Nonlinear Fiber Optics and Application

授課老師:林家弘 教授

Textbook:

1. Nonlinear Fiber optics
2. Applications of Nonlinear Fiber Optics

(Author: G. P. Agrawal)

Reference book:

Fundamentals of Photonics

(Author: B.E.A. Saleh and M. C. Teich)

Program:

Fiber desk

上課時間

Tuesdays 5, 6, 7

評分標準： 1. 平時分數 10%（出席率，聽講，發問）

2. 期中考 30%

3. 期末報告 60%

課程內容

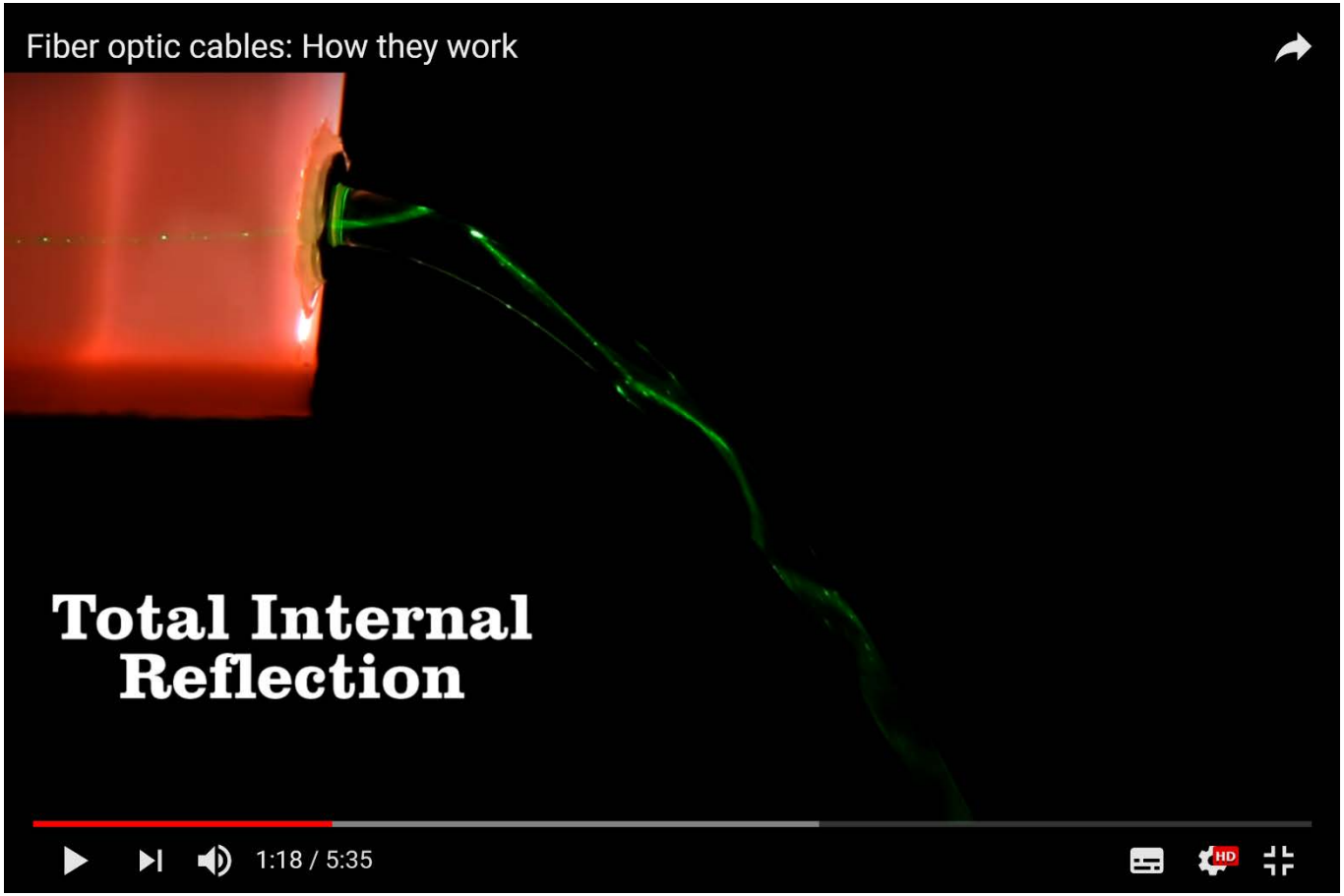
- 第一週 光纖簡介 I（歷史回顧與光纖製作）
- 第二週 光纖簡介 II（光纖基礎參數）
- 第三週 光纖極化與應用
- 第四週 光纖非線性簡介
- 第五週 脈衝傳播方程式I（非線性薛定格方程式）
- 第六週 脈衝傳播方程式II（Split step Fourier method）
- 第七週 群速度色散 I（色散造成脈衝的變寬）
- 第八週 群速度色散 II（三階色散效應）
- 第九週 期中考

課程內容

- 第十週 自相位調變 I（自相位調變造成光頻譜的變寬）
- 第十一週 自相位調變 II（高階非線性光學效應）
- 第十二週 產業導師
- 第十三週 光孤子動態 I
- 第十四週 光孤子動態 II
- 第十五週 產業導師
- 第十六週 光纖雷射I（連續波光纖雷射）
- 第十七週 光纖雷射II（短脈衝光纖雷射）
- 第十八週 期末考

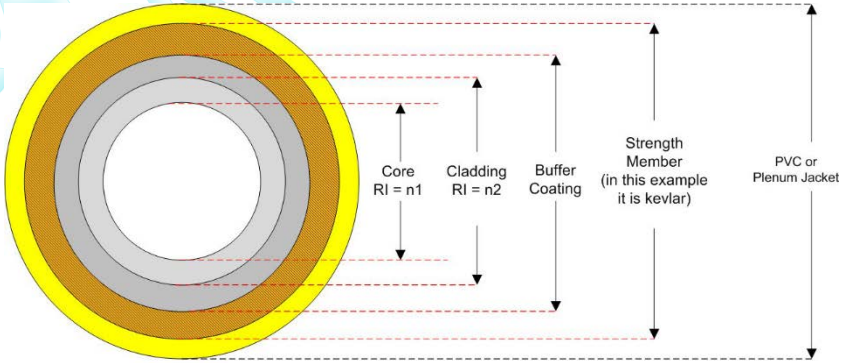
Fiber optic cables: How they work

- https://www.youtube.com/watch?v=0MwMkBET_5I



1.1 Historical Perspective

- **Total internal reflection (**know from the **nineteenth century)**
  - the **basic phenomenon** responsible for guiding of light in optical fibers.
- **1920s**：**Uncladded glass fibers** were fabricated.
- **1950s**：The field of **fiber optics** was **born** when the use of a **cladding layer** led to considerable improvement in the **fiber characteristics**.
- **1960s**：mainly for the purpose of **image transmission** through a **bundle of glass fibers**.
  - These early fibers were extremely lossy (**loss >1000 dB/km**) from the modern standard.



RI = Refractive Index n1>n2

- **1979**：Further progress in **fabrication technology** resulted in a **loss** of only **0.2 dB/km** in the **1.55-μm** wavelength region.
  - The availability of low-loss **silica fibers** led to
    - a **revolution** in the field of **optical fiber communications**.
    - the **advent** of the new field of **nonlinear fiber optics**.
- **1972**：**Stimulated Raman-** and **Brillouin-scattering** were studied.
- **1973**：It was suggested **optical fibers** can support **soliton-like pulses** as a result of an **interplay** between the **dispersive** and **nonlinear effects**.
- **1980**：**Optical solitons** were observed in a **experiment** and led to **a number of** advances during the 1980s in the **generation** and **control** of **ultrashort optical pulses**.
- 1987：Pulses as short as **6 fs** were generated.

The Nobel Prize in Physics 2009

Charles K. Kao, Willard S. Boyle, George E. Smith

Charles K. Kao - Facts

Photo: U. Montan

Charles Kuen Kao

Born: 4 November 1933, Shanghai, China

Affiliation at the time of the award: Standard Telecommunication Laboratories, Harlow, United Kingdom, Chinese University of Hong Kong, Hong Kong, China

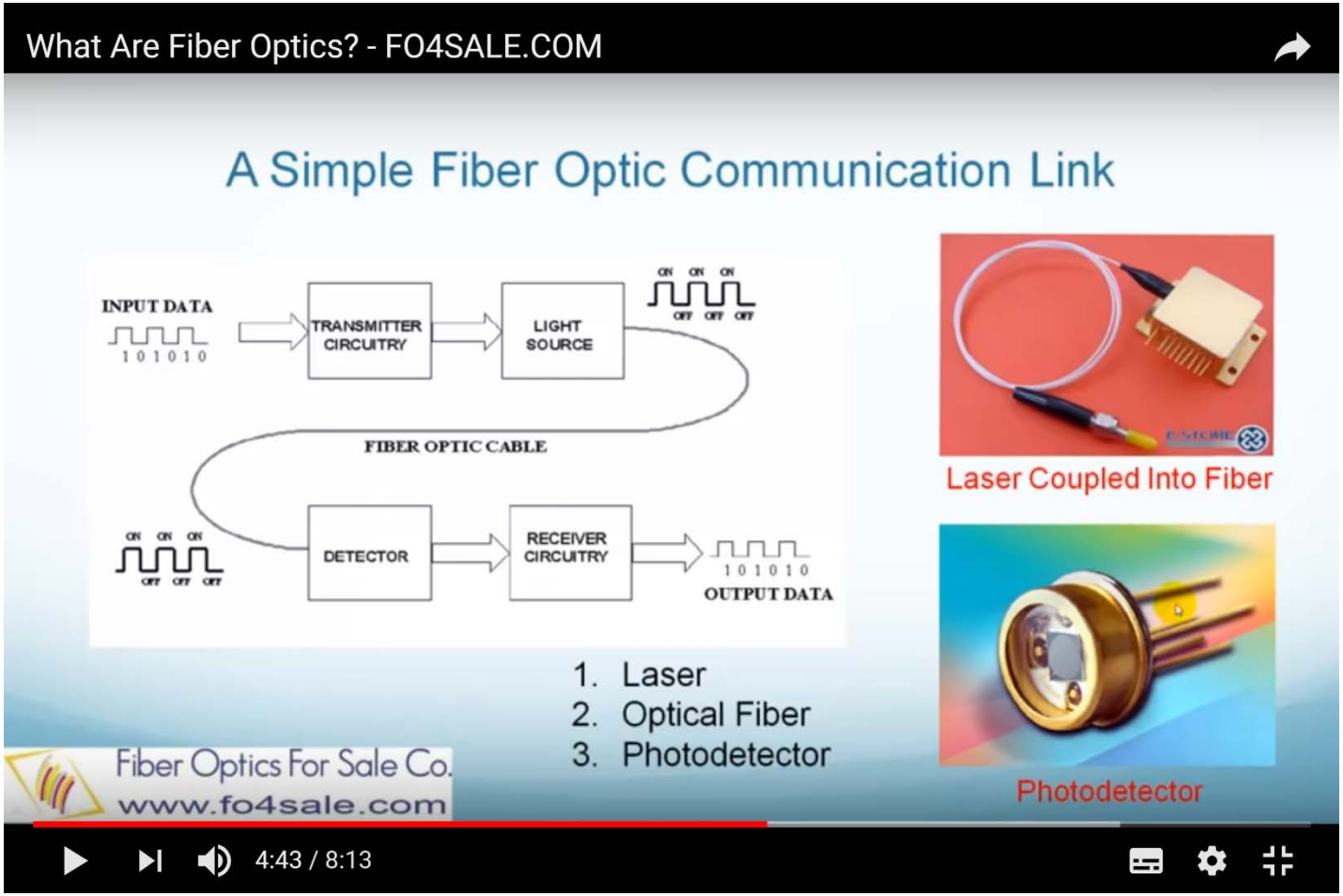
Prize motivation: "for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

Field: fiber technology, instrumentation

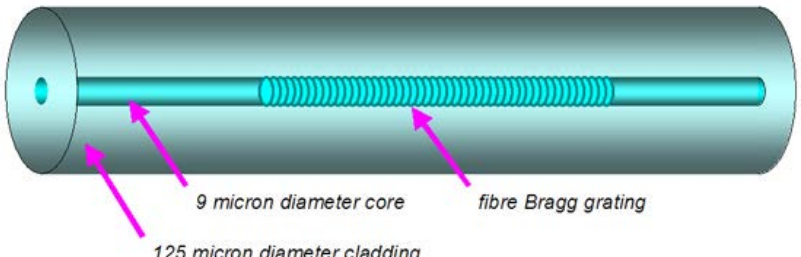
高錕為光纖通訊、電機工程專家，華文媒體譽之為「光纖之父」、普世譽之為「光纖通訊之父」，曾任香港中文大學校長。2009年，獲諾貝爾物理學獎一半獎項，以表揚他「在光傳輸於纖維的光學通信領域突破性成就」

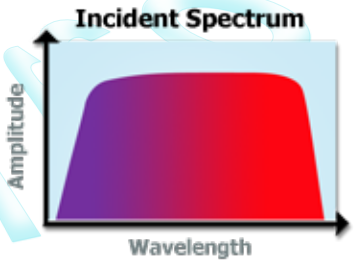
What Are Fiber Optics?

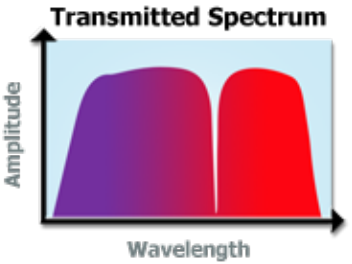
- https://www.youtube.com/watch?v=7h2xr-pi5VQ

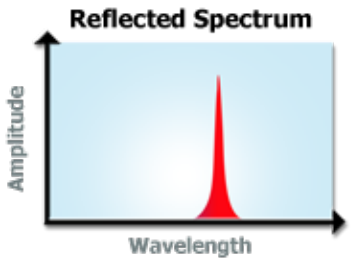


- A new dimension was added when **optical fibers** were doped with **rare-earth elements (烯土元素)** and used to make **amplifiers** and **lasers**.
- **Erbium-doped fiber amplifiers(EDFA)** attracted the most attention because they operate in the wavelength region near **1.55 μm** and are thus useful for **fiber-optic lightwave systems**.
- **After 2000**: two **nonlinear effects** occurring inside optical fibers were employed to develop new types of **fiber-optic amplifiers**
  - **stimulated Raman scattering**
  - **four-wave mixing.**
- **1978**：first made of **fiber gratings**.

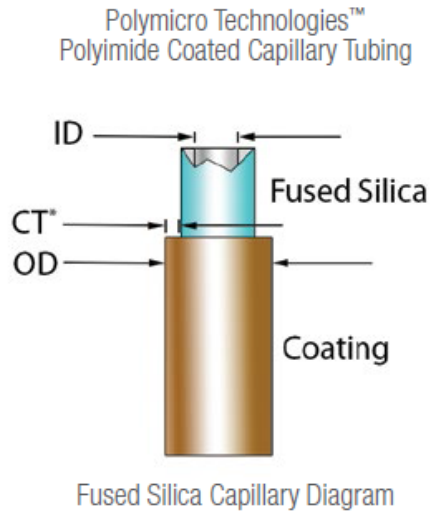




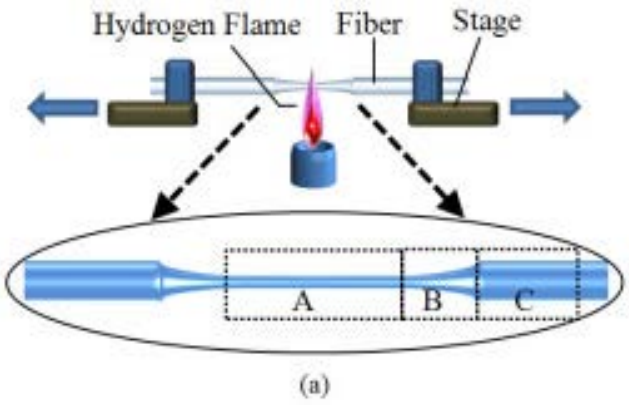


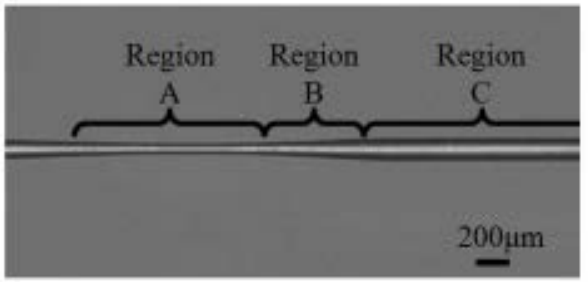


- 1996：new types of fibers were developed, known under names such as
  - photonic crystal fibers,
  - holey fibers,
  - microstructure fibers,
  - tapered fibers,



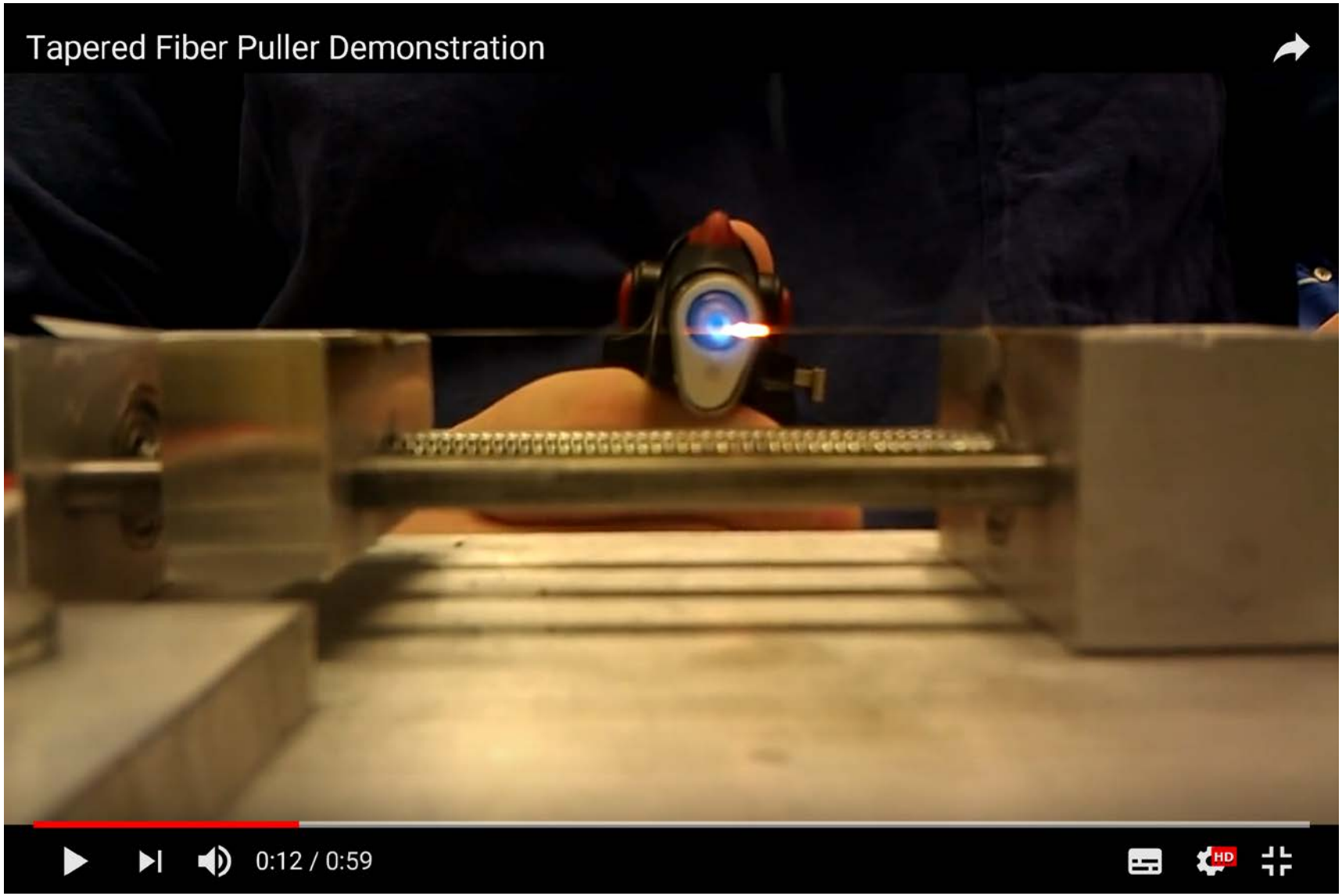
- With these developments, the field of nonlinear fiber optics has grown considerably after 2000 and is expected to continue to do so in the near future.



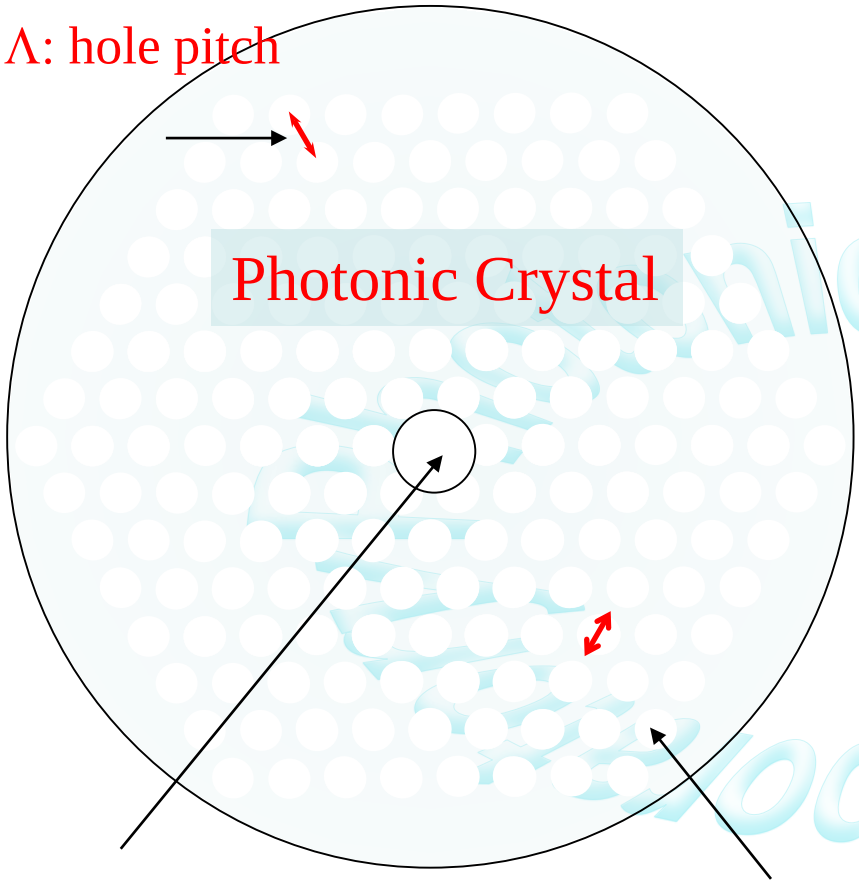


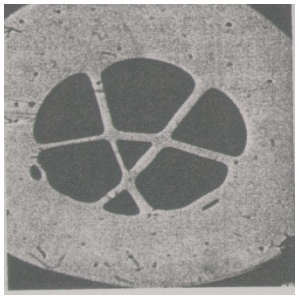
Tapered Fiber Puller Demonstration

- https://www.youtube.com/watch?v=TR72sQmturk

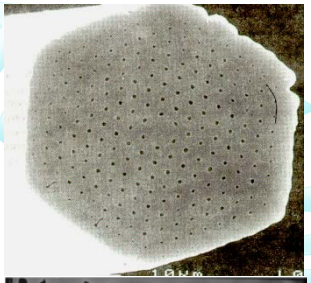


Photonic Crystal fibers

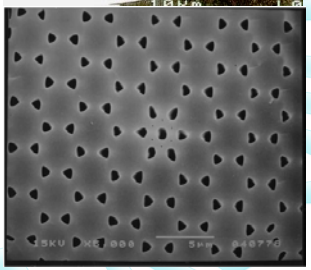




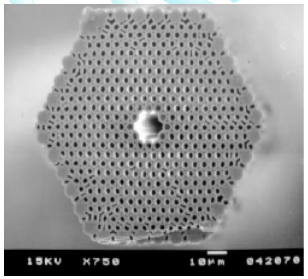
1974
Kaiser *et al.*
Air-silica fibers



1996
Knight, Birks,
Russell, Atkin,
Photonic crystal fiber



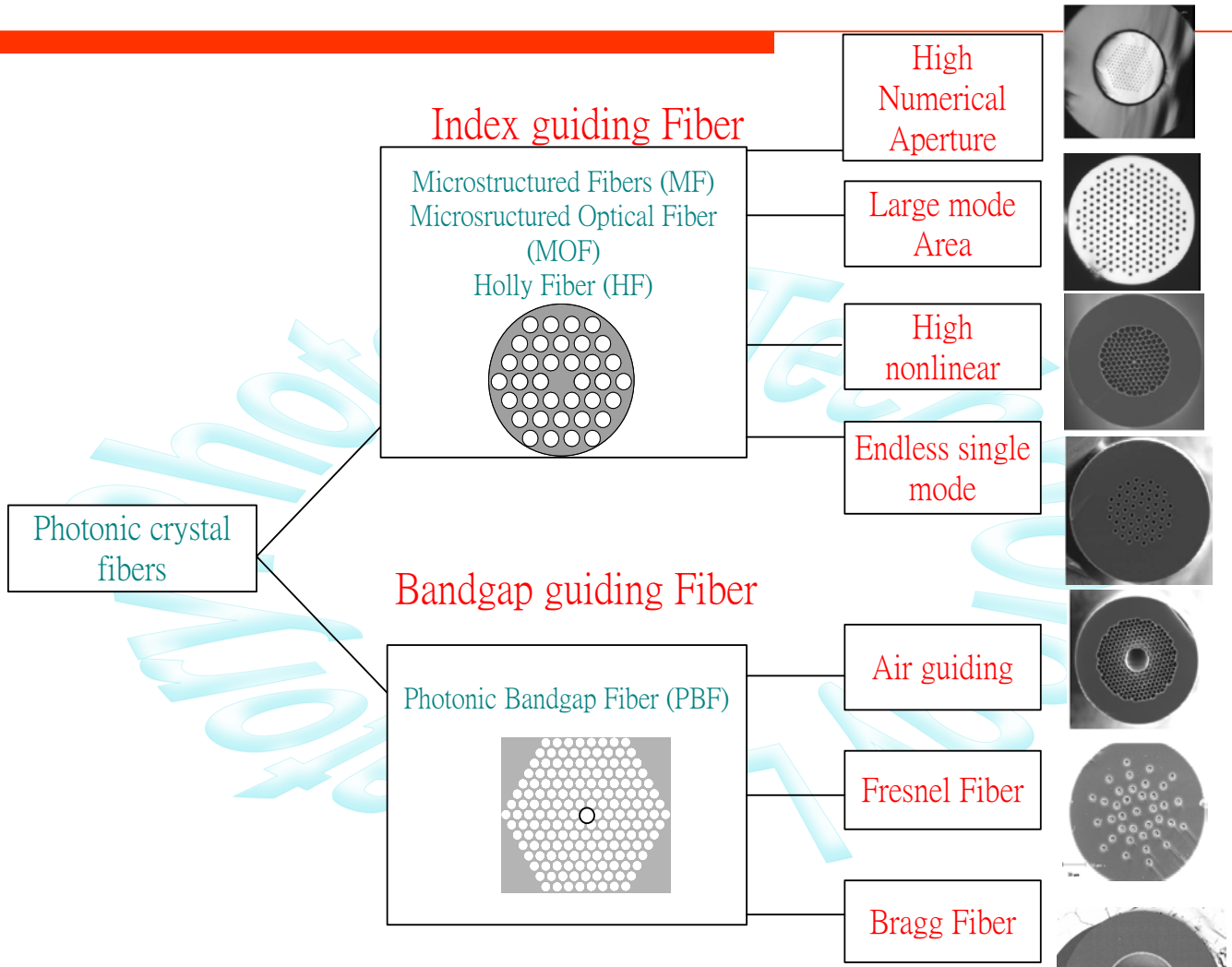
1998
Knight, Broeng,
Birks, Russell
Photonic bandgap
fiber (PGB)



1999
Cregan, Mangan, Knight,
Birks,
Russell, Roberts, Allan
SM PGB

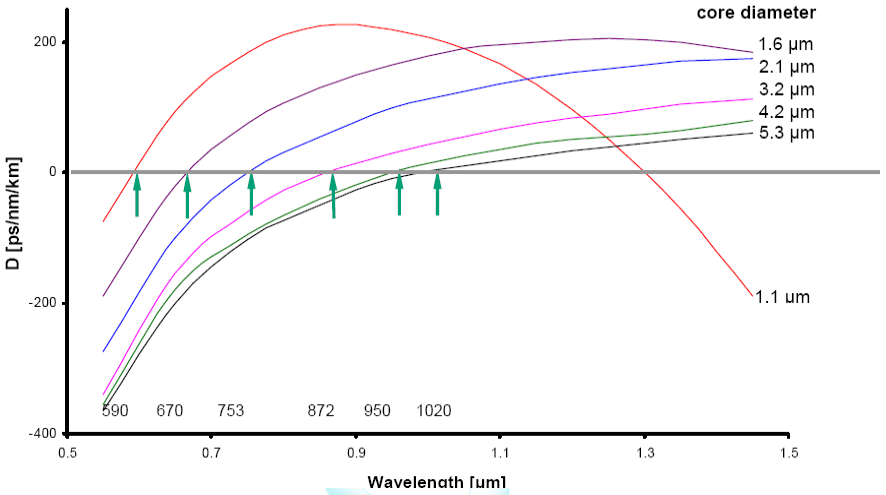
T.K. Birks, P.J. Roberts,P.S.J. Russel, Atkin, Shepherd, Electron. Lett. **31**, 1941-1942 (1995)

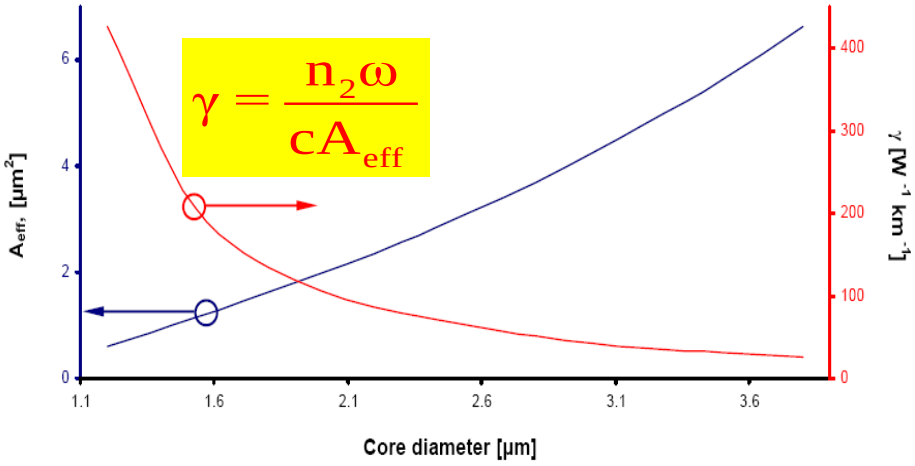
Kinds of the Photonic crystal fiber

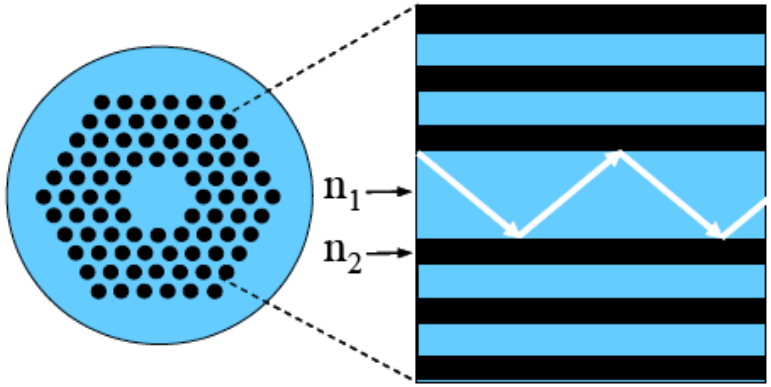


Nonlinear PCF (microstructure fiber)

- **Feature**
  - pure silica core surrounded by regular array of air holes
- **Property**
  - **Dispersion properties** can be tailored in broad range
    - **from 1.3 mm to visible**
  - Small mode area
    - Highly nonlinearity

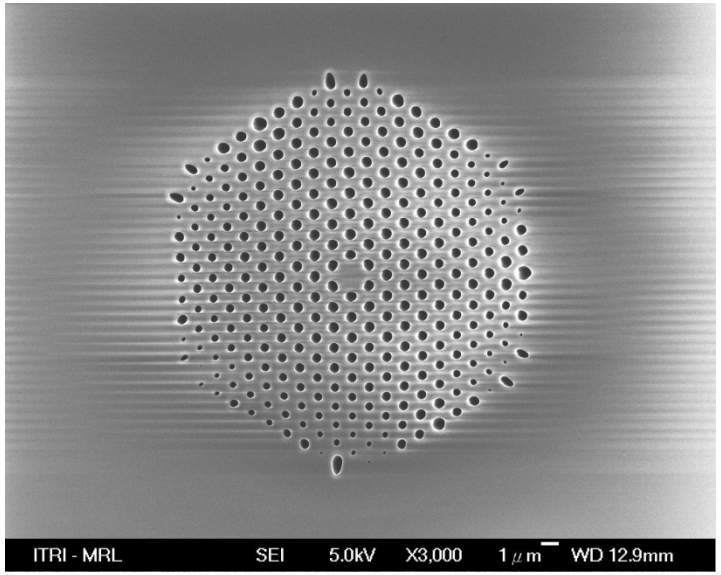


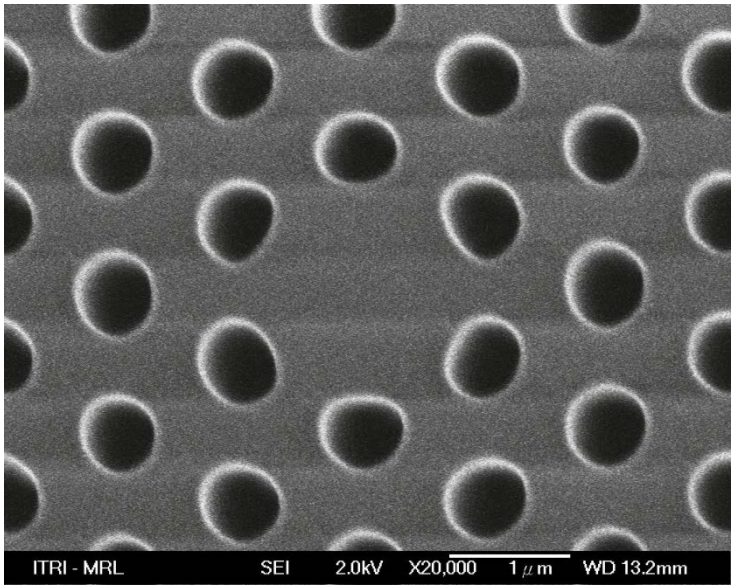




Blaze Photonics Crystal Fibre. Inc

SEM & Specification of the MFs





Item name	Core diameter (mm)	Cladding diameter (mm)	Zero dispersion Wavelength (nm)	Cut off Wavelength (nm)	Mode field Diameter (mm)
NL-1.7-790	1.7	129	790 & 1400	680	1.53

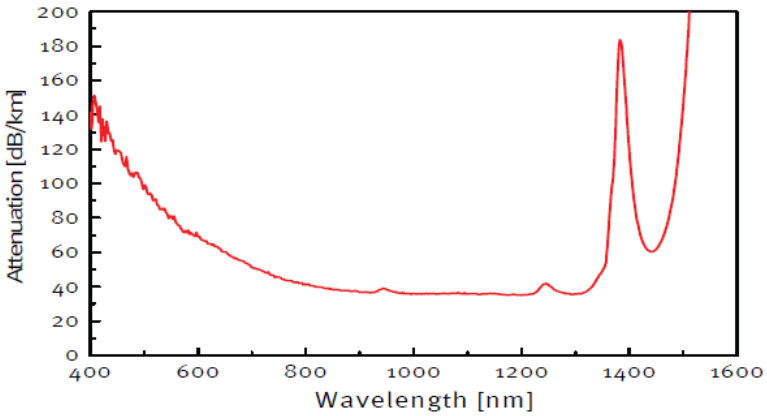
Crystal Fibre Inc. 1 m long

NL PM 750

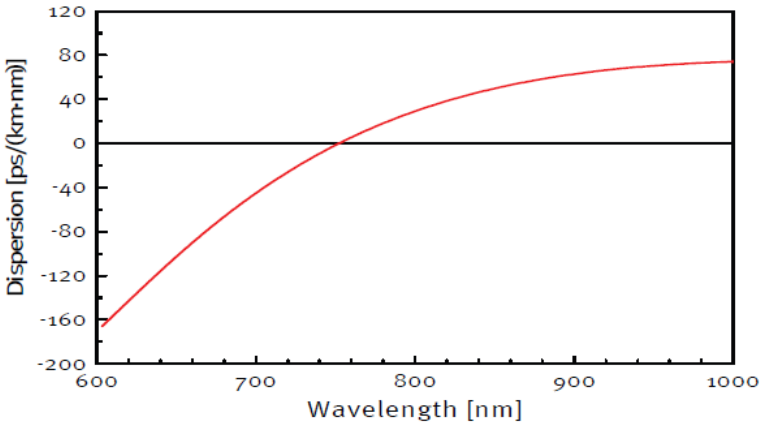
Physical properties	
Material	Pure Silica
Cladding diameter	120 ± 5 µm
Coating diameter	240 ± 10 µm
Coating material, single layer	Acrylate
Core diameter	1.8 ± 0.3 µm

Optical properties	
Short Zero dispersion wavelength	750 ± 15 nm
Long Zero dispersion wavelength	1260 ± 20 nm
Attenuation @ 780 nm	‹0.05 dB/m
Cut-off wavelength	‹650 nm
Mode field diameter @ 780 nm	1.6 ± 0.3 µm
Numerical aperture @ 780 nm	0.38 ± 0.05
Nonlinear coefficient @ 780 nm	~ 95 $(Wkm)^{-1}$
Birefringence @ 780 nm	›$3 \cdot 10^{-4}$

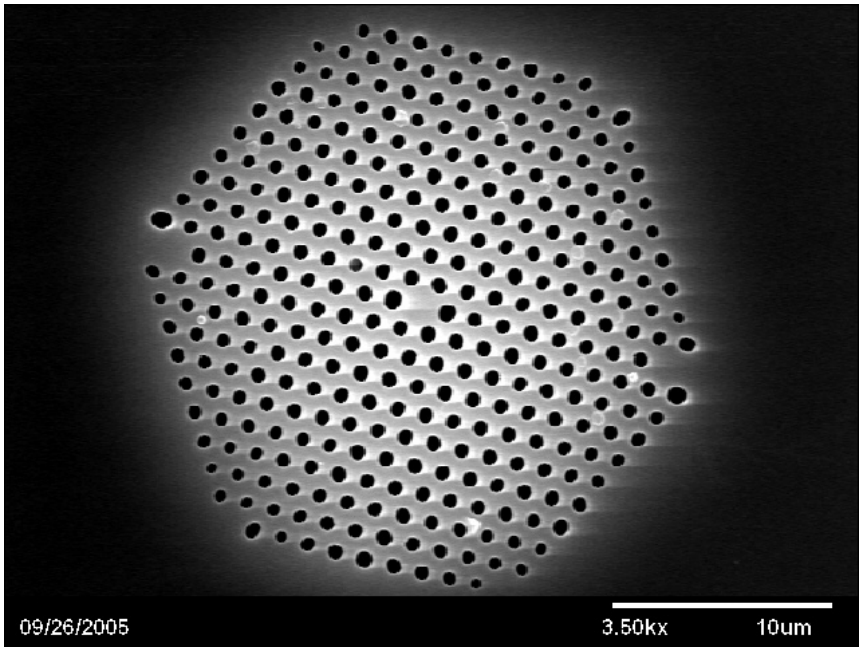
Typical spectral attenuation

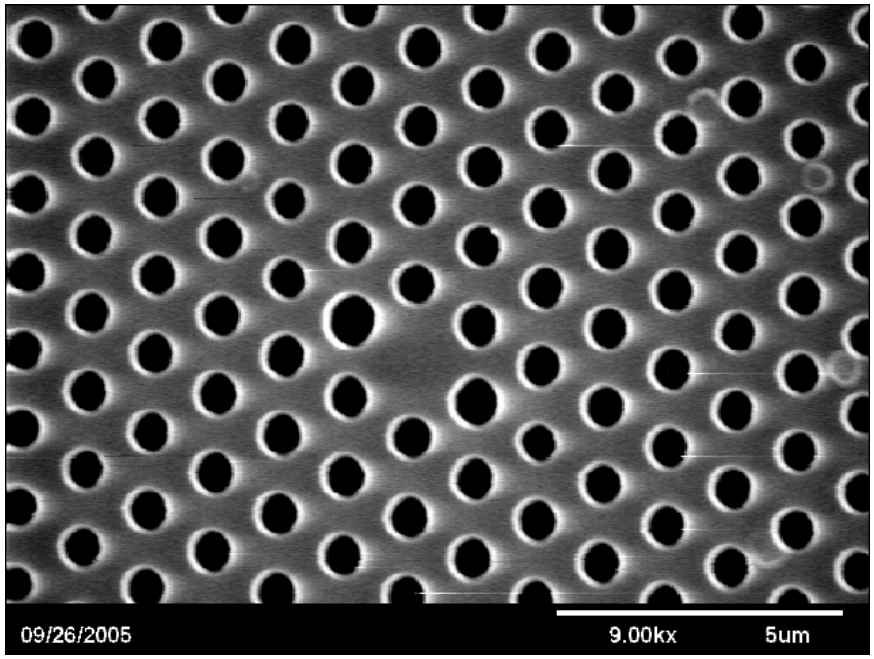


Typical measured dispersion



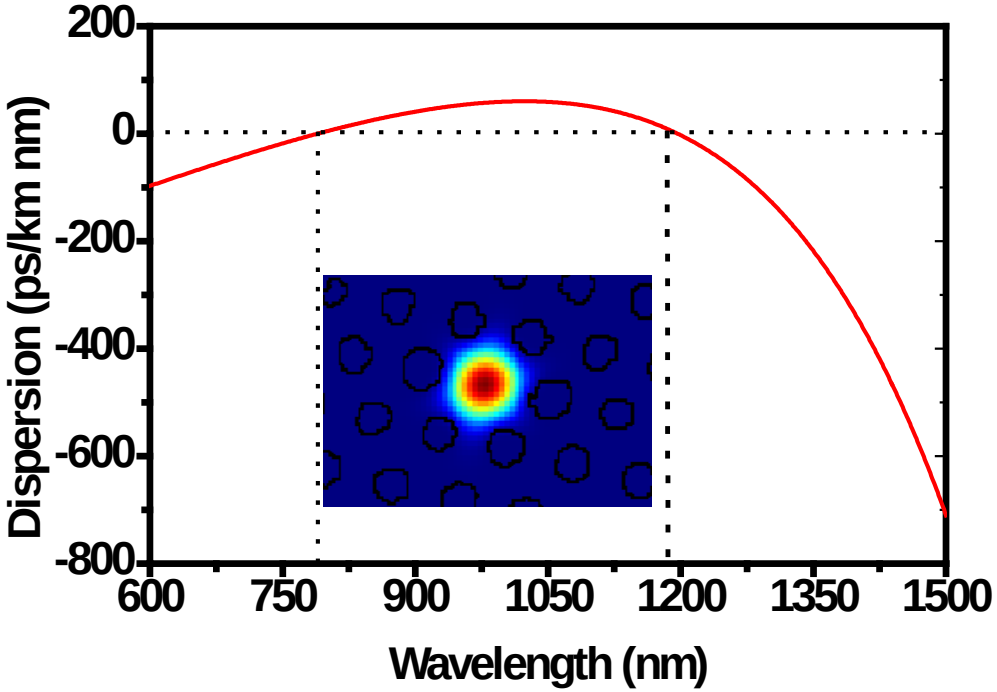
SEM & Specification of the MFs





Item name	Core diameter (mm)	Cladding diameter (mm)	Zero dispersion Wavelength (nm)	Cut off Wavelength (nm)	Mode field Diameter (μm)
NL-PM-760	1.7	117	760 & 1160	600	1.55

Dispersion Curves and the parameters



Mode Solutions

Lumerical solutions, Inc

$$\gamma = \frac{n_2 \omega}{c A_{eff}}$$

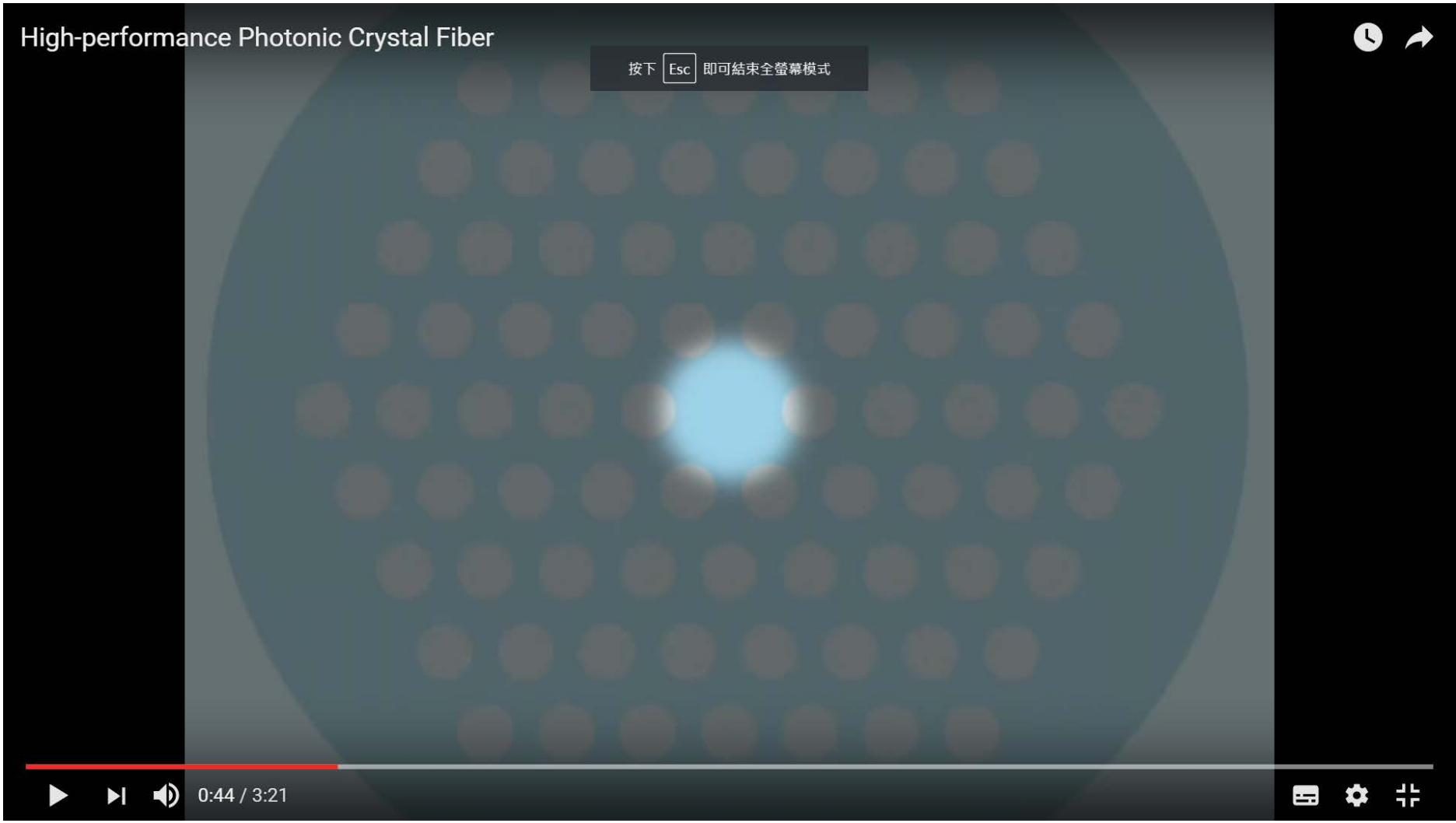
g=74 (1/km W) @ 1064 nm

β_2 (ps^2/km)	β_3 (ps^3/km)	β_4 (ps^4/km)	$\beta_5 * 10^{-6}$ (ps^5/km)	$\beta_6 * 10^{-8}$ (ps^6/km)
-57.79207	-0.08328	0.00153	-9.20867	5.66594

The pumping wavelength near the longer wavelength zero dispersion point.

Photonic crystal fiber

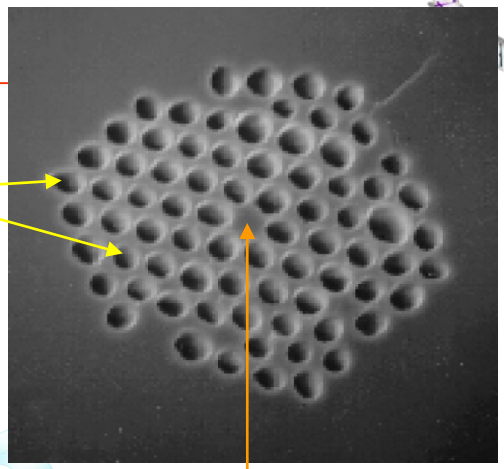
- https://www.youtube.com/watch?v=2yzI9NM8bIY

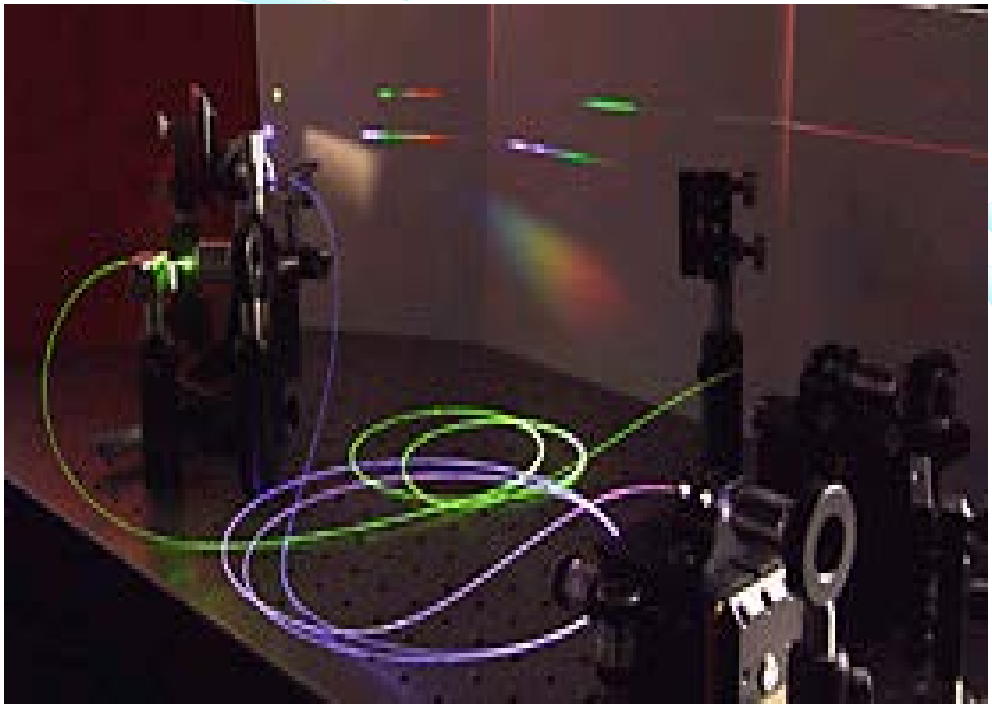


From you tube

Microstructure fiber

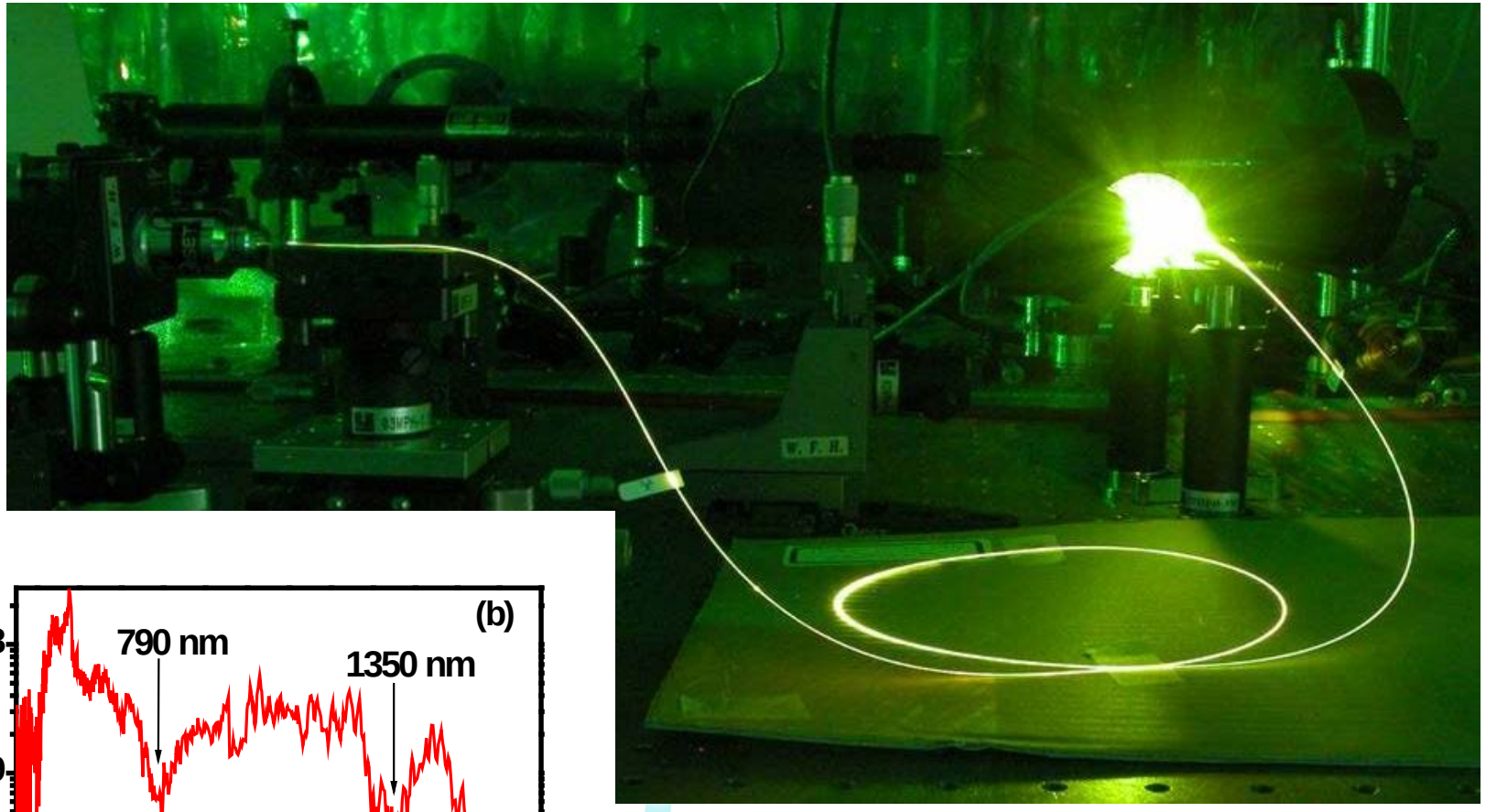
In microstr**ucture fiber**, air holes act as the **cladding** surrounding a glass core. Such fibers have different dispersion properties.

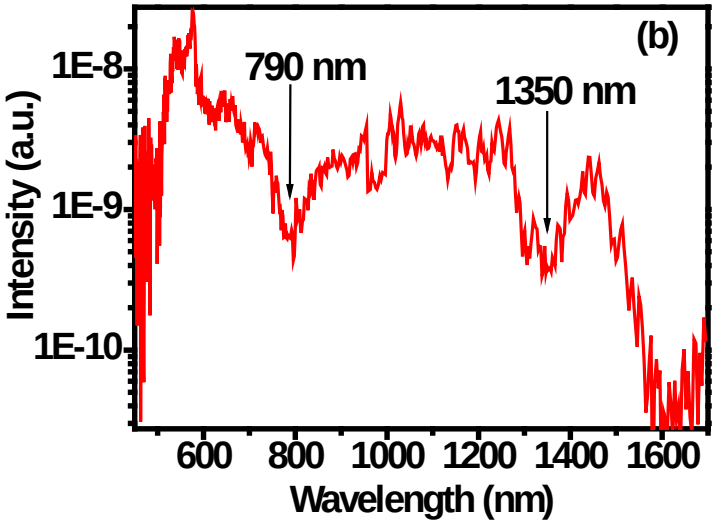




Such fiber has many applications, from medical imaging to optical clocks.

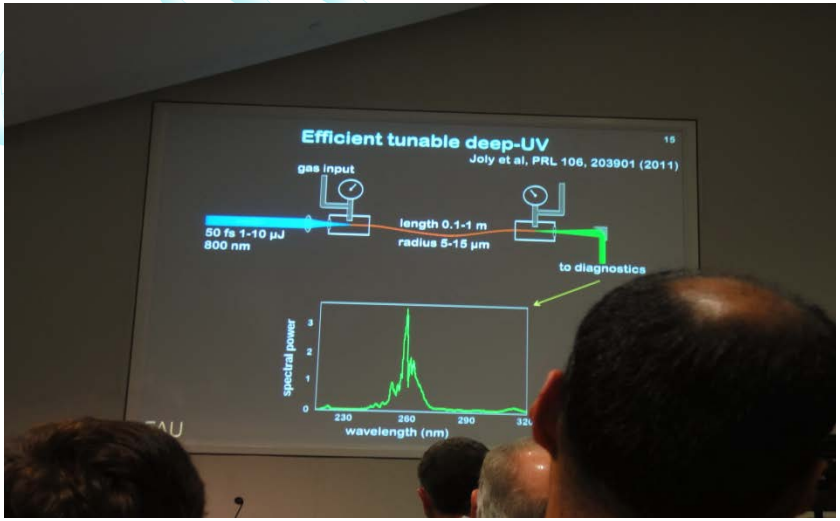
Photography and spectrum of SC from the





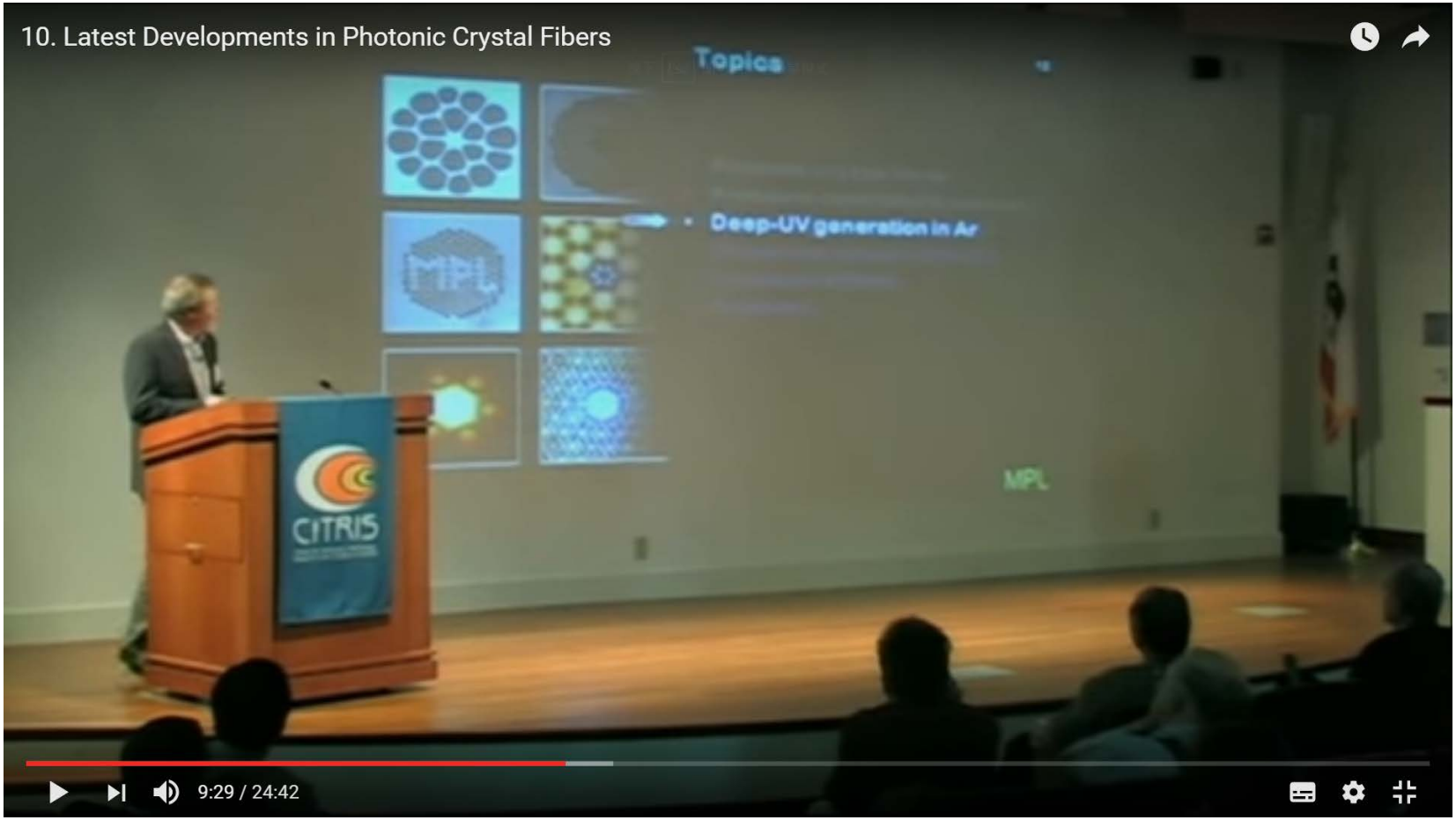
Two dips can be seen near the zero dispersion point.

Russell at CLEO-PR 2011 (Australia)



Photonic Crystal Fiber for SCG

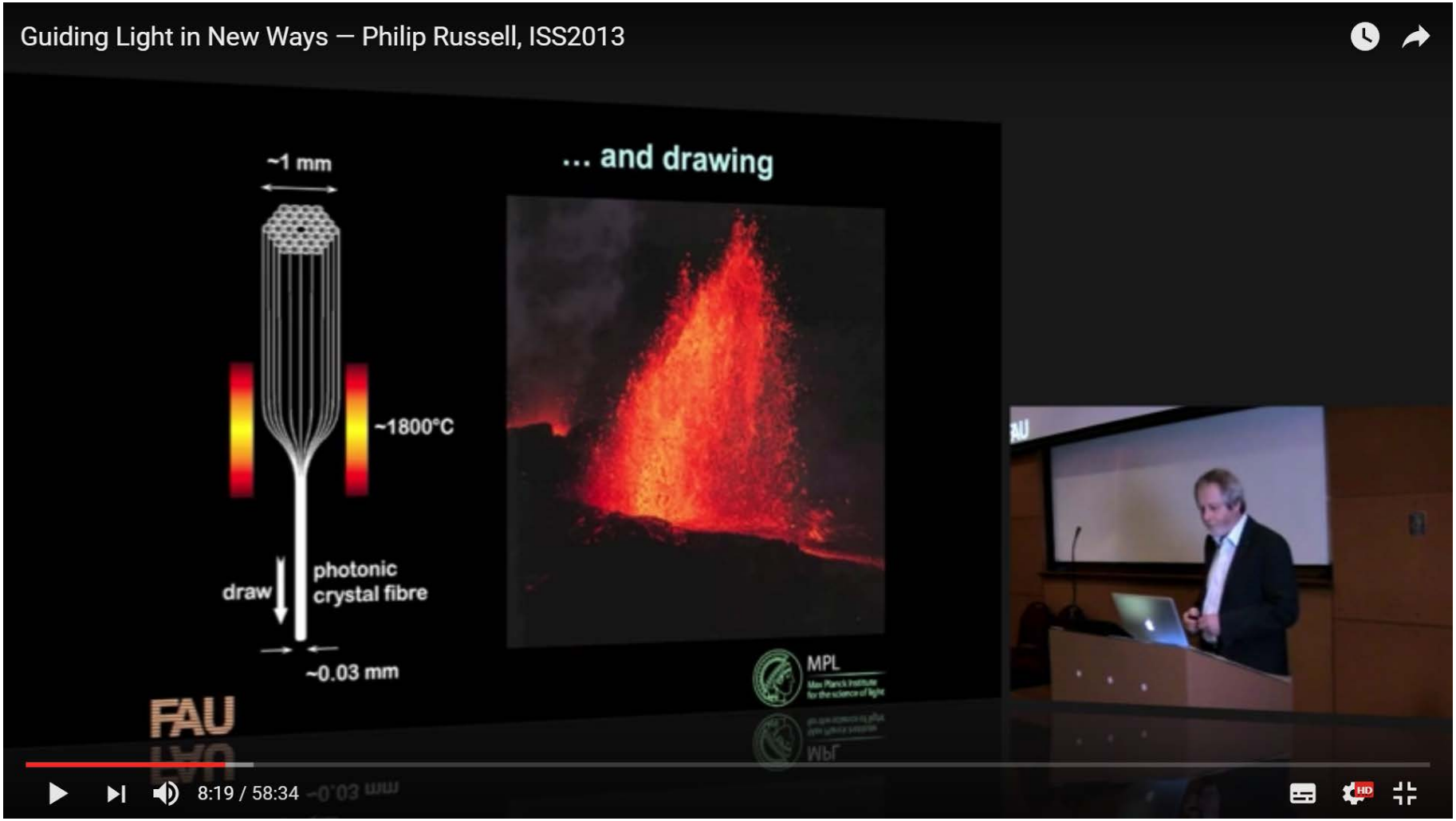
- https://www.youtube.com/watch?v=IgoWPW0aC80



From you tube

Talk by Russell

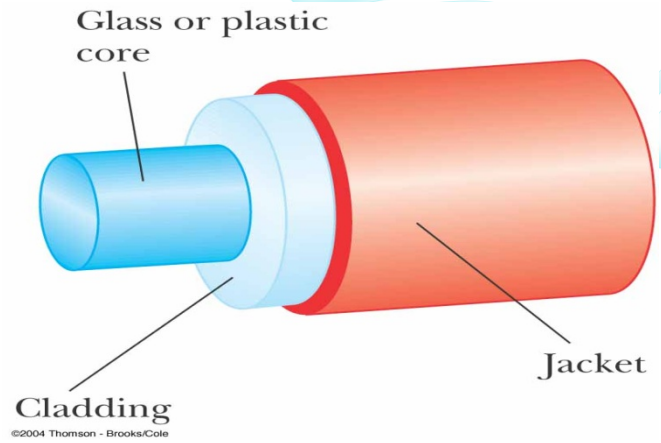
- https://www.youtube.com/watch?v=5je47GPW_Mc



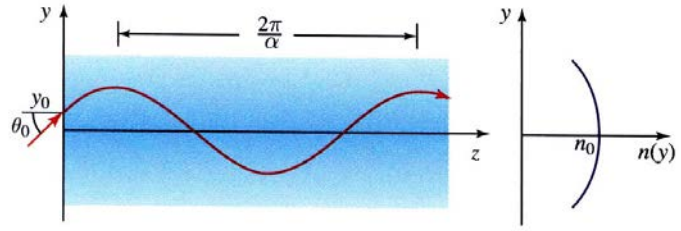
From you tube

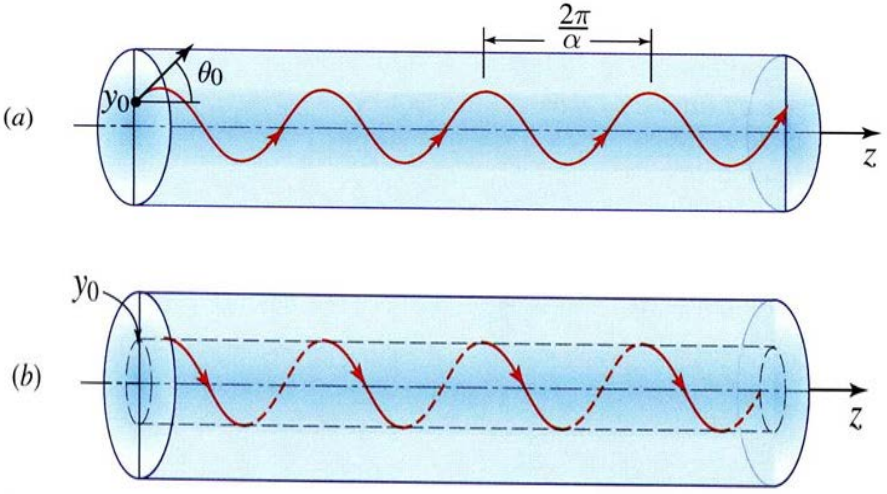
1.2 Fiber Characteristics

- **Step-index fibers (階梯 or 突變)**, an optical fiber consists of
  - a central glass core with **refractive index index n_1.**
  - surrounded by a **cladding layer** whose refractive index n_c is slightly lower.



- **Graded-index fibers**
  - in which the **refractive index** of the **core** decreases gradually from center to core boundary.





- **Schematic illustration** of the **cross section (橫截面)** and the **refractive-index** profile of a **step-index fiber**.

- Two parameters that characterize an optical fiber are

  - **Relative core–cladding index difference (纖芯−包層相對折射率差)**

$$\Delta = (n_1 - n_c)/n_1$$

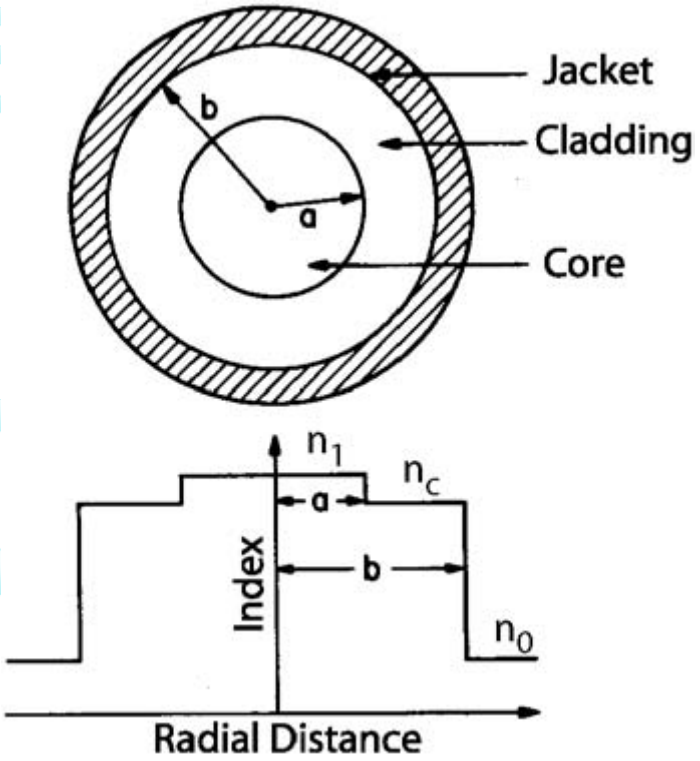
  - **V parameter**

$$V = k_0 a (n_1^2 - n_c^2)^{1/2}$$

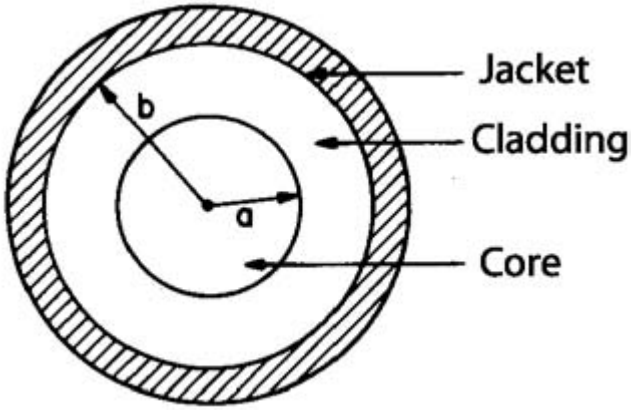
$k_0 = 2\pi/\lambda$

a：core radius.

λ：wavelength of light.



- **V** parameter: determines the **number of modes** supported by the fiber.
  - if **V < 2.405**：a **step-index fiber** supports a **single mode**.
- The **main difference** between the **single-mode** and **multimode fibers** is the **core size**.
  - **Multimode fibers**: the core radius ***a*** is typically **25 μm**
  - **Single-mode fibers** (with **Δ ≈ 0.003):** require ***a*** to be **<5 μm**.
  - A standard value of ***b* = 62.5 μm** is commonly used for both single-mode and multimode fibers.

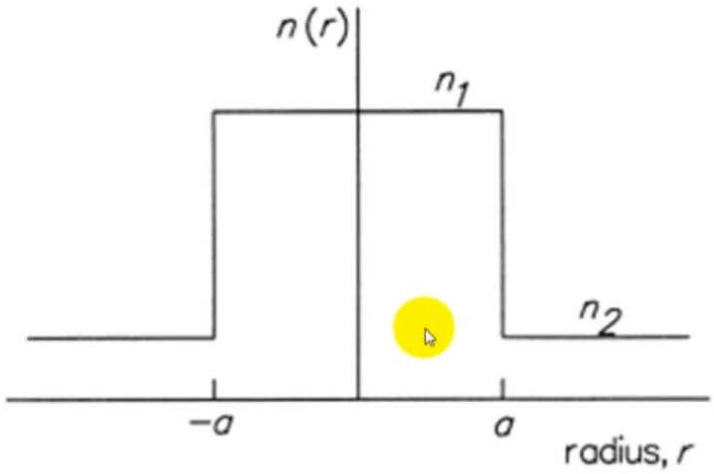


Multimode Fiber

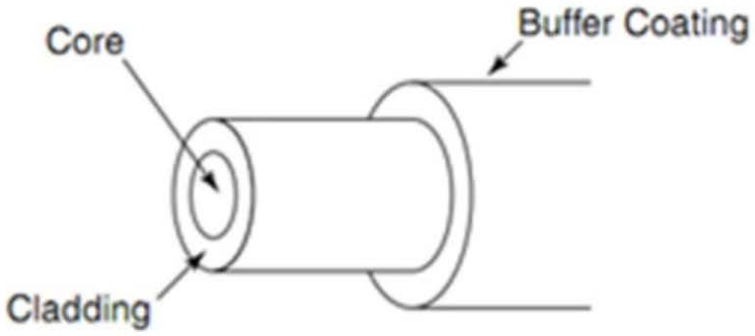
- https://www.youtube.com/watch?v=6xYOzY4zj0o

What is Multimode Optical Fiber?

Step-Index Fiber Structure



Refractive index profile of a step-index fiber.



Optical fiber construction

Fiber Optics For Sale Co.
FOSCO.
www.fo4sale.com

0:47 / 8:03

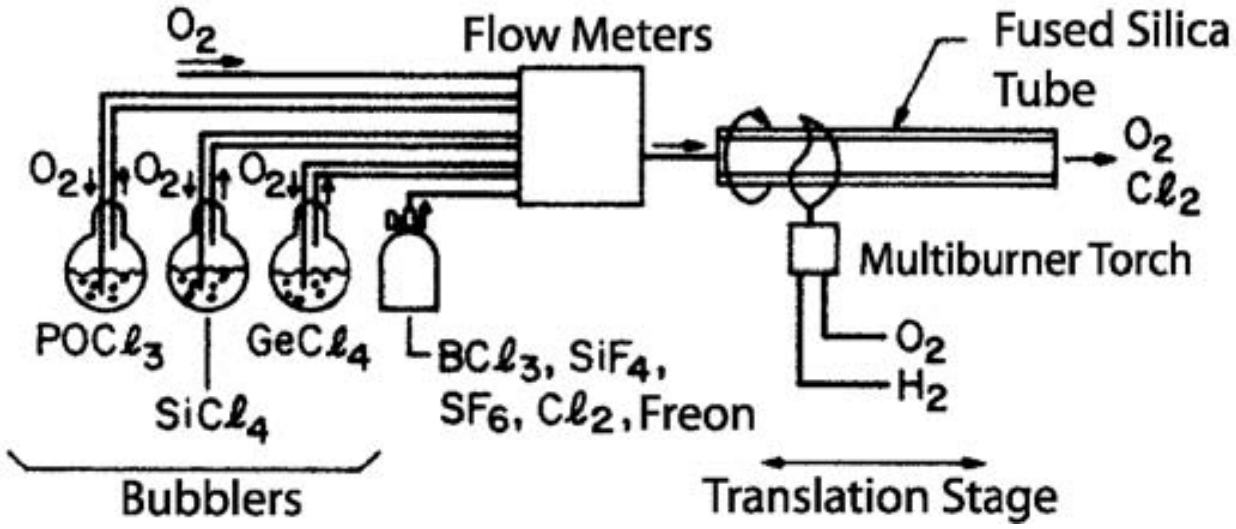
1.2.1 Material and Fabrication

- For **low-loss optical fibers**：
  - The material is **pure silica glass (石英玻璃 quartz glass)** synthesized by **fusing SiO_2 molecules**.
  - The **refractive-index difference** between the **core** and the **cladding** is realized by the **selective use of dopants** during the fabrication process.
    - **Core**: Dopants such as **GeO_2**（二氧化鍺）and **P_2O_5** (五氧化二磷) **increase** the **refractive index** of pure silica
    - **Cladding**: **boron** (B, 硼) and **fluorine** (F, 氟) are used because they decrease the refractive index of silica.
- Fiber **amplifiers** and **lasers**
  - the **core** of silica fibers is co-doped with **rare-earth ions** (稀土離子) using dopants such as **$ErCl_3$** (Erbium chloride, 氯化鉺) and **Nd_2O_3** (Neodymium Oxide, 氧化釹).

- The **fabrication** of **optical fibers** involves two stages.
  - **First stage**, a **vapor-deposition method (氣相沉積)** is used to make a **cylindrical preform (圓柱預置棒)** with the **desired refractive index profile** and the **relative core-cladding dimensions**.
  - **Second stage**, the preform is drawn into a fiber using a **precision-feed mechanism** that feeds it into a **furnace (高溫爐)** at a proper speed.
- The **three commonly used methods** are
  - **modified chemical vapor deposition (MCVD)** (改進化學氣相沉積法)
  - **outside vapor deposition(OVD)** (外氣相沉積法)
  - **vapor-phase axial deposition(VAD)** (氣相軸向沉積法)

Cladding Layer

- In **MCVD process**, successive layers of **SiO_2** are deposited on the inside of a **fused silica tube (熔融石英管)** by mixing the vapors of **$SiCl_4$** (四氯化矽 or 四氯硅烷) and **O_2** at a temperature of **≈1800 ℃**
- To ensure uniformity, the **multiburner torch (多嘴火焰)** is moved back and forth across the tube length.
- The **refractive index** of the **cladding layers** is controlled by **adding fluorine** (氟) to the tube.

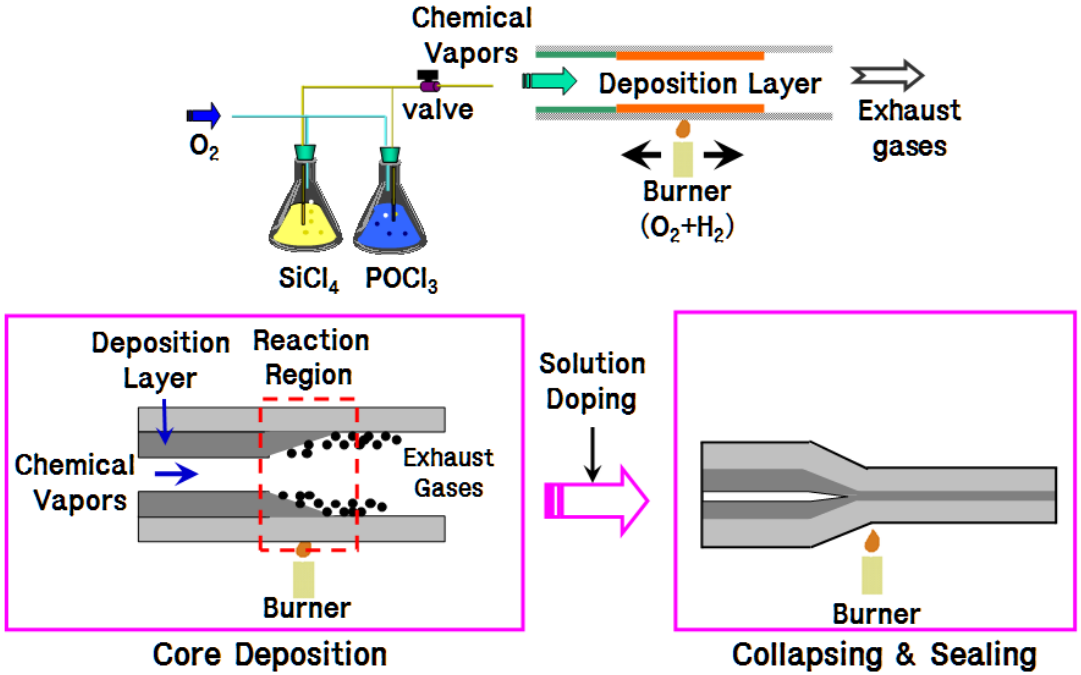


Core layer

- When a sufficient **cladding thickness** has been deposited with multiple passes of the torch, the vapors of **$GeCl_4$** (Germanium Tetrachloride, 四氯化鍺) or **$POCl_3$** (三氯氧磷) are added to the **vapor mixture** to form the **core**.

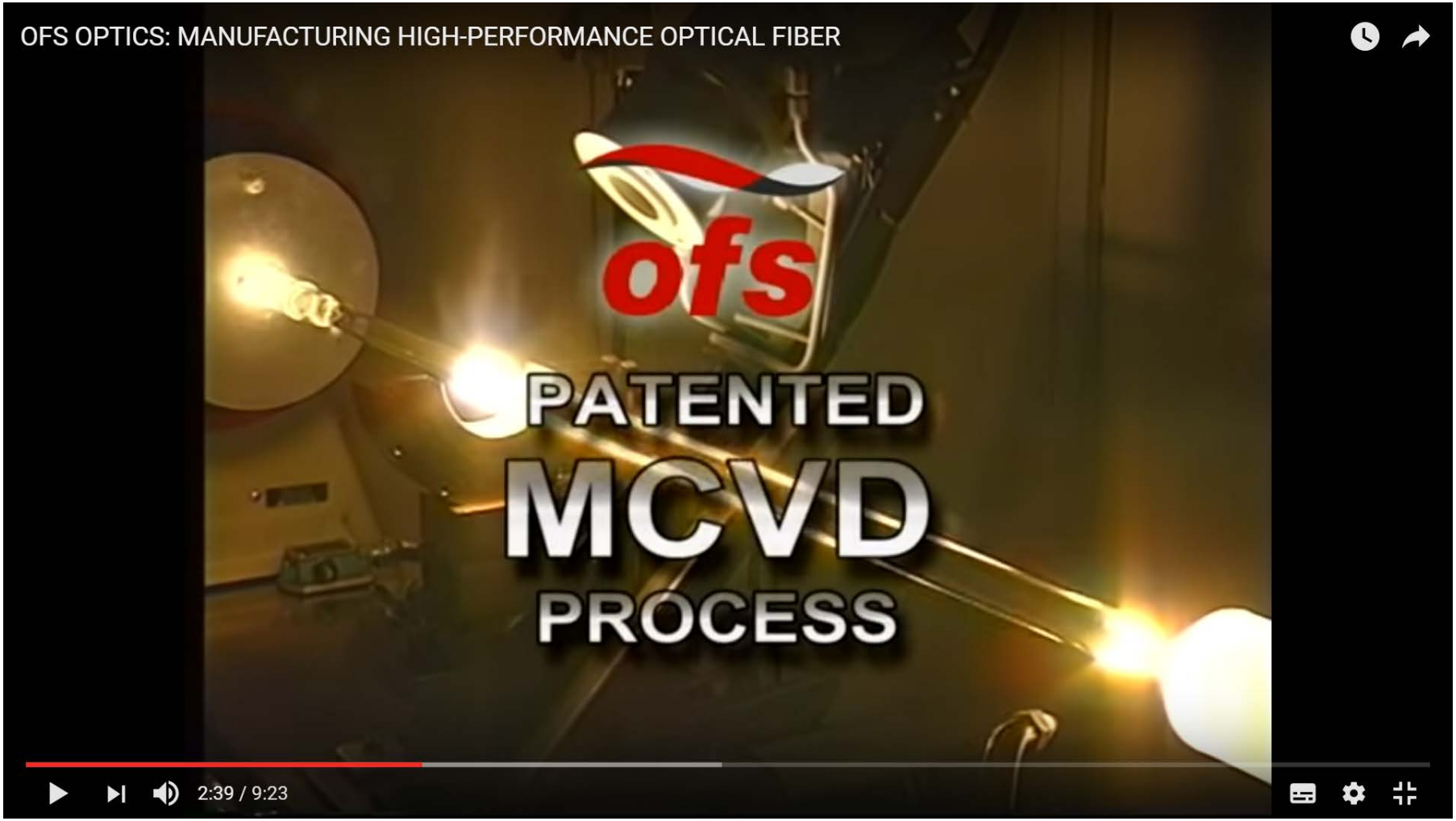
Preform

- When all layers have been deposited, the **torch temperature** is raised to **collapse the tube** into a **solid rod** known as **the preform**.



Fiber from ofs

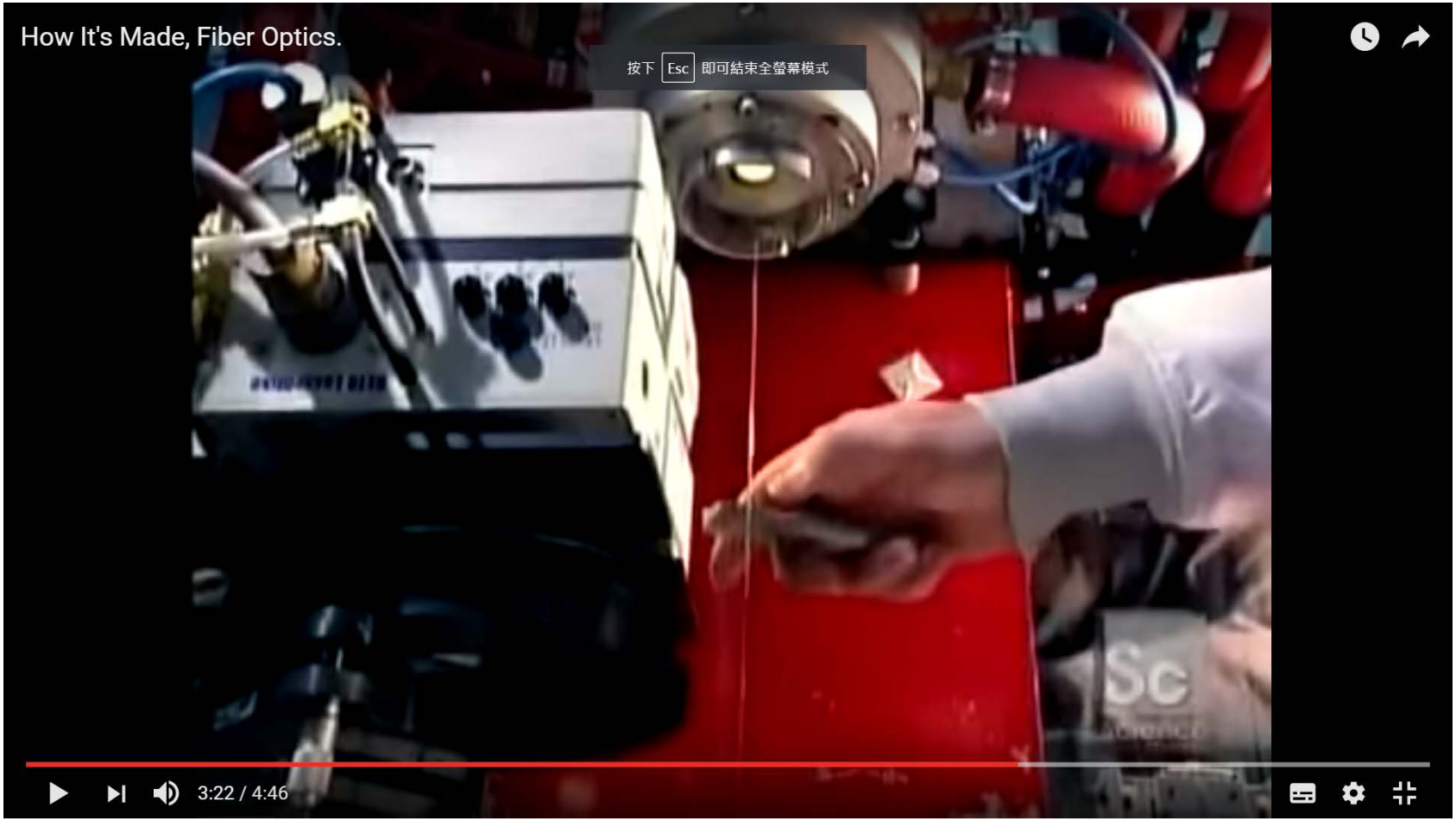
- https://www.youtube.com/watch?v=liKOYbgIC_c



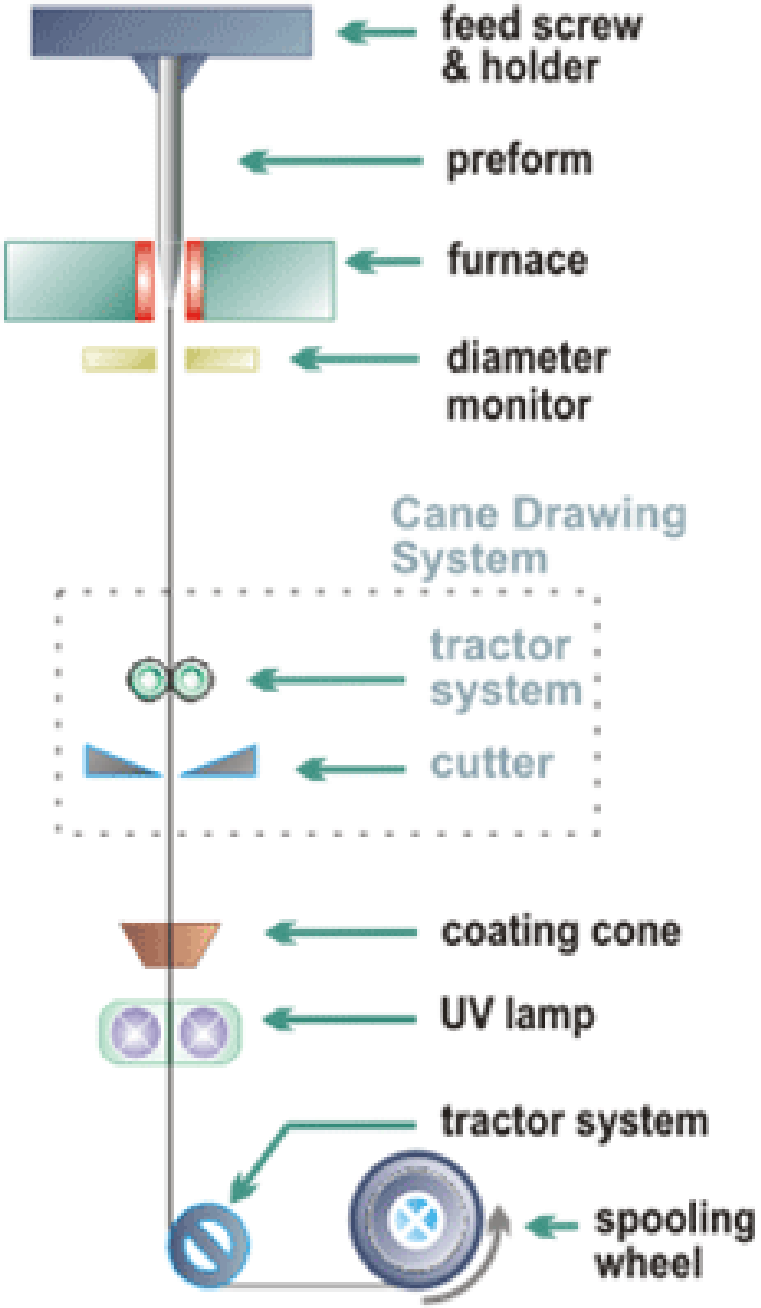
From YouTube

Manufacture of Optical Fiber

- https://www.youtube.com/watch?v=uSnjo5tOGQA



From YouTube


feed screw & holder
preform
furnace
diameter monitor
Cane Drawing System
tractor system
cutter
coating cone
UV lamp
tractor system
spooling wheel

Fiber manufacture from Thorlabs

- https://www.youtube.com/watch?v=crZjy9nGj-k

From YouTube