Fiber Optic Telecommunications

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Outline

Basic Properties of Optical Fibers

- What is an optical fiber ?

Modern Optical Communication System
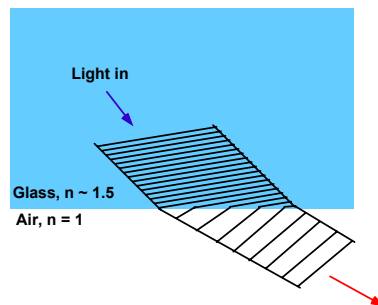
- How does it work ?
- Advantages of fiber optics

Refraction of Light

Refractive index:

$$n = \frac{C_{vacuum}}{C_{material}}$$

Light in

Glass, n ~ 1.5

Air, n = 1

Total Internal Reflection

Snell's law:

$$n_{glass} \cdot \sin I = n_{air} \cdot \sin R$$

Glass, n ~ 1.5

A

I

R

Air, n = 1
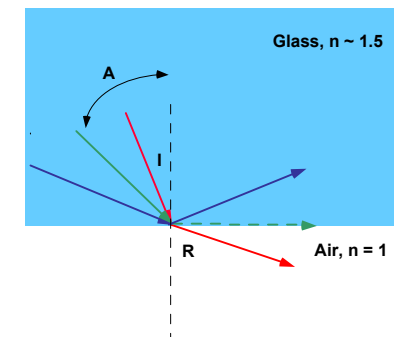
Critical angle A ~ 41.8°

Light Guiding by a Water Jet

Total Internal Reflection can confine light in a material denser than its surroundings

Daniel Colladon (Swiss physicist), 1841
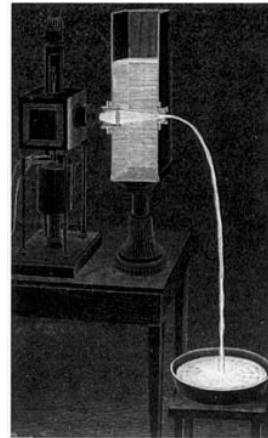
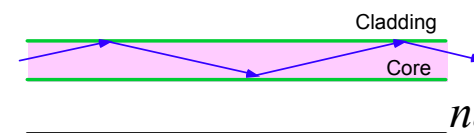Fiber Optic Telecommunications
TUT, March 2007

Optical Fibers

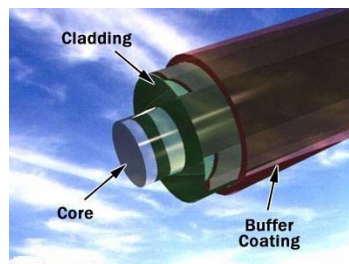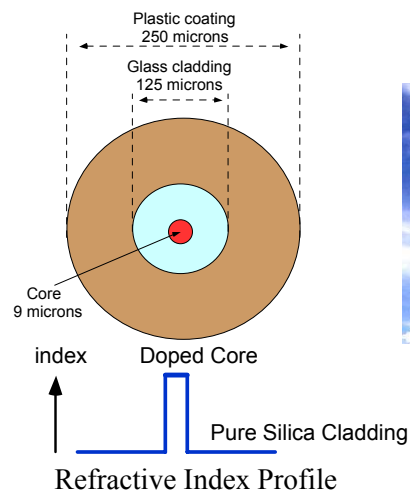No Cladding: light leaks out

Cladding prevents leaking

Cladding

Core

$n_{core} > n_{clad} > n_{air}$

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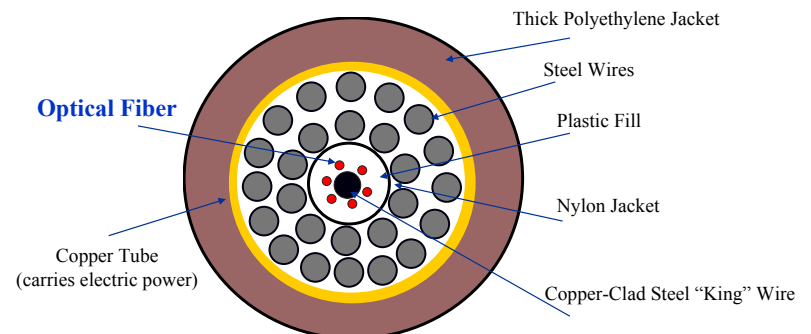TUT, March 2007

Optical Fibers

Plastic coating
250 microns

Glass cladding
125 microns

Cladding

Core

Buffer Coating

Core
9 microns

index   Doped Core

Pure Silica Cladding

Refractive Index Profile

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Fiber Cable

Cross Section: Deep-Sea Submarine Cable

Thick Polyethylene Jacket

Steel Wires

Plastic Fill

Optical Fiber

Nylon Jacket

Copper Tube
(carries electric power)

Copper-Clad Steel "King" Wire

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Attenuation in Optical Fibers

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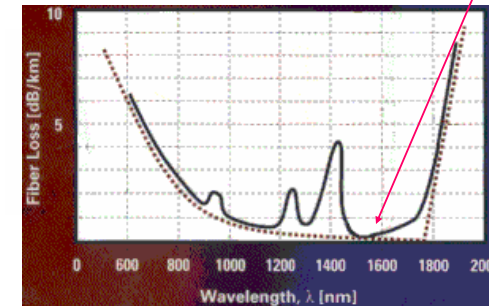Measured in decibels: $dB = -10\log_{10}(P_{out}/P_{in})$

Loss values
- Fibers made of standard glass:
  - 1000 dB/km, $\sim 10^{-100}$ % ($\sim$ 90% per meter)
- Plastic fibers: 100 dB/km   ($\sim$ 90% per 100 meters)
- Silica fibers: 0.2 dB/km   Less than 5% per km !

Attenuation vs. Wavelength

Signal Wavelength $\sim$ 1.55 microns

Fabrication of Optical Fibers

Fabrication of silica fibers by a two-step process

1. Preform fabrication

- Modified Chemical Vapor Deposition (MCVD) Method
- Outside Vapor Deposition (OVD) Method
- Vapor-phase Axial (VAD) Method

2. Drawing into an optical fiber

**Fabrication of multi-component glass fibers**

1. Single-step double-crucible method
2. Rod-in tube method
   - 1. Preform fabrication
   - 2. Drawing into an optical fiber

The core of a silica based fiber can have a purity of better than 0.1 ppb (parts per billion (10^{-9})). Such high degree of purity has been made possible by Chemical Vapor Deposition (CVD) techniques originally developed for Semiconductor Industry. The method uses the difference in the vapor pressures of the liquid metal halides of the material and those of the impurities.

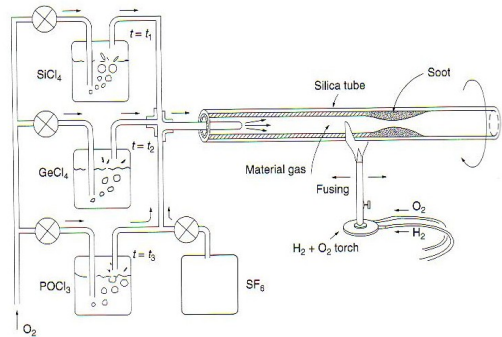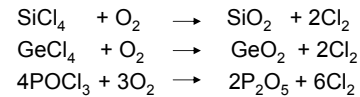Vapor pressures for metal halides and potential impurities
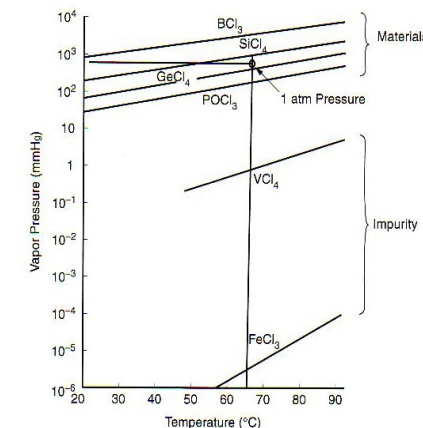
Modified Chemical Vapor Deposition (MCVD)

A chemical reaction takes place inside a silica tube with the aid of a H_2/O_2 burner outside the tube. The metal halide vapors are oxidized and small glass particles, called "soot", are deposited on the inside wall of the tube.

$$SiCl_4 + O_2 \longrightarrow SiO_2 + 2Cl_2$$
$$GeCl_4 + O_2 \longrightarrow GeO_2 + 2Cl_2$$
$$4POCl_3 + 3O_2 \longrightarrow 2P_2O_5 + 6Cl_2$$

Purified oxygen gas is bubbled into reservoirs containing liquid metal halides, at a prescribed pressure and temperature.

Fiber Drawing

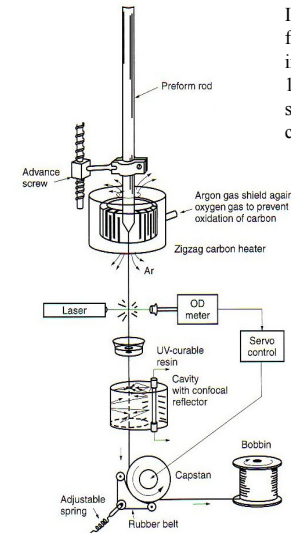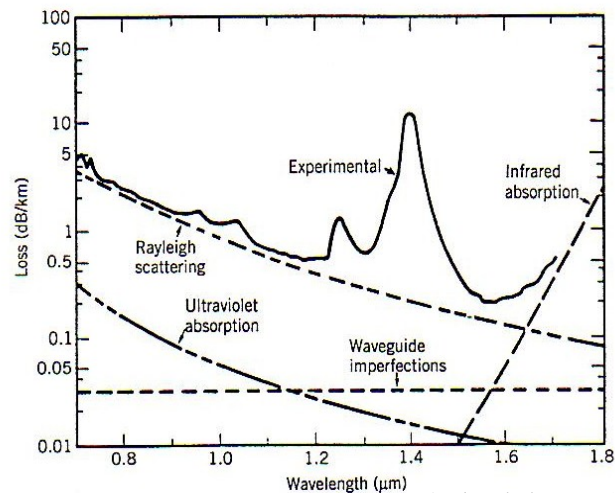In the second step of the process, an optical fiber is drawn from the preform rod. The lower end of the preform is heated in a furnace to ~ 2000-2100 °C (melting temperature is ~ 1900 °C). The fiber diameter is controlled by the pulling speed. Feedback signal from the fiber diameter measurement controls the pulling speed.

Loss spectrum of a single-mode fiber produced in 1979:

(T. Miya et al., Electron. Lett. **15**, 106, 1979)

In 2000 Lucent scientists published a study on spatial distribution of OH concentration in fiber preforms. The concentration was found to increase with increasing distance from the center of the preform. Based on some new diffusion modeling and their experiments, they concluded that water enters the preform rod from the outside of the rod and diffuses into the molten, flowing glass much faster than what was earlier extrapolated from low temperature measurements. So to make "dry" fibers, they simply changed the O_2–H_2 torch to a dry heat source, such as O_2 plasma torch.

Loss and dispersion of the Lucent's Dry "AllWave" fiber:
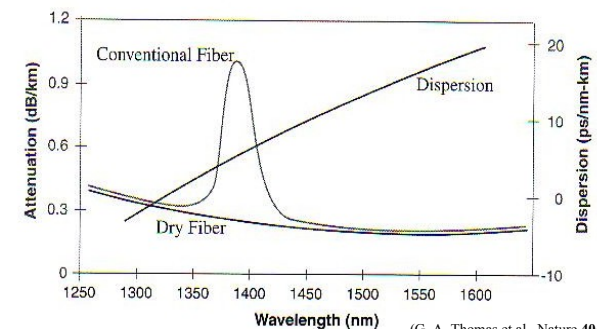
(G. A. Thomas et al., Nature **404**, 262, 2000)

Why Optical Fibers ?

Some Advantages

- Light weight
- Immune to EM-interference
- Nearly impossible to tap

Key Advantages

- Attenuation is independent of the modulation speed

- Ultra-High Carrier Frequency
  - f ~ 190 THz @ 1.55 μm wavelength
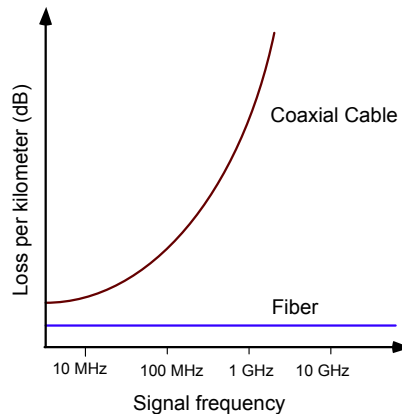   (1 Trillion Hz = 10^{12} Hz)

Attenuation: Fiber vs. copper

Coaxial Cable
Loss depends strongly on frequency
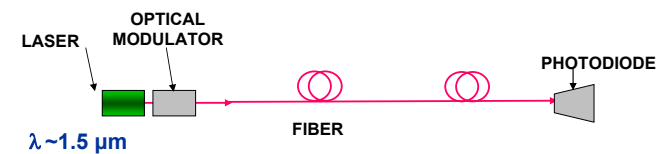
Optical Fiber
Loss does not depend on frequency
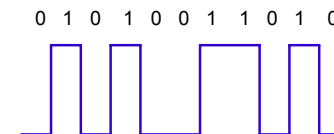
High speed transmission possible !!

Fiber Optic Telecommunications

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

0 1 0 1 0 0 1 1 0 1 0

Importance of the Carrier Frequency ?

Higher the carrier frequency

⇓

Greater the systems' transmission capacity (bandwidth)

The Electromagnetic Spectrum

The Optical Spectrum

Radio   Microwaves   X Rays   Gamma Rays

10 GHz   100 THz

Frequency (Hz)

10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22}

100 MHz

Wavelength (m)

100   1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-10} 10^{-14}
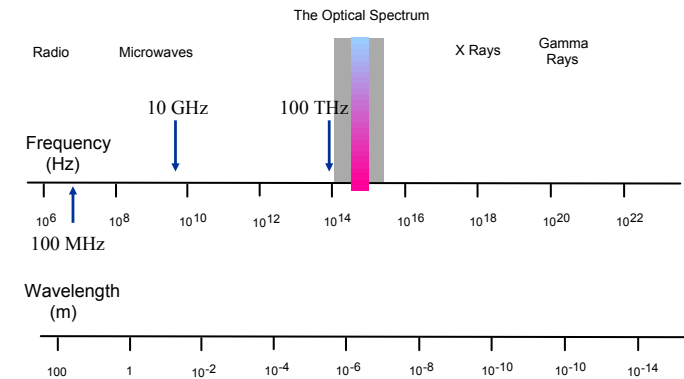
Modulation frequency higher than the carrier frequency ?
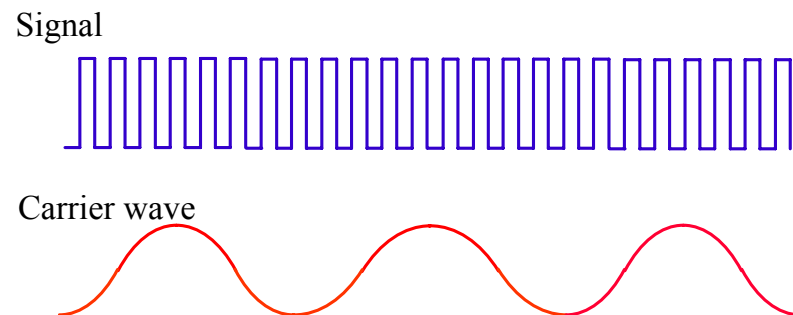
Signal

Carrier wave

Modulation

Signal

Carrier wave

Modulated signal

On   Off   Off   On

Envelope of modulation
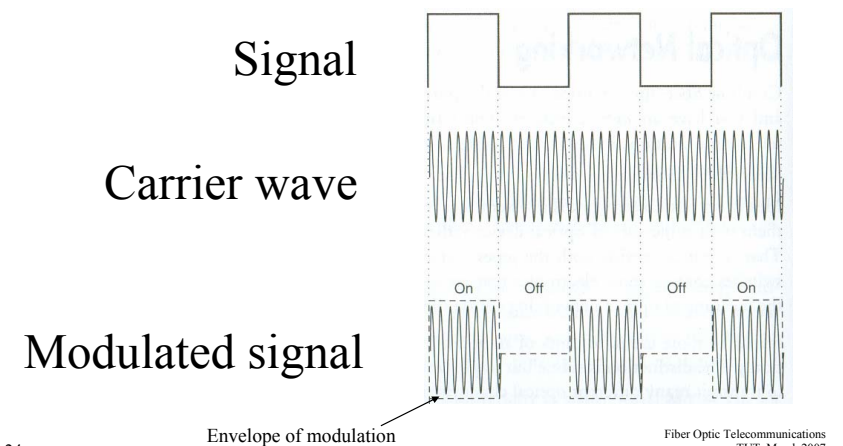
Fiber Optics

- Fundamentally nearly unlimited bandwidth !!
  - Carrier frequency ~ 190 THz

1.55 µm wavelength Window (~ 100 nm)
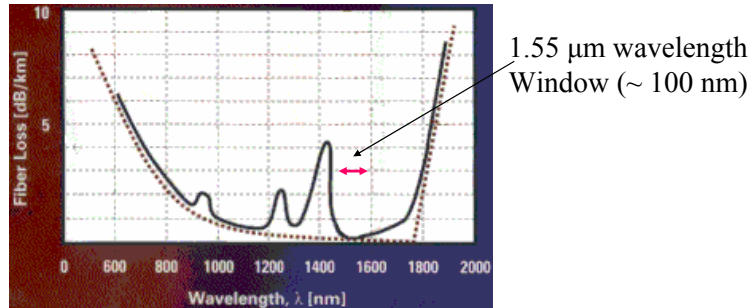
Dense Wavelength Division Multiplexing (DWDM)
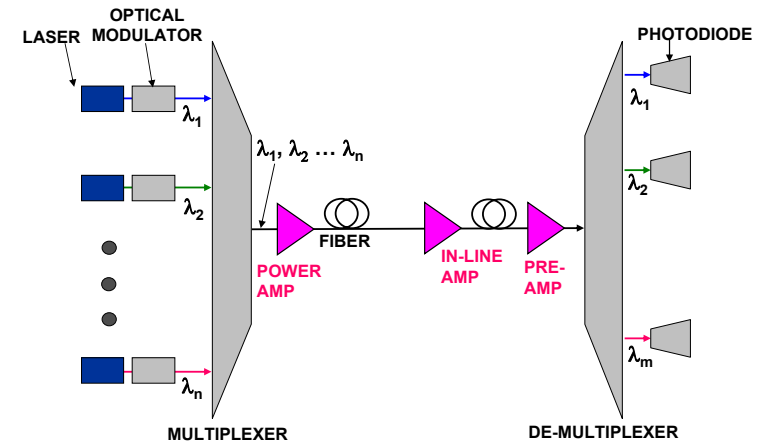
Erbium Doped Fiber Amplifier (EDFA)

- The key enabler of DWDM systems
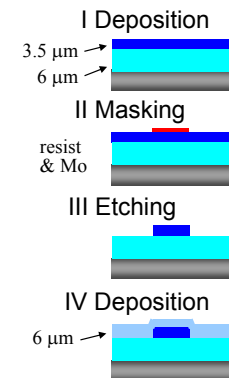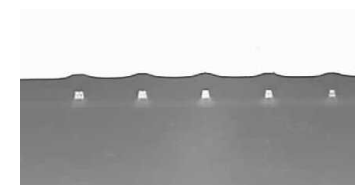- Gain through stimulated emission in an Er^{3+}-doped single-mode fiber
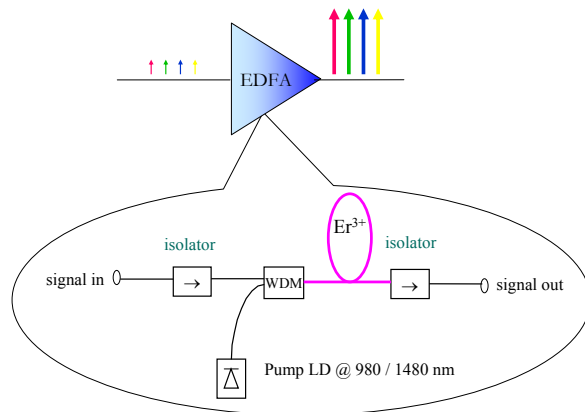
Glass Waveguides on Si

- Three silicon oxynitride layers on a thick silicon substrate (1.3 mm)
- Film deposition with PECVD technique ($n \approx 1.48$, $\Delta n \approx 0.008$)
- Two layer masking process
- Plasma etching of the waveguide core

Microscope image with visible light:

I Deposition

II Masking

III Etching

IV Deposition

State-of-the-Art DWDM

Example:

Distance: 1200 km
Number of wavelengths: 125
Total capacity: 5 Tbit/s

How much is 1 Tbit/s?
   - 10 million phone calls
   - hundreds of thousands of TV channels

Qwest's North-American Fiber-Optic Backbone System

Qwest's Global Fiber-Optic Network
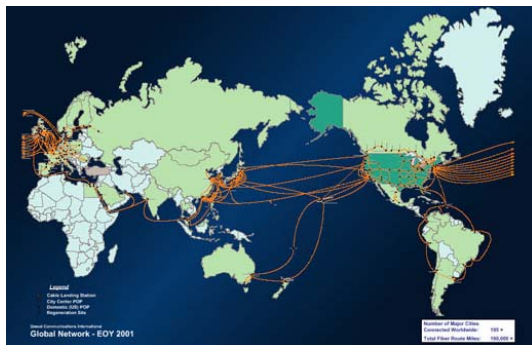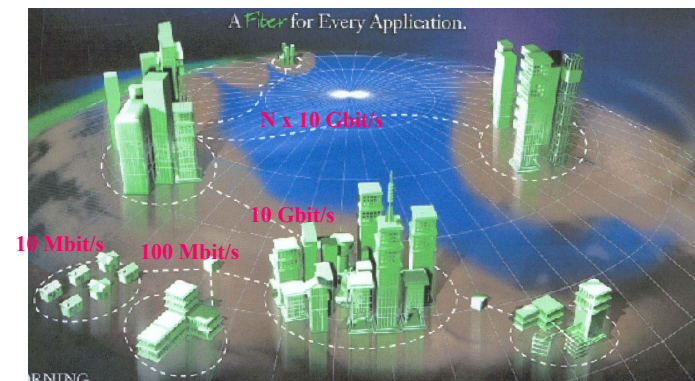
Submarine Fiber-optic System

Fiber Manufacturing / System Assembly / Cable Laying