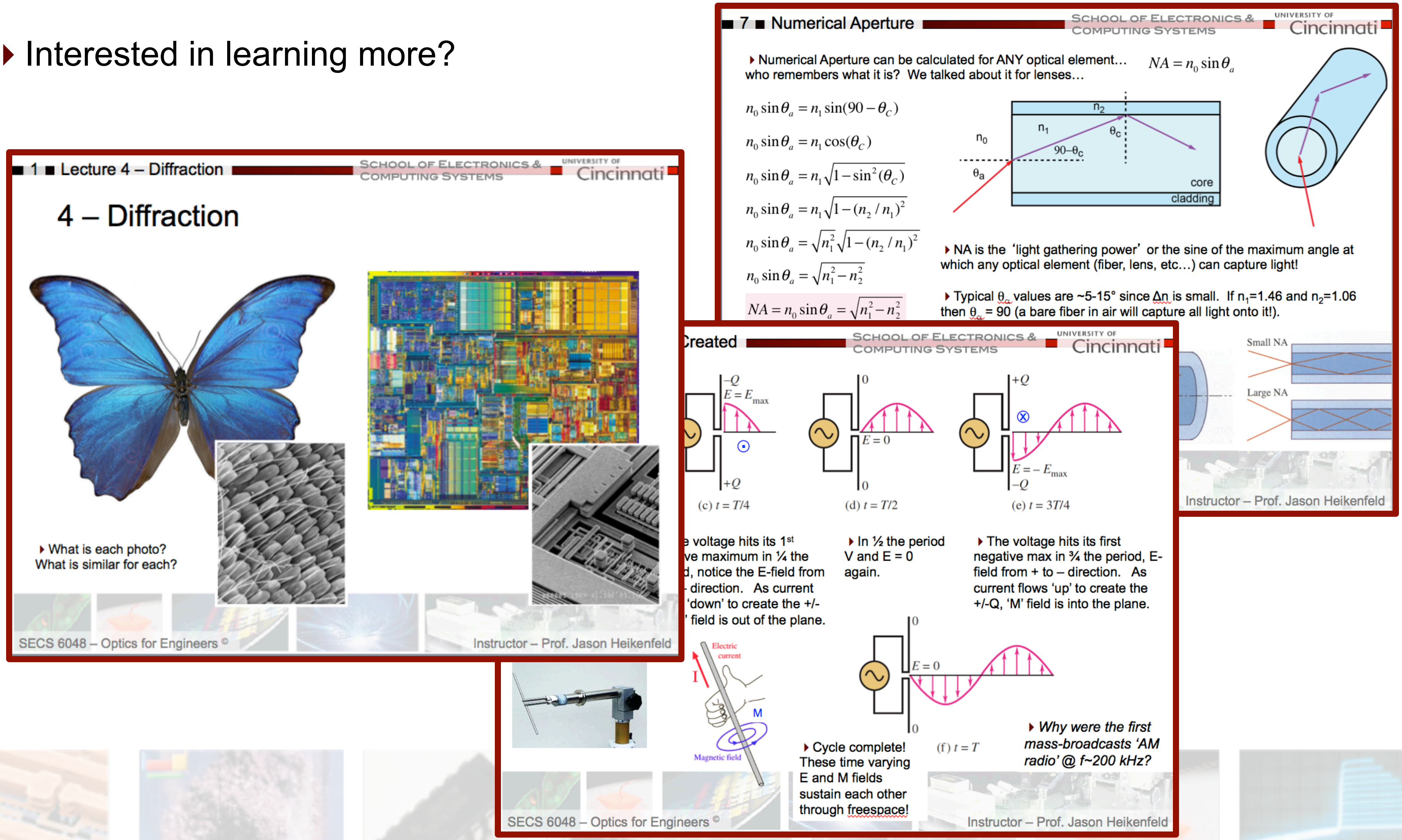
8.3 – LASERs! *and Silicon Photonics…*

Father of blue LEDs and blue laser diodes Shuji Nakamura.

- This lecture touches on many topics in Optics, which is beyond the main scope of this course…

- Interested in learning more?



- The word LASER is an acronym for *Light Amplification by Stimulated Emission of Radiation*

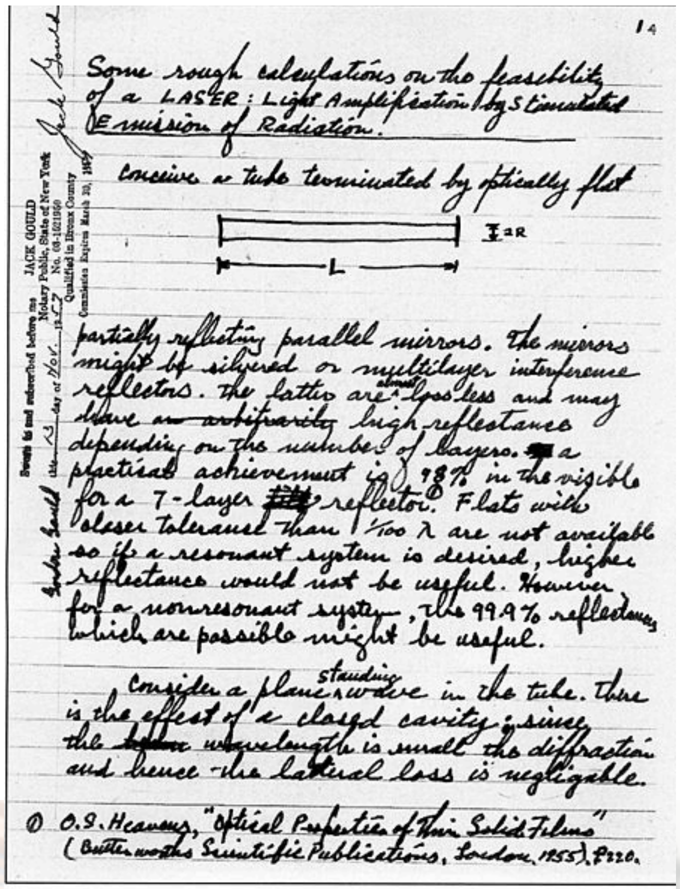
- The laser is a source of light that is
  - –Highly directional
  - –Monochromatic
  - –Coherent

- Since the first demonstration of semiconductor lasers, lasers have become a common place device used for conveying information

- Applications of lasers include
  - –Telecom
  - –Optical storage
  - –Pointers
  - –Range/Speed finders
  - –Construction (levels, survey measurement, etc.)
  - –Printers
  - –etc..

- Note, the Laser is a great example of why we have basic research. When the the Laser was discovered they were searching for applications… None of the above applications existed!

Columbia University, graduate student Gordon Gould was working on a doctoral thesis about the energy levels of excited thallium. In November 1957, Gould noted his ideas for a "laser".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Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

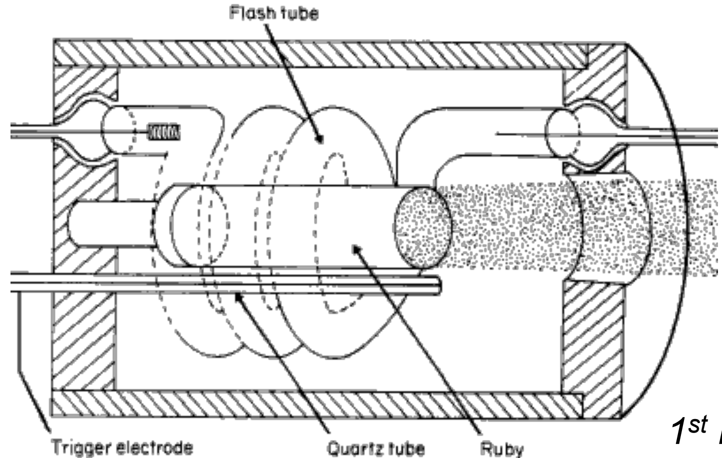
Conceive a tube terminated by optically flat

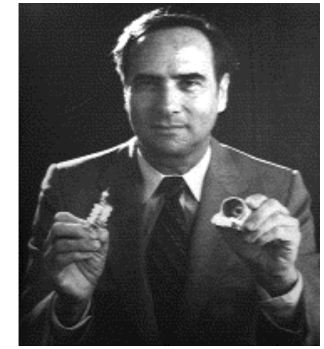
partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost lossless and may have an arbitrarily high reflectance depending on the number of layers. a practical achievement is 98% in the visible for a 7-layer reflector. Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectances which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity since the wavelength is small the diffraction and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955), p.220.

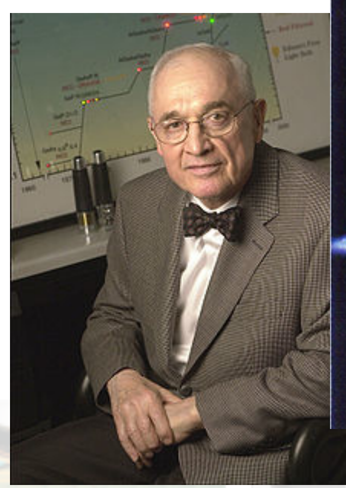
Sworn to and subscribed before me this 13 day of Nov. 1957 — JACK GOULD, Notary Public, State of New York

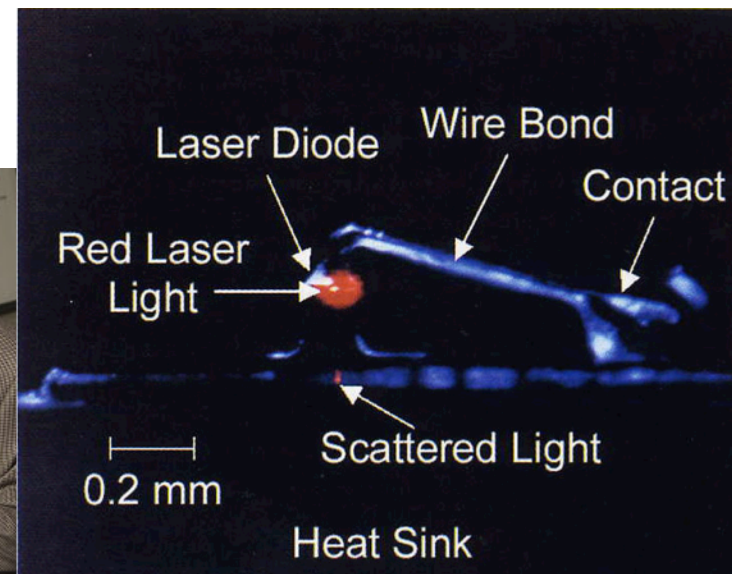




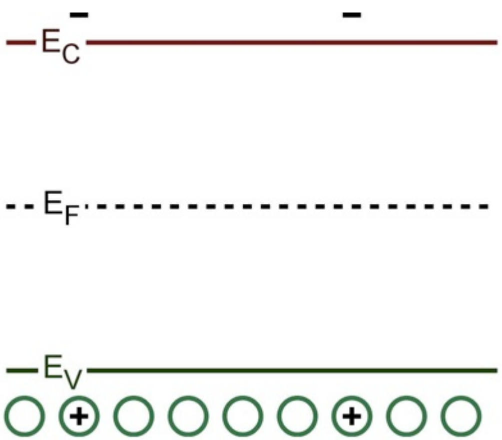
1st Ruby Laser (Al_2O_3:Cr) 1960 by Dr. T.H. Maiman.

Father of the LED and diode Laser (1962) while at GE: Nick Holonyak, Jr.





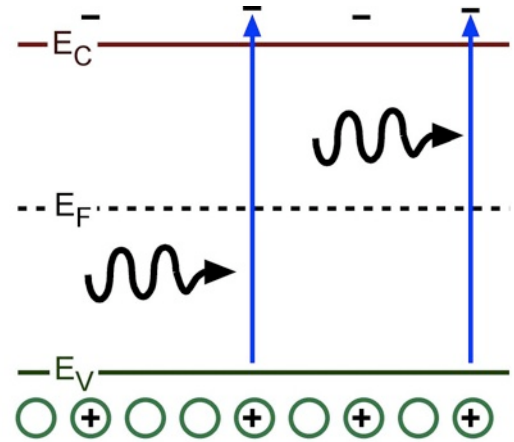
- Semicon. at room temperature



most electrons in the valence band

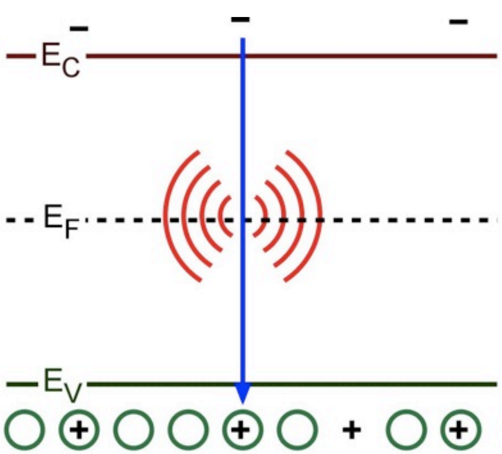
- Absorption

☆ *Circles with no + charge are just an electron in the valence band. These can absorb photons.*



all incoming photons with E>Eg are absorbed

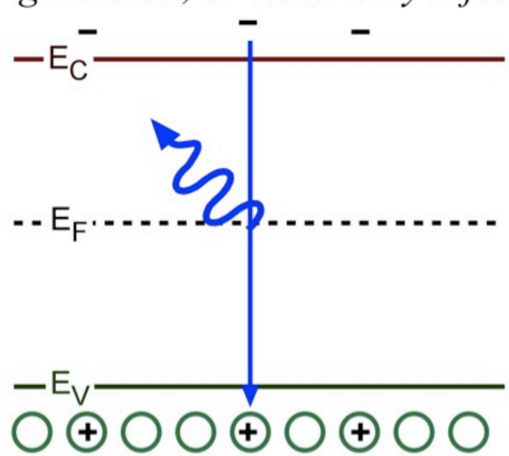
- Non-radiative Recombination



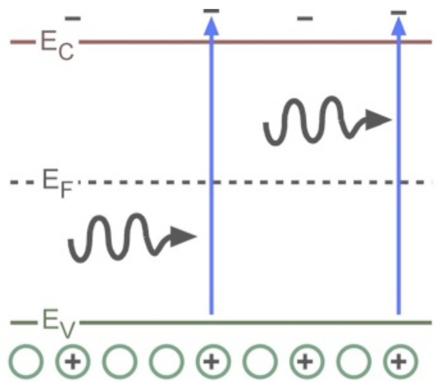
some can recombine non-radiatively and create phonons (vibrations / heat)

- Spontaneous Emission (LED) ☆

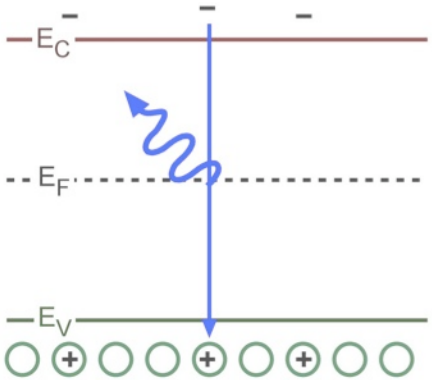
electrons could be thermally or optically generated, or electricaly injected



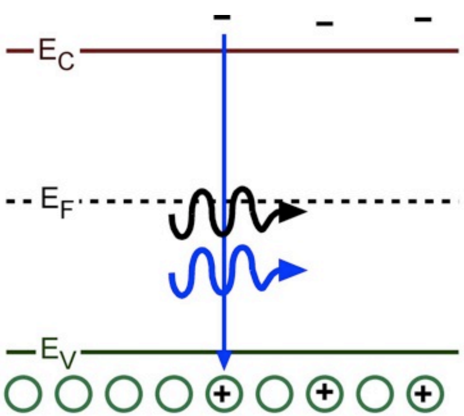
- Absorption



- Spontaneous Emission (LED)



- **Stimulated Emission (LASER)** ☆



there is a chance that an ***incoming photon*** *could stimulate recombination and form a* ***second photon*** *with the same phase and direction*

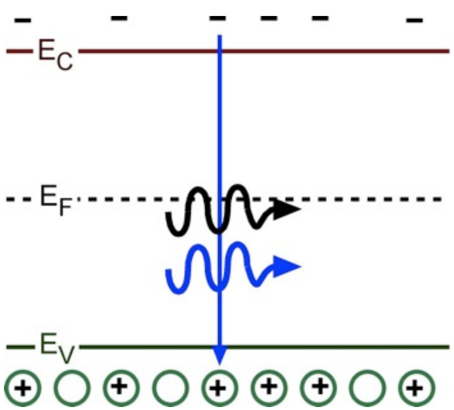
- However… easier said than done!

(1) Difficult to get the photon to the e-h pairs because it most often will be absorbed first.

(2) Difficult to have a photon next to an e-h pair before the e-h pair undergoes spontaneous emission.

Both of these make it difficult to achieve LASING. There are are a few additional device aspects that we need to add, else we will just have a regular LED…

- First thing we need: Population Inversion ☆



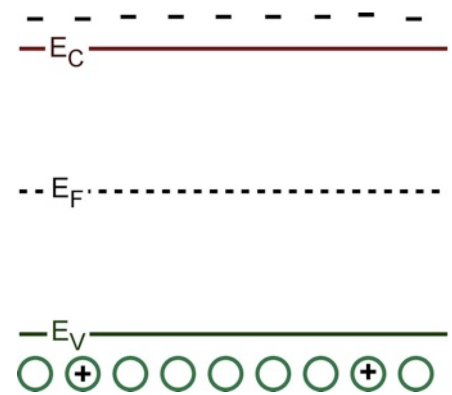
More e-h pairs than e’s in valence band.

Therefore a photon is more likely to encounter an e-h pair (stimulated emission) than a electron in the valence band (absorption).

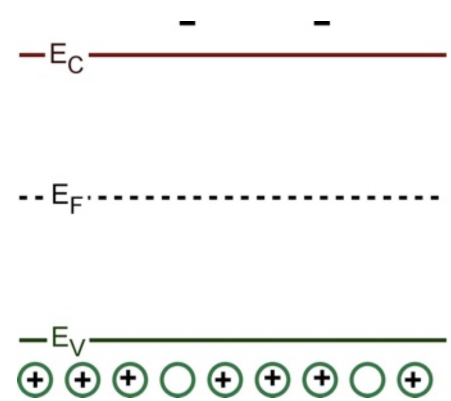
- Carrier lifetime, is long or short better?

- How can we electrically inject such a large excess of e-h pairs?

We can inject excess electrons from n-type material!

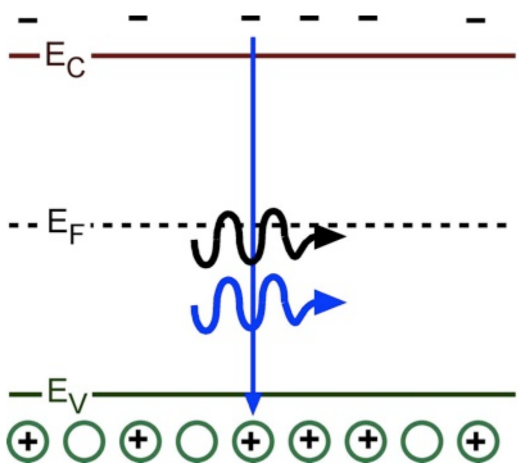


We can inject excess holes from p-type material! (a hole injection is just removing an electron…)



So what type of device structure do we need?

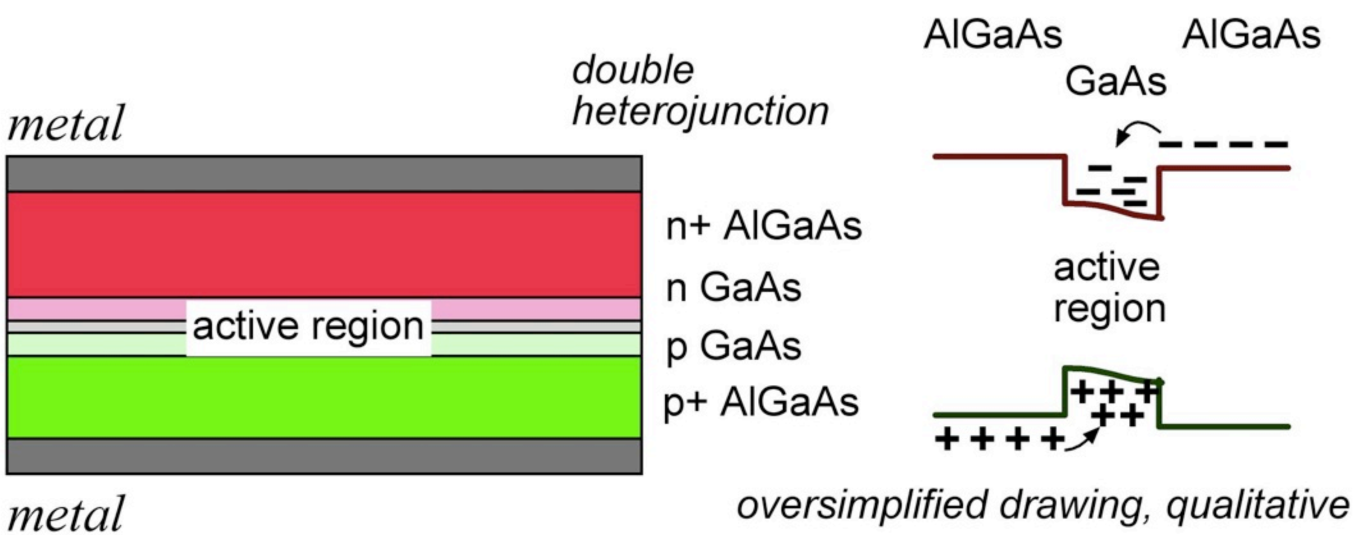
- So use a PN junction to inject e's and h's on both sides of the region with population inversion.



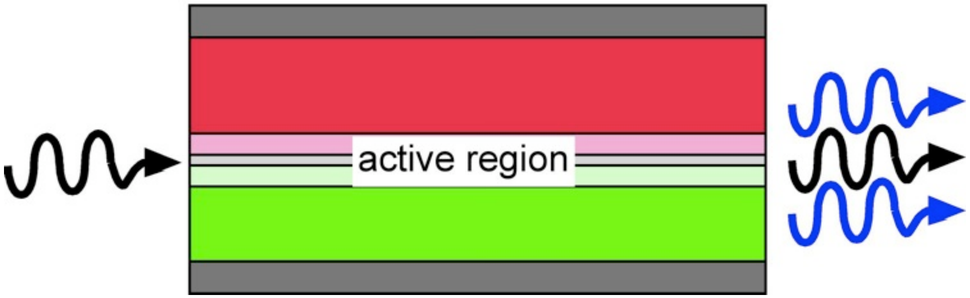
- However, to achieve such a high excess, we MUST confine these carriers somehow…

- otherwise high-concentration will spread out due to diffusion!

- To confine injected carriers, use a double heterojunction again!



- Great, this is how you make an semiconductor optical amplifier!



- What is this useful for? *Next slide*.

- Note, this is not yet a laser (we need to add one more device design aspect, we will get to that in a moment).

Booster Amplifier

SAO11b, SAC11b

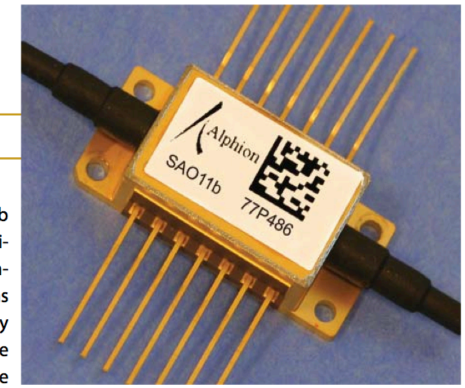
Booster Amplifier

Features and Applications

- Wide optical bandwidth
- O-Band and C-Band versions
- Supports rates up to 160 Gb/s
- High output power
- 14-Pin MSA package
- Booster Amplifier
- Telecom and Datacom
- Loss compensation
- 40G and 100G amplifiers

Description

The QLight® SAO11b and SAC11b are semi-conductor optical am-plifiers (SOA) for use as booster amplifiers. They significantly increase output power and are suitable for fixed and tunable ITU transmitters and transponders. They are based on the Alphion pro-prietary QLight® technology platform for the manufacturing of advanced discrete photonic devices.



The amplifiers are available in a MSA compliant, 14-pin butterfly package, based on the Alphion standard packaging platform. The use of a laser-welded, hermetic, organics-free package ensures highly reliable operation. The package incorpo-rates both a thermistor and a thermo-electric cooler to provide stable operation of the SOA over the full operating temperature range.

Alphion offers a broad range of SOAs supporting wavelengths form 1000 nm to 1600 nm, with gain options from 5 to 30 dB and we can optimize parameters to meet your specific application needs.

3X to 1000X

Absolute Maximum Ratings*

Parameter	Symbol	Min	Typ	Max	Unit
Operating Temperature	T_{case}	0		70	°C
Storage Temperature	T_{store}	-40		85	°C
Operating Bias Current	I_f			450	mA
Optical Amplifier Reverse Bias	V_{rev}			2	V
Thermistor Current	I_{therm}			5	mA
TEC Current	I_{TEC}			1.8	A
TEC Voltage	V_{TEC}			3.4	V

*Stresses in excess of the Absolute Maximum Rating can cause permanent damage to the device. These are at these or any other conditions in excess of those given in the operational section of the datasheet. Exposu device reliability.

Operating Specifications*

		SAO11b			SAC11b			
Parameter	Symbol	Min	Typ	Max	Min	Typ	Max	Unit
Operating Wavelength	λ	1290		1330	1530		1570	nm
Peak Gain	G_{pk}	9.5			9.5			dB
Gain Ripple	GR		0.2			0.2		dB
Saturation Output Power	P_{3dB}	11			12			dBm
Forward Voltage	V_f		2			2		V
Operating Bias Current	I_{op}		300			300		mA
Thermistor Resistance	R_{therm}		10			10		kΩ
Total Power Consumption	P			4			4	W

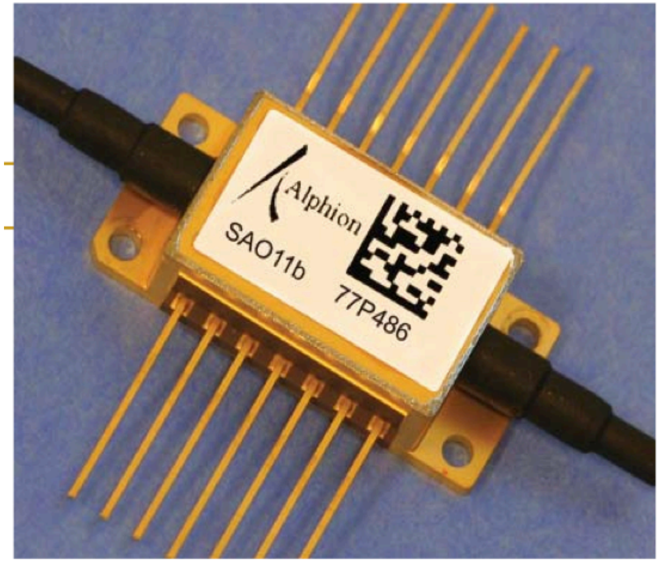
*Specifications are subject to change without notice
**Additional gain and power options available upon request

- *Great! Now we have amplification, but not LASING…*

Why not lasing? The above only amplifies if you insert photons into one end…

- Spontaneous emission (like that in an LED) occurs in:

(a) only one direction
(b) all directions (is random)
(c) occurs only when stimulated
(d) occurs at random times
(e) both b&d



- Stimulated emission requires:

(a) an electron-hole pair, ready to recombine
(b) a photon to stimulate the recombination
(c) both a&b
(d) niether a&b

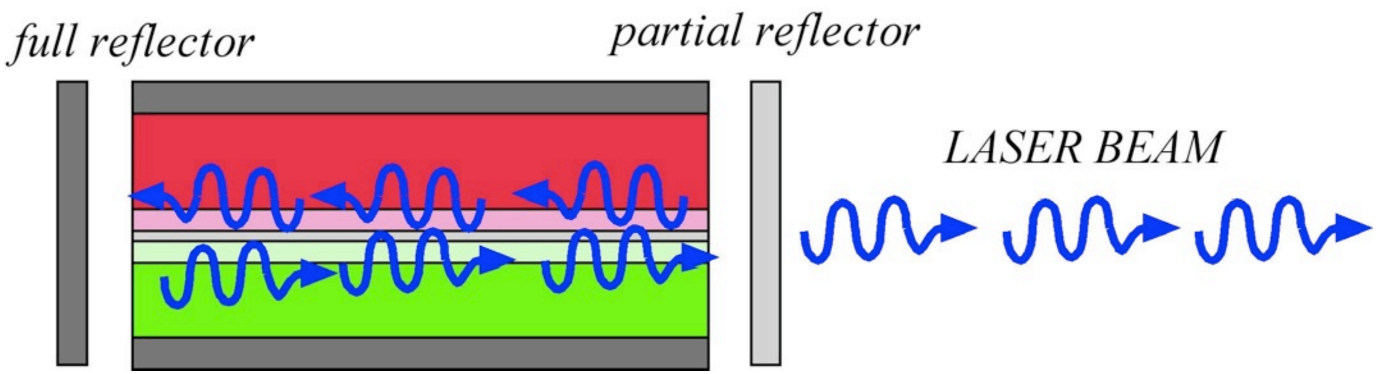
- Stimulated emission produces:

(a) two photons moving in any random direction
(b) two photons that are in phase
(c) two photons that travel in the same direction
(d) both b&c

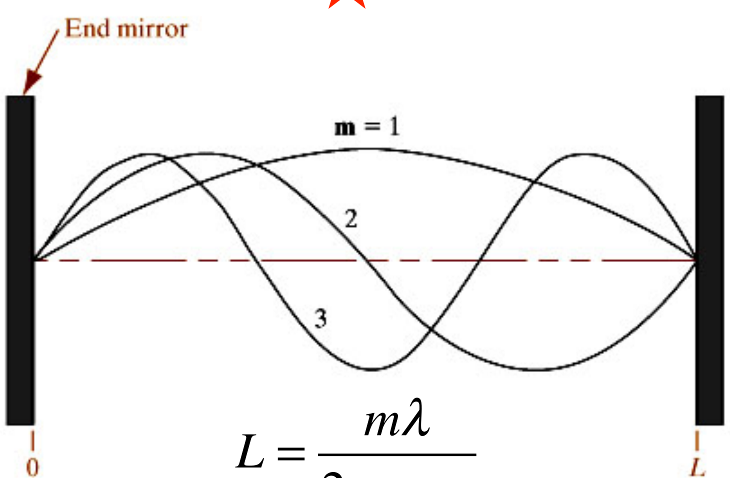
- True/false: population inversion requires more electron-hole pairs than electrons in the valence band.

- True/false: a diode and a homojunction is the best way to achieve population inversion.

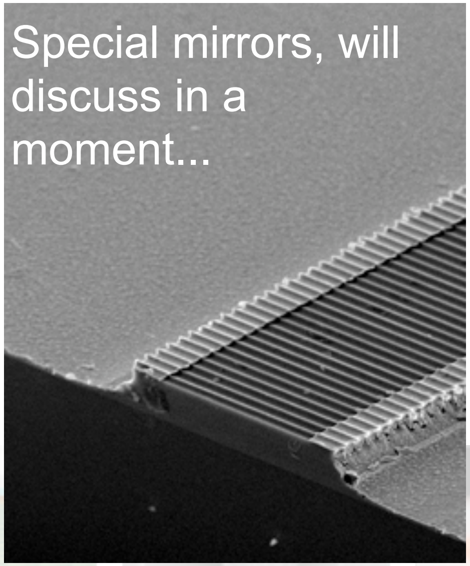
- To turn an amplifier into a Laser, we need to recycle part of the light (only let a fraction out)…. *helps build up enough photons to stimulate emission (catch e-h pairs before spontaneously recombine!)*



- A LASER is COHERENT, ALL in phase, so must have a resonant cavity to keep reflected photons in phase!



$$L = \frac{m\lambda}{2n_{semicon}}$$



www.unine.ch/phys/meso/DFB/DFB.htm

- Example with fancy mirrors… Vertical Cavity Surface Emitting Laser (can make arrays).

Where is the active layer?

Where are the mirrors?

850nm 10mW VCSEL
www.root.cz/clanky/bezvlaknova-optika-4/

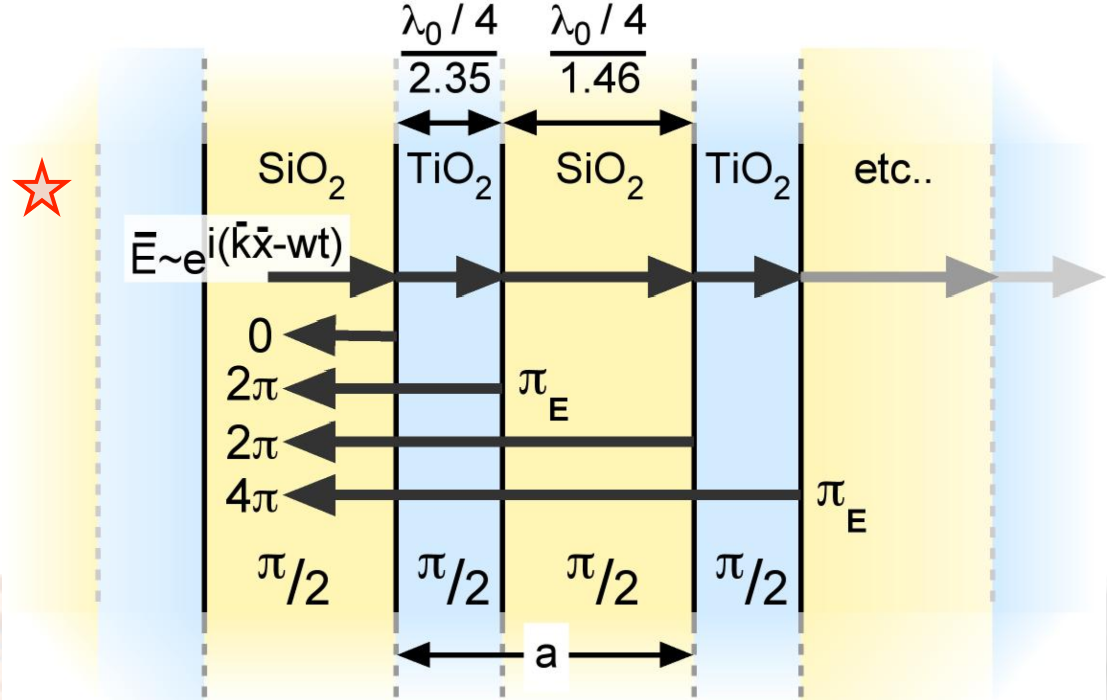
I think these were optically pumped…

- So why not use a simple Al mirror with R=90%? Two reasons…

For most lasers, the mirror must reflect without loss to avoid (1) photon loss with 'n' reflections (0.9^n) and (2) mirror damage by the high optical power….

- There are special mirrors without optical loss, called 'photonic crystal' or 'dielectric reflectors' or 'distributed Bragg reflectors'. They work based on interference principles…

- key advantage over metal mirrors is use of 'dielectrics' which have extremely low (~zero) optical absorption!



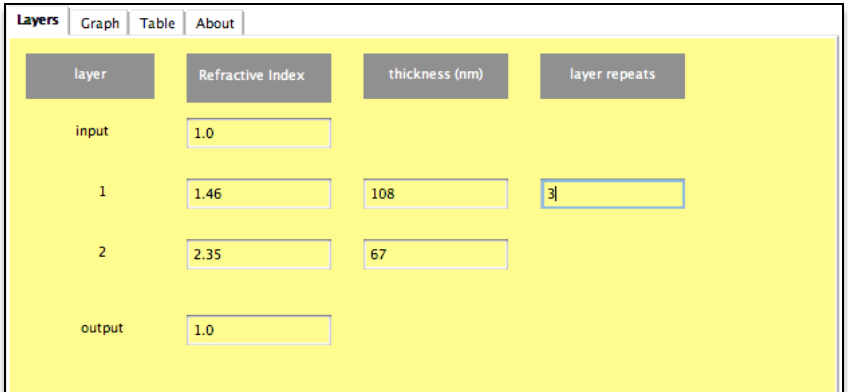
- For lasers the low index material can also be air (n=1, previous slides)

What if layers are $\lambda/2$ thick?

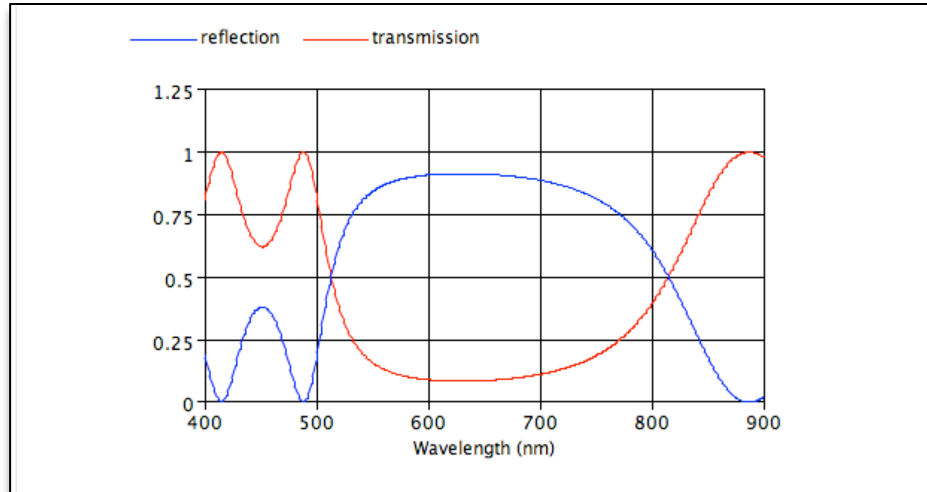
Example Pi + Pi + Pi = 3 Pi, all out of phase! So becomes a perfect transmitter!

NO Fresnel reflect! Anti-glare or antireflective coatings on lenses!

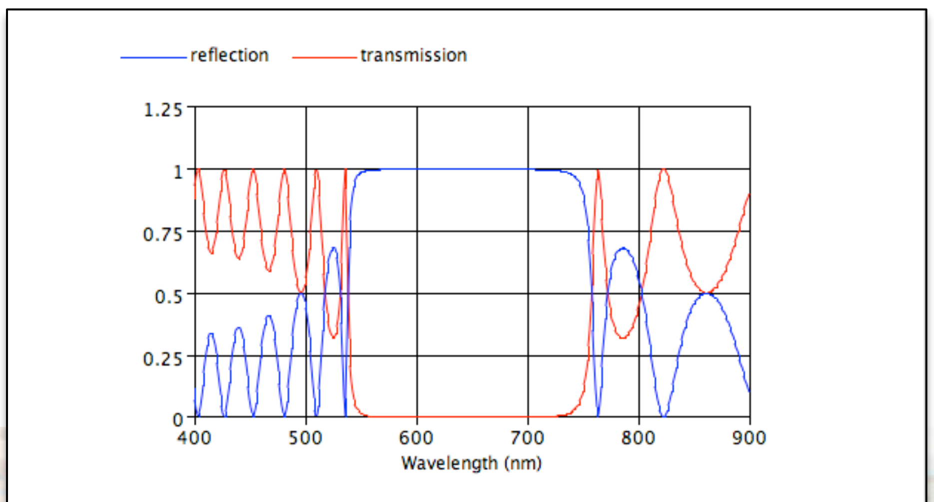
http://cops.tnw.utwente.nl/education/5_oc_optlay.html



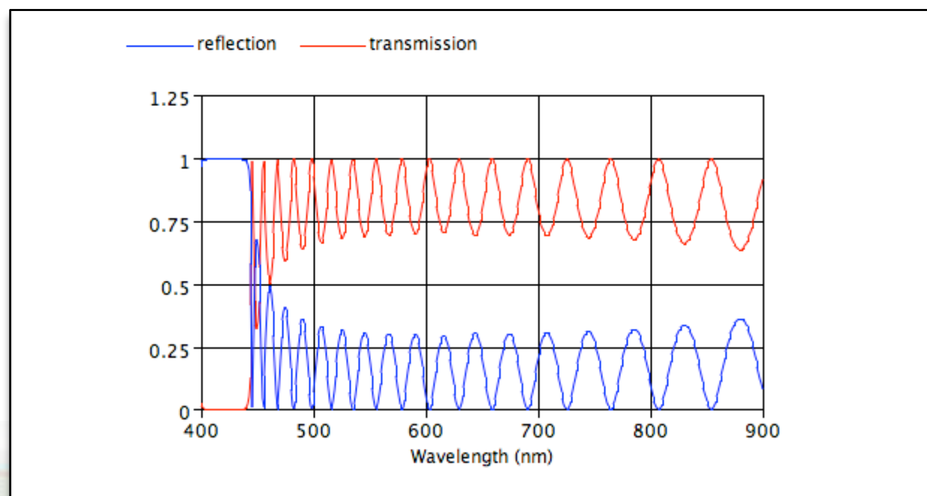
- λ/4 with 3 layer repeats (0.5 μm thick)



- λ/4 with 10 layer repeats (1.75 μm thick)

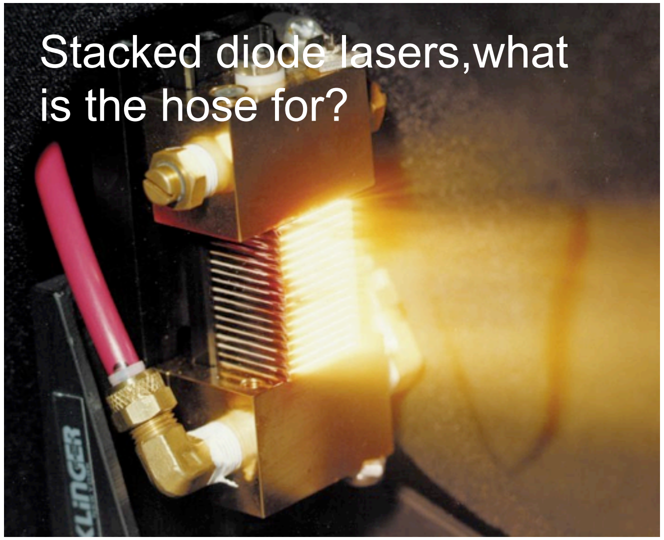


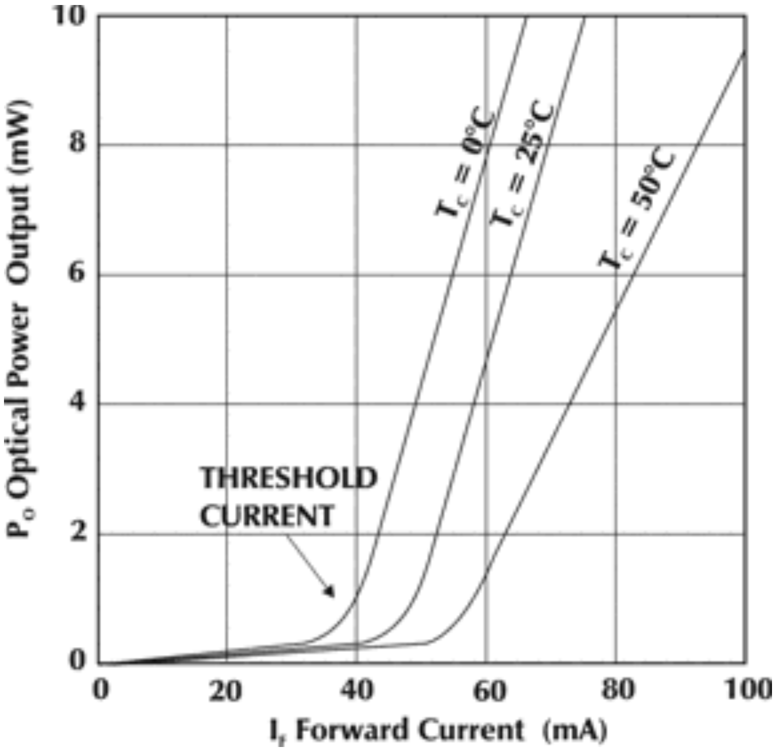
- λ/2 thick with 10 layer repeats (3.5 μm thick)



- Summarize LASER requirements:

  - *Direct bandgap semiconductor.*
  - *Population inversion (strong injection, confinement).*
  - *Back reflection (recycling) of light.*
  - *An optical cavity of precise length.*





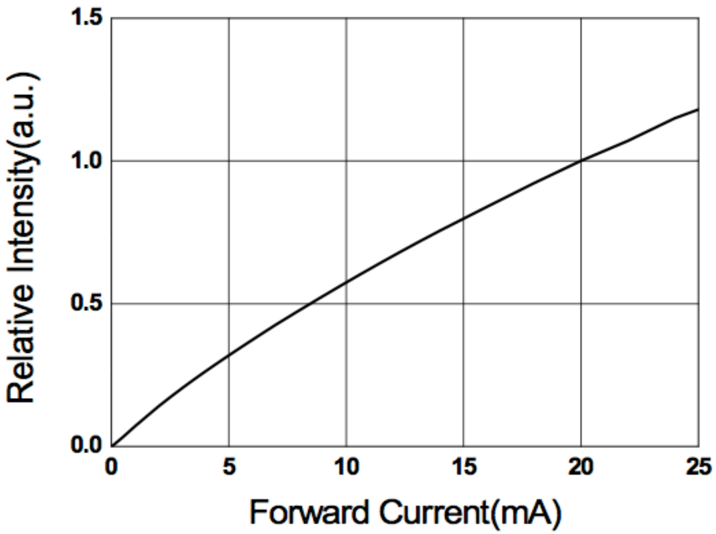
Notice there is a threshold *current* (not a voltage), why?

Why a lower threshold current for lower temp?

Last question (see picture above)…

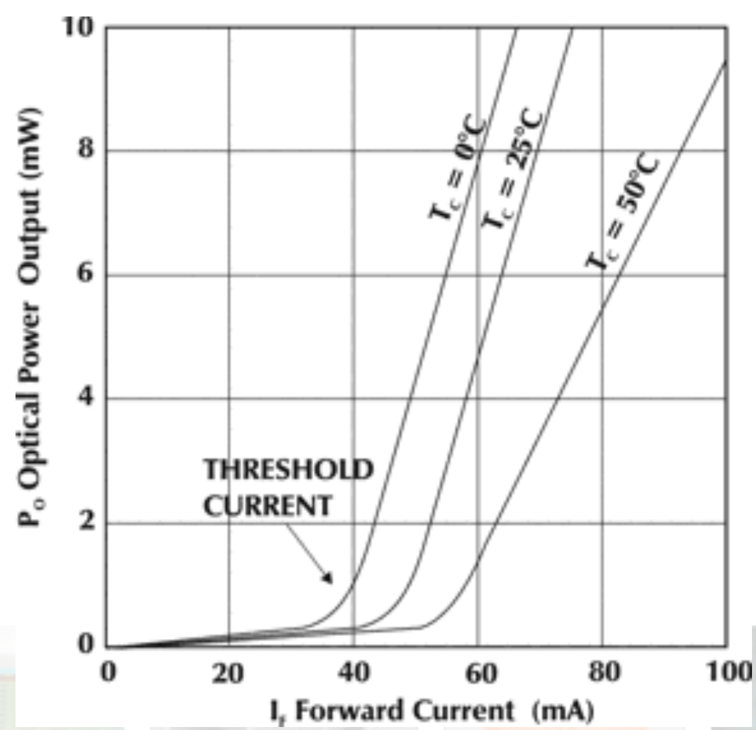
http://www.fiber-optics.info/

- Another question, this plot below… why type of semiconductor device is it for?



- One more review… label each section (1st linear, curve, 2nd linear) and explain what criteria are being satisfied in terms of:

(1) No emission
(2) Spontaneous emission
(3) Stimulation emission
(4) Both



- Why do we need mirrors on the ends of a laser to partially reflect/recycle photons inside the laser?

- Do the mirrors need to be of any precise distance apart?

- Can we use a regular old mirror like aluminum or silver?

- Do LEDs have a threshold current for LED emission to occur?

- Do Laser's have a threshold current for lasing to occur?

- Lets talk about applications…

Smaller wavelength of light, you are able to image a smaller feature!

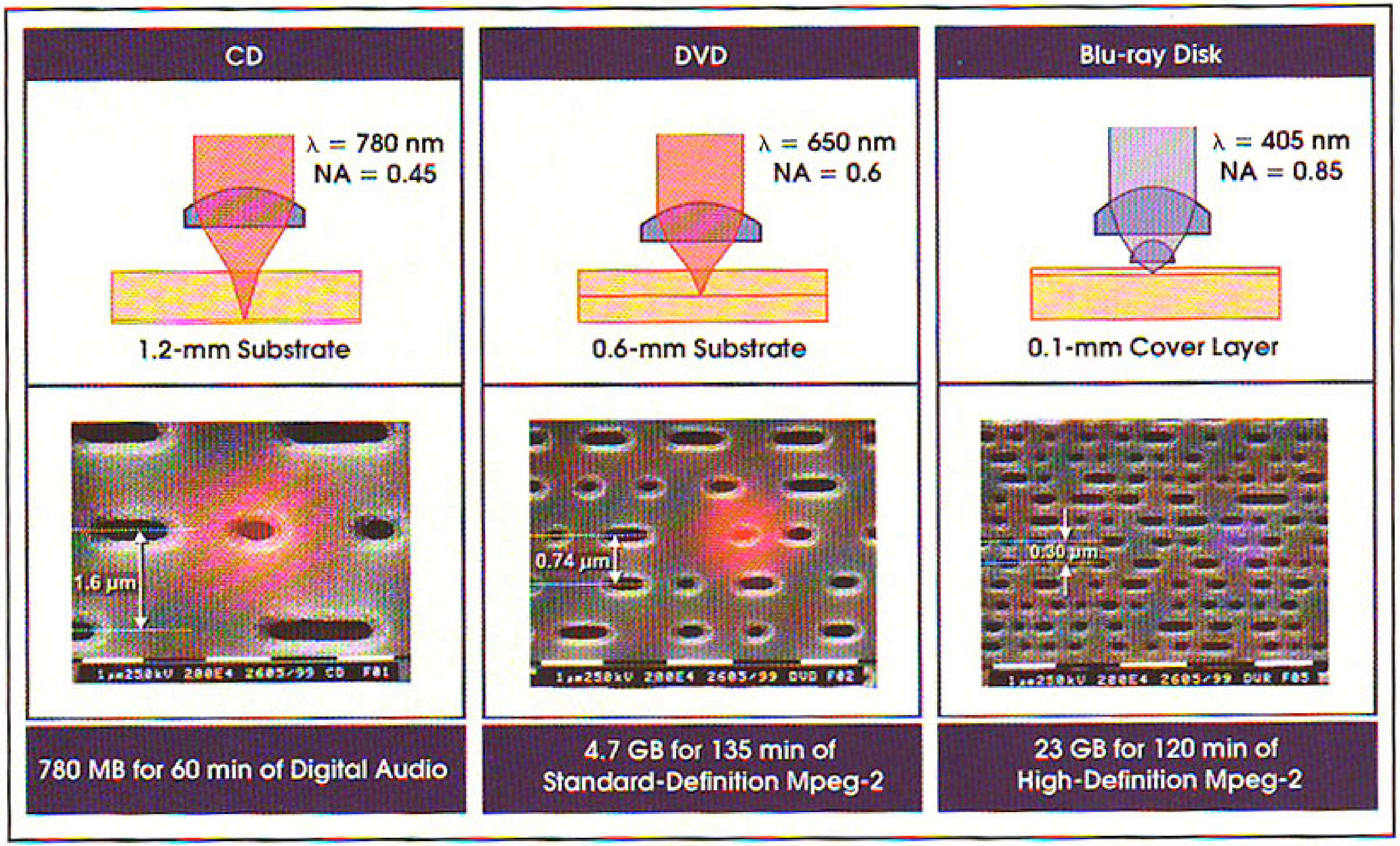


Figure 5. *Optical storage densities have increased significantly with the evolution of CD, DVD and Blu-ray technologies.*

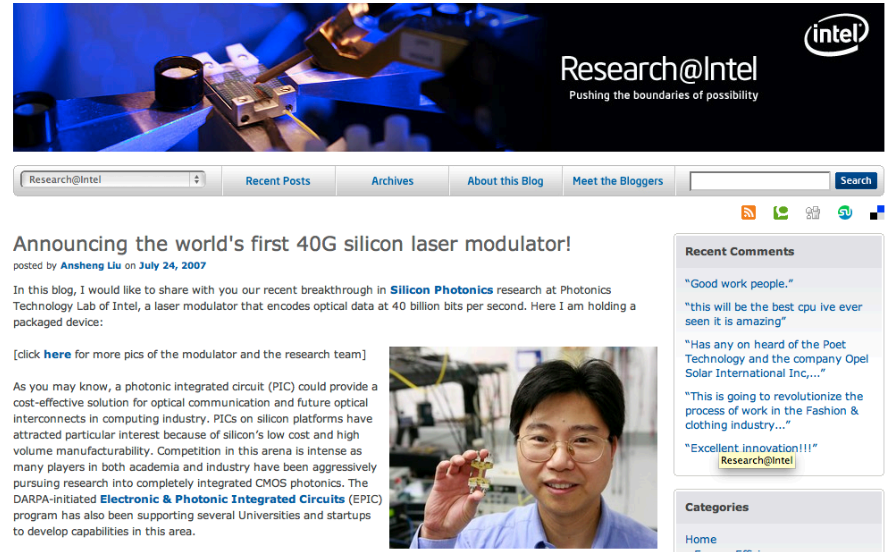
Credit: Photonics spectra

- Laser's dominate in high-speed data generation.

- Split laser down two waveguide paths (arms) of the same length…

- Velocity of light in material is c/n (refractive index)

- Use a ***pn junction*** (again!) to inject carriers which raises refractive index and can slow the light down in one of the 'arms'… can control in or out of phase (see diagram below). ☆



Announcing the world's first 40G silicon laser modulator!

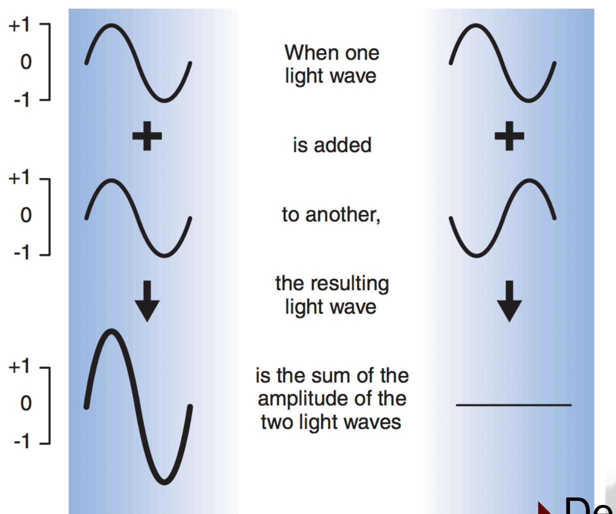
posted by Ansheng Liu on July 24, 2007

In this blog, I would like to share with you our recent breakthrough in Silicon Photonics research at Photonics Technology Lab of Intel, a laser modulator that encodes optical data at 40 billion bits per second. Here I am holding a packaged device:

[click here for more pics of the modulator and the research team]

As you may know, a photonic integrated circuit (PIC) could provide a cost-effective solution for optical communication and future optical interconnects in computing industry. PICs on silicon platforms have attracted particular interest because of silicon's low cost and high volume manufacturability. Competition in this arena is intense as many players in both academia and industry have been aggressively pursuing research into completely integrated CMOS photonics. The DARPA-initiated Electronic & Photonic Integrated Circuits (EPIC) program has also been supporting several Universities and startups to develop capabilities in this area.

- Why 'traveling' wave electrodes? Anything special?



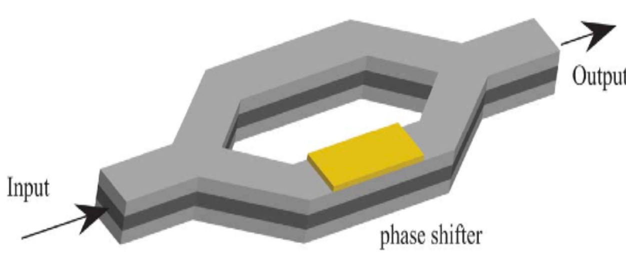


Figure 1a

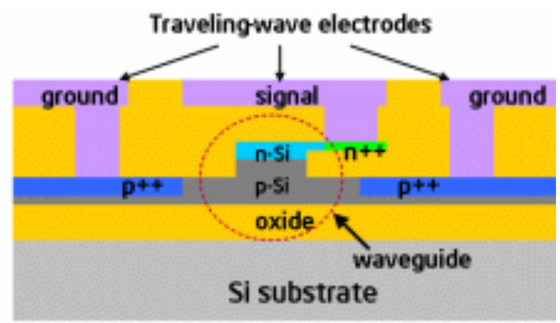
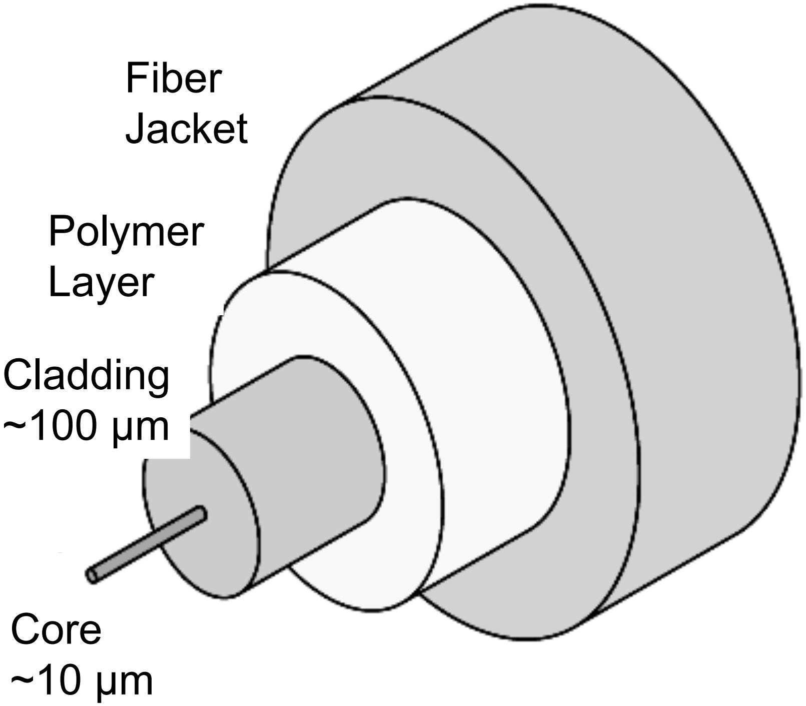


Figure 1b

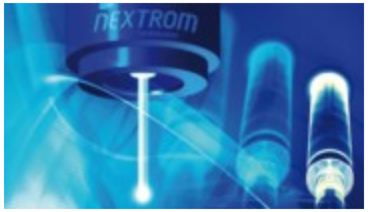
$$\Delta n \approx 3x10^{-21}(1/cc) \quad \times \quad N(cc)$$

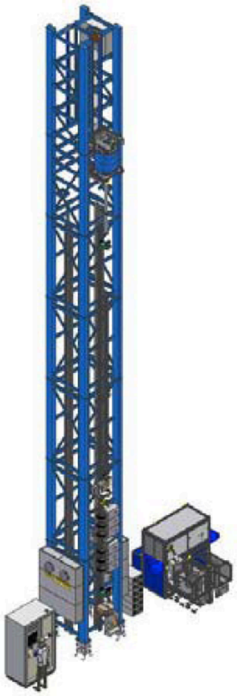
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 25, NO. 3, MARCH 2007

- Design laser for long recombination lifetime (efficient lasing).. design this PN junction in the waveguide for FAST recombination (fast modulation!)



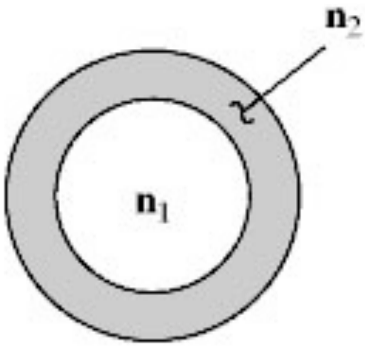
- Fiber preform has core and cladding, but is ~10 cm wide, heated till soft and then drawn downward to the base where polymer protective layer is added.

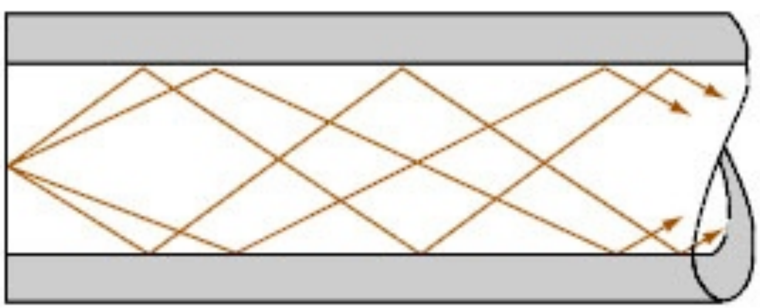




- Typical fiber core n~1.46 (SiO_2)

- Cladding is typically ~0.1 to 0.3 lower to support TIR



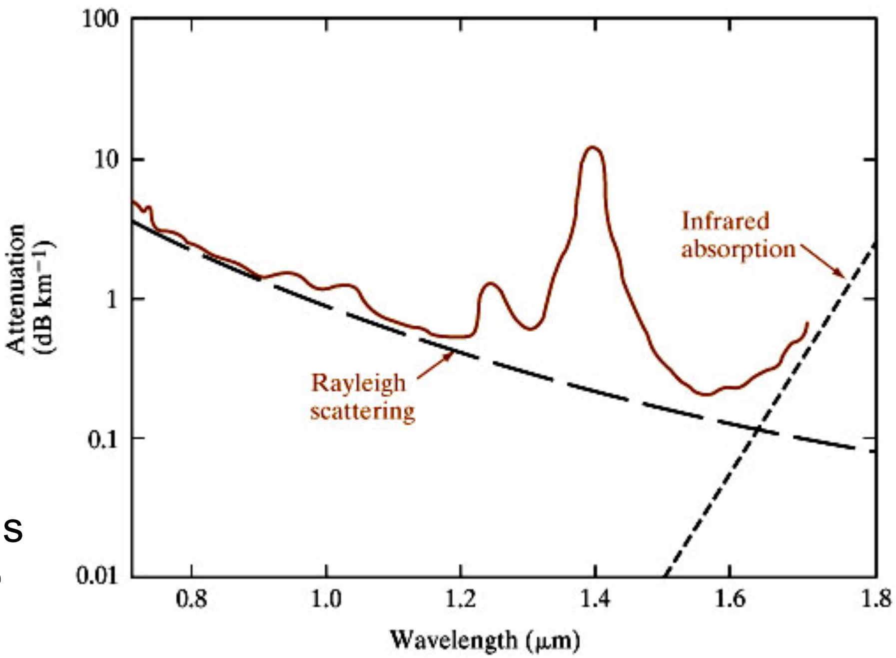


- Lowest loss is ~0.15 dB/km at 1.5 μm

$$\alpha(dB/km) = \frac{-10}{z(km)}\log\left(\frac{P(z)}{P(0)}\right)$$

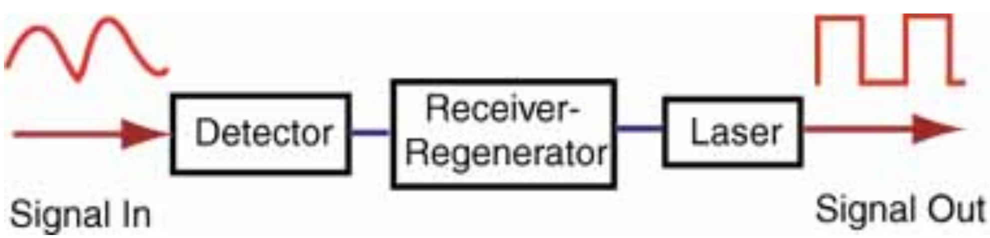
$$if\ \frac{P_z}{P_0} = 0.10, \alpha = 0.3$$

$$then\ z = 30{,}000m \quad (30\,km)$$



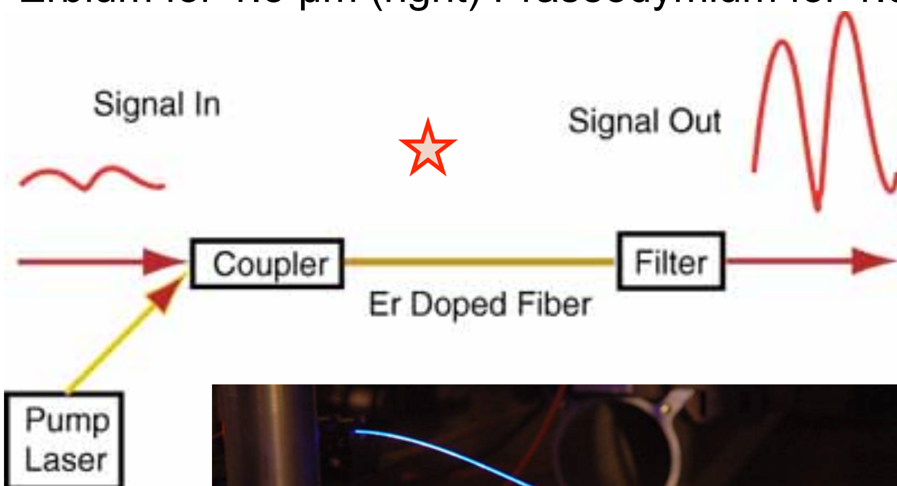
- How far can you go? What data rate? …depends on *fiber loss*, *receiver quality, and dispersion (take senior opto courses to learn more).*

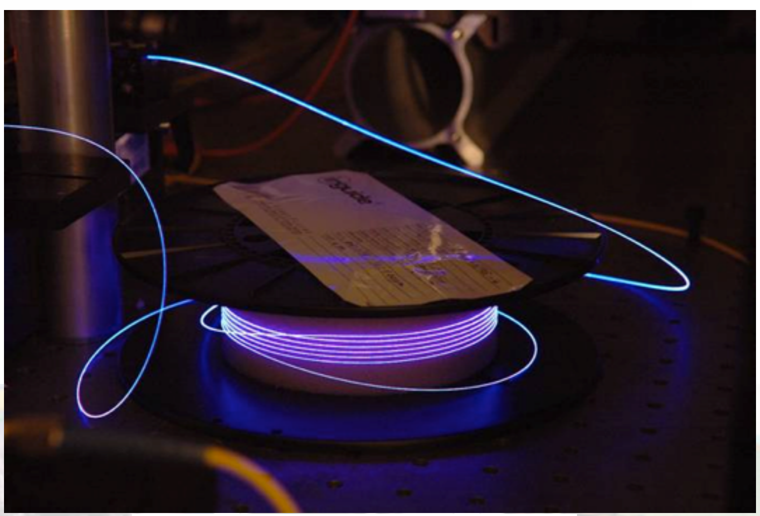
- One way to go even further… what problems exist with this approach shown below?



www.thefoa.org/tech/fiberamp.htm

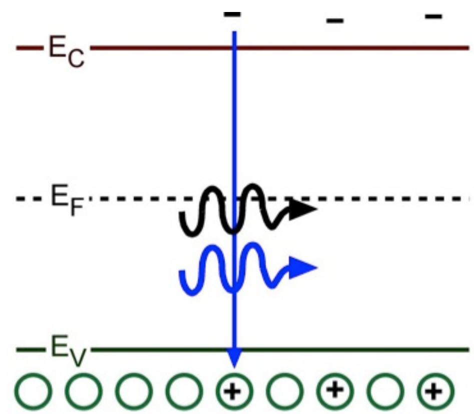
- Semiconductor amplifiers (SOAs) used for short-haul and more local area amplification.
- For long-haul and highest performance, use a Fiber amplifier! (unlike SOAs: no currents, less noise..)
- Erbium for 1.5 μm (right) Praseodymium for 1.3 μm



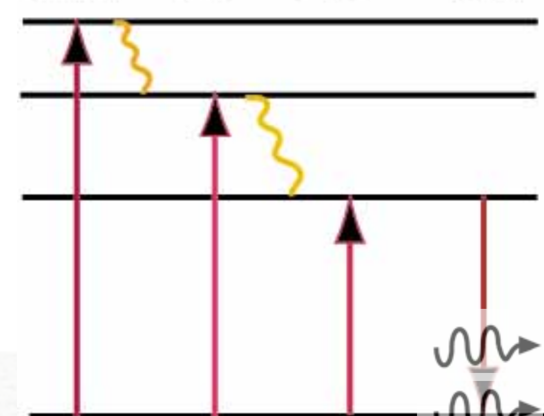


www.thefoa.org/tech/fiberamp.htm

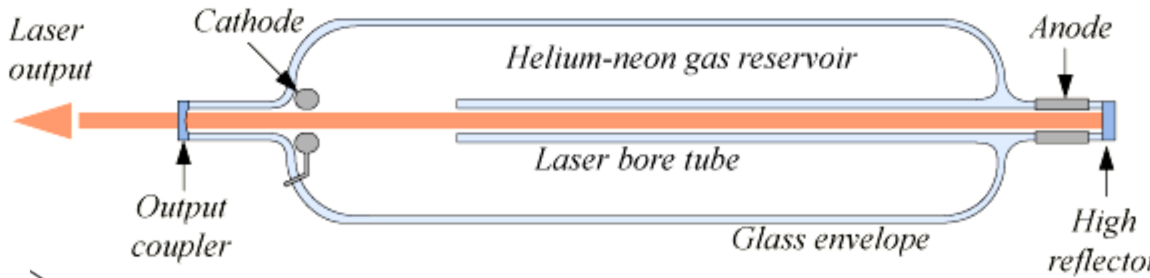
Stimulated emission (semicond.)



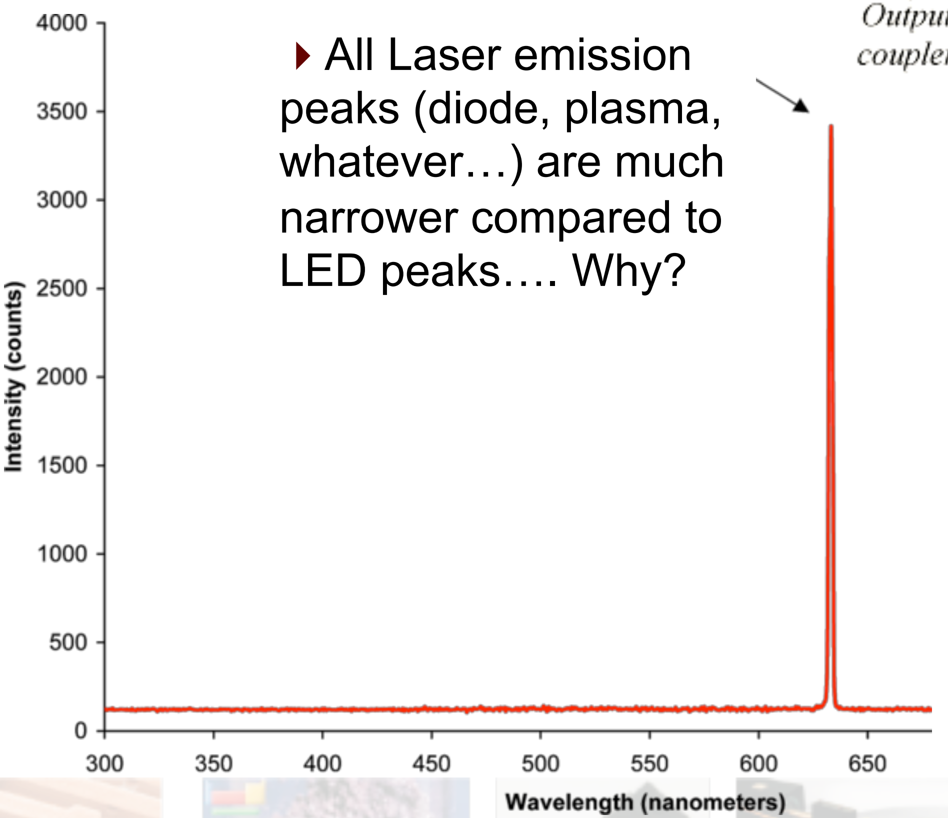
Stimulated emission (Erbium) in a fiber!

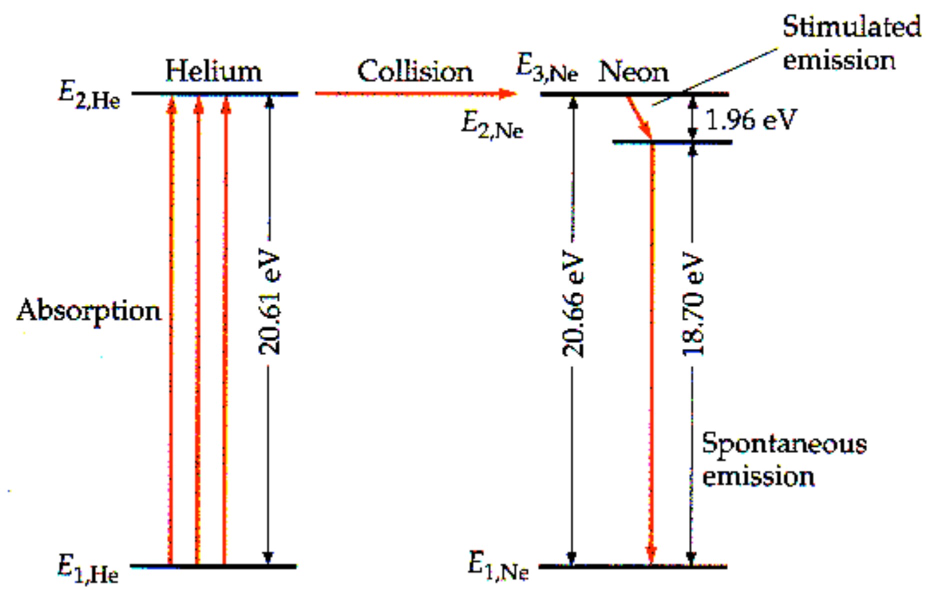


- NOT A LASER DIODE: Gas lasers are very common (use excited atomic transitions to provide energy for stimulation emission).



- All Laser emission peaks (diode, plasma, whatever…) are much narrower compared to LED peaks…. Why?





- NOT A LASER DIODE: Solid state and fiber lasers are optically pumped (normally glasses with special atoms inside them).

YLS-XXXX
kW Class Ytterbium Fiber Laser System
CW, QCW, SM
Random
3kW - 10kW
1070-1080 nm
Available in 100, 200 or 300 μm diameter

- Last topic – in a recent issue of IEEE spectrum!

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BMW Laser Headlights Slice Through the Dark

Lasers are more efficient and offer a more natural white light

By Lawrence Ulrich
Posted 25 Oct 2013 | 14:00 GMT

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Photo-illustration: Smalldog Imageworks

Its lights are brighter—and whiter.

"At just 10 square micrometers, the laser's active light-emitting area is 1/10 000th the size of a 1-square-millimeter LED."

"**Lasers also beat LEDs where it matters most:** efficiency. It's true that LEDs are more efficient at turning electricity into light, though laser efficiency is rapidly catching up. But for overall system efficiency, it's no contest: LEDs are nowhere near as good at getting the light to where you want it to go. That intense laser, for example, can be beamed into a fiber-optic strand and lose only 10 to 20 percent of its initial energy, as opposed to what an LED could lose—up to 90 percent, experts say."

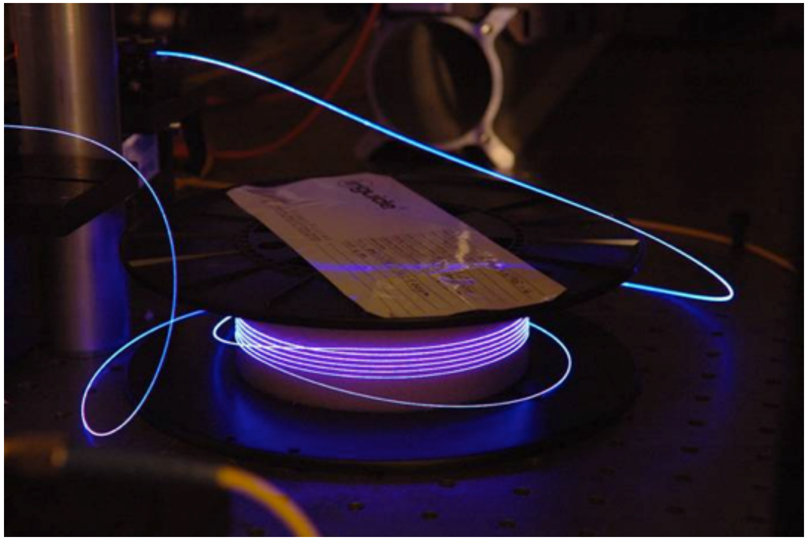
They direct the laser onto a phosphor, like that done in white LEDs…

- What is the best way to modulate laser light?
(a) switch the laser diode on/off fast as possible.
(b) leave laser on, and modulate optical interference with waveguides and pn junctions.
(c) neither a or b

- What material is used for nearly all high-speed and long-haul optical fibers?

- We did not cover this, but you should be able to answer it… at the end of an optical fiber, where the optical data is received, the receiver typically is some sort of:
(a) magic device
(b) reverse biased diode :)

- Are we done with diodes yet ?!?!?!?!
(a) yes, there can't possibly be more applications for them…
(b) no, based on how this course has gone it is a safe bet that they are also the basis for the next lecture on CMOS cameras / CCDs ;)

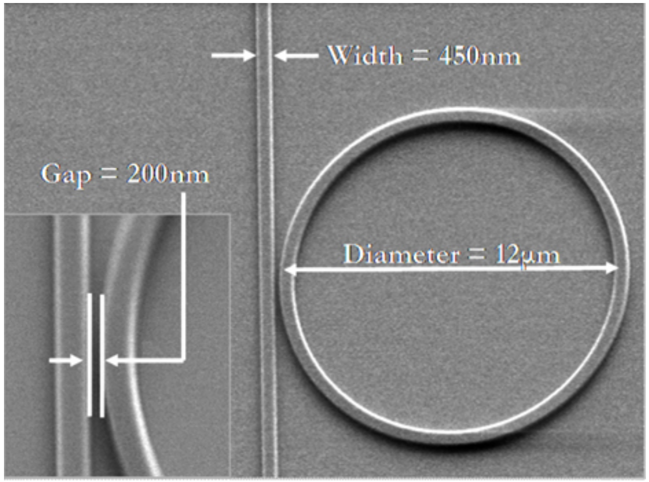


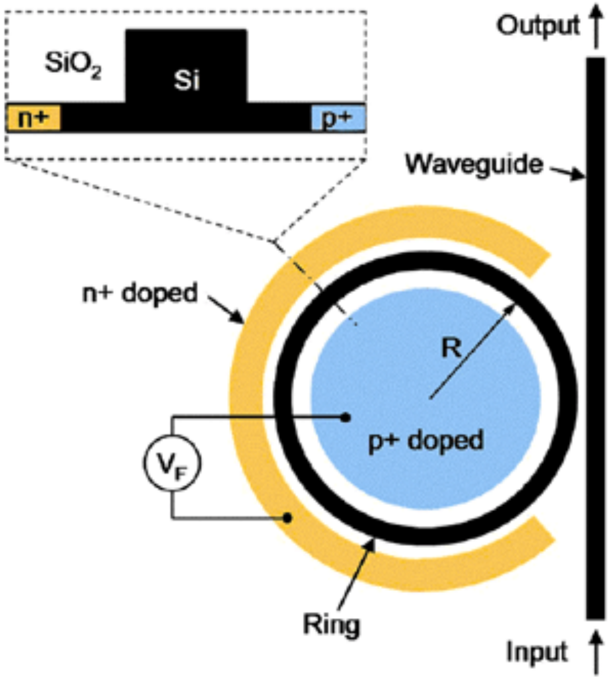
- Basic concept: http://www.youtube.com/watch?v=LU8BsfKxV2k

- You could switch the laser on/off directly, but that introduces undesirable artifacts (chirp, etc.), and in some cases is slower… why? *Think about a PN junction in forward bias… think RC…*

- I told you that PN junctions were important to the whole course! Even switching of lasers! *This PN junction might be best designed for FAST recombination (lots of material defects).*

The ring is surrounded by an outer ring of n-type silicon, and the region inside the ring is p-type, making the waveguide itself the intrinsic region of a PIN diode. When a voltage is applied across the junction, electrons and holes are injected into the waveguide, changing its refractive index and its resonant frequency so that it no longer passes light at the same wavelength. As a result, turning the voltage on switches the light beam off.





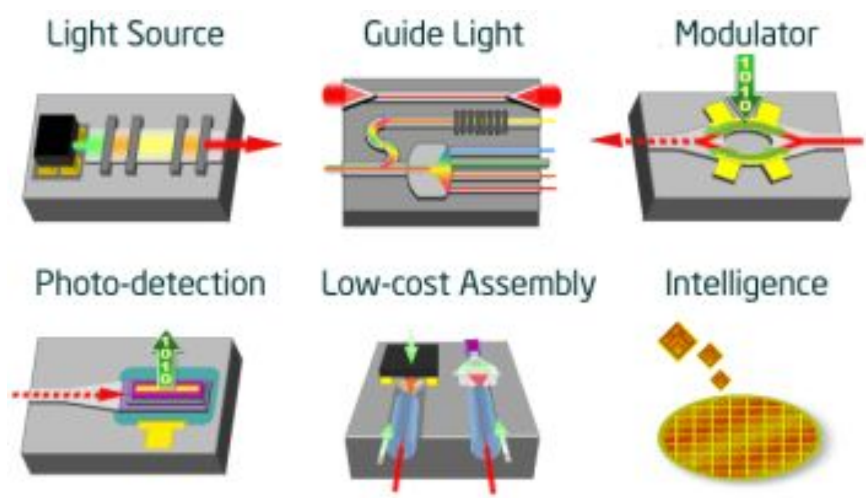
- There are other ways to modulate lasers, most are based on interference and modulating refractive index…

http://www.news.cornell.edu/stories/May05/LipsonElectroOptical.ws.html

- We can do amazing things on Silicon, but the biggest problem we have is that it is indirect bandgap!

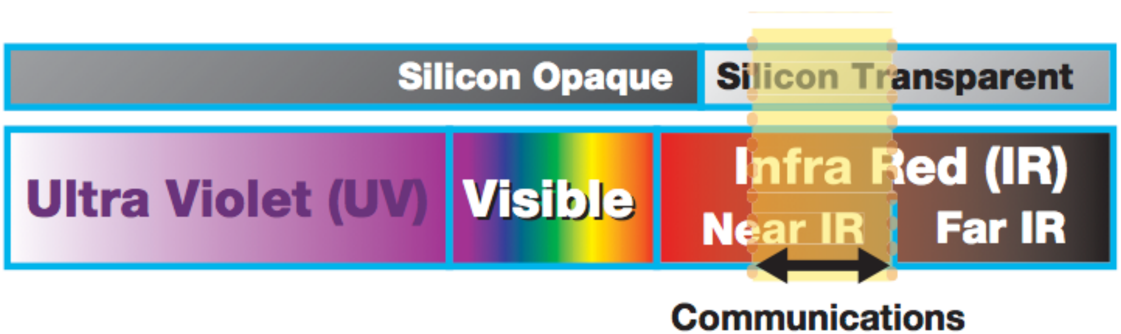
- People are solving that problem, and figuring how to guide and modulate light in Si chips… what wavelengths?

- The payoff is huge, move data around chips without RC time constants, and/or run optical fibers directly into a chip (not a separate chip).



http://www.youtube.com/watch?v=8JtzQsGrg80

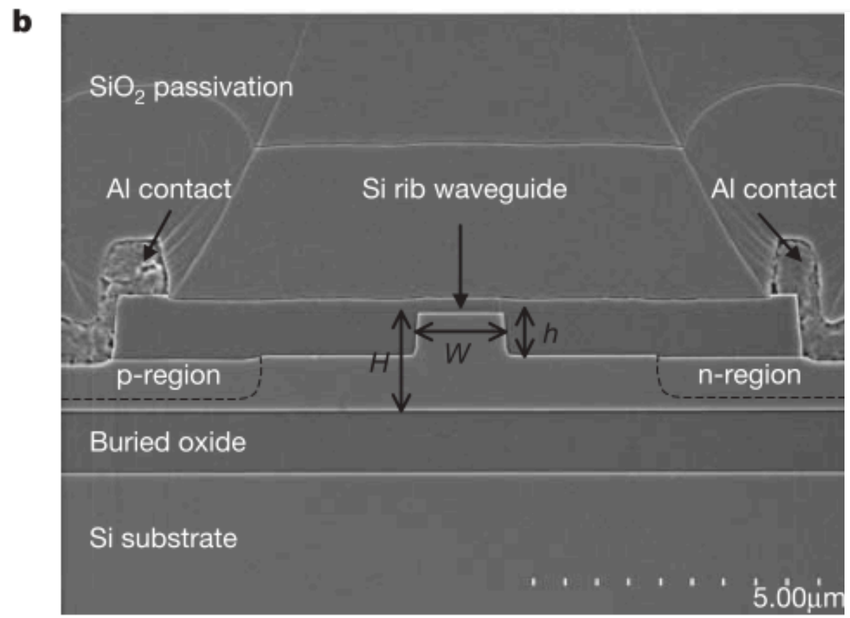
http://www.youtube.com/watch?v=vz3DaACN_54



- So we can waveguide, we can detect, we can modulate a laser signal, what is missing on Si still?

- How do they get Si to emit light? In 2005 Intel made an optically pumped Si Raman laser…

When light hits a substance, it causes the atoms in the substance to vibrate. Some of the photons can gain (steal) or lose (give away) a bit of energy in amounts associated with a single vibration (phonon). This results in a secondary light of a different wavelength. This same effect can be used to make a Raman laser… The Raman effect is 10,000 times stronger in silicon than in glass (periodic Si lattice). The lasing is the same in all aspects except no population inversion is required.



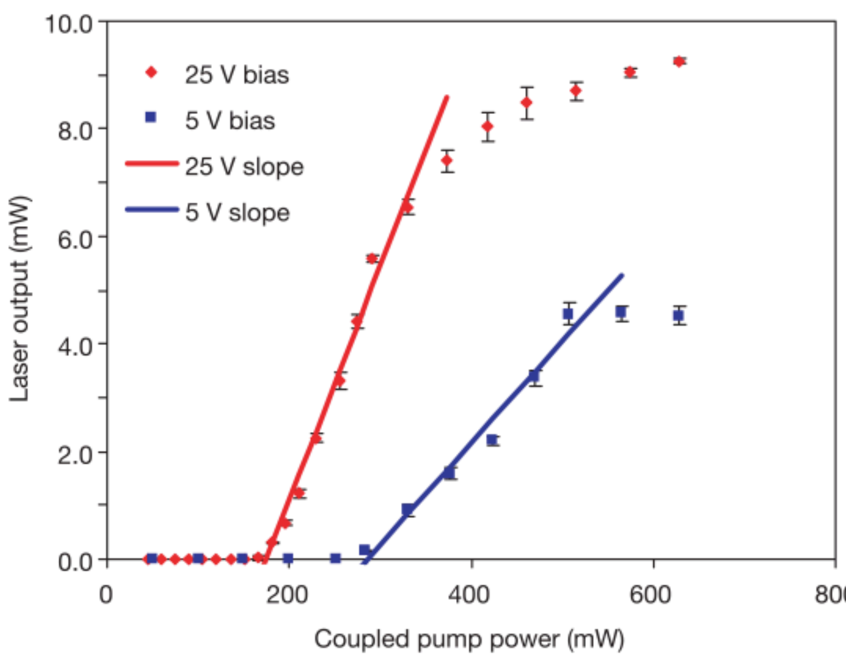
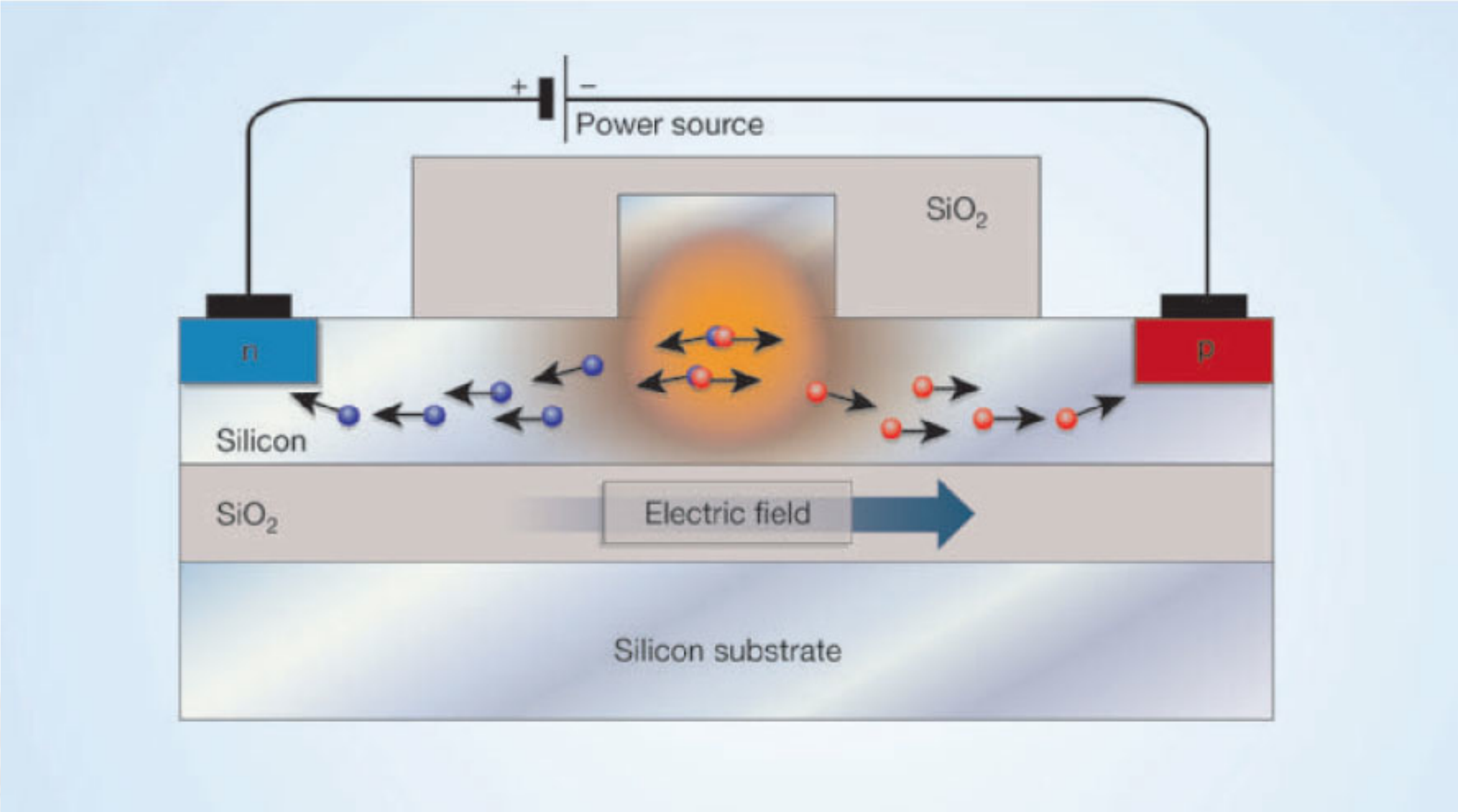
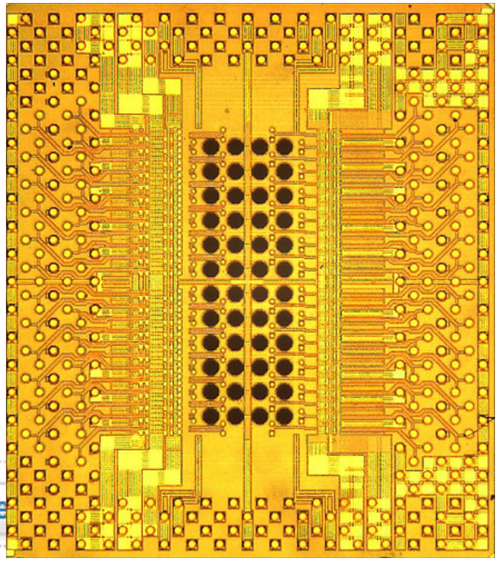


Figure 1 Silicon waveguide used in the Raman laser experiment. **a**, Schemat of the silicon waveguide laser cavity with optical coatings applied to the facets and a p-i-n structure along the waveguide. **b**, Scanning electron microscope cross-section image of a silicon rib waveguide with a p-i-n diode structure.

- How do they get Si to emit light?

A ridge-shaped waveguide made of silicon is surrounded by silica (SiO2). The large difference in refractive index between silicon and silica ensures that the light intensity is tightly confined within the waveguide so that a large Raman amplification can be obtained. This structure is embedded within a semiconductor device, which enhances the laser output by draining off unwanted electrons and holes that are created by the two-photon absorption (honestly, not sure why… this is fairly advanced stuff).





IBM Has a Trillion-Bit, Insane Bandwidth "Holey Optochip"

5:00 PM - March 10, 2012 by Douglas Perry - source: IBM

IBM has a prototype chip that features enough bandwidth to download 500 HD movies in just one second, or all content held by the Library of Congress in just about one hour.

This claim boils down to a parallel optical transceiver that is first to boast the capability of transferring one trillion bits (1 Tbps or about 116.4 GBps). According to IBM, the chip is about eight times faster than any parallel optical component that is available today and delivers a 100,000 times the "raw" speed that is equivalent to the bandwidth that is typically consumed by end users today (10 Mbps).

IBM said that key to improving the speed of the chip was adding 48 holes (optical vias) to a standard 90 nm CMOS, which provides access to 24 receiver and 24 transmitter channels. The fact that it is based on optical communication features gave the chip its name - the Holey Optochip. IBM says the 5.2 mm x 5.8 mm chip can be fabricated using today's silicon manufacturing techniques, which gives the technology instant scale. Apparently the chip is also very power-efficient at a power consumption of just 5 watts.

There was no information when or if this chip will be put into production.