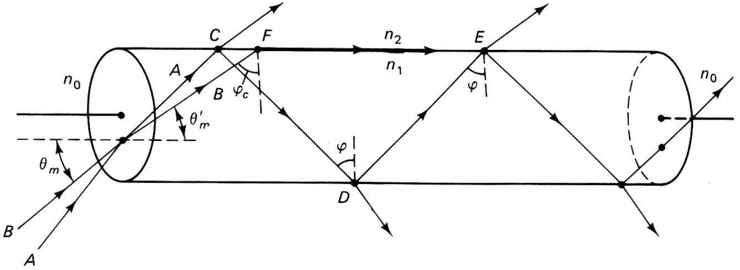
Optical fibers I

- Consider light propagating in a cylinder of dielectric media as shown below.
- When the angle of incidence φ is larger than the critical angle

$$n_1 \sin \varphi_c = n_2$$

then a large fraction of the light will remain within the cylinder. One can bend the fiber within reason.

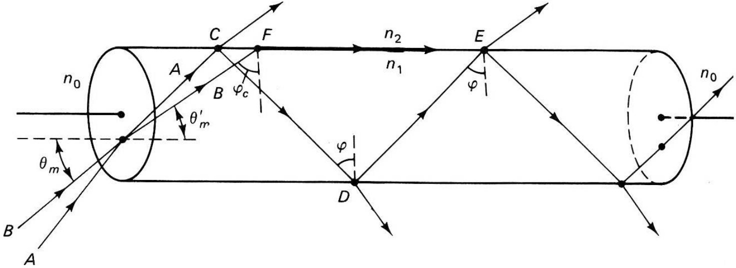


Optical fibers II

- Since $\theta'_m = (\pi/2 - \varphi_c)$, we have $\sin\theta'_m = \sin(\pi/2 - \varphi_c) = \cos\varphi_c$
- Now $\cos\varphi_c = \sqrt{1 - \sin^2\varphi_c}$ so

$$\begin{aligned} \text{N.A.} = n_0 \sin\theta_m &= n_1 \sin\theta'_m = n_1 \cos\varphi_c \\ &= n_1\sqrt{1-\sin^2\varphi_c} = n_1\sqrt{1-(\frac{n_2}{n_1})^2} \\ &= \sqrt{n_1^2 - n_2^2} \qquad (1) \end{aligned}$$

gives the numerical aperture of the fiber (its angular acceptance).

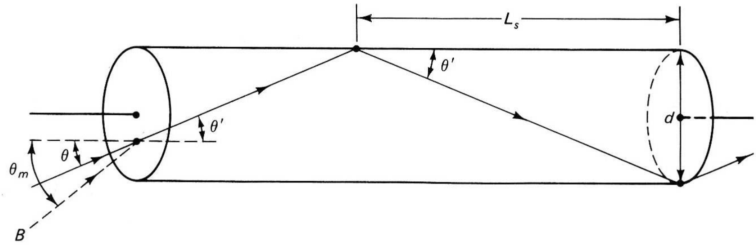


Optical fibers III

There's a skip distance L_s between two successive reflections of

$$\tan\theta' = \frac{d}{L_s} \qquad \Rightarrow \qquad L_s = \frac{d}{\tan\theta'} = d\sqrt{\left(\frac{n_1}{n_0\sin\theta}\right)^2 - 1} \qquad (2)$$

using Snell's law to relate to the incoming angle.



Optical fibers IV

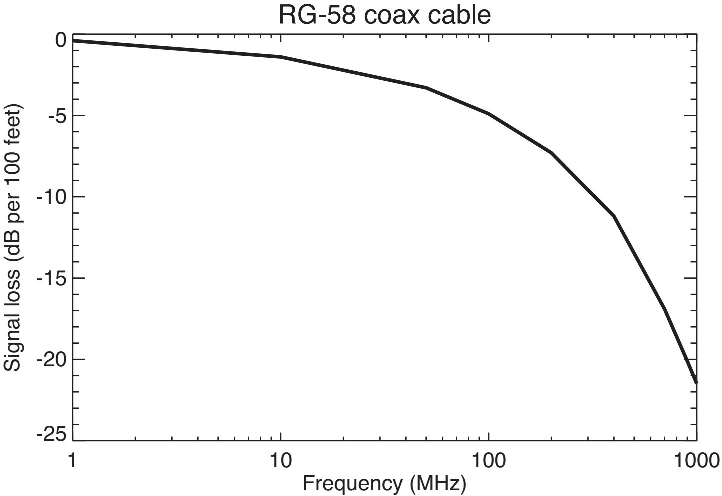
- Consider light making m bounces relative to light traveling straight down the fiber. We want the light to all have the same phase within $\pi/2$ to have it propagate together (Rayleigh quarter wave criterion).
- We therefore want to meet the condition

$$m\left[\varphi_r + 2\pi\frac{n_1}{\lambda}\left(\sqrt{L_{s,\ \max}^2 + d^2} - L_s\right)\right] \leq \frac{\pi}{2} \tag{3}$$

  This will give a limit on the diameter of the fiber.
- Note that optical frequencies are on the order of 10^{15} Hz, whereas capacitance in electrical cables tends to limit them to working at around 10^9 Hz.
- One can switch multiple optical frequencies (light colors) on one fiber: wavelength dispersive multiplexing.

Coax cables

Here's a plot of signal loss in RG-58 coax cable (the kind we use in lab, with BNC connectors):



Optical fibers: transmission

Here's a look at the spectral transmission of glass fibers (from Pedrotti and Pedrotti):

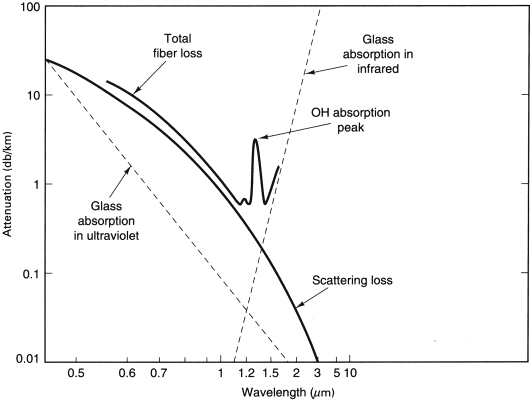


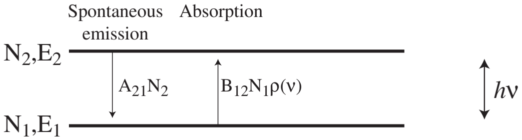
Figure 24-6 Contributions to the net attenuation of a germanium-doped silica glass fiber. [From H. Osanai, T. Shioda, T. Moriyama, S. Araki, M. Horiguchi, T. Izawa, and H. Takara, "Effects of Dopants on Transmission Loss of Low-OH-Content Optical Fibers," *Electronics Letters* 12, No. 21 (October 14, 1976): 550. Adapted with permission.]

Fiber optics and telecom

Here's the eighteen-year history of the stock price of Corning:

Einstein and radiation

- Consider a two-level system, with energies $E_2 - E_1 = h\nu$, and populations N_1 and N_2:



- **Spontaneous emission**: the rate at which we lose electrons from state N_2 is proportional to the number of electrons in that state:

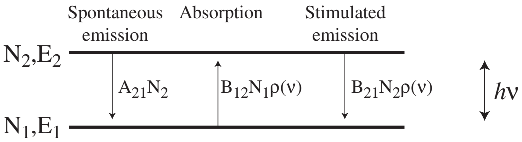
$$\left(\frac{dN_2}{dt}\right)_{\text{spont}} = -A_{21}N_2 \tag{4}$$

- **Absorption**: the rate at which we pump electrons up to state N_2 is proportional to the number of electrons in state N_1 and the photon density $\rho(\nu)$:

$$\left(\frac{dN_1}{dt}\right)_{\text{abs}} = -\left(\frac{dN_2}{dt}\right)_{\text{abs}} = -B_{12}N_1\rho(\nu) \tag{5}$$

Einstein and radiation II

- Einstein proposed a third process:



- **Stimulated emission**: we can also drive transitions from state 2 to state 1 in proportion to the population of state 2 and the photon density $\rho(\nu)$:

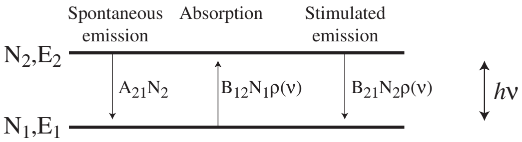
$$\left(\frac{dN_2}{dt}\right)_{\text{stim}} = -B_{21}N_2\rho(\nu) \tag{6}$$

- And remember our other two processes:

$$\left(\frac{dN_2}{dt}\right)_{\text{spont}} = -A_{21}N_2 \qquad \text{and} \qquad \left(\frac{dN_2}{dt}\right)_{\text{abs}} = B_{12}N_1\rho(\nu)$$

Einstein and radiation III

- Assume thermodynamic equillibrium, and assume $\rho(\nu)$ is the Planck blackbody spectrum.



- With the system in equilibrium, N_1 and N_2 evolve towards constant values. As a result,

$$\frac{dN_2}{dt} = 0 = -N_2 A_{21} - N_2 B_{21} \rho(\nu) + N_1 B_{12} \rho(\nu) \qquad (7)$$

which gives

$$\begin{aligned} (N_1 B_{12} - N_2 B_{21}) \rho(\nu) &= N_2 A_{21} \\ \rho(\nu) &= \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} = \frac{A_{21}}{B_{12}(N_1/N_2) - B_{21}} \end{aligned}$$

Einstein and radiation IV

- Again,

$$\rho(\nu) = \frac{A_{21}}{B_{12}(N_1/N_2) - B_{21}}$$

- Now use $\rho(\nu)$ as provided by a Planck blackbody spectrum, and realize that $N_1/N_2 = \exp[h\nu/k_B T]$. This gives

$$\begin{aligned}
\frac{8\pi h\nu^3}{c^3}\frac{1}{\exp[h\nu/k_B T] - 1} &= \frac{A_{21}}{B_{12}\exp[h\nu/k_B T] - B_{21}} \\
\frac{8\pi h\nu^3}{c^3}B_{12}\exp[h\nu/k_B T] - \frac{8\pi h\nu^3}{c^3}B_{21} &= A_{21}\exp[h\nu/k_B T] - A_{21} \\
\left(\frac{8\pi h\nu^3}{c^3}B_{12} - A_{21}\right)\exp[h\nu/k_B T] &= \left(\frac{8\pi h\nu^3}{c^3}B_{21} - A_{21}\right) \\
\left(\frac{8\pi h\nu^3}{c^3}\frac{B_{12}}{B_{21}} - \frac{A_{21}}{B_{21}}\right)\exp[h\nu/k_B T] &= \left(\frac{8\pi h\nu^3}{c^3} - \frac{A_{21}}{B_{21}}\right)
\end{aligned}$$

- This must be true for any temperature T! The only way that can be so is for the quantities inside () to be zero on either side of the equation!

Einstein and radiation V

- Pick the right hand term:

$$\left(\frac{8\pi h\nu^3}{c^3} - \frac{A_{21}}{B_{21}}\right) = 0 \qquad \rightarrow \qquad \frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

  That is, the spontaneous emission coefficient A_{21} divided by the stimulated emission coefficient B_{21} scales like ν^3. Stimulated emission declines like ν^{-3} or λ^3 relative to spontaneous emission, so it's easier to get stimulated emission with microwaves than it is with x rays.

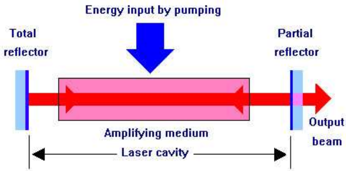
- Now use the above result in the left hand term:

$$\left(\frac{8\pi h\nu^3}{c^3}\frac{B_{12}}{B_{21}} - \frac{A_{21}}{B_{21}}\right) = 0 \rightarrow \frac{8\pi h\nu^3}{c^3}\left(\frac{B_{12}}{B_{21}} - 1\right) = 0 \rightarrow B_{12} = B_{21}$$

  That is, the stimulated emission and absorption coefficients are one and the same! Recall Fermi's golden rule for transition rates: the rate is the same for $1 \rightarrow 2$ as for $2 \rightarrow 1$.

Lasers

Who invented the laser? Many people were in the stew. Wikipedia has a good, concise history.



Laser cavity

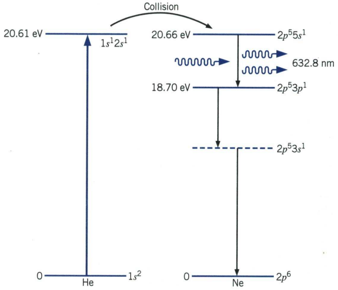
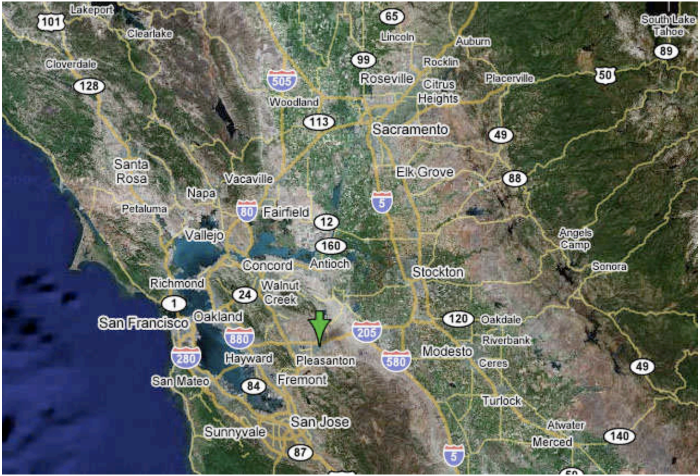


FIGURE 8.20 Sequence of transitions in a He-Ne laser.

Helium-Neon laser scheme (Krane Fig. 8.20)

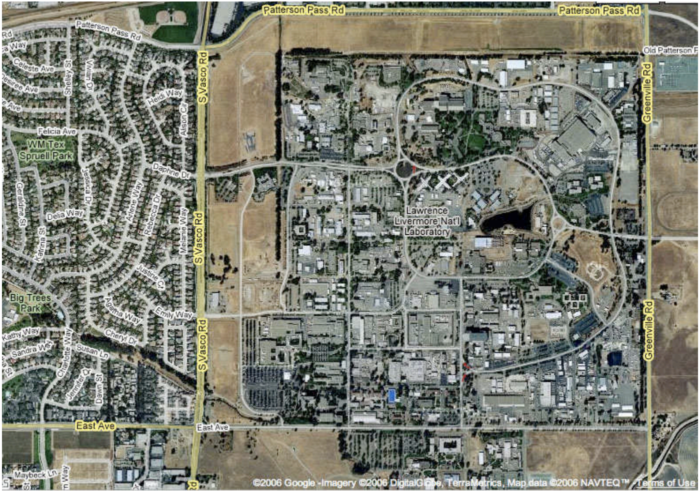
Let's go to Livermore

For the biggest, baddest laser around, let's go to Livermore; it's one of the two nuclear weapons physics lab, along with Los Alamos in New Mexico.



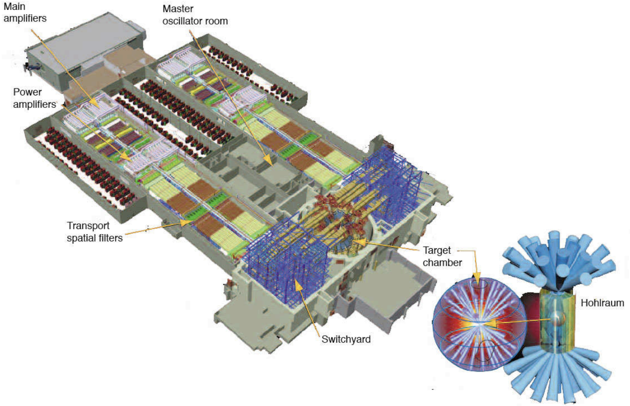
Livermore lab

Lawrence Livermore National Lab. NIF is at the upper right.



NIF: National Ignition Facility

Anticipated operation: 2009. Cost: $1B? Web site:
http://www.llnl.gov/nif/
192 beams (3072 slab amplifiers), total energy of 1.8 MJ, pulse duration 3–20 nsec. During those 3-20 nsec, the lasers emit a power of 5×10^{14} Watts. US electric power generating capacity: 1×10^{12} Watts.



NIF: an aerial view

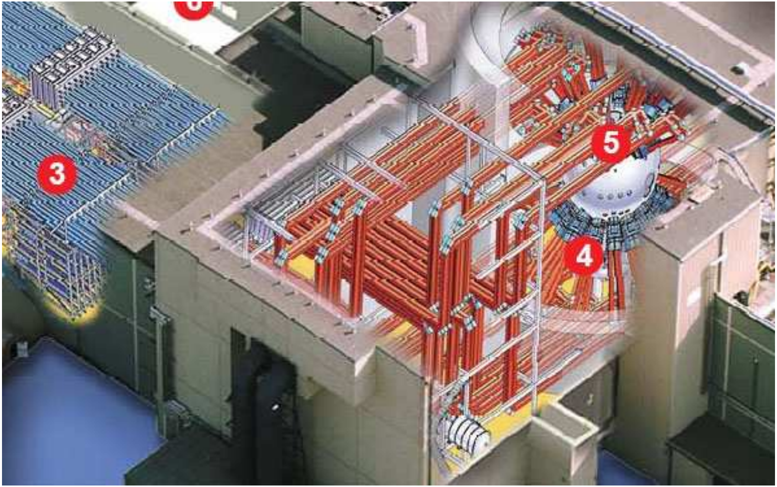
About the size of a football stadium:

NIF components

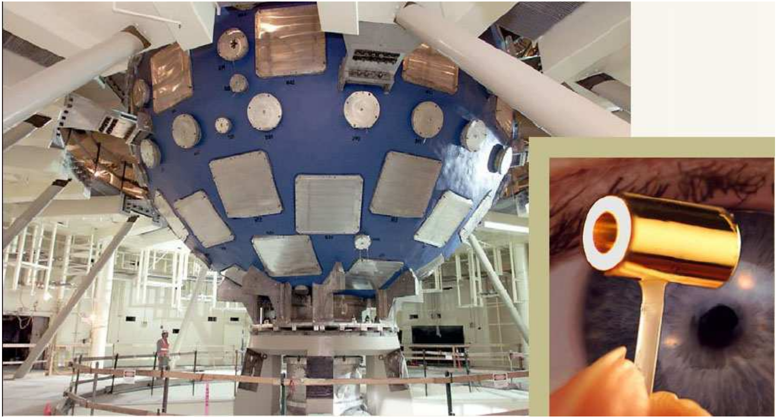
Part of one capacitor bank

One replaceable amplifier slab on its mounting robot

NIF target chamber

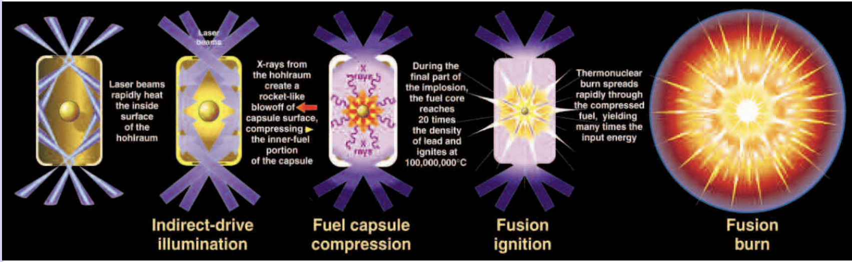


NIF target chamber II, and Hohlraum



Hohlraum leading to fusion

Direct laser heating of pellet produced too many nonuniformities. Indirect heating instead!



Mini H-bomb. Relevant to understanding weapons, supernovae. Future energy source???

Diode lasers

Recall that lasers need a population inversion and a dense photon field. $n \simeq 4$ for silicon so edges of chip are like half-silvered mirrors! See also Serway Figs. 12.44-46.

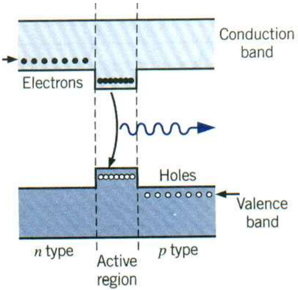


FIGURE 11.55 The energy bands in a diode laser. The active region has a smaller gap than the n-type and p-type regions on either side.

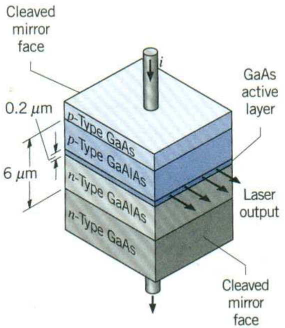


FIGURE 11.56 A diode laser. The lasing action occurs in the thin GaAs layer.