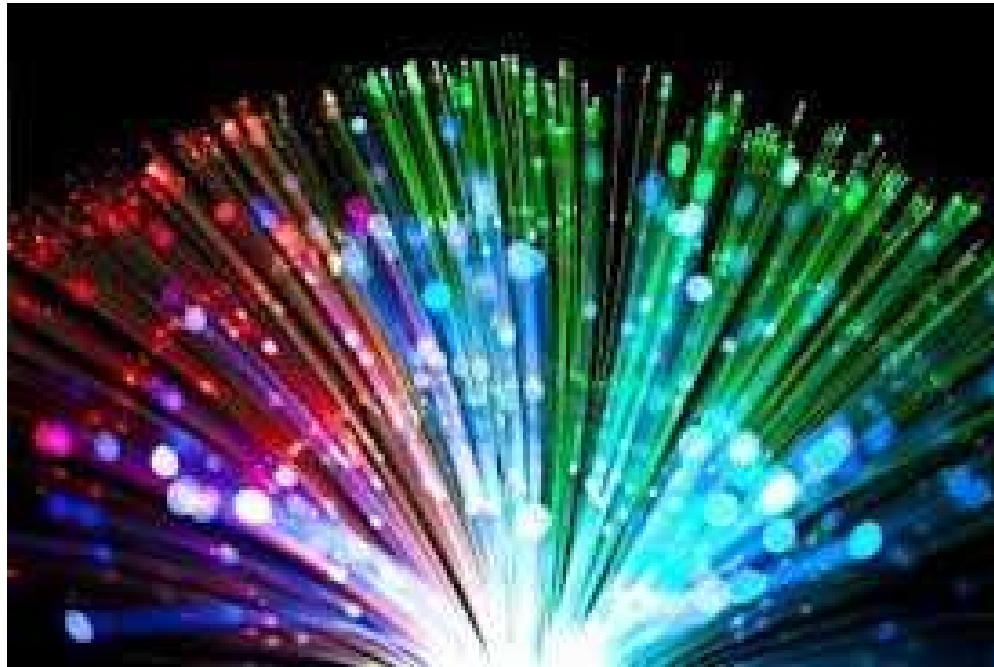
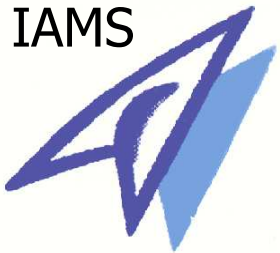


光纖的原理與應用



IAMS



陳應誠

中央研究院原子與分子科學研究所

2013年7月30日, 科學營



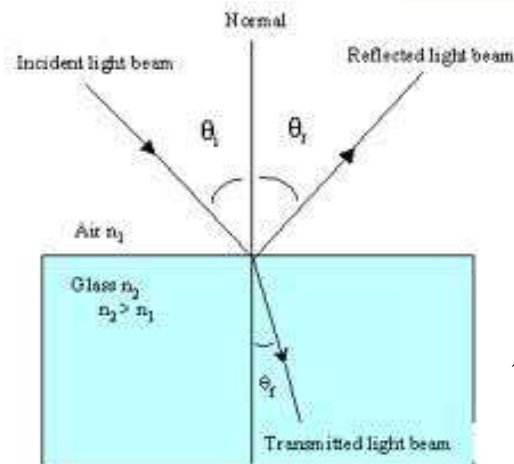
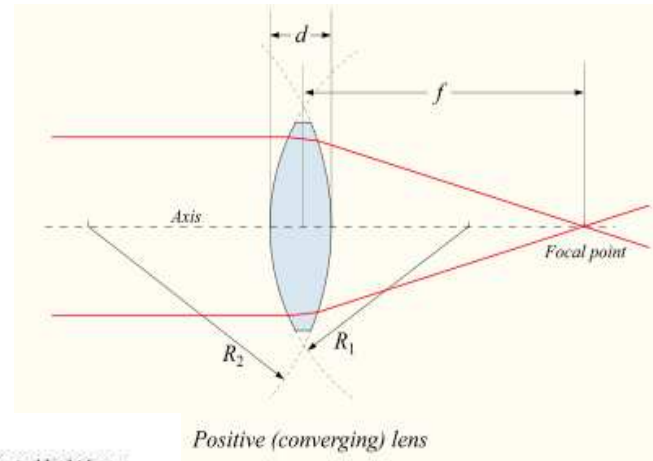
大綱

- 光的反射、折射、全反射
- 光纖的基本原理
- 光纖的應用：
 - 光通信
 - 光纖感測
 - 實驗室用途
- 將光耦合至光纖

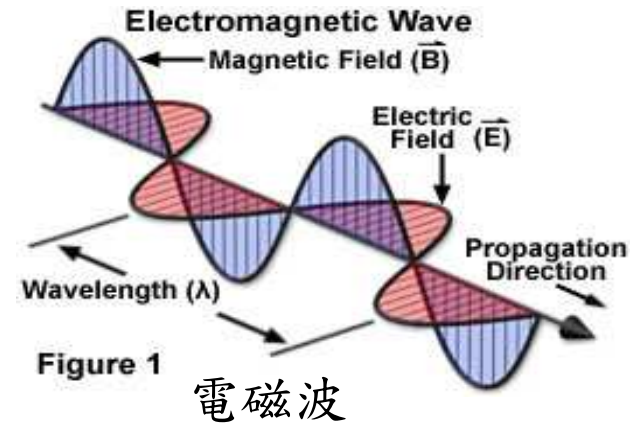
光是什麼？

- 它是光束—幾何光學，真空中沿直線前進，有反射折射現象等
- 它是一種電磁波!波動光學
(波是什麼?能量在兩種不同形式轉換傳播出去)
 - 有疊加、干涉、繞射、穿隧、共振等現象

幾何光學



反射與折射



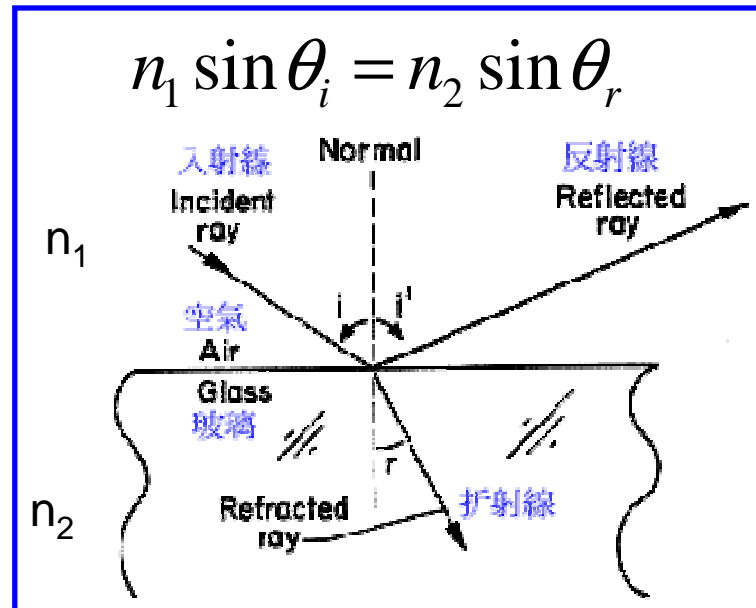
波的干涉

光的反射與折射

- 光的反射與折射都是介質對光的反應產生的電磁場與原入射電磁場總合的結果。
- 折射率:介質對入射光反應程度的一參數

$$n(\lambda) \equiv \frac{c}{v(\lambda)} = \text{Speed of light in vacuum/phase velocity in medium}$$

- 相速度:光的波前移動速度
- 對一平整的介面:入射角=反射角
- 折射遵守Snell's Law

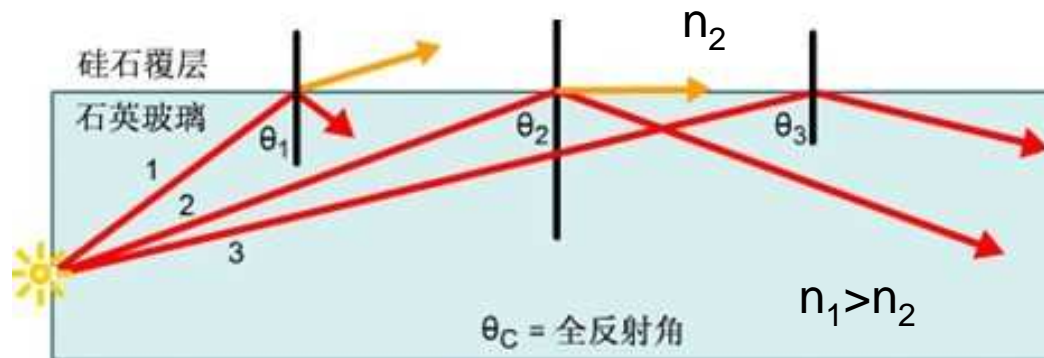


光的全反射

- 光從折射率大的介質打至折射率小的介質，當入射角大於一臨界角度以上，所有的光會反射（沒有折射光）。

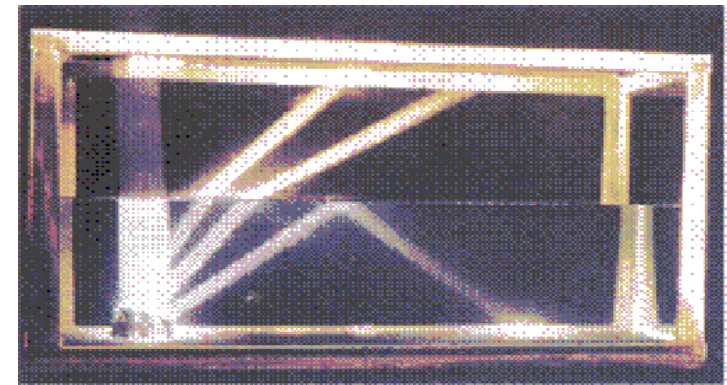
$$n_1 \sin \theta_i = n_2 \sin \theta_r \quad (n_1 > n_2); \sin \theta_r = \frac{n_1 \sin \theta_i}{n_2} \leq 1$$

$$\text{Critical Angle} \Rightarrow \theta_r = \frac{\pi}{2} \Rightarrow \frac{n_1 \sin \theta_i}{n_2} = 1 \Rightarrow \theta_i = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$



- Ray 1: $\theta_1 < \theta_c$, 反射 + 折射
Ray 2: $\theta_2 = \theta_c$, 反射 + 折射
Ray 3: $\theta_3 > \theta_c$, 所有入射光將全部反射

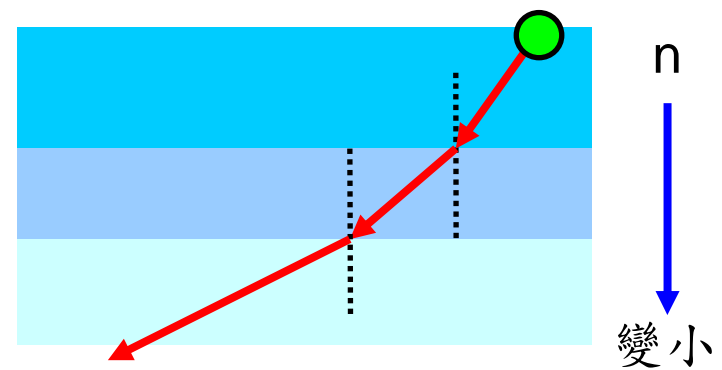
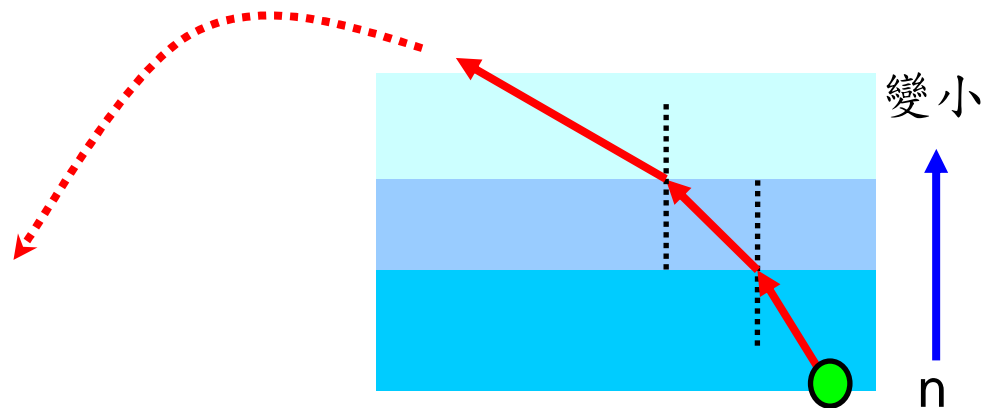
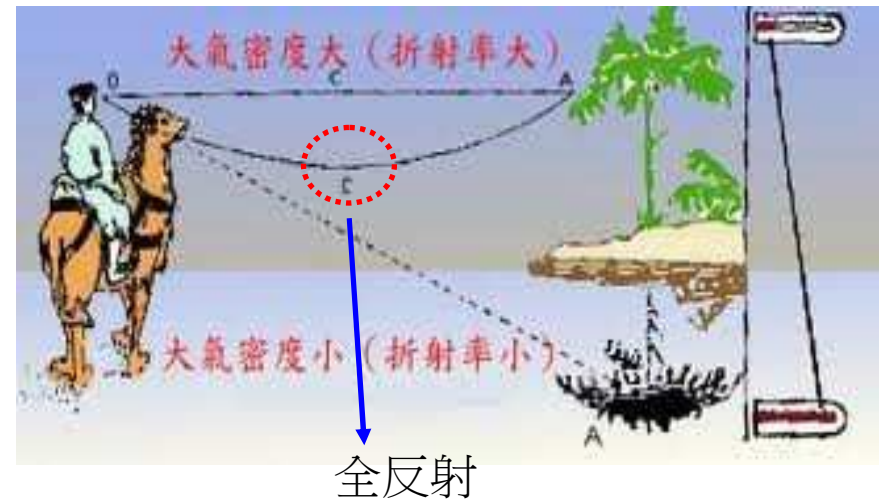
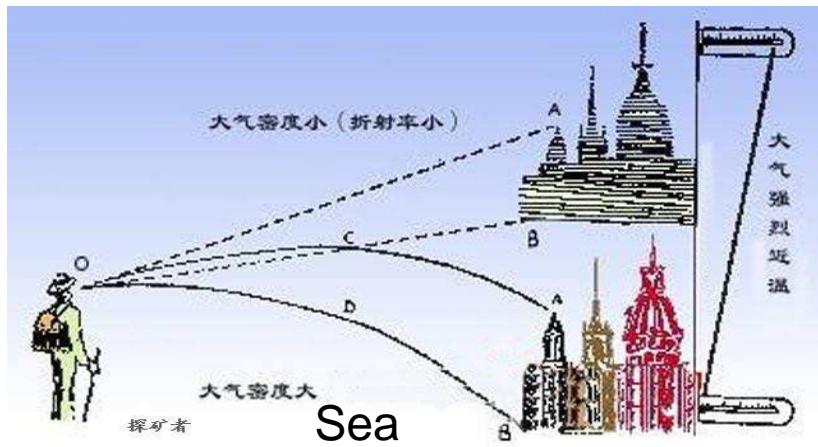
图 2.13 全反射原理



水槽內看到全反射的實驗。

自然界中折射/反射對光的導引：海市蜃樓

- 在地表垂直溫差較大的環境（如海面或沙漠、路面），空氣折射率隨地表高度改變（溫度較高區空氣密度較小、故折射率較小），光因折射及/或(全)反射路徑呈曲線，人會誤認遠處物體變高或變近現象。



Video: Mirage in desert

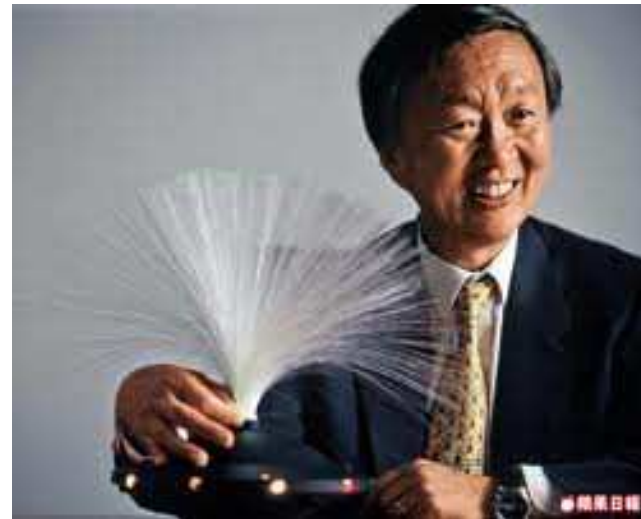
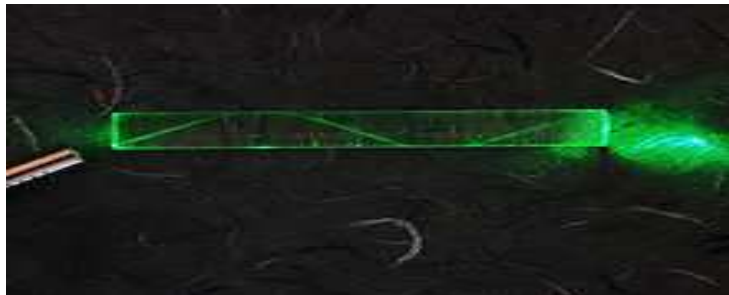
<http://video.sina.com.cn/p/news/v/2013-06-10/193162533473.html>

Video: Mirage on the sea

<http://video.sina.com.cn/p/news/s/v/2008-08-02/192960111940.html>

光的導引

- 利用介質（如水或丙烯酸等）形成的導管及全反射現象，可做出光的導管（即“巨型”光纖）。
- 但是要有具體光傳輸應用的光纖，最重要的考量是其傳輸損失必須夠小
- 高錕博士於1966年提出以石英基玻璃纖維當光導進行光通訊的構想，關鍵是損失要小於20dB/km。他獲頒2009年諾貝爾物理獎。
- 1970年Corning glass 公司才做出損失約20dB/km的光纖[每公里損失約99%功率]。現今最好的光纖損失約0.18dB/km(@1550nm)[每公里損失約4%]。
- 現今，光纖通訊已經於每天的日常生活中使用，Internet如此發達、傳遞資料量如此高都要拜光纖的發展所賜。



高錕

Dielectric-fibre surface waveguides for optical frequencies

K. C. Kao, B.Sc.(Eng.), Ph.D., A.M.I.E.E., and G. A. Hockham, B.Sc.(Eng.), Graduate I.E.E.

Synopsis

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

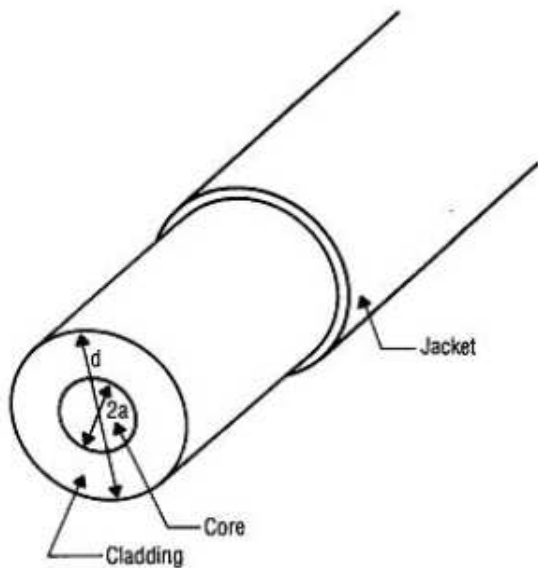
Paper 5033 E, first received 24th November 1965 and in revised form 15th February 1966

Dr. Kao and Mr. Hockham are with Standard Telecommunication Laboratories Ltd., Harlow, Essex, England

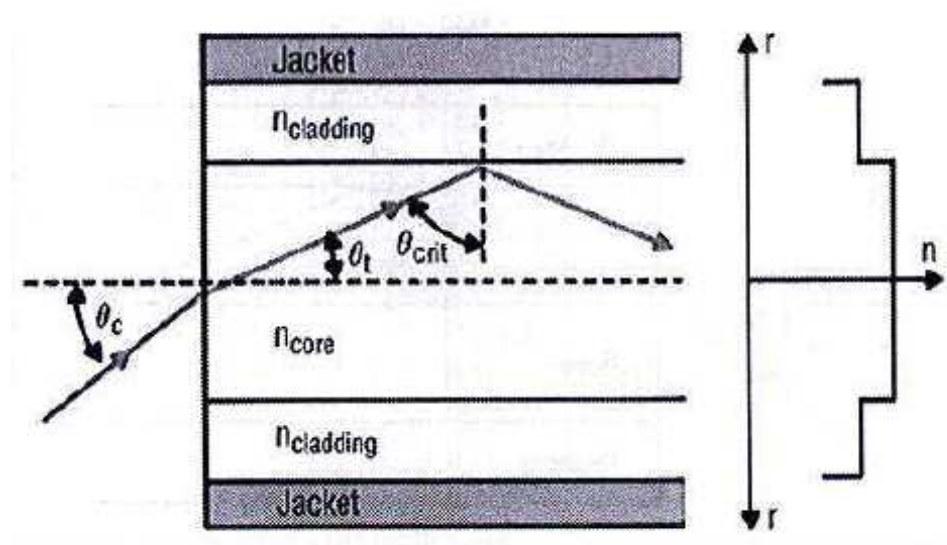
PROC. IEE, Vol. 113, No. 7, JULY 1966

光纖: Structure

- Core: SiO_2 doped with GeO_2 ; $4\text{-}8\ \mu\text{m}$ for single-mode fiber, $50\text{-}100\ \mu\text{m}$ for multi-mode fiber
- Cladding: pure SiO_2 or with less GeO_2 , $125\text{-}140\ \mu\text{m}$
- Jacket: Plastic for protection, $500\text{-}1000\ \mu\text{m}$

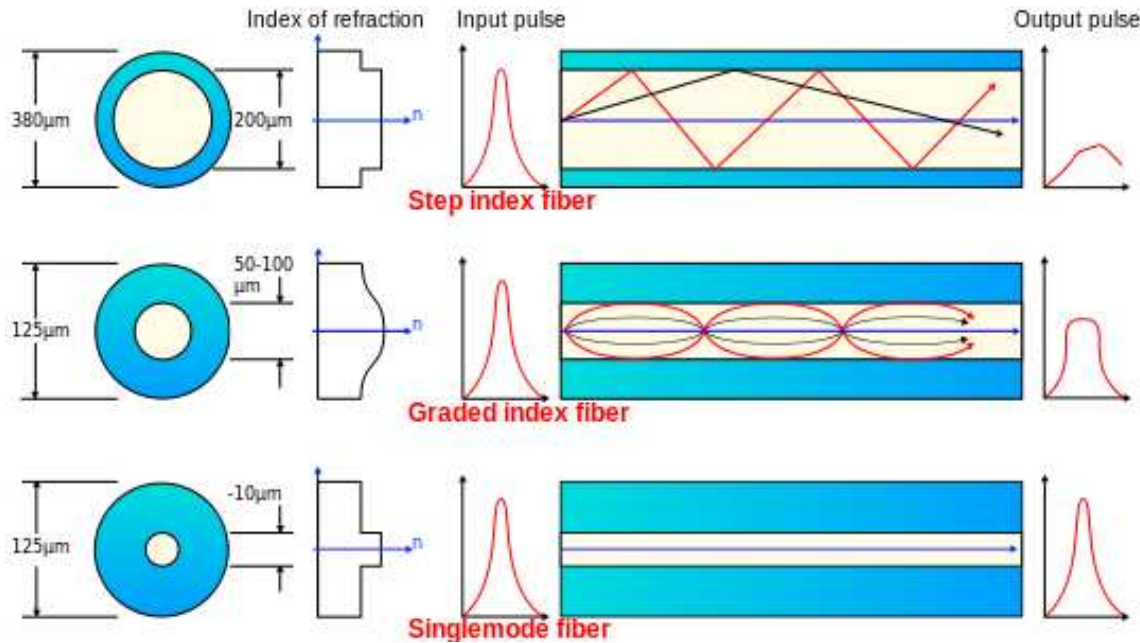


圖一 光纖剖面



圖二 步階式光纖

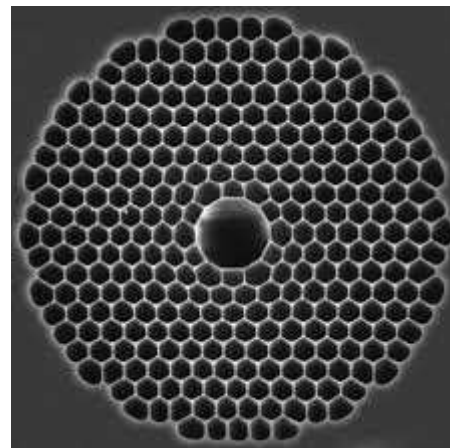
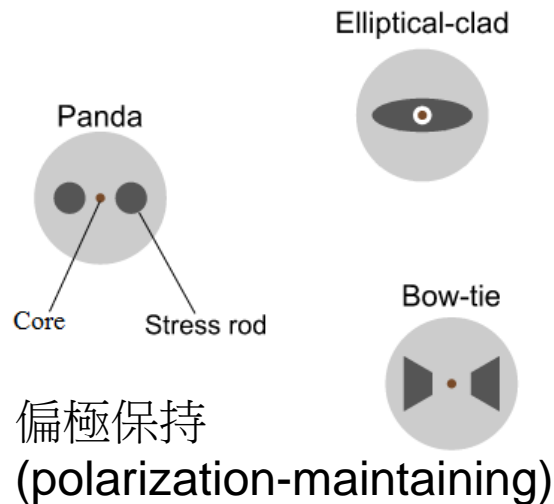
光纖：型式



多模 (multi-mode)

(減少不同光程的色散效應)

單模 (single mode)



中空光子晶格光纖
(hollow core photonic Band-gap fiber)

光纖:接受角或Numerical Aperture

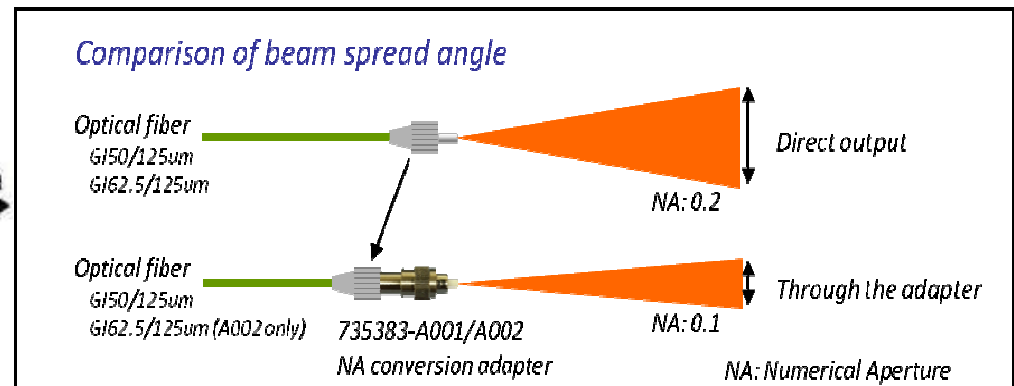
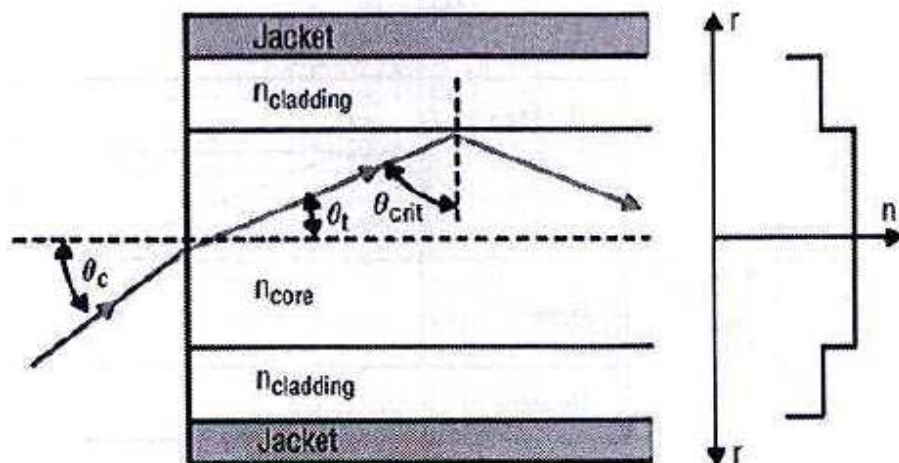
- 只有入射角小於一臨界角度的光，才能藉由全反射在光纖內來回反射及長距離傳遞，超出此角度的入射光會有部分折射至cladding層並快速損失

$$n_0 \sin \theta_c = n_{core} \sin \theta_t = n_{core} \sin(90 - \theta_{crit})$$

$$= n_{core} \cos \theta_{crit} = n_{core} \sqrt{1 - \sin^2(\theta_{crit})}$$

$$n_{core} \sin \theta_{crit} = n_{cl} \sin 90 = n_{cl}$$

$$\therefore n_0 \sin \theta_c = \sqrt{n_{core}^2 - n_{cl}^2} \equiv N.A.$$



光纖：橫模(Transverse Mode)

- 除了上述接受角外，考慮光的傳遞之Maxwell波動方程，在橫 (radial) 方向還要滿足邊界條件 (駐波條件)，光才能在core穩定傳播

$$2\pi \left[\frac{2a}{\lambda_0 / (n_{core} \cos \theta)} \right] - 2\phi = 2m\pi$$

m : 整數

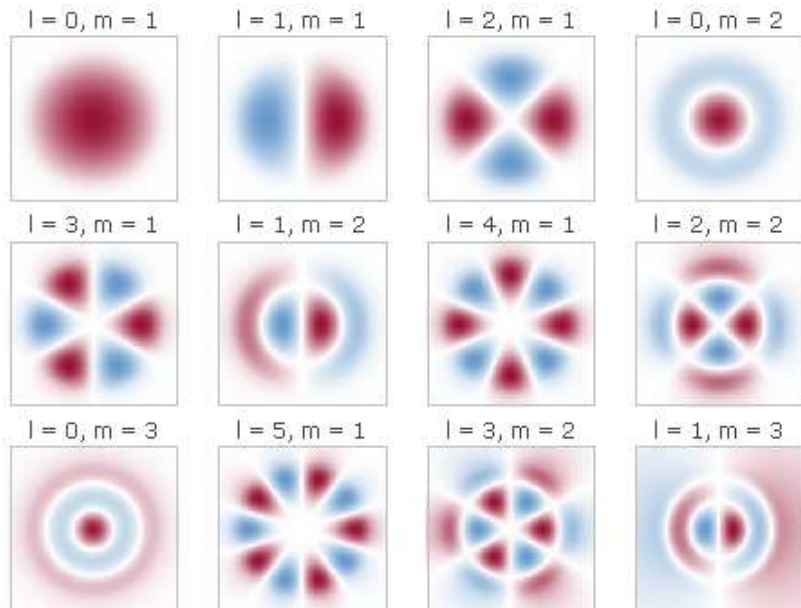
其中 a 為核心半徑

$$\text{or } \frac{2\pi a n_{core} \cos \theta}{\lambda_0} - \phi = m\pi$$

λ_0 為光波於真空中的波長

ϕ 為界面全反射引進之相位差

- 最多的傳播模態數可由最大接受角估計。



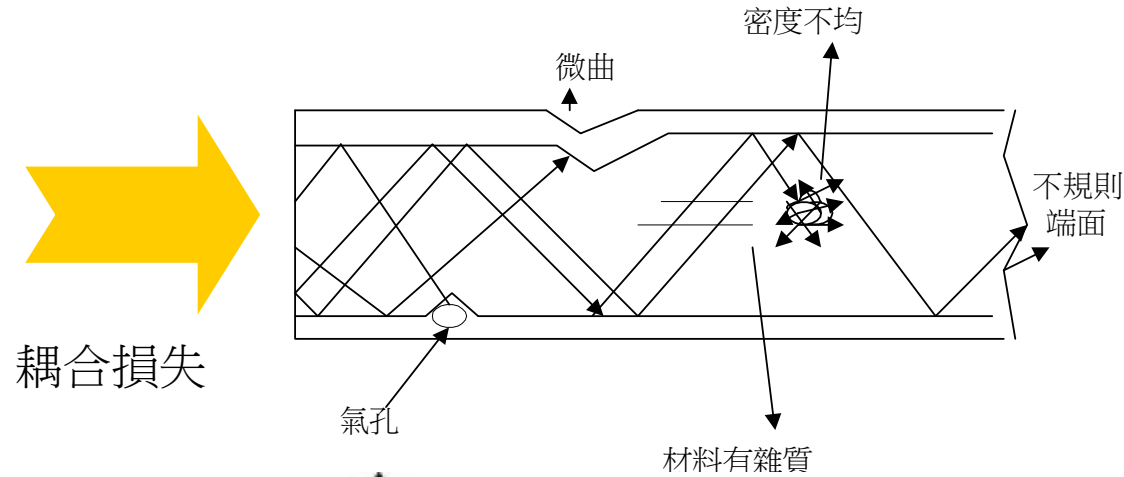
$$m \leq \frac{2a n_{core}}{\lambda_0} \sqrt{1 - \left(\frac{n_{cl}}{n_{core}}\right)^2} - \frac{\phi}{\pi} \equiv \frac{V}{\pi} - \frac{\phi}{\pi}$$

$$\text{where } V \equiv \frac{2\pi a}{\lambda_0} \sqrt{n_{core}^2 - n_{cl}^2}$$

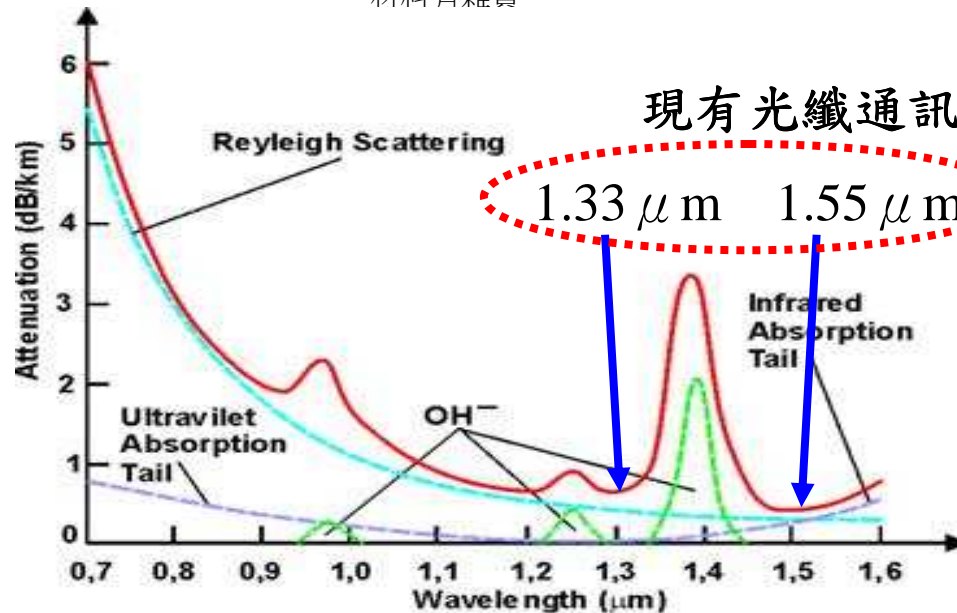
若core半徑較小， $V < 2.405$ ，則只有單一模態；若core半徑較長，則可允許多模態。

光纖：光功率損失

- 損失來源：光耦合進光纖損失、光纖連接不當損失、光纖本身吸收或散射損失、光纖受彎曲或應力產生的損失。

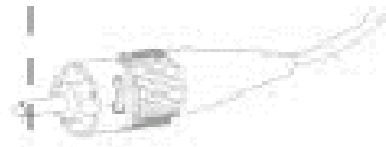


$$dB \equiv -10 \log_{10} \left(\frac{P_{in}}{P_{out}} \right)$$



光纖：連接器型式

Fiber Connector Styles



ST Connector
A slotted bayonet type connector. This connector is one of the most popular styles.



SC Connector
A push/pull type connector. This connector has emerged as one of the most popular styles.



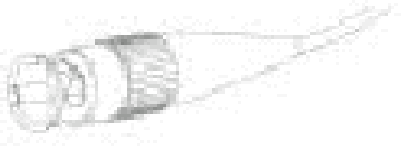
FC Connector
A slotted screw-on type connector. This connector is popular in singlemode applications.



SMA Connector
A screw-on type connector. This connector is waning in popularity.



FDDI Connector
A push/pull type dual connector. This connector is one of the more popular styles.



Mini-BNC Connector
A bayonet style connector using the traditional BNC connection method.



Biconic Connector
A screw-on style connector. This connector is almost obsolete.



MT-RJ Connector
A new RJ style housing fiber connector with two fiber capability.



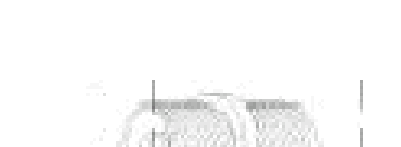
ST Feedthru
A slotted bayonet type feedthru. ST connectors are one of the most popular styles.



SC Feedthru
A push/pull type feedthru. SC connectors are one of the most popular styles.



FDDI Feedthru
A push/pull type feedthru. FDDI connectors are popular in both singlemode and multimode applications.



FC Feedthru
A slotted screw-on type feedthru. FC connectors are popular in singlemode applications.



F-SMA



FDDI/MIC



ESCON



T-ST



T-SC



T-SC-Duplex



T-SC/APC-8°/9°



MTRJ (male)



MTRJ (female)



LC



LC-Duplex



FC/PC



FC/APC



DIN



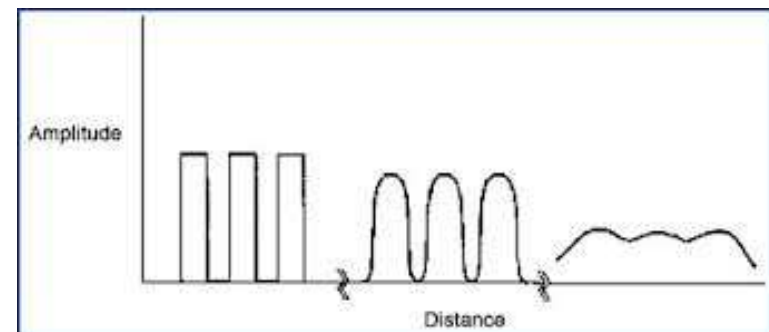
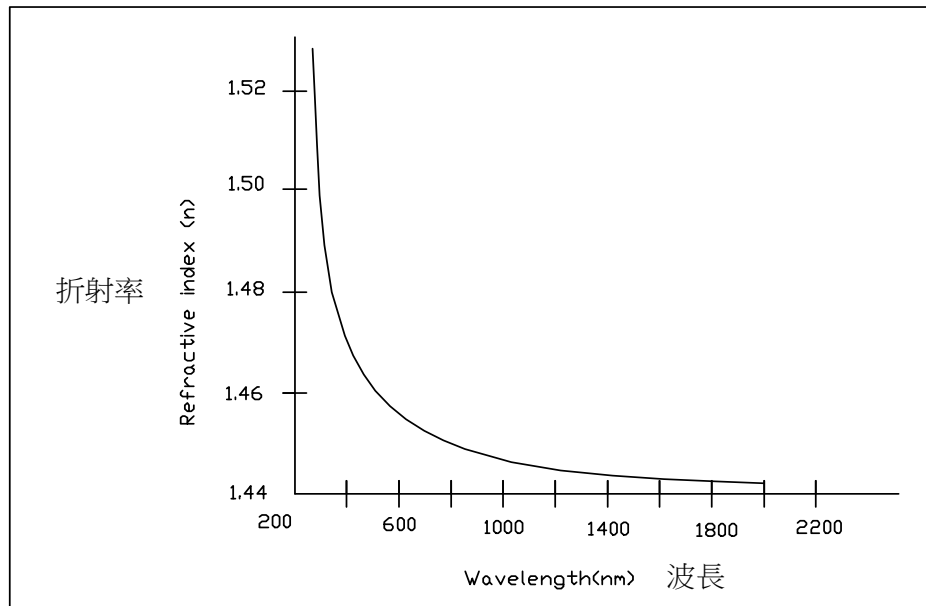
E-2000



E-2000/APC

光纖：信號傳輸之色散與失真

- 色射關係：不同波長，介質的折射率不一樣，行進速度不一樣。
- 富利葉分析：一個光脈衝（方波或其它波形）可分解成一些不同頻率的正弦波之組合。
- 信號失真：因不同頻率（波長）成分行進速度不一致，在光纖內傳遞一段距離後，波形會變形，這會對光通信之最高信息量設下限制。



Description

Thorlabs' single mode 1310BHP fiber delivers high performance across a broad spectral range in the telecom region, and also features exceptional core / clad concentricity specifications.

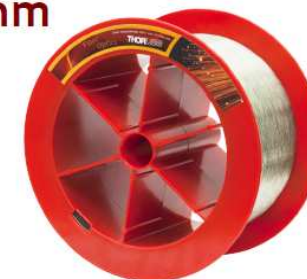
Specifications 規格

Geometrical & Mechanical	
Cladding Diameter	125 ± 1.0 μm
Coating Diameter	245 ± 15 μm
Core Diameter	8.5 μm
Core-Clad Concentricity	<0.5 μm
Coating-Clad Offset	≤ 5 μm
Coating Material	UV Cured, Dual Acrylate
Operating Temperature	-55 to 85 °C
Short-Term Bend Radius	≥6 mm
Long-Term Bend Radius	≥13 mm
Proof Test Level (245 coat)	≥200 kpsi (1.4 GN/m ²)

Optical	
Numerical Aperture (nominal)	0.13
Attenuation	0.5 dB/km @ 1310 nm 0.5 dB/km @ 1550 nm
Operating Wavelength	1300 - 1625 nm
Second Mode Cut-Off	1260 ± 30 nm
Mode Field Diameter (1/e ² fit- near field)	8.6 ± 0.5 μm @ 1310 nm 9.7 ± 0.5 μm @ 1550 nm
Bend Loss per Turn @ 13 mm Radius	<0.01 dB @ 1310 nm
Bend Radius for 0.05 dB per 100 turns (nominal)	Less than LTBR 22 mm @ 1550 nm 24 mm @ 1625 nm

1310BHP

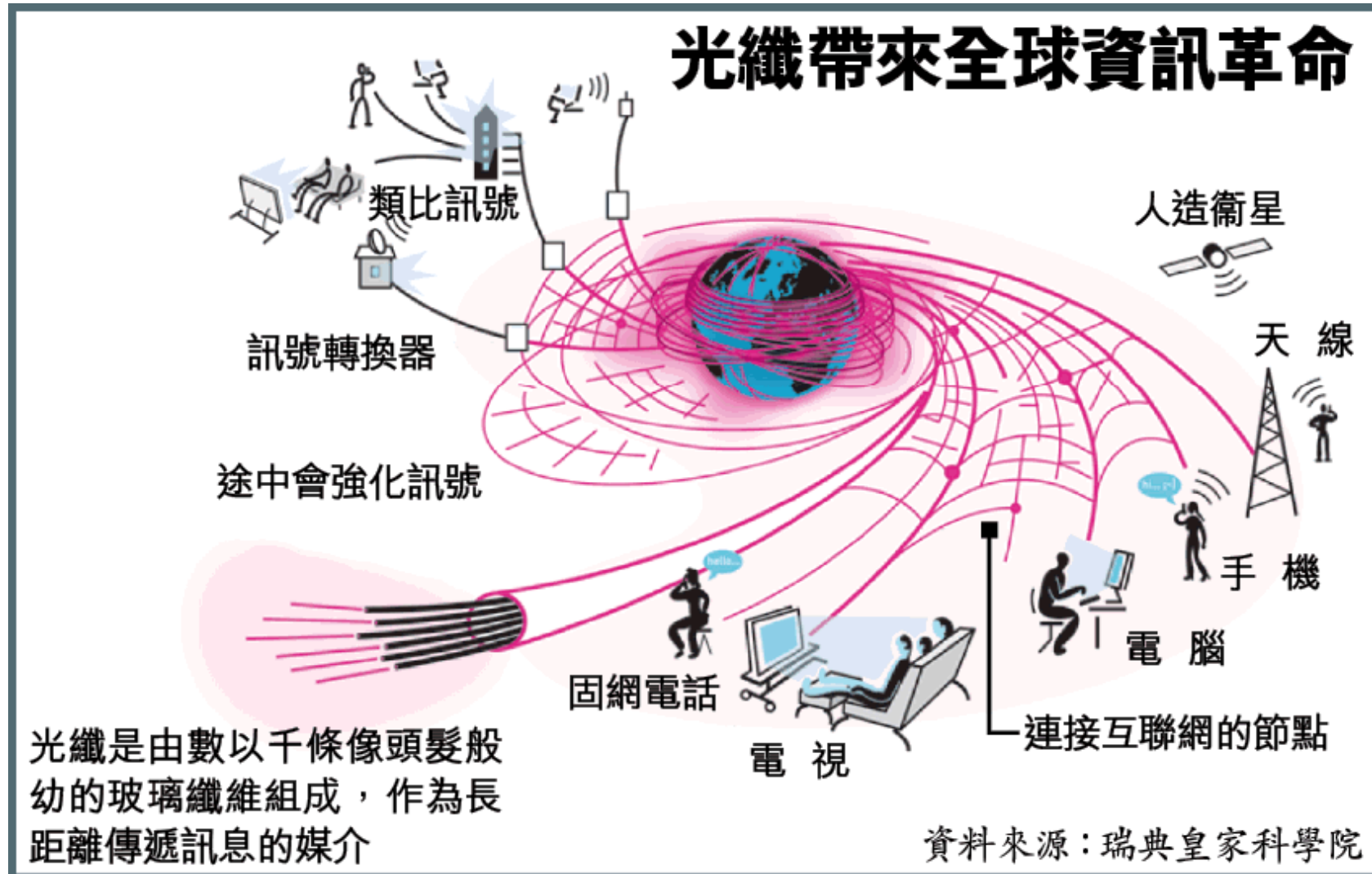
Single Mode Fiber:
1300 to 1625 nm

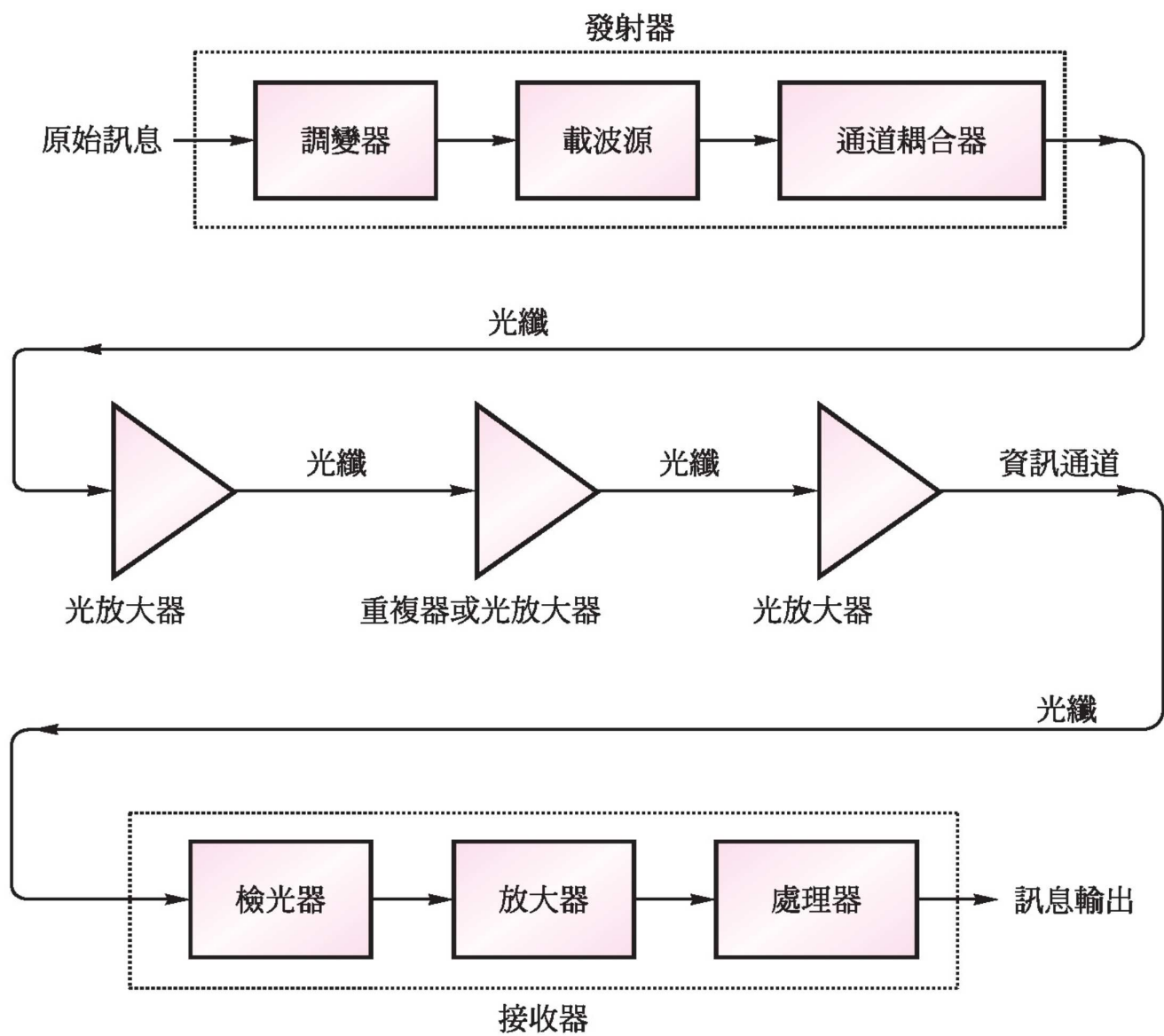


1310BHP

光纖通信

- 有長距離、高頻寬、不受惡劣環境或電磁波干擾的優點。





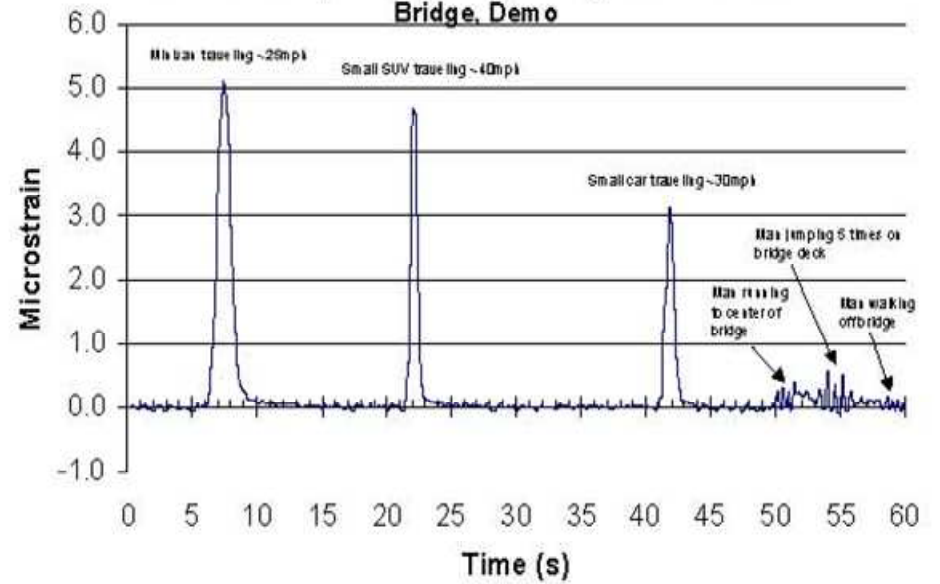
詳細的光纖數位傳輸系統方塊圖

光纖感測

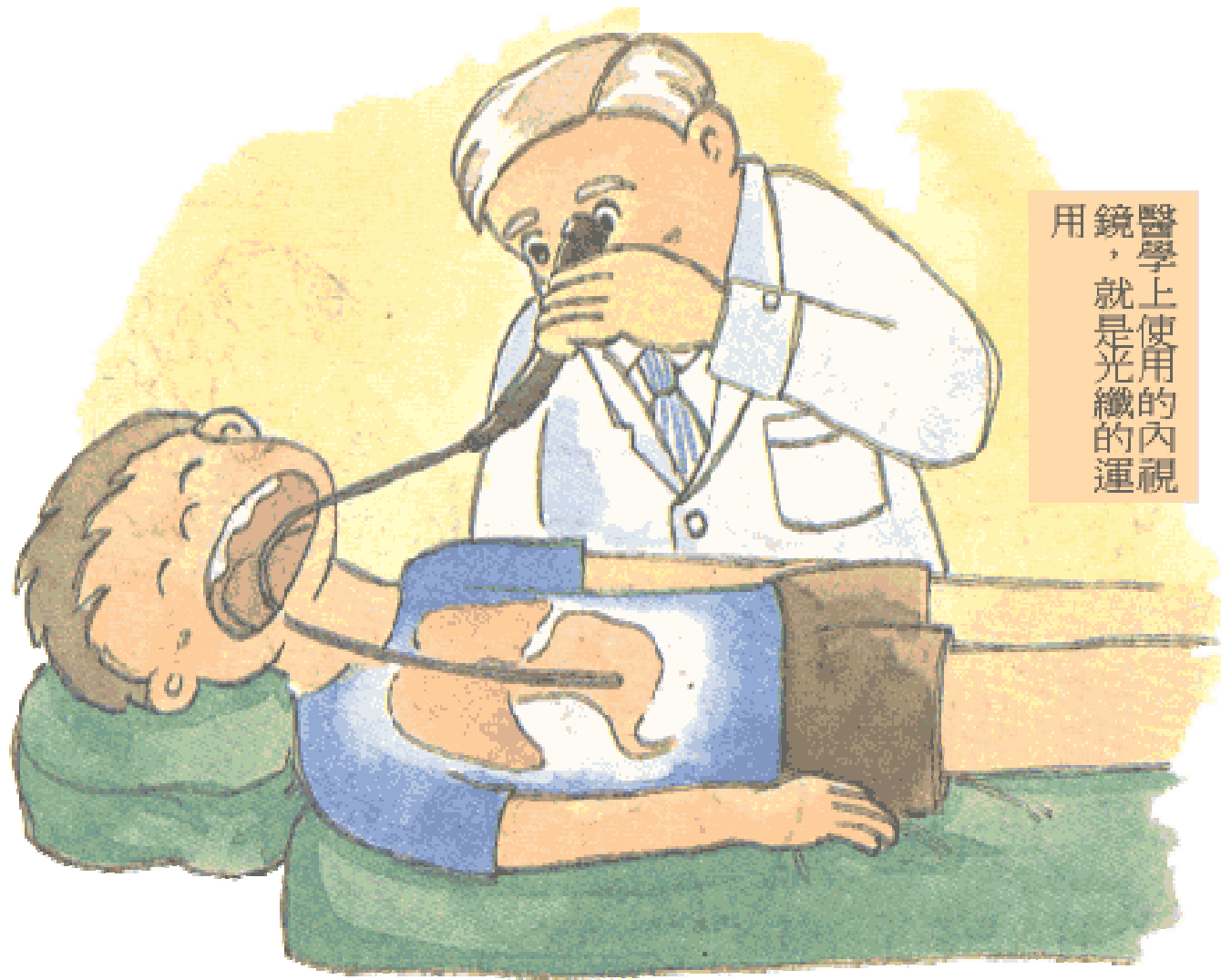
- 由於光纖特性容易受待測環境因素變化影響而有所改變，我們也可運用這個特點，以此調制光纖量測的信號。光纖感測器有如下的幾個優點：靈敏度高。不受電磁雜訊之干擾，信號傳輸迅速。體積小、重量輕、壽命長、價格低廉。適於特殊環境之工作。具有絕緣、耐高壓、耐高溫、耐腐蝕等優點。光學佈置之幾何形狀彈性大，可依環境要求調整。
- 光纖感測器信號的檢出有光強度型及相位干涉型兩種方式。光強度型其主要原理是利用幾何物理量的變化調制信號強弱，以用之於諸如壓力、應力、加速度、聲波、轉速、溫度、磁場、電壓、電場等等檢測領域。雖然靈敏度較相位干涉式低，但其結構及原理十分簡單，操作方便，並且可以採用較低廉的光纖為其優點。



Fast Demodulation of Sensor T1FC (Transverse Beam, External to Composite, Flexure, Center) on Horsetail Falls Bridge, Demo

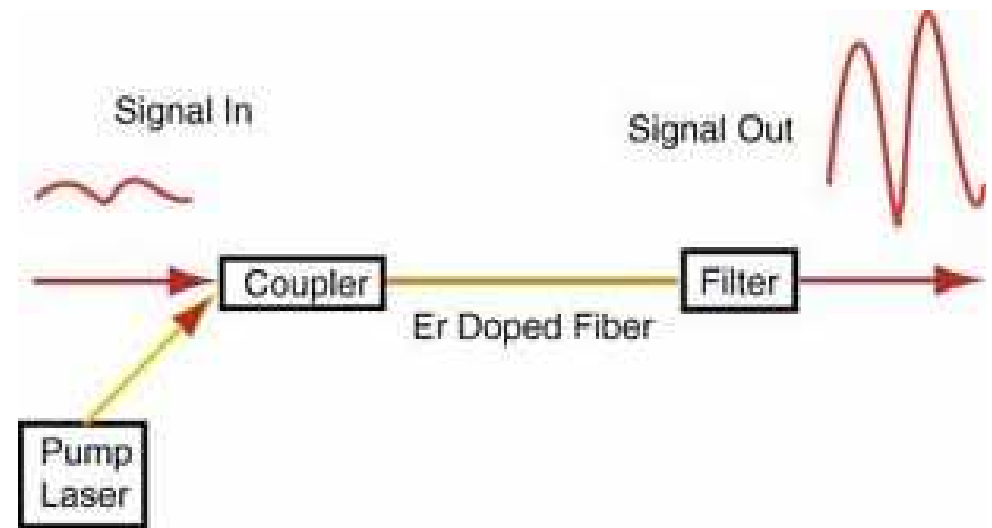
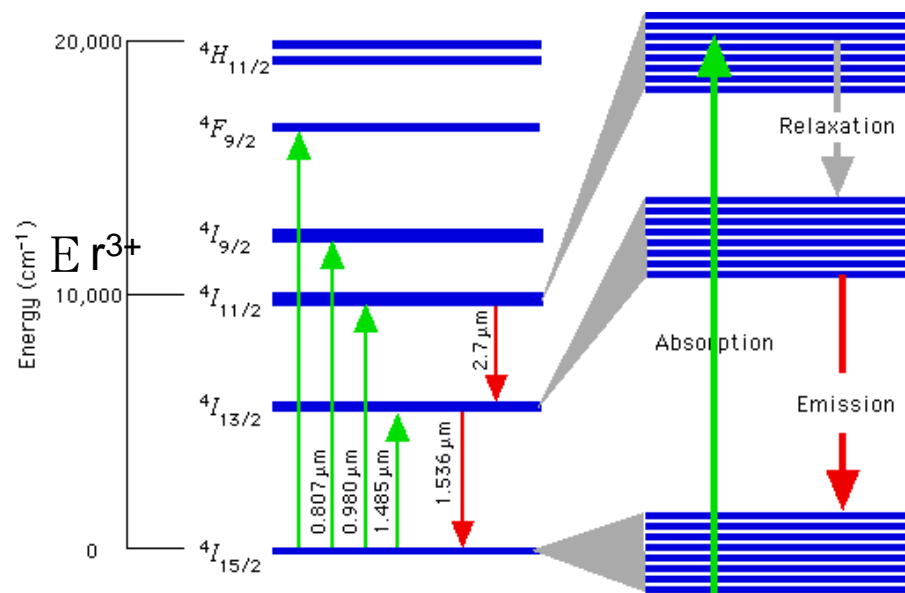


光纖於醫學應用



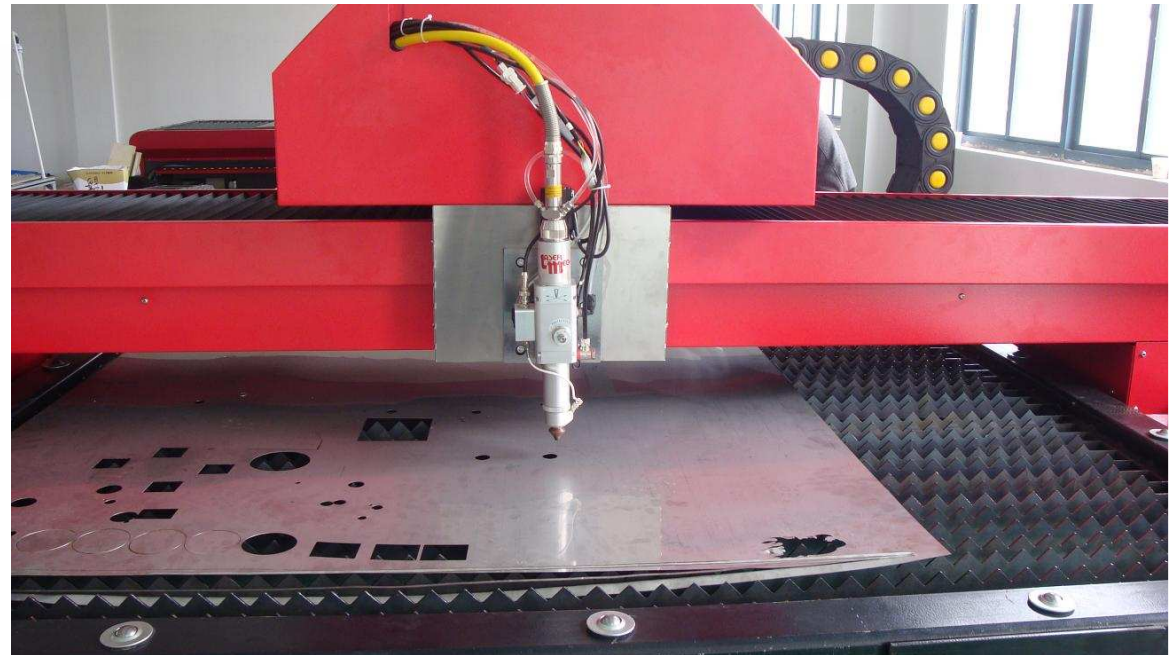
醫學上使用的內視鏡，就是光纖的運用。

光纖光放大器與雷射



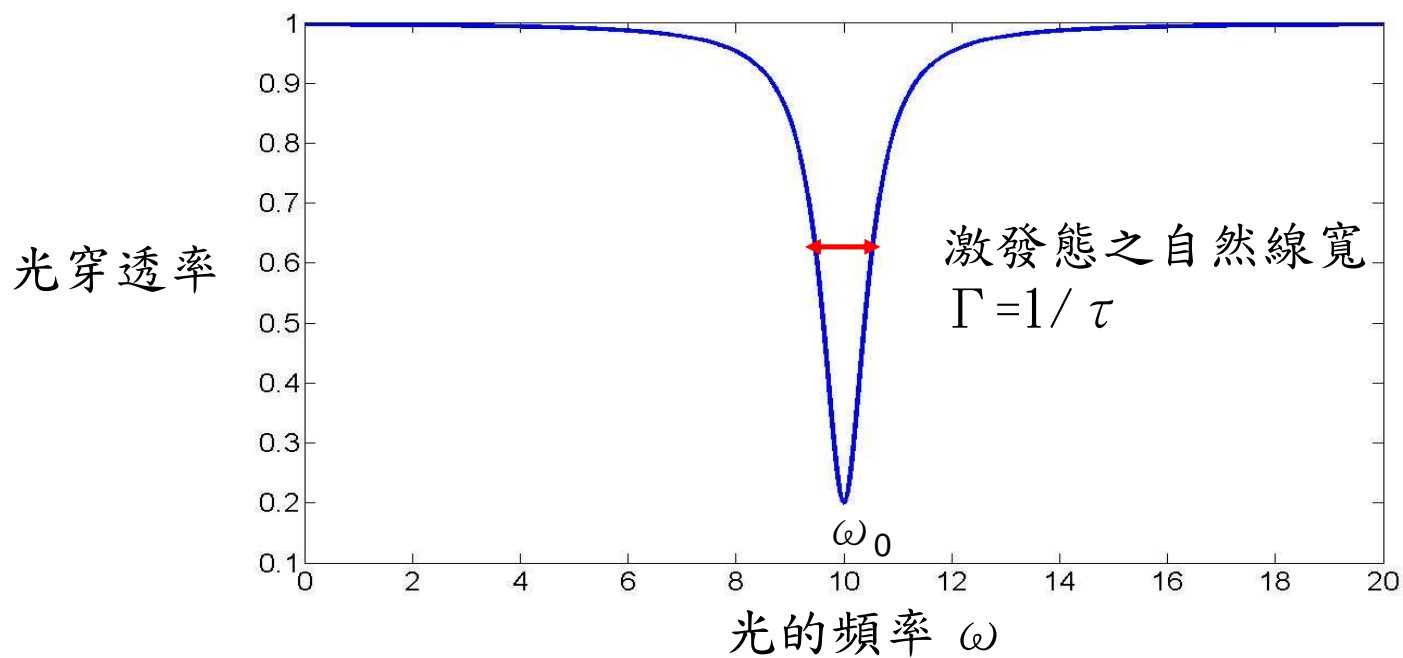
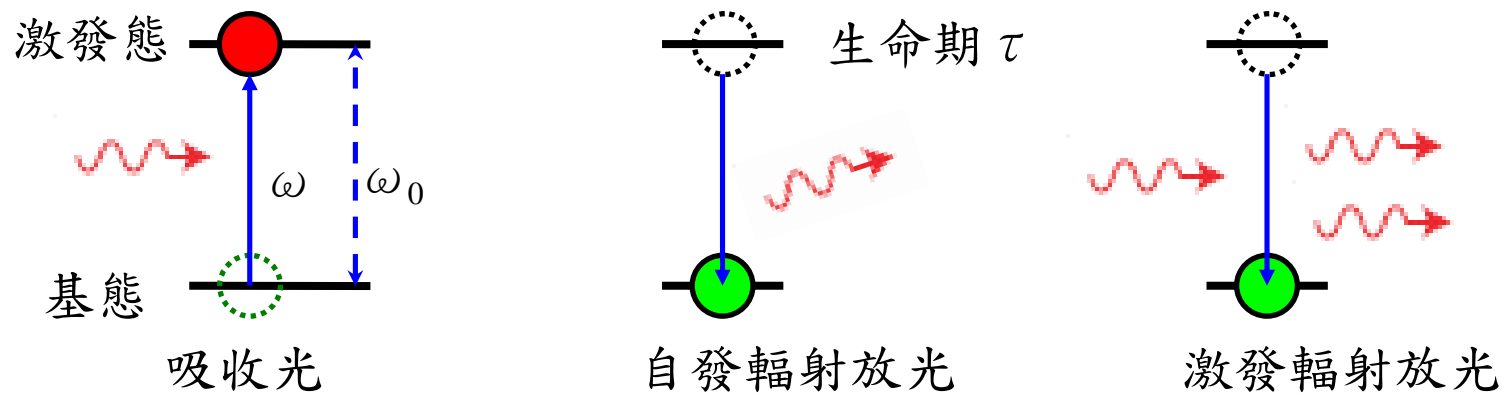


Fiber laser



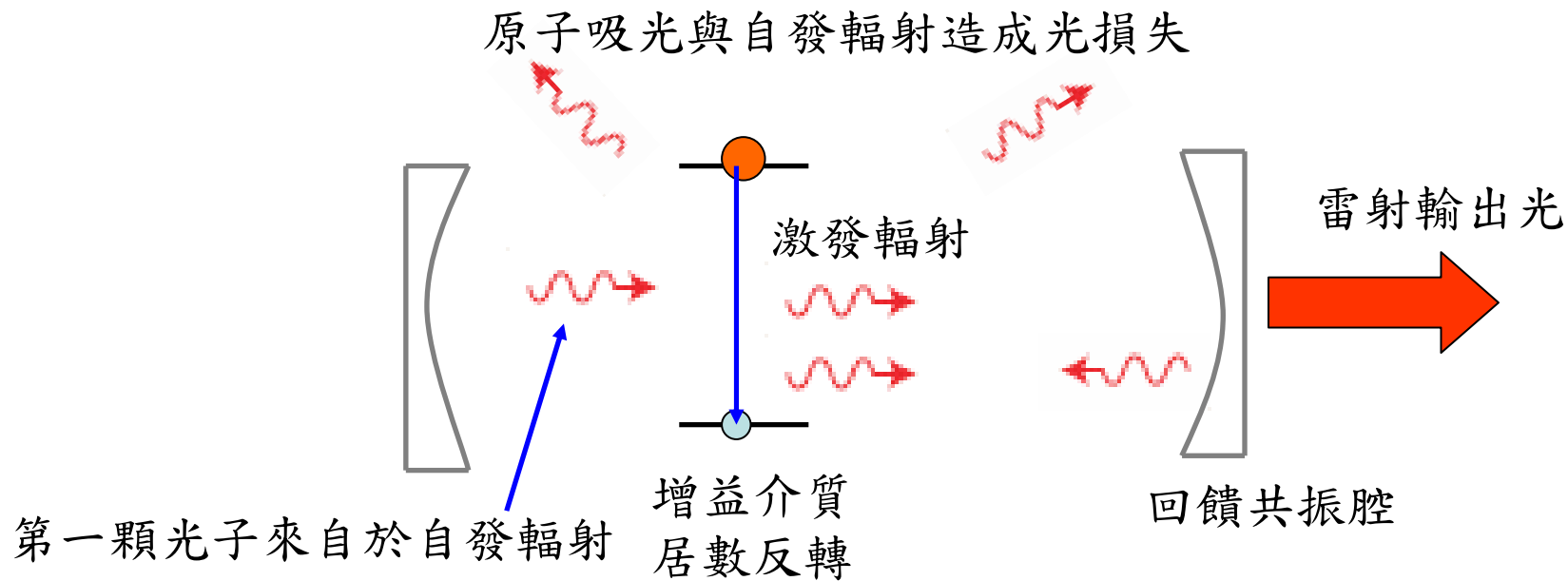
500Watt Fiber Laser Cutting Machine

光與原子的交互作用



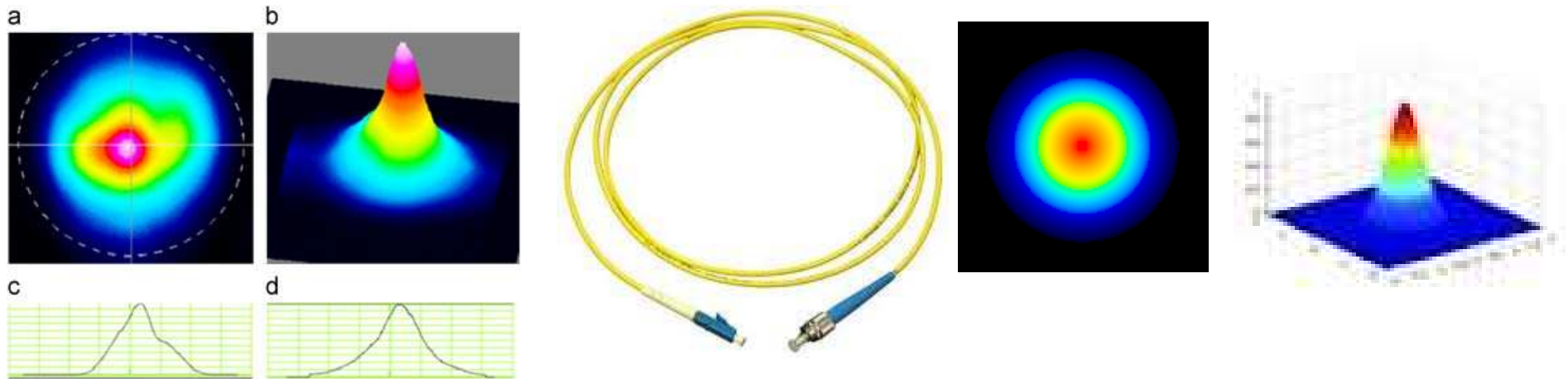
雷射光

- LASER, **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- 雷射和一般光源的最大差別在於其單頻性（同調性）



光纖於實驗室應用

- 某些雷射光（例如半導體雷射）形狀不好，可耦合進單模光纖整成高斯光束，以利應用。但會犧牲部分功率，因此光的高效率耦合至光纖是一重要工作。
- 許多雷射可集中於一溫度、振動控制良好的光學桌，並以光纖將光導至實驗區。避免因光路走太遠，光學桌或機械元件熱漲冷縮造成光路改變。



本次實驗

- 實驗儀器：單模光纖一條、多模光纖兩條、紅光半導體雷射一台、光纖耦合器、物鏡兩個、光偵測器、三用電表、鏡子兩個、光纖檢測器 (fiber checker)。
- 實驗描述：
 - 可以先用光纖檢測器快速讓光耦合至單模或多模光纖，觀察其輸出光的形狀。
 - 決定單模光纖的Numerical Aperature
 - 嘗試自己將半導體雷射光耦合自單模光纖，嘗試不同物鏡、光路安排，讓能耦合入光纖的效率最高。