Module 2: Optical Fiber Materials

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Outlines

1. Introduction

2. Physical properties

   - Optical properties
   - Thermal properties
   - Mechanical properties
   - Chemical properties

3. Optical fibers

   - Types of optical fibers
   - Fabrication techniques
   - Cabling and handling

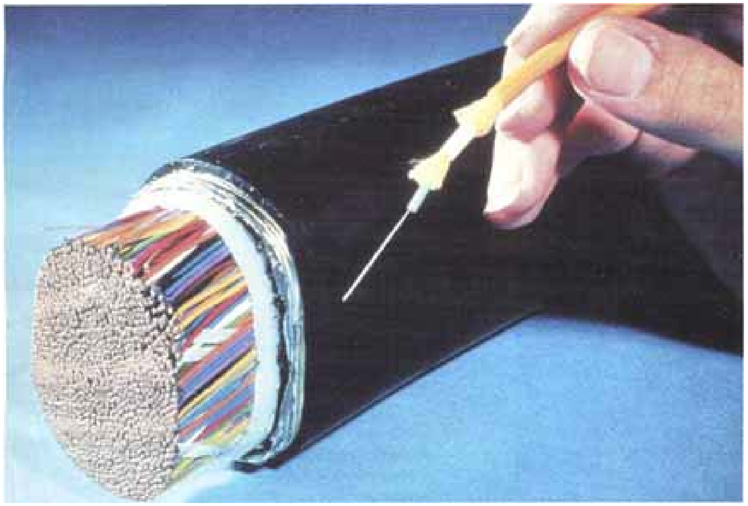
Introduction

Applications of fiber optic communication include:

- Telephones
- Internet
- LANs - local area networks
- CATV - for video, voice and Internet connections
- Utilities - management of power grid
- Security - closed-circuit TV and intrusion sensors

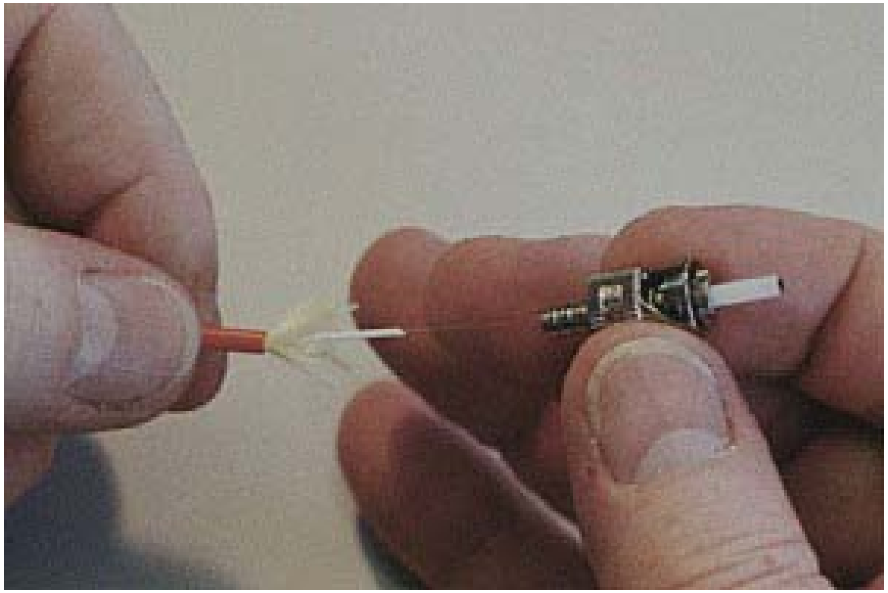
Advantages

- Economics: Fewer repeaters
- Capacity: Much wider bandwidth (> 10 GHz)
- Distance
- Weight/size
- Freedom from interference
- Safety: Electrical isolation
- Security: More difficult to tap

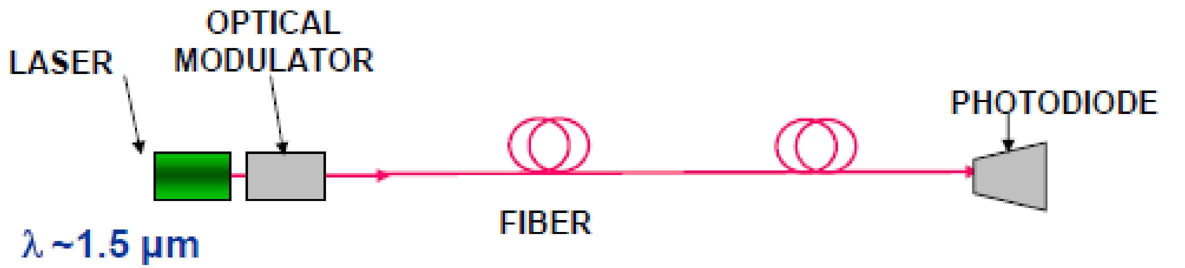


Challenges

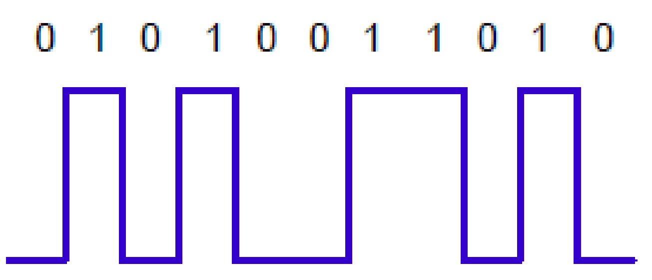
- Higher initial cost in installation
- More expensive to repair
- Strength: Lower tensile strength



Fiber Optic Telecommunication



Digital Transmission: at speeds as high as 10 or 40 Gbit/sec



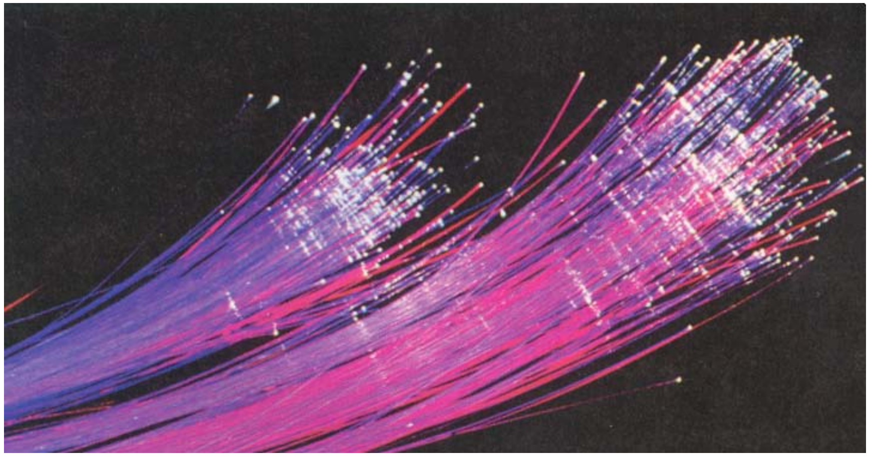
Optical fiber plays the central role!

Optical fiber materials

Requirements:

- Low propagation lost
- Low dispersion
- Easy to process
- High mechanical strength
- High chemical stability
- Low cost

Glassy materials (fused silica, polymer)



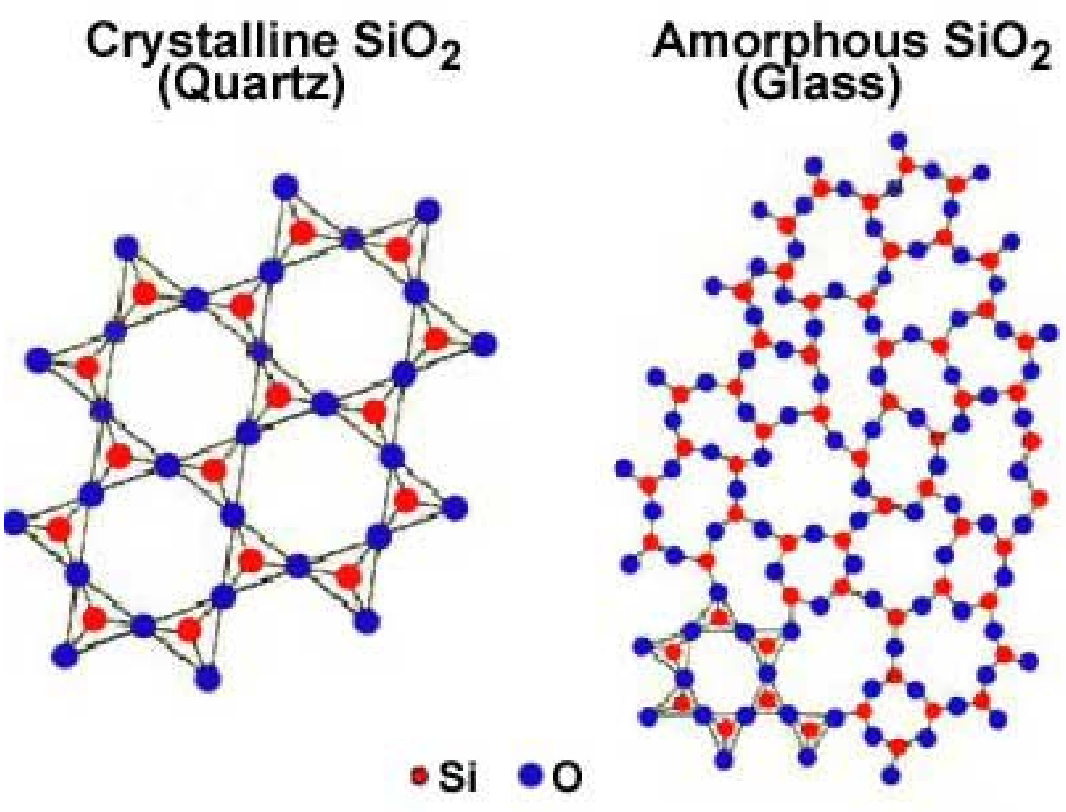
Glassy materials

1945 American Society for Testing Materials:
“Glass is a an inorganic product of fusion which has cooled to a rigid condition without crystallization”

Satisfactory for glasses most familiar to us: windows, containers …
But new methods other than cooling a melt were developed: sputtering, sol gels…

1976:
“Glass is an X-ray amorphous material which exhibits the glass transition, this is being defined as the phenomenon in which a solid amorphous phase exhibits with changing temperature a more or less sudden change in the derivative thermodynamic properties, such as heat capacity and expansion coefficient, from crystal-like to liquid like values.”

Glassy structure



Glasses have the mechanical rigidity of crystals, but the random disordered arrangement of molecules that characterizes liquids

Properties of glassy state

- Lack of long range repeatable order, non-crystalline structure
- Typically produced from the liquid state by continuous cooling
- Exhibits what is known as the glass transition
- Can be formed from most liquids, provided cooling rate is sufficiently high

How to make glass?

- Mix and heat a composition of chemicals to high temperature
- Keep the mixture at high temperature for chemical reaction
- Quickly reduce the temperature to annealing point
- Anneal at moderate temperature to reduce internal stresses
- Slowly bring to room temperature

Optical properties

Refractive index:

$$\tilde{n}(\omega) = n(\omega) + i^*k(\omega)$$

$$\acute{\varepsilon}(\omega) = \varepsilon_1(\omega) + i^* \varepsilon_2(\omega)$$

$$\acute{\varepsilon}(\omega) = [n(\omega) + i^*k(\omega)]^2$$

Fused silica: **1.46**

Soda-Lime glass: **1.518**

ZBLAN: **1.5**

Pb-silicate glass : **2.5**

Fused quartz: **2.126**

Dispersion

Dispersion is the phenomenon in which the phase velocity

(or group velocity) of a wave depends on its frequency

Sellmeier equation:

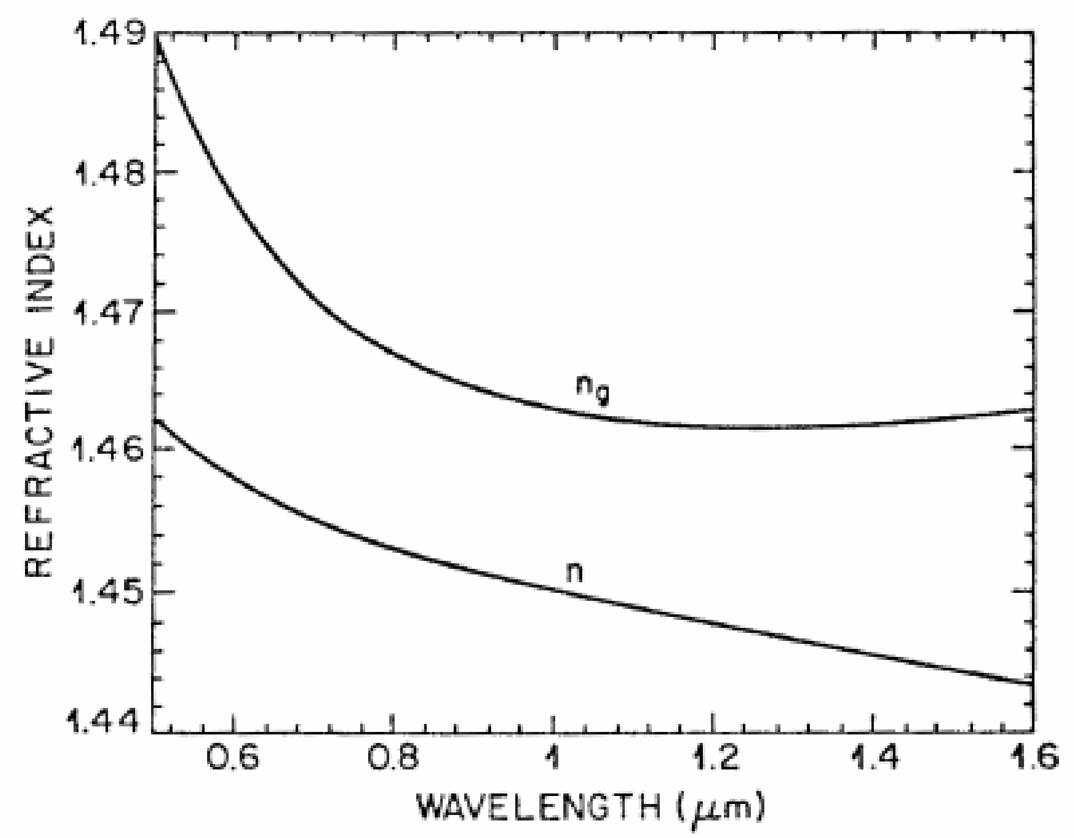
$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$$

$n(\lambda)$	is the refractive index
A_i	is the i : th Sellmeier coefficient related to the i : th oscillator wavelength (i = 1...3)
λ_i	is the i : th oscillator wavelength
λ	is the signal wavelength

$$\lambda_{1s} = 0.0684\ \mu\text{m}, \quad A_{1s} = 0.69617$$
$$\lambda_{2s} = 0.1162\ \mu\text{m}, \quad A_{2s} = 0.40794$$
$$\lambda_{3s} = 9.8962\ \mu\text{m}, \quad A_{3s} = 0.89748$$

← For fused silica

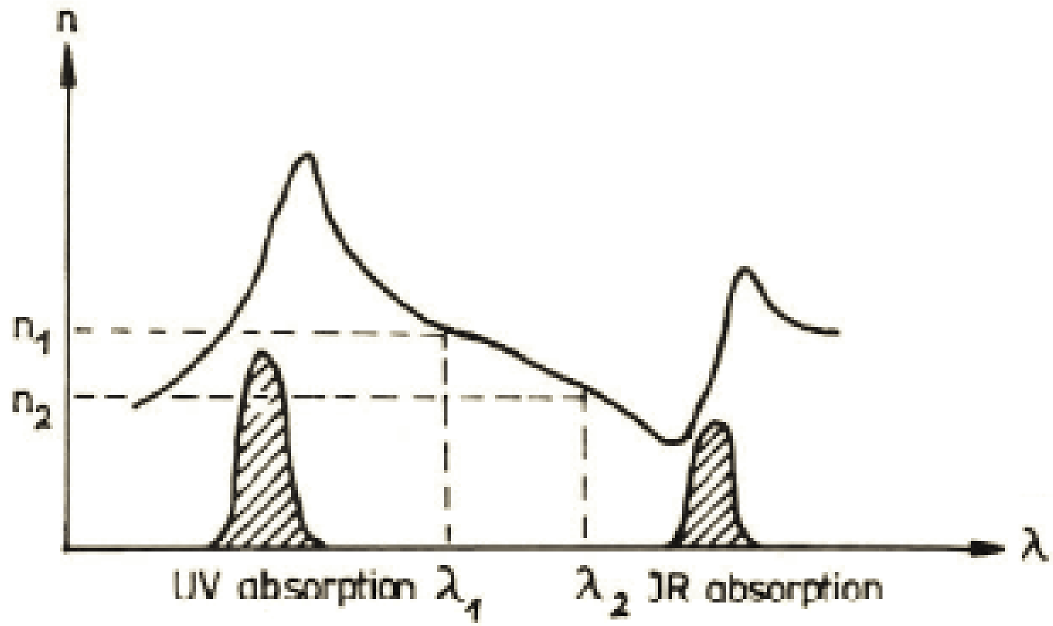
Dispersion


1.49
1.48
1.47
1.46
1.45
1.44
REFRACTIVE INDEX
n_g
n
0.6
0.8
1
1.2
1.4
1.6
WAVELENGTH (μm)

Dispersion

Normal dispersion in transparent window

Anomalous dispersion at resonances



Group velocity dispersion:

$$D = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}.$$

Attenuation

Fiber Attenuation

Measured in decibels: $dB = -10\log_{10}(P_{out}/P_{in})$

Loss values

- Fibers made of standard glass:

 1000 dB/km, ~ 10^{-100} % (~ 90% per meter)

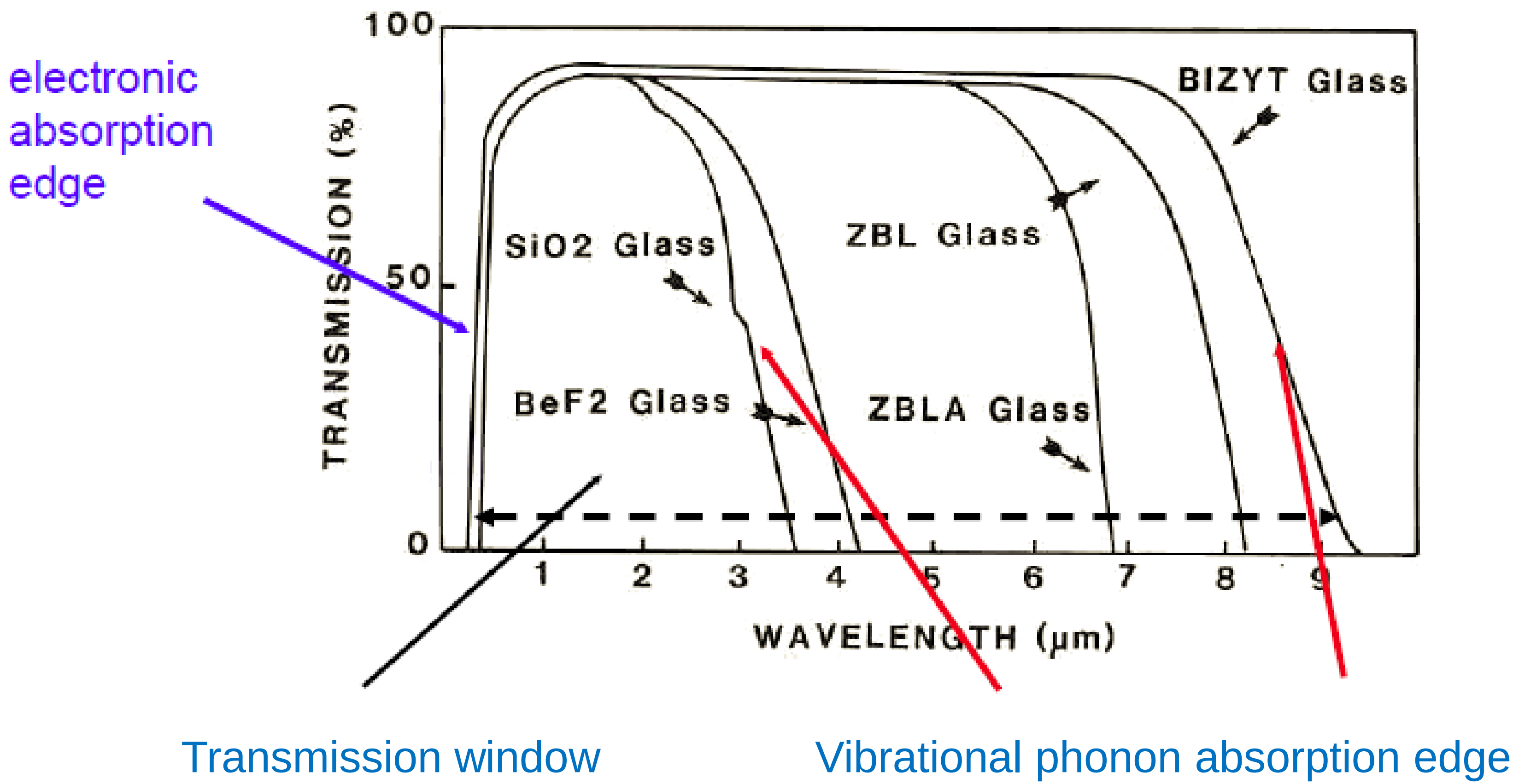
- Plastic fibers: 100 dB/km (~ 90% per 100 meters)

- Silica fibers: 0.2 dB/km Less than 5% per km !

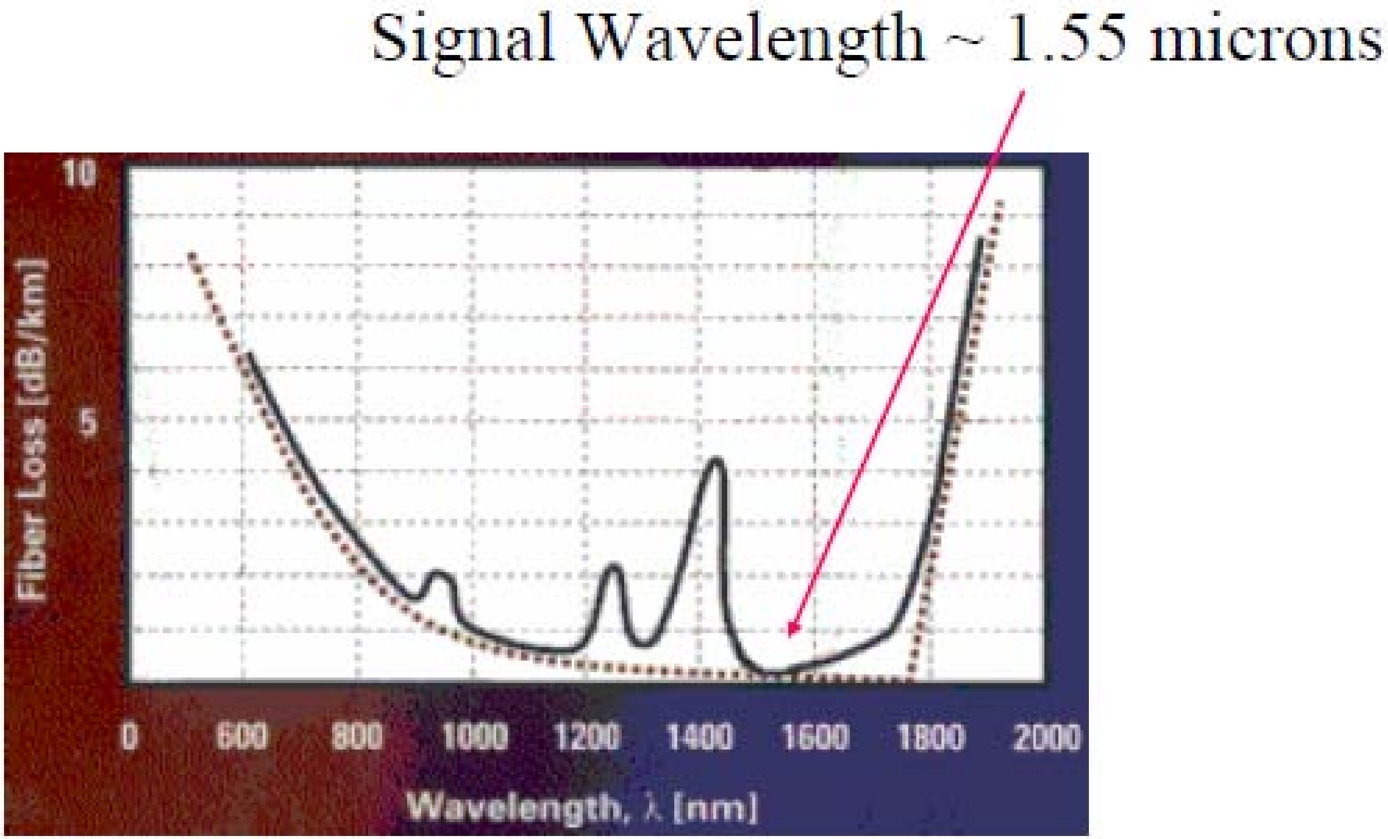
Loss mechanisms in optical fiber

- Intrinsic absorption
- Scattering loss
- Bending loss

Attenuation



Attenuation



Attenuation

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.

Predict the loss in optical fiber could be < 20dB/km

Loss was ~1000dB/km at that time

Attenuation

Physics

The Nobel Prize in Physics 2009

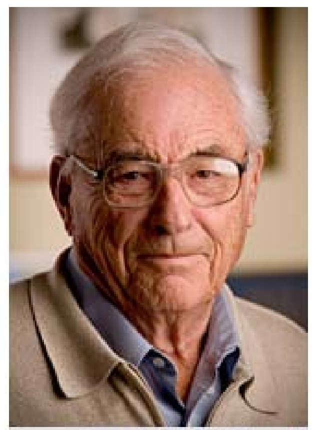
"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

"for the invention of an imaging semiconductor circuit – the CCD sensor"

Photo: Richard Epworth

Charles K. Kao

1/2 of the prize



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Willard S. Boyle

1/4 of the prize

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George E. Smith

1/4 of the prize

Attenuation

Attenuation: Fiber vs. copper

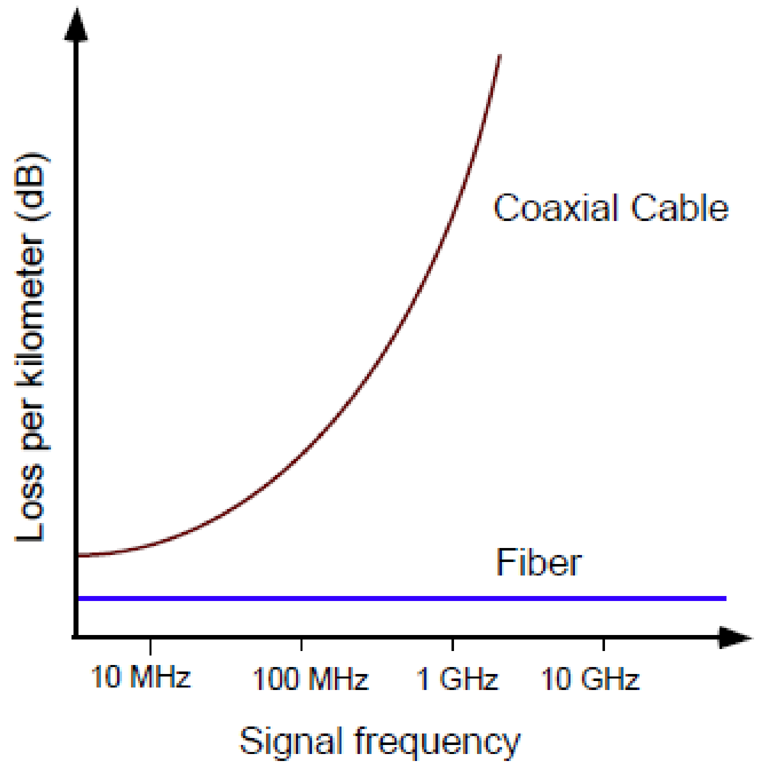
<u>Coaxial Cable</u>

Loss depends strongly on frequency

<u>Optical Fiber</u>

Loss does not depend on frequency

High speed transmission possible !!



Thermal properties

Most materials:
• Viscosity of melt ~ water (10-2Pas)
• Cooling melt → rapid crystallization ~ Tm

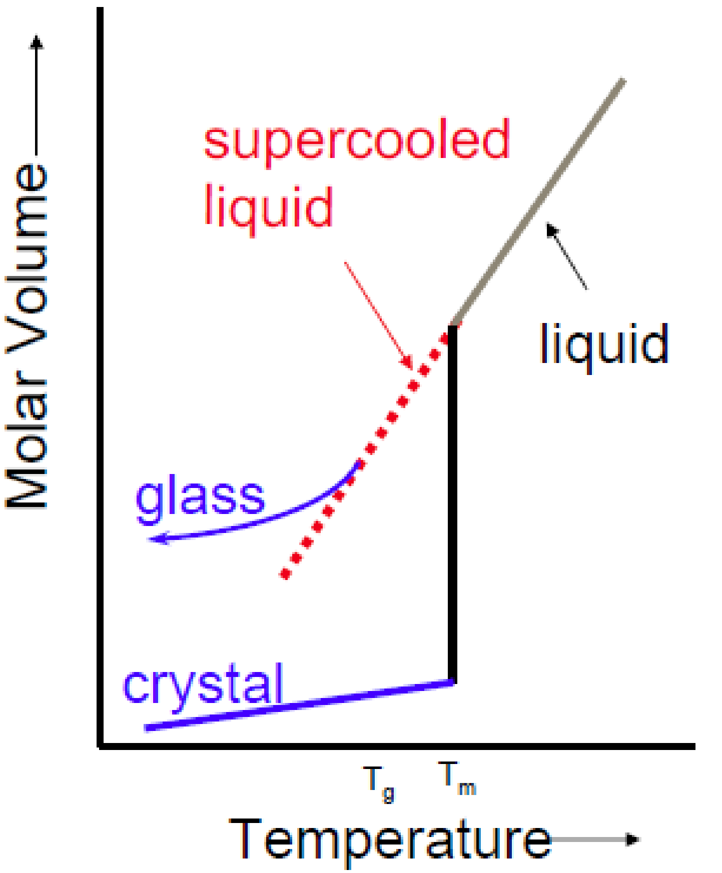
Glass forming materials:

• Melt with considerable higher viscosity

• Significantly less crystallization below Tm

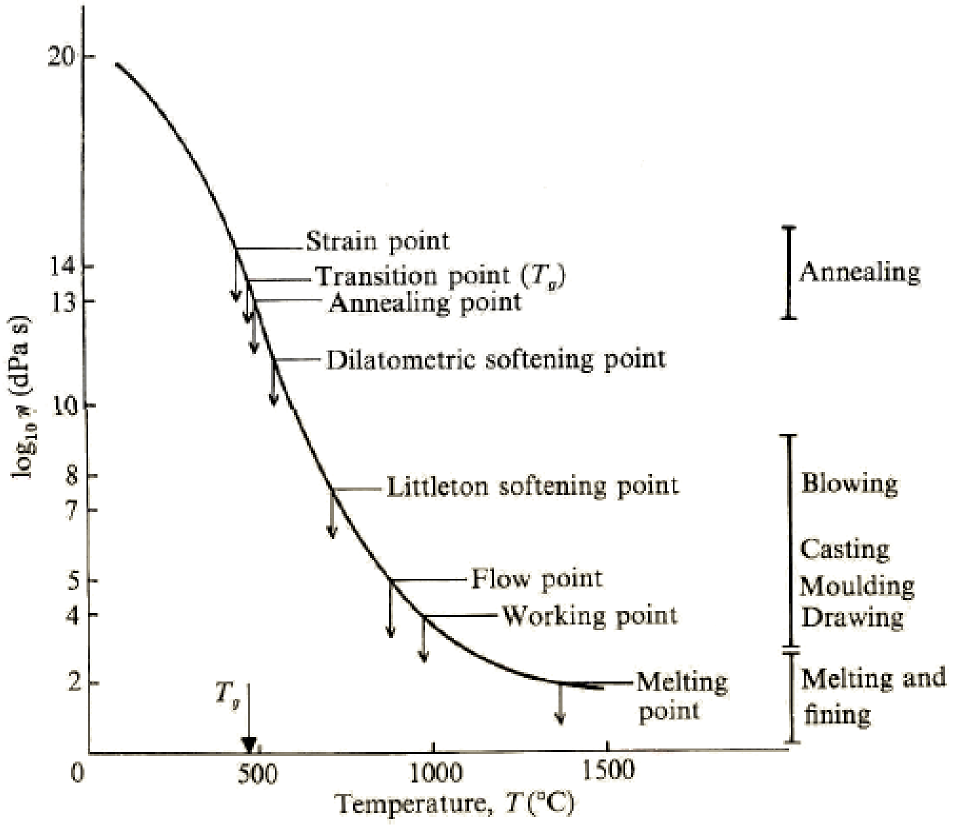
• If crystallization rate is low enough fast cooling below Tm w/o crystallization possible

• further cooling: viscosity rising to such high values that the mechanical properties become similar to a solid



Thermal properties

Typical dependence of viscosity of a glass on temperature



Thermal properties

Typical thermal properties of fused silica

Coefficient of thermal expansion: 5.5×10^{-7}/°C (average from 20 °C to 320 °C)

Thermal conductivity: 1.3 W/(m·K)

Specific heat capacity: 45.3 J/(mol·K)

Softening point: 1665 °C

Annealing point: 1140 °C

Mechanical properties

The main failure mechanism is through crack formation

- Fabrication imperfection
- Environmental factors

Solution:

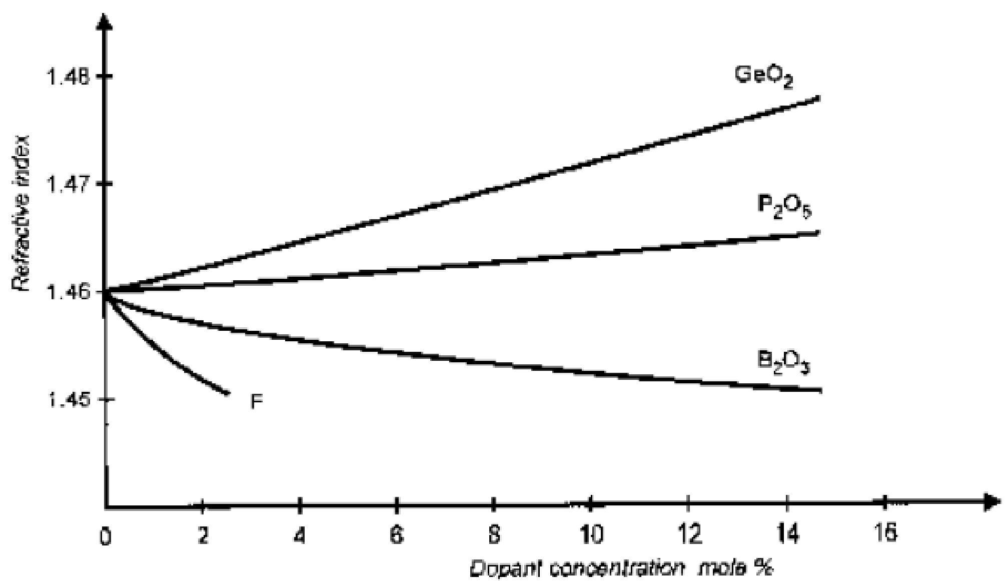
- Fiber protection coating
- Tensile strength testing before installation

PTR-200-RPT

Chemical properties

Optical properties can be optimized by varying chemical composition

- Refractive index
- Transmission window
- Dispersion



Optical fibers

Lecture on Wednesday