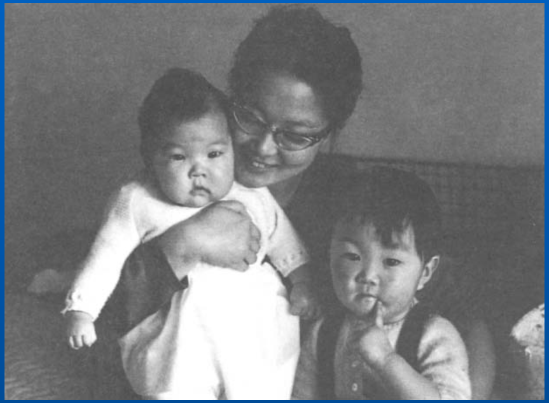
Transmission of Light in Fiber for Optical Communication

Mrs. Gwen MW Kao
on behalf of
Professor Charles K Kao
Nobel Laureate in Physics 2009

8 December 2009
Aula Magna
Stockholm University


Sand from centuries past;
Send future voices fast.

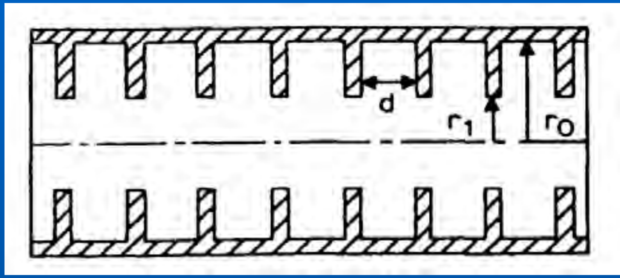
Early years

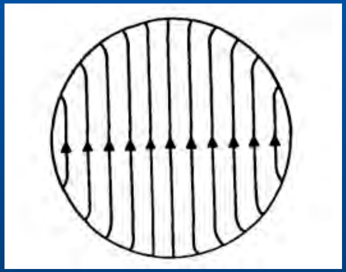


STL building in 1960's

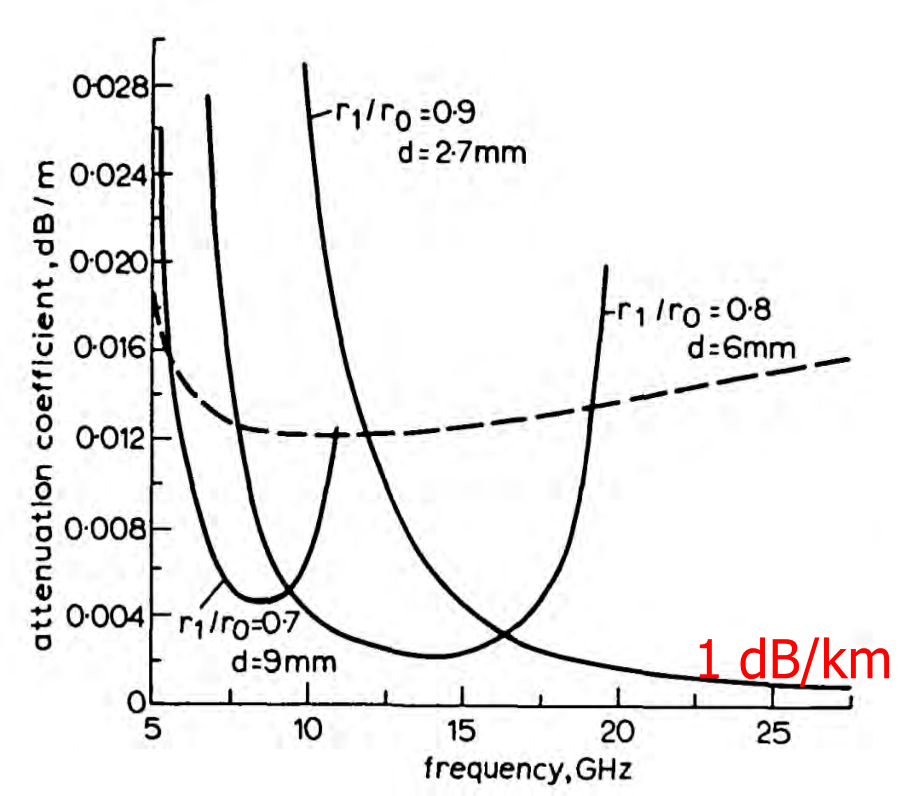
Now called Kao-Hockham Building in Harlow, Essex, UK

Low-loss corrugated circular waveguide





HE11 Mode



P.J.B. Clarricoat & P.K. Saha, "Attenuation in Corrugated Circular Waveguide," *Elect. Lett.*, Vol.**12**, pp.370-2, 1970.

Young Kao at workplace

Laser invented

1917: Einstein postulated stimulated emission

1953: Townes, Gordon, and Zeiger demonstrated Maser

1958: Townes and Schawlow invented Laser

Charles H. Townes

Arthur L. Schawlow

http://www.bell-labs.com/history/laser/invention/

A race between mm waveguide and optical communication

Millimeter Waveguide	Optical Communication
Mature technology	Unknown technology
Ready for deployment	Promising but nothing is sure
Expensive	Potentially low cost
Phone monopoly can afford the cost	Who are the investors?
Moderate capacity improvement	100,000X better

Odds favored the matured millimeter wave technology

Two key questions raised by Prof Kao

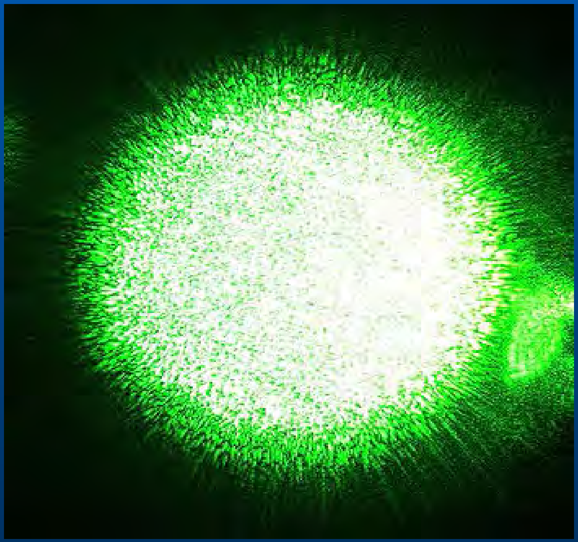
1. *Is Ruby laser a suitable source for optical communication?*
2. *What material has sufficiently high transparency at such wavelengths?*

Difficult problems but fortune favors the brave!

Free space optical communications

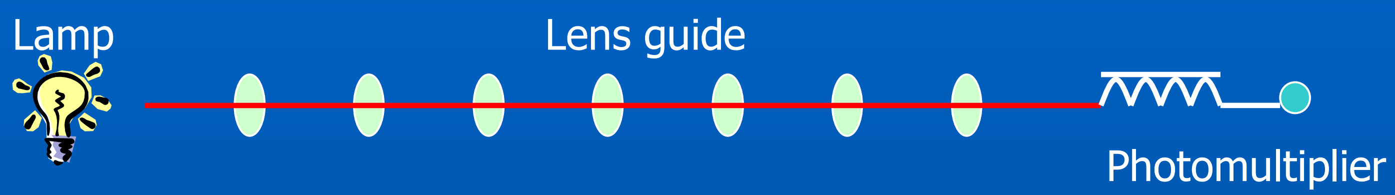
Laser flickers in free space!

A waveguide needed.



http://en.wikipedia.org/wiki/Speckle_pattern

Con-focal lens system



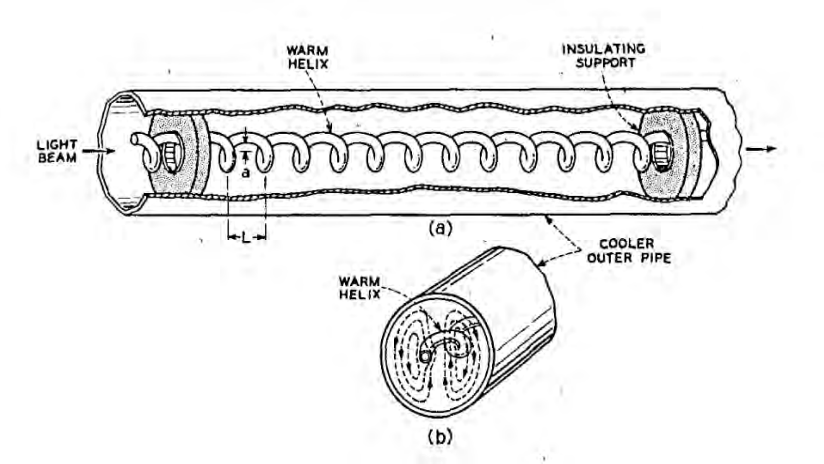
Alignment of the lenses is critical!

Thermal gradient can cause beam to shift by many cm

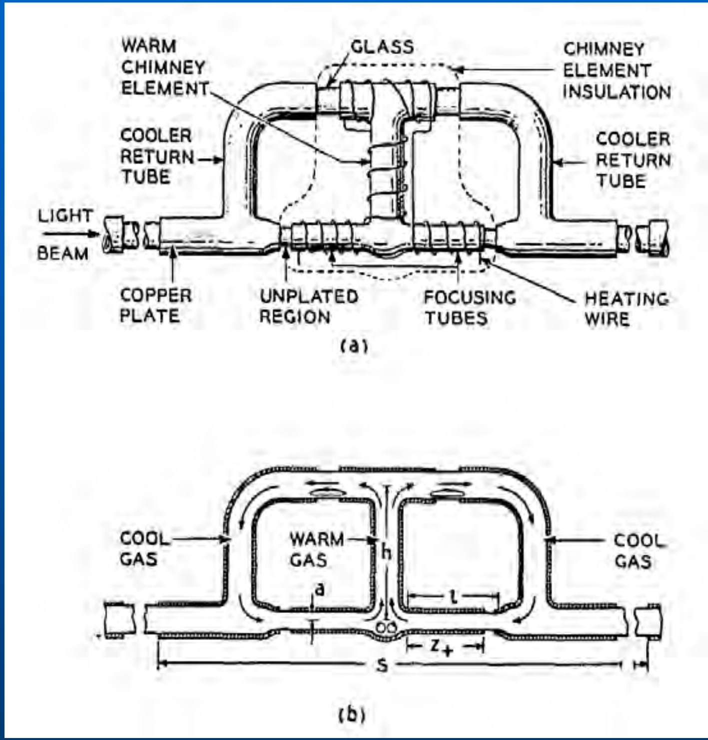
O.E. DeLange, "Losses suffered by coherent light redirected and refocused many times in an enclosed medium," *Bell Sys. Tech. J.,* Vol.**44**, p. 283, 1965.

D. Gloge, "Experiments with an underground lens waveguide," *Bell Sys. Tech. J.*, Vol.**46**, 721, 1967.

Gas lens system

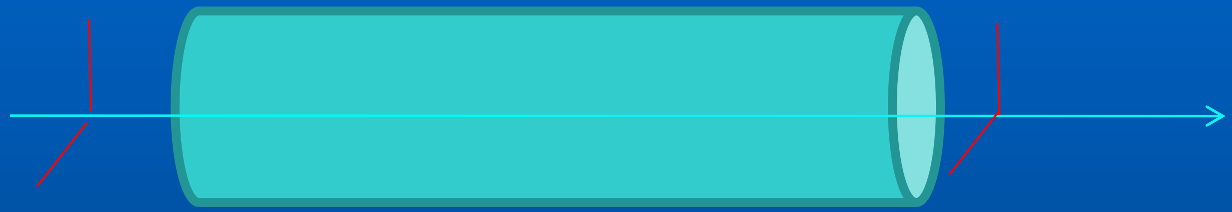


Difficult to insulate!



D.W. Berreman, "Convective Gas Light Guides or Lens Trains for Optical Beam Transmission ," *J. Opt. Soc. Of Am.*, Vol.**55**, pp.239-247, 1965.

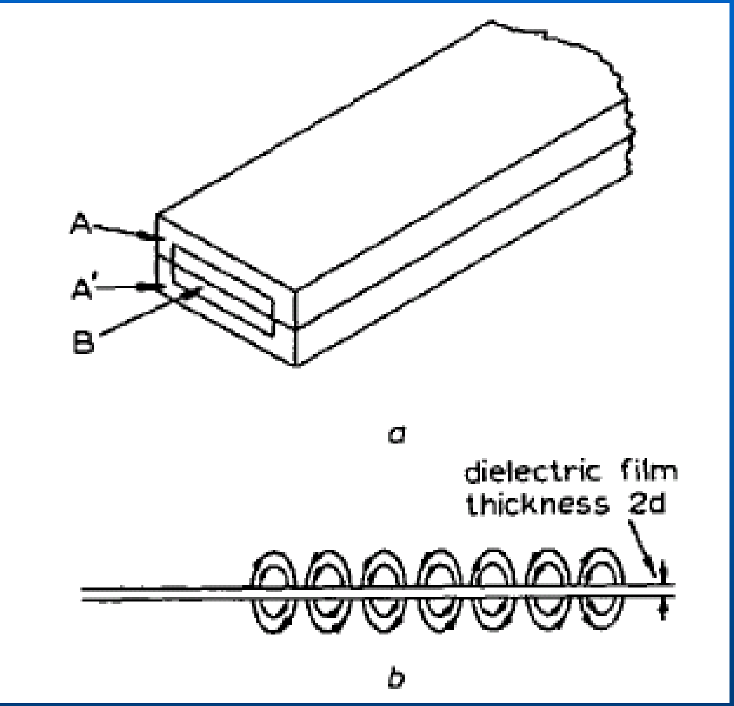
Hollow metallic and dielectric waveguides



Large bending loss and expensive

E.A.J. Marcatili and R.A. Schmeltzer, "Hollow metallic and dielectric Waveguides for long distance optical transmission and lasers," Bell Sys. Tech. J. Vol.43, p.1783, 1964.

Thin film waveguide



a. A thin film waveguide surrounded by supporting material

b. Field structure of guided wave

Confinement not strong enough and light escapes in bends

A.E. Karbowiak, "New type of waveguide for light and infrared waves," *Elect. Lett.*, Vol. 1, pp.47-8, April 1965.

Prof Kao's team pursued dielectric silica waveguide approach

- Problems to be solved
  - Loss reduction in dielectric waveguide materials
  - Physical and waveguide limitations for glass fiber
  - Better light source needs
    - a semiconductor laser in the near infrared
    - emission characteristics matching the diameter of a single mode fiber
    - durability and can work at room temperatures
  - Measurement of the optical loss of highly transparent materials

Optical loss of transparent materials

- Intrinsic loss in the materials itself (infrared absorption)
- Extrinsic loss due to impurity ions
- Rayleigh scattering loss due to structure non-uniformity

Is silica glass a suitable material ?
But all experts said its loss is too high!

What needs to be done

- *Impurities, particularly transition elements such as iron, copper, manganese, have to be reduced to parts per million or even parts per billion.*
- *High temperature glasses are frozen rapidly and are more homogeneous, leading to a lower scattering loss.*

The 1966 paper

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.

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

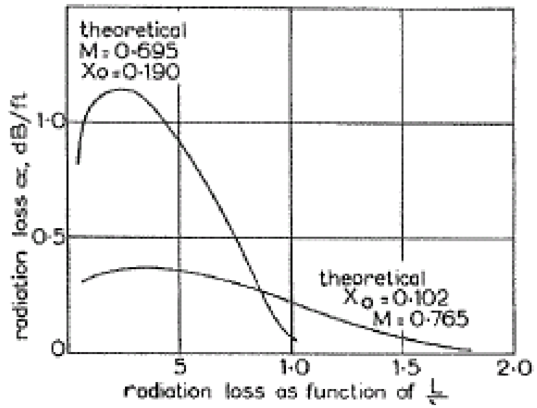
The birthday of optical fiber communication

Waveguide design

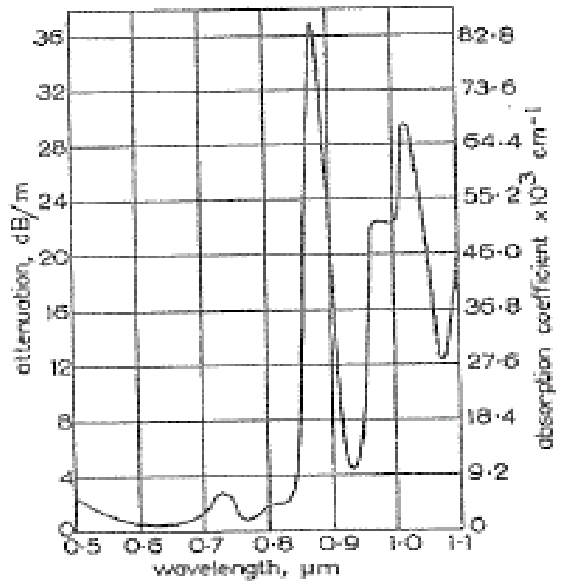
- The following form of optical waveguide has a larger information capacity and possible advantages in basic material cost.
- A fiber of glassy material in a cladded structure
- Core diameter ~ λ_0
- Overall diameter ~ 100 λ_0
- Refractive index of the core ~ 1% higher than the cladding.
- Single HE_{11}, E_0 or H_0 mode operation
- Information capacity in excess of 1 Gc/s. …

Detailed analysis of fiber losses

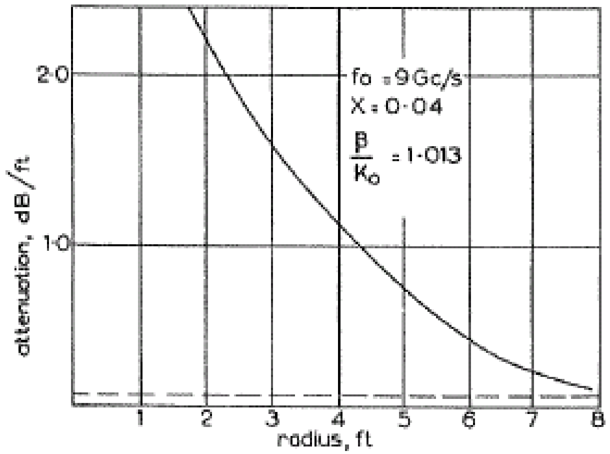
Intrinsic loss can be as low as 1 dB/km!



Radiation loss



Attenuation of PMMA



Bending loss

Main points of the 1966 paper

- Loss can be reduced if the mode is properly chosen;
- Proposal for a fiber surrounded by a cladding of lower index - became the standard technology;
- Negligible energy loss due to fiber bends larger than 1 mm;
- Estimation of fiber losses for non-uniform cross-section;
- Analysis of the properties of a single mode fiber;
- Bandwidth limited by dispersion.

Conclusions of the 1966 paper

- The realization of a successful fiber waveguide depends, at present, on the availability of suitable low-loss dielectric material. The crucial material problem appears to be one which is difficult but not impossible.
- Certainly, the required loss figure of around 20 dB/km is much higher than the lower limit of loss figure imposed by fundamental mechanisms.

In hindsight

In hindsight, the revolutionary conclusion was too conservative.

To date, loss is 1/100 as predicted, bandwidth is 10,000 times predicted!

Prof Kao travelled to convince the world

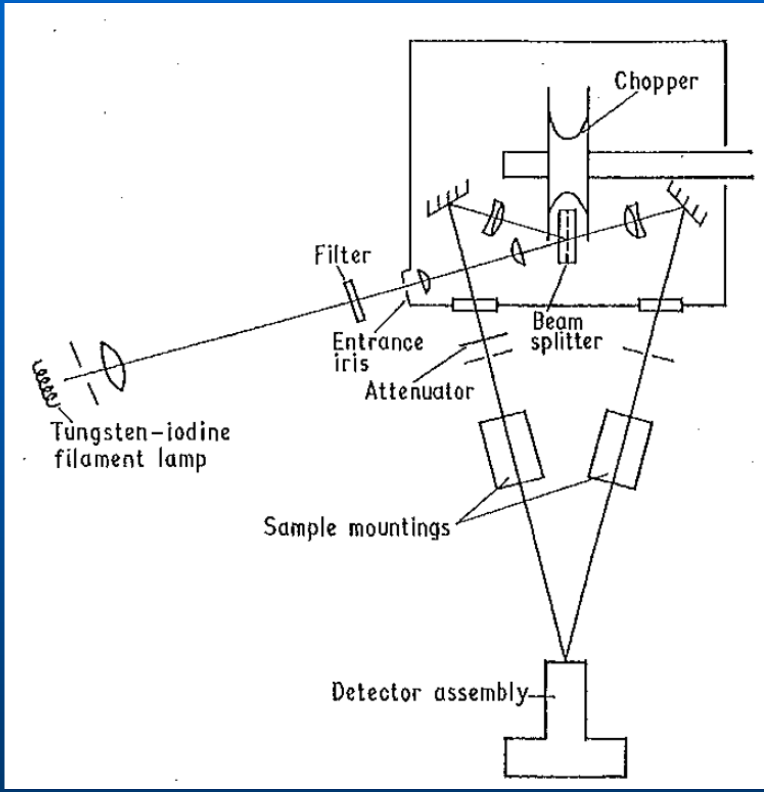
At an early OFC meeting

Science Museum
South Kensington, London

Measurement problems

- Two formidable challenges
  - A sample size only ~ 20 cm – difficult to measure low-loss
  - End surface reflection loss could be an order of magnitude higher than the actual loss

Measurement of fiber loss



Double Beam Spectrophotometer

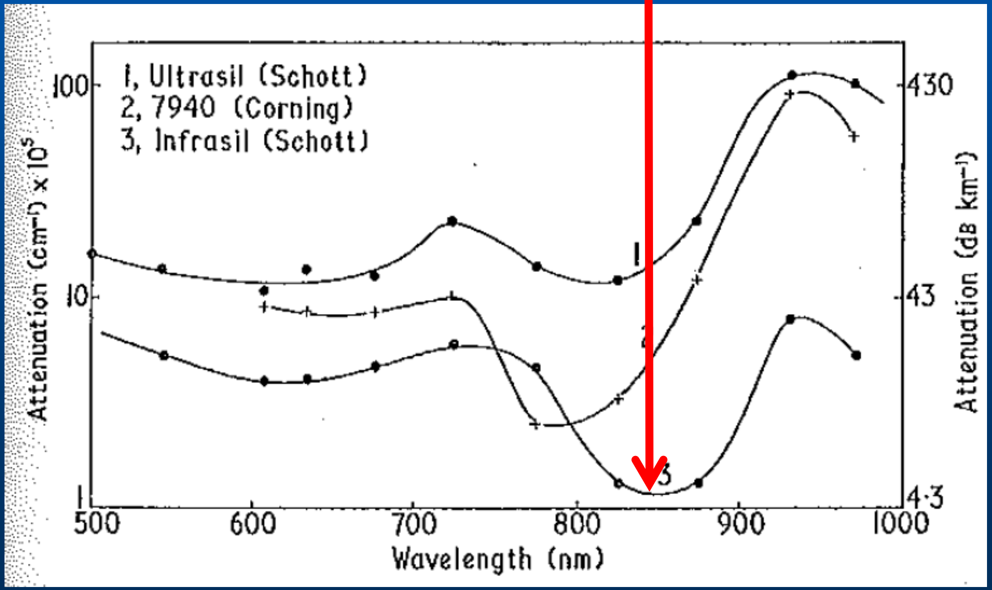
- Loss too low to measure
- Built a double beam spectrophotometer to improve sensitivity by 10X!
- The surface effect was characterized by a homemade *ellipsometer*.

M.W. Jones and K.C. Kao, "Spectrophotometric studies of ultra low loss optical glasses II" J. Sci. Instrum. (J. Phys. E), Vol.2, pp. 331-5, 1969.

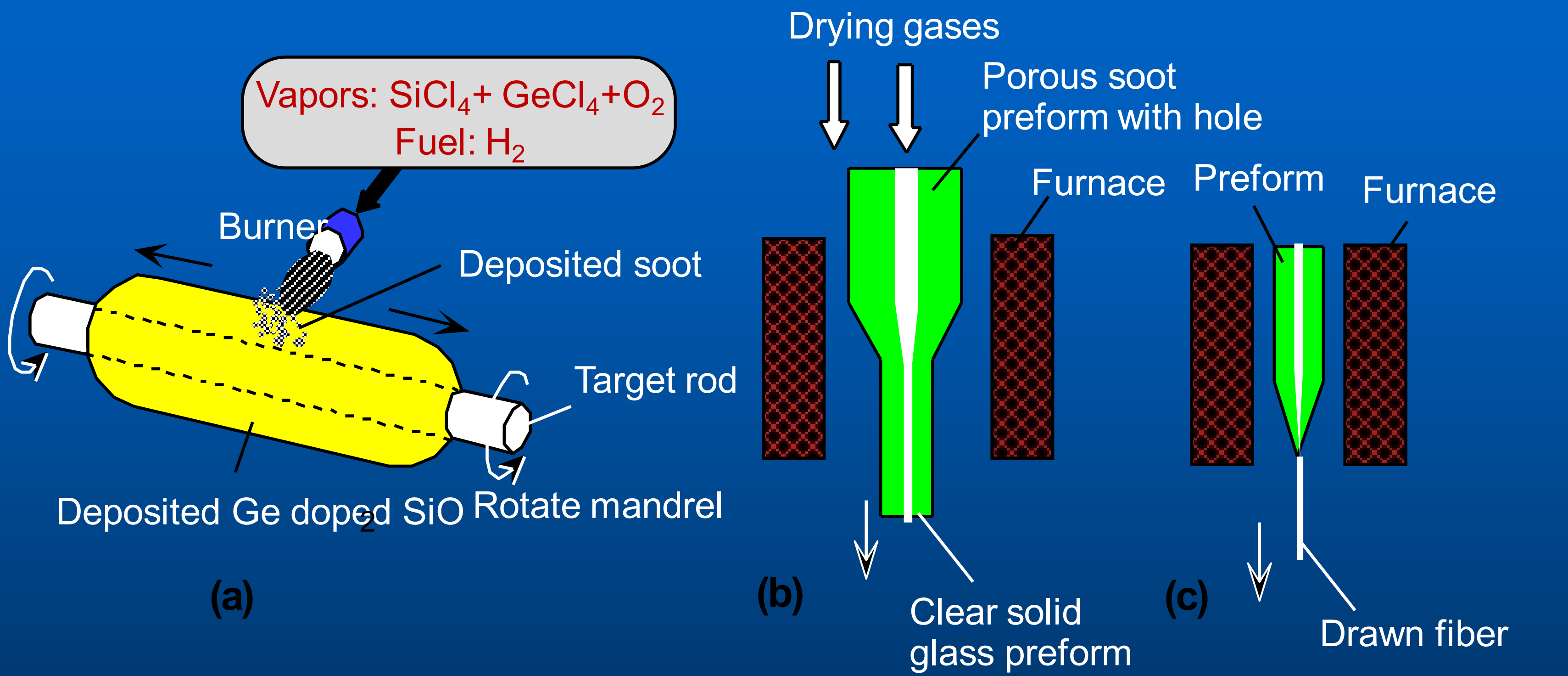
Demonstration of silica glass as waveguide material

- An Infrasil sample from Schott Glass showed an attenuation as low as 5 dB/km at a window around 850 nm!
- 850 nm - GaAs laser emission region.

M.W. Jones and K.C. Kao, "Spectrophotometric studies of ultra low loss optical glasses II" J. Sci. Instrum. (J. Phys. E), Vol.2, pp. 331-5, 1969.



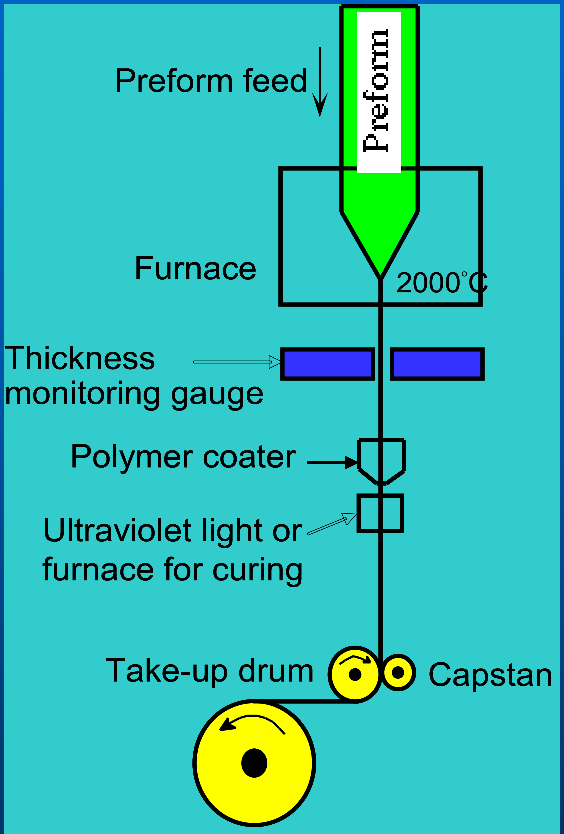
The race to develop the first low-loss optical fiber



Outside Vapor Deposition Method used by Corning in 1970

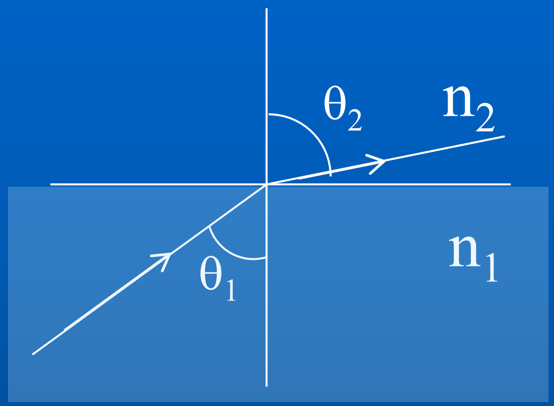
Fiber drawing

- Many optical fiber production methods invented
  - OVD
  - VAD
  - MCVD
  - PCVD



Schematic illustration of a fiber drawing tower.

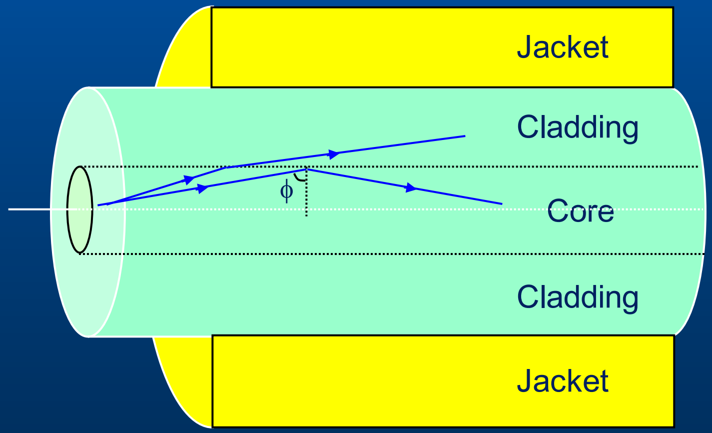
Light guiding inside fiber



Snell's Law : $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Note: if we increase θ_1 to θ_c such that $\theta_2 = 90^o$

$$\rightarrow \quad \sin\theta_c = \frac{n_2}{n_1}, \quad n_2 < n_1$$



If $\theta_1 > \theta_c$

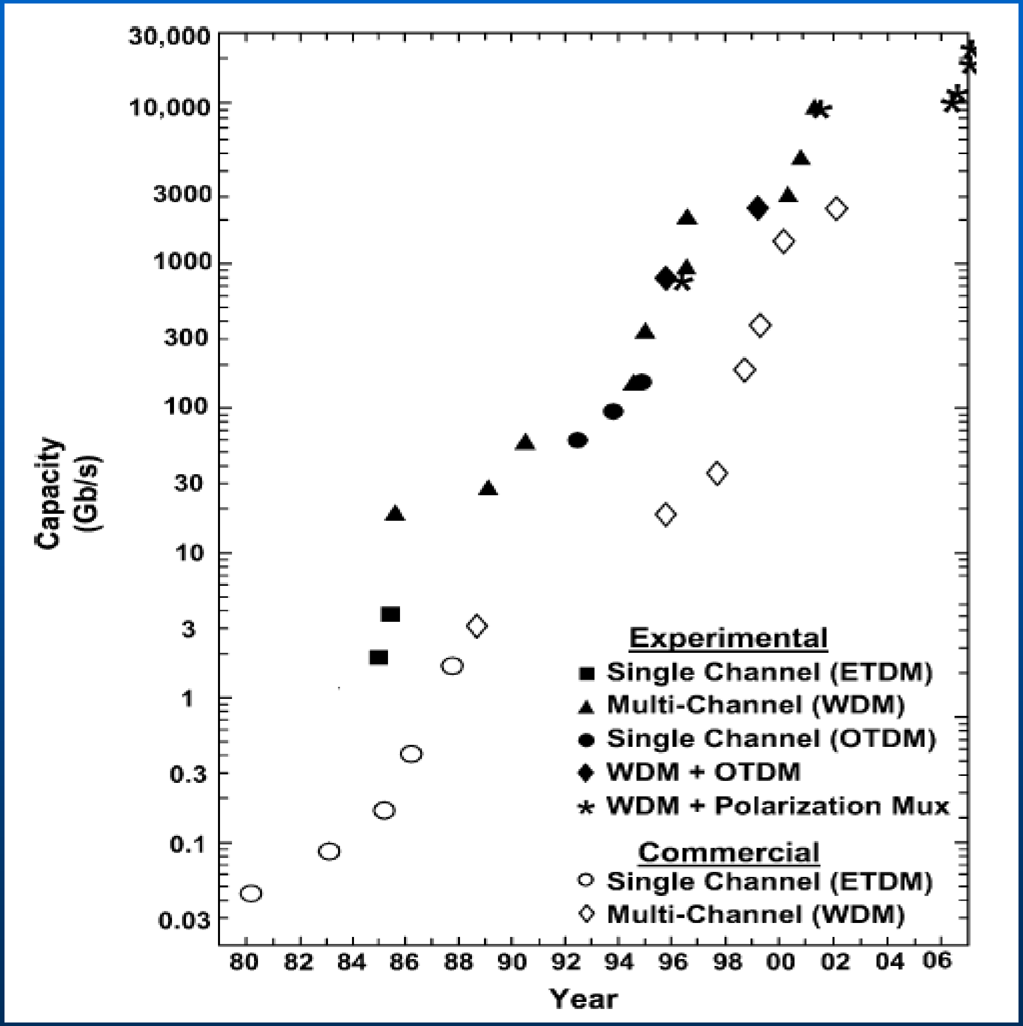
→ **Total Internal Reflection**

High-capacity experimental demonstration

15.5 Terabits/sec capacity

- 155 wavelengths
- 100 Gbps each
- over 7000 km

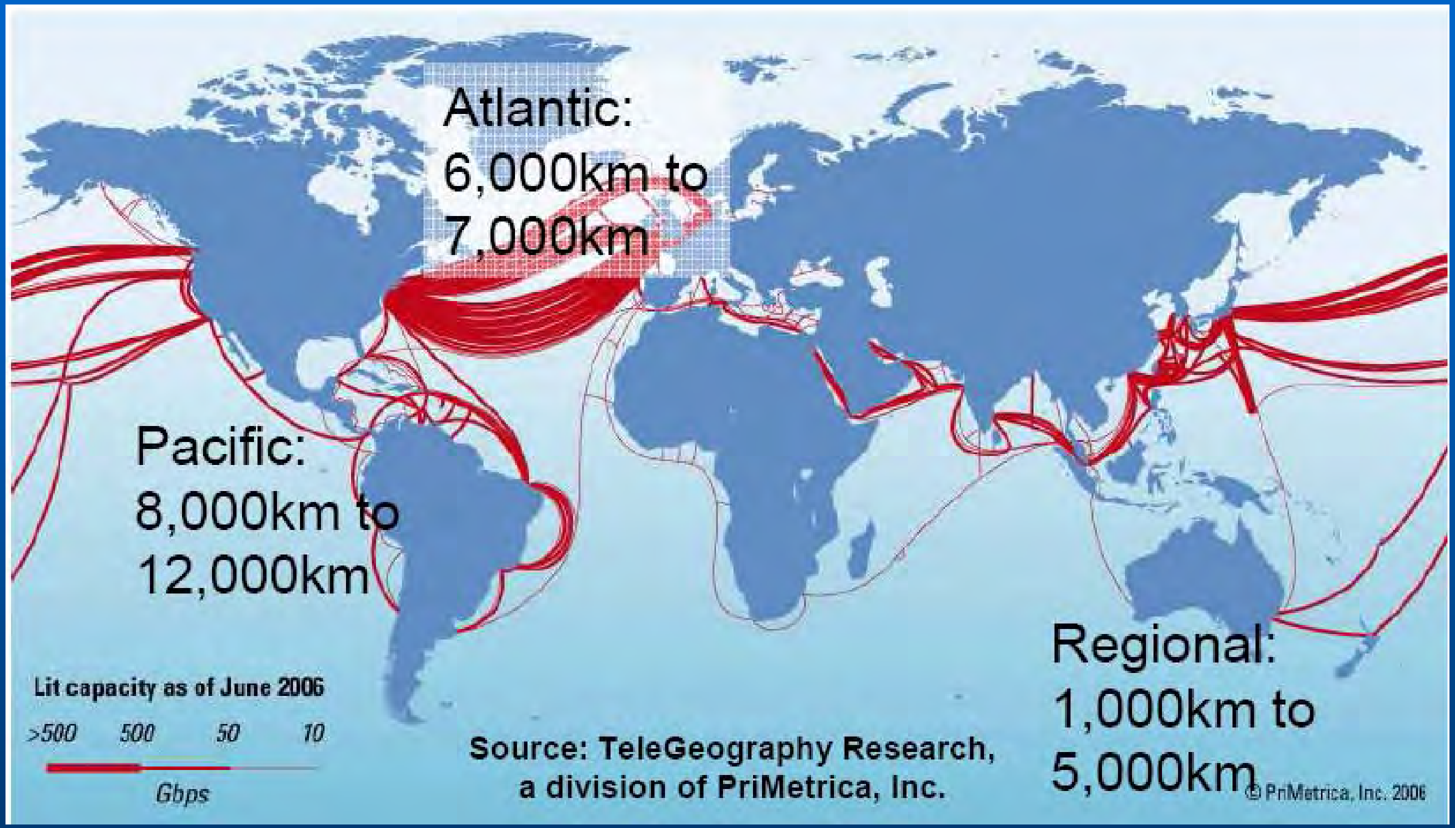
A. H. Gnauck, et al., "High-Capacity Optical Transmission Systems," *J. Lightwave Technol*. **26**, 1032-1045 (2008)



Hundreds of millions of km of fiber cables deployed

New industries created

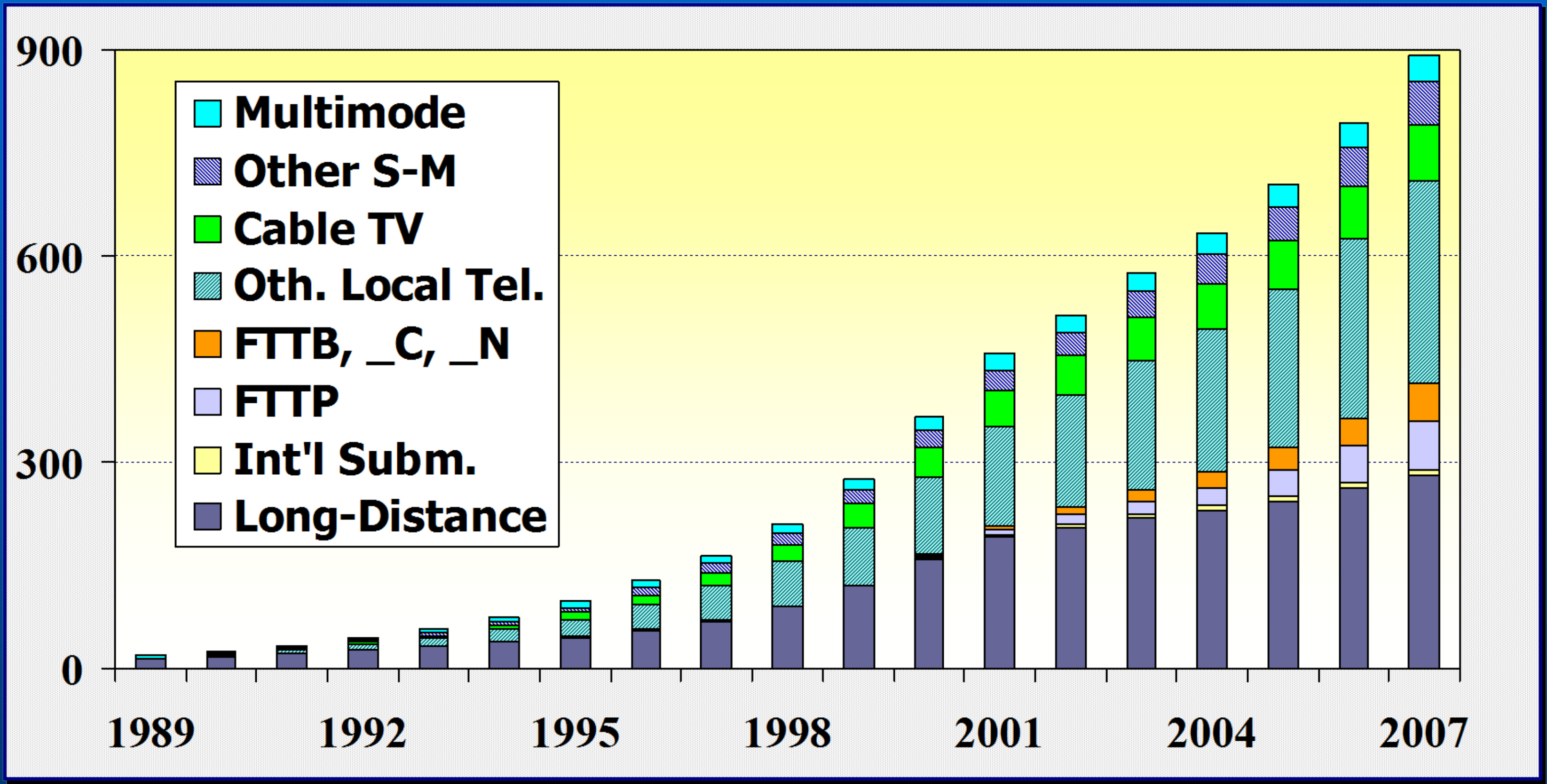
Submarine fiber optic systems



- Over 420,000 km of fiber in over 100 undersea fiber optic systems are deployed.

Courtesy: JX Cai, Tyco Telecommunications

Global fiber deployment (million km)

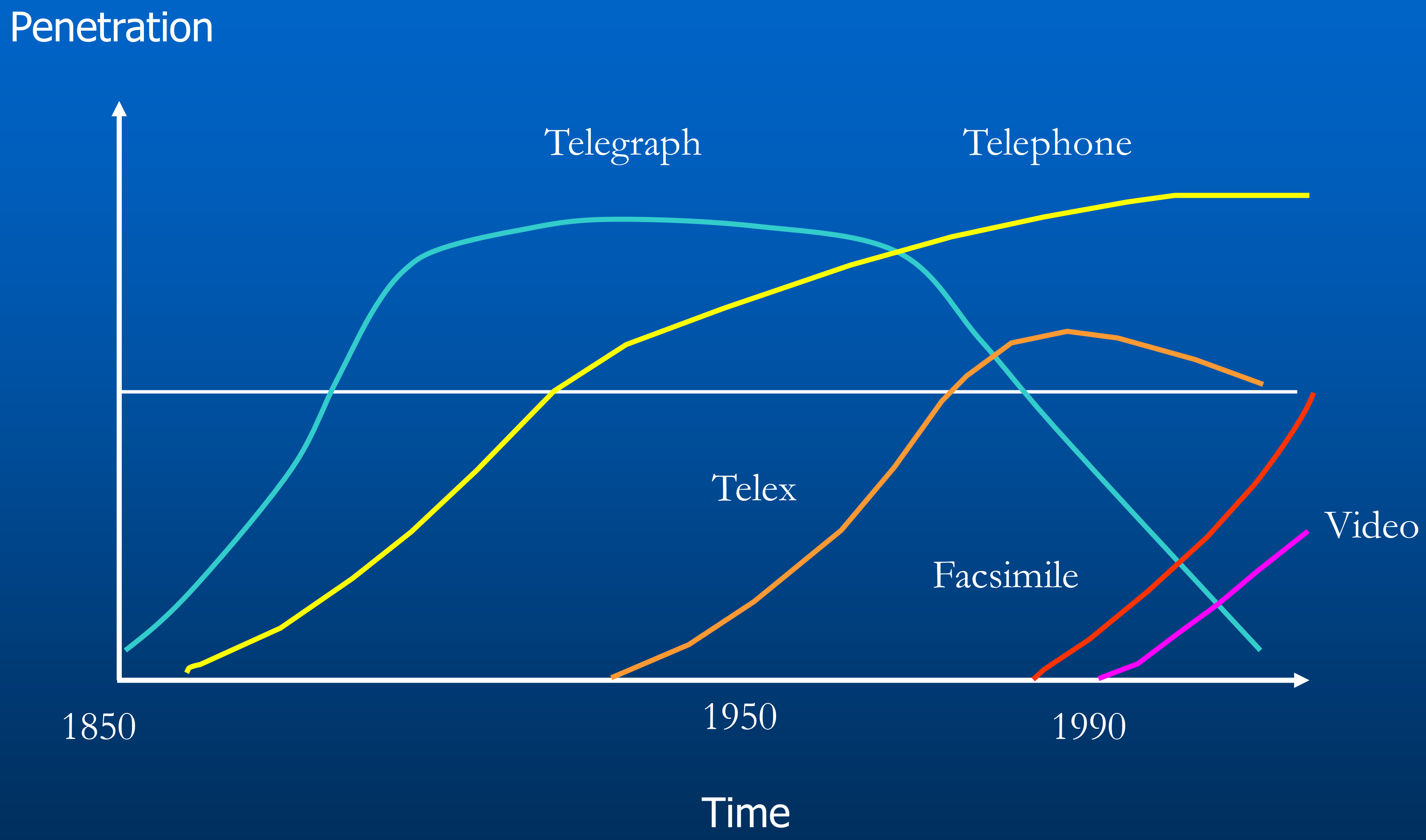


Other S-M = utility, railway, highway, government, military, premises, etc.

Other local tel. =CO trunks, metro rings, business/office parks, CLEC, etc.

Source: KMI Research, CRU Group

Telecomm service life cycle



When will fiber become obsolete?

- *"I cannot think of anything that can replace fiber optics."*
- *"In the next 1000 years, I can't think of a better system."*
- *"But don't believe what I say, because I didn't believe what experts said either."*

Courtesy of
Radio Television
Hong Kong

Fiber around the globe

Acknowledgement

The Chinese University of Hong Kong

- Prof Kenneth Young
- Prof Wing Wong
- Prof Kwok Cheung
- Prof Lian Chen

for their support in compiling this lecture