光學

2022基礎實驗技術訓練

雷射光電支援中心
陳蔚然

基礎 機械 電子 光學 控制 量測 系統

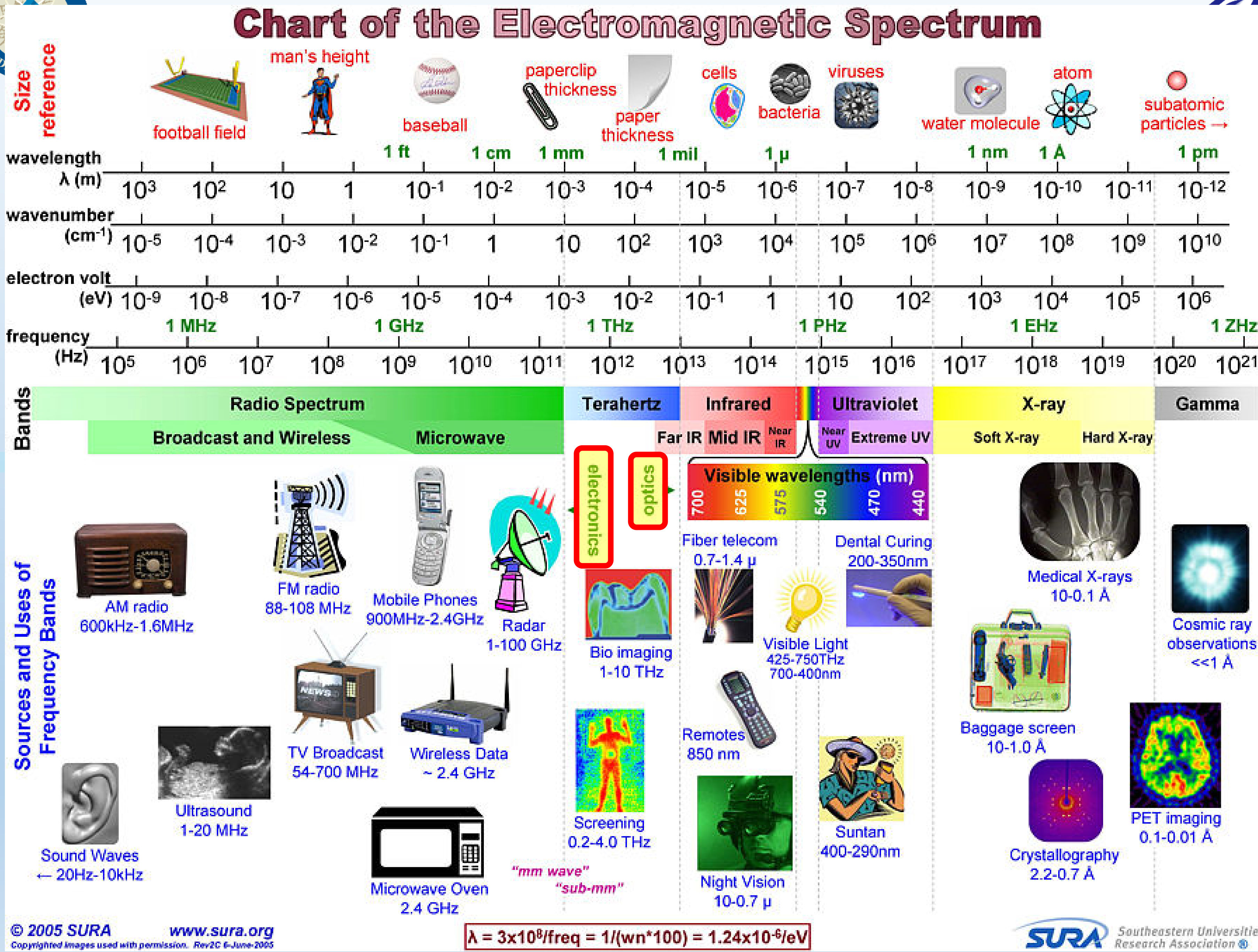
Chart of the Electromagnetic Spectrum
Size reference
football field
man's height
baseball
paperclip thickness
paper thickness
cells
bacteria
viruses
water molecule
atom
subatomic particles →
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10^3 10^2 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
wavenumber (cm^{-1})
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
electron volt (eV)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21}
Bands
Radio Spectrum
Terahertz
Infrared
Ultraviolet
X-ray
Gamma
Broadcast and Wireless
Microwave
Far IR
Mid IR
Near IR
Near UV
Extreme UV
Soft X-ray
Hard X-ray
electronics
optics
Visible wavelengths (nm)
700 625 575 540 470 440
Sources and Uses of Frequency Bands
AM radio 600kHz-1.6MHz
FM radio 88-108 MHz
Mobile Phones 900MHz-2.4GHz
Radar 1-100 GHz
Bio imaging 1-10 THz
Fiber telecom 0.7-1.4 μ
Visible Light 425-750THz 700-400nm
Dental Curing 200-350nm
Medical X-rays 10-0.1 Å
Cosmic ray observations <<1 Å
TV Broadcast 54-700 MHz
Wireless Data ~ 2.4 GHz
Remotes 850 nm
Baggage screen 10-1.0 Å
Sound Waves ← 20Hz-10kHz
Ultrasound 1-20 MHz
Microwave Oven 2.4 GHz
"mm wave"
"sub-mm"
Screening 0.2-4.0 THz
Night Vision 10-0.7 μ
Suntan 400-290nm
Crystallography 2.2-0.7 Å
PET imaging 0.1-0.01 Å
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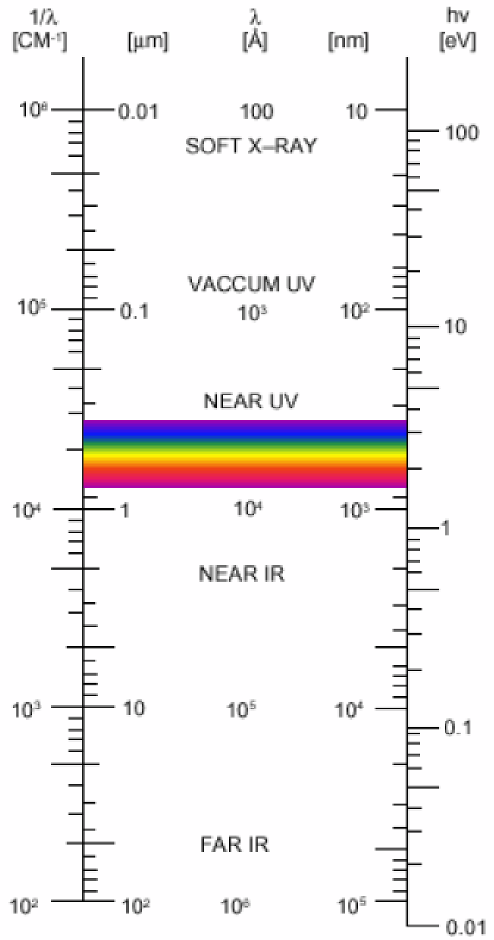
Copyrighted images used with permission. Rev2C 6-June-2005
$\lambda = 3x10^8/freq = 1/(wn*100) = 1.24x10^{-6}/eV$
SURA Southeastern Universities Research Association

光學（實驗控制與測量）

- 元件
  - 光源：雷射光與其他光源、光的亮度等特性
  - 光學元件：反射鏡、透鏡、稜鏡、分光鏡、光窗、波長板、極化鏡、濾光片與衰減片、光纖、光柵、標準具、光學晶體（調制）、法拉第旋轉器、光圈與快門
  - 特性與功能：光學材料、色散、光學規格、光學鍍膜、功率範圍
- 工具
  - 光機械元件特性（結構和溫度穩定度、背隙、真空相容性）
  - 光學元件的清潔
  - 光學元件組裝
- 光路
  - 光束特性：高斯光束與ABCD law
  - 基本光路：直線定位、擴束與縮束、干涉儀、光纖耦合、空間濾波器、能量調節器、延遲光路、透鏡成像、傳繼成像系統
- 光路模擬
  - 軟體：GaussianBeam, reZonator……
- 調校（說明、演示）
  - 光學系統架設技巧

光譜—光波長分類



$$eV = 1.24 \times 10^{-4} \times 1/\lambda\,(cm^{-1})$$

$$eV = \frac{1240}{\lambda\,(nm)}$$

25–200 nm	vacuum ultraviolet	VUV
200–400 nm	ultraviolet	UV
400–700 nm	visible	VIS
700–1000 nm	near-infrared	NIR
1–3 μm	short-wavelength infrared	SWIR
3–5 μm	medium-wavelength infrared	MWIR
5–14 μm	long-wavelength infrared	LWIR
14–30 μm	very long wavelength infrared	VLWIR
30–100 μm	far-infrared	FIR
100–1000 μm	submillimeter	SubMM

UV分類

- Terrestrial Solar UV: 290-380 nm.
- UV-A: 320-380 nm. Ozone is transparent. Cellular damage by photochemical reactions.
- UV-B: 290-320 nm. Ozone is absorptive. DNA absorbs and induces many bioeffects.
- UV-C: 190-290 nm. Air is transparent but ozone absorbs so heavily that we do not see this range at earth surface.
- Vacuum UV: < 190 nm. Ionizing N_2 and O_2.
- Extreme UV: < 50 nm.
- Soft x-ray: < 30 nm.
- X-ray: < 1 nm.

Ref: Lasers in Medicine, edited by R. W. Waynant (CRC Press, London, 2002), Chap. 4.

IR分類

一般使用者的分類是：

•**近紅外線**（NIR, IR-A *DIN*）：波長在0.75－1.4微米，以水的吸收來定義，由於在二氧化矽玻璃中的低衰減率，通常使用在光纖通信中。在這個區域的波長對影像的增強非常敏銳。例如，夜視設備。

•**短波長紅外線**（SWIR, IR-B *DIN*）：1.4－3微米，水的吸收在1,450奈米顯著的增加。1,530至1,560奈米是主導遠距離通信的主要光譜區域。

•**中波長紅外線**（MWIR, IR-C *DIN*）也稱為中紅外線：波長在3－8微米。被動式的紅外線追熱導向飛彈技術在設計上就是使用3－5微米波段的大氣窗口來工作。

•**長波長紅外線**（LWIR, IR-C *DIN*）：8－15微米。這是"熱成像"的區域，在這個波段的感測器不需要其他的光或外部熱源，例如太陽、月球或紅外燈，就可以獲得完整的熱排放量的被動影像。有時也會被歸類為"遠紅外線"

•**遠紅外線**（FIR）：50－1,000微米

IR分類

天文學家通常將以如下的波段區分紅外線的範圍

名稱	縮寫	波長
近紅外線	NIR	（0.7-1）至5微米
中紅外線	MIR	5至（25-40）微米
遠紅外線	FIR	（25-40）至（200-350）微米

可以依不同感測器可偵測的範圍來分類

- 近紅外線：波長範圍為0.7至1.0 μm（由人眼無法偵測的範圍到矽可響應的範圍）
- 短波紅外線：波長範圍為1.0至3 μm（由矽的截止頻率到大氣紅外線窗口的截止頻率），InGaAs範圍可以到1.8 μm，一些較不靈敏的鉛鹽也可偵測到此範圍。
- 中波紅外線：波長範圍為3至5 μm（由大氣紅外線窗口定義，也是銻化銦及HgCdTe可覆蓋的範圍，有時是硒化鉛可覆蓋的範圍）
- 長波紅外線：波長範圍為8至12或是7至14 μm（是HgCdTe及微測輻射熱計（英語：microbolometer）可覆蓋的範圍）
- 遠紅外線（VLWIR）：波長範圍為12至30 μm，是摻雜矽可覆蓋的範圍

光的傳播

Light is a kind of electro-magnetic wave.

$$\mathbf{E}(x, y, z, t) = \mathbf{A}(x, y, z, t)e^{i\phi(x,y,z,t)}$$

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{A}(\mathbf{r}, t)e^{i\phi(\mathbf{r},t)}$$

A: amplitude vector. ϕ: phase.

電磁波特性

$$\vec{E}\,e^{i(\vec{k}\cdot\vec{r}-\omega t+\emptyset)}$$

振幅
偏振

高亮度

材料加工
核融合
雷射武器

方向

高方向性

雷射測距
光雷達
准直儀

頻率

高單色性

精密測量
標準長度、時間、頻率
通信
高解析光譜

相位

高相干性

全像術
干涉儀

波前

Wavefront: surfaces of constant phase for the electromagnetic field .

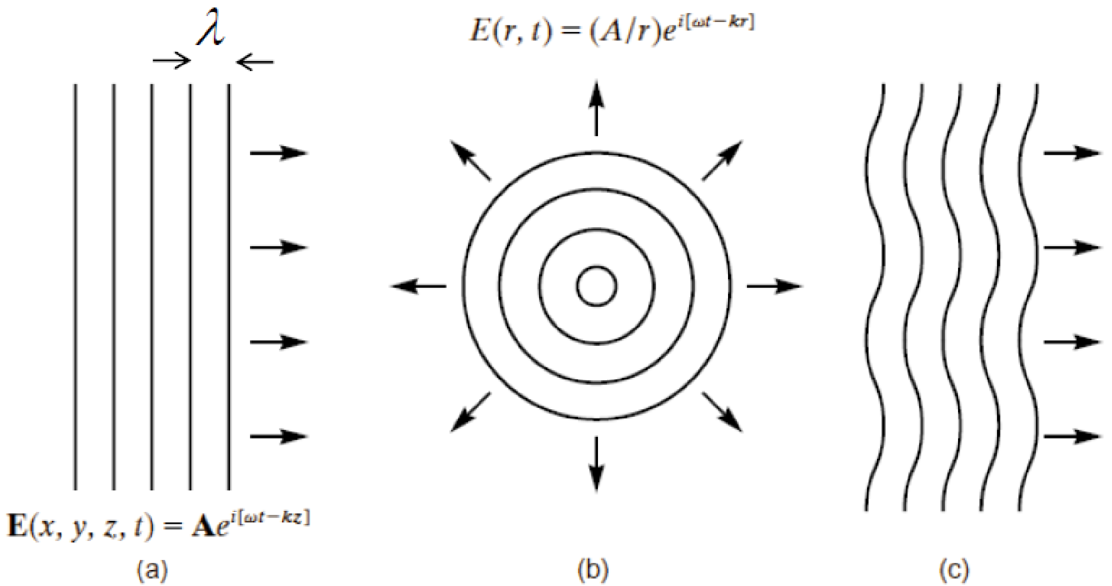
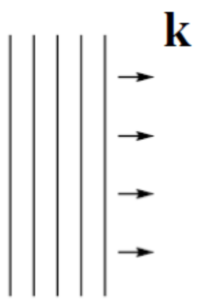


FIGURE 1 Examples of wavefronts: (*a*) plane wave; (*b*) spherical wave; and (*c*) aberrated plane wave.

波向量與波數

Wave Vector: the vector whose direction is normal to the wavefront and magnitude $2\pi/\lambda$.



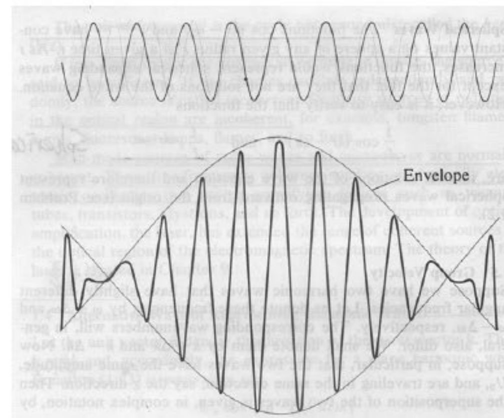
For a plane wave, **A** is constant, and

$$\phi = \mathbf{k} \cdot \mathbf{r} - \omega t$$

The magnitude of **k**, $k = 2\pi/\lambda$, is also called the *wave number*.

相速度與群速度

Phase velocity $v = \frac{\omega}{k} = \frac{c}{n}$



If we have two frequency components, $\omega + \Delta\omega$ and $\omega - \Delta\omega$, the envelope moves with a speed

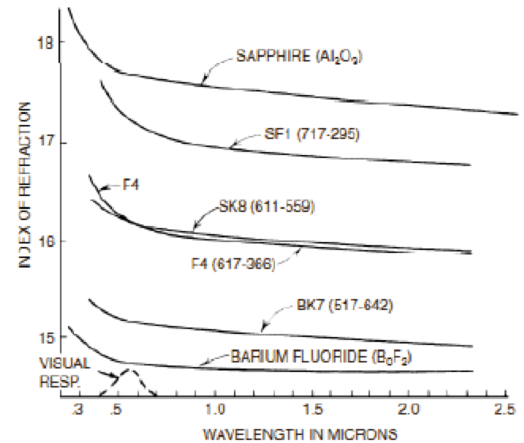
$$v_g = \frac{\Delta\omega}{\Delta k}$$

For a number of frequency components, $v_g = \frac{d\omega}{dk}$

v_g is called group velocity.

色散

Dispersion: n is a function of λ.



Sellmeier equation:

$$n^2(\lambda) = a + \frac{b\lambda^2}{c - \lambda^2} + \frac{d\lambda^2}{e - \lambda^2} + \frac{f\lambda^2}{g - \lambda^2} + \cdots$$

In catalogs of optical materials, the coefficients a, b, c ... can be found for various transparent materials.

色散與群速度

Usually, the quantity $dn/d\lambda$ is used to describe the magnitude of dispersion.

Since $\omega = kc/n$

$$v_g = \frac{d\omega}{dk} = \frac{d}{dk}\left(\frac{kc}{n}\right) = \frac{c}{n}\left(1 - \frac{k}{n}\frac{dn}{dk}\right)$$

or $$\frac{1}{v_g} = \frac{n}{c} - \frac{\lambda}{c}\frac{dn}{d\lambda}$$

吸收

When light propagates in a medium, it is always accompanied by energy dissipation.

$$E = E_0 e^{-\alpha z/2} e^{i(kz-\omega t)}$$

α is the coefficient of absorption.

光學基材

Mirror

Pyrex: excellent mirror substrate; low coefficient of thermal expansion

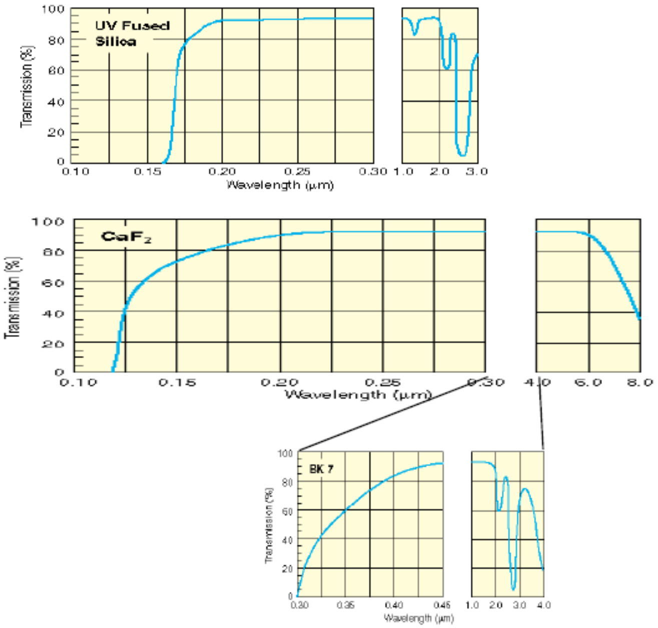
Zerodur: "zero" thermal expansion

Lens or window

UV fused silica: excellent transmissive properties from IR to UV

Calcium Fluoride (CaF_2): wider transmission bands than fused silica, small n_2

Glasses: BK7, SF14, etc: different transmission, dispersion....



https://www.cvilaseroptics.com/onlinecatalog/

光學元件表面品質

Surface flatness: How flat the surface is.

RMS amplitude of surface ripples

When preservation of wavefront is critical, a $\lambda/10$ to $\lambda/20$ surface should be selected.

Surface quality: How much the surface scatters.

In the scratch-dig specification, the first number is the width of the largest scratch (in 0.1 μm), and the second is the diameter of the largest bubble or pit (in 10 μm).

For demanding laser systems 20-10 to 10-5 scratch-dig is appropriate. If some scatter is tolerable, 40-20 can be used.

鍍膜

Reflective coatings

Metallic: broadband, insensitive to wavelength, angle of incidence, and polarization. But lower damage threshold.

Dielectric: reflectivity can be specified from low (10%) to near total reflection. Available either broadband or narrowband. Best for 0-45° angle of incidence.

- High Energy: resist optical damage of high power CW lasers and high energy pulsed lasers. Wavelength must be specified.

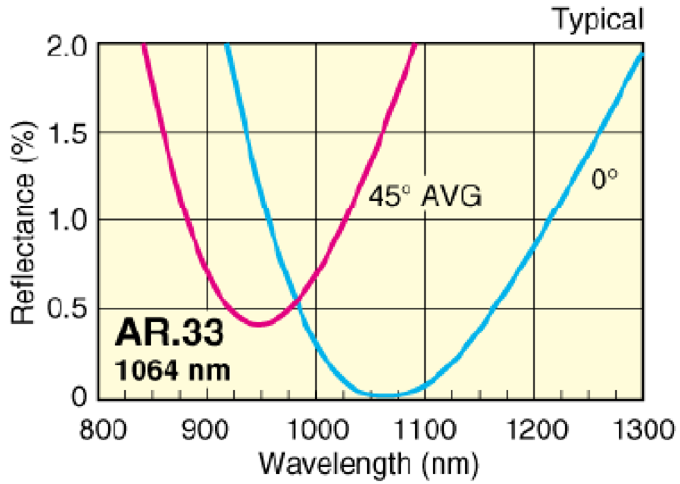
- Ultrafast mirror coating : to minimize dispersion effects on ultrashort laser pulses.

- Cavity mirror coating: high transmission for pump wavelengths and high reflection for the lasing wavelength.

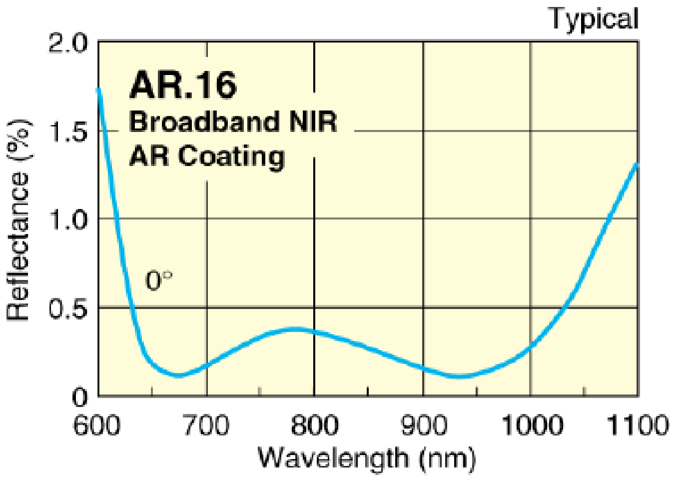
鍍膜

Anti-reflection coatings

V-coating



BBAR-coating



能量流與強度

For a plane electro-magnetic wave

$$\mathbf{E} = \mathbf{E}_0 \cos(\mathbf{k}\cdot\mathbf{r} - \omega t)$$

$$\mathbf{H} = \mathbf{H}_0 \cos(\mathbf{k}\cdot\mathbf{r} - \omega t)$$

Poynting vector $\mathbf{S} = \mathbf{E}\times\mathbf{H} = \mathbf{E}_0 \times \mathbf{H}_0 \cos^2(\mathbf{k}\cdot\mathbf{r} - \omega t)$

Its average value is $\langle \mathbf{S} \rangle = \frac{1}{2}\mathbf{E}_0 \times \mathbf{H}_0$

The magnitude of $<\mathbf{S}>$ is $I = \frac{1}{2}E_0 H_0 = \frac{n}{2Z_0}|E_0|^2$

強度單位

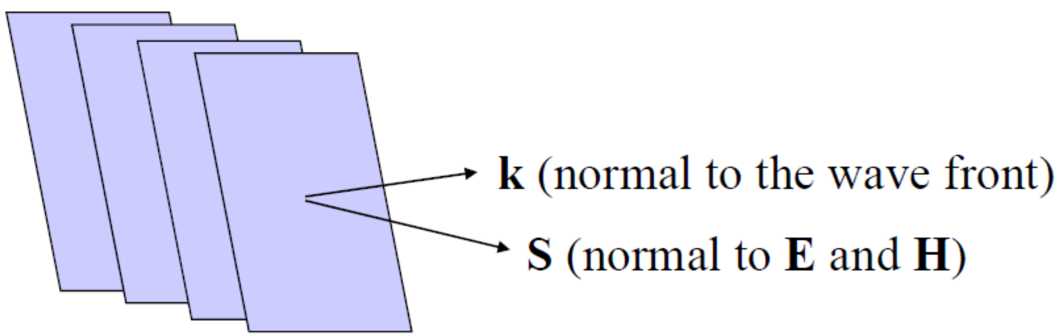
$$I = \frac{1}{2} E_0 H_0 = \frac{n}{2Z_0} |E_0|^2$$

$$Z_0 = \sqrt{\mu_0 / \varepsilon_0} = 377\ \Omega$$

For E_0 in V/m, the unit of intensity is then W/m^2.
In optics, however, W/cm^2 is used frequently.

能量流方向

The direction of energy flow is not always the same as that of the wave vector.



光學材料與元件

- 各式元件特性與功能
  - 資料查找、光學材料、色散、光學規格、光學鍍膜、功率範圍
  - 反射鏡、透鏡、稜鏡、分光鏡、波長板、極化鏡、濾光片與衰減片、光窗、標準具、光柵、法拉第旋轉器、光纖、光圈與快門
  - 雷射介質、非線性晶體。

光學元件

spherical lens

mirror

prism

polarizer or non-plarizing beam splitter

cylindrical lens

filter

window

objective

wave plate

損壞閾值

Fluence threshold: thermal effects. Energy fluence = pulse energy/beam area. (Unit: J/cm^2)

This is often used for pulsed lasers. As a rule of thumb, the fluence threshold increases as a function of the square root of the time domain. For instance, if the damage threshold is 2 J/cm^2 for 10 ns pulses, at the 1 μs time domain the optic can withstand 20 J/cm^2.

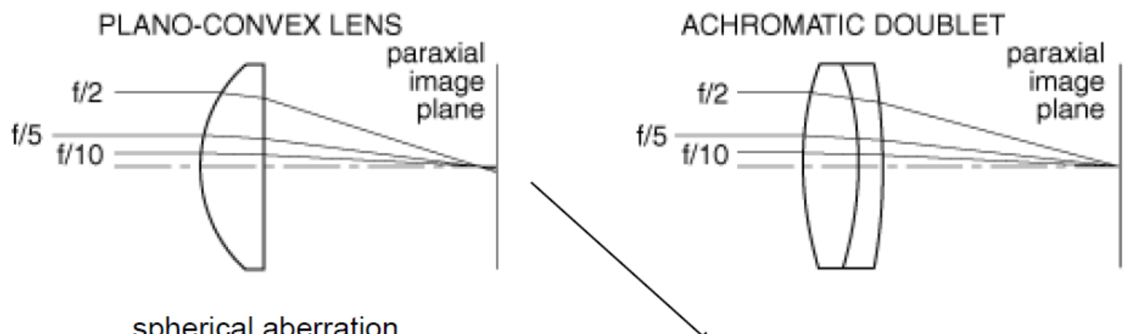
Intensity threshold: electric field breakdown. Intensity = power/beam area. (Unit: MW/cm^2)

This is important for both cw and pulsed lasers. The intensity threshold scales with wavelength, so the threshold at 532 nm will be half that at 1064 nm.

Beyond either threshold, laser can damage the optics.

挑選正確的鏡片

f/# = focal length/beam diameter
On a lens, it means the lowest *f/#* this lens can achieve.



spherical aberration

chromatic aberration

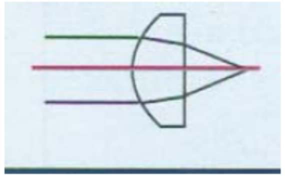
focal spot diameter

$$d = \frac{4\lambda}{\pi} \cdot f/\#$$

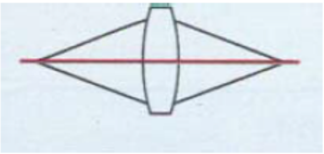
挑選正確的鏡片

!

Plano-convex lenses: Focusing parallel rays of light to a point. Minimize spherical aberration in situations where the object and image are at unequal distances from the lens. For optimum performance, the curved surface should face the infinite conjugate.



Bi-convex lenses: Minimize spherical aberration in situations where the object and image are at equal or near equal distances from the lens.



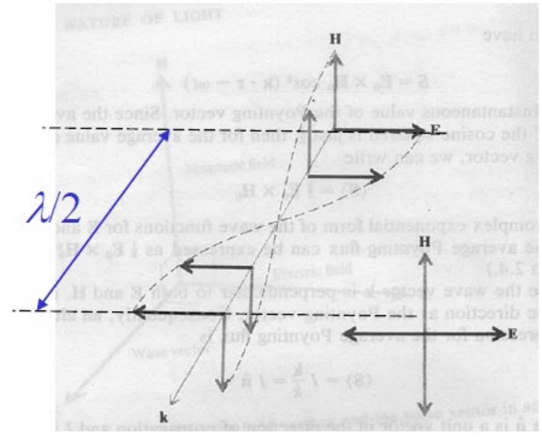
偏振

$$\mathbf{E} = \mathbf{E}_0 \cos(\mathbf{k} \cdot \mathbf{r} - \omega t)$$

We usually use the direction of **E** as the direction of polarization.

If the direction of E is constant, the light is called "linearly polarized."

linearly polarized



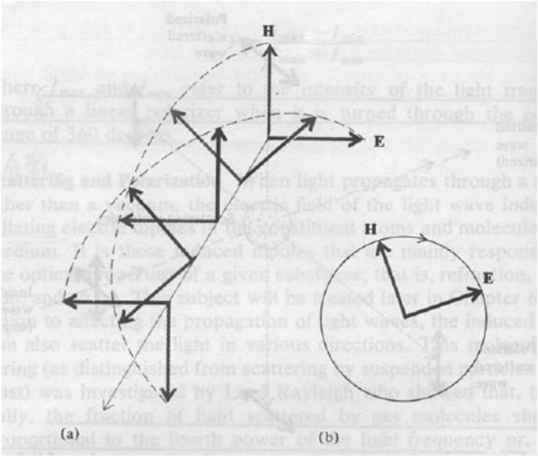
偏振

Generally, the electric field is represented as

$$\mathbf{E} = E_{0x}\cos(kz - \omega t + \phi_x)\hat{\mathbf{i}} + E_{0y}\cos(kz - \omega t + \phi_y)\hat{\mathbf{j}}$$

$E_{0x} = E_{0y}$ and $\phi_y - \phi_x = -\pi/2$: right circularly polarized.

right-hand circularly polarized

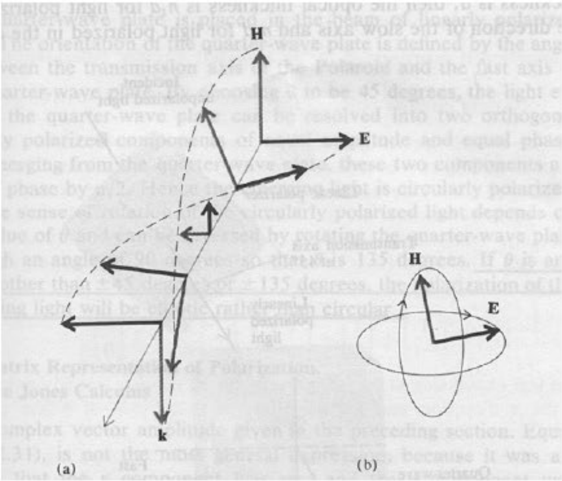


偏振

right-hand elliptically polarized

$E_{0x} \neq E_{0y}$ and $\phi_y - \phi_x = -\pi/2$:

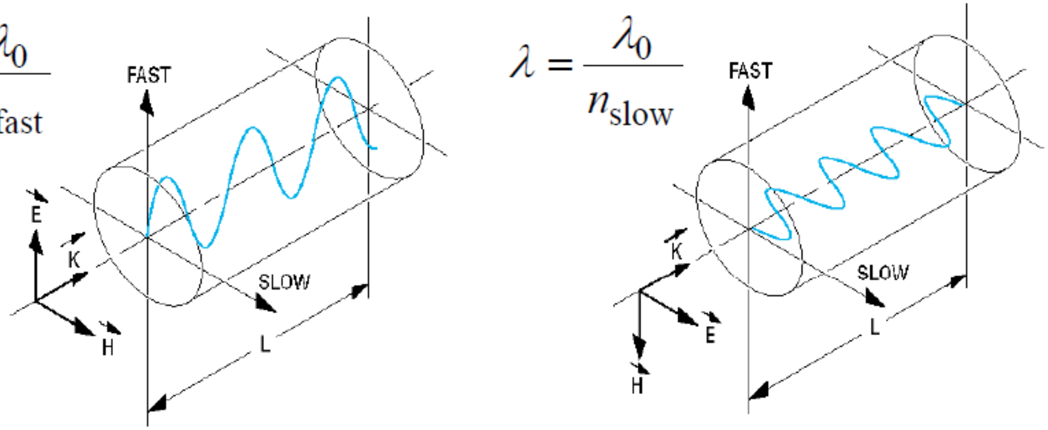
right elliptically polarized.



光的偏振：波長板

Waveplates are birefringent crystals, which have different refractive indices for different polarizations.

$$\lambda = \frac{\lambda_0}{n_{\mathrm{fast}}} \qquad \lambda = \frac{\lambda_0}{n_{\mathrm{slow}}}$$

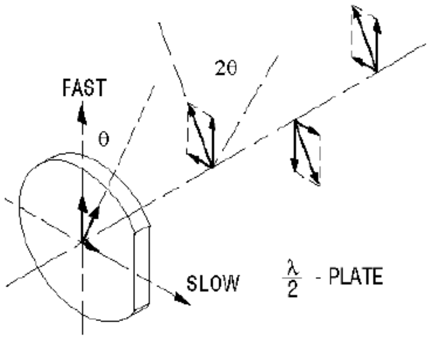


Retardation $\Gamma = (n_{\mathrm{slow}} - n_{\mathrm{fast}})\omega L / c$

光的偏振：波長板

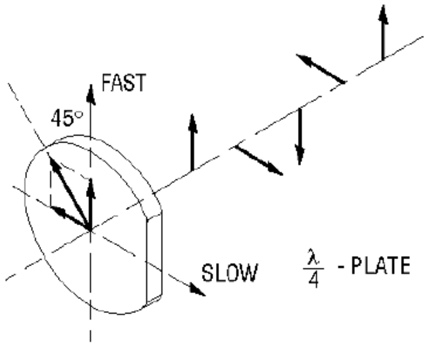
$\Gamma = (2m+1)\pi$: *m*-order half wave plate

The half-waveplate can be used to rotate the polarization of linearly polarized light.
Rotate the half-waveplate exactly θ around the beam axis (in either direction) and we will have rotated the polarization of the beam by 2θ.

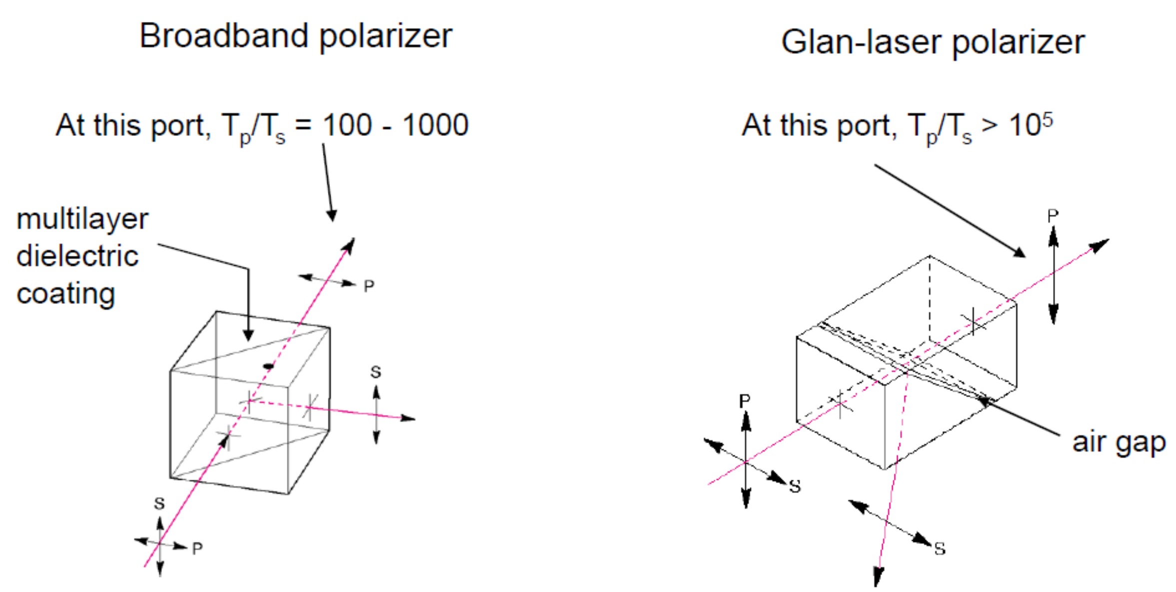


$\Gamma = (2m+1/2)\pi$: *m*-order quarter wave plate

Quarter-waveplates are used to turn linearly-polarized light into circularly-polarized light, and vice versa. To do this, we must orient the waveplate so that equal amounts of fast and slow waves are excited.



光的偏振：檢偏器



T_p/T_s is the extinction ratio, which is the most important specification of a polarizer.

瓊斯向量(Jones Vector)

$$\mathbf{E} = E_{0x}\cos(kz - \omega t + \phi_x)\hat{\mathbf{i}}$$
$$+ E_{0y}\cos(kz - \omega t + \phi_y)\hat{\mathbf{j}}$$

We can write the electric field as

$$\begin{bmatrix} E_{0x} \\ E_{0y} \end{bmatrix} = \begin{bmatrix} |E_{0x}|e^{i\phi_x} \\ |E_{0y}|e^{i\phi_y} \end{bmatrix}$$ called the Jones vector.

瓊斯向量(Jones Vector)

Normalized Jones vector:

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad \text{linearly polarized in } x$$

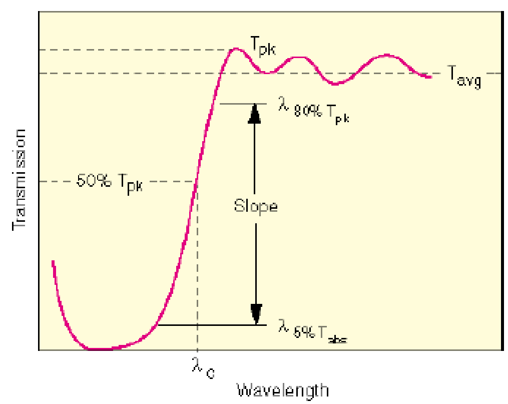
$$\begin{bmatrix} 1 \\ i \end{bmatrix} \quad \text{left circularly polarized}$$

ABCD Law

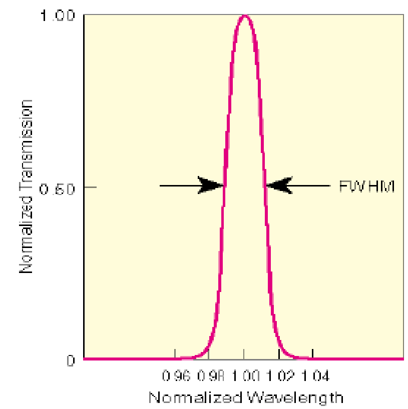
- 光束追蹤演算法
- $\begin{bmatrix} x_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_1 \\ \theta_1 \end{bmatrix}$

濾片

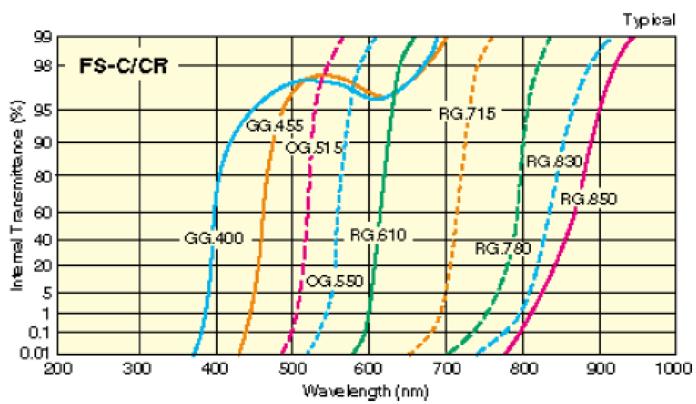
long wavelength pass filter

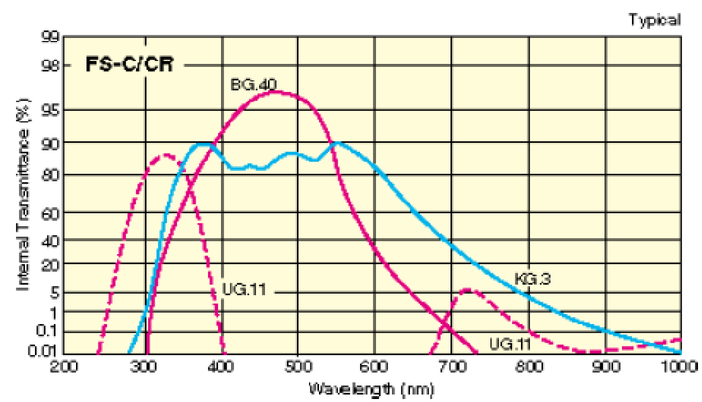


band pass filter
interference filter

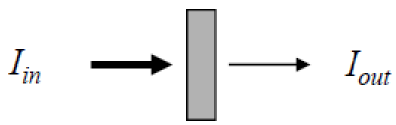


Color-glass filters



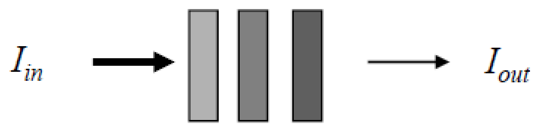


衰減片

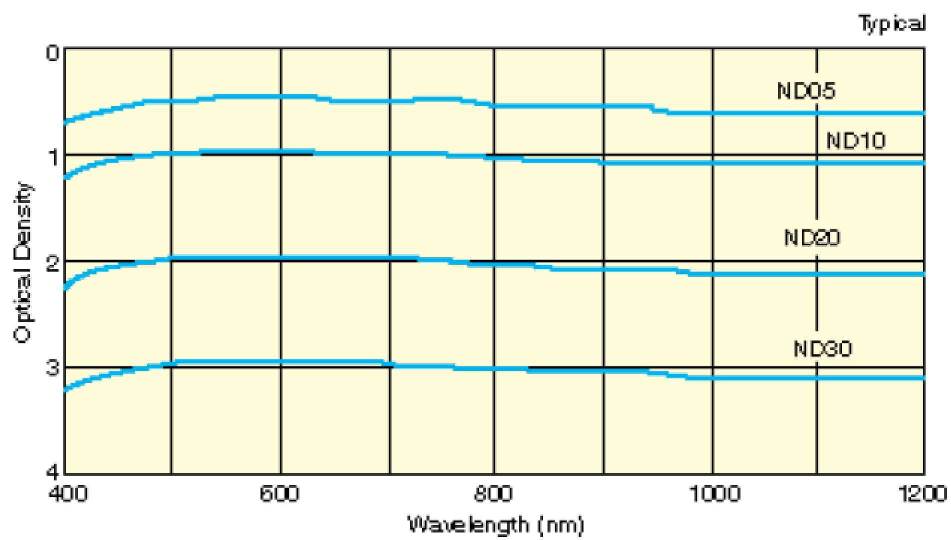


$I_{out} = I_{in} \times 10^{-O.D.}$

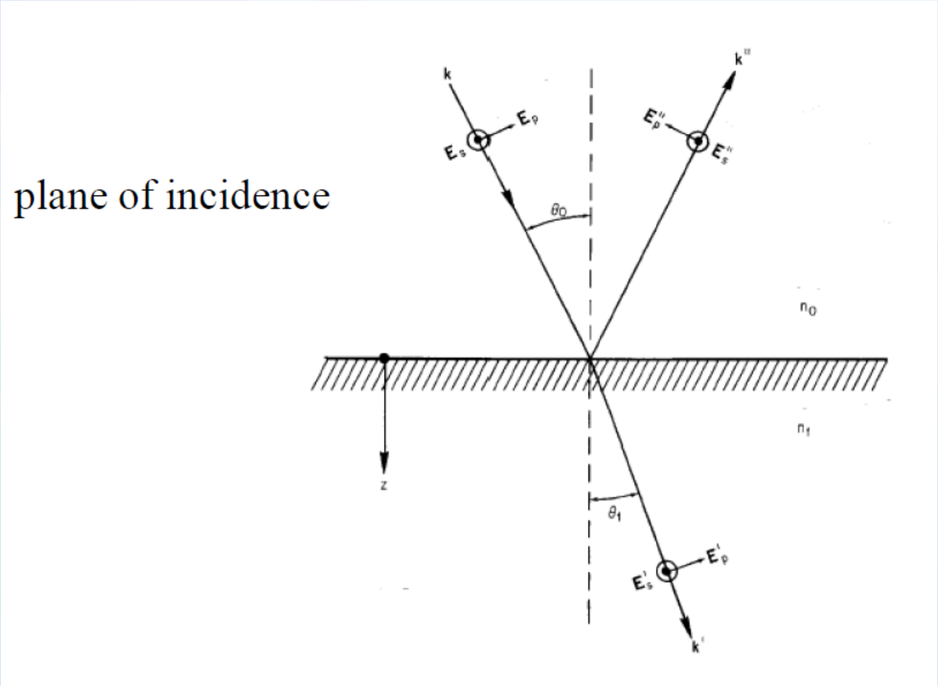
O.D.is optical density.



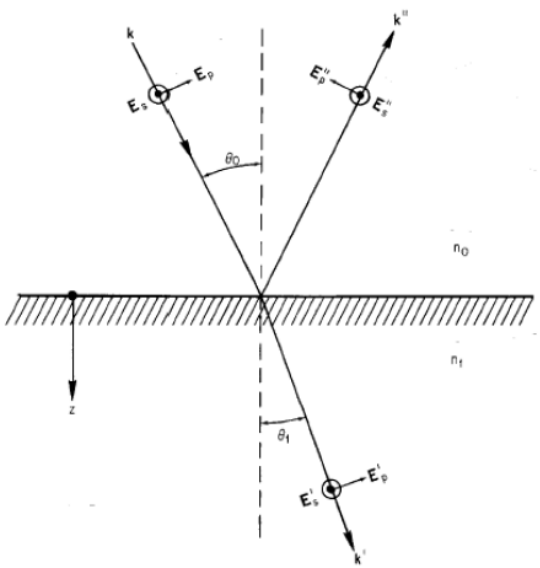
$I_{out} = I_{in} \times 10^{-\Sigma(O.D.)}$



通過介面的波



反射與透射



$$\frac{E_s''}{E_s} \equiv r_s = \frac{n_0 \cos\theta_0 - n_1 \cos\theta_1}{n_0 \cos\theta_0 + n_1 \cos\theta_1}$$

$$\frac{E_p''}{E_p} \equiv r_p = \frac{n_1 \cos\theta_0 - n_0 \cos\theta_1}{n_1 \cos\theta_0 + n_0 \cos\theta_1}$$

$$\frac{E_s'}{E_s} \equiv t_s = \frac{2n_0 \cos\theta_0}{n_0 \cos\theta_0 + n_1 \cos\theta_1}$$

$$\frac{E_p'}{E_p} \equiv t_p = \frac{2n_0 \cos\theta_0}{n_1 \cos\theta_0 + n_0 \cos\theta_1}$$

反射與透射

With Snell's law,

$$\frac{\sin\theta_0}{\sin\theta_1}=\frac{n_1}{n_0}$$

$$r_s=\frac{-\sin(\theta_0-\theta_1)}{\sin(\theta_0+\theta_1)}$$

$$r_p=\frac{\tan(\theta_0-\theta_1)}{\tan(\theta_0+\theta_1)}$$

$$t_s=\frac{2\sin\theta_1\cos\theta_0}{\sin(\theta_0+\theta_1)}$$

$$t_p=\frac{2\sin\theta_1\cos\theta_1}{\sin(\theta_0+\theta_1)\cos(\theta_0-\theta_1)}$$

反射率與穿透率

For optical intensity,

$$R_s = r_s^2 = \frac{\sin^2(\theta_0 - \theta_1)}{\sin^2(\theta_0 + \theta_1)}$$

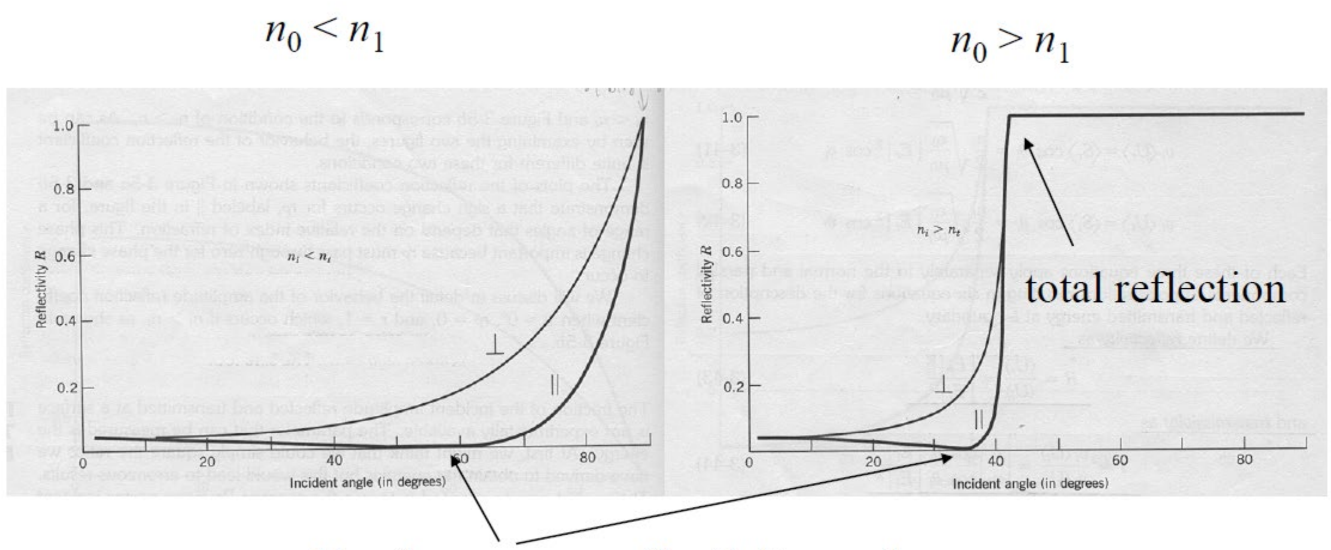
$$R_p = r_p^2 = \frac{\tan^2(\theta_0 - \theta_1)}{\tan^2(\theta_0 + \theta_1)}$$

And $T_s = 1\text{-}R_s$, $T_p = 1\text{-}R_p$.

For normal incidence,

$$R_s = R_p = \frac{(n_0 - n_1)^2}{(n_0 + n_1)^2}$$

反射率與入射角關係



For the *p*-wave, reflectivity can be zero.

Ref: R. Guenther, *Modern Optics* (John Wiley & Sons, New York, 1990).

布魯斯特角

$$R_p = r_p^2 = \frac{\tan^2(\theta_0 - \theta_1)}{\tan^2(\theta_0 + \theta_1)}$$

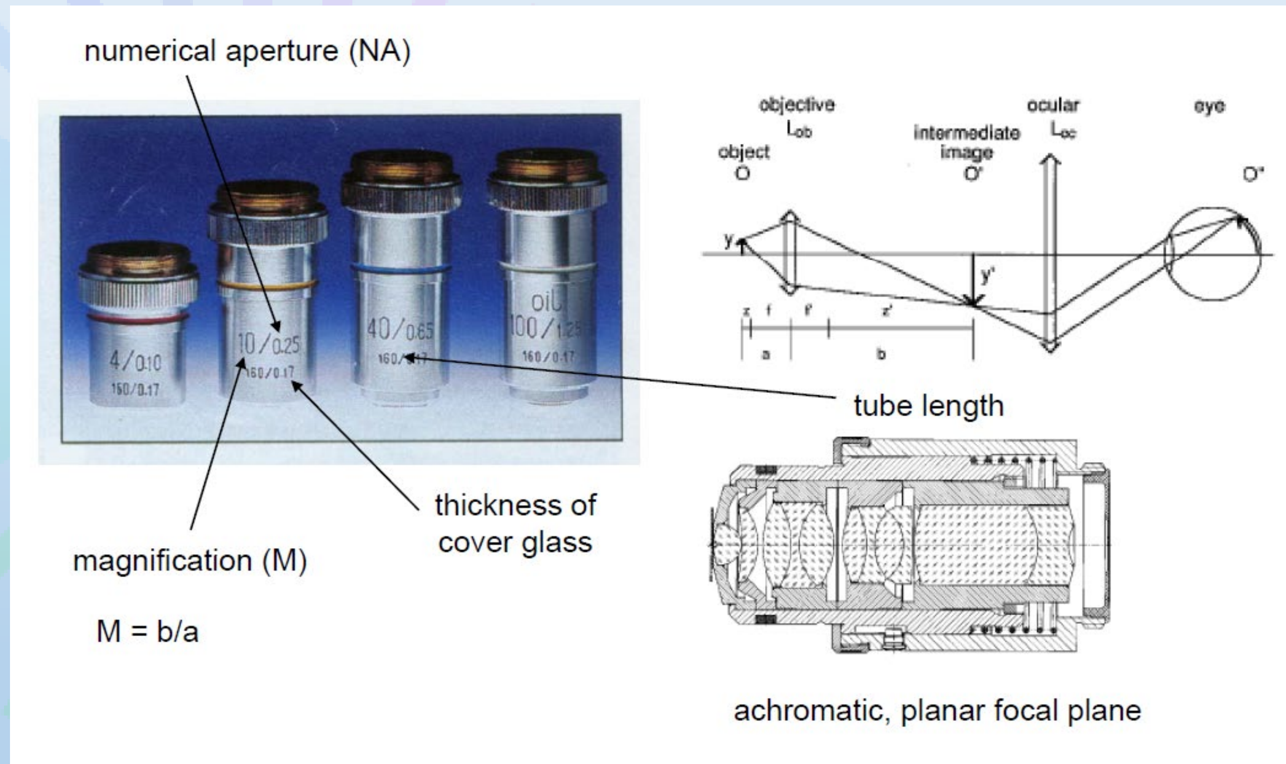
When $\theta_0 + \theta_1 = \pi/2$, $R_p = 0$.

$$\frac{n_1}{n_0} = \frac{\sin\theta_0}{\sin(\pi/2 - \theta_0)} = \tan\theta_0$$

$$\theta_B = \tan^{-1}\left(\frac{n_1}{n_0}\right)$$

Only the *p*-wave has Brewster's angle. At this angle, the reflected wave is pure *s*-wave.

物鏡

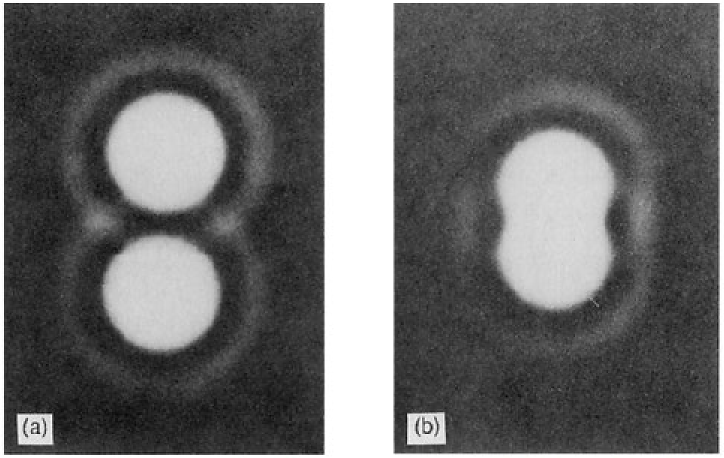

numerical aperture (NA)
magnification (M)
thickness of cover glass
tube length
M = b/a
objective
object
intermediate image
ocular
eye
achromatic, planar focal plane

物鏡：解析度與聚焦

Rayleigh criterion:

resolution ~ $0.61\lambda/NA$

NA ~ 1/(2f/#)



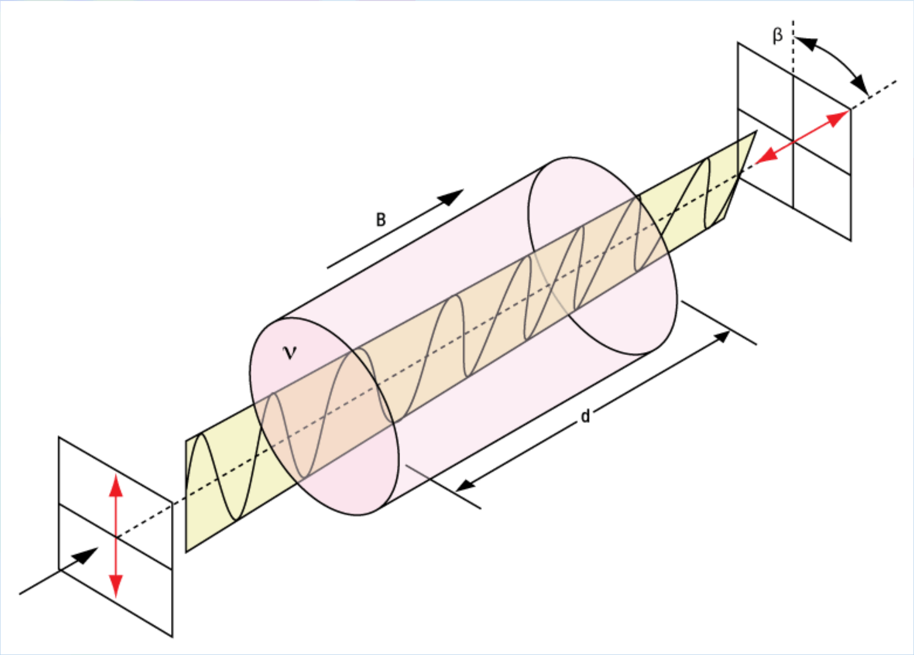
clearly resolved   resolution limit

To focus a laser beam, the smallest spot radius ~ $0.82\lambda/NA$.

A better estimation is $w_0 = \dfrac{\lambda f}{\pi w}$ ← effective focal length

法拉第旋轉器

- Optical Isolator



全反射

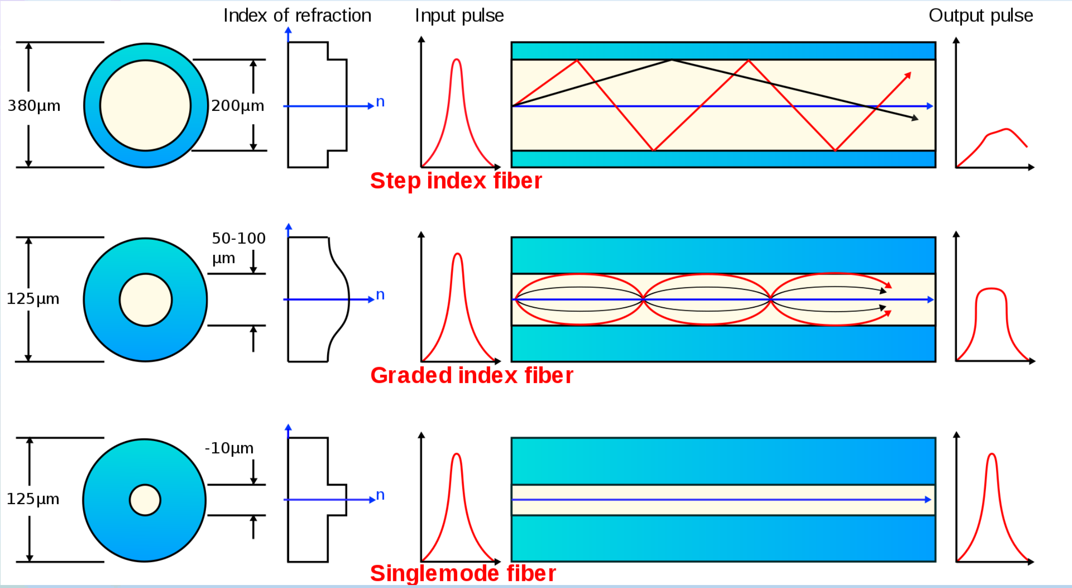
$$\frac{\sin\theta_0}{\sin\theta_1} = \frac{n_1}{n_0}$$ When $n_0 > n_1$

Total reflection occurs if $\theta_0 > \theta_c$, where

$$\theta_c = \sin^{-1}\left(\frac{n_1}{n_0}\right)$$ is called the critical angle.

光纖

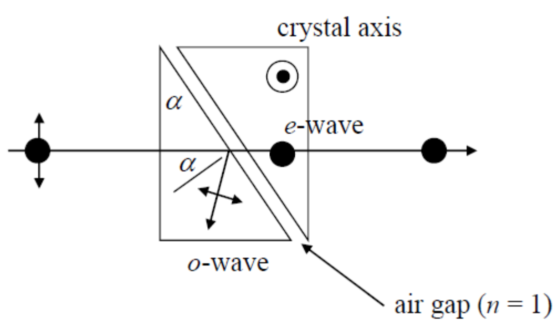
- 單模光纖
- 多模光纖
- 光子晶體光纖
- ……



圖片來源：維基百科 https://commons.wikimedia.org/w/index.php?curid=2790879

全反射產生的偏振

Polarizer made by total reflection



For total reflection of the *o*-wave, we set

$$n_e < 1/\sin\alpha < n_o$$

光圈與光學斬波器

雷射介質

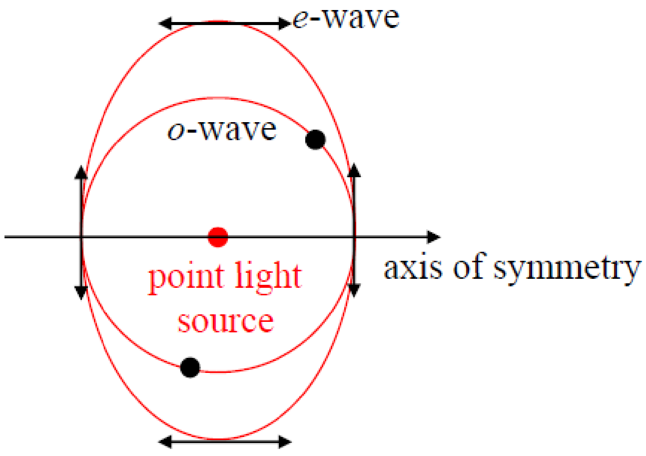
- 氣體
  - F_2 157 nm，ArF 193 nm，He-Ne 632.8 nm
- 液體
  - 染料
- 固體
  - Ti:Sapphire，Nd:YAG，Nd:YVO_4
- 半導體
  - InGaN，GaAlAs
- 光纖
  - Yb 1.0 μm，Er 1.5 μm
- 量子點

雙折射

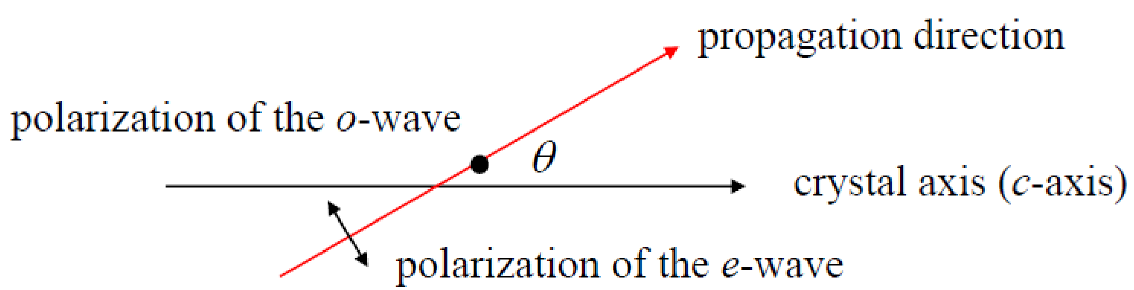
The refractive index is different for different propagation directions and polarizations.

For crystals with a single axis of symmetry (called *c*-axis), such as calcite (CaCO3), two wavefronts from a source are generated due to different refractive index n_e and n_o.

For calcite, $n_e < n_o$, and we call this crystal *negative* uniaxial.



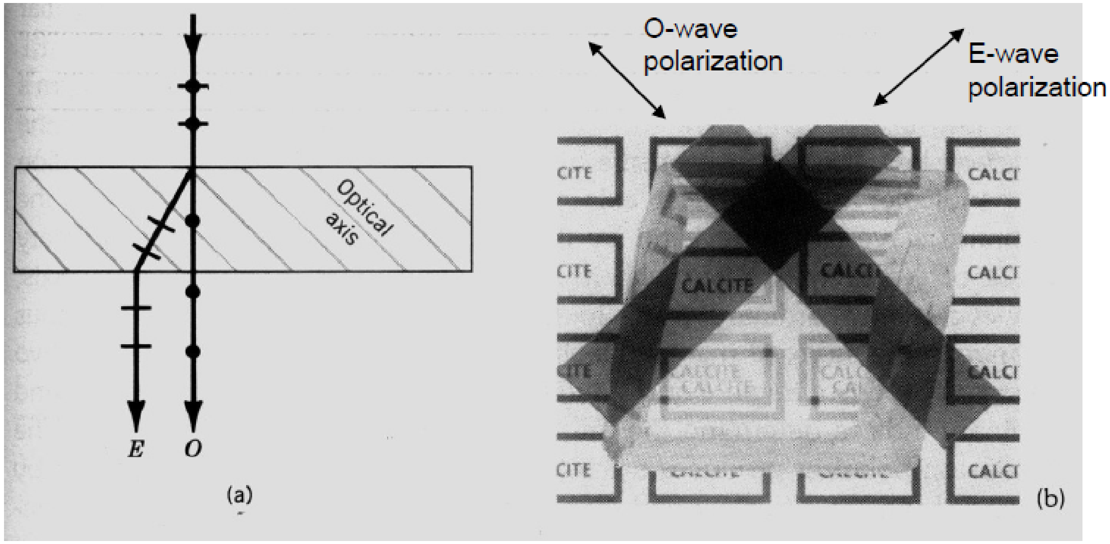
o-ray與e-ray



The polarization of *o*-wave is normal to the plane defined by the propagation direction and *c*-axis. For uni-axial crystals, *o*-wave sees a n_o independent of θ.

The polarization of *e*-wave is parallel to the plane defined by the propagation direction and *c*-axis. For uni-axial crystals, *e*-wave sees a n_e dependent of θ. $n_e(\theta = 0) = n_o$.

雙折射作用



(a) When the optical axis is unparallel to the crystal surface, the incident extraordinary wave does not obey Snell's law.

(b) In this condition, birefringence results in a double image. The polarization of the two images are orthogonal.

Ref: R. Guenther, *Modern Optics* (John Wiley & Sons, New York, 1990), Chap. 13.

非線性晶體

- KDP
- KTP
- BBO
- LBO
- PPLN
- KBBF
  - 修習非線性光學課程

干涉

Linear superposition

$$\mathbf{E}_1 = \mathbf{E}_{01} \exp i\left(\mathbf{k}_1 \cdot \mathbf{r} - \omega t + \phi_1\right)$$
$$\mathbf{E}_2 = \mathbf{E}_{02} \exp i\left(\mathbf{k}_2 \cdot \mathbf{r} - \omega t + \phi_2\right)$$

$$I(x, y, z, t) = \langle |\mathbf{E}_1|^2 \rangle + \langle |\mathbf{E}_2|^2 \rangle + \langle \mathbf{E}_1 \cdot \mathbf{E}_2^* \rangle + \langle \mathbf{E}_1^* \cdot \mathbf{E}_2 \rangle$$

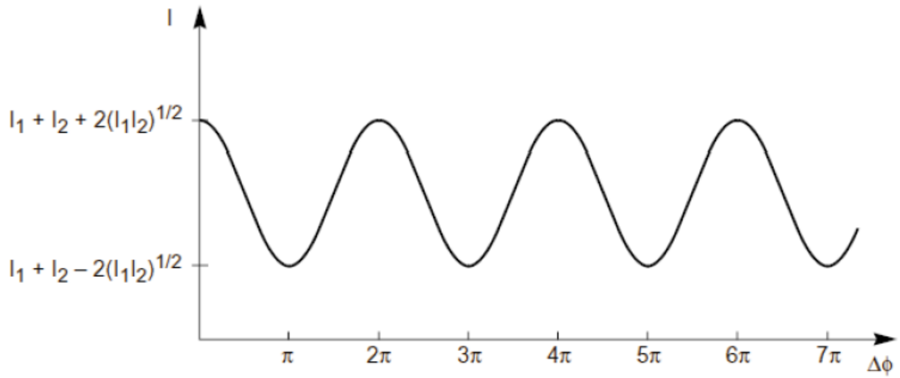
or $$\boxed{I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\phi}$$

where $$\Delta\phi = \left(\mathbf{k}_1 \cdot \mathbf{r} - \mathbf{k}_2 \cdot \mathbf{r}\right) + \left(\phi_1 - \phi_2\right)$$

If light is from the same source, this term is zero.

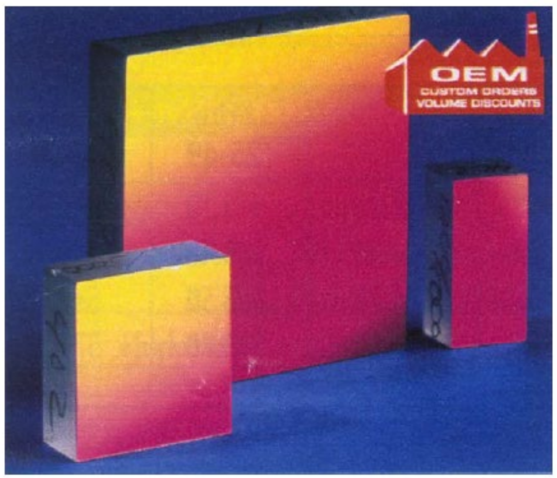
This term is *optical path difference* (OPD).

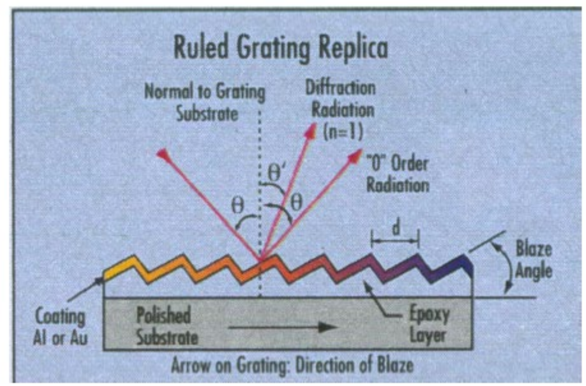
干涉條紋



	$\Delta\phi$	OPD
Bright fringe	$2m\pi$	$m\lambda$
Dark fringe	$2(m+1)\pi$	$(m+1/2)\lambda$

光柵



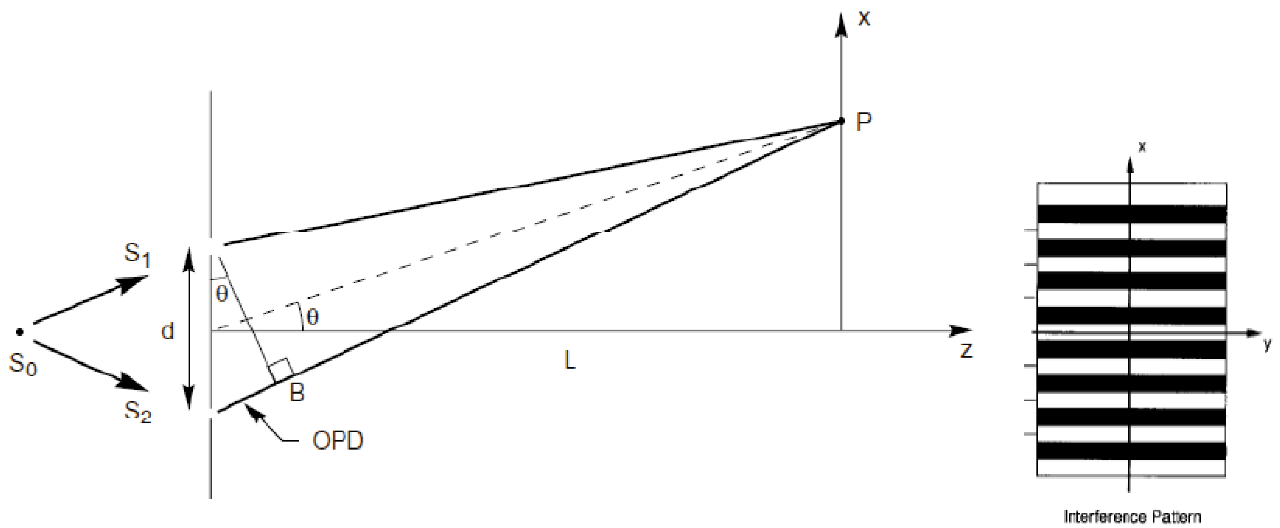


$$\sin\theta'^{(n)} = \sin\theta + \frac{n\lambda}{d}$$

angular dispersion $$\frac{\delta\theta'}{\delta\lambda} = \frac{n}{d \times \cos\theta'}$$

Do not touch the face of gratings! Even lens-tissue is prohibited!

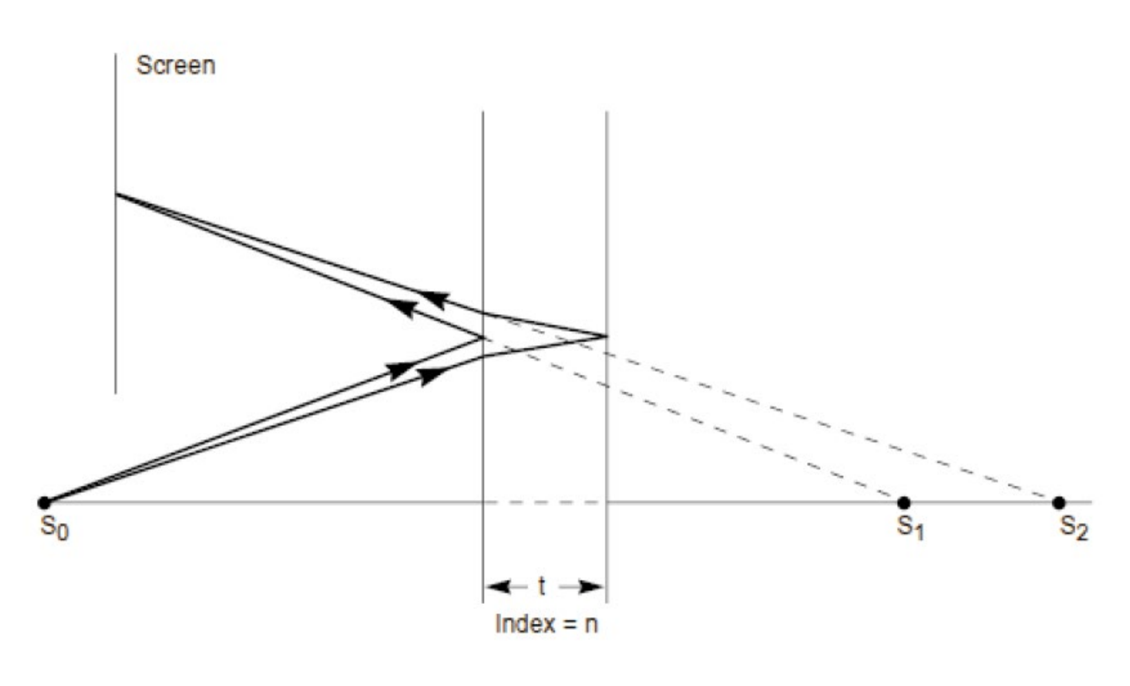
楊氏干涉實驗



$$\text{OPD} \approx \overline{S_2B} = d\sin\theta \approx d\theta \approx \frac{dx}{L}$$

$$x = \frac{m\lambda L}{d} \quad , m = 0, 1, 2, 3.... \quad \text{for bright fringe}$$

雙反射



干涉與同調

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\phi$$

where $\Delta\phi = (\mathbf{k}_1 \cdot \mathbf{r} - \mathbf{k}_2 \cdot \mathbf{r}) + (\phi_1 - \phi_2)$

If the light is from two difference sources, $(\phi_1 - \phi_2)$ may not be zero. If $(\phi_1 - \phi_2)$ is a constant, we call the two light sources "completely coherent."

Nevertheless, $(\phi_1 - \phi_2)$ is usually a function of time and space.

同調與干涉條紋

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\Delta\phi$$

can also be written as

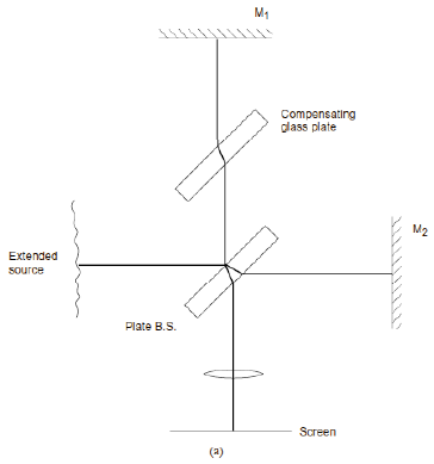
$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\mathrm{Re}\{\gamma_{12}(\tau)\}$$

When $|\gamma_{12}(\tau)| = 0$, there is no interference fringes at all. Therefore we can use an interferometer to measure the degree of coherence.

同調時間與同調長度

For a single light source, we define coherence time τ_0:

$$
\begin{aligned}
|\gamma(\tau)| &= 1 - \tau/\tau_0 \quad \text{for } \tau < \tau_0 \\
&= 0 \quad \text{for } \tau \geq \tau_0
\end{aligned}
$$



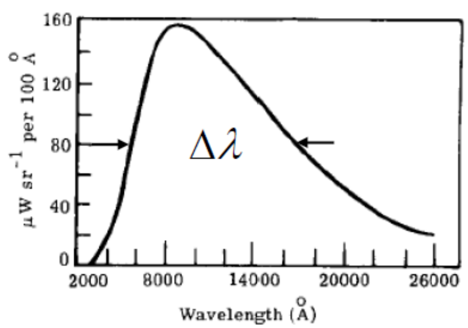
With a Michelson interferometer,

$$I = I_0\left[1 + \cos\left(2\pi d/\lambda\right)\right]$$

If $d > c\tau_0$, we see no fringes.

Coherence length: $l_c = c\tau_0$

同調時間與線寬



Almost every light source is band-limited. So there is a spectral width $\Delta\lambda$.

A Michelson interferometer can be used to determine the spectral width:

$$\Delta\nu \equiv \frac{1}{\tau_0} \qquad l_c = c\tau_0 = \frac{c}{\Delta\nu}$$

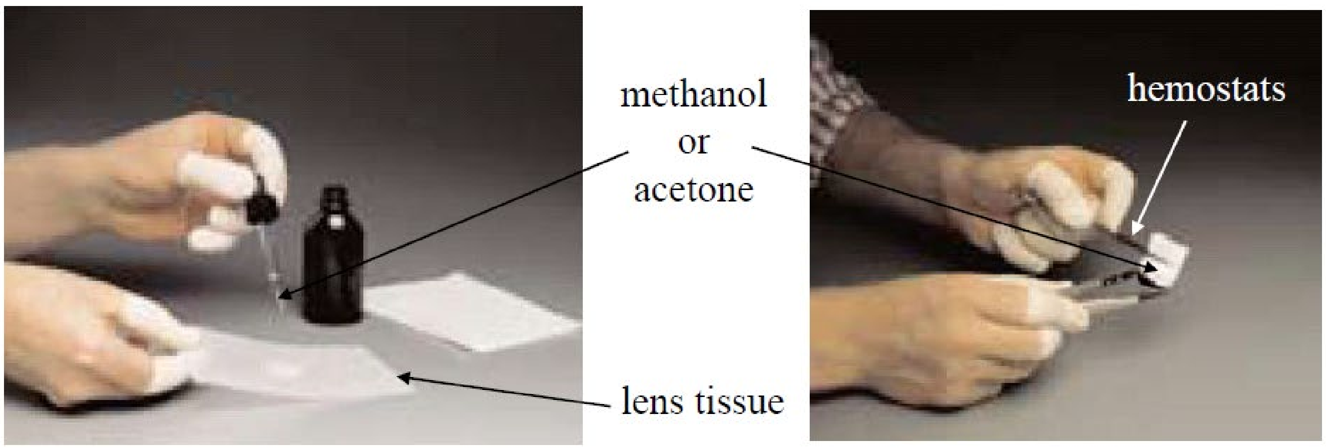
Since

$$\frac{\Delta\nu}{\nu} = \frac{|\Delta\lambda|}{\lambda}$$

$$l_c = \frac{\lambda^2}{\Delta\lambda}$$

光學元件清潔

Drop and Drag | **Brush**



Before first-time use or storage.

For installed optics.

Ref: Newport Catalog 2004, pp. 539-540.

光機械元件

- https://www.newport.com/
- https://www.thorlabs.com/navigation.cfm
- https://www.unice-eo.com/

光學元件組裝

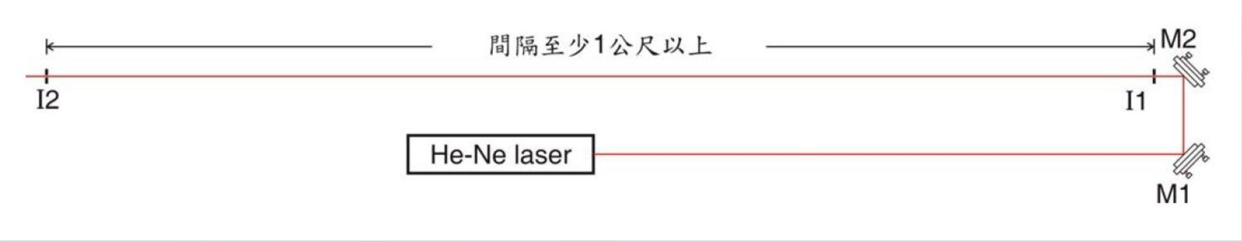
- 注意事項
- 清潔
- 穩固

基本光路與調校

- 調整平行光通過一對相距1公尺以上的光圈
- 架設延遲光路
- 架設能量調節器
- 空間濾波器
- 光纖耦合
- 雷射光擴束
- 量測雷射光束空間分佈
- 偏軸拋物面鏡聚焦與焦點量測
- 架設傳繼成像系統
- 架設Mach-Zehnder干涉儀

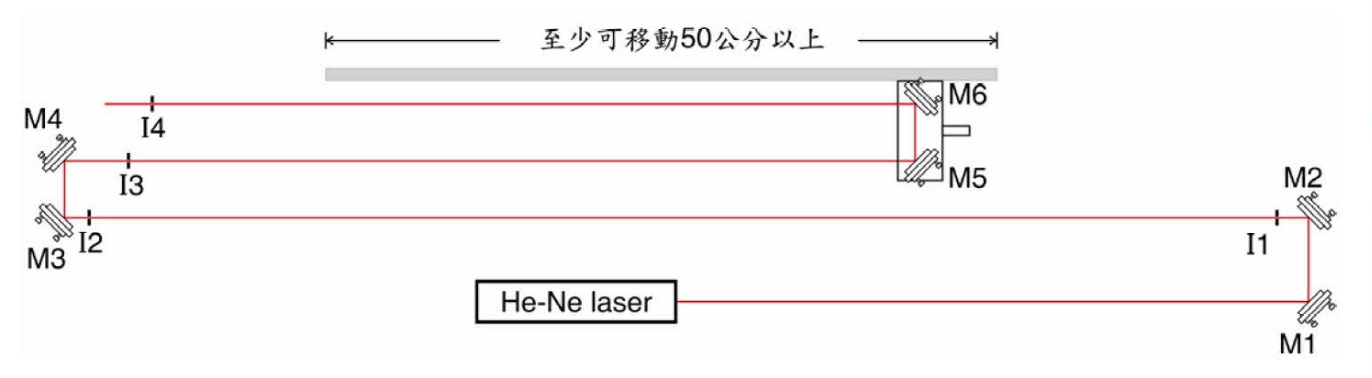
光路調校

如何調整平行光過一組光圈

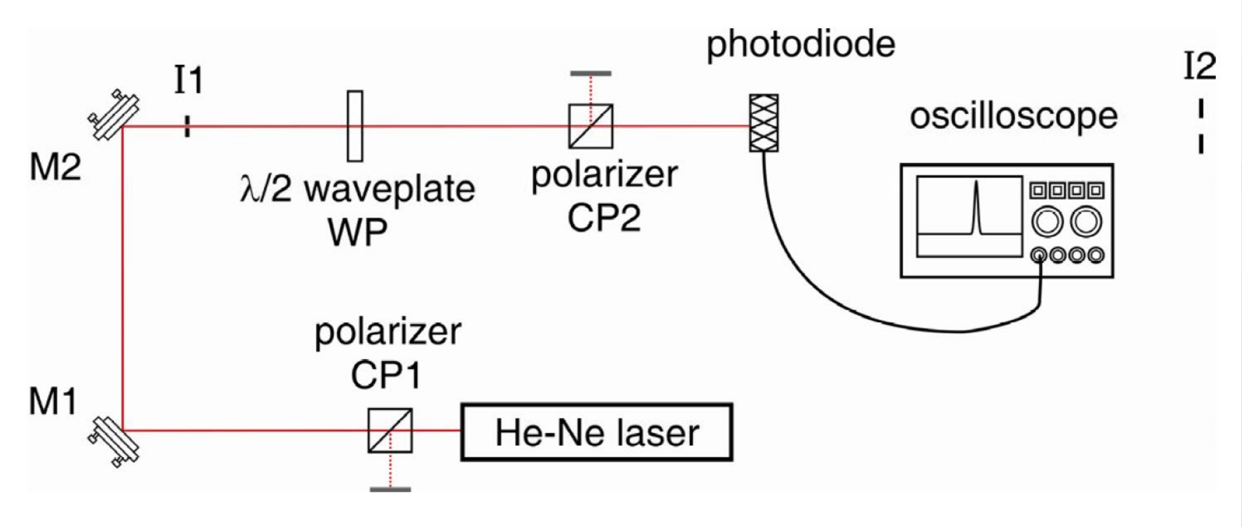


延遲光路

- Pump-probe 系統

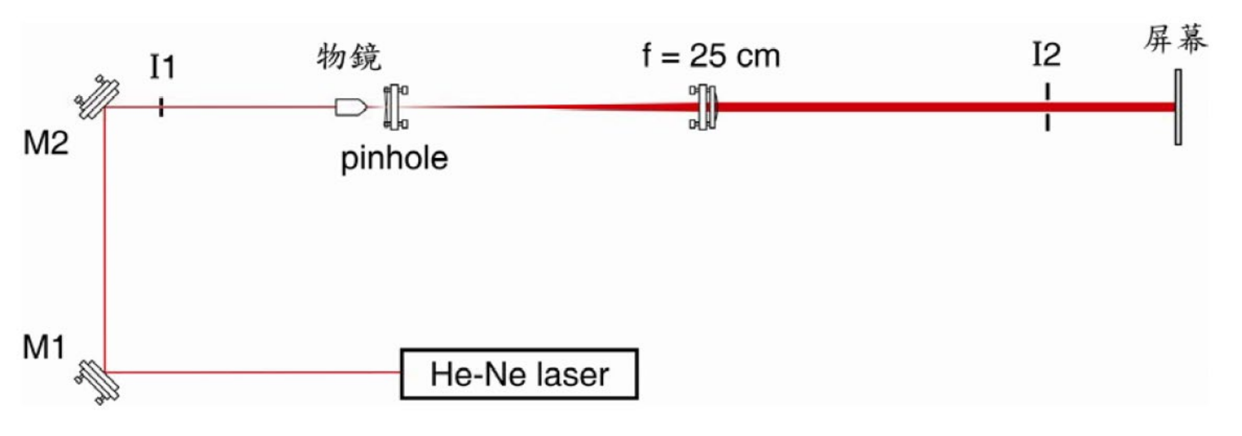


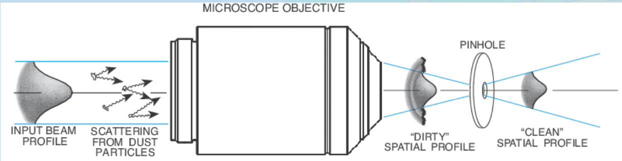
能量調節器

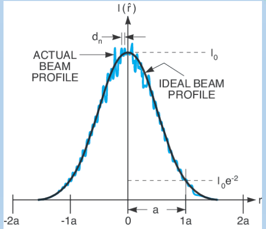


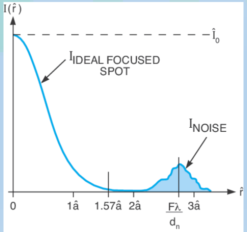
photodiode
I2
I1
oscilloscope
M2
λ/2 waveplate
WP
polarizer
CP2
polarizer
CP1
M1
He-Ne laser

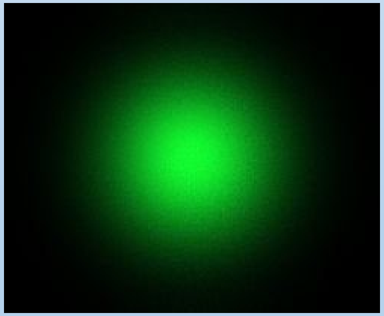
空間濾波器





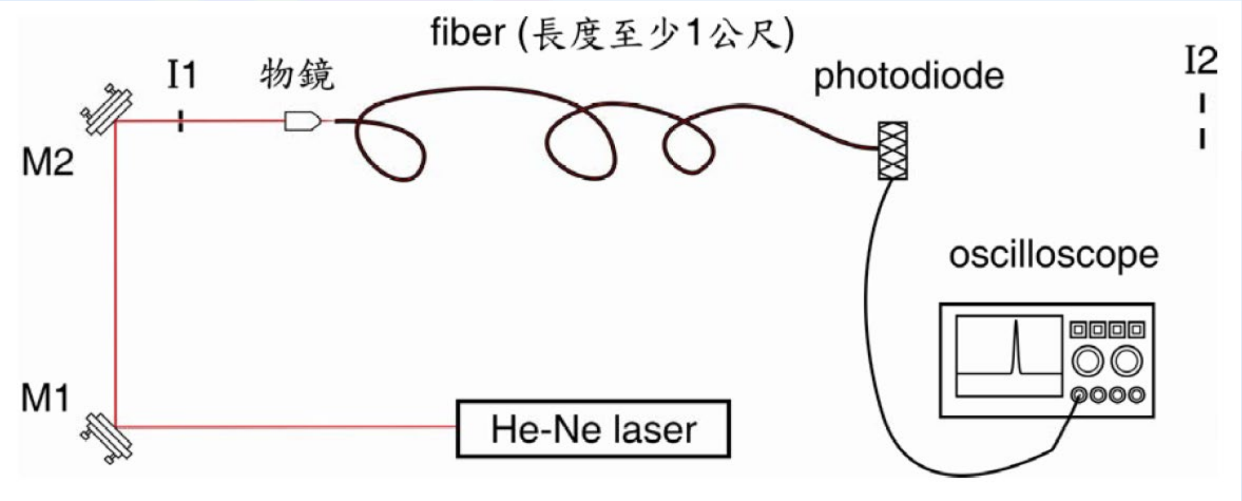




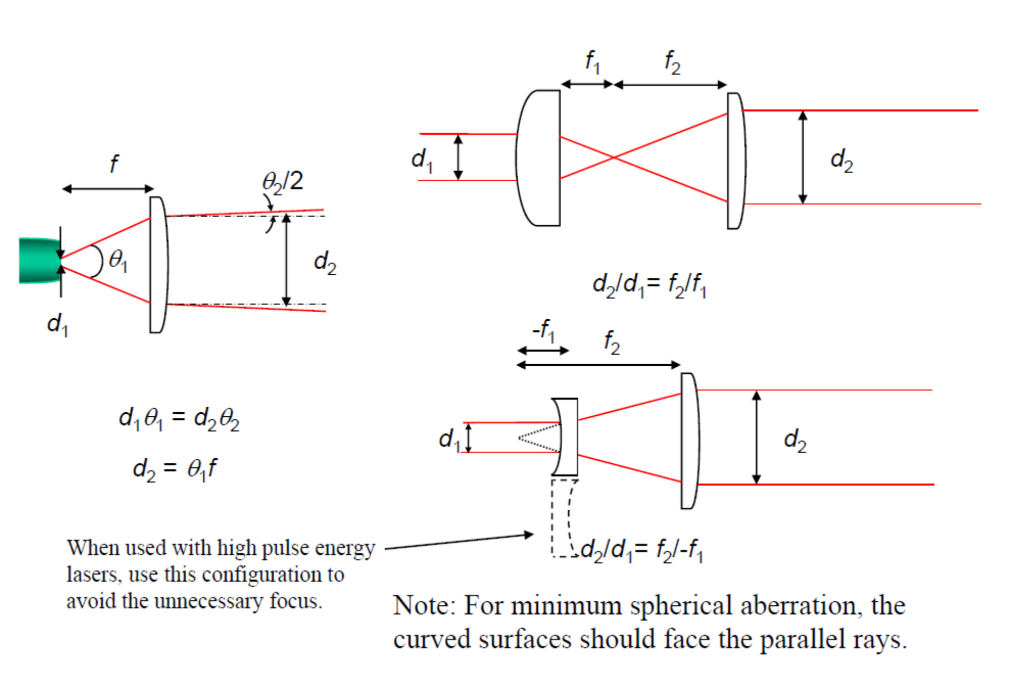


https://www.newport.com/n/spatial-filters

光纖耦合

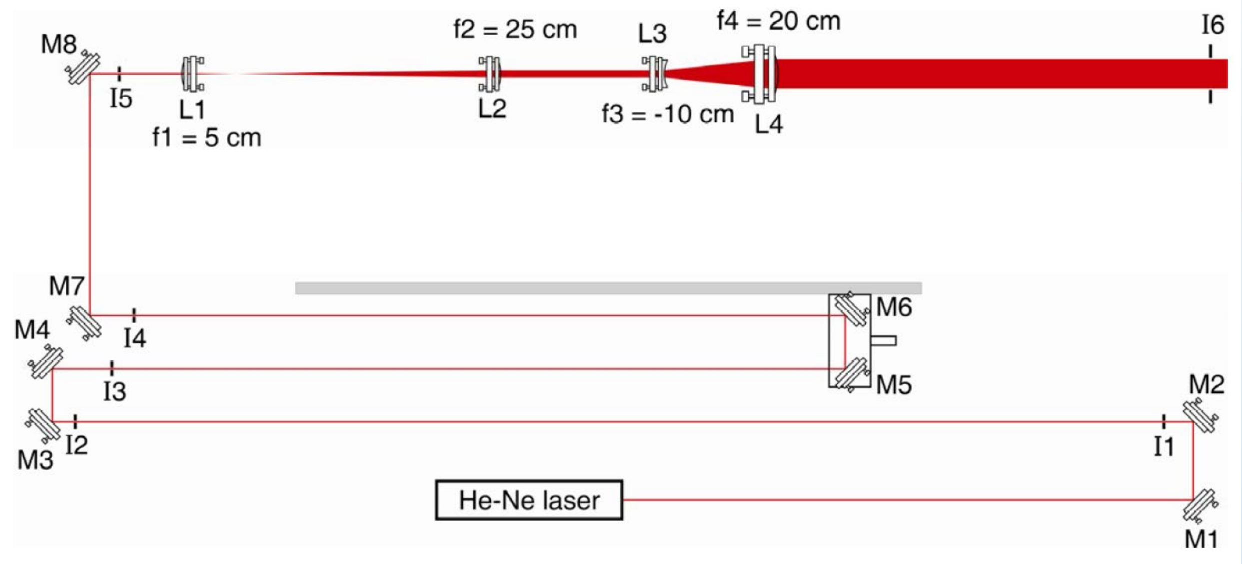

fiber (長度至少1公尺)
I1
物鏡
photodiode
I2
M2
oscilloscope
M1
He-Ne laser

光束的平行與擴束

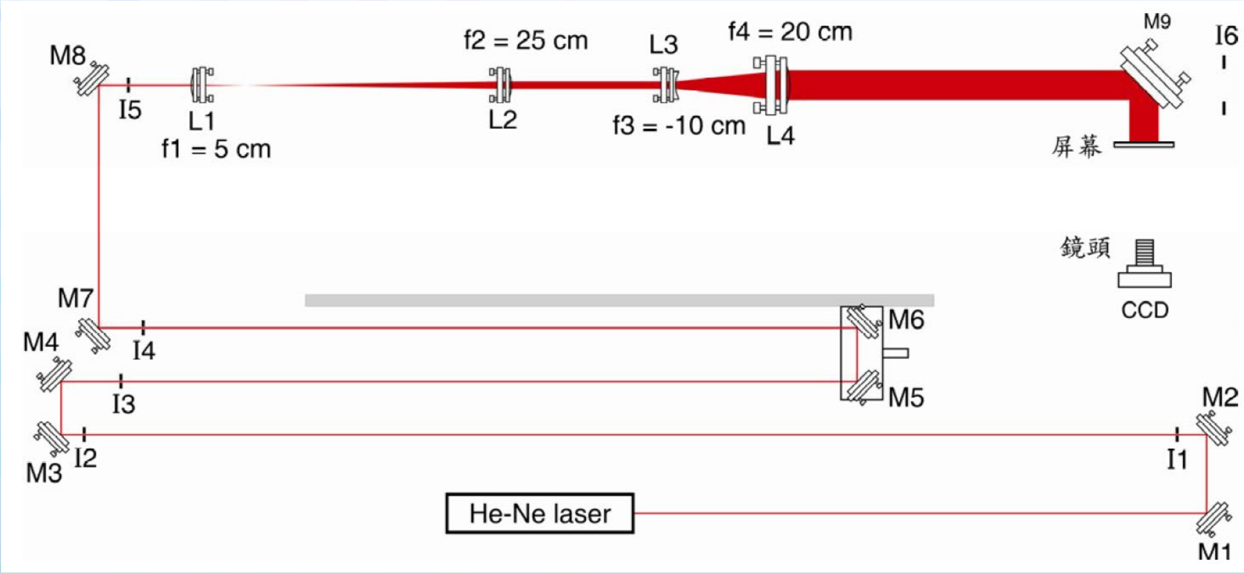


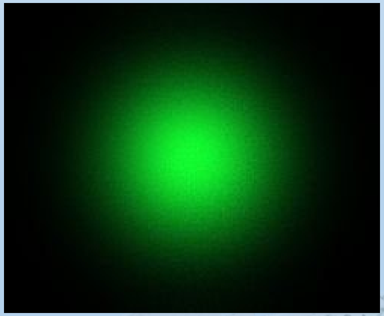
f
θ2/2
θ1
d2
d1
d1θ1 = d2θ2
d2 = θ1f
f1
f2
d1
d2
d2/d1= f2/f1
-f1
f2
d1
d2
d2/d1= f2/-f1
When used with high pulse energy lasers, use this configuration to avoid the unnecessary focus.
Note: For minimum spherical aberration, the curved surfaces should face the parallel rays.

雷射光擴束

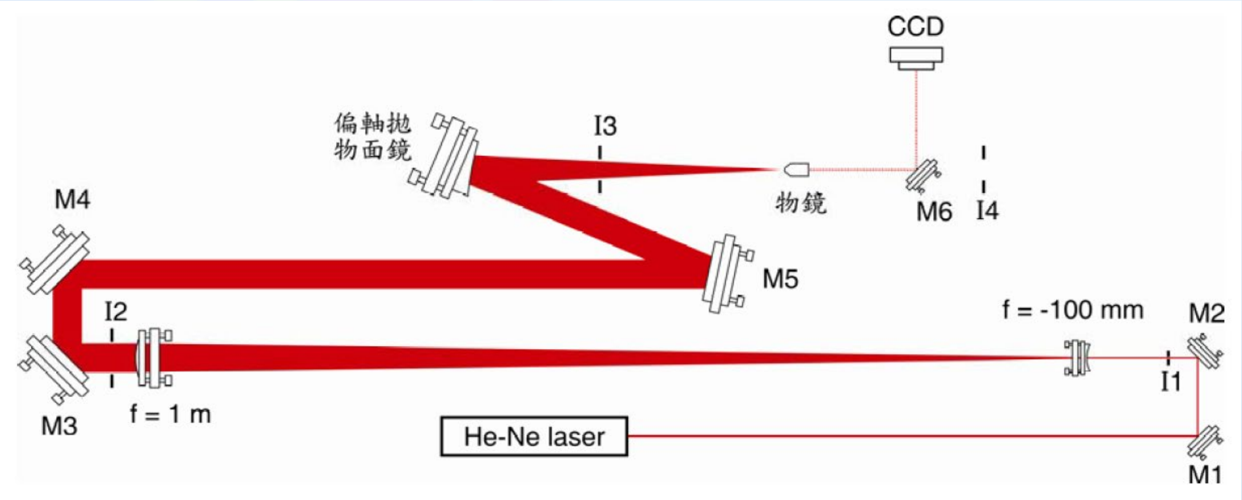

M8
I5
L1
f1 = 5 cm
f2 = 25 cm
L2
L3
f3 = -10 cm
f4 = 20 cm
L4
I6
M7
I4
M6
M4
I3
M5
M2
M3
I2
I1
He-Ne laser
M1

量測雷射光束空間分佈

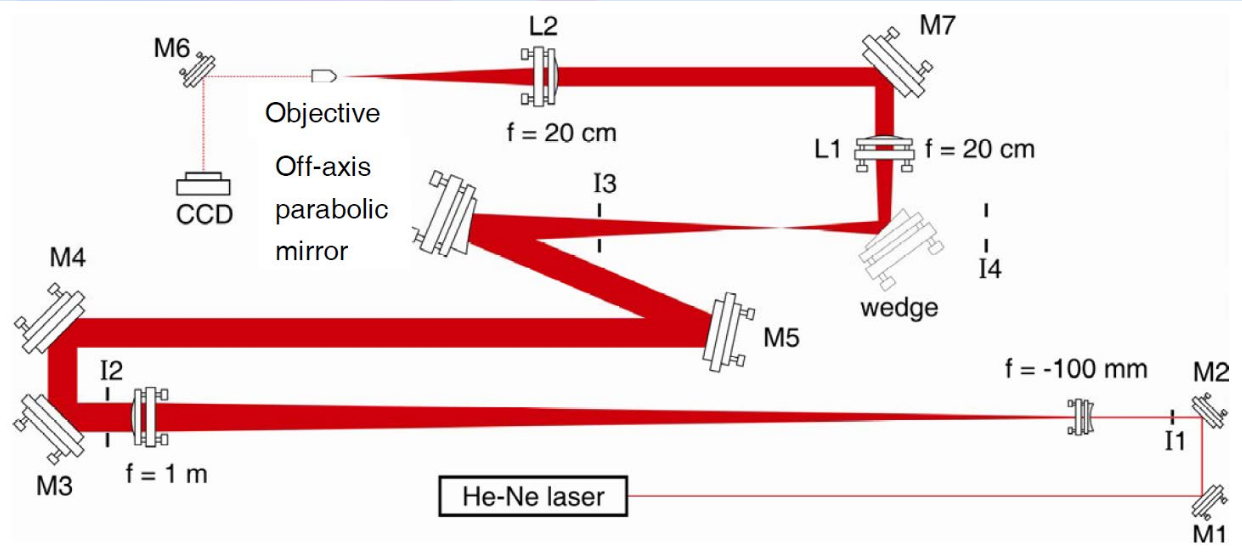

M8
I5
L1
f1 = 5 cm
f2 = 25 cm
L2
L3
f3 = -10 cm
f4 = 20 cm
L4
M9
I6
屏幕
鏡頭
CCD
M7
M6
M4
I4
I3
M5
M2
M3
I2
I1
He-Ne laser
M1



偏軸拋物面鏡聚焦

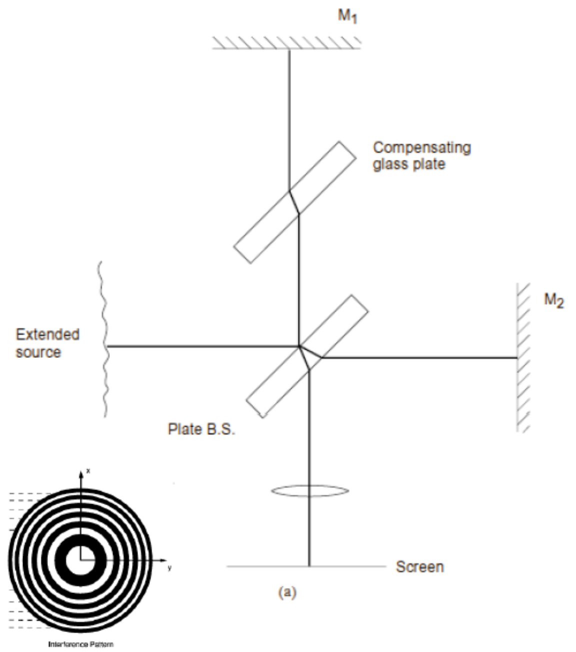


傳繼成像系統



M6
L2
M7
Objective
f = 20 cm
L1
f = 20 cm
Off-axis
parabolic
mirror
CCD
I3
I4
M4
wedge
M5
I2
f = -100 mm
M2
I1
M3
f = 1 m
He-Ne laser
M1

邁克森干涉儀



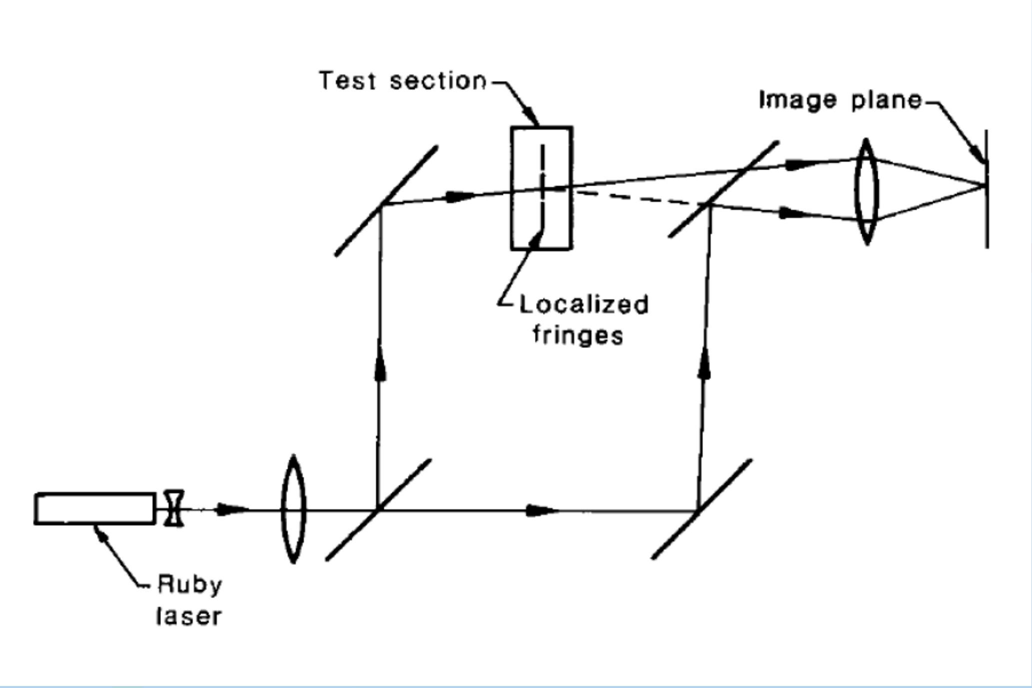
This interferometer is widely used for precision length measurement.

$$I = I_0[1+\cos(4\pi\Delta L/\lambda)]$$

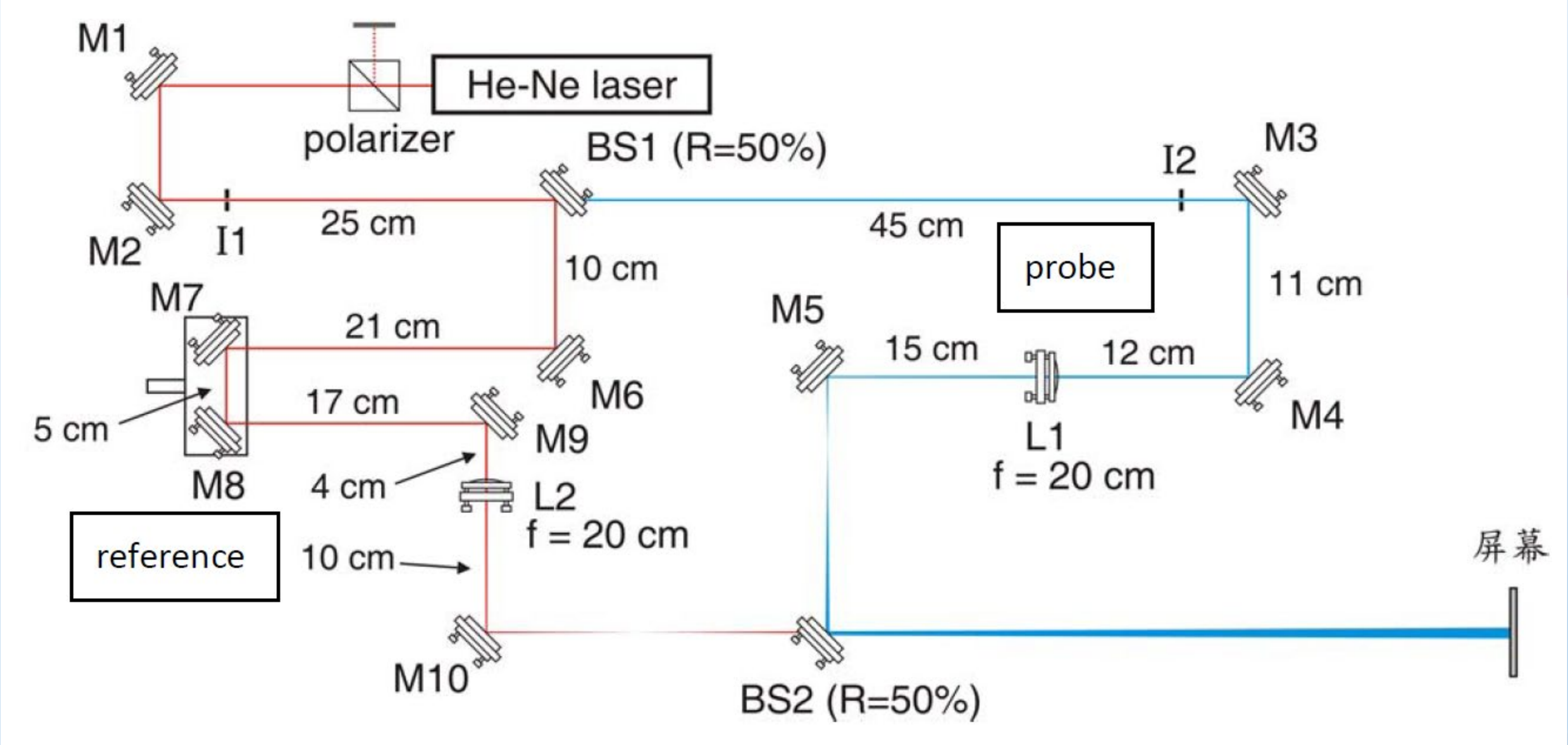
arm difference

OPD of $\lambda/100$ is easy to determine.

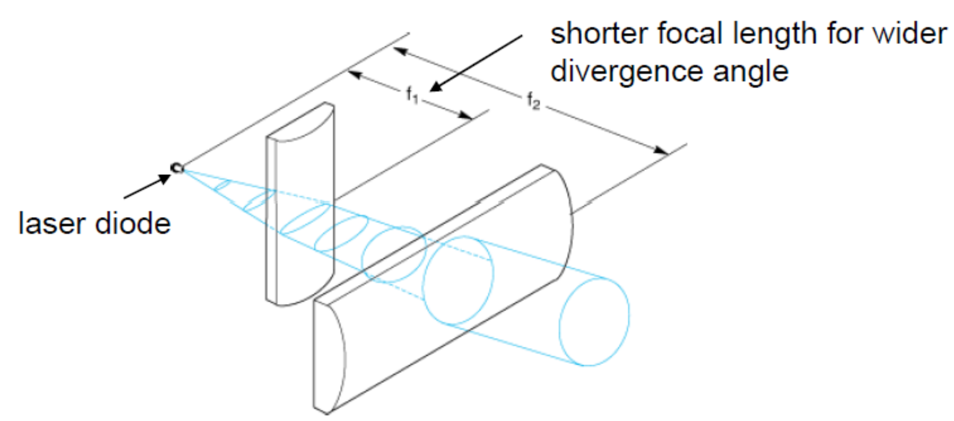
Mach-Zehnder干涉儀



架設Mach-Zehnder干涉儀



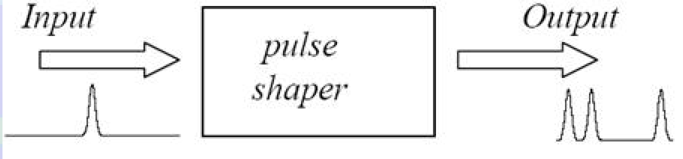
光束塑型



To shape an elliptic beam into a circular beam or vice versa.

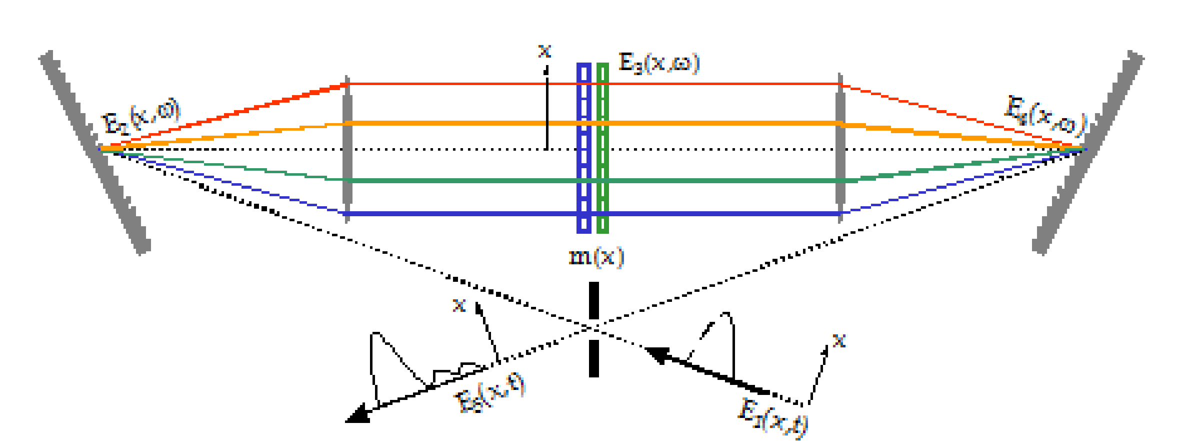
Shearing Interferometer

雷射光脈衝整型



https://en.wikipedia.org/wiki/Femtosecond_pulse_shaping

- 4-f pulse shaper



https://www.intechopen.com/books/advances-in-solid-state-lasers-development-and-applications/pulse-shaping-techniques-theory-and-experimental-implementations-for-femtosecond-pulses

超快脈衝測量

- Autocorrelation
- FROG
- SPIDER

Autocorrelator

1. measurement of ultra-short pulse duration

   time: 50 fs ↔ distance: 15 μm

2. sum frequency generation

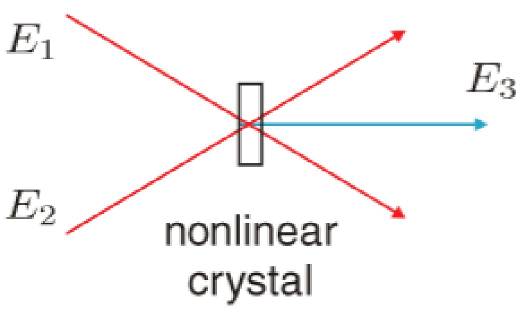
$$E_3(t) \propto E_1(t)\, E_2(t)$$

$$\omega_3 = \omega_1 + \omega_2$$

second harmonic generation

$$\omega_1 = \omega_2 = \omega$$

$$\omega_3 = 2\,\omega$$

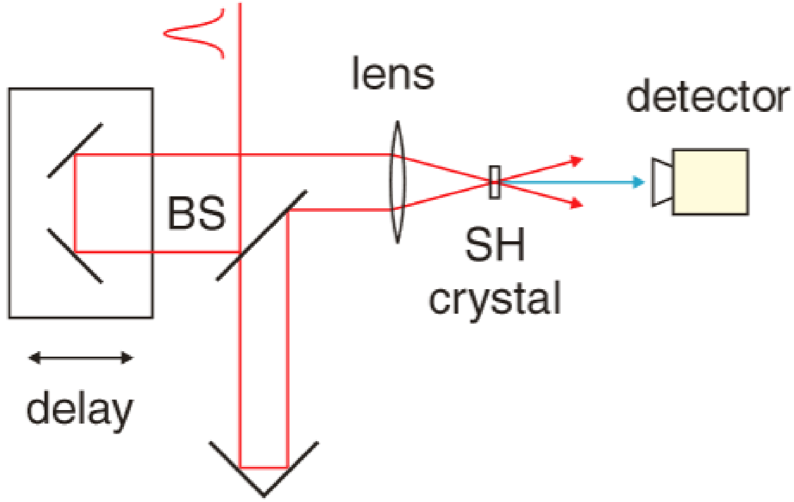


3. intensity autocorrelation

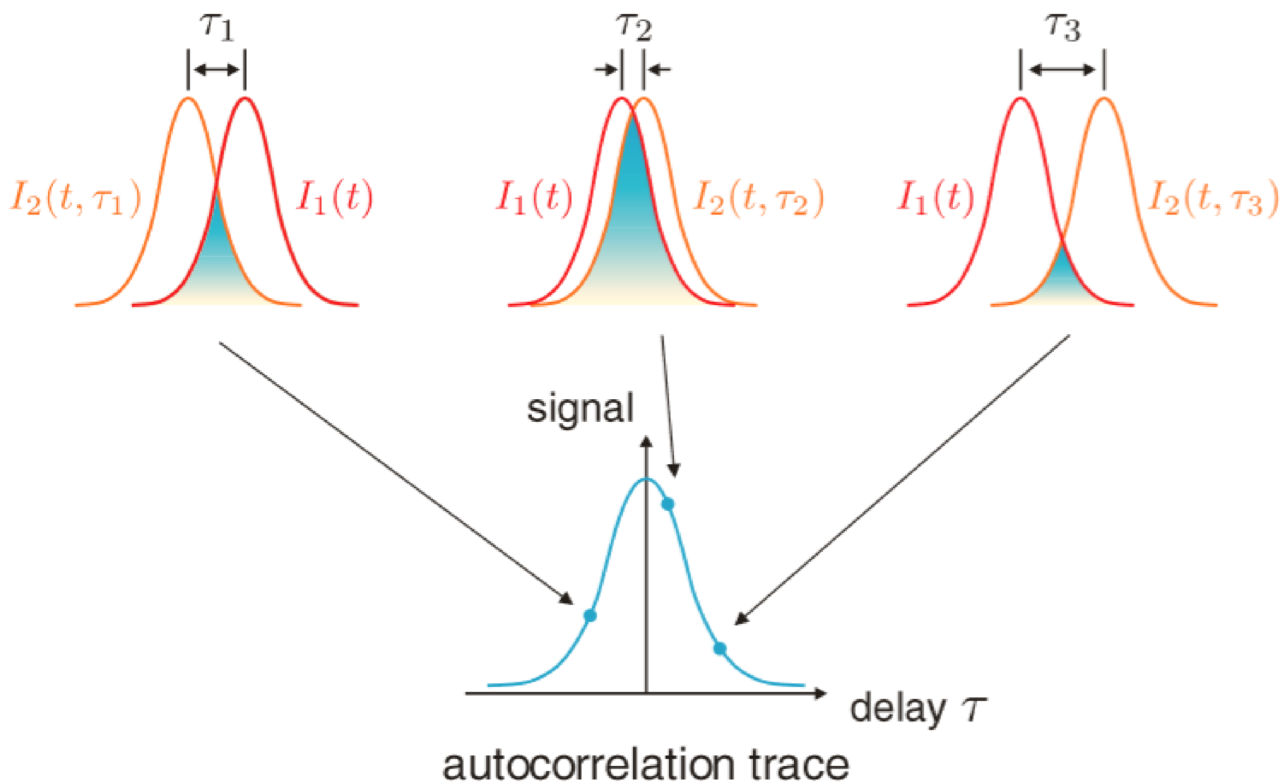
$$E_1(t) = E(t) = A(t)\cos(\omega t), \quad I_1(t) = I(t)$$

$$E_2(t,\tau) = E(t+\tau) = A(t+\tau)\cos(\omega t + \phi_\tau), \quad I_2(t,\tau) = I(t+\tau)$$

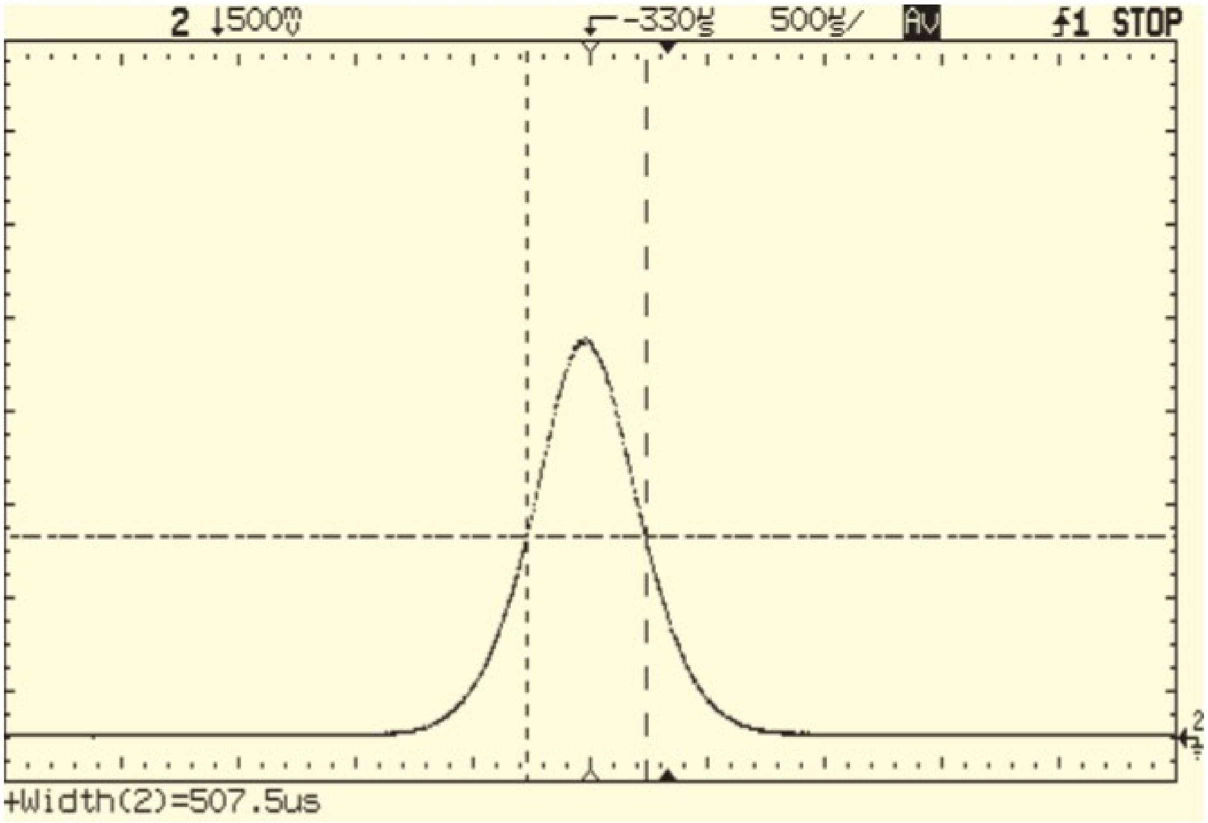
$$\text{signal}(\tau) \propto \int_{-\infty}^{\infty} I(t)\, I(t+\tau)\ \mathrm{d}t$$



4. autocorrelation trace



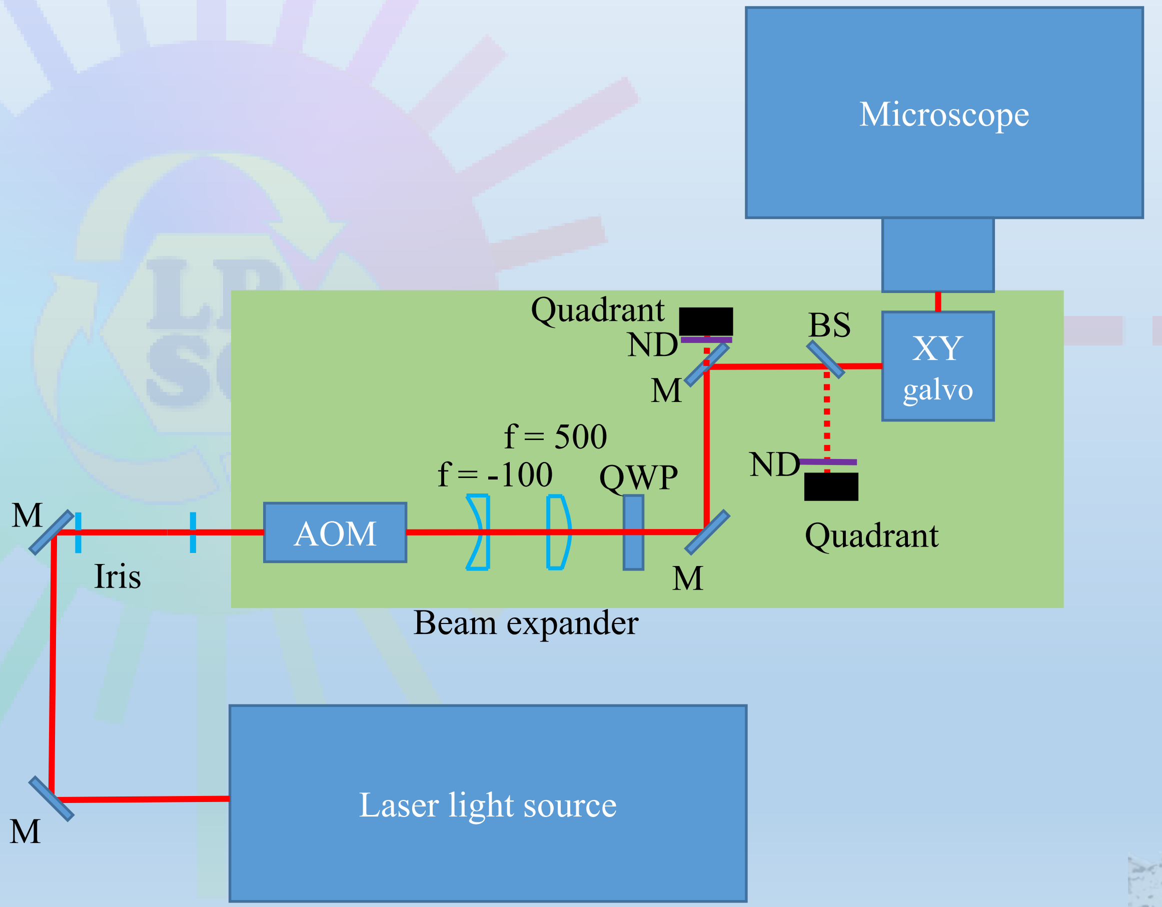
5. example of intensity autocorrelation trace



光路模擬

- GaussianBeam
- reZonator

Optical System



Optical System

Mirror : CVI, TLMB-800-45-1025, 740-860 nm, > 99.0% reflectivity x6
Iris: Thorlabs, ID8/M, 0.7-8 mm X2
Beam expander: CVI, PLCX-25.4-128.8-C-700-900, +250 mm X1
CVI, PLCC-25.4-25.8-C-700-900, FS, -50 mm X1
Quarter wave plate: CVI, QWPO-800-08-4-AS10 X1
Quadrant: Thorlabs, PDQ80A, quadrant position detector X2
Thorlabs, KPA101, PSD auto aligner X2
Thorlabs, KPZ101, piezo controller X4
Thorlabs, KCH601, power supply X1
Thorlabs, POLARIS-K1S2P, piezoelectric mirror mount X2
ND filter: CVI, LW-3-1037-C , wedge windows 3° X2
Beamsplitter: CVI, W2-PW1-1004-UV-700-900-0, AR coating Windows X2
Optics mount: Thorlabs, POLARIS-K1S4, Polaris mirror mount X6
Thorlabs, POLARIS-N5, mirror mount adjusters X12
Thorlabs, RS3P, pedestal posts x10
Thorlabs, RS075, pillar posts X10
Thorlabs, AE8E25E, adapter #8-32 to ¼-20 X10
Thorlabs, PH3E, post holders X10
Thorlabs, CF125C/M-P5, clamping fork, 5 pack X4
Thorlabs, ER10, cage sys. Rods 10” X4
Thorlabs, CP06, cage plate for 1” X1
Thorlabs, CPTR20, cage to post adapters X1
Thorlabs, RSP1, rotation mount for quarter wave plate X1
Thorlabs, TR3-P5, ½” posts, 5 pack X2
Thorlabs, TR2-P5, ½” posts, 5 pack X2
Thorlabs, LMR1, fixed lens mounts X2

如何變成高手？

- 多練習光路架設
- 多看光電元件型錄
- 多逛光電廠商網站
- 多研究論文實驗光路圖

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
- Wikipediahttps://en.wikipedia.org/wiki/Femtosecond_pulse_shaping
- MKShttps://www.newport.com/
- Thorlabshttps://www.thorlabs.com/navigation.cfm
- 宏惠光電https://www.unice-eo.com/
- GaussianBeam: http://gaussianbeam.sourceforge.net/
- reZonator: http://www.rezonator.orion-project.org/