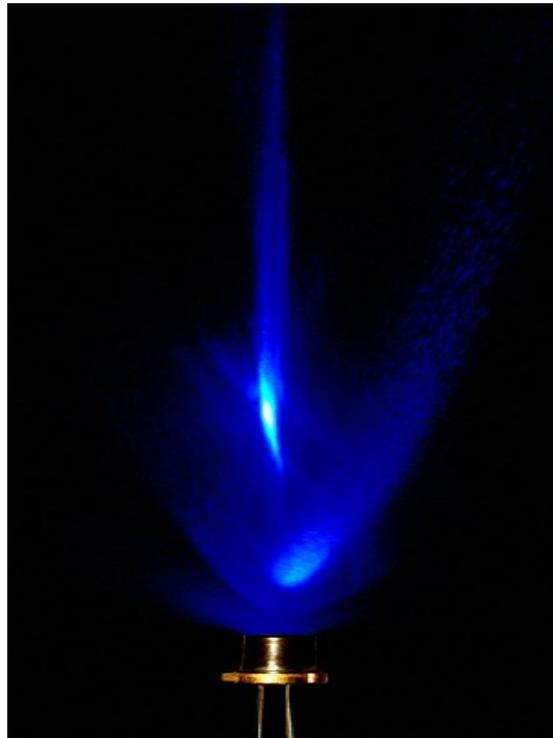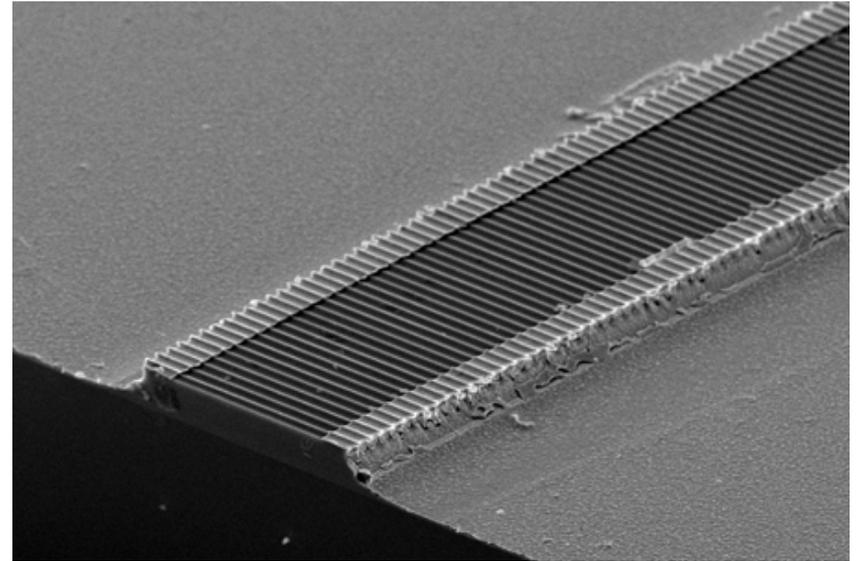# Semiconductor lasers

- Optical processes in semiconductors
- Absorption, gain, and pumping
- Types of semiconductor lasers
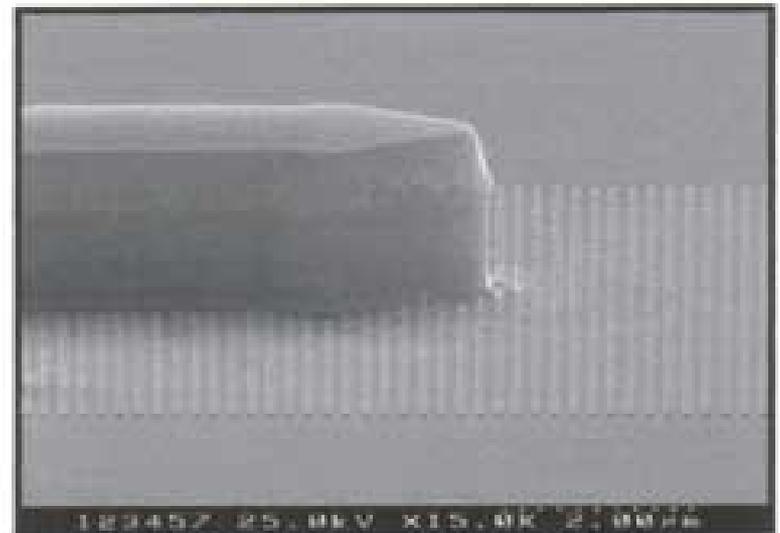

University of Neuchatel, Switz.

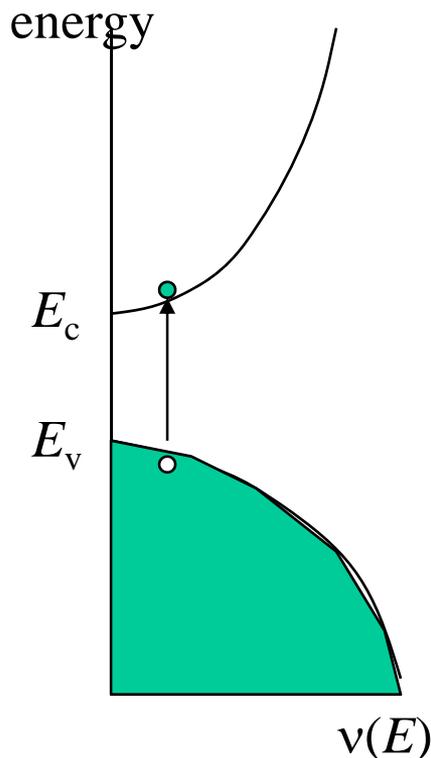Kagaku Co. GaInAsN 1.3 micron DFB

Osram Opto, GaN

Optical processes in semiconductors

Same processes we've been discussing (absorption, spontaneous emission, stimulated emission) all still relevant - just need to treat the electronic states correctly.

Consider a generic semiconductor:

energy

E_c

E_v

$\nu(E)$

Optical transitions must conserve energy and momentum.

Recall that the useful way to think about electrons in periodic solids is as Bloch states, characterized by a wavevector k and a band index.

Each band has an effective mass due to band curvature.

Initial and final states for absorption or emission are going to be Bloch states in different bands.

States and matrix elements

Recall that the generic form for the Hamiltonian for nonrelativistic charged matter has a term:

$$H = \frac{1}{2m}(\mathbf{p} - q\mathbf{A})^2 + ...$$

Just looking at the interaction term gives us

$$H' = -\frac{q}{m}\mathbf{p} \cdot \mathbf{A} = -\frac{q}{2m}A_0\mathbf{p} \cdot \hat{\mathbf{e}}\exp(i\mathbf{k}_{rad} \cdot \mathbf{r} - i\omega_0 t) + ...$$

Assuming our usual plane wave form for the radiation.

The matrix element between an initial state in the conduction band and a final state in the valence band is then:

$$\left\langle \psi_{v\mathbf{k}} \left| H' \right| \psi_{c\mathbf{k}'} \right\rangle = \frac{e}{2m}A_0 \exp(-i\omega_0 t)\mathbf{M}_{v\mathbf{k}c\mathbf{k}'}$$

where

$$\mathbf{M}_{v\mathbf{k}c\mathbf{k}'} = \int d\mathbf{r}\left\{ u_{v\mathbf{k}}^*(\mathbf{r})\exp[-i\mathbf{k} \cdot \mathbf{r}](\hat{\mathbf{e}} \cdot \mathbf{p}\exp[i\mathbf{k}_{rad} \cdot \mathbf{r}])u_{c\mathbf{k}'}^*(\mathbf{r})\exp[i\mathbf{k}'\mathbf{r}] \right\}$$

States and matrix elements

$$\mathbf{M}_{v\mathbf{k}c\mathbf{k}'} = \int d\mathbf{r} \left\{ u_{v\mathbf{k}}^*(\mathbf{r}) \exp[-i\mathbf{k}\cdot\mathbf{r}] (\hat{\mathbf{e}}\cdot\mathbf{p}\exp[i\mathbf{k}_{rad}\cdot\mathbf{r}]) u_{c\mathbf{k}'}^*(\mathbf{r}) \exp[i\mathbf{k'r}] \right\}$$

Here we've used our familiar Bloch wavefunctions. Remember that the u's have the same periodicity as the lattice, so we can expand them as a series using reciprocal lattice vectors:

$$u_{n\mathbf{k}}(\mathbf{r}) = \sum_j u_j(n,\mathbf{k}) \exp(i\mathbf{G}_j\cdot\mathbf{r})$$

Plugging these expansions in, we find

$$\mathbf{M}_{v\mathbf{k}c\mathbf{k}'} = \sum_j \sum_l u_j^*(v,\mathbf{k}) u_l^*(c,\mathbf{k}) \int d\mathbf{r} \left\{ \exp[-i(\mathbf{k}-\mathbf{k}_{rad}+\mathbf{G}_j)\cdot\mathbf{r}] (\hat{\mathbf{e}}\cdot\mathbf{p}) \exp[i(\mathbf{k'}+\mathbf{G}_l)\cdot\mathbf{r}] \right\}$$

Remember, **p** is an operator. Using it we get

$$\mathbf{M}_{v\mathbf{k}c\mathbf{k}'} = \sum_j \sum_l (\hbar\hat{\mathbf{e}}\cdot(\mathbf{k'}+\mathbf{G}_l)) u_j^*(v,\mathbf{k}) u_l^*(c,\mathbf{k}) \int d\mathbf{r} \left\{ \exp[-i(\mathbf{k}-\mathbf{k}_{rad}-\mathbf{k'}+\mathbf{G}_j-\mathbf{G}_l)\cdot\mathbf{r}] \right\}$$

Remember, we can write **r** as $\mathbf{R}_b+\rho$, where $\mathbf{R}_b$ points to unit cell b, and rho points to positions within the unit cell.

States and matrix elements

Doing this,

$$\mathbf{M}_{v\mathbf{k}c\mathbf{k}'} = \sum_{j}\sum_{l}\cdots\int_{cell} d\rho\left\{\exp[-i(\mathbf{k} - \mathbf{k}_{rad} - \mathbf{k}' + \mathbf{G}_{j} - \mathbf{G}_{l})\cdot\rho]\right\}$$

$$\times\sum_{b}\exp[i(\mathbf{k}' - \mathbf{k} + \mathbf{k}_{rad})\cdot\mathbf{R}_{b}$$

This only gives a nonzero total result if $\quad\mathbf{k}' + \mathbf{k}_{rad} \approx \mathbf{k}$

• This is basically conservation of momentum.

• Note that, since $\mathbf{k}_{rad}$ is usually small compared to the Bloch wavevectors, transitions are essentially *vertical*. This is another illustration of why *indirect* gap semiconductors are not optically active in bulk.

• Again, look at the pivotal role played by the periodicity of the lattice. You can see that breakdown of the Bloch picture for electrons could make a big difference here (*e.g.* optically active nanostructured silicon).

States and matrix elements

So, matrix elements for interband transitions in semiconductors look like a polarization factor (on the order of 1) times this sort of integral. Getting the units right, we can write:

Material system	$2|M|^2/m$ (in eV)
Ga As	28.8
$Al_x Ga_{1-x} As$ (x < 0.3)	29.83 + 2.85 x
$In_x Ga_{1-x} As$	28.8 - 6.6 x
In P	19.7
$In_{1-x} Ga_x As_y P_{1-y}$ (x = 0.47 y)	19.7 + 5.6 y

Jones, Harvard.

Remember, by Fermi's golden rule optical transition rates are proportional to these numbers.

Absorption

Beyond computing matrix elements between states at the band edges, we need to worry about densities of states, energetic constraints, and distribution functions.
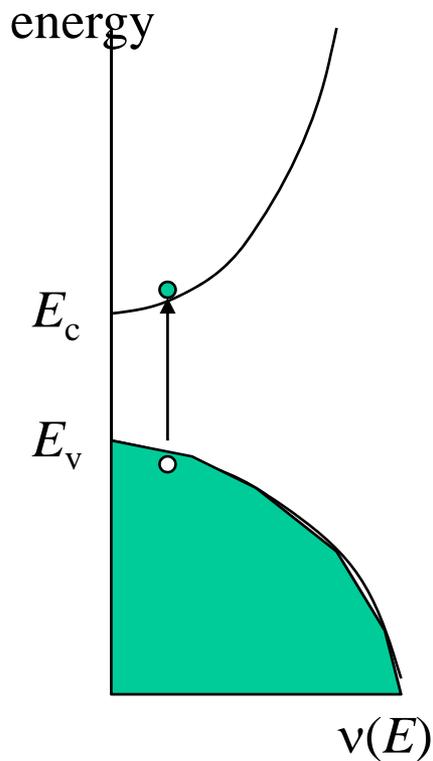
For a generic undoped direct gap semiconductor, one would assume that absorption should only kick in once the radiation has sufficient energy to overcome the band gap and produce electron-hole pairs.

That is, expect something like:

energy

E_c

E_v

$\nu(E)$

$\hbar\omega = E_c - E_v$

$\log(I_{out}/I_{in})$

0

ω
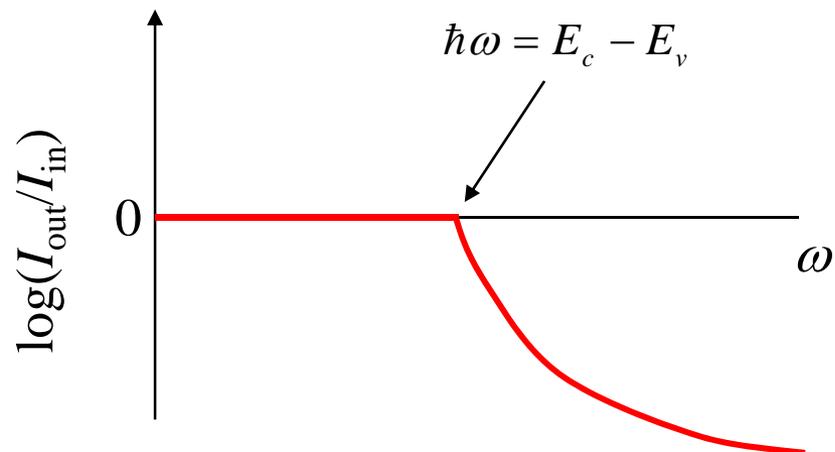
Emission

Let's look here first and see where band structure plays a role.
We know:

$$\hbar\omega = E_2 - E_1$$

$$\hbar k_c = \sqrt{2m_e^*(E_2 - E_c)}$$

$$\hbar k_v = \sqrt{2m_h^*(E_v - E_1)}$$

$$\hbar k_c = \hbar k_v$$

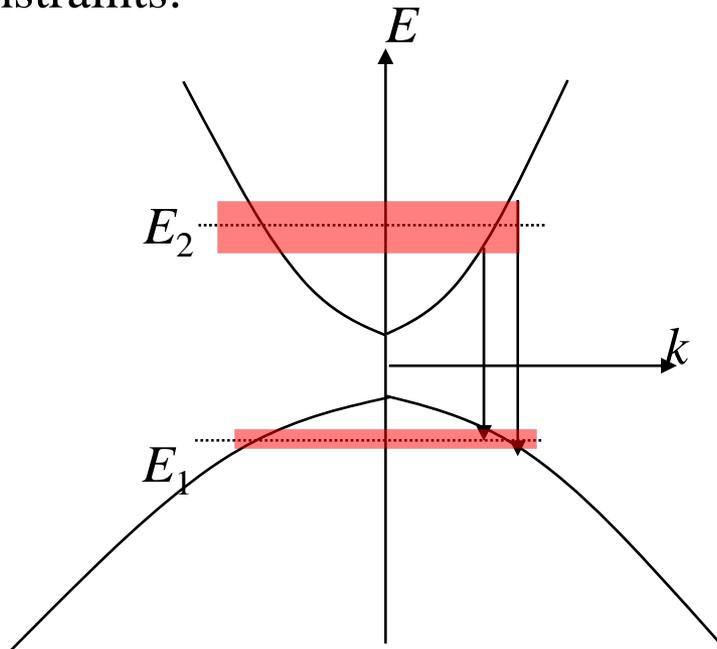$$\Rightarrow E_2 - E_c = \frac{m_h^*}{m_e^*}(E_v - E_1)$$
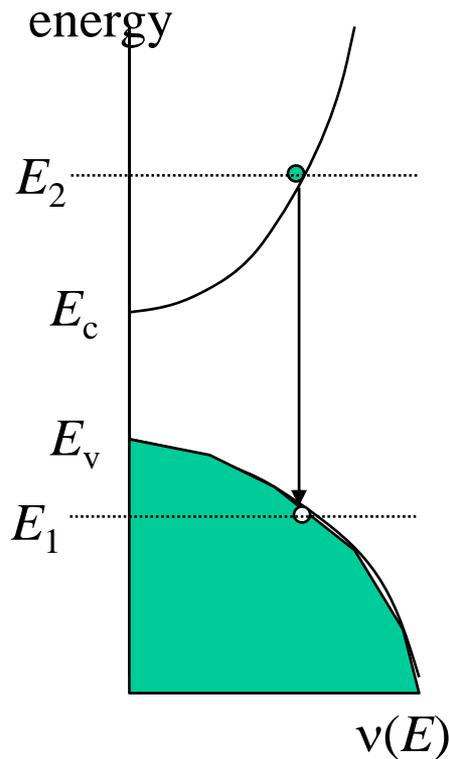
Notice that different band densities of states mean that E_2 and E_1 are not necessarily centered around midgap.

Want to do statistical average

As you might have guessed, we're going to end up doing a statistical average, worrying about contributions from different initial and final single particle states.

Need to see how differentials will work with our momentum and energy constraints:
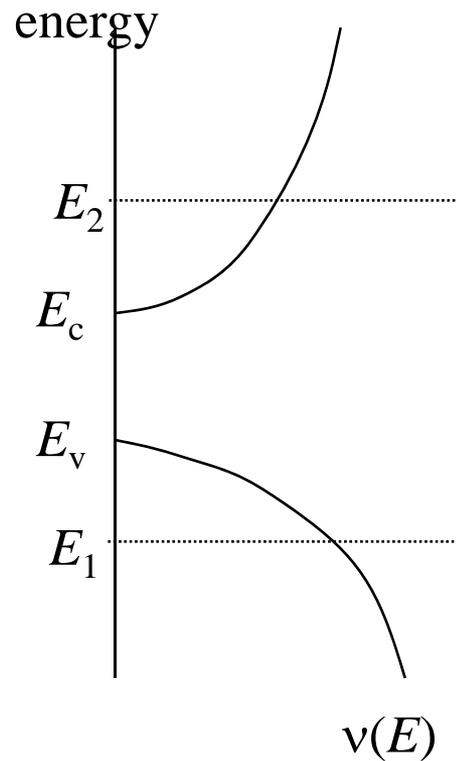
$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m_e^*} \rightarrow dE_2 = \frac{\hbar^2 k}{m_e^*} dk$$

$$\frac{\partial E}{\partial k} = \frac{\hbar^2 k}{m_h^*} \rightarrow dE_1 = \frac{\hbar^2 k}{m_h^*} dk$$

$$\rightarrow dE_1 = \frac{m_e^*}{m_h^*} dE_2$$

Joint density of states

How many states are there such that an intensity $I(\omega)d\omega$ produces transitions?

Need joint density of states:

$$\nu_{cv}(\hbar\omega) \equiv \frac{2}{8\pi^3} \int d\mathbf{k}\left\{\delta(E_c(\mathbf{k}) - E_v(\mathbf{k}) - \hbar\omega)\right\}$$

This expresses the constraint of energy conservation, and can be rewritten in terms of a surface integral in k-space over the surface defined by
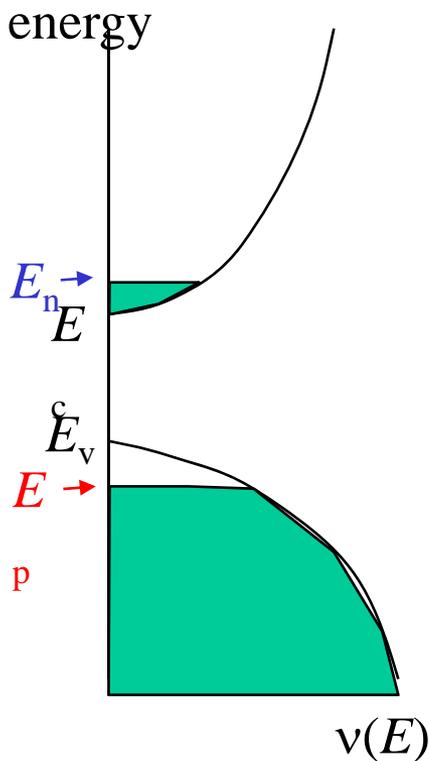
$$E_c(\mathbf{k}) - E_v(\mathbf{k}) - \hbar\omega = 0$$

The result is:

$$\nu_{cv}(\hbar\omega) = \frac{2}{8\pi^3} \int\int \frac{dS}{\left|\nabla_k(E_c - E_v)\right|_{E_c - E_v = \hbar\omega}}$$

energy

E_2

E_c

E_v

E_1

$\nu(E)$

- This is calculable for a given band structure.

- This is why optical measurements can tell us a lot about band structure.

Pumping

In this context, pumping is any process that leads to an out-of-equilibrium situation between the electrons and holes (conduction and valence bands):

energy

E_n →
E_c

E_v

E →

p

$\nu(E)$

Here there are different "quasi-Fermi levels" for the electrons and the holes.

This can be established by optical pumping, but is most commonly done by electrical bias of a *p-n* junction or something analogous.
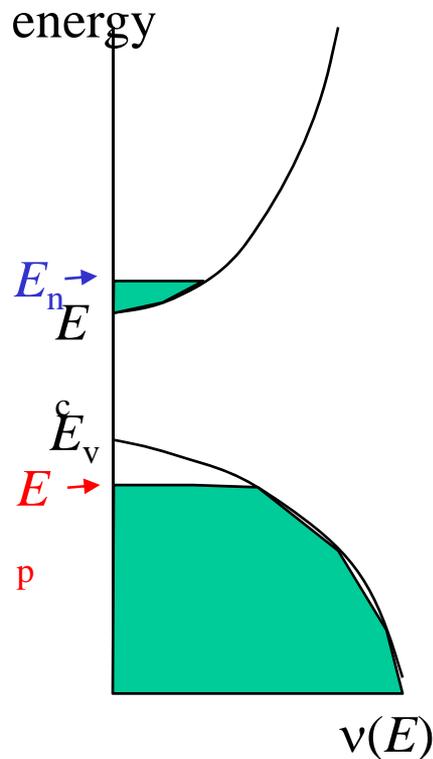
What happens as pump strength is increased?

• At first, stimulated emission can occur.

• Once frequency is larger than energy scale of pumping, rapid absorption kicks in.

energy

E_n

E_c

E_v

E_p

$\nu(E)$

$\hbar\omega = E_c - E_v$

$\hbar\omega = E_n - E_p$

$\log(I_{out}/I_{in})$

0

ω
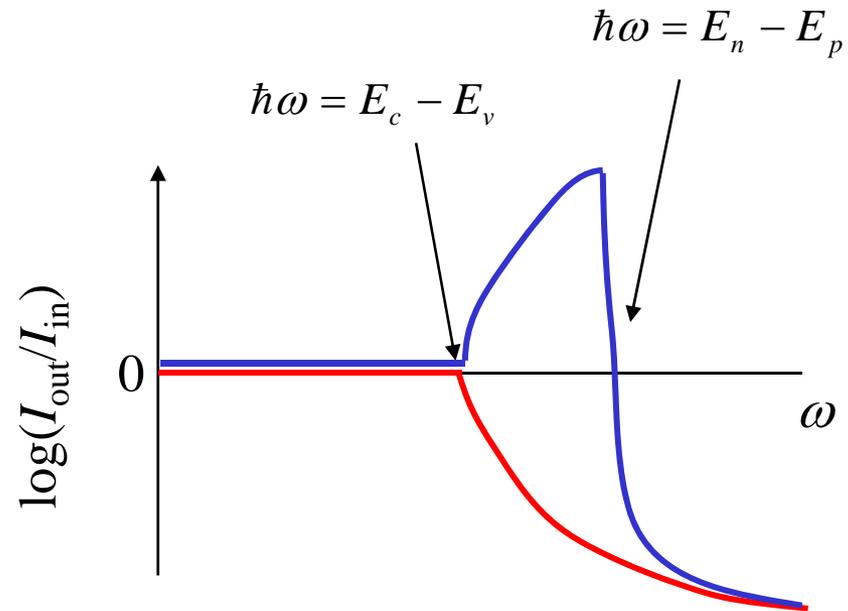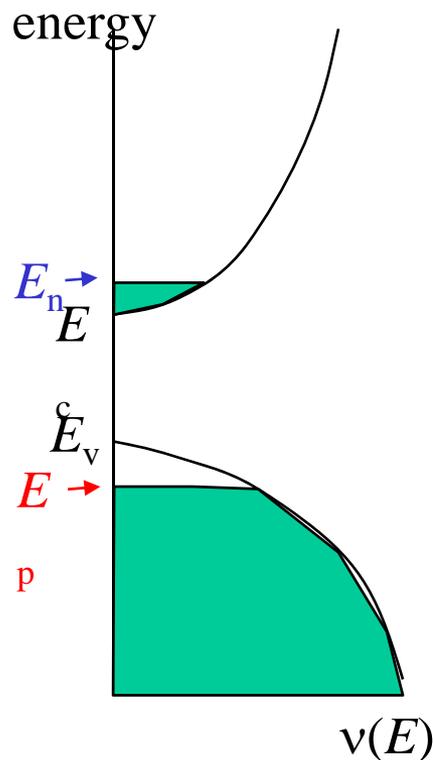
Let's see a little more why this happens.

Rate equations

Neglect spontaneous processes for the moment.

$$R_{1\rightarrow 2} = B_{12}\left(\frac{1}{c}I(\omega)d\omega\right)\upsilon_{vc}(\omega)\cdot\left[f_v(E_1)(1-f_c(E_2))\right]$$

$$R_{2\rightarrow 1} = B_{21}\left(\frac{1}{c}I(\omega)d\omega\right)\upsilon_{vc}(\omega)\cdot\left[f_c(E_2)(1-f_v(E_1))\right]$$

$$R_{2\rightarrow 1} - R_{1\rightarrow 2} = B_{21}\left(\frac{1}{c}I(\omega)d\omega\right)\upsilon_{vc}(\omega)\cdot\left[f_c(E_2)-f_v(E_1)\right]$$
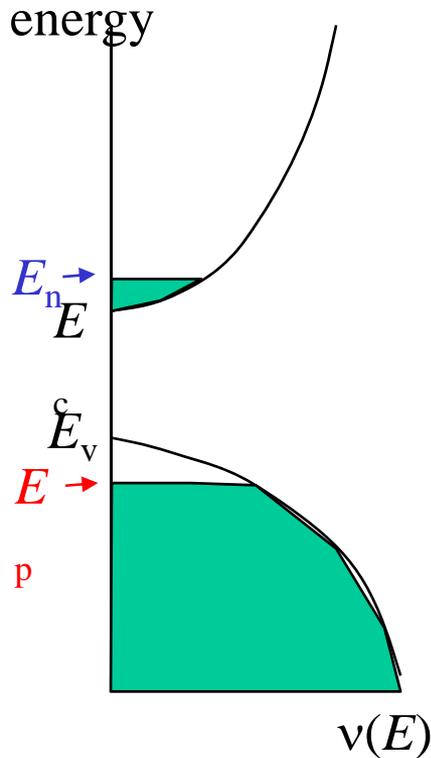
Can find characteristic length scale for change in intensity during propagation through medium:

$$\gamma(\omega) \equiv \frac{dI(\omega)/dz}{I(\omega)} = \frac{\text{power / volume}}{I(\omega)} = \frac{\hbar\omega\cdot[R_{2\rightarrow 1} - R_{1\rightarrow 2}]}{I(\omega)d\omega}$$

energy

E_{F_n}

E_c

E_v

E_{F_p}

$\nu(E)$

Rates

energy

E_n
E
c
E_v
E
p

$\nu(E)$

Rewriting,

$$\gamma(\omega) \equiv B_{21} \frac{1}{c} \nu_{vc}(\omega) \cdot \left[f_c(E_2) - f_v(E_1) \right]$$

Can find the joint density of states for the case of simple 3d parabolic bands:

$$\nu_{vc}(\omega) = \left(\frac{2 m_e^* m_h^*}{m_e^* + m_h^*} \right)^{1/2} \sqrt{\hbar\omega - E_{gap}}$$
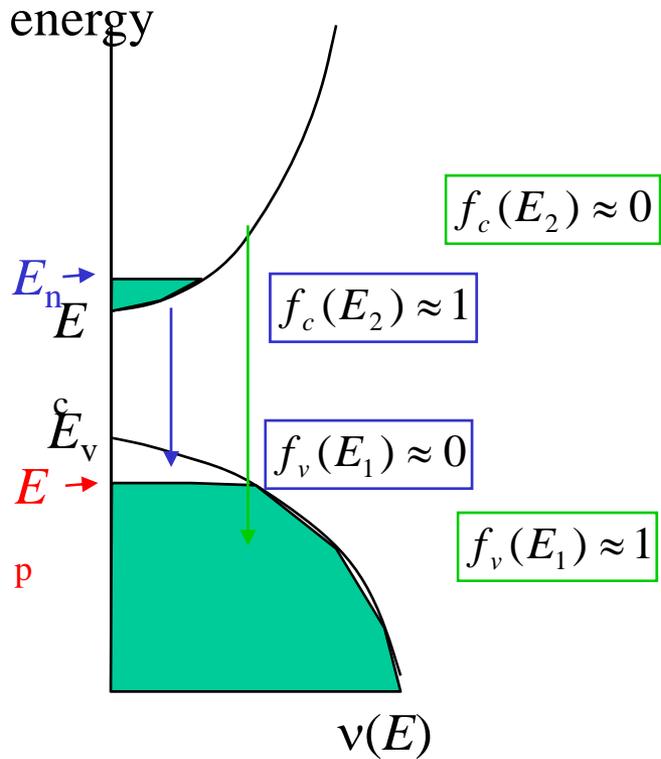
3 cases:

First, incident frequency below band gap.

- No absorption

- No emission

- $\gamma = 0$.

Transparency, gain, and absorption

Case II: $\qquad E_{gap} < \hbar\omega < E_n - E_p$

energy

Result: gain.

$f_c(E_2) \approx 0$

$\gamma \propto \sqrt{\hbar\omega - E_{gap}}$

E_n

E

$f_c(E_2) \approx 1$

E_c

E_v

$f_v(E_1) \approx 0$

E

Case III: $\qquad \hbar\omega > E_n - E_p$

p

$f_v(E_1) \approx 1$

$\nu(E)$

Result: loss.

$\gamma \propto -\sqrt{\hbar\omega - E_{gap}}$

Pumping methods

One could pump the system optically, but this is usually not done in real devices. Mostly done in special circumstances (trying to make an unusual system, *e.g.* semiconductor quantum dots, to lase).

More typically, pumping is done *electrically*.

The canonical example of this is a biased *pn* junction:

E_c

E_v

p side

n side
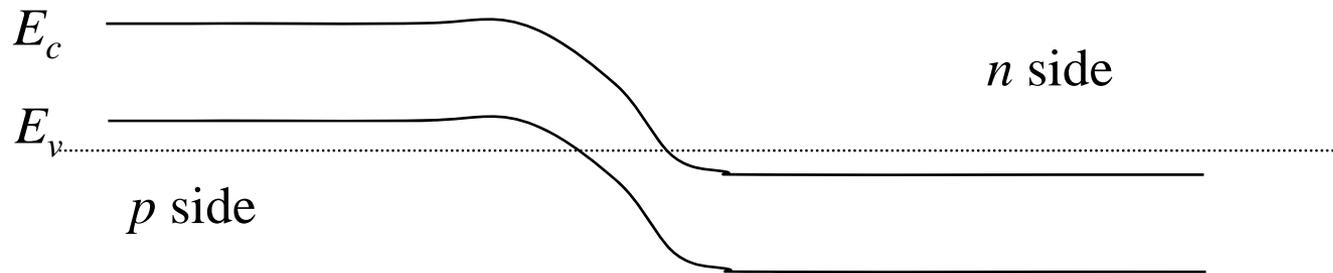
The recombination of electrons and holes happens in the depletion region, as carriers diffuse in.

Of course, one needs more than just *some* carriers to make a laser….

Current densities for electrical pumping

Here's where things get tricky:

Recombination rate ~ n x p.

• To maintain steady state, the input current must be equal to the recombination rate.

• To get densities of states up to the point where anything useful can be done requires $n \sim p \sim 10^{18}$ / cm^3.

• Can plug in numbers, and find current density ends up on the order of 10 kA/cm^2 (!).

Homojunction laser

One can imagine actually making a *pn* junction system like this, from, say, GaAs.

One complication:

- We want to get the light out.

- The light generated is higher in energy than the band gap of GaAs.

- The leads therefore can *absorb* it readily.

Clearly what we really want to do is something clever: arrange things so that the source and drain electrodes are *transparent* at the frequency generated by the laser.

This is equivalent to working in a 4-level (nonsemiconductor) laser, where $E_{pump} = E_4 - E_1 > E_3 - E_2$.

Heterojunction laser

Once again, MBE technology is a huge help. The key is the heterojunction laser:

E_c _____⌐‾‾‾‾‾‾‾‾‾‾‾‾‾‾‾‾‾

E_v _____⌐‾‾‾‾‾‾‾⌐_____
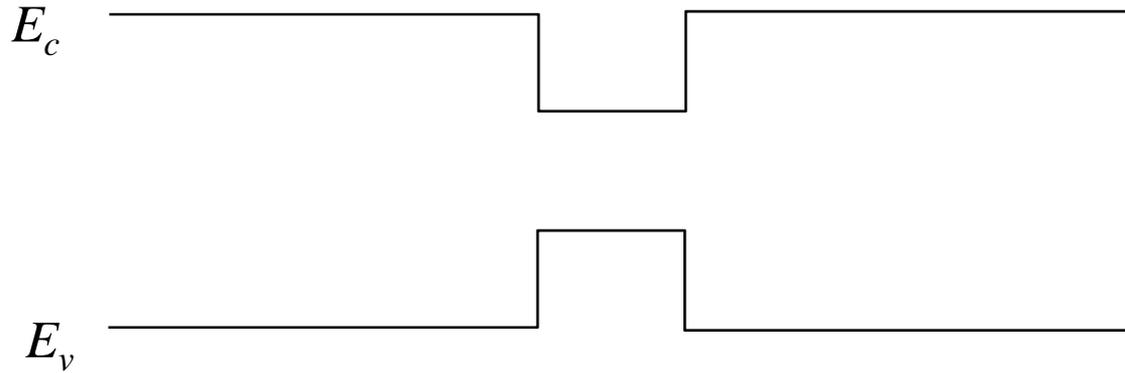
When the well width is small enough that confinement effects really start to matter, this is called a quantum well laser.

Bandwidth considerations

All we've shown is that it's possible to get light amplification by stimulated emission in these semiconductor systems.

How do we really make a working laser? We need a *cavity* - we need to build up a population of photons in a particular mode so that the Bose factor in stimulated emission really works for us.
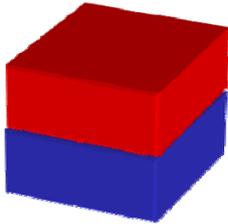
If this is a slab of *pn* material, and we have cleaved mirror-like facets, we've made a cavity. What are the modes?

In a long 1-d cavity, modes are spaced in frequency by *c/2nL*, the light travel time up the cavity and back. For GaAs and $L = 250$ microns, the modes are spaced by ~ 170 GHz.

Note that the *gain bandwidth*, is set by the voltage we apply, which can be much larger (~ 10 THz in GaAs).

Result of simple cleaved surface cavity:

Power spectrum

raw emission profile

cavity modes
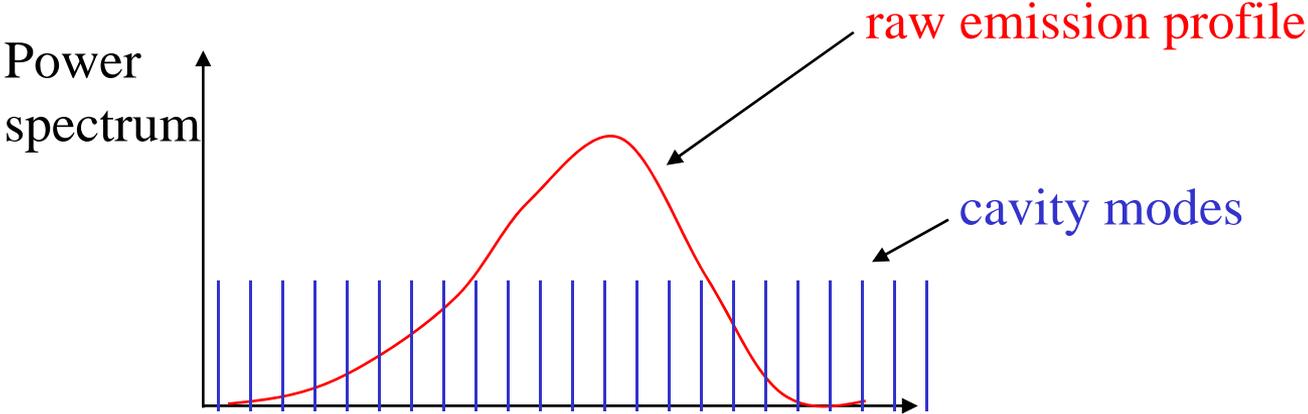
Result is a *multimode* laser:

Relative power spectrum
– frequency
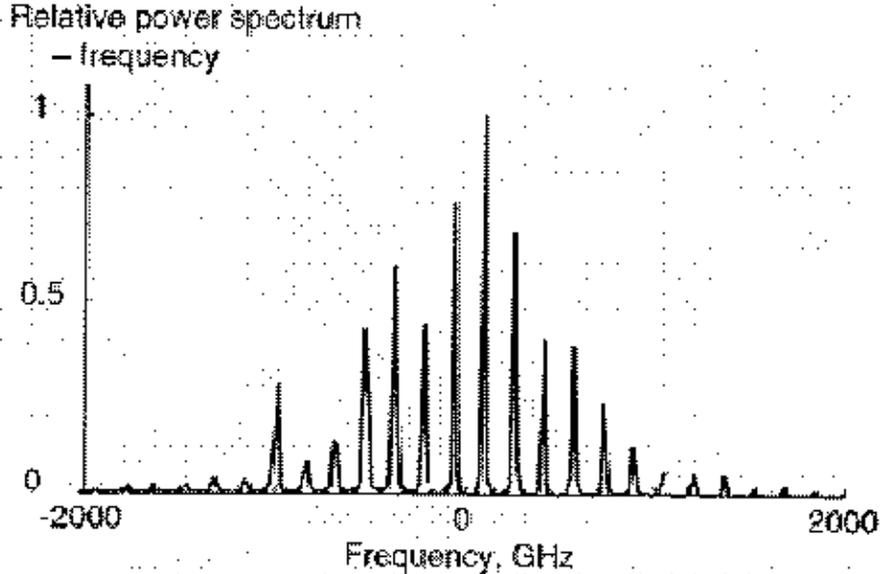
from Carroll, *Distributed Feedback Semiconductor Lasers*

Types of cavities

- External cavities – can be tunable

- Cleaved surfaces with distributed feedback (DFB)

- Distributed Bragg reflectors

Goals:

- Single mode operation

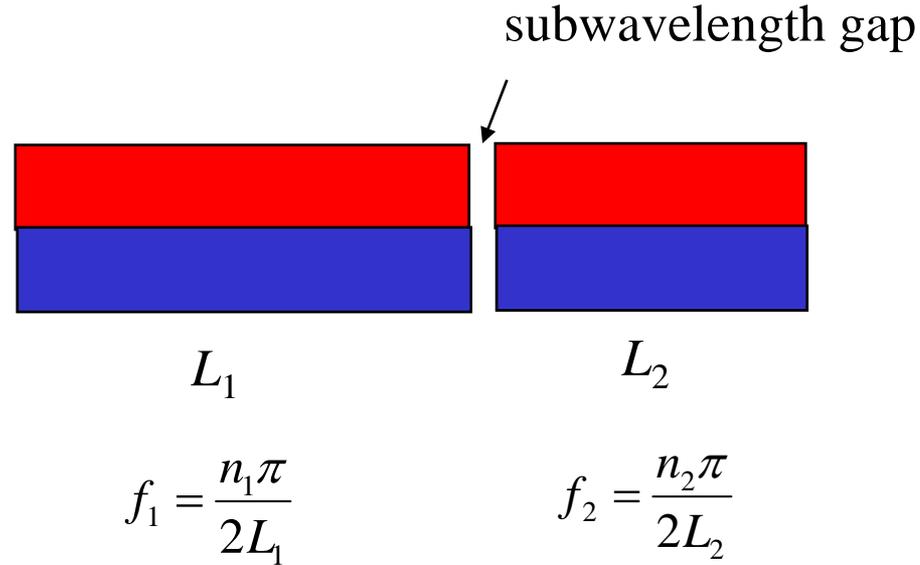- Manufacturable

- Stable

- Low parasitic losses

- Ideally, tunable.

External cavity (tunable!)

Antireflection coating
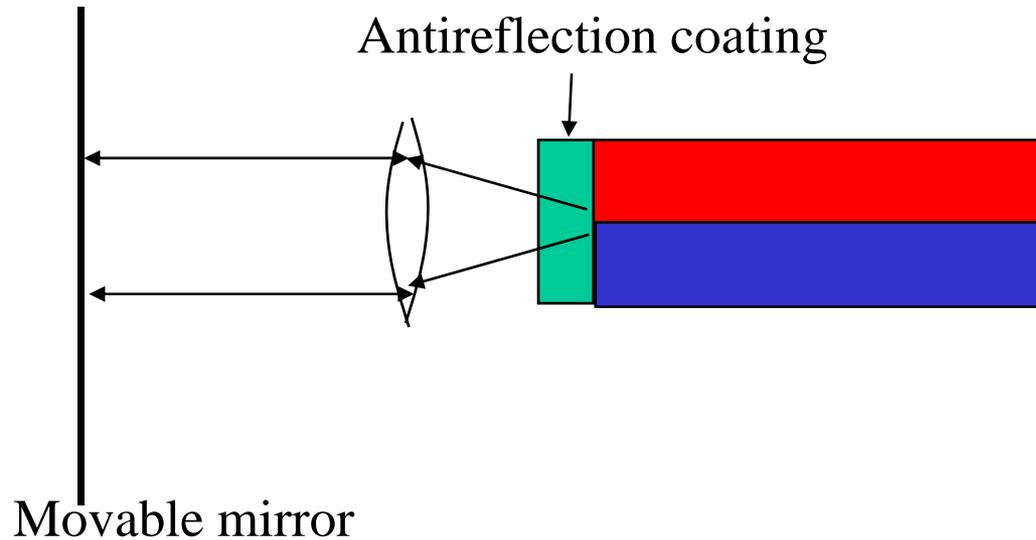
Movable mirror

Can have linewidths as small as 1 MHz.

Can be tunable over broad frequency range.

Needs moveable mirror – expensive + limits stability

Coupled media

subwavelength gap

$$L_1 \qquad\qquad L_2$$

$$f_1 = \frac{n_1 \pi}{2L_1} \qquad\qquad f_2 = \frac{n_2 \pi}{2L_2}$$

Coupling of modes of two separate multimode cavities via evanescent fields.

Tough to get good stability and well-controlled linewidths.

External diffraction grating

Antireflection coating

rotatable diffraction grating
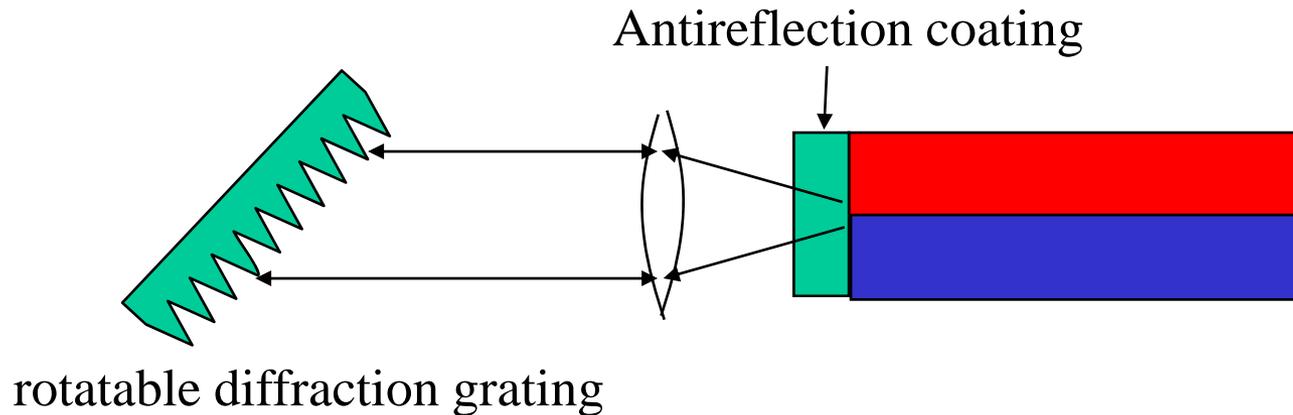
Uses Bragg condition for diffraction to select particular wavelengths with high precision – you know the selectivity of a grating goes like 1 / N, the number of ridges.

Can get linewidths as narrow as 100 kHz.

Can tune across wavelengths by as much as 10 nm.

Again, expensive – requires rotating grating.

DFB: incorporating the grating directly

Can also do this with a waveguide material in proximity to the active region, coupled by evanescent fields.

Distributed feedback grating selects the mode with intensity commensurate with periodic index variation.

Ridge spacing = $\lambda/2$.

Again, linewidth goes like $1/N$, number of ridges – can be narrower than spacing between modes.
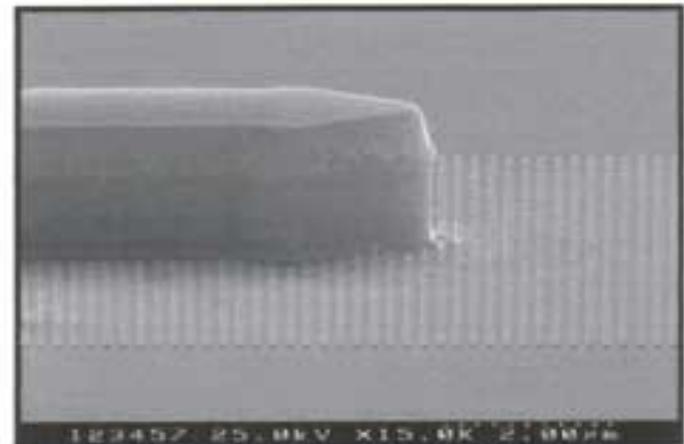
DBR: dielectric mirrors to the rescue.

Can position DBRs outside the active region:

This adds the additional possibility of incorporating tuning:

electrooptic material
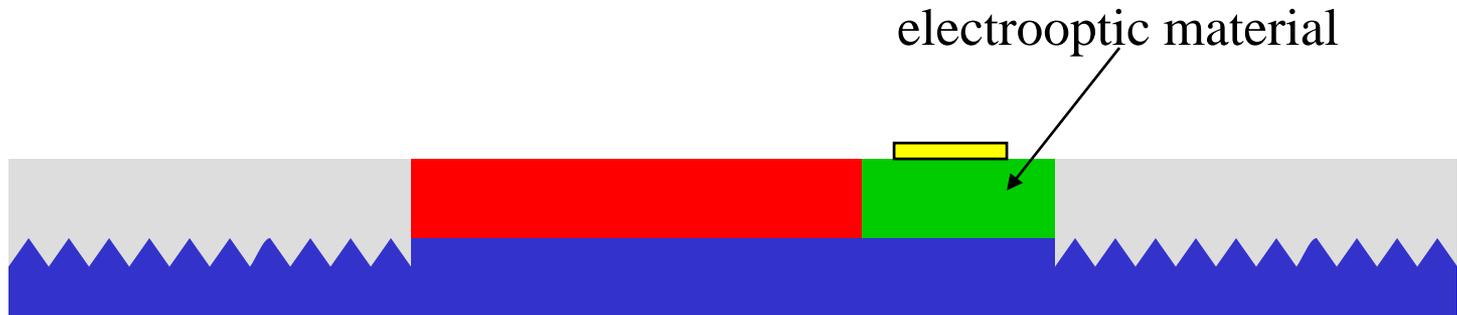
Applying a bias to the gate w.r.t. the *n* material changes the index of the EO material, changing the effective length of the cavity.

Heterojunctions again

I've been drawing all these cartoons as if the devices are just pn junctions. In fact, there are a few different heterojunction designs commonly used:

PIN structure

- undoped interaction region with smaller band gap

- no doping = fewer defects = fewer nonradiative recombinations

- Index contrast can give some light-guiding, though well thickness usually much smaller than wavelength.
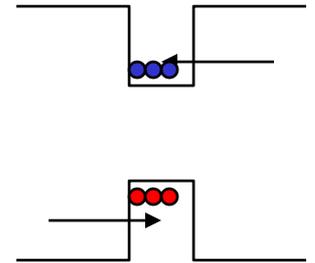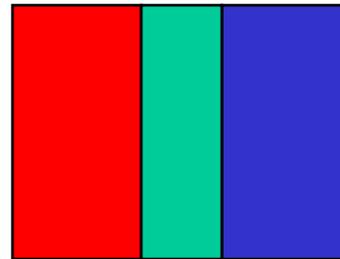
Separate confinement heterostructures (SCH)
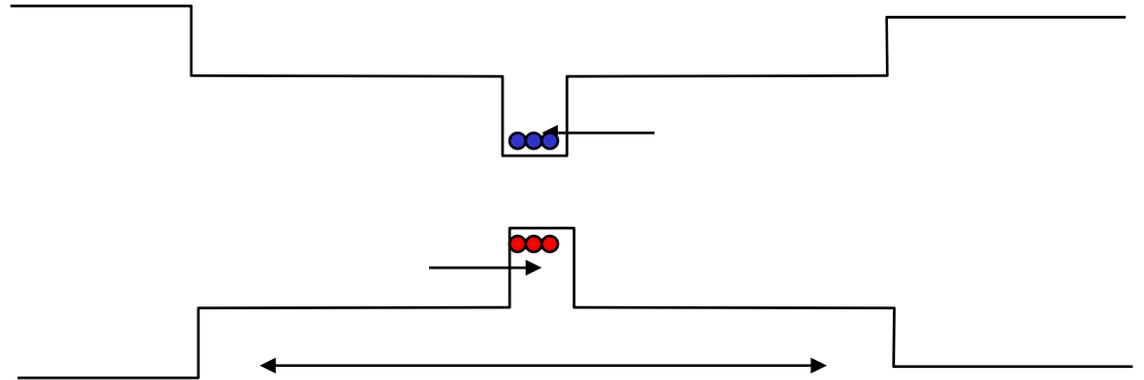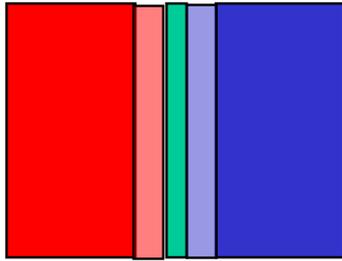
To improve light guiding, uses intervening injection layers that are still doped, but can provide index contrasts on length scales more appropriate to optical waveguiding (~ wavelength).

Note, too, that one can get lateral confinement by things like ion damage:
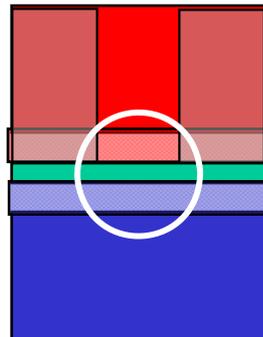
Graded index
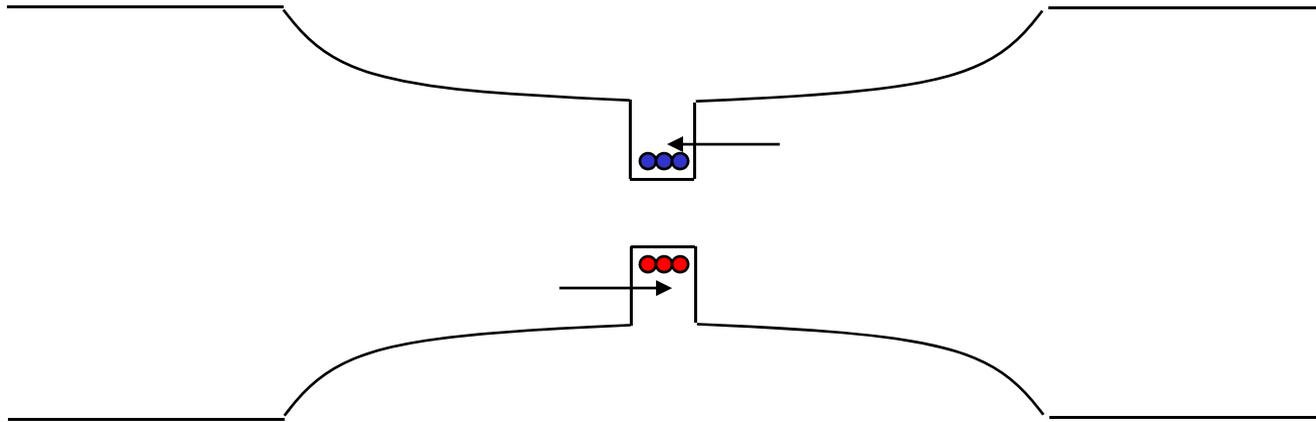
Again, through MBE technology it is possible to *continuously vary* the index of refraction and band gap in a controlled manner, for example, by grading the Al concentration in $Al_xGa_{1-x}As$.

This allows better engineering of light-guiding.

Such structures are called GRaded INdex Semiconductor Confined Heterostructures: GRINSCH.

VCSELS

The vertical version of the DBR cavity.

Dielectric mirrors by layer deposition rather than lateral patterning - can be superior in precision and accuracy.

Getting emission preferentially from one side of a VCSEL is a simple matter of having fewer periods of quarter wave layers on one of the two mirrors.

At right is a TEM of a blue VCSEL. The multiple quantum well active region is about 200 nm thick, and contains ~ 10 distinct layers (wells and spacers).

SiO_2/HfO_2 DBR, $R \sim 99\%$

InGaN/GaN MQW heterostructure

SiO_2/HfO_2 DBR, $R \sim 99.9\%$
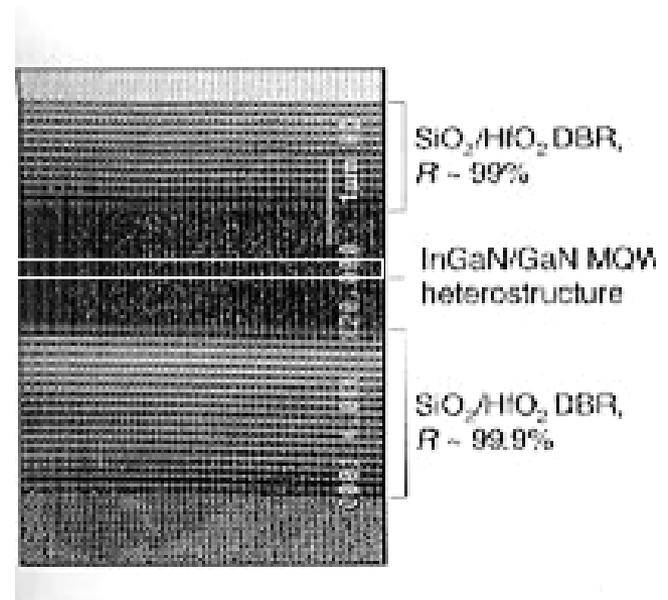
Nurmikko *et al.*, Japan

These structures have been engineered so that confinement effects in the ~ 20nm wells enhance the particular emission wavelength.

Quantum cascade lasers

Rather than just relying on bulk band gaps available to us, one can make a structure with a large number of coupled quantum wells.
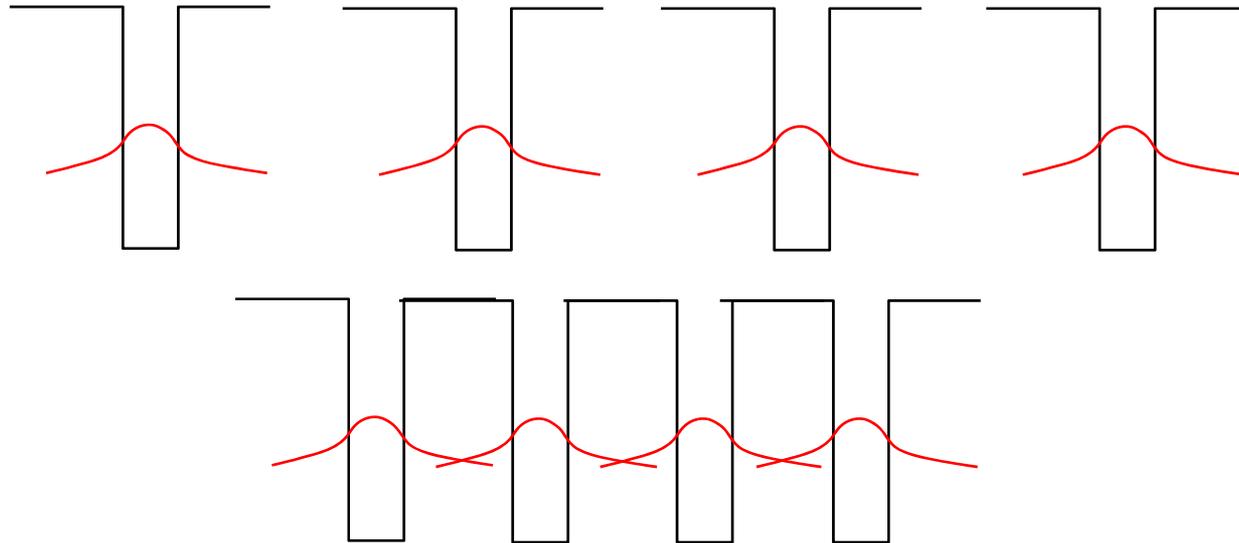
Unsurprisingly, the result is an ensemble of so-called "minibands".

These minibands can be calculated and designed precisely: "band gap engineering"

By engineering gaps between minibands and wavefunctions, can design optical transitions at wavelengths otherwise inaccessible.

Quantum cascade lasers

The result of this kind of engineering is at right: a series of "injector" multilayers and "active" miniband layers.

These superlattices can be repeated in series.

This is the real difference: a single electron can be "recycled" many times to produce multiple emissions.

State of the art:

• coherent emission from the mid-IR all the way out to 60 microns (!!).
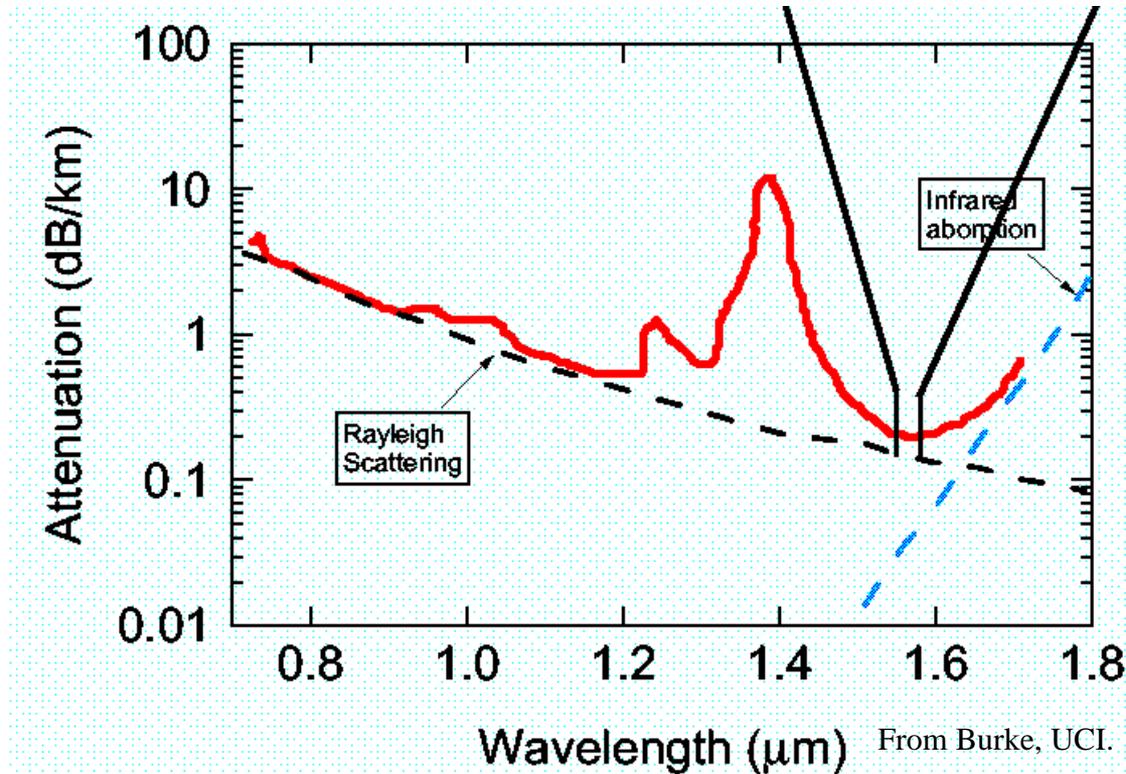
• some progress on high speed switching, etc.
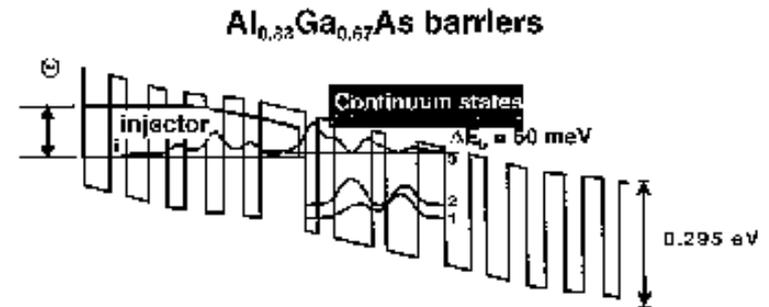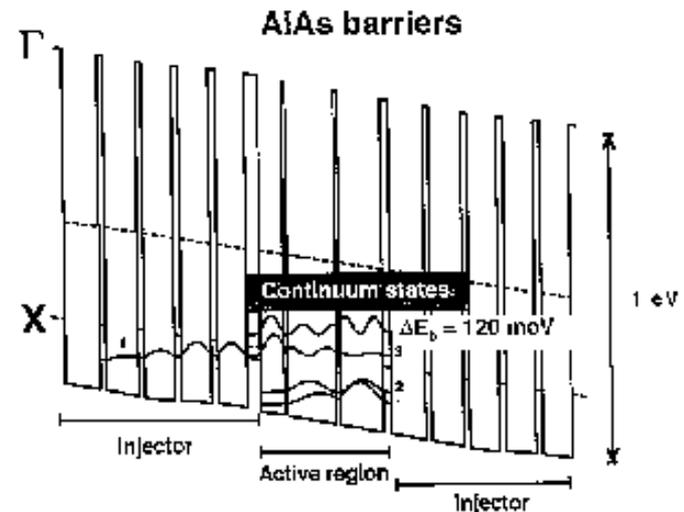
Sirtori *et al.*, IEEE J. Quant. Elect. **38**, 547 (2002)

Longer term goals:

From Burke, UCI.

More efficient, faster, versatile optical sources.

Of particular interest are 1.3 and 1.2 micron wavelength regimes.

Summary

- Semiconductor systems, through the ability to engineer band gaps, provide an impressive set of tools for producing optical emission at desired wavelengths.

- Coupling this emission with the nonequilibrium carrier distributions possible in junction structures can give effective population inversion and optical gain.

- That gain plus the ability to fabricate a variety of mode-selecting optical cavity structures leads to an impressive variety of semiconductor laser devices.

- Available wavelengths can go all the way from mm radiation (the THz regime) into the ultraviolet.

- Nanofabrication, particularly of uniform layer thicknesses on the order of 10 nm, is an enabling technology.

Optical communications: basic tools and ideas

- Wavelength division multiplexing: the basic idea

- History and trends

- Current technology: optical fiber + passive components

- Current technology: active components

- Current technology: detectors

- Research

WDM: the basic idea

Conceptually, rather like AM radio.

Pick a typical carrier frequency in a convenient low-attenuation band of the fiber: 1.55 microns = 193.5 THz.

Want to modulate the amplitude of that carrier so that large amplitude = 1, small amplitude = 0.

Resulting power spectrum has *sidebands*.
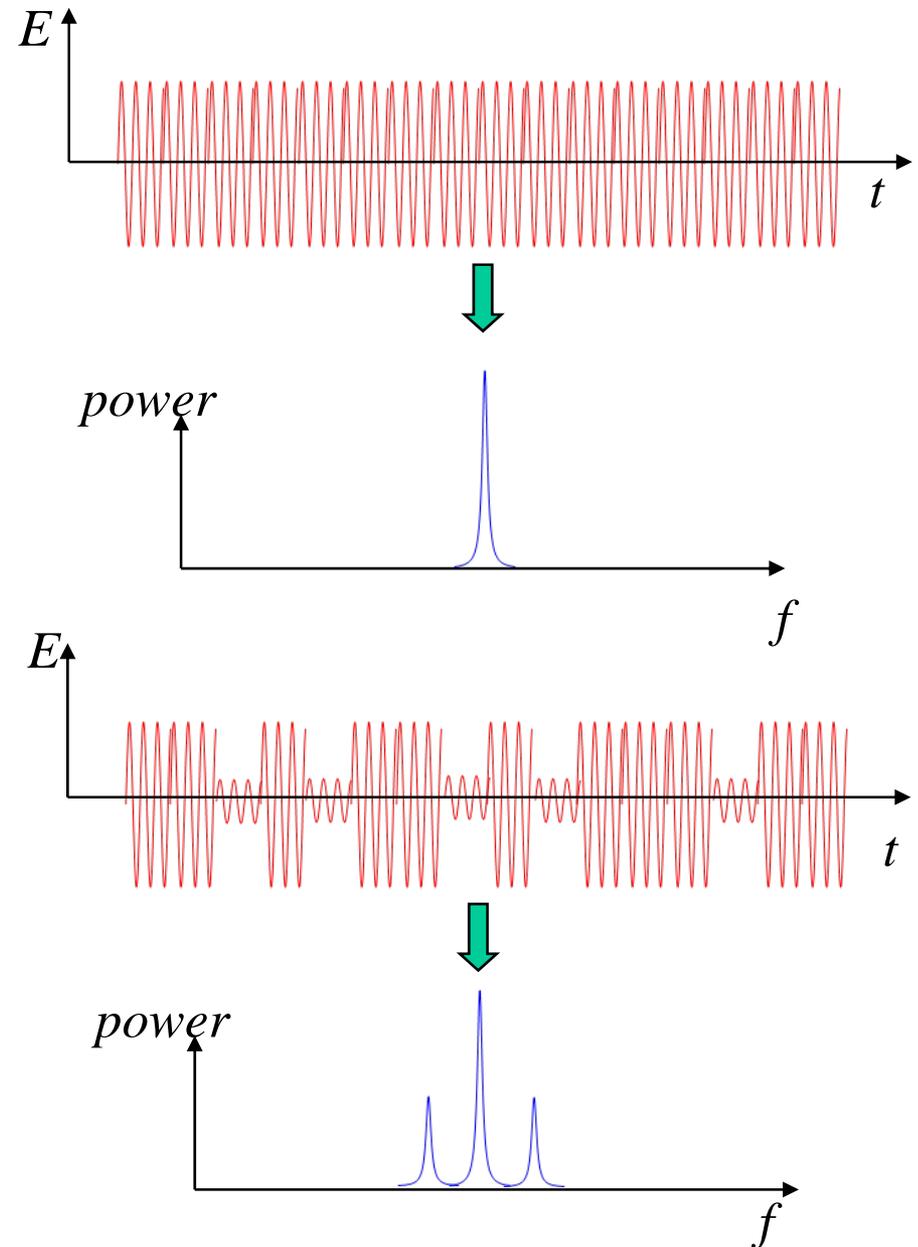
The communications spectrum

Depending on how often we want to have amplifiers to boost the signal strength, we can define a useable bandwidth around the carrier frequency.

Clearly we need to separate channels far enough in frequency that the modulation sidebands of "neighboring channels" don't overlap.

The faster we modulate carriers, the more restrictive this becomes.

Definitions

amplifier

transmitter

modulator

TX ▬ █ ▶ ◯ ▶ ◯ ▶ RX

receiver

laser
λ

detector

λ₁ TX ▬ █

wavelength multiplexer

wavelength Demultiplexer

RX

λₙ TX ▬ █

RX
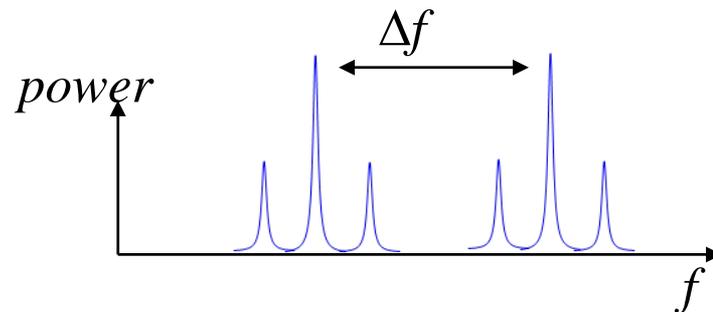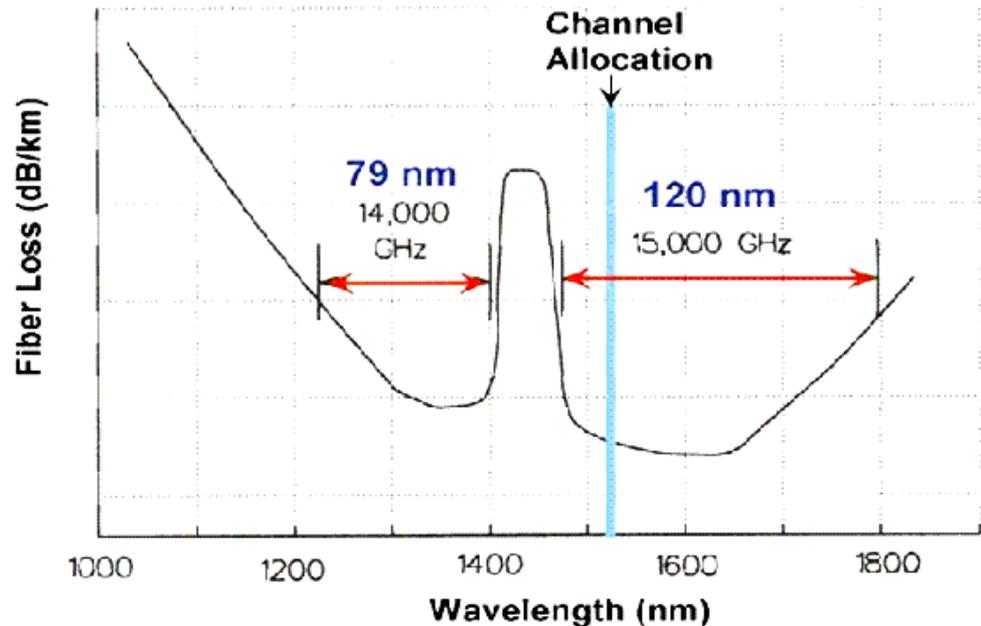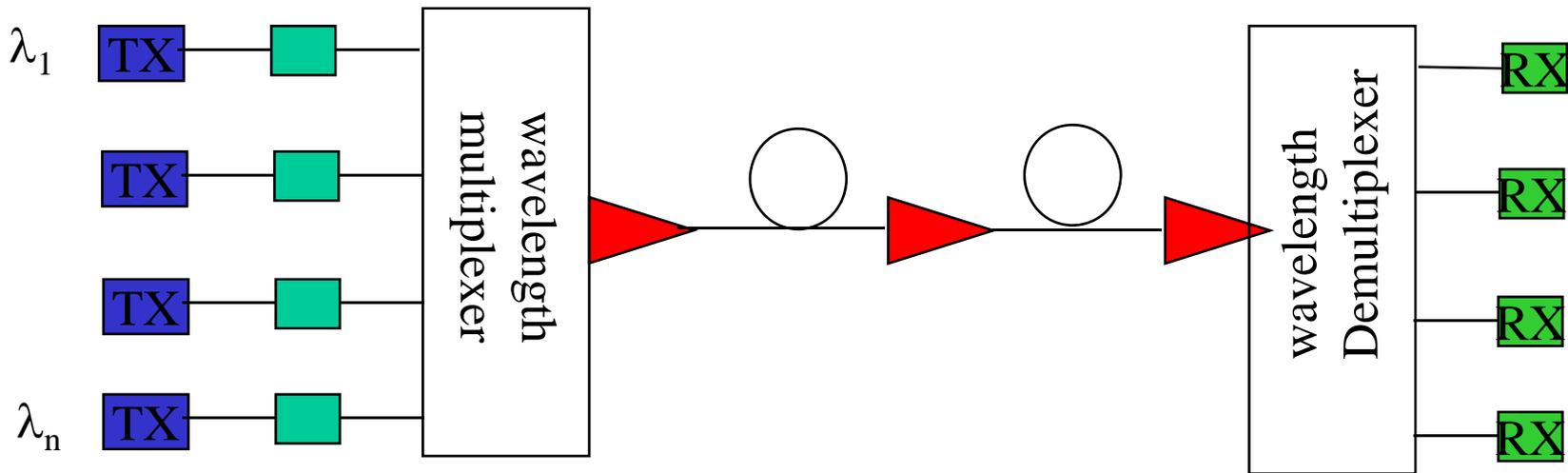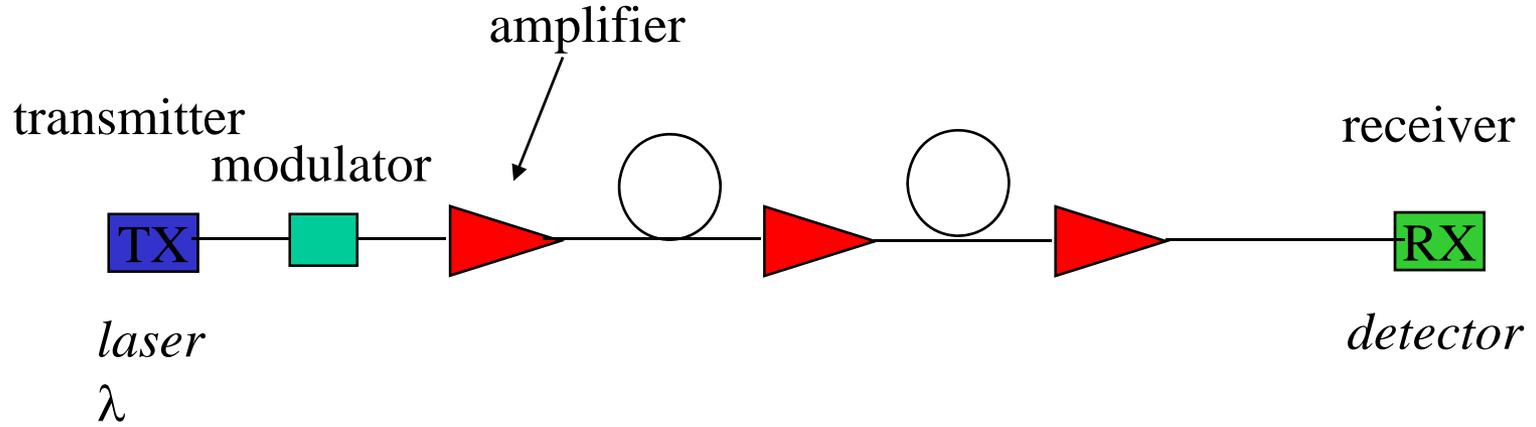
Definitions and numbers

Passing multiple independently modulated carriers of differing wavelengths down a single fiber is called *wavelength division multiplexing*.

Original work had a few channels spaced by ~ 100 nm (~10 THz).

Current practice is called *dense* WDM (DWDM), and has channels spaced by numbers like 1.6 nm, 0.8 nm, 0.4 nm (200 GHz, 100 GHz, and 50 GHz, respectively).

A typical attenuation rate for optical power in a modern fiber is 0.2 dbm/km, equiv. to $T = 0.955$ through 1 km of glass.

Amplifiers in-line are usually placed every 80 - 120 km.

History

1626 - Snell's law

1870 - Tyndall observes light guiding in thin water jet

1873 - Maxwell's EM theory

1897 - Rayleigh analyzes waveguide, electron discovered

1899-1903 - Marconi, Hertz, and radio

1930 - First expts. in Germany using silica fiber

1940s - development of radar + microwave waveguides

1960 - Ruby laser invented

1962 - Semiconductor laser invented

1966 - Kao and Hockham (UK) suggest optical fiber for communications.

1970s - rapid improvements in glass quality, techniques

1975 - 1 GHz bandwidth over 1 km.

Trends in optical communications
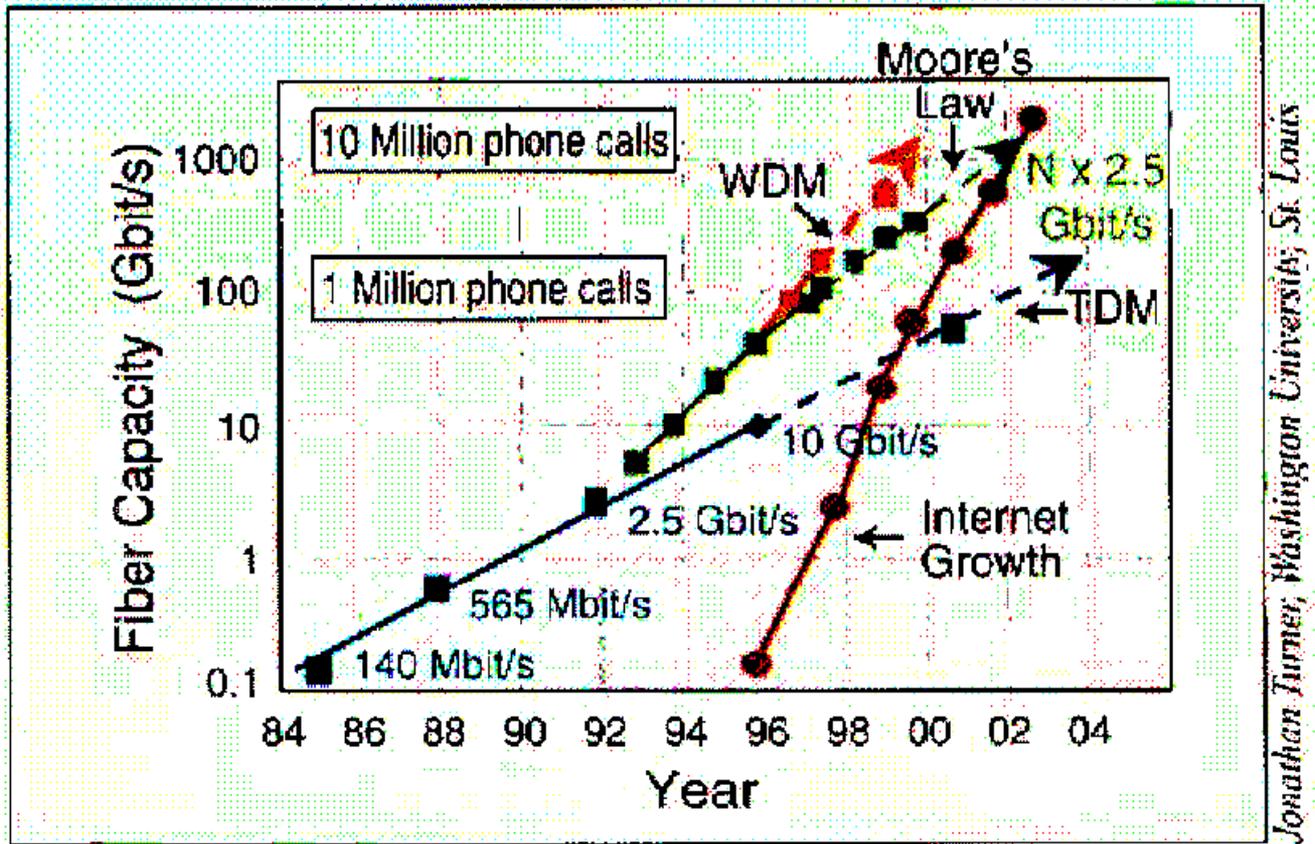
Like many other high tech metrics, achievable fiber capacity has been skyrocketing exponentially over the last 10 years.

Trends in optical communications
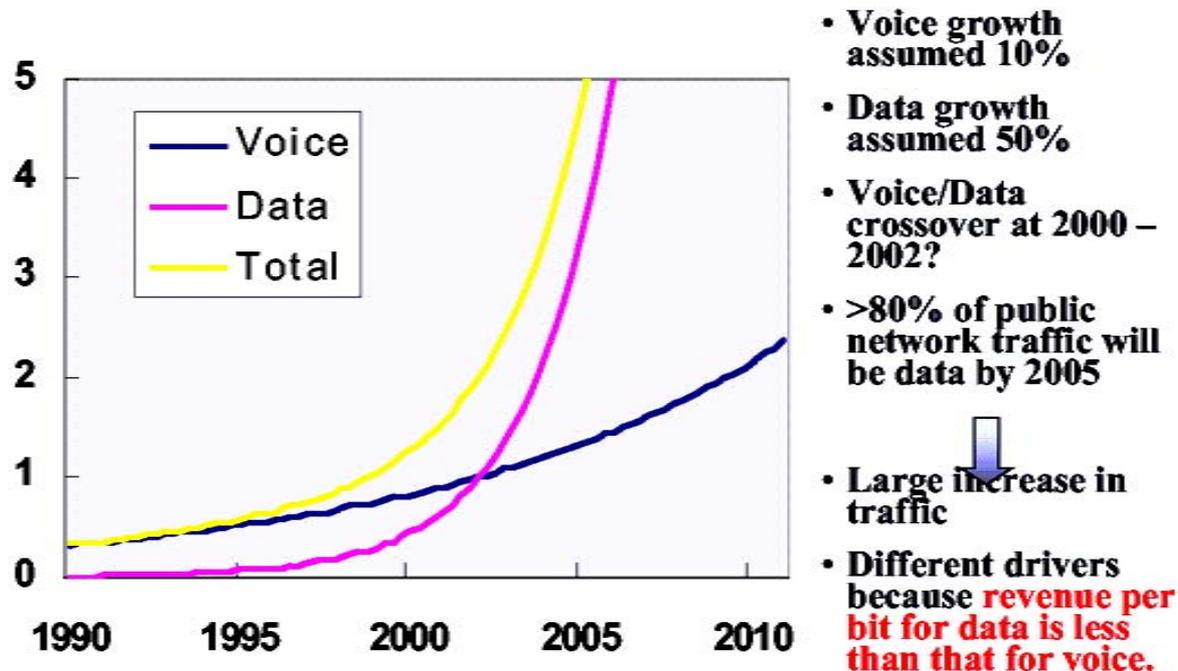
Assuming data networks continue to grow (*e.g.* video on demand, etc.), then it's possible long distance phone service will be *free* soon.

Optical fiber

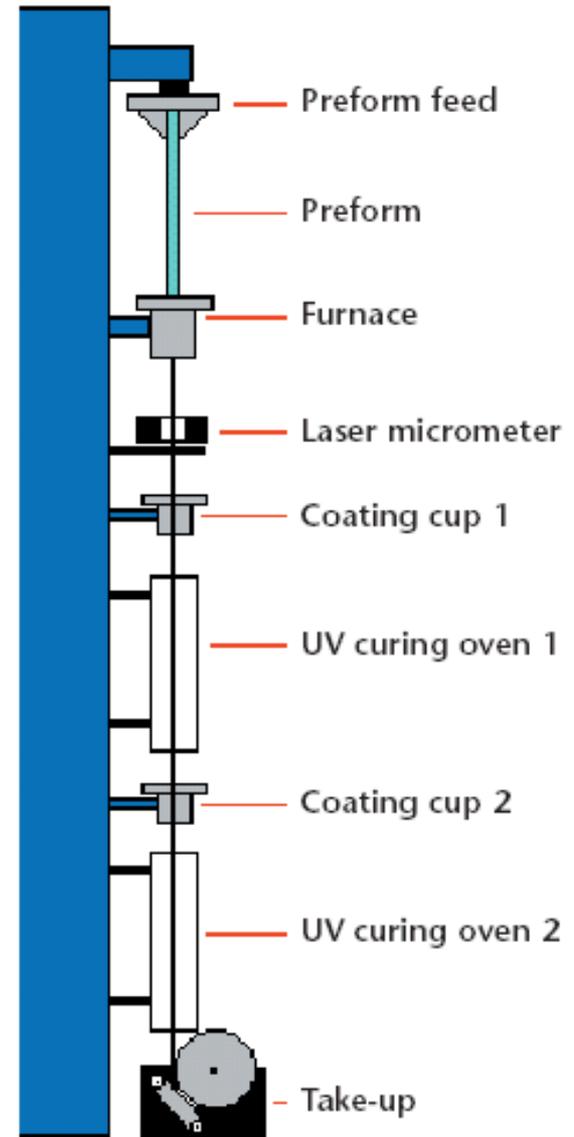Monomode optical fiber is designed to guide light pretty well for wavelengths between 1.3 and 1.6 microns.

Typical core diameters are ~ 10 microns, with cladding ~ 125 microns thick.

Again, the two reasons for the interest in 1.5 microns and 1.3 microns are the low attenuation and the low dispersion there.

Typical spec dispersion: 3.5 ps/(nm-km).

Fiber is drawn from large "preforms".

Preforms are made by furnace melting of SiO_2 (+ any dopants) "soot" prepared by combustive chemistry from raw components.

Preform feed

Preform

Furnace

Laser micrometer

Coating cup 1

UV curing oven 1

Coating cup 2

UV curing oven 2

Take-up

fluent.com

Passive components

There are a number of *passive* components in optical networks. We've already encountered some of these:

- Antireflection coatings to increase efficiency of signal injection.

- Index modulated fibers for filtering.

- Chirped fiber gratings for dispersion compensation

λ_1

λ_2

λ_3

$$\lambda_3 < \lambda_2 < \lambda_1$$
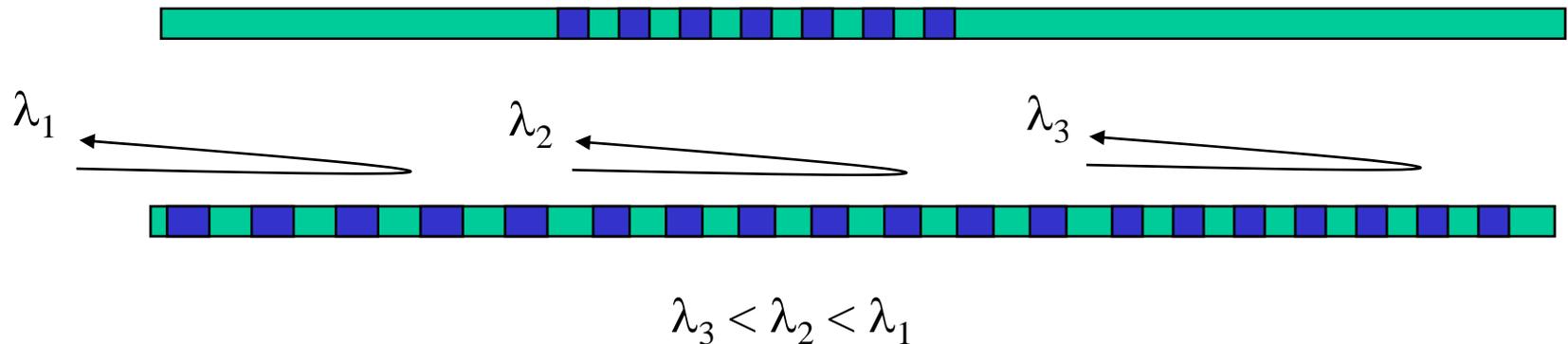
Passive components

Passive fiber gratings can also be used for selectively dropping signals from certain channels:

iec.com
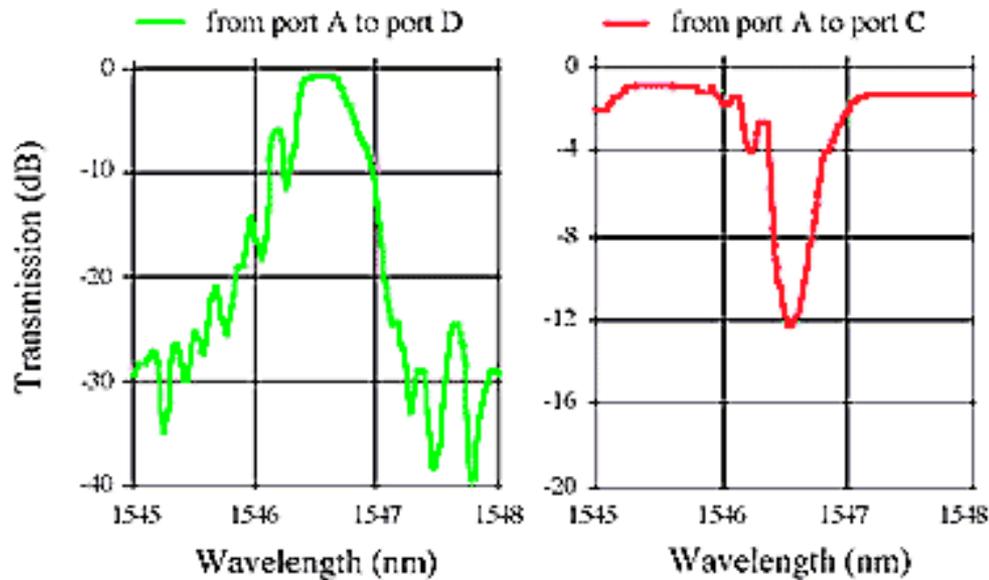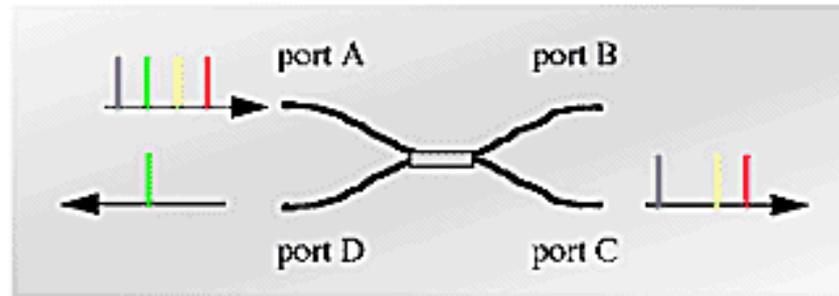
Optical modulators

How do you modulate an optical signal at high rf frequencies?

Could modulate the current into the semiconductor laser? No.
Way too many problems with this - the biggest ones:

- SC laser electrical impedance changes dramatically depending on drive - very hard to match to rf electronics.

- Takes time to build up to threshold and get stable lasing.

Better approach: modulate the light intensity directly somehow.

One dominant method uses *interferometers* and either the electrooptic effect or the acoustooptic effect.

Another uses *switchable absorption*.

Optical modulators

One common idea is to use a Mach-Zehnder interferometer geometry:
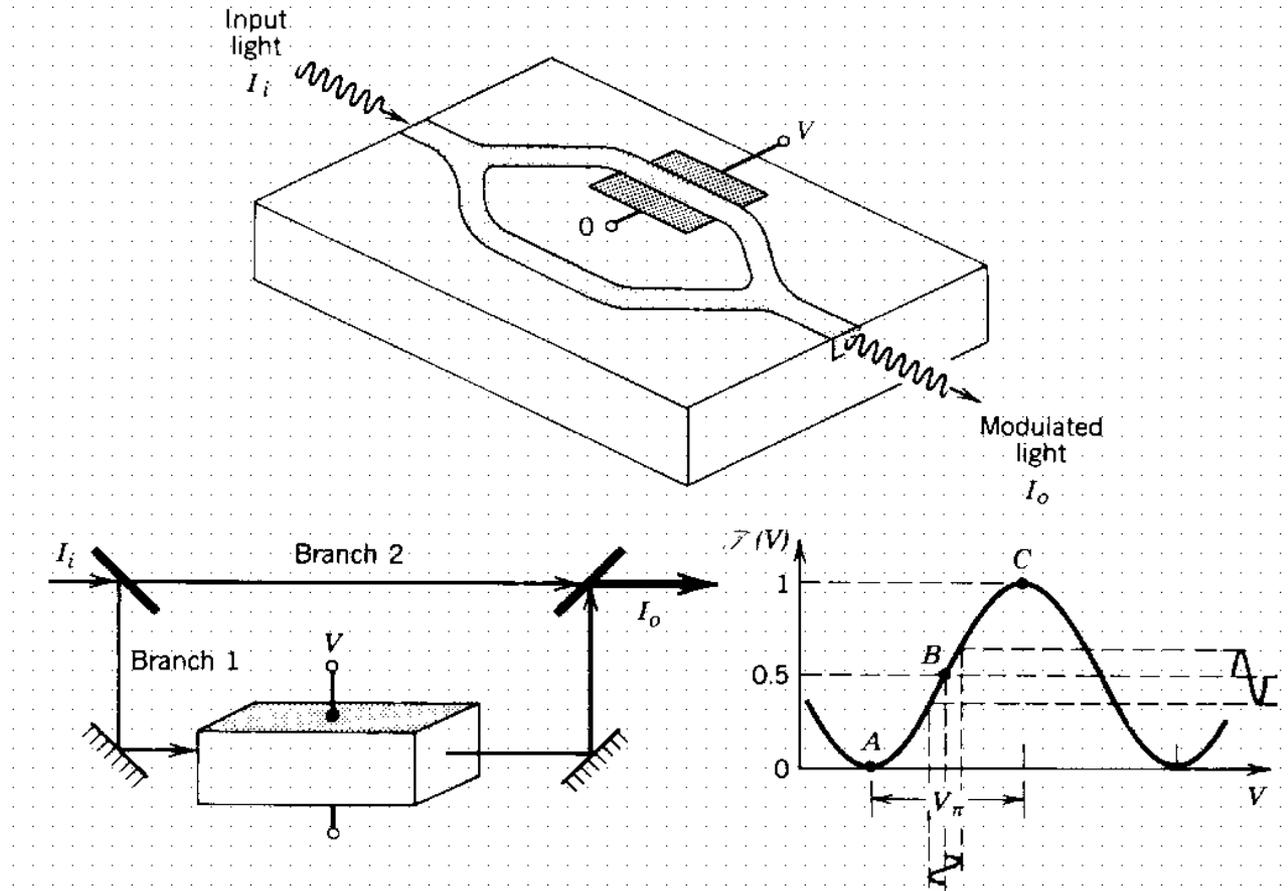
Optical modulators
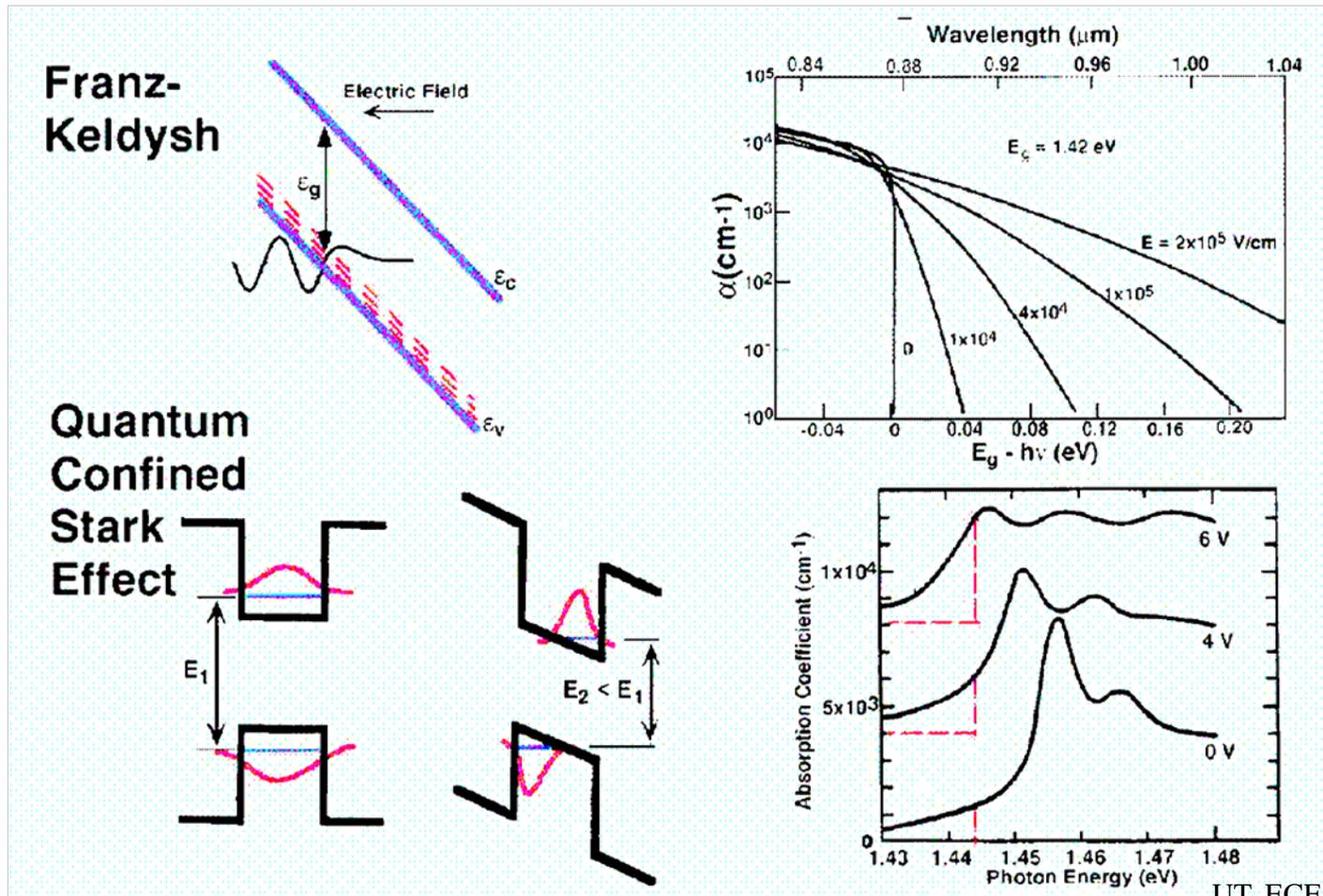

Electrooptic Modulators: Lumped and Traveling Wave
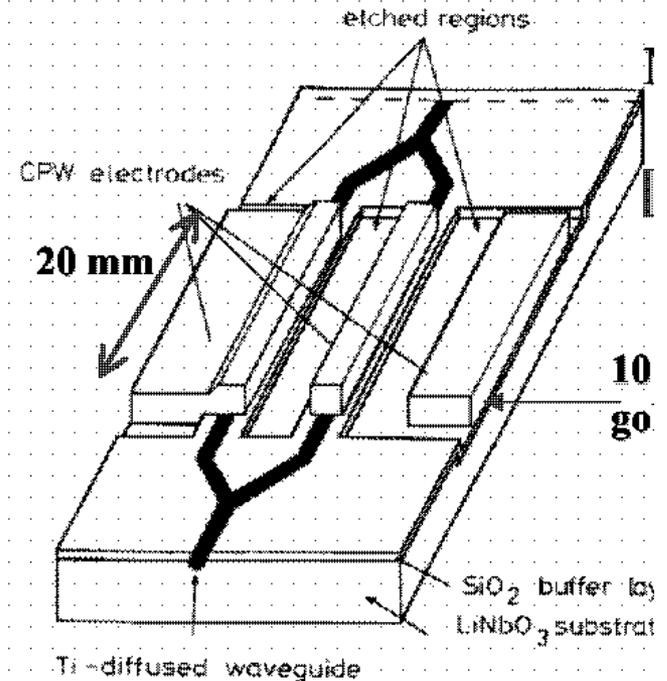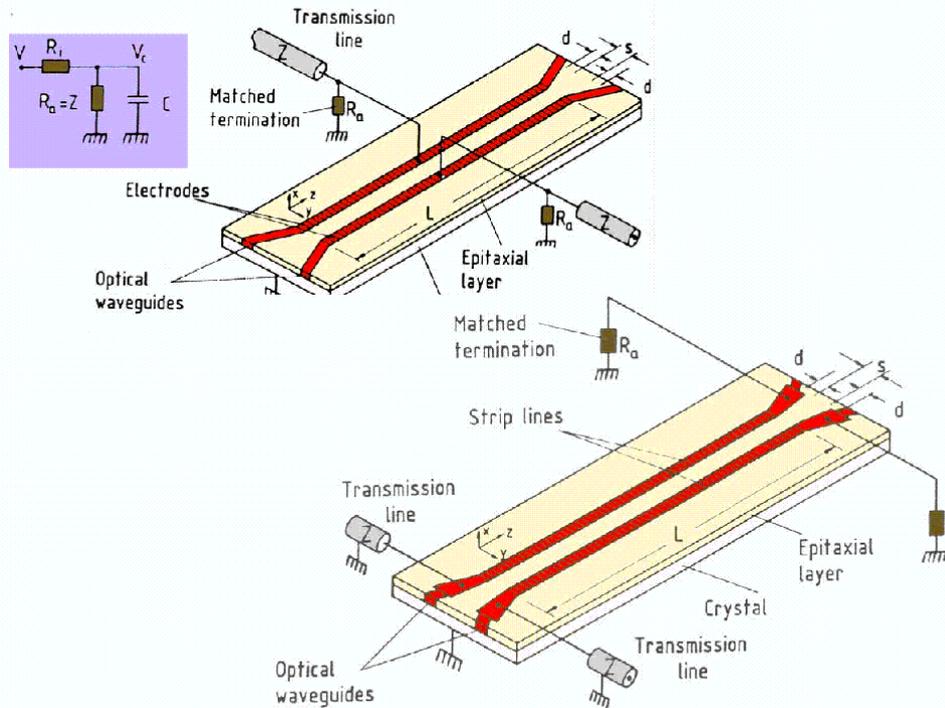
Serious rf engineering challenges - need to have electrical part of this (with nontrivial impedance) work correctly at many GHz frequencies.

Optical modulators

Adsorption modulators work as you might imagine: electrically switchable absorption at the carrier frequency of interest.
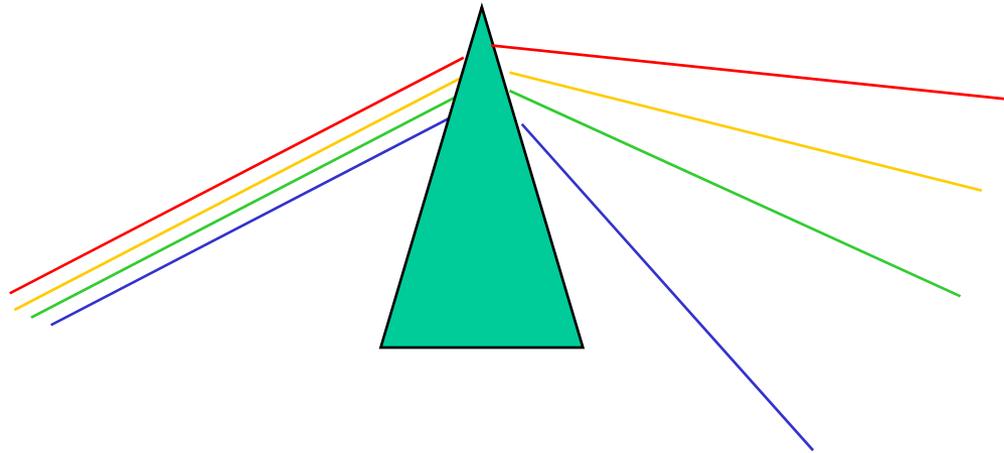
A couple of approaches:

Optical multiplexers

Just to give a flavor of how these work: remember that we want to take a single input fiber and distribute the different information-carrying wavelengths into individual fibers.
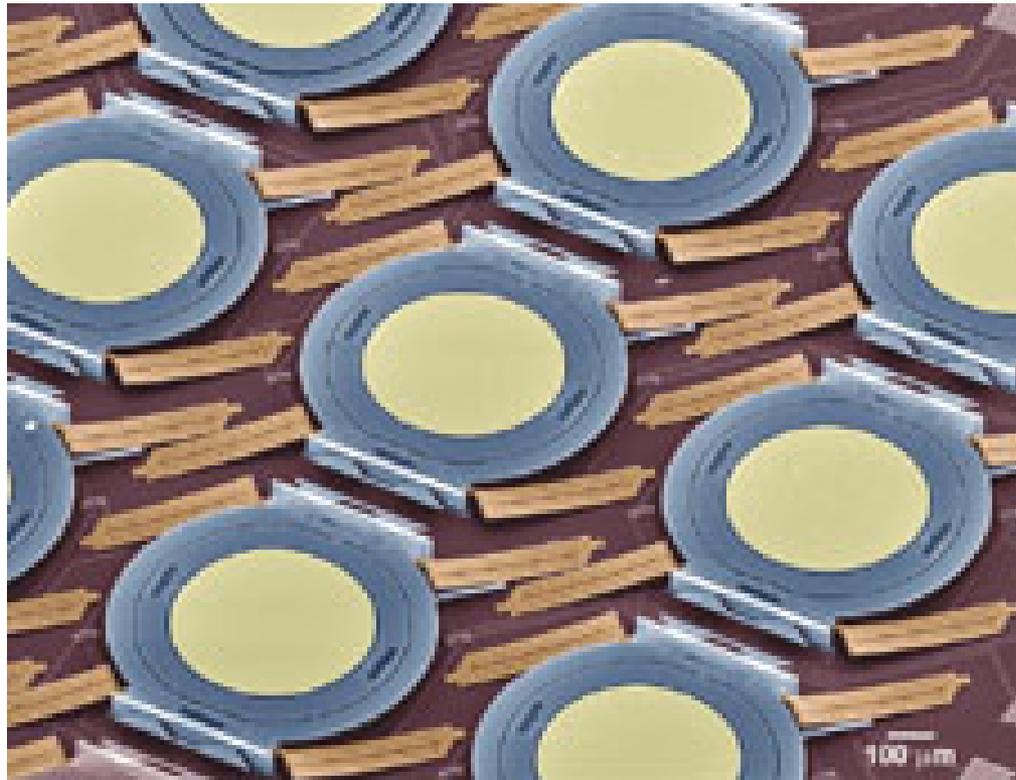
One basic version is to use a prism!

Optical switching

Sometimes one is interested in switching whole new streams of signals.

Historically, this has been done using large mirrors and lenses on servo-controlled mountings.

Recent approach:

Detectors

Several different types of detectors are used these days.

Requirements: must be efficient and *fast* at converting optical signals back into electrical pulses.

Common types:

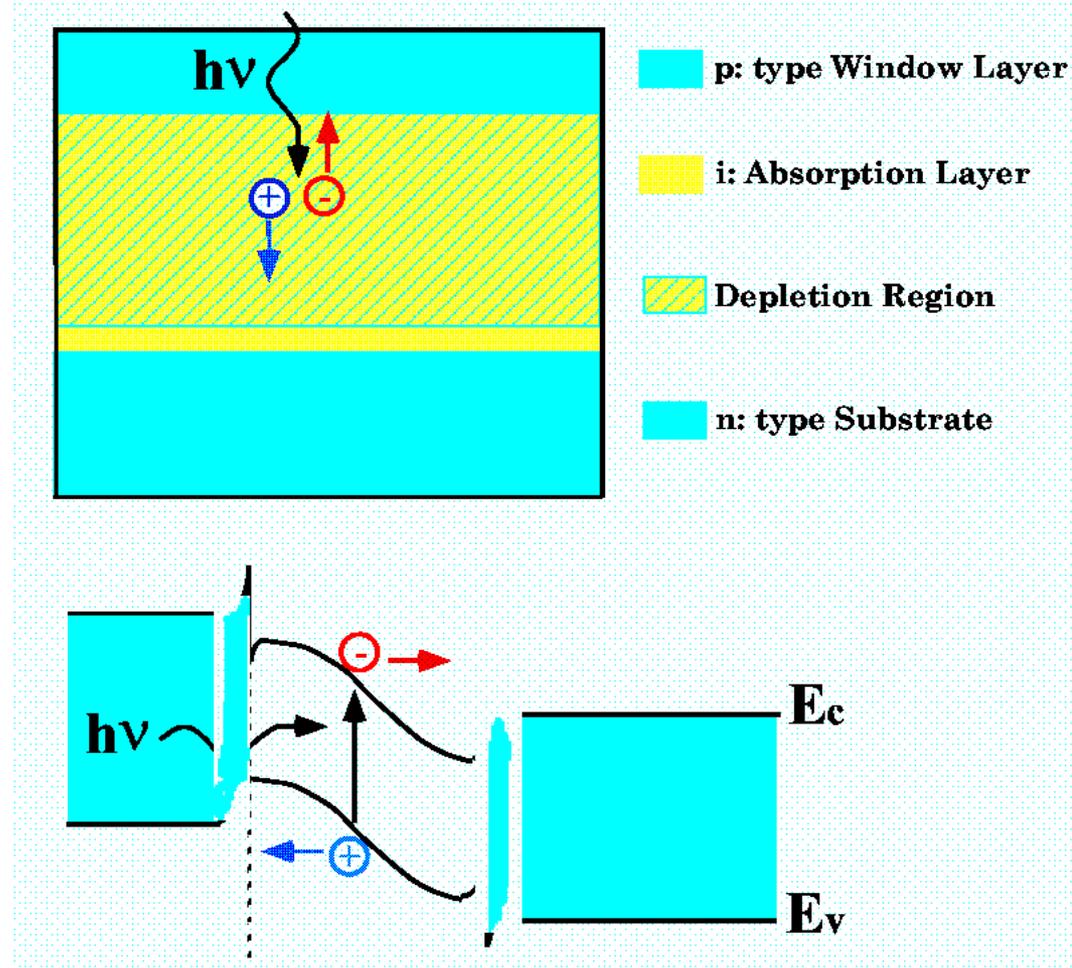- PIN diodes

- Avalanche diodes

- MIM structures

PIN diodes

Biased pn junction with absorption of light designed to occur in depleted / undoped region.

Electrons and holes produced then run to the respective contacts.
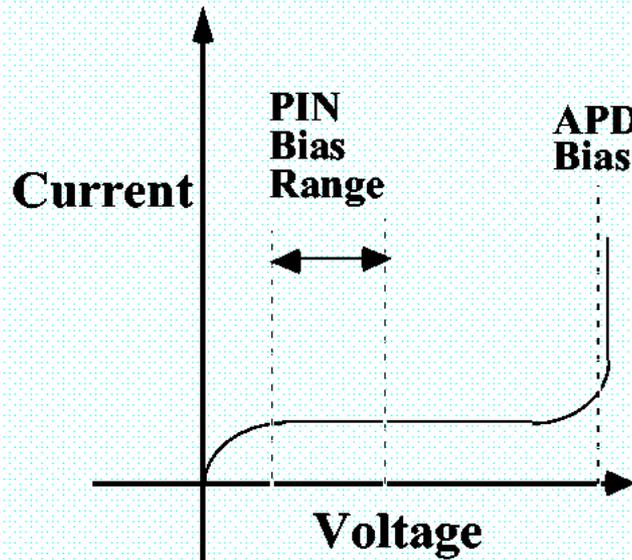
Speed limited by diffusion of carriers.

Typical bandwidth: 20 GHz.

Weakness: better diffusion at larger biases, but more leakage - *dark current*.
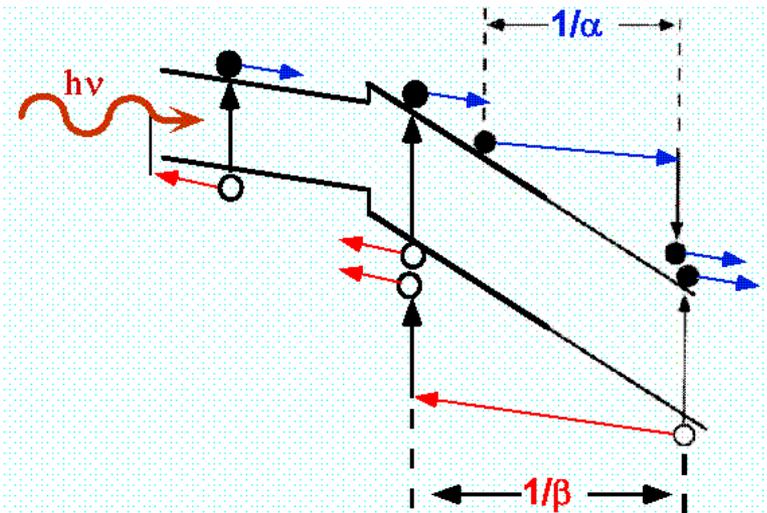
hν

p: type Window Layer

i: Absorption Layer

Depletion Region

n: type Substrate

hν

E_c

E_v

Avalanche diodes

PIN Bias Range

APD Bias

Current

Voltage

$h\nu$

$1/\alpha$

$1/\beta$

α = electron ionization coefficient
β = hole ionization coefficient
$k = \alpha/\beta \ (k < 1)$

PIN Photodiodes

less expensive
lower voltage
less control of bias
less temperature sensitive
simpler bias circuits
higher reliability

Avalanche Photodiodes

better performance
(sometimes)

MIM structures

Advantages
- **Compatible with FETs**
- **Low Capacitance**
- **High Speed**

Disadvantages
- **Dark Current (sometimes)**
- **Contact Shadowing**
- **Long-Wavelength Structures**

CONTACTS

hν

ABSORBING LAYER

SUBSTRATE
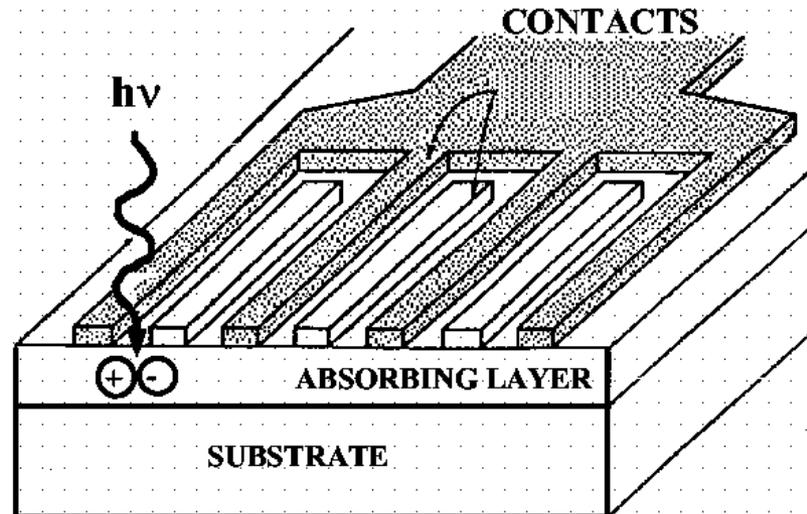
Metal-Semiconductor-Metal Contact

Ohmic → **MSM Photodiode**

⇓ ⇓

Photoconductor **Schottky Barrier**

The bottlenecks

- Trying to squeeze more and better quality out of optical fibers.

- Lack of ready supply of faster, efficient modulators.

- Lack of integration leads to more need for amplifiers, etc.: insertion losses at every interface.

Research:

As you might imagine, research is continually focused on higher carrying capacity and lower cost.

Eventual goals are terabit per second type speeds, and FTTC: "fiber to the curb".
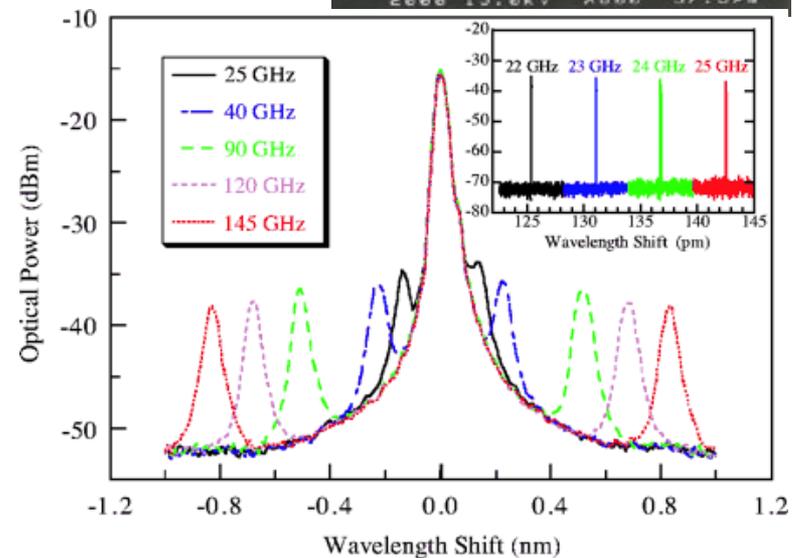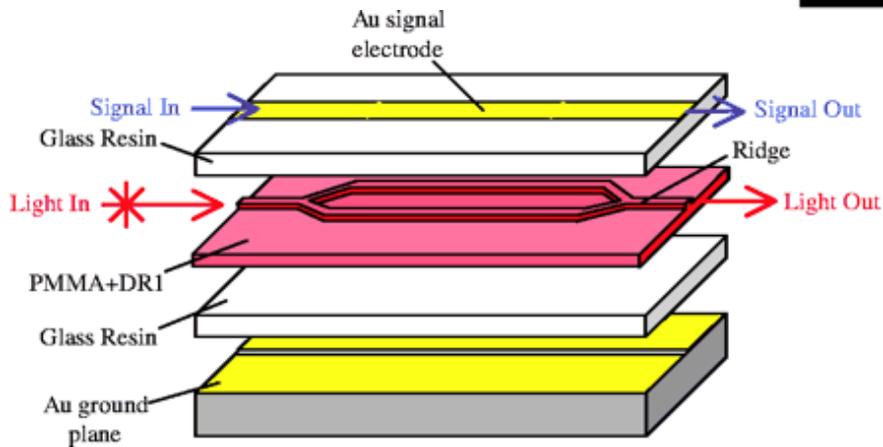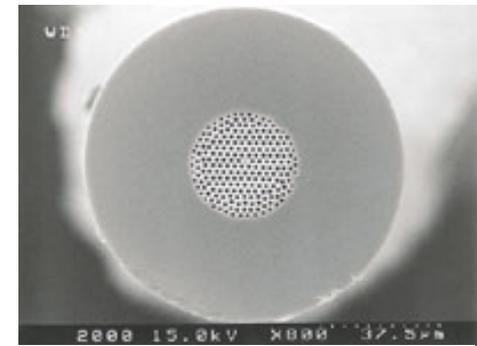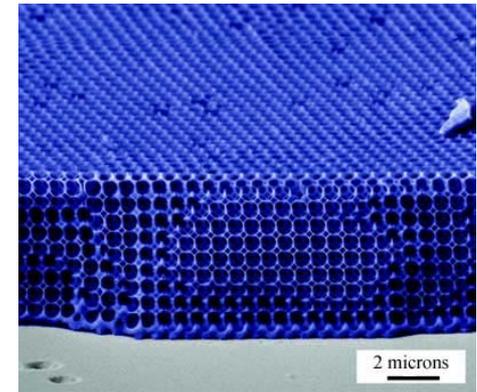
Natural research directions:

- New materials

- New structures

    - New sources

    - New detectors

http://mph-roadmap.mit.edu/about_ctr/report2005/

New materials

Have already discussed several examples:

- Photonic bandgap fibers and materials

- Novel polymer passive coatings

- Polymer-based modulators

2 microns

2000 15.0kV X800 37.5μm

Au signal electrode

Signal In — Signal Out

Glass Resin — Ridge

Light In — Light Out

PMMA+DR1

Glass Resin

Au ground plane

Optical Power (dBm)

- 25 GHz
- 40 GHz
- 90 GHz
- 120 GHz
- 145 GHz

22 GHz 23 GHz 24 GHz 25 GHz

Wavelength Shift (pm)

Wavelength Shift (nm)

New sources

Interest in a variety of new laser sources spanning new frequency ranges, lower thresholds, etc.

Key insight is to use quantum confinement.
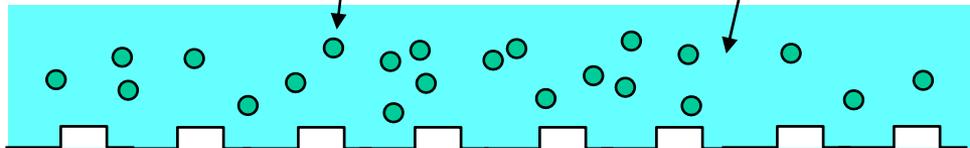
Examples include:

- Nanocrystal based lasers

- Nanowire based lasers

- Single photon sources

# New sources: nanocrystals

5 nm
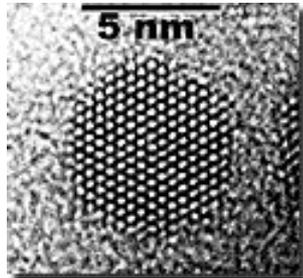
CdSe nanocrystal

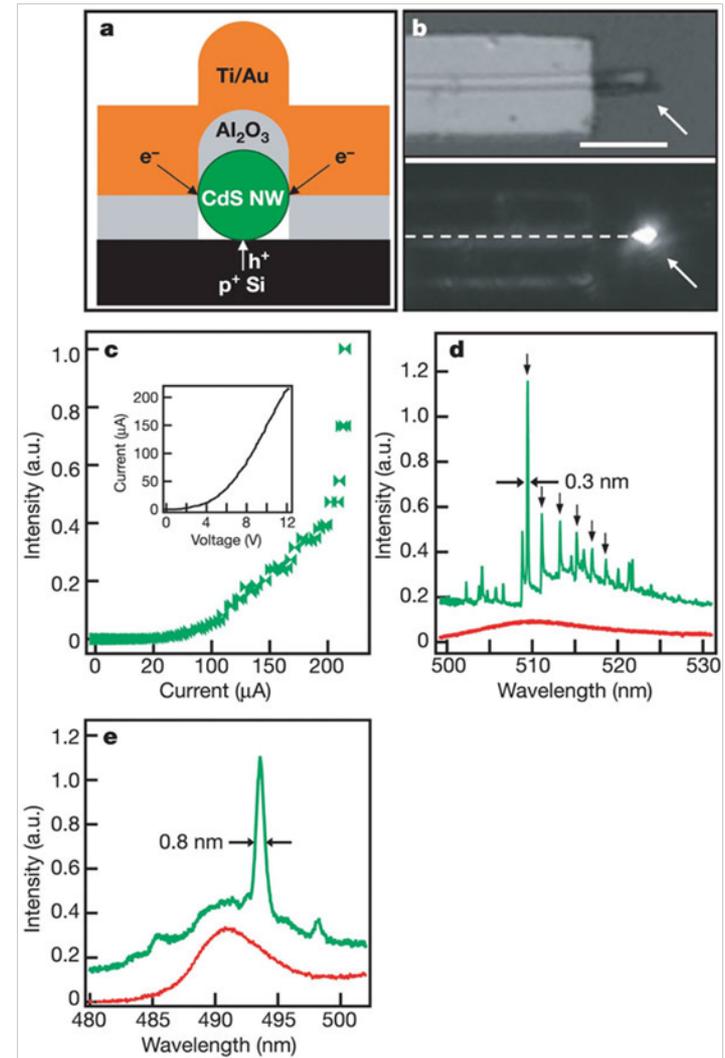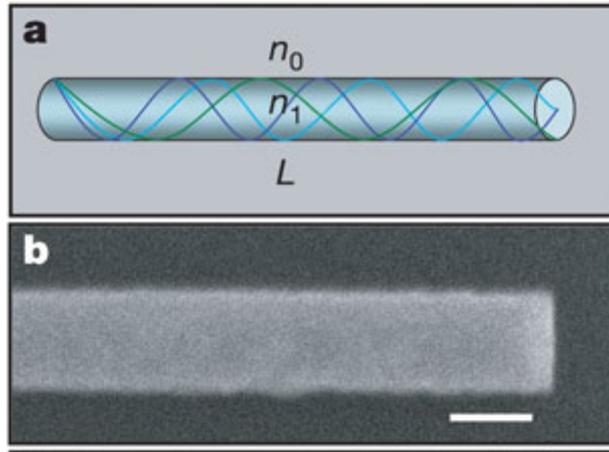Bouwendi group, MIT

TiO_2

SiO_2 - 330 nm grating

- Nanocrystals provide well-controlled confinement effects.

- Varying concentration of crystals allows change in average index of gain medium, allowing different colors to use same grating.

- Optically pumped for the moment….

- Also looking at other resonator configurations.
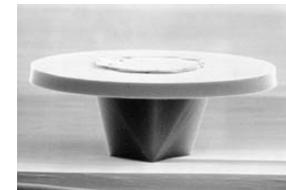
Bell Labs

New sources: nanowires

- Nanowires also show big confinement effects, and are large enough to allow easy electrical pumping.

- Can act as their own resonating cavities!

Optical interconnects

There is great excitement about trying to use light as an interconnect technology on computer chips.

Advantages:

- Speed

- Power dissipation

Disadvantages:

- Si not optically active (usually).

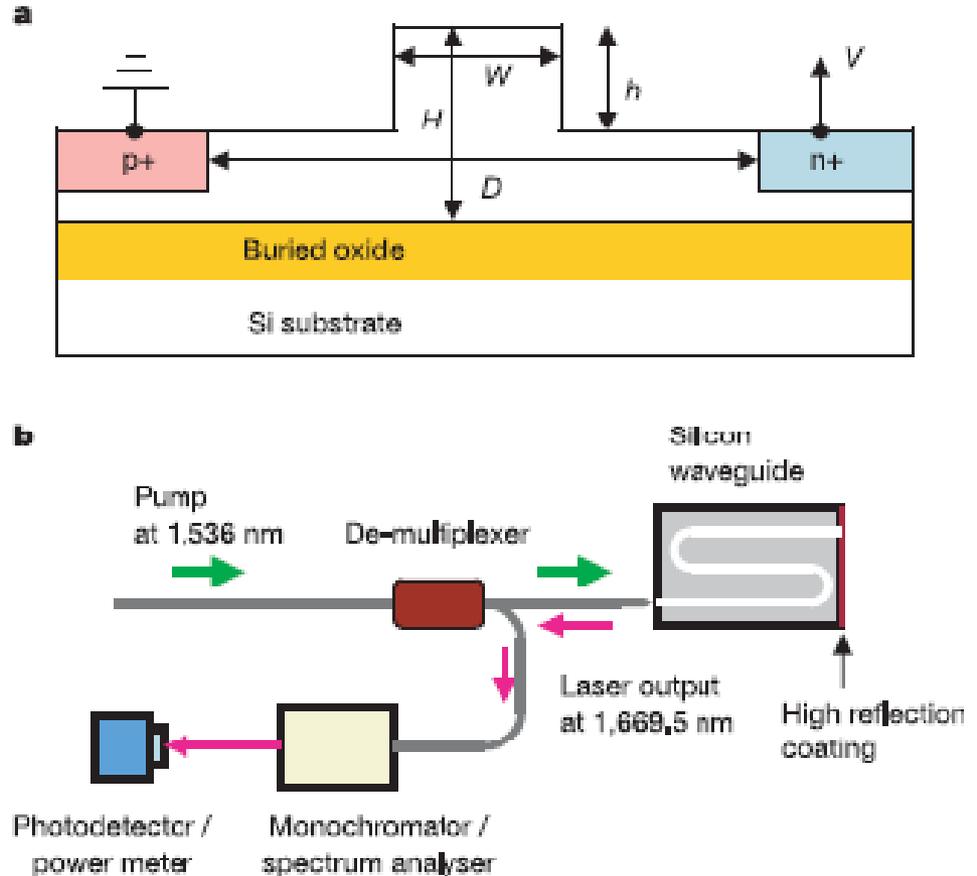- Photons are *big*.

- Power dissipation

Si Raman laser

Intel (2005)

Uses stimulated Raman emission to produce light.

When stimulated emission happens in cavity, and Bose factor can build up, can get gain.

Optically pumped.

Rong *et al*., Nature 433, 292 (2005).

Si "hybrid laser"

Intel, UCSB (2006)

Basic idea:

- InP LED

- Wafer bond to Si

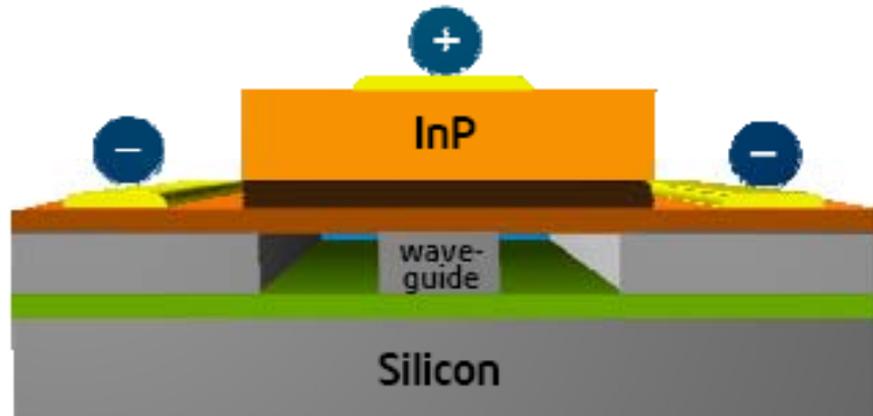- Si ridge acts as waveguide/cavity.

Figure 1. Cross-section schematic of a hybrid silicon laser.

Intel

Si modulator

Intel (2005)

Si itself has basically no electro-optic coefficient.

However, free carriers certainly have some effect on dielectric function.

Cool idea: use MOSFETs as tunable dielectrics in SOI waveguide structure.
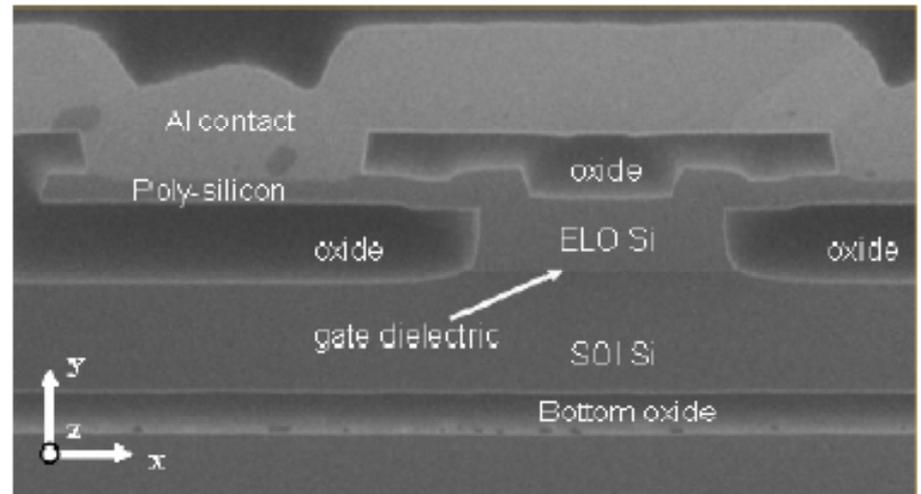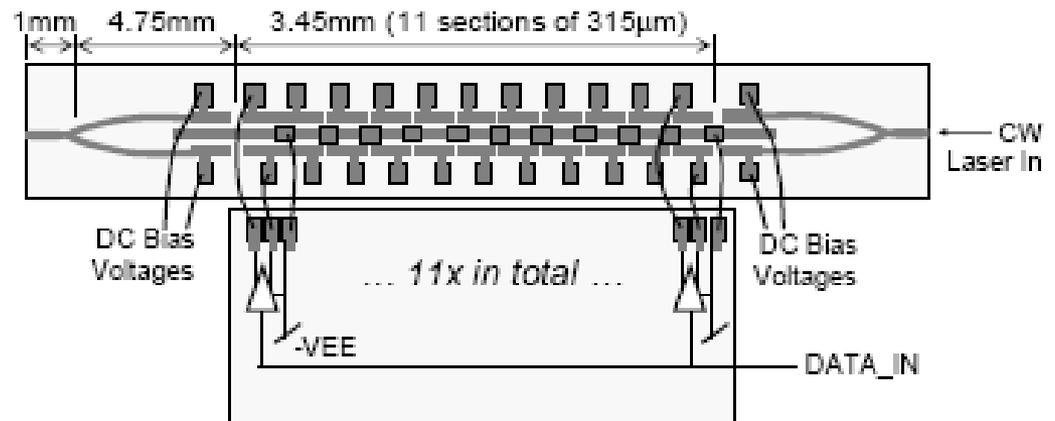
Result: 10 GHz modulator.

Fig. 1. SEM cross-section of the new phase shifter with ELO-Si rib.

Liao *et al*., Optics Express **13**, 3129 (2005)

New ideas:

Quantum cryptography….