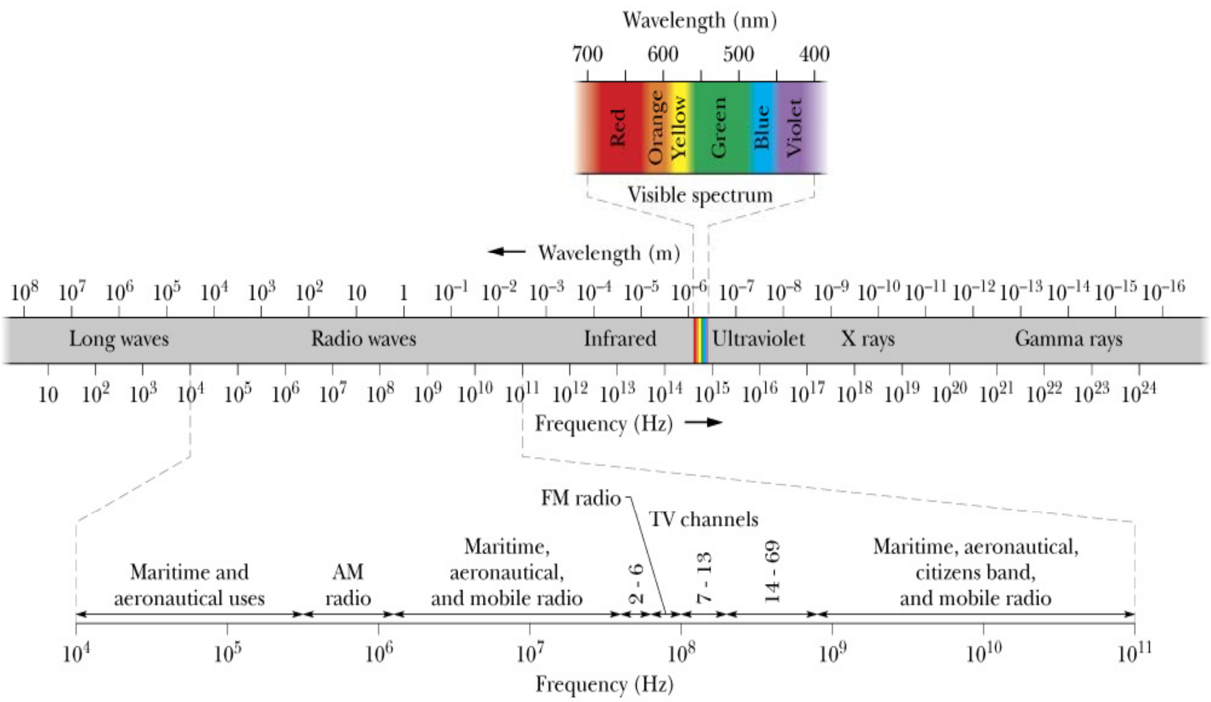
Lecture 15

Light Interference, Reflection and Refraction

http://physics.njit.edu/~sirenko/

Physics 103 Spring 2012

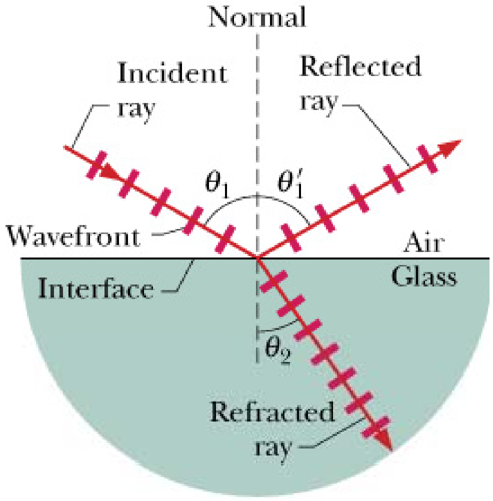
Electromagnetic Spectrum



Speed of light

$$c = 299792458 \text{ m/s},$$

Refraction and Reflection of Light

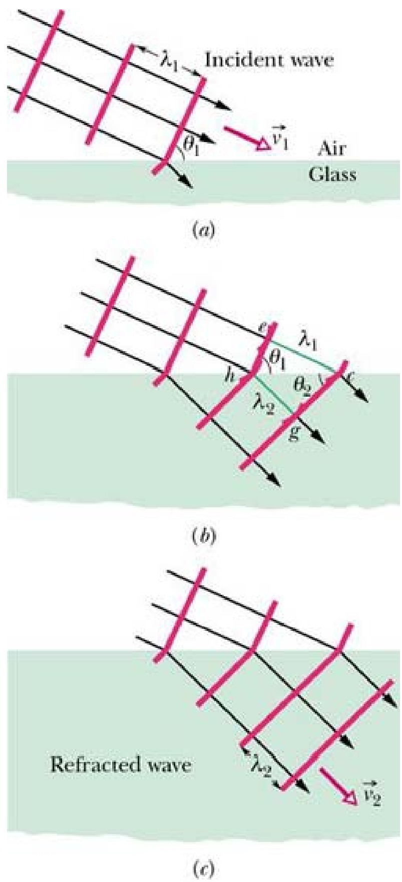


Some Indexes of Refraction[a]

Medium	Index	Medium	Index
Vacuum	Exactly 1	Typical crown glass	1.52
Air (STP)[b]	1.00029	Sodium chloride	1.54
Water (20°C)	1.33	Polystyrene	1.55
Acetone	1.36	Carbon disulfide	1.63
Ethyl alcohol	1.36	Heavy flint glass	1.65
Sugar solution (30%)	1.38	Sapphire	1.77
Fused quartz	1.46	Heaviest flint glass	1.89
Sugar solution (80%)	1.49	Diamond	2.42

$$\theta'_1 = \theta_1 \quad \text{(reflection)}.$$

$$n_2 \sin\theta_2 = n_1 \sin\theta_1 \quad \text{(refraction)}.$$

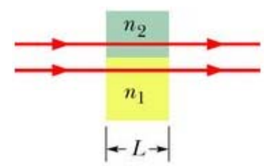


$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \text{(law of refraction).}$$

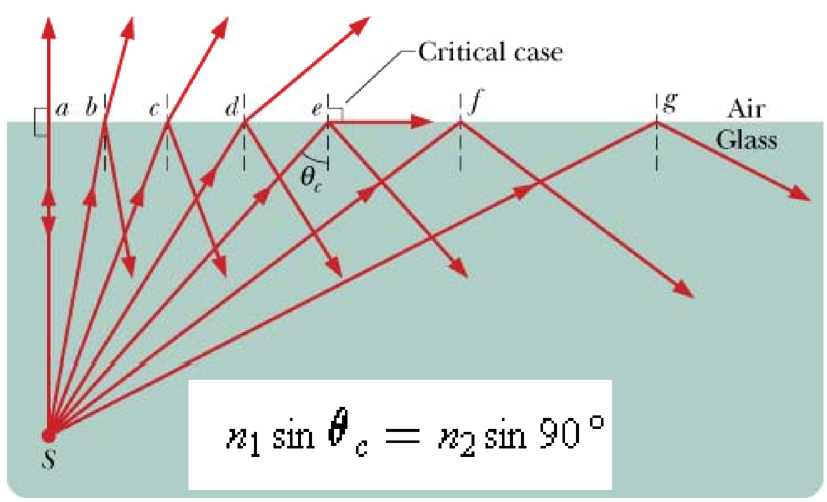
$$n = \frac{c}{v} \quad \text{(index of refraction)}$$

$$f_n = \frac{v}{\lambda_n}.$$

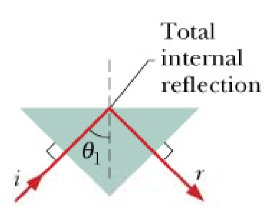


$$f_n = \frac{c/n}{\lambda/n} = \frac{c}{\lambda} = f$$

Total internal Reflection

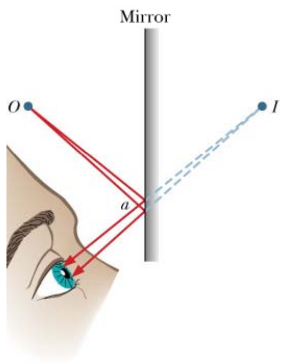


$$n_1 \sin\theta_c = n_2 \sin 90°$$

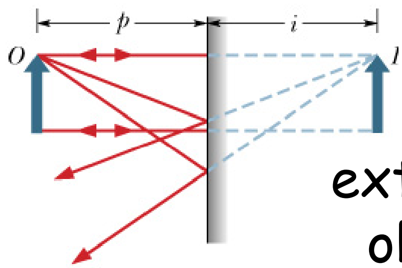


$$\theta_c = \sin^{-1}\frac{n_2}{n_1} \quad \text{(critical angle)}$$

Mirror images: flat mirror



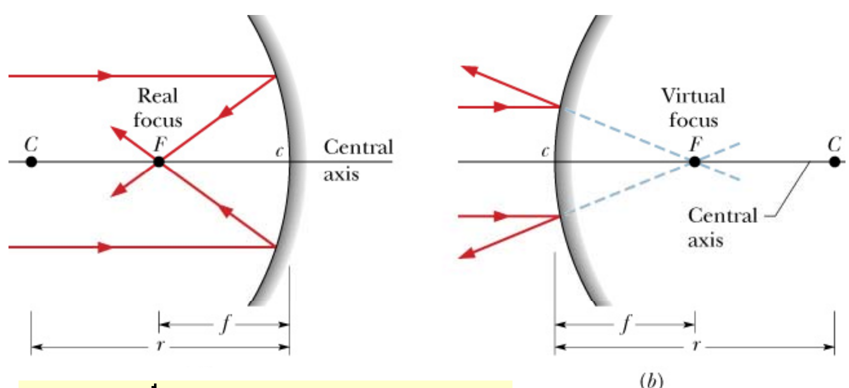
point



extended object

Mirror images: Concave and convex mirrors

Focal Points

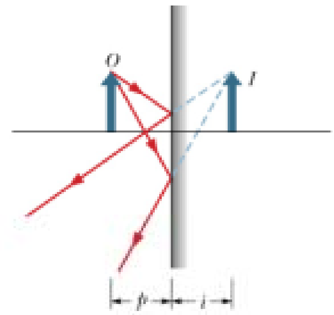


$$f = \frac{1}{2}r \quad \text{(spherical mirror)}$$

Concave mirror

Convex mirror

Mirror images: Convex mirror



For convex and plane mirrors only
a virtual image can be formed

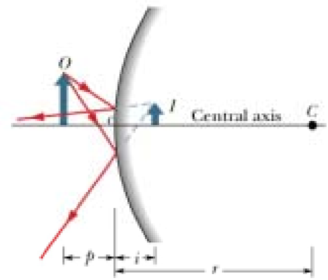
$$f = \frac{1}{2}r \quad \text{(spherical mirror)}$$

$$\frac{1}{p} + \frac{1}{i} = \frac{1}{f} \quad \text{(spherical mirror)}.$$

$$|m| = \frac{h'}{h} \quad \text{(lateral magnification)}.$$

$$m = -\frac{i}{p} \quad \text{(lateral magnification)}.$$

i of a virtual image is negative



Mirror images: Concave mirror

Real images form on the side of a mirror where the object is, and virtual images form on the opposite side.

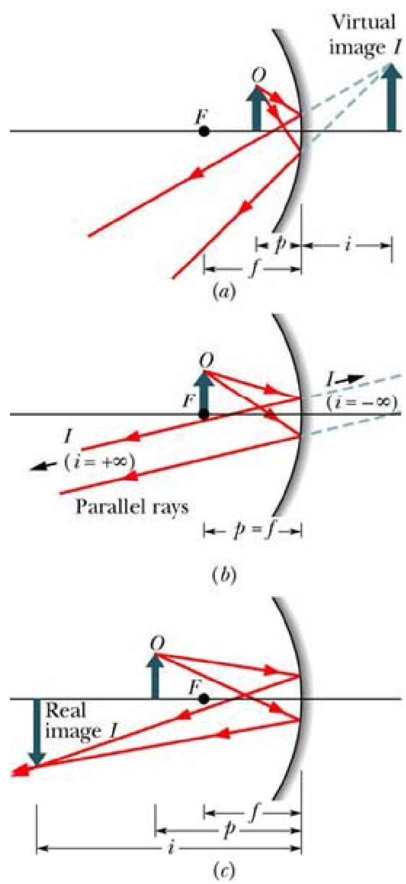
$$f = \frac{1}{2}r \quad \text{(spherical mirror)}$$

$$\frac{1}{p} + \frac{1}{i} = \frac{1}{f} \quad \text{(spherical mirror)}.$$

$$|m| = \frac{h'}{h} \quad \text{(lateral magnification)}.$$

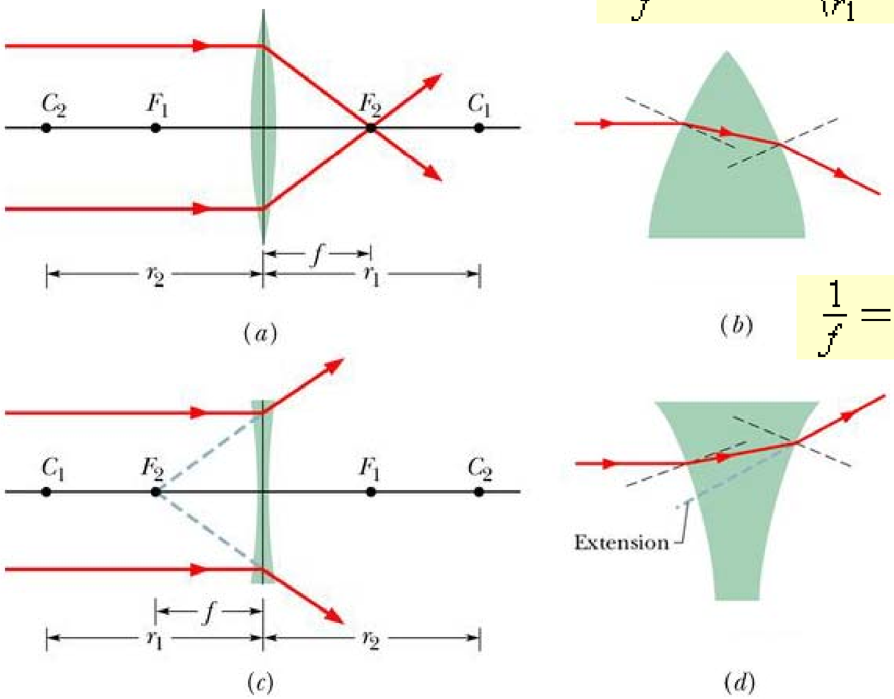
$$m = -\frac{i}{p} \quad \text{(lateral magnification)}.$$

i of a real image is positive
i of a virtual image is negative



Thin Lenses

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad \text{(thin lens in air)}$$

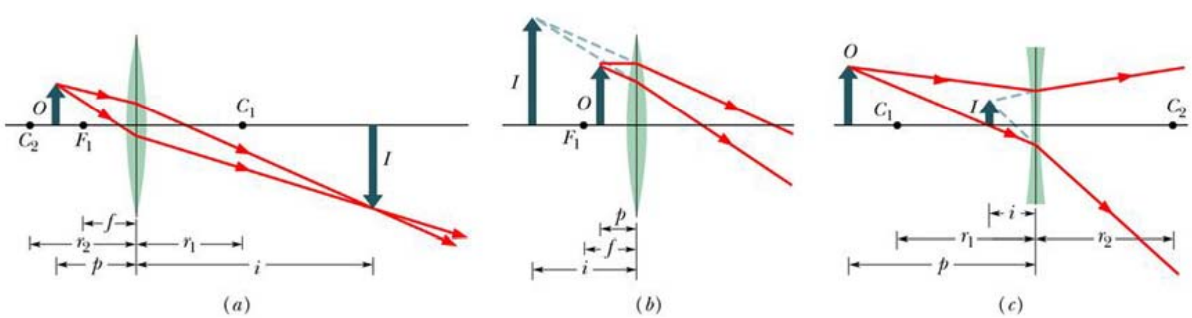


$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad \text{(thin lens)}$$

Thin Lenses

$$\frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \quad \text{(thin lens in air)}$$

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{i} \quad \text{(thin lens)}$$



real inverted image
Of the object further away than F from the lens

virtual image
Of the object between F and L

virtual image (always)

Review & Summary

Real and Virtual Images

An *image* is a reproduction of an object via light. If the image can form on a surface, it is a *real image* and can exist even if no observer is present. If the image requires the visual system of an observer, it is a *virtual image*.

Image Formation

Spherical mirrors, spherical refracting surfaces, and *thin lenses* can form images of a source of light—the object—by redirecting rays emerging from the source. The image occurs where the redirected rays cross (forming a real image) or where backward extensions of those rays cross (forming a virtual image). If the rays are sufficiently close to the *central axis* through the spherical mirror, refracting surface, or thin lens, we have the following relations between the *object distance* p (which is positive) and the *image distance* i (which is positive for real images and negative for virtual images):

1. **Spherical Mirror:**

$$\frac{1}{p}+\frac{1}{i}=\frac{1}{f}=\frac{2}{r},$$

where f is the mirror's focal length and r is the mirror's radius of curvature. A *plane mirror* is a special case for which $r \to \infty$, so that $p = -i$. Real images form on the side of a mirror where the object is located, and virtual images form on the opposite side.

Thin Lens:

$$\frac{1}{p}+\frac{1}{i}=\frac{1}{f}=(n-1)\left(\frac{1}{r_1}-\frac{1}{r_2}\right),$$

where f is the lens's focal length, n is the index of refraction of the lens material, and r_1 and r_2 are the radii of curvature of the two sides of the lens, which are spherical surfaces. A convex lens surface that faces the object has a positive radius of curvature; a concave lens surface that faces the object has a negative radius of curvature. Real images form on the side of a lens that is opposite the object, and virtual images form on the same side as the object.

Lateral Magnification

The *lateral magnification* m produced by a spherical mirror or a thin lens is

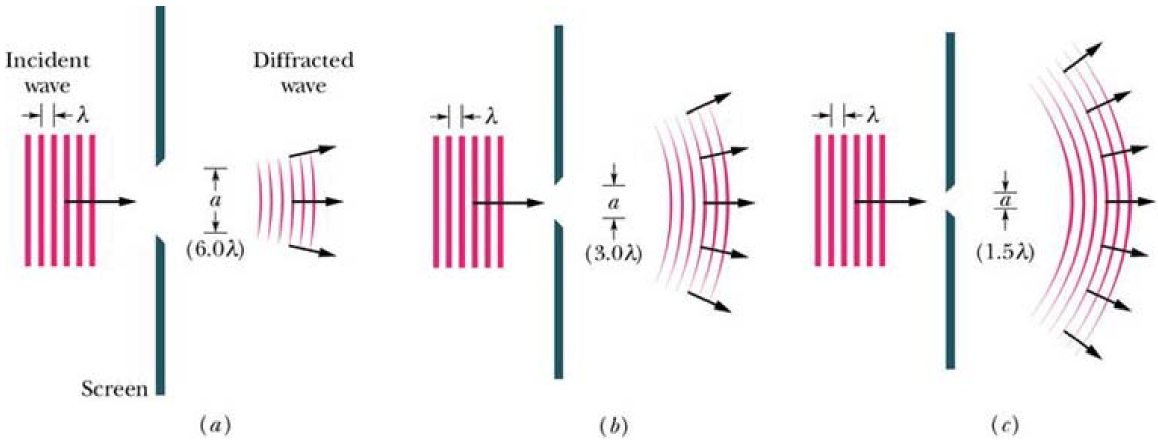
$$m = -\frac{i}{p}.$$

The magnitude of m is given by

$$|m| = \frac{h'}{h},$$

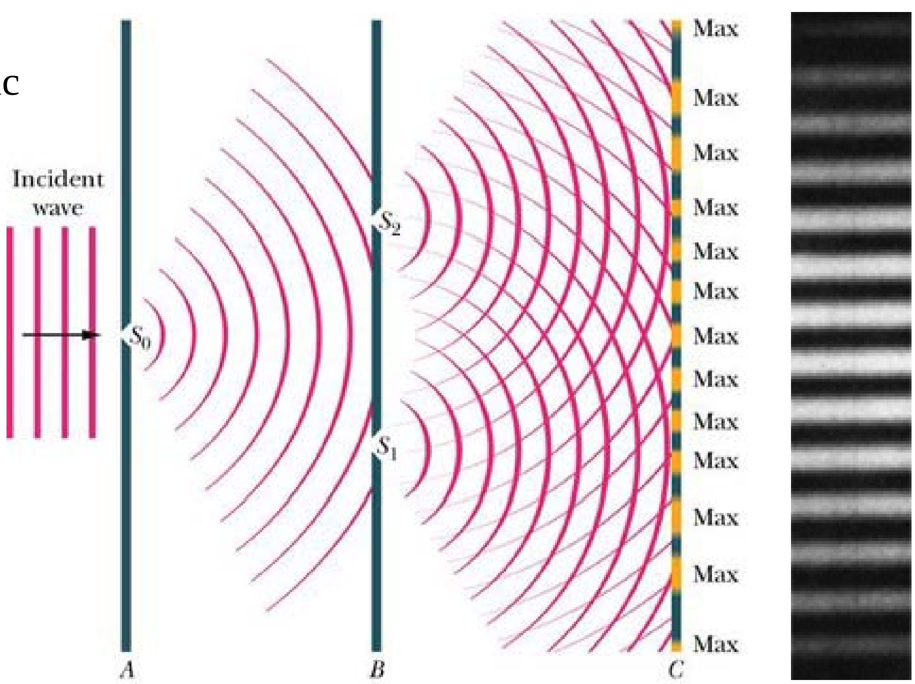
where h and h' are the heights (measured perpendicular to the central axis) of the object and image, respectively.

Diffraction

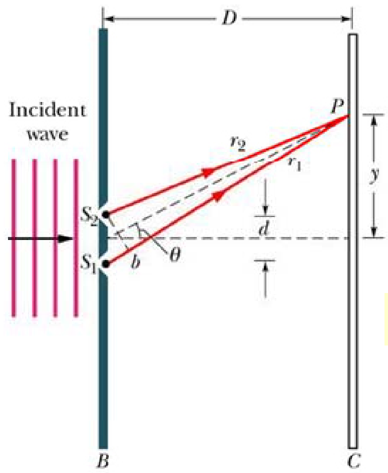


Young's Interference Experiment

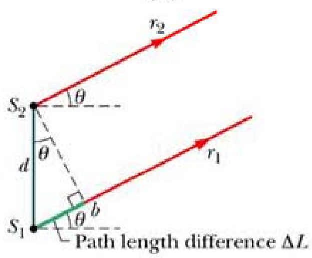
Light from a distant monochromatic source



Young's Interference Experiment



(a)



(b)

The phase difference between two waves can change if the waves travel paths of different lengths.

$$\Delta L = d \sin\theta \quad \text{(path length difference)}.$$

$$d \sin\theta = m\lambda, \text{ for } m = 0, 1, 2, \ldots \quad \text{(maxima – bright fringes)}$$

$$\theta = \sin^{-1}\left(\frac{2\lambda}{d}\right)$$

$$d \sin\theta = \left(m + \tfrac{1}{2}\right)\lambda, \text{ for } m = 0, 1, 2, \ldots \quad \text{(minima – dark fringes)}$$

$$\theta = \sin^{-1}\left(\frac{1.5\lambda}{d}\right)$$

Fast Internet

- History of Telecom
- Components for Telecom and WDM
- Results for High-speed Modulators and PISOAs
- What is "fast" today ? And do we really want 40 Gbit/s ?
- Is it ever going to be "fast enough" ?

1Gbit = 10^9 bit; 1 Tbit = 10^{12} bit

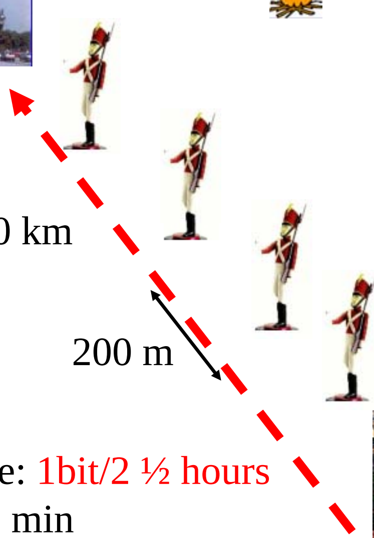
Web

The Web began in March 1989, when Tim Berners-Lee of **CERN** (a collective of European high-energy physics researchers) proposed the project to be used as a means of transporting research and ideas effectively throughout the organization.

History of telecommunication

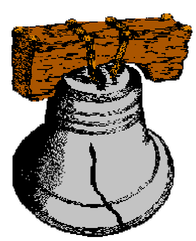
- Smoke Telegraph
- Drum
- St.Petersburg – Moscow (1796)

St.-Petersburg

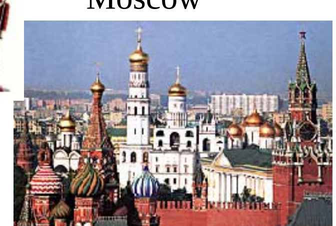


600 km

200 m



Emperor's Inauguration in Moscow



200 years ago:

Transmission rate: 1bit/2 ½ hours

$T = L/S_{sound} = 30$ min

From the History of Telecommunication

•St.Petersburg – Moscow (1796)

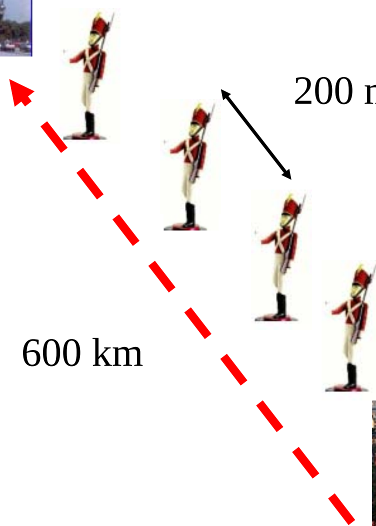
~200 years ago:

Transmission rate: 1bit/2 ½ hours

$T = L/S_{sound} = 30$ min

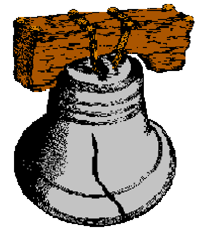


St.-Petersburg



200 m

600 km



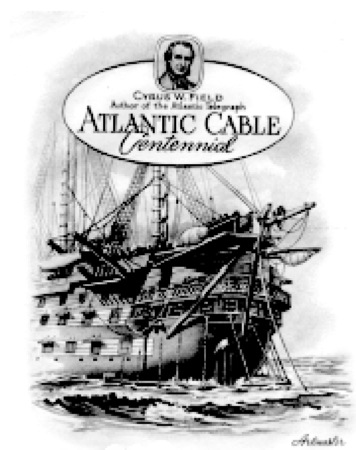
Emperor's Inauguration in Moscow

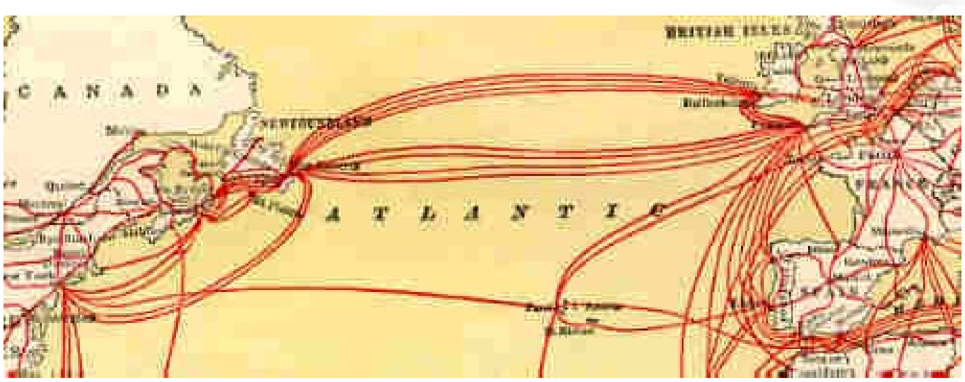
History of telecommunication (*Cont.*)

Transatlantic Cable Communications

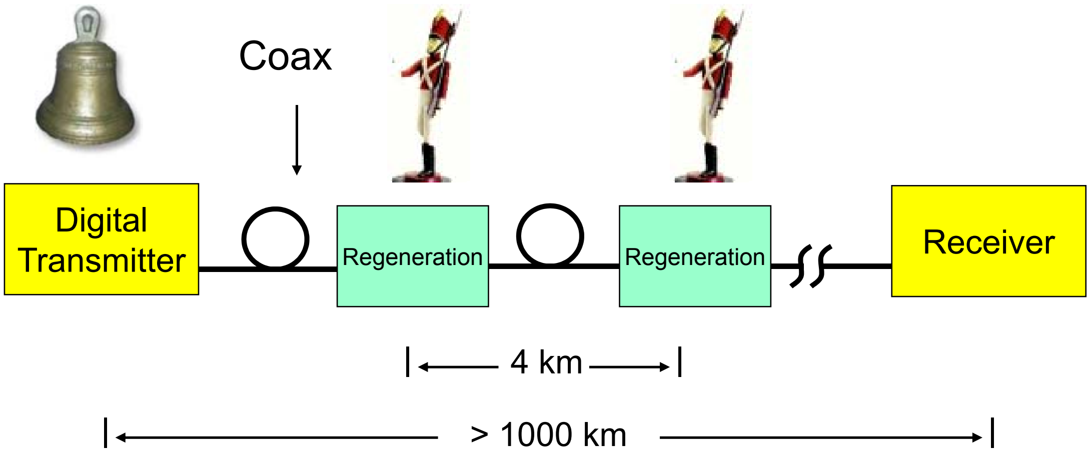
(based on Patent for Electromagnetic Telegraph by Samuel Morse, 1837);

Morse Code; about 10 bit/s



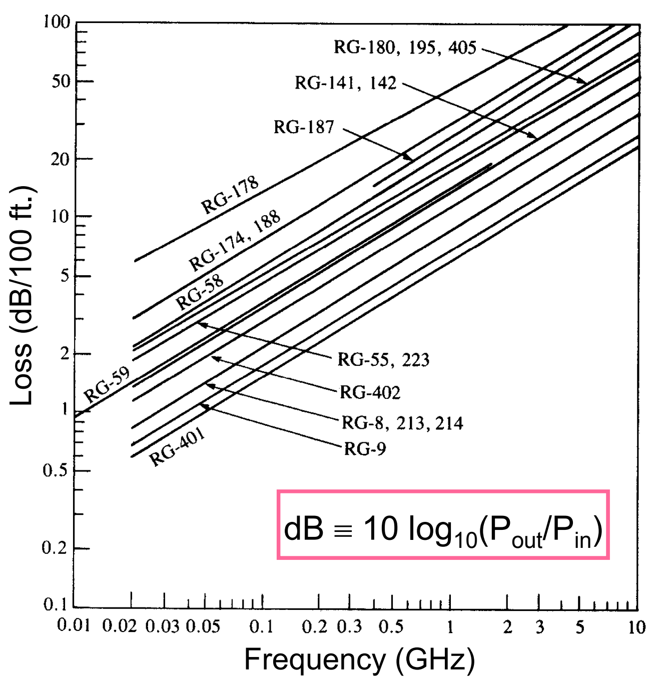


A “High-Speed” Coaxial Cable Transmission System (1982)



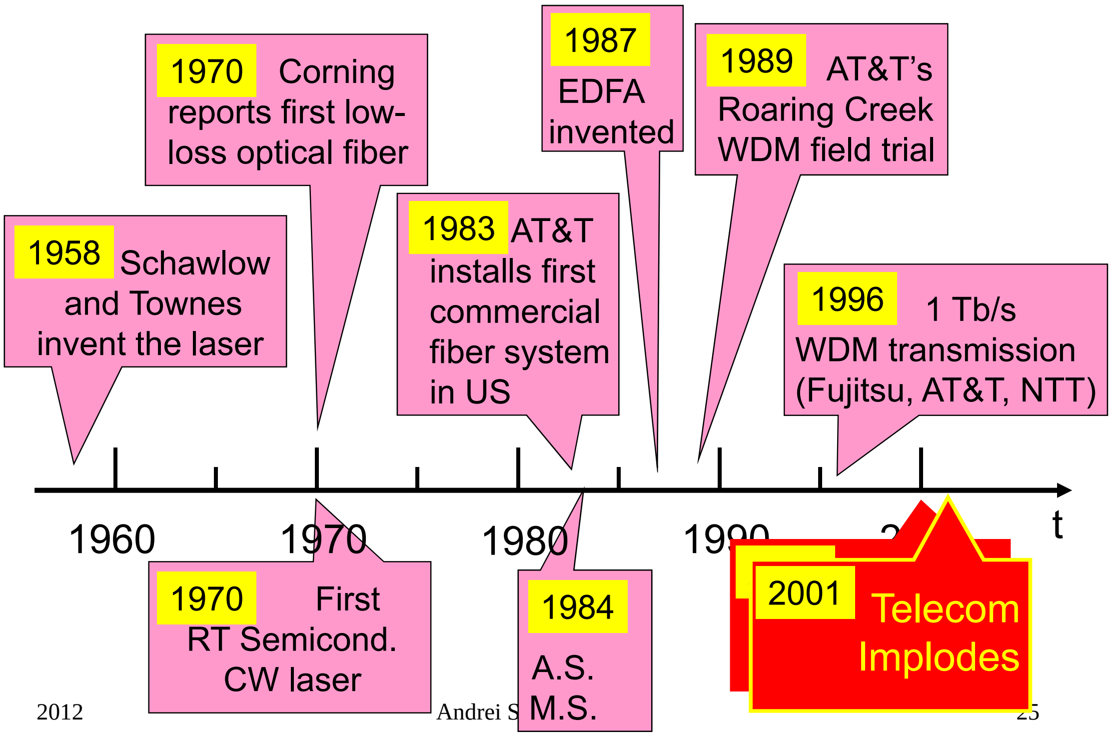
- 560 Mb/s per coax

Coaxial Cable (electrical waveguide) Loss

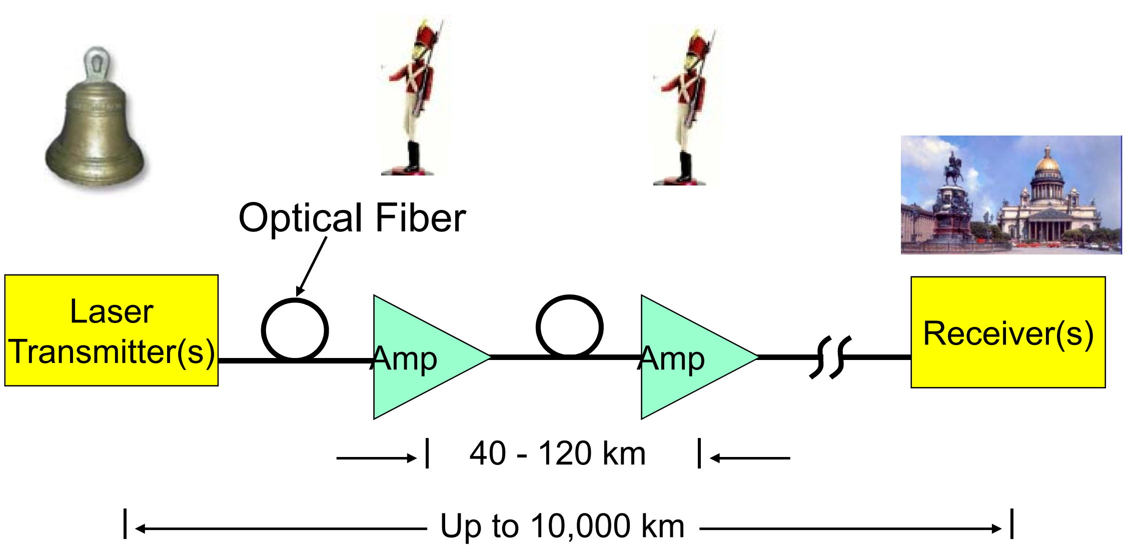


Optical fiber

Selected Milestones in Optics

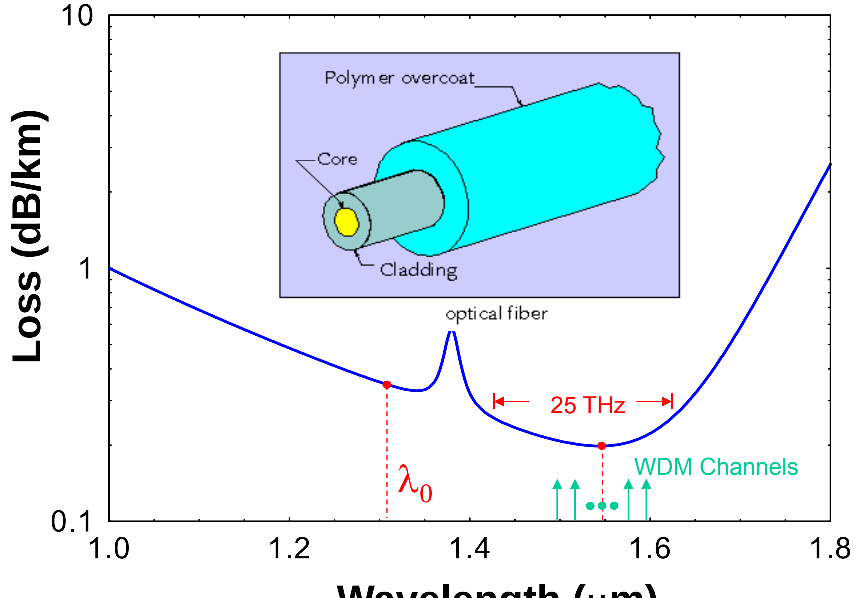


An Optical Transmission System



- > 100 Gb/s per fiber
- 4 Tbit/s per fiber is possible with EDFA

Optical Fiber (optical waveguide) Loss



S-band: 1270 nm --- 1530 nm

C-band : 1530 nm --- 1580 nm

L-band: 1580 nm --- 1610 nm

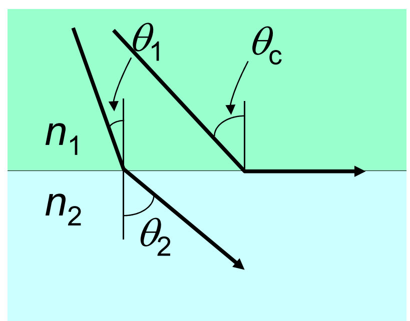
Waveguiding in Optical Fiber

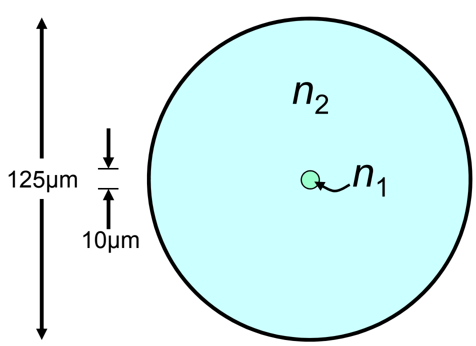
Snell's Law

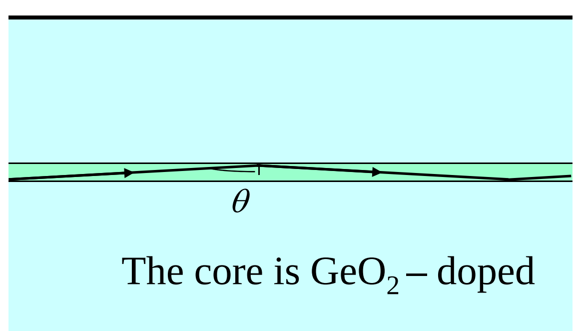
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Total Internal Reflection

$$\theta > \theta_c = \sin^{-1}(n_2/n_1)$$



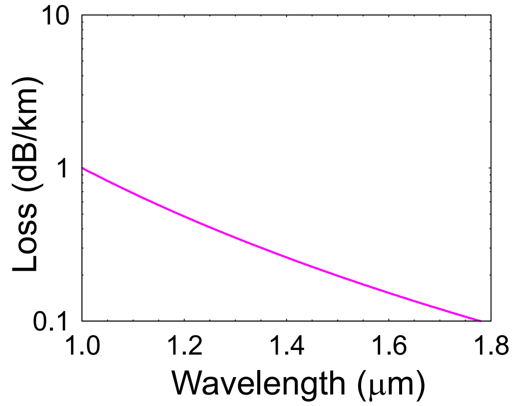




Note: High Speed transmission requires single-mode

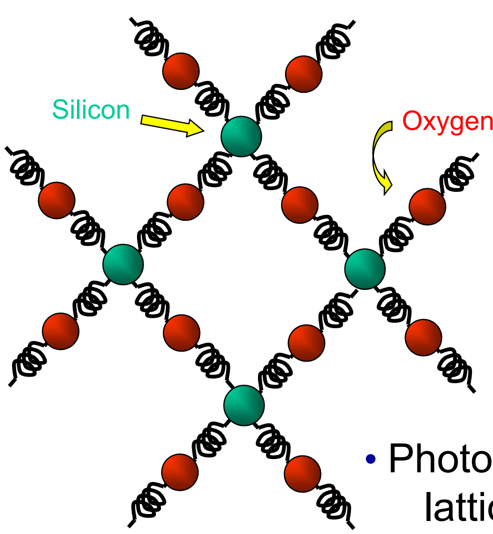
Fundamental Loss in Silica Glass
I. Rayleigh Scattering

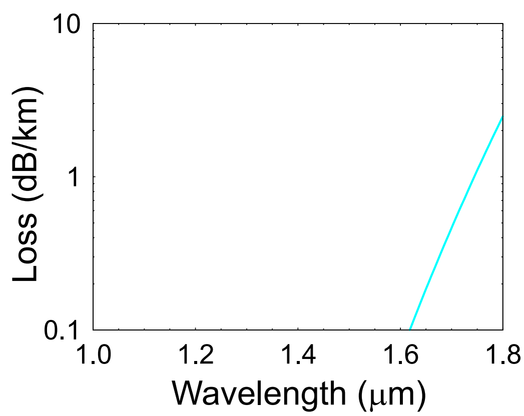
Loss = $A\lambda^{-4}$



- Light scattered by composition and density fluctuations
- Large effect for short wavelengths

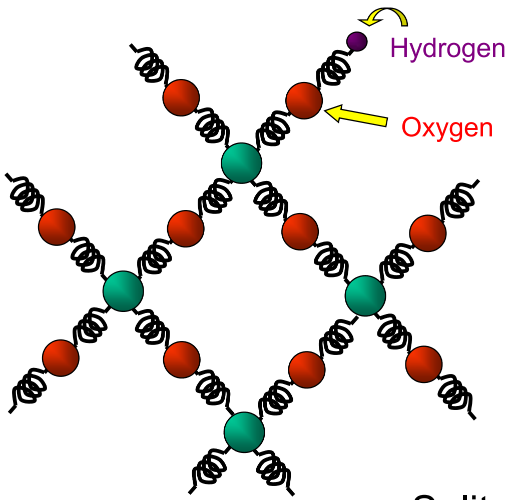
Fundamental Loss in Silica Glass
II. Lattice Vibrations (Phonons)

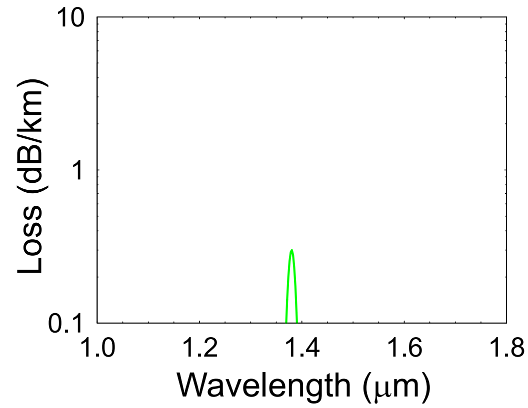




- Photons converted to lattice vibrations (TO @ ~ 960 cm^{-1})
- Increased loss for increased wavelength

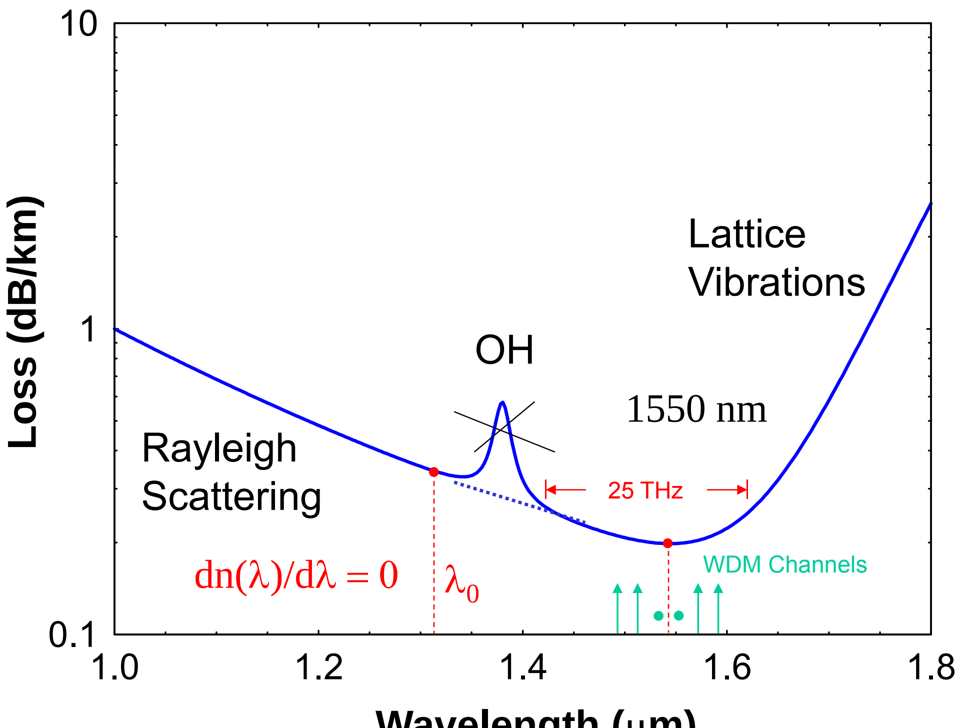
Extrinsic Loss in Silica Glass
Water Vibrations



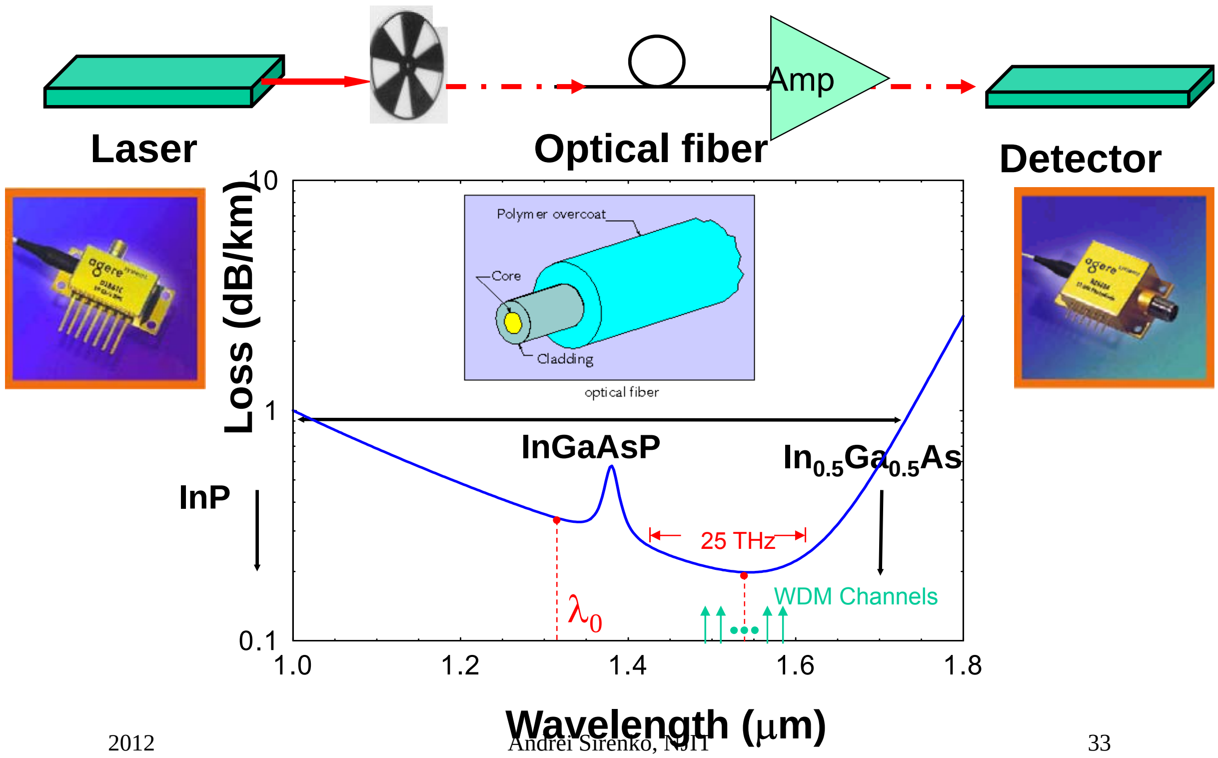


- Splits low-loss band into two “windows”
- Reduced or eliminated in modern SMF

Conventional Single-Mode Fiber Loss

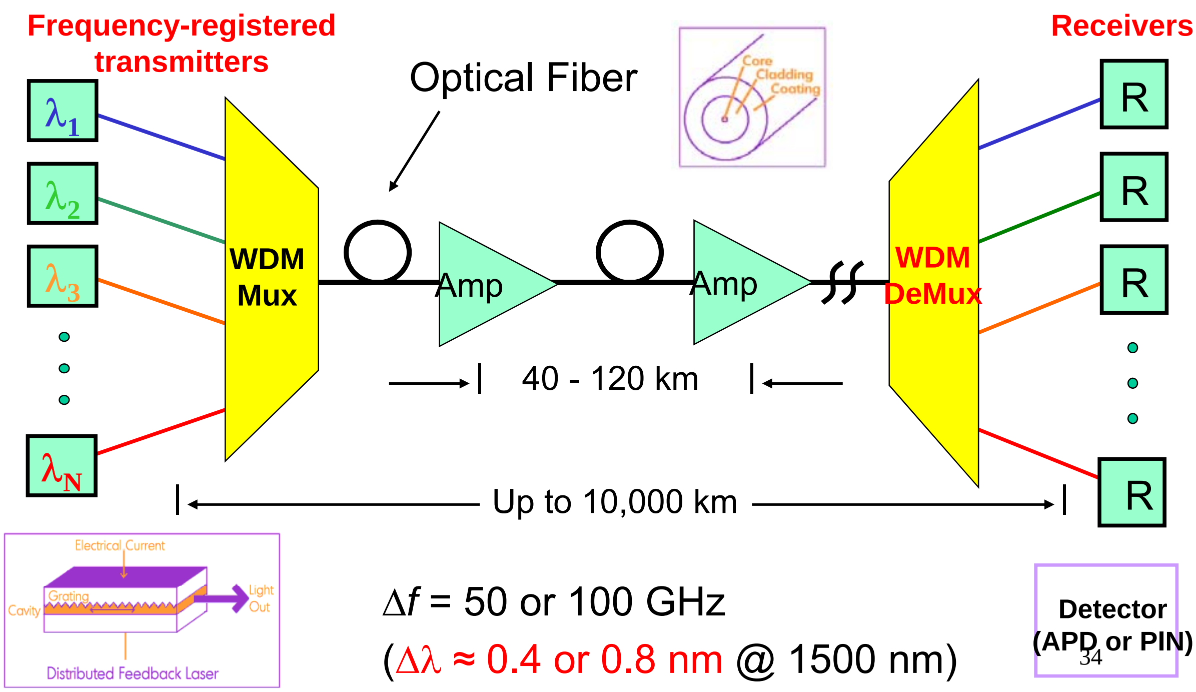


InP-based Optoelectronic devices



A WDM Optical Transmission System

λ_1, λ_2, λ_3, λ_4,… different lasers or one tunable laser

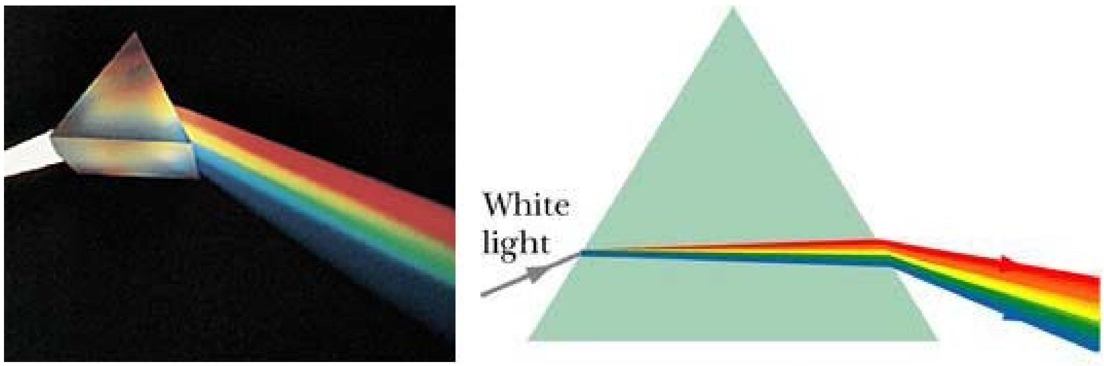


Δf = 50 or 100 GHz

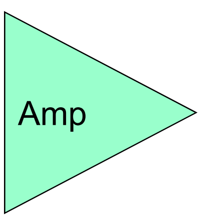
($\Delta\lambda \approx$ 0.4 or 0.8 nm @ 1500 nm)

Dispersion of the refractive index:

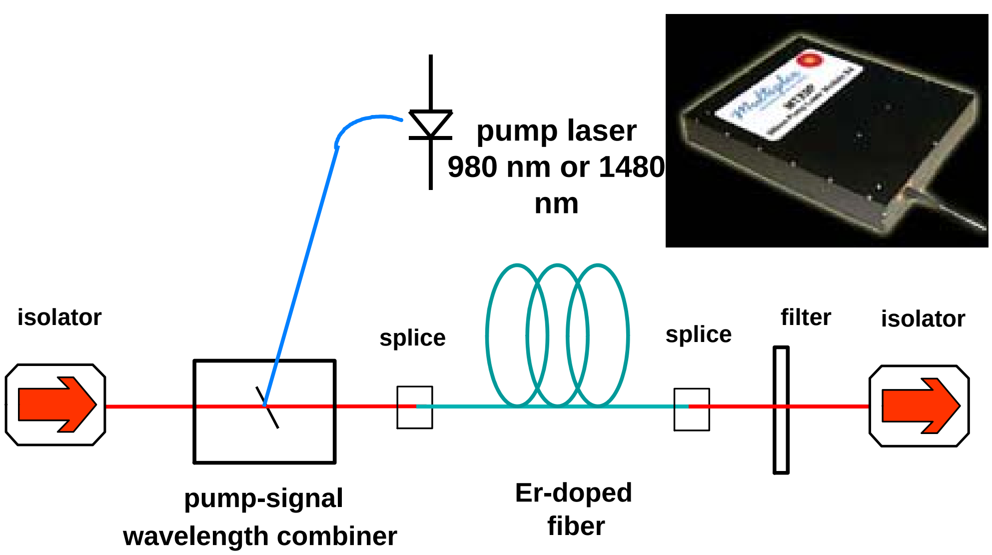
Newton's prism



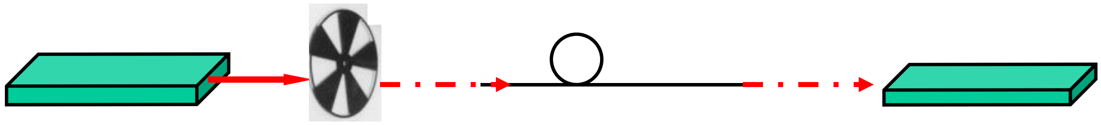
(a) (b)

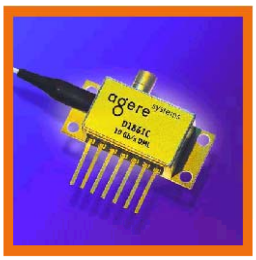


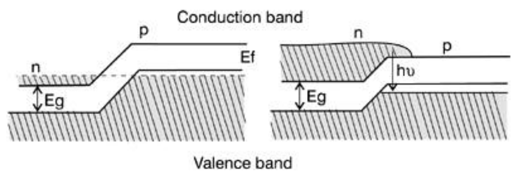
Erbium-Doped Fiber Amplifier (EDFA)



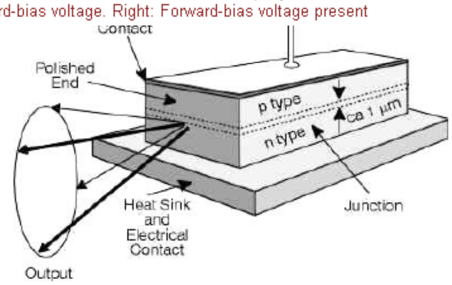
InP-based Optoelectronic devices



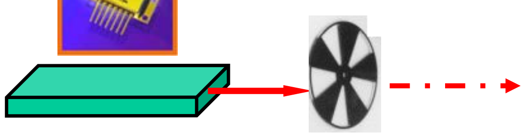


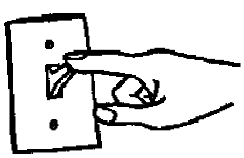


Band structure near a semiconductor p-n junction.
Left: No forward-bias voltage. Right: Forward-bias voltage present

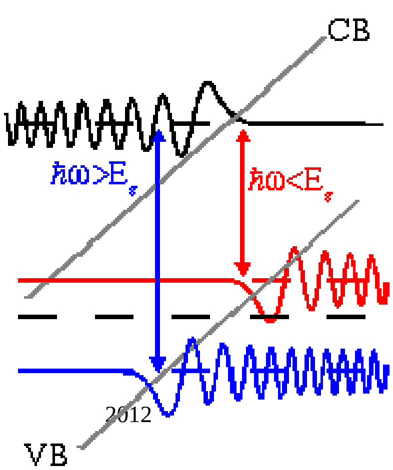


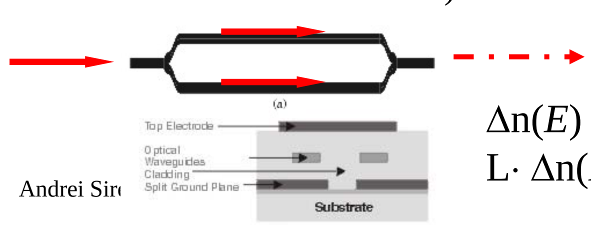
Light modulation at the GHz frequency





- Direct Modulation with the electrical current
- Electro absorption modulators
  Franz-Keldysh effect / Stark shift
- $LiNbO_3$ and InP-based Mach-Zehnder Modulator
  (E-field controlled constructive-destructive interference in waveguides)

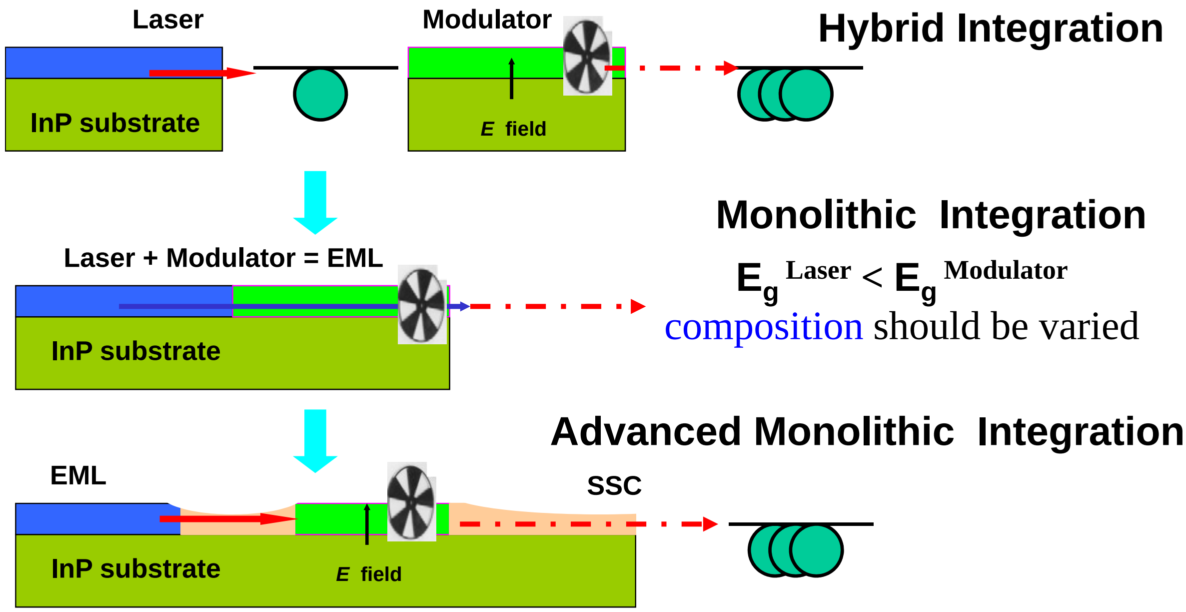




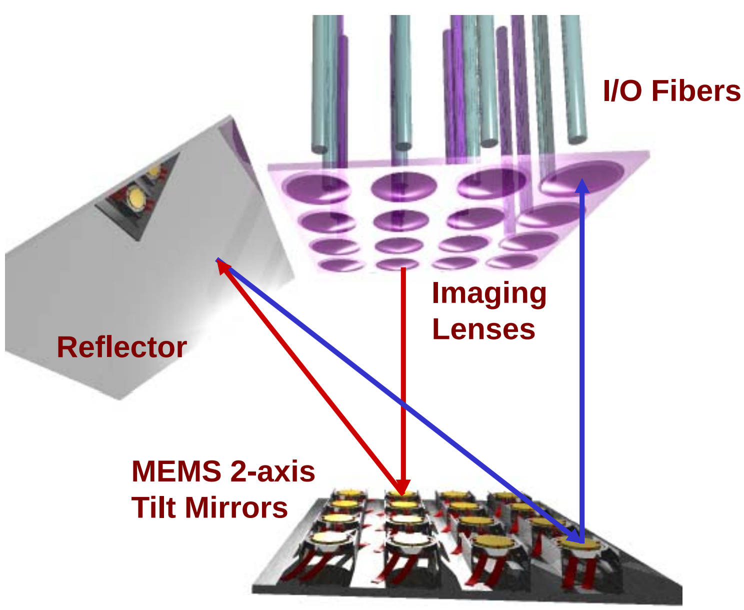
$\Delta n(E)$

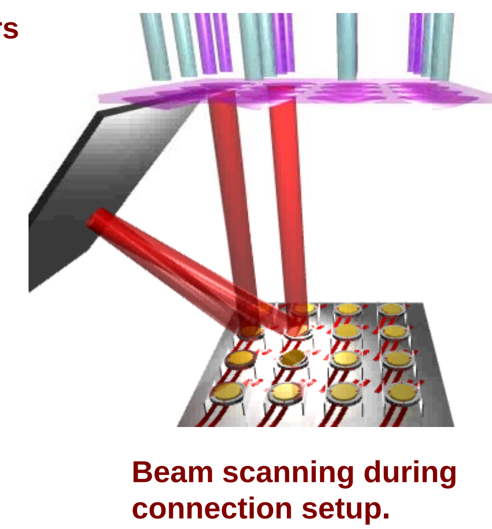
$L \cdot \Delta n(E) = \lambda$

EML SAG Structures
for integration of optoelectronic devices



MEMS OXC-- 2N Mirror Design





Beam scanning during connection setup.

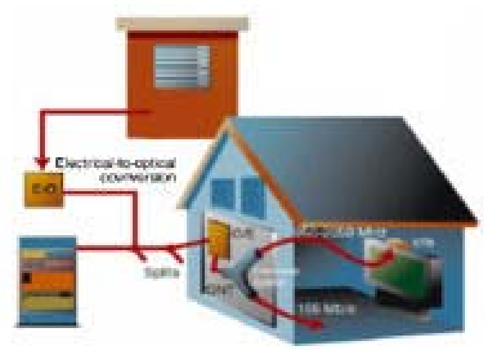
2N MEMS mirrors in an NxN single-mode fiber optical crossconnect.

Lucent Technologies
Bell Labs Innovations

Future of the Fast Telecom:

combination of InP-based 40Gbit/s and CMOS or/and SiGe technology

Driving Forces:



- Image transfer, sharing, and analysis
- Military and Medical applications
- National Security (40 Gbit/s)
- Fiber-to-the-Premises (FTTP) for

High-speed multimedia content and services
Interactive Video and TV on demand

Will the customers pay for that ???

Michelson's Interferometer