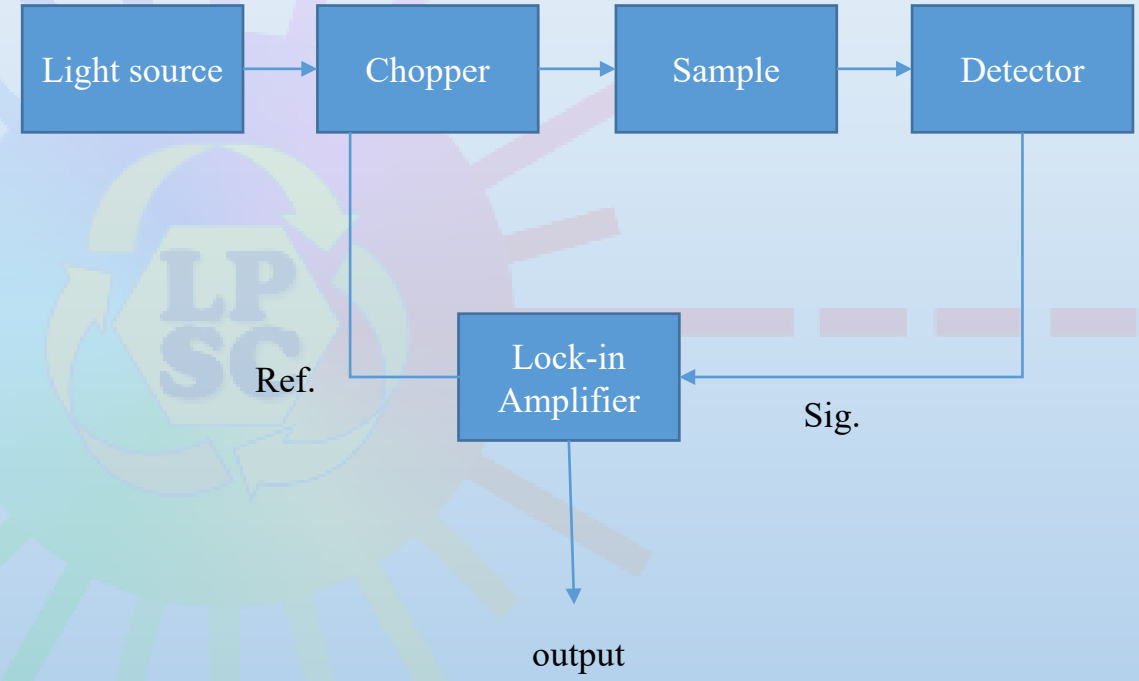
鎖相放大器

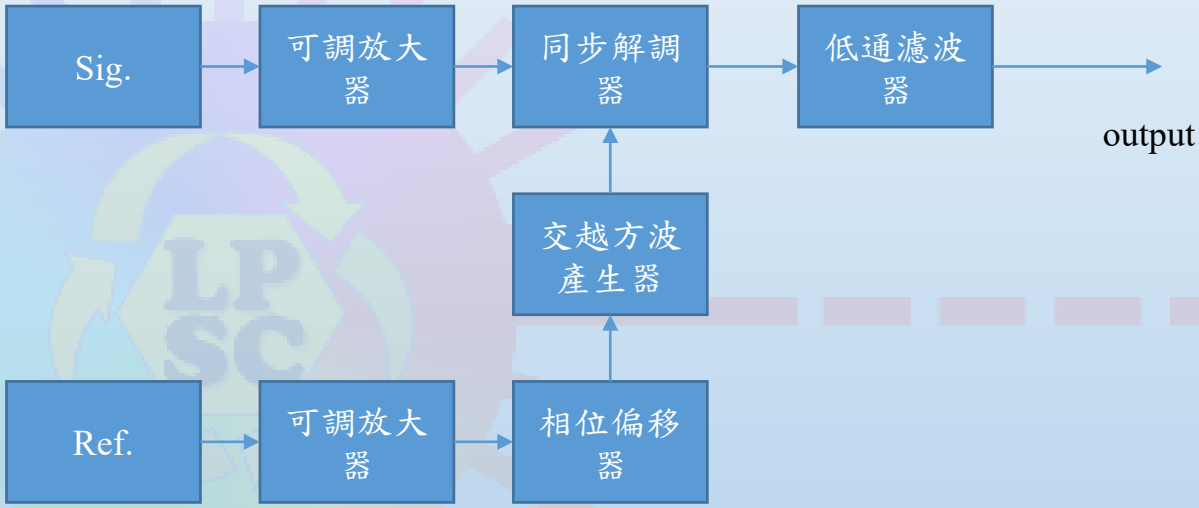


https://www.thinksrs.com/downloads/pdfs/manuals/SR830m.pdf

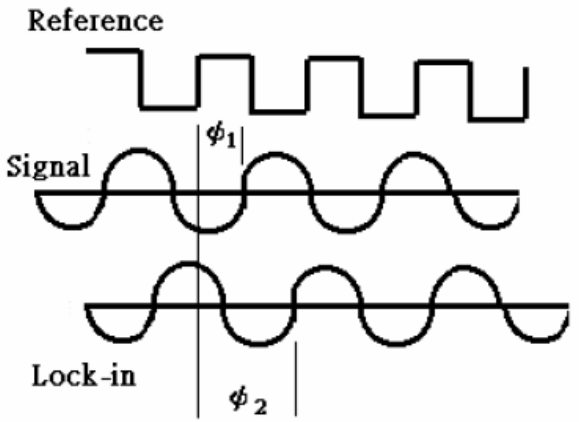
鎖相放大器(Lock-in Amplifier)

- 調變（Modulation）
- 可調放大器（Tuning amplifier：Band pass filter）
- 同步解調器（Synchronous demodulator），相位靈敏偵測器（Phase sensitive detector）
- 低通濾波器（Low pass filter）積分器


Light source
Chopper
Sample
Detector
Ref.
Lock-in Amplifier
Sig.
output


Sig.
可調放大器
同步解調器
低通濾波器
output
交越方波產生器
Ref.
可調放大器
相位偏移器

鎖相放大器



考慮一輸入訊號 $e_1 = E_1 \sin(2\pi f_1 + \phi_1)$

與一參考訊號 $e_2 = E_2 \sin(2\pi f_2 + \phi_2)$

兩訊號通過混合器(mixer)混乘後得到一結果訊號：

$$e_3 = e_1 \times e_2 = E_1 E_2 \sin(2\pi f_1 + \phi_1)\sin(2\pi f_2 + \phi_2)$$

$$= \frac{E_1 E_2}{2}\cos[2\pi(f_1 - f_2) + (\phi_1 - \phi_2)] - \frac{E_1 E_2}{2}\cos[2\pi(f_1 + f_2) + (\phi_1 + \phi_2)]$$

(difference frequency component)　(sum frequency component)

PSD 輸出的兩個訊號均為 AC，假如輸出的兩個訊號通過低通濾波器，AC 訊號將全被濾掉。如果 f_1 等於 f_2 時，difference frequency component 訊號變成 DC 訊號，在這狀況下 PSD 輸出為 $e_3 = \frac{E_1 E_2}{2}\cos(\phi_1 - \phi_2)$，這是一個非常好的訊號，它是一個直流訊號 $(\cos(\phi_1 - \phi_2) \approx 1)$ 與訊號振幅成比例的。

訊號處理器


SRS
GATED INTEGRATOR & BOXCAR AVERAGER
GATE SCANNER SR200
ANALOG PROCESSOR SR 235
FAST PREAMP SR240A
COMPUTER INTERFACE SR 245
FAST SAMPLER SR 255
POWER SUPPLY & DISPLAY MODULE
Stanford Research Systems
Stanford Research Systems, Inc.

Boxcar Integrater

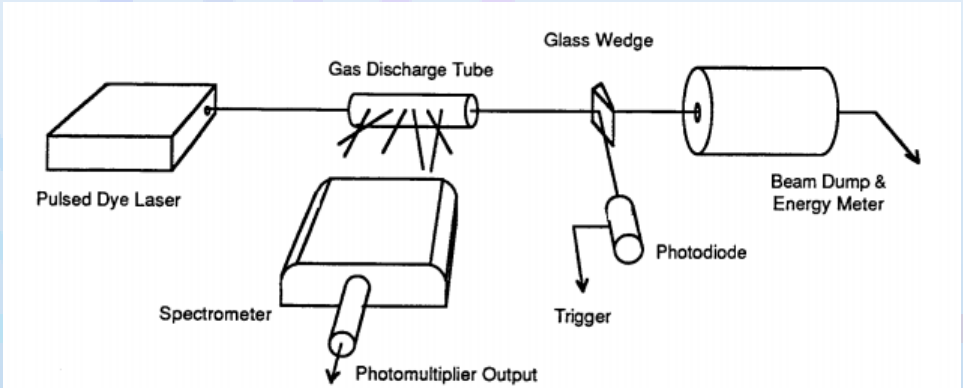
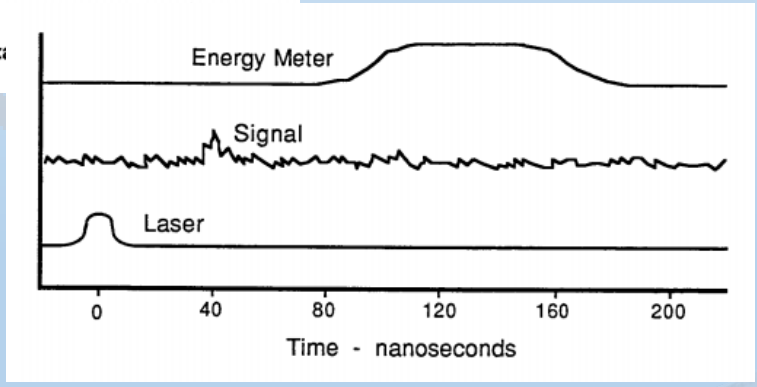


Figure 3 - Experiment For Application Ex

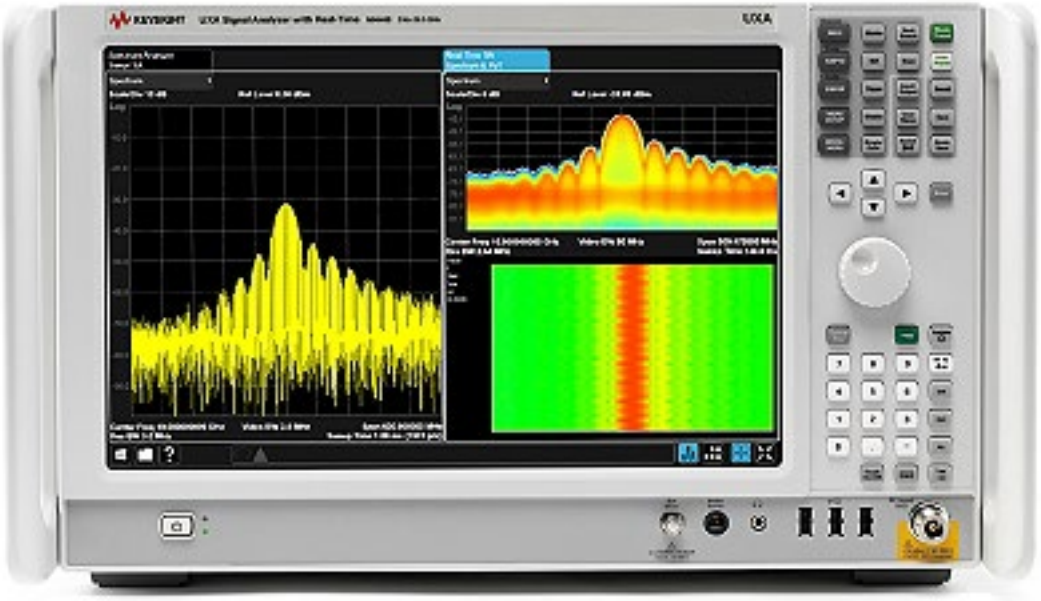


https://www.thinksrs.com/downloads/pdfs/manuals/Boxcarm.pdf

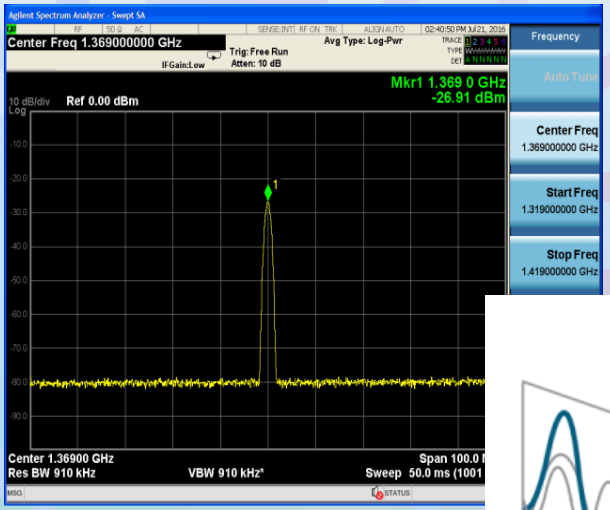
光子計數器

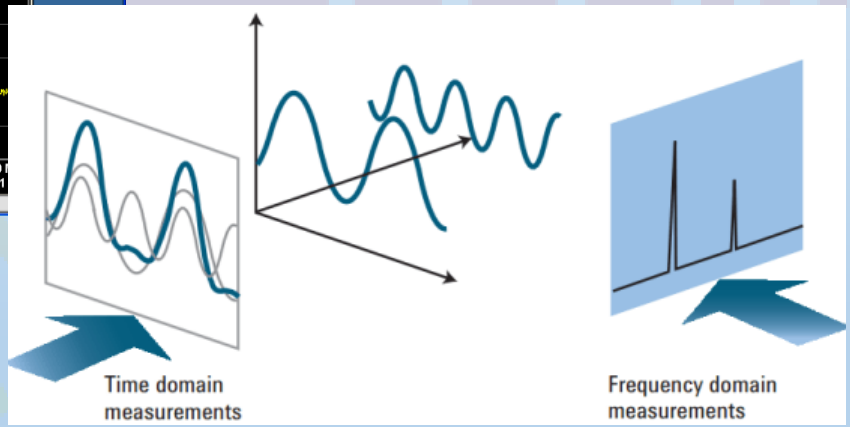
https://www.thinksrs.com/downloads/pdfs/manuals/SR400m.pdf

頻譜分析儀

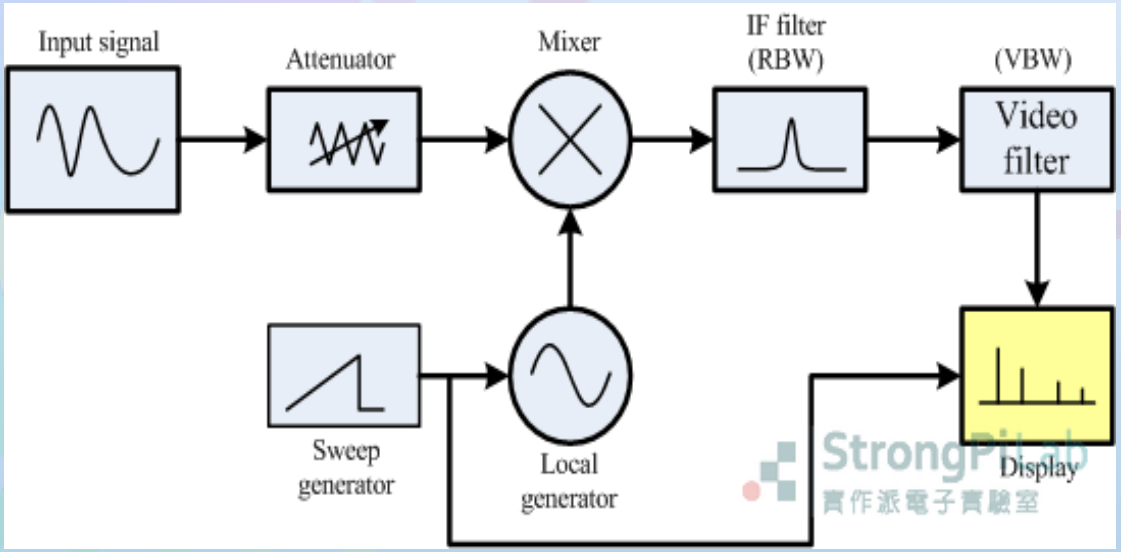


時域→頻域


Agilent Spectrum Analyzer - Swept SA
Center Freq 1.369000000 GHz
Trig: Free Run
Atten: 10 dB
Avg Type: Log-Pwr
Mkr1 1.369 0 GHz
-26.91 dBm
10 dB/div
Log
Ref 0.00 dBm
Center 1.36900 GHz
Res BW 910 kHz
VBW 910 kHz*
Sweep 50.0 ms (1001
Frequency
Auto Tune
Center Freq
1.369000000 GHz
Start Freq
1.319000000 GHz
Stop Freq
1.419000000 GHz


Time domain
measurements
Frequency domain
measurements

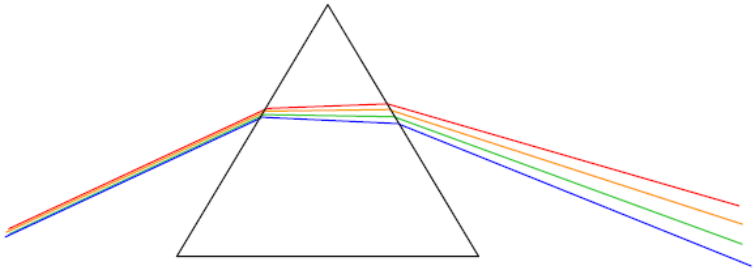
掃瞄式頻譜架構


Input signal
Attenuator
Mixer
IF filter
(RBW)
(VBW)
Video
filter
Sweep
generator
Local
generator
Display

光譜量測技術簡介

- 分光鏡與光譜儀
- 吸收光譜
- 螢光光譜與拉曼光譜
- 高解析度光譜儀
- 高靈敏度方法
- 非線性光譜

稜鏡分光

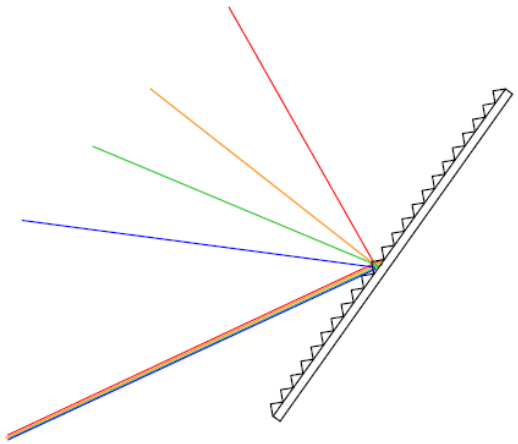


紅光折射率: 1.5145

（BK7玻璃）

藍光折射率: 1.5253

光柵分光



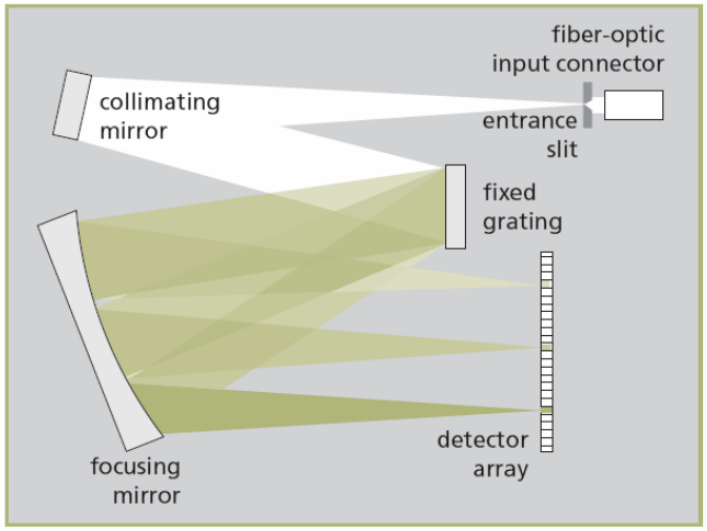
$$\sin\theta_d = \sin\theta_i + \frac{m\lambda}{d}$$

θ_i = 入射角

θ_d = 反射角

光柵光譜儀

resolving power $R = mN = \frac{\lambda}{\Delta\lambda} = \frac{W(\sin\theta_i - \sin\theta_d)}{\lambda}$



W = grating width

N = number of illuminated grooves

A symmetric Czerny-Turner spectrometer

可攜式光譜儀


Ocean Optics
HR4000CG-UV-NIR
www.oceanoptics.com | +1 727-733-2447

吸收係數

$$dI = -\alpha I\, dz$$

$$I(z) = I(0)e^{-\alpha z}$$

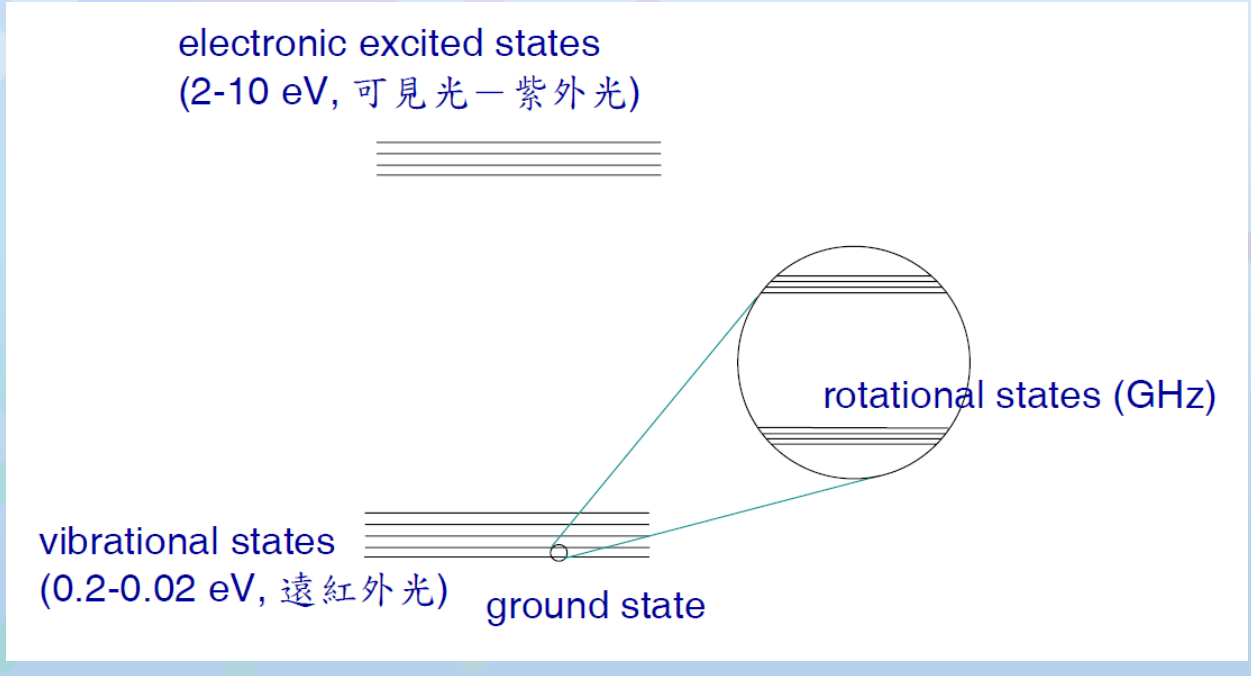
$\alpha = \sigma n$ = 吸收係數

σ = 吸收截面積

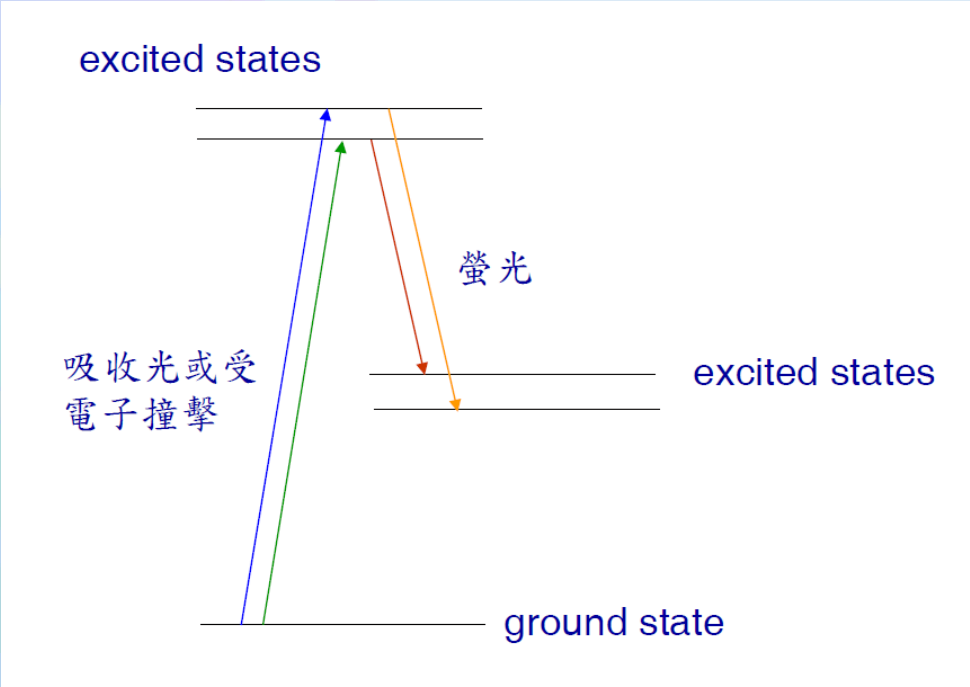
n = 分子密度

$$\frac{dI}{I} = -\frac{\sigma N}{A} = -\frac{\sigma N\, dz}{A\, dz} = -\sigma\left(\frac{N}{V}\right) dz = -\sigma n\, dz$$

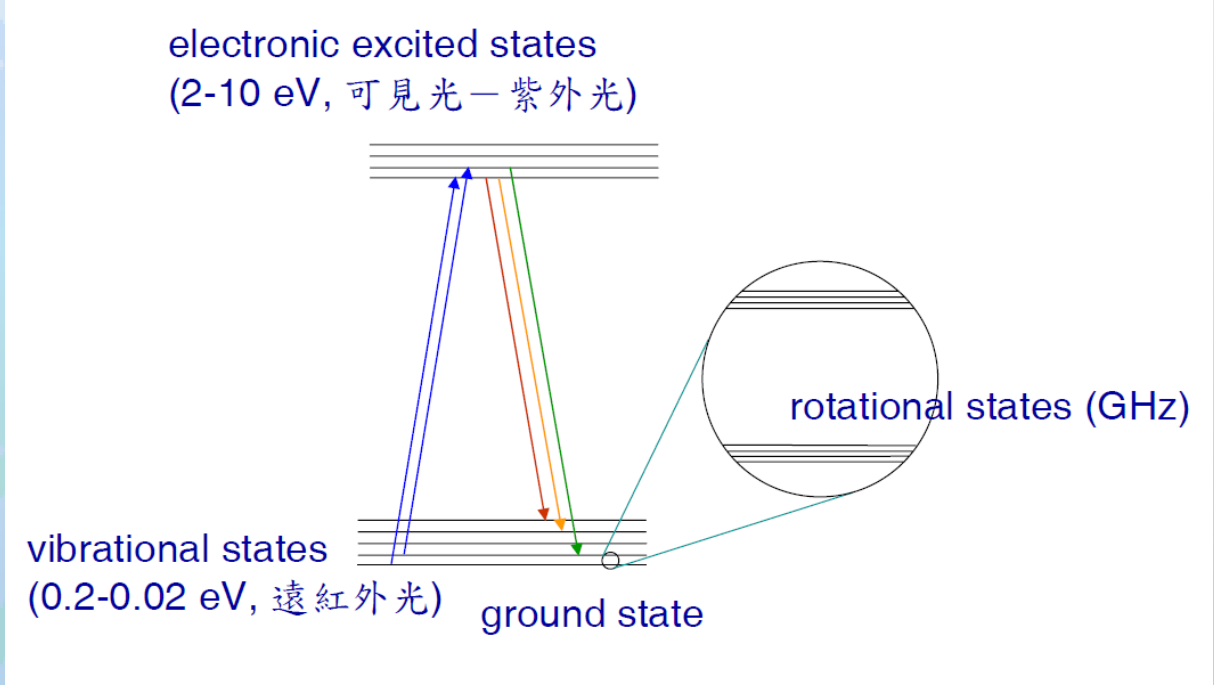
分子能階


electronic excited states
(2-10 eV, 可見光－紫外光)
rotational states (GHz)
vibrational states
(0.2-0.02 eV, 遠紅外光)
ground state

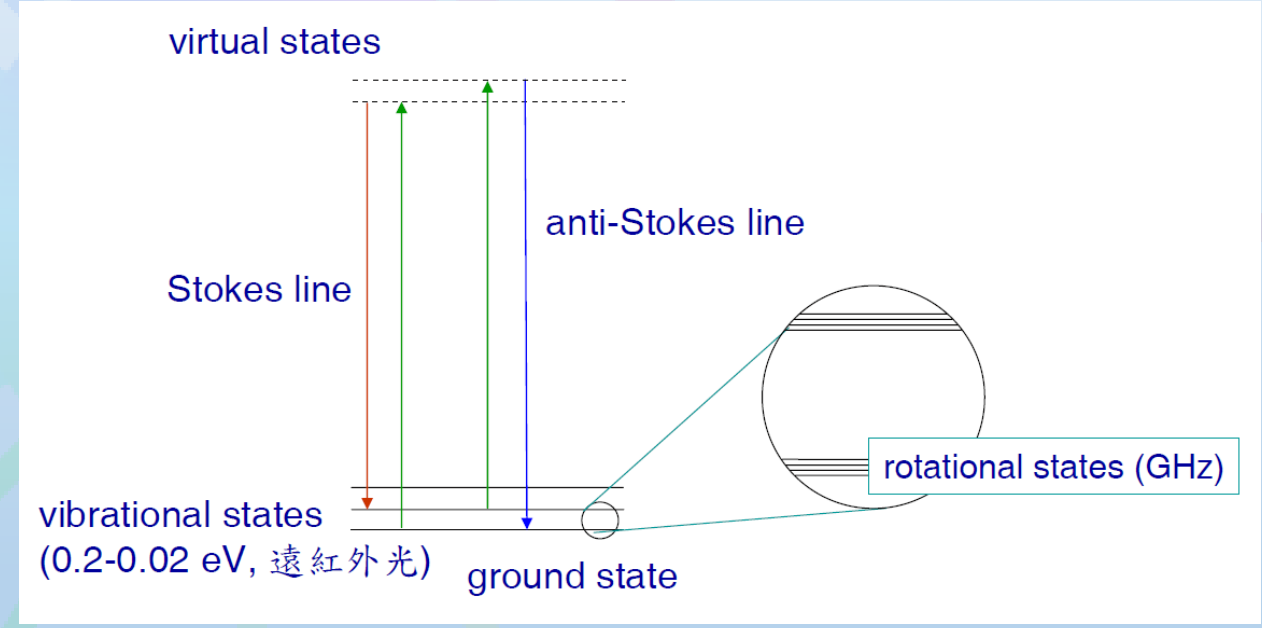
螢光光譜



雷射引致螢光光譜


electronic excited states
(2-10 eV, 可見光－紫外光)
rotational states (GHz)
vibrational states
(0.2-0.02 eV, 遠紅外光)
ground state

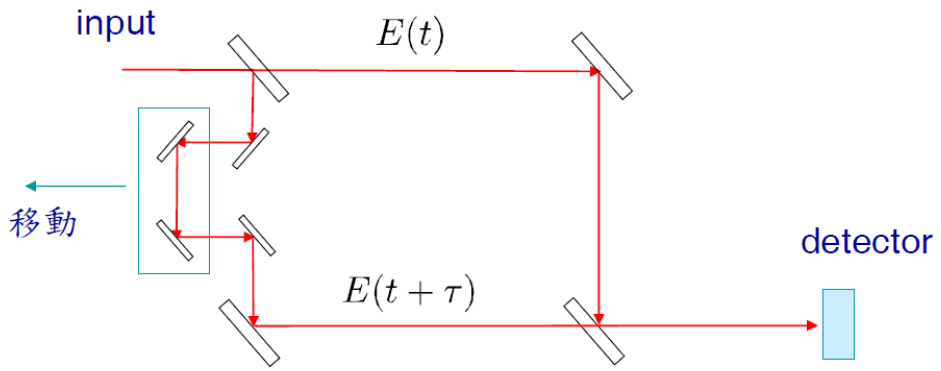
拉曼光譜


virtual states
anti-Stokes line
Stokes line
rotational states (GHz)
vibrational states
(0.2-0.02 eV, 遠紅外光)
ground state

高解析光譜

- Fourier-transform光譜儀
- Fabry-Perot干涉儀

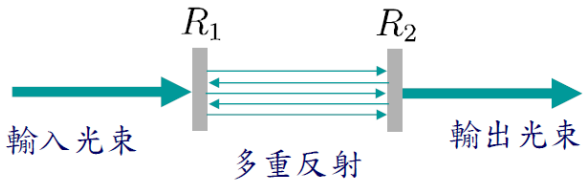
自相關函數的測量



$$\int_{-\infty}^{\infty} |E(t) + E(t+\tau)|^2 \, dt$$

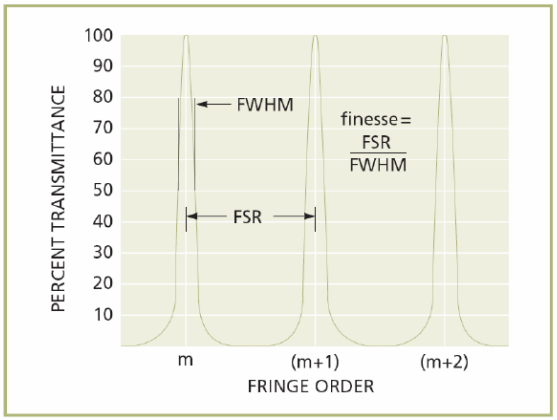
$$= \int_{-\infty}^{\infty} \left[|E(t)|^2 + |E(t+\tau)|^2 + E(t)E^*(t+\tau) + E^*(t)E(t+\tau) \right] dt$$

Fabry-Perot干涉儀



free spectral range FSR = $\frac{c}{2d}$

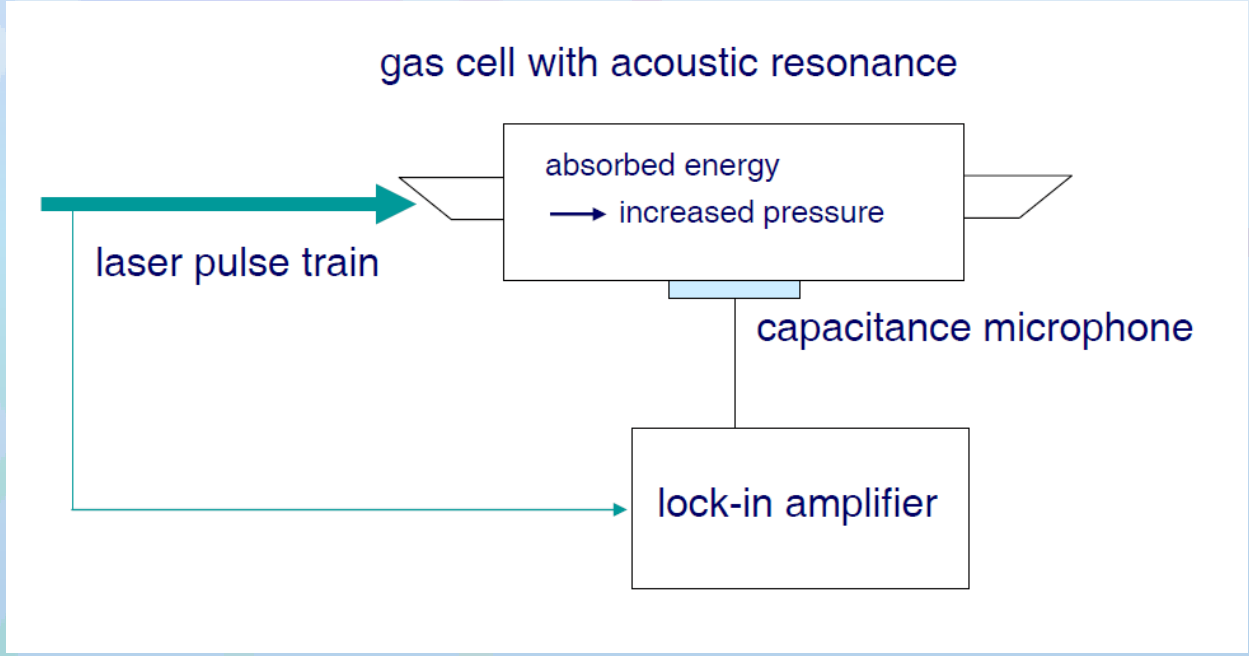
finesse $\mathcal{F} = \frac{\pi(R_1R_2)^{1/4}}{1-\sqrt{R_1R_2}}$



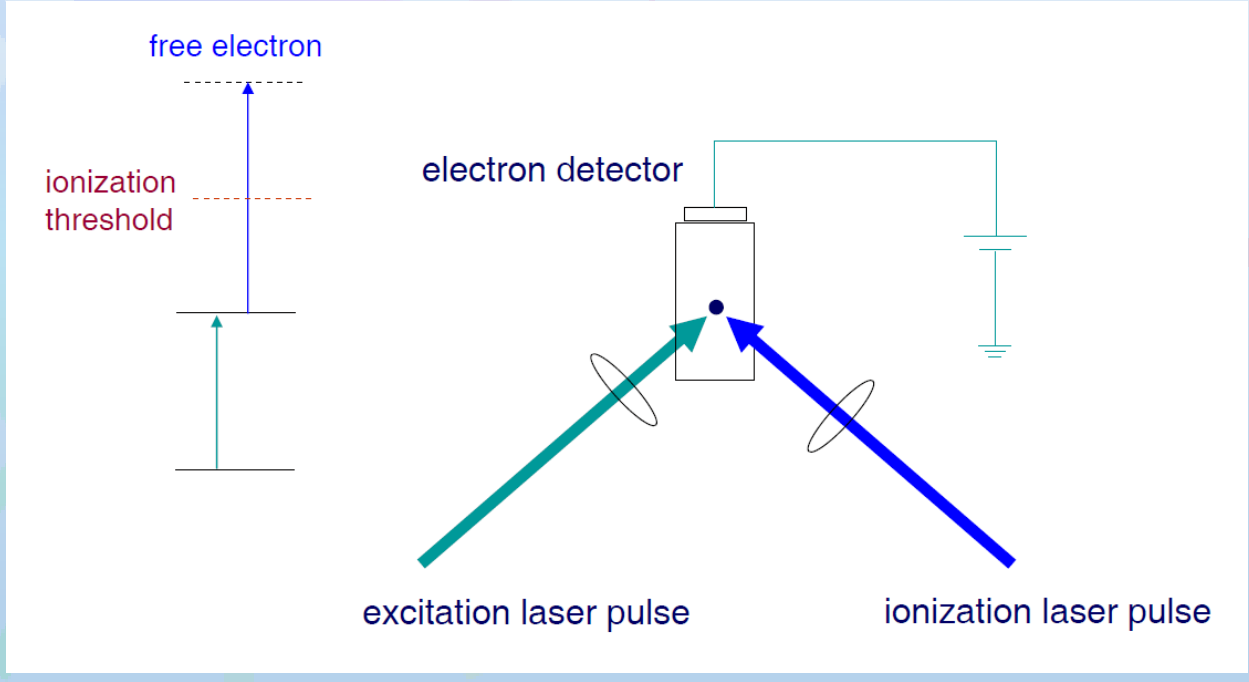
高靈敏度量測方法

- 聲光光譜
- 游離光譜
- 光電子光譜

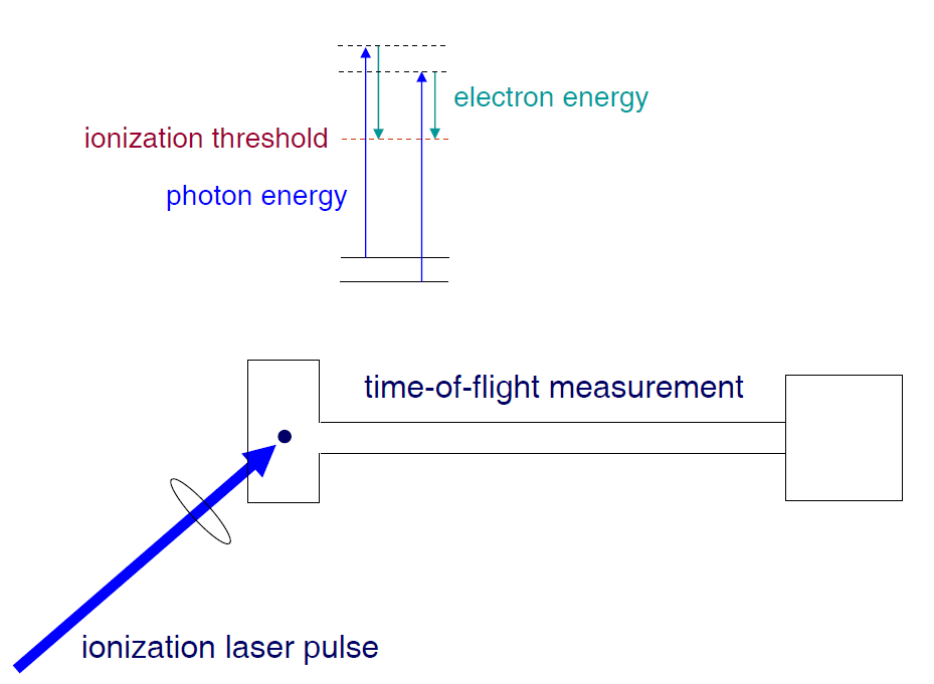
聲光光譜


gas cell with acoustic resonance
absorbed energy
increased pressure
laser pulse train
capacitance microphone
lock-in amplifier

游離光譜


free electron
ionization
threshold
electron detector
excitation laser pulse
ionization laser pulse

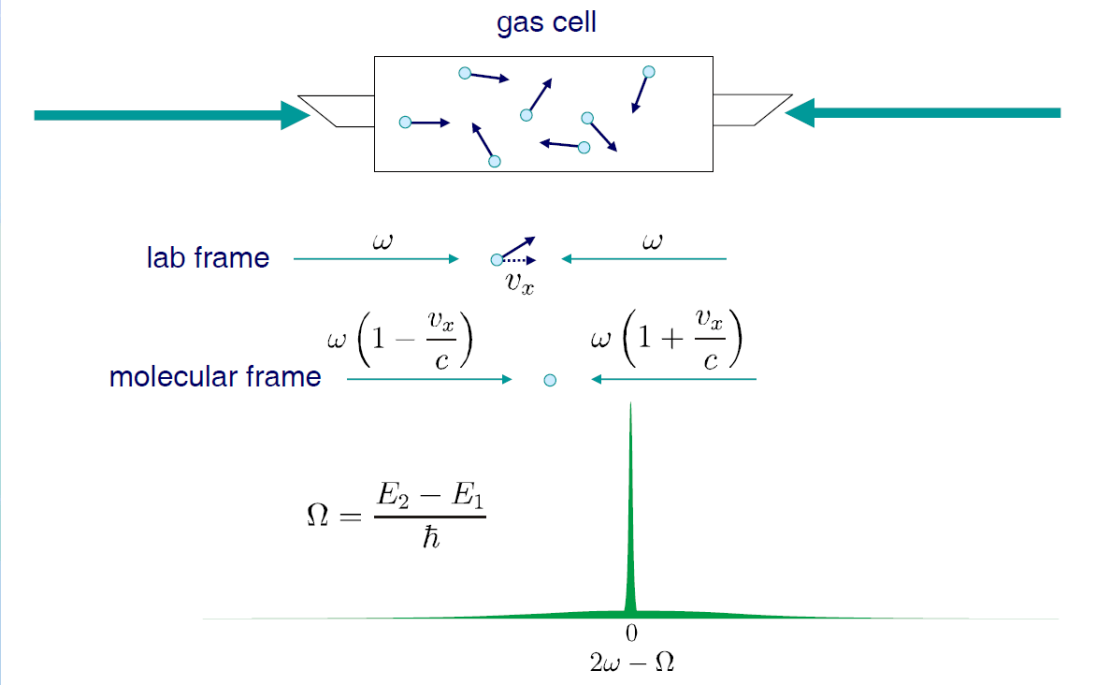
光電子光譜


electron energy
ionization threshold
photon energy
time-of-flight measurement
ionization laser pulse

非線性方法

- 雙光子無都卜勒吸收
- 同調拉曼光譜

雙光子光譜


gas cell
lab frame
ω
ω
v_x
$\omega\left(1-\frac{v_x}{c}\right)$
$\omega\left(1+\frac{v_x}{c}\right)$
molecular frame
$\Omega = \frac{E_2 - E_1}{\hbar}$
0
$2\omega - \Omega$

參考資料

- 中央研究院原子與分子科學研究所暨國立中央大學物理系，強場物理與超快技術實驗室 暑期新生訓練講義。http://hfp.phy.ncu.edu.tw/訓練/暑期新生訓練
- 實作派電子實驗室https://www.strongpilab.com/
- Stanford Research Systems https://www.thinksrs.com/index.html
- 太克台灣 https://tw.tek.com/
- 是德科技 https://www.keysight.com/tw/zh/home.html
- HAMAMATSU濱松光子學 https://www.hamamatsu.com/jp/en.html