Lecture 9
Stimulated Emission Devices LASERS

ECE 325
OPTOELECTRONICS

Menoufia University

April 17, 2019

Kasap – 4.1A&B, 4.2A, 4.8, 4.9, 4.15, and 4.19

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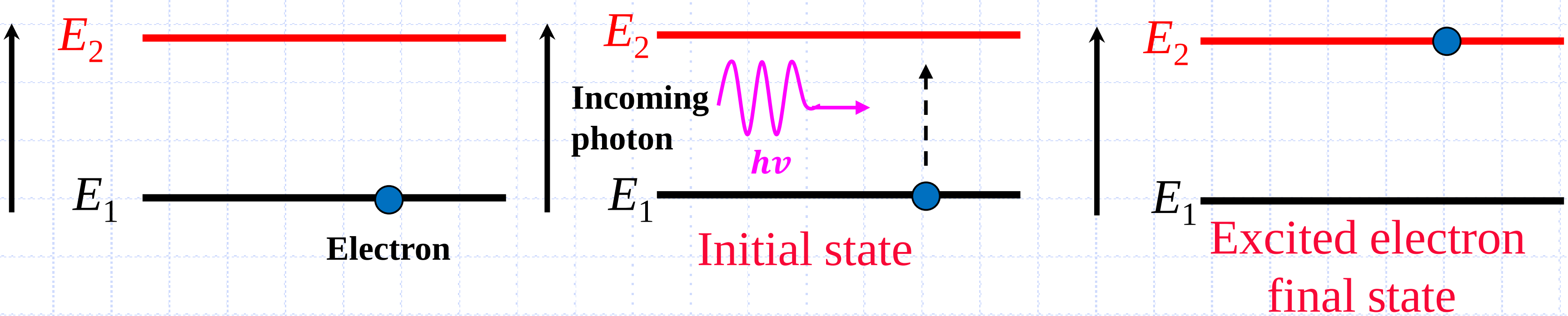
LASER

- A system for photon amplification
- LASER ⇔ **Light Amplification by Stimulated Emission of Radiation**

Absorption

- An electron in an atom can be excited from an energy level E_1 (ground state) to a higher energy level E_2 by the absorption of a photon of energy $hv = E_2 - E_1$.
- The energy now acquired by the electron is $hv = E_2 - E_1$.

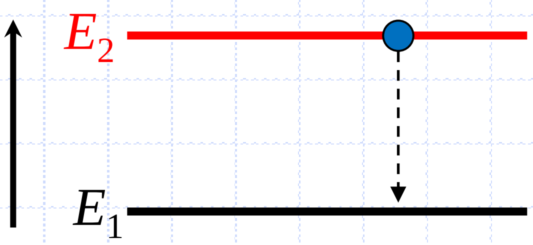


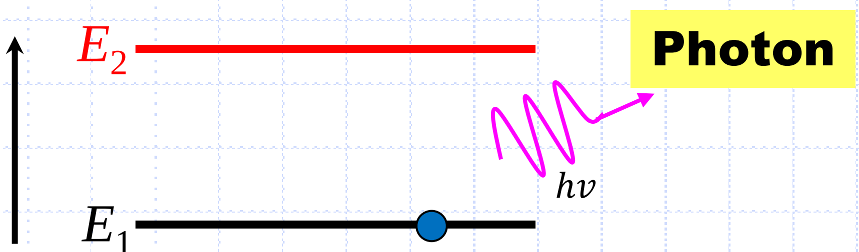
- When an electron at a higher energy level transits down in energy to an unoccupied energy level, it emits a photon.
- There are two possibilities for the emission process:

1. Spontaneous emission, or
2. Stimulated emission.

Spontaneous Emission

- In spontaneous emission, the electron undergoes the downward transition from level E_2 to E_1 by itself quite **spontaneously**.
- The emitted photon has:
  - energy $hv = E_2 - E_1$.
  - a random direction.
- The transition is spontaneous provided that the state with energy E_1 is **empty**.

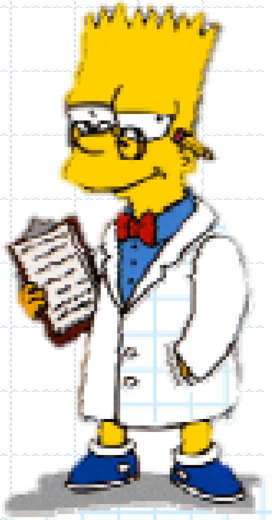


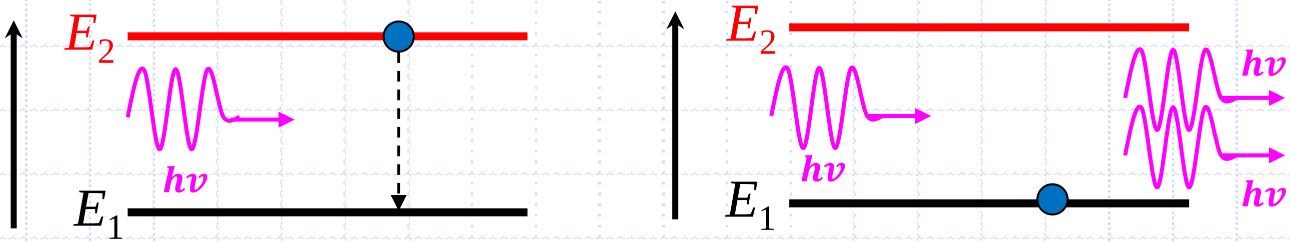


Initial state

Stimulated Emission

- In stimulated emission, an incoming photon of energy $h\nu = E_2 - E_1$ stimulates the whole emission process by inducing the electron at E_2 to transit down to E_1.
- The two photons:
  - have the same energy, i.e., $h\nu = E_2 - E_1$
  - are in phase,
  - are in the same direction, and
  - have the same polarization.





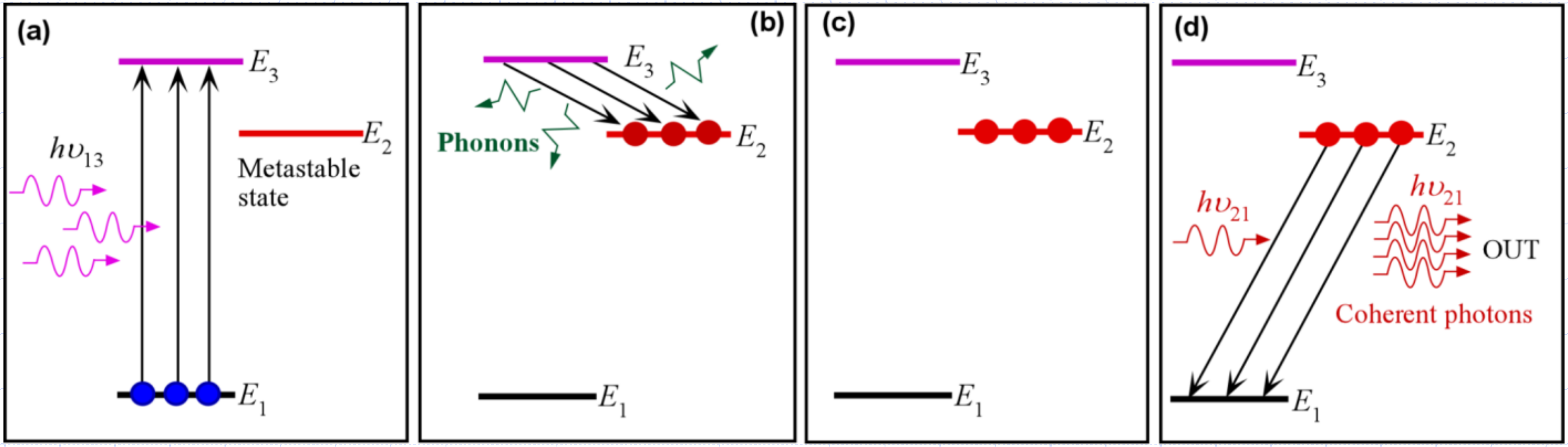
Coherent light

- Basis for **photon amplification** since one incoming photon results in two outgoing photons which are in phase.
- How does one achieve a ***practical light amplifying device*** based on this phenomenon?

Population Inversion

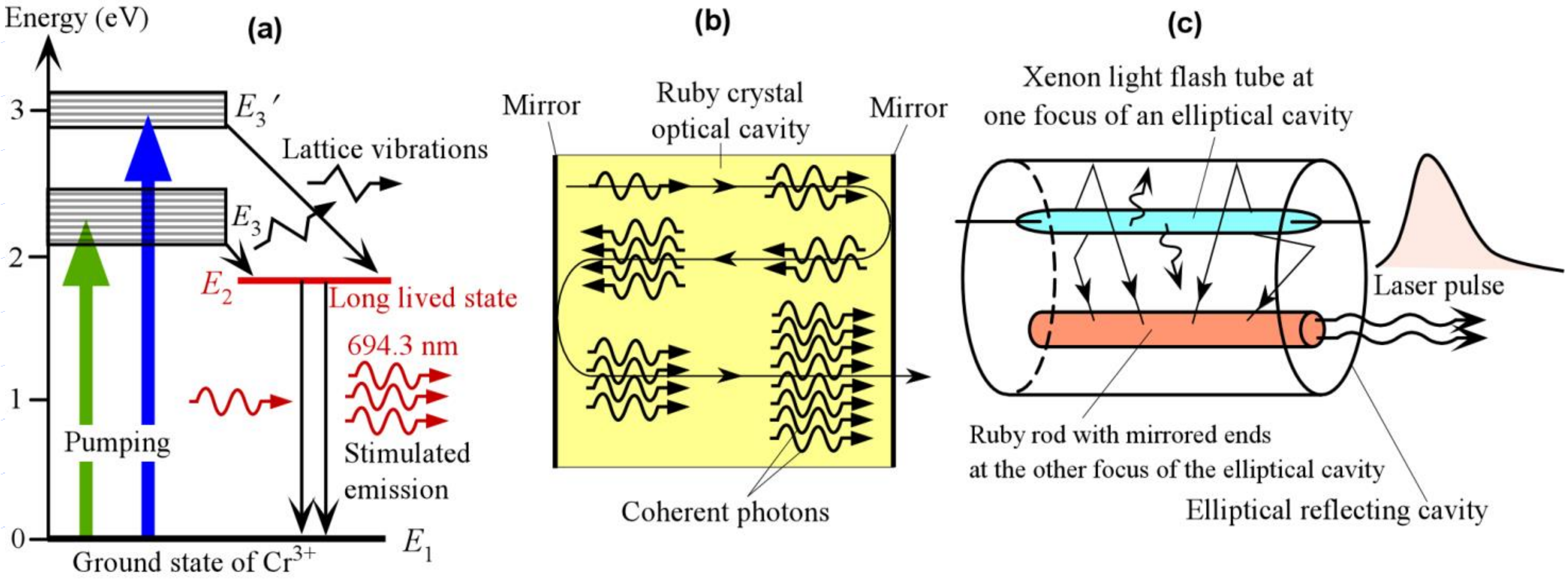
- To obtain stimulated emission, the incoming photon should not be absorbed by another atom at E_1.
- We must therefore have the **majority** of the atoms at the energy level E_2. If this were not the case, the incoming photons would be absorbed by the atoms at E_1.
  - When there are more atoms at E_2 than at E_1, we have what is called a **population inversion**.
- Under normal equilibrium conditions, as a result of Boltzmann statistics, **most of the atoms** would be at E_1, and very few at E_2.
- We therefore need to **excite** the atoms, cause **population inversion**, to obtain stimulated emission.
- Two energy levels is not enough to create population inversion!!
  - Since in the steady state, the incoming photon flux will cause as many **upward** excitations as **downward** stimulated emissions.
- We need at least 3 energy levels!!!

The LASER Principle



The principle of the LASER, using a ruby laser as an example. (a) The ions (Cr^{3+} ions) in the ground state are pumped up to the energy level E_3 by photons from an optical excitation source. (b) Ions at E_3 rapidly decay to the long-lived state at the energy level E_2 by emitting lattice vibrations (phonons). (c) As the states at E_2 are long-lived, they quickly become populated and there is a population inversion between E_2 and E_1. (d) A random photon (from spontaneous decay) of energy $h\upsilon_{21} = E_2 - E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

3-Level Lasers: The Ruby Laser

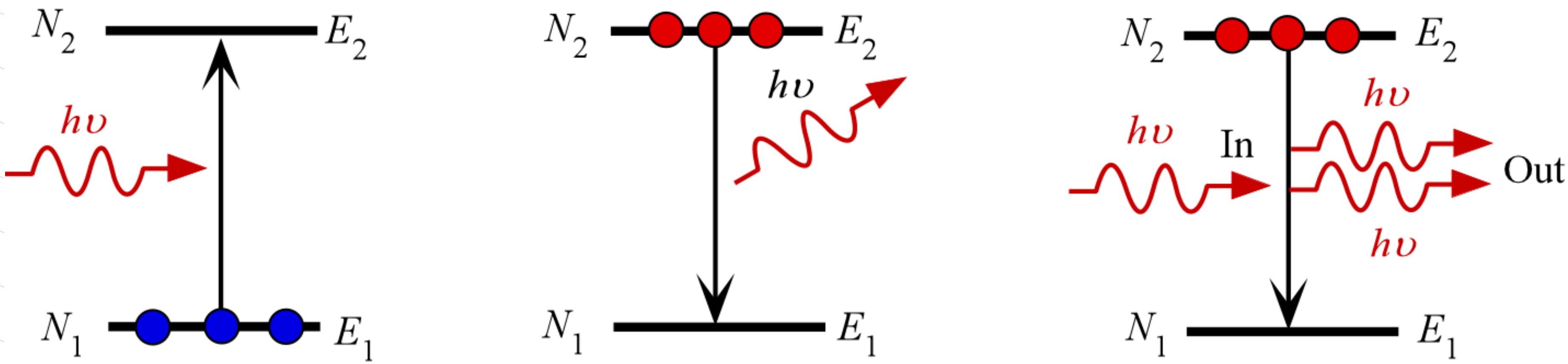


(a) A more realistic energy diagram for the Cr^{3+} ion in the ruby crystal (Al_2O_3), showing the optical pumping levels and the stimulated emission. (b) The laser action needs an optical cavity to reflect the stimulated radiation back and forth to build-up the total radiation within the cavity, which encourages further stimulated emissions. (c) A typical construction for a ruby laser, which uses an elliptical reflector, and has the ruby crystal at one focus and the pump light at the other focus.

3-Level Lasers: The Ruby Laser

Theodore Harold Maiman was born in 1927 in Los Angeles, son of an electrical engineer. He studied engineering physics at Colorado University, while repairing electrical appliances to pay for college, and then obtained a Ph.D. from Stanford. Theodore Maiman constructed this first laser in 1960 while working at Hughes Research Laboratories (T.H. Maiman, "Stimulated optical radiation in ruby lasers", *Nature*, **187**, 493, 1960). There is a vertical chromium ion doped ruby rod in the center of a helical xenon flash tube. The ruby rod has mirrored ends. The xenon flash provides optical pumping of the chromium ions in the ruby rod. The output is a pulse of red laser light. (Courtesy of HRL Laboratories, LLC, Malibu, California.)

Einstein B_{12} Coefficient



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

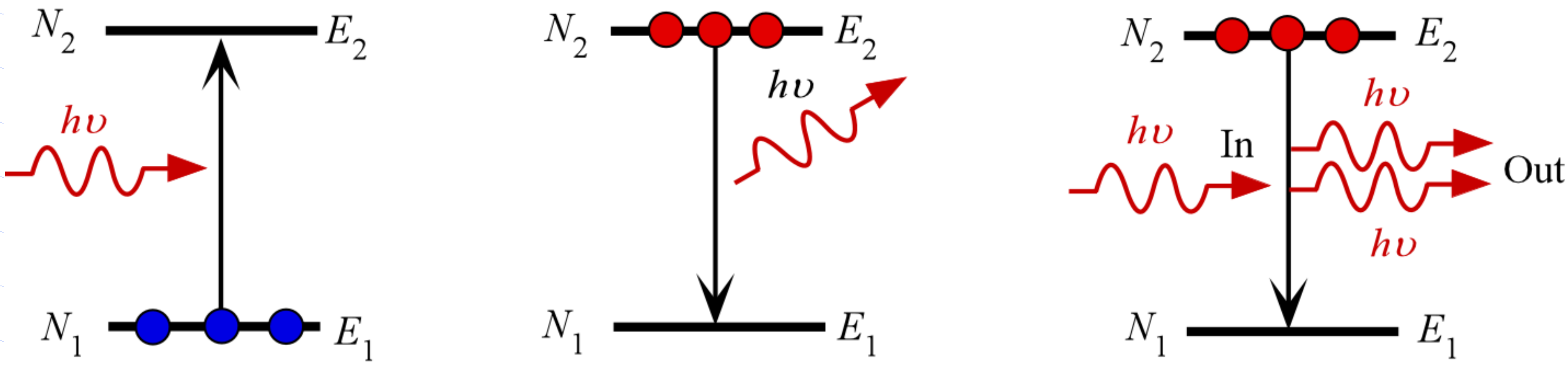
- N_1: the number of atoms per unit volume with energy E_1
- N_2: the number of atoms per unit volume with energy E_2
- R_{12}: the rate of transition from E_1 to E_2 by absorption

$$R_{12} = B_{12} N_1 \rho(\upsilon)$$

$R_{12} = -dN_1/dt$; $B_{12} N_1 \rho(\upsilon)$: **Absorption**

- B_{12} : the **Einstein coefficient for absorption.**
- $\rho\,(\nu)$: the photon energy density per unit frequency

Einstein A_{21}, B_{21} Coefficients



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

- R_{21}: the rate of transition from E_2 to E_1 by spontaneous and stimulated emission

$$R_{21} = A_{21}N_2 + B_{21}N_2\rho(\upsilon)$$

R_{21} = $-dN_2/dt$; $A_{21}N_2$: **Spontaneous emission**; $B_{21}N_2\rho(\upsilon)$: **Stimulated emission**

- A_{21}: the **Einstein coefficient for spontaneous emission**
- B_{12}: the **Einstein coefficient for stimulated emission**

Einstein Coefficients

In thermal equilibrium (no external excitation)

- There is no net change with time in the population at E_1 anf E_2

⇨ $$R_{12} = R_{21}$$

- Boltzmann statistics demands

$$\frac{N_2}{N_1} = \exp\left[-\frac{(E_2 - E_1)}{k_B T}\right]$$

Einstein Coefficients

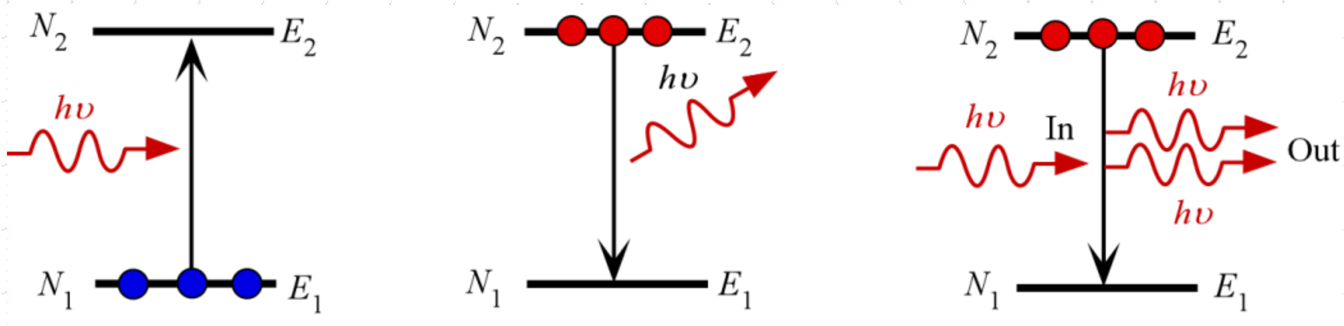
Plank's black body radiation distribution law

- In thermal equilibrium, radiation from the atoms must give rise to an equilibrium photon energy density, $\rho_{eq}(\nu)$, that is given by

Planck's black body radiation law

$$\rho_{\text{eq}}(\upsilon) = \frac{8\pi h\upsilon^3}{c^3\left[\exp\left(\frac{h\upsilon}{k_B T}\right) - 1\right]}$$

Einstein Coefficients



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

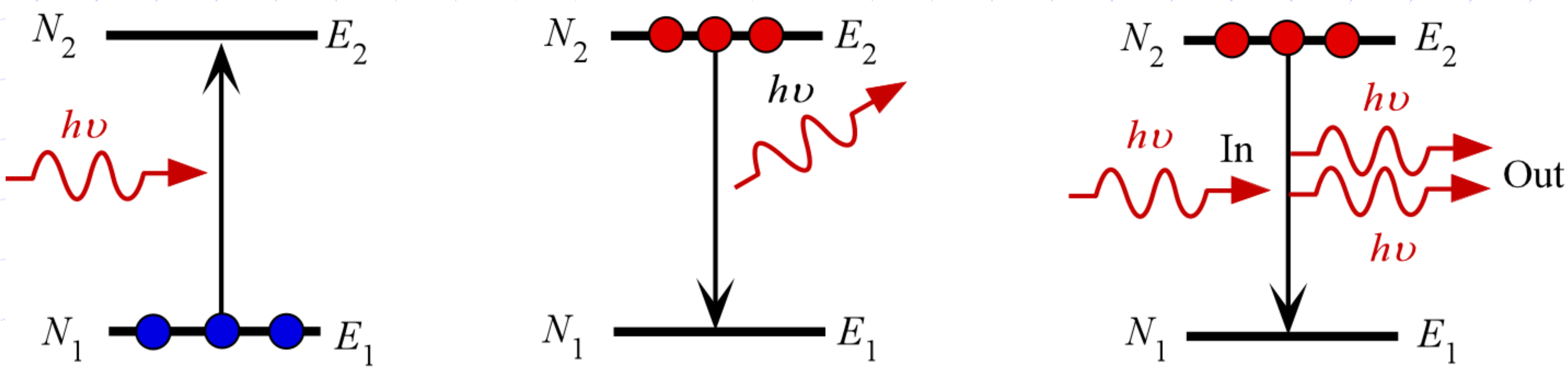
$$B_{12} = B_{21}$$

$$A_{21}/B_{21} = 8\pi h\upsilon^3/c^3$$

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} = \frac{B_{21}N_2\rho(\upsilon)}{A_{21}N_2} = \frac{B_{21}\rho(\upsilon)}{A_{21}} = \frac{c^3}{8\pi h\upsilon^3}\rho(\upsilon)$$

$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$

LASER Requirements



(a) Absorption **(b)** Spontaneous emission **(c)** Stimulated emission

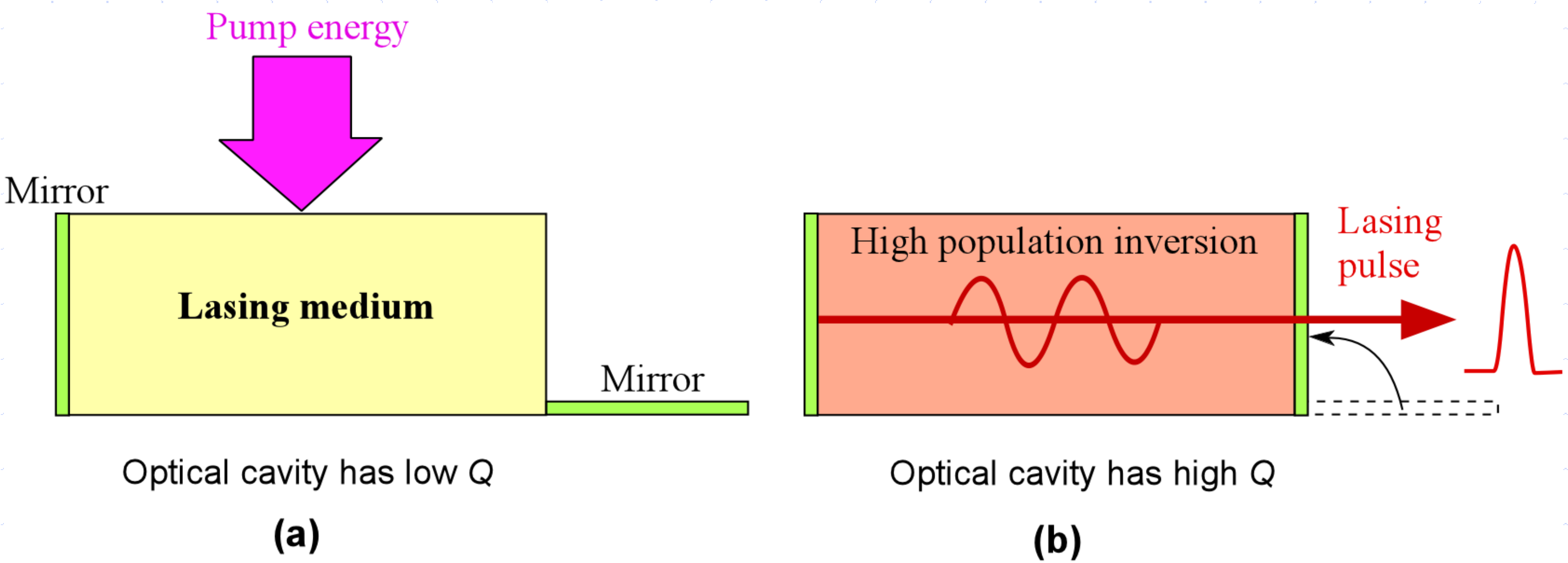
$$\frac{R_{21}(\text{stim})}{R_{12}(\text{absorp})} = \frac{N_2}{N_1}$$

Population inversion

$$\frac{R_{21}(\text{stim})}{R_{21}(\text{spon})} \propto \rho(\upsilon)$$

Optical cavity

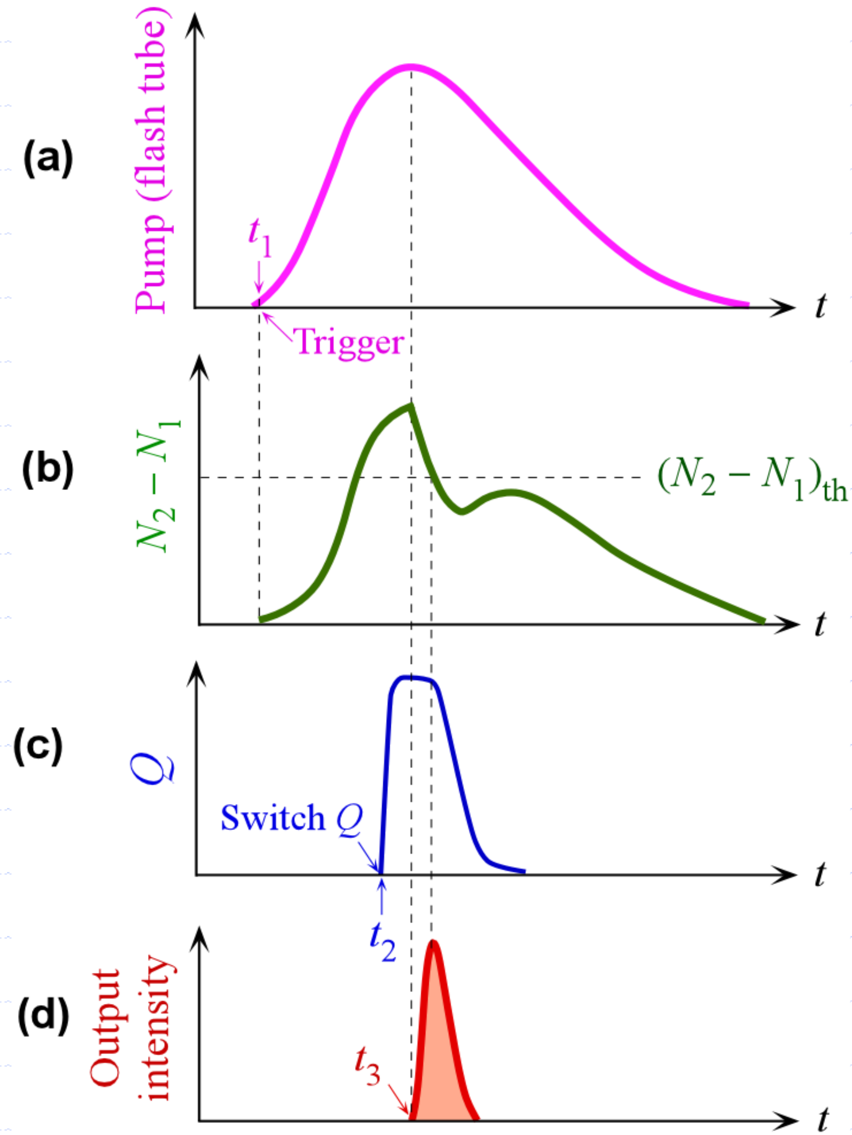
Q-Switching



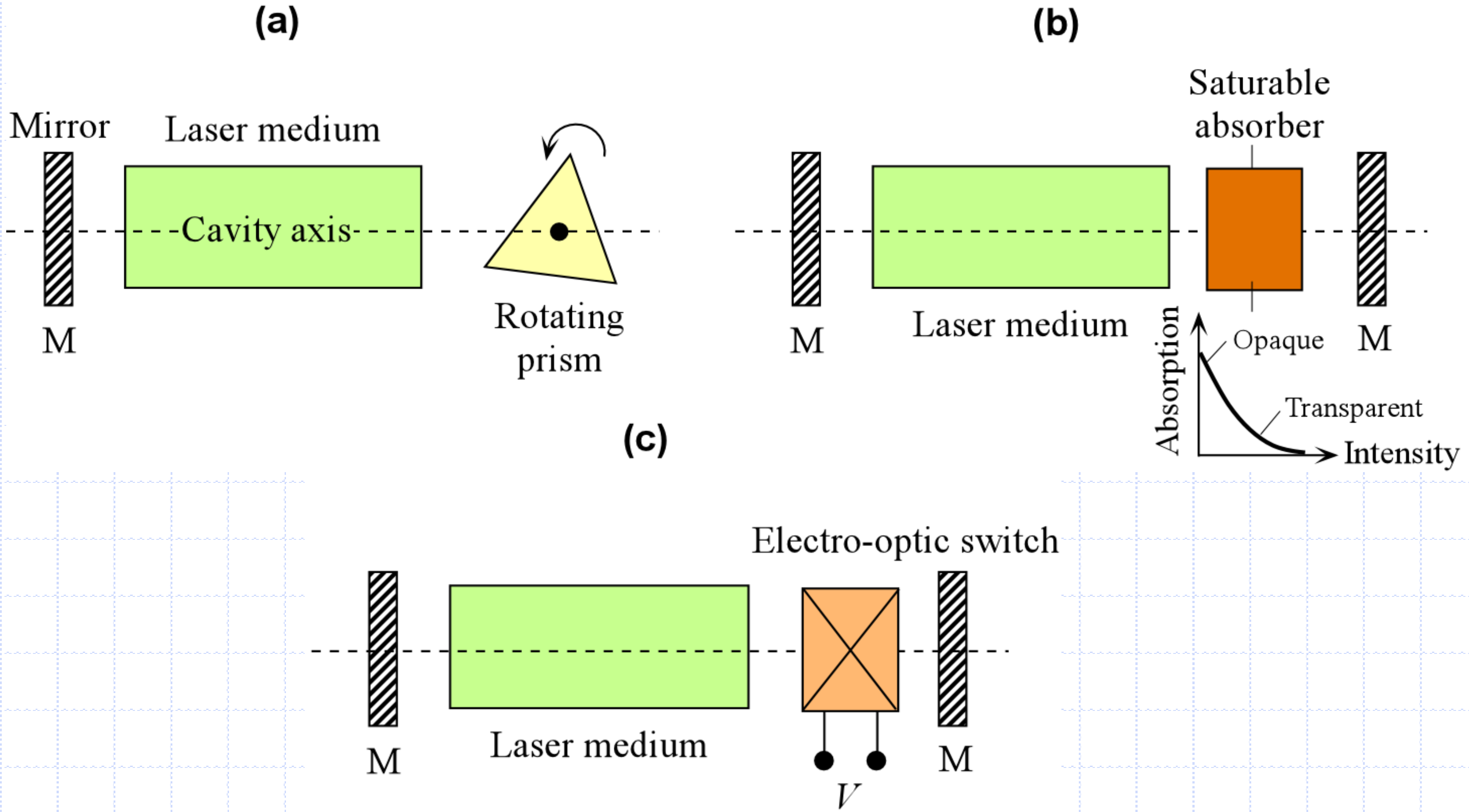
(a) The optical cavity has a low *Q* so that pumping takes the atoms to a very high degree of population inversion; lasing is prevented by not having a right hand mirror. (b) The right mirror is "flung" to make an optical resonator, *Q* is switched to a high value which immediately encourages lasing emissions. There is an intense pulse of lasing emission which brings down the excess population inversion.

Q-Switching

A simplified schematic of Q-switching in the generation of short laser pulses. (a) The pump profile *i.e.* the flash tube output. (b) The evolution of the population difference $N_2 - N_1$ with time. (c) The switching of the optical cavity Q during the pumping procedure while the population inversion is very large and greater than the normal threshold population. (d) The output light pulse.

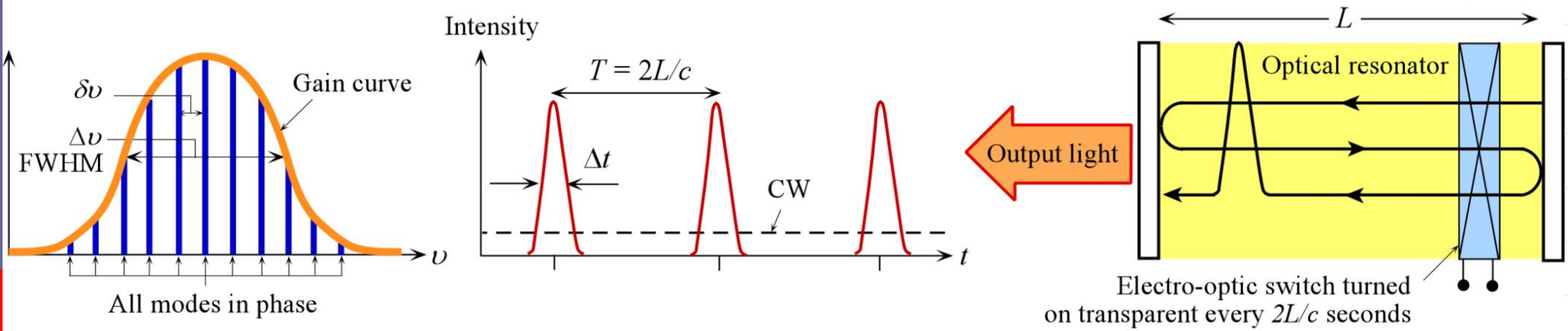


Q-Switching



(a) *Q*-switching by using a rotating prism. (b) *Q*-switching by using a saturable absorber. (c) *Q*-switching by using an electro-optic (EO) switch. Normally a polarizer is also needed before or after the switch but this is part of the EO switch in this diagram.

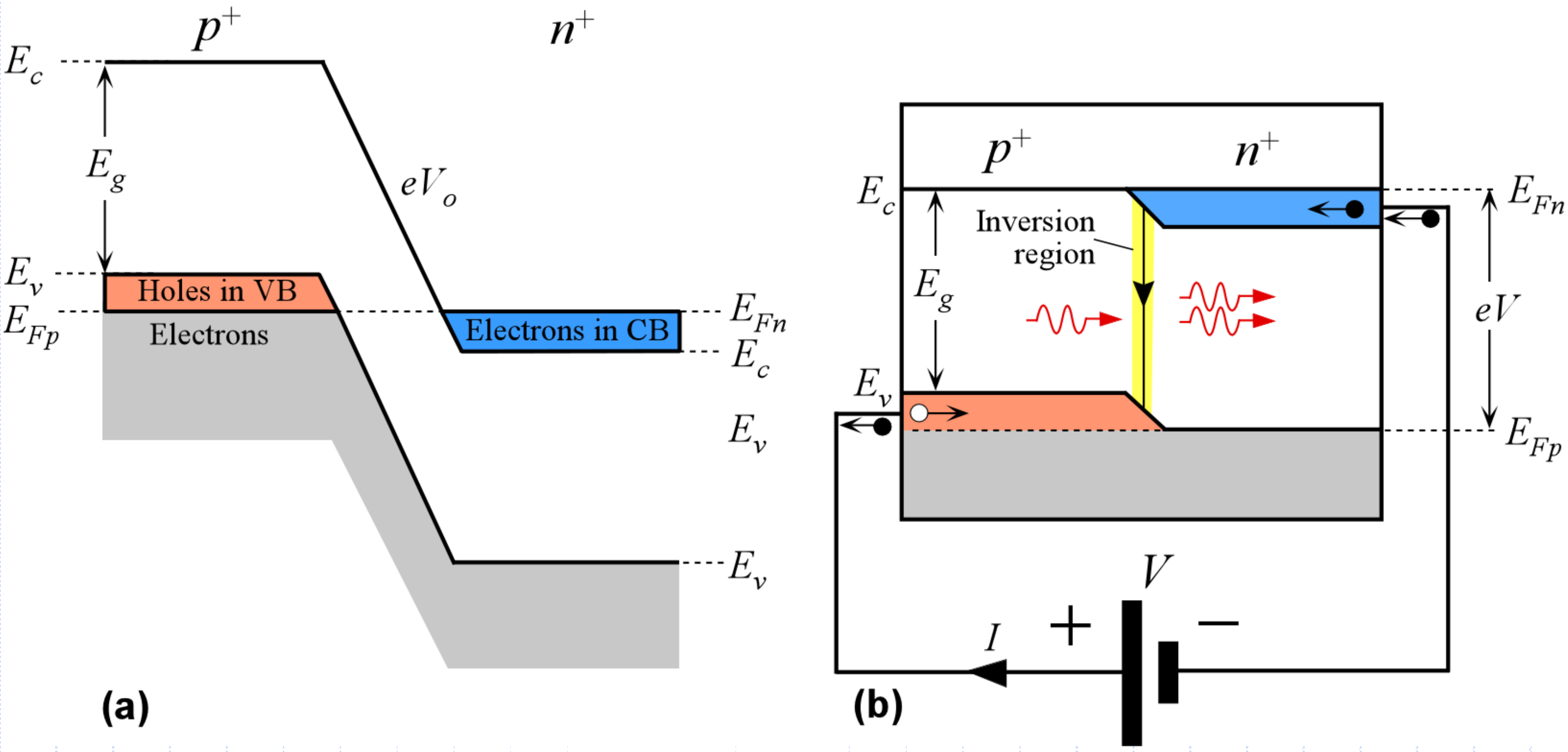
Mode-Locking



(a) (b) (c)

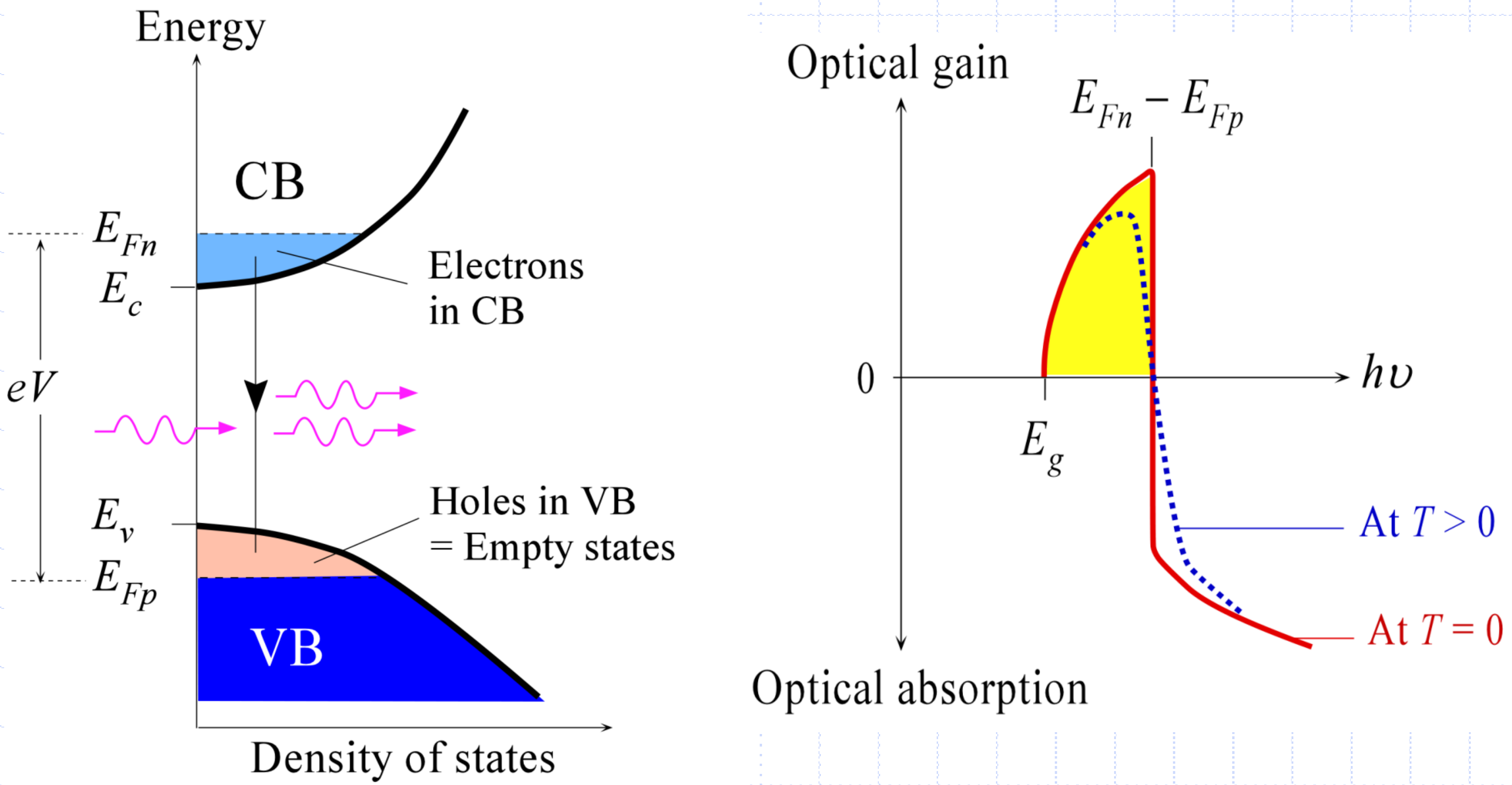
(a) A mode-locked laser has its *N* modes all in phase so that the modes add correctly to generate a short laser pulse every *T* seconds. D*u* is the full width at half maximum (FWHM). (b) The output light intensity from a mode locked laser is a periodic series of short intense optical pulses that are separated in time by $T = 2L/c$, the round trip time for the pulse in the resonator. (c) A laser can be mode-locked by using an EO switch in the optical cavity that becomes transparent exactly at the right time, every *T* seconds. Each time the pulse in the resonator impinges on the left mirror, every $T = 2L/c$ seconds, a portion of it is transmitted, which constitutes the output from a mode-locked laser

Semiconductor Laser Diode



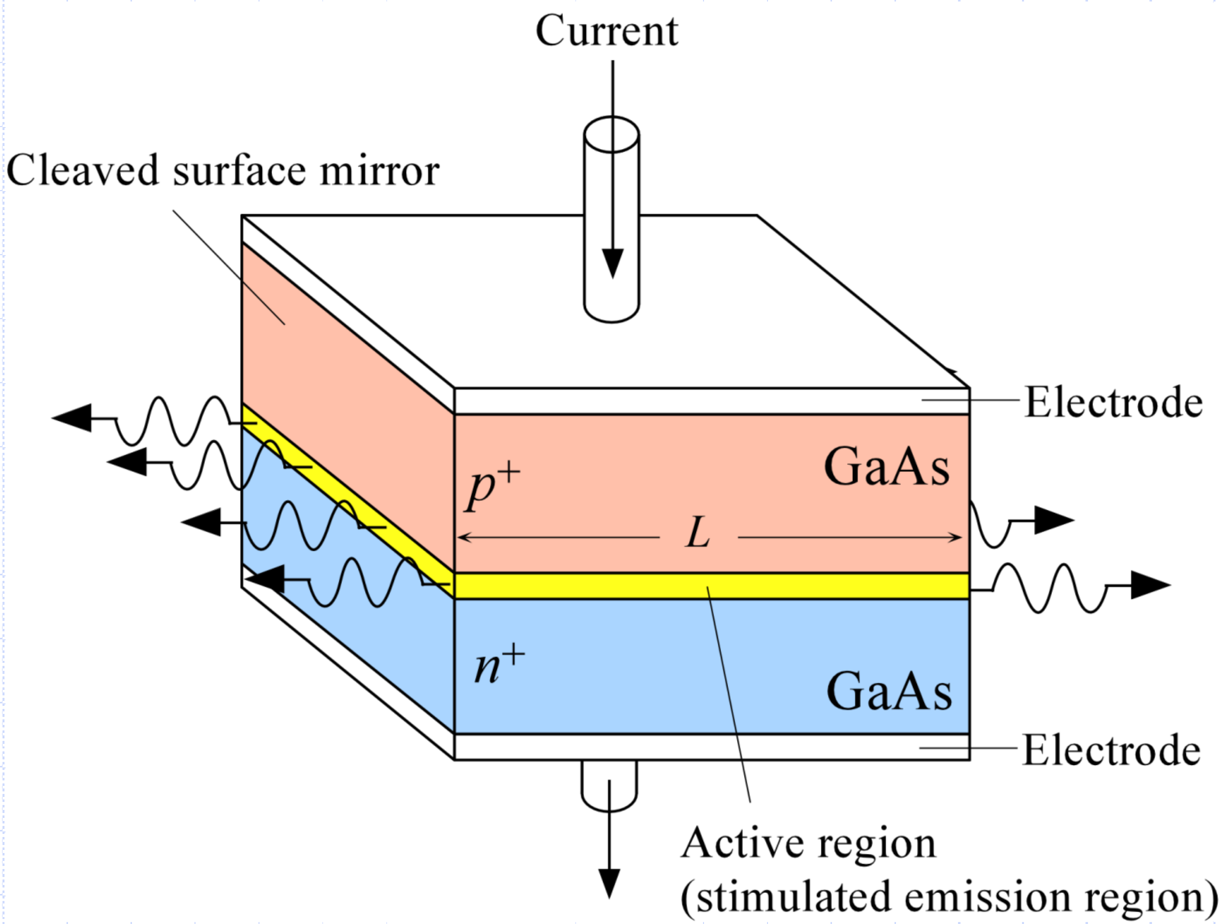
(a) The energy band diagram of a degenerately doped *pn* with no bias. (b) Band diagram with a sufficiently large forward bias to cause population inversion and hence stimulated emission.

Semiconductor Laser Diode



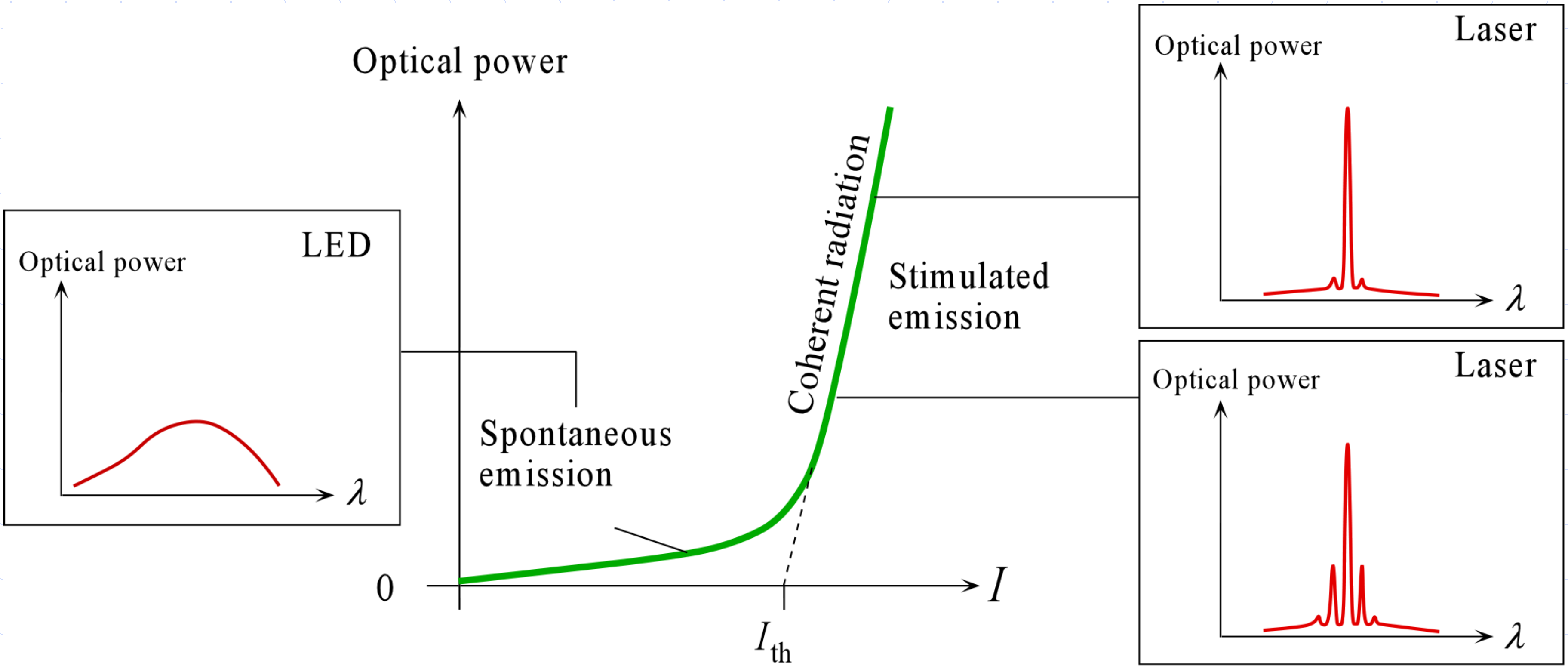
(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T > 0$ in the SCL under forward bias such that $E_{Fn} - E_{Fp} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy ($h\upsilon$).

Semiconductor Laser Diode



A schematic illustration of a GaAs homojunction laser diode. The cleaved surfaces act as reflecting mirrors.

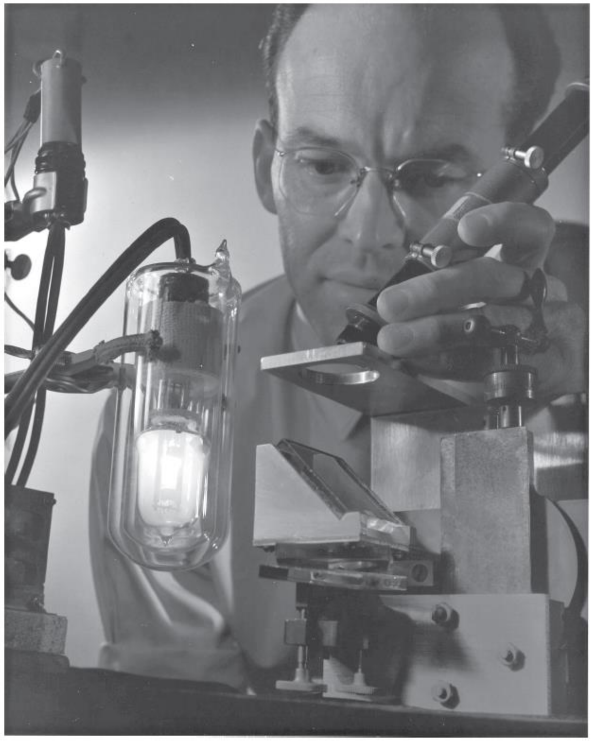
Semiconductor Laser Diode Output



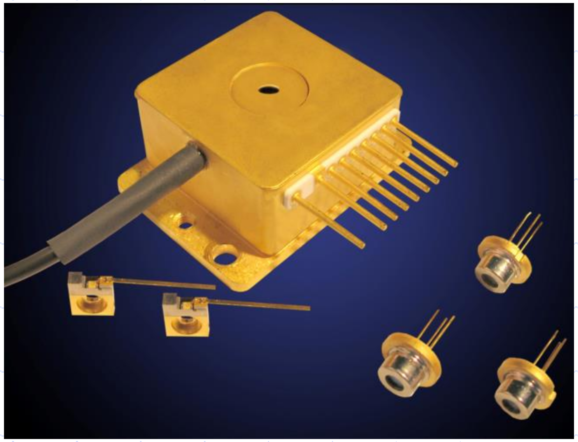
Typical output optical power vs. diode current (*I*) characteristics and the corresponding output spectrum of a laser diode. I_{th} is the threshold current and corresponds to the extension of the coherent radiation output characteristic onto the *I*-axis.

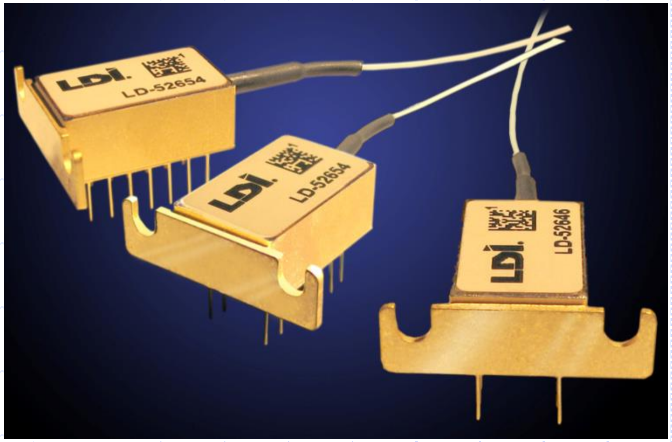
Semiconductor Laser Diode

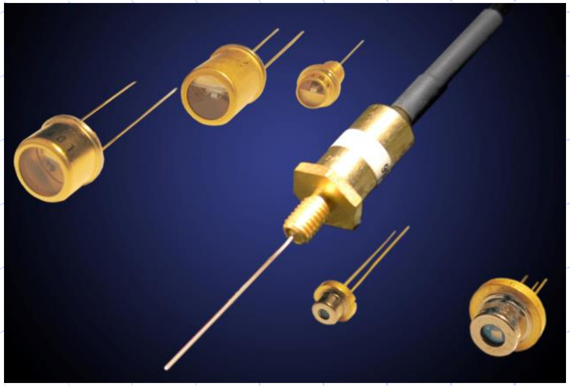
Robert Hall and his colleagues, while working at General Electric's Research and Development Center in Schenectady, New York, were among the first groups of researchers to report a working semiconductor laser diode in 1962. He obtained a US patent in 1967, entitled "Semiconductor junction laser diode" for his invention. When Robert Hall retired from GE in 1987, he had been awarded more than forty patents. (R.N. Hall, *et al*, *Phys Rev Letts, 9*, 366, 1962.) *(Courtesy of GE)*



Semiconductor Laser Diodes

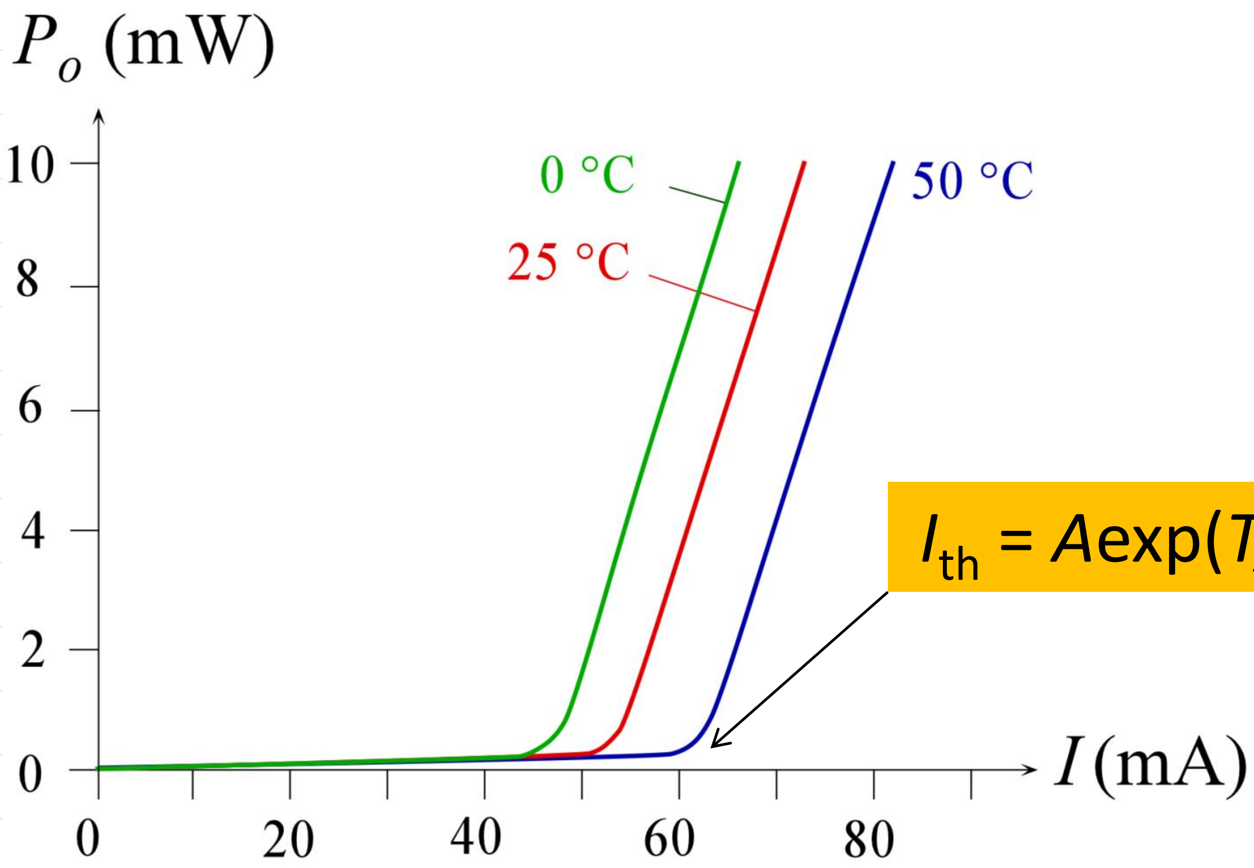






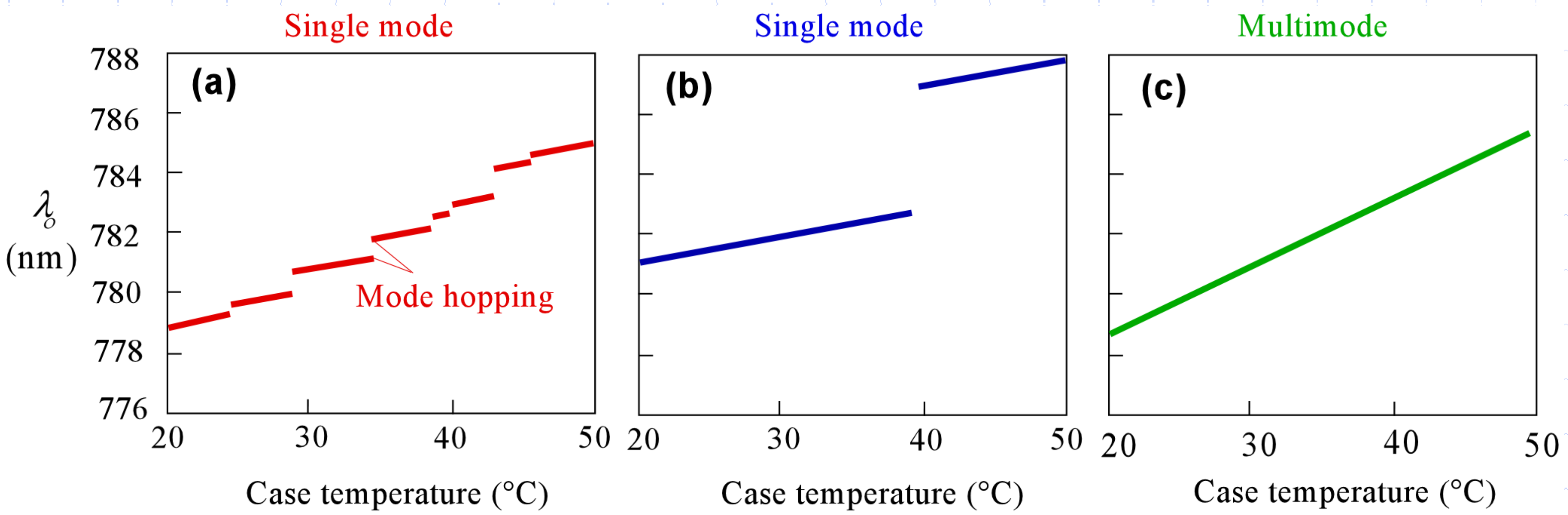
Top left: High power (0.5 – 7 W) CW laser diodes with emission at 805 nm and a spectral width of 2.5 nm. Applications include medical systems, diode pumped lasers, analytical equipment, illuminators, reprographics, laser initiated ordnance *etc*. Top right: Typical pigtailed laser diodes for telecom. These are Fabry-Perot laser diodes operating at peak wavelengths of 1310 and 1550 nm with spectral widths of 2 and 1.3 nm respectively. The threshold currents are 6 mA and 10 mA, and they can deliver 2 mW of optical power into a single mode fiber. Lower left: High power 850 and 905 nm pulsed laser diodes for use in range finders, ceilometers, weapon simulation, optical fuses, surveying equipment *etc*. (Courtesy of OSI Laser Diode Inc.)

Elementary Laser Characteristics



Output optical power vs. diode current at three different temperatures. The threshold current shifts to higher temperatures.

Elementary Laser Characteristics



Peak wavelength λ_o vs. case temperature characteristics. (a) Mode hops in the output spectrum of a single mode LD. (b) Restricted mode hops and none over the temperature range of interest (20 – 40 °C). (c) Output spectrum from a multimode LD.

EXAMPLE: Laser output wavelength variation with temperature

The refractive index n of GaAs is approximately 3.6 and it has a temperature dependence $dn/dT \approx 2.0 \times 10^{-4}\ \mathrm{K}^{-1}$. Estimate the change in the emitted wavelength at around 870 nm per degree change in the temperature for a given mode.

Solution

Consider a particular given mode with wavelength λ_m, $m\left(\frac{\lambda_m}{2n}\right) = L$

If we differentiate λ_m with respect to temperature,

$$\frac{d\lambda_m}{dT} = \frac{d}{dT}\left[\frac{2}{m}nL\right] \approx \frac{2L}{m}\frac{dn}{dT}$$

where we neglected the change in the cavity length with temperature.

Substituting for L/m in terms of λ_m,

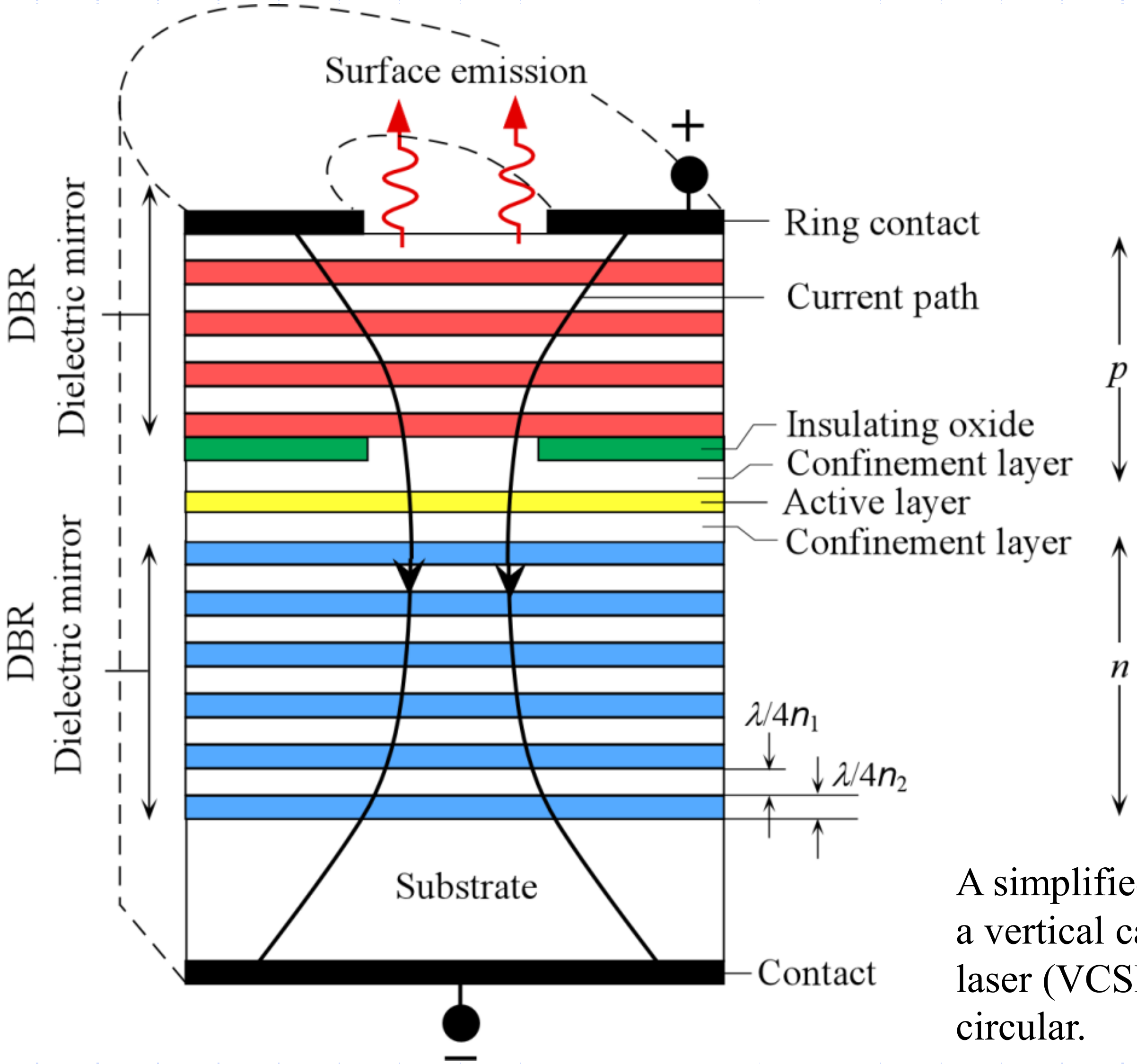
$$\frac{d\lambda_m}{dT} \approx \frac{\lambda_m}{n}\frac{dn}{dT} = \frac{870\,\mathrm{nm}}{3.6}(2\times10^{-4}\ \mathrm{K}^{-1}) = 0.048\ \mathrm{nm\ K}^{-1}.$$

Note that we have used n for a passive cavity whereas n above should be the effective refractive index of the active cavity which will also depend on the optical gain of the medium, and hence its temperature dependence is likely to be somewhat higher than the dn/dT value we used. It is left as an exercise to show that the changes in λ_m due to the expansion of the cavity length with temperature is much less than that arising from dn/dT. The linear expansion coefficient of GaAs is $6 \times 10^{-6}\ \mathrm{K}^{-1}$.

Light Emitters for Optical Fiber Communications

- Choice of light source depends on communication distance and bandwidth required
- For short haul applications, such as local networks, LEDs are preferred because they are simpler to drive, cheaper to produce, have a longer lifetime, and provide the necessary output power even though the output spectrum is broader
- LEDs are used in multimode and graded index fibers b/c the dispersion arising from finite linewidth of the output spectrum is not a major concern
- For long haul and wide bandwidth communications, Laser diodes are used because of their narrow linewidth and high output power.
- Output spectrum of a laser diode can be very narrow (0.01 nm – 0.1 nm)
- Very fast operation defined by the rise time associated with inversion in a laser diode make it more amenable for high speed applications even when wide bandwidths are required.

Vertical Cavity Surface Emitting Lasers (VCSELs)



A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL). The cross section is circular.

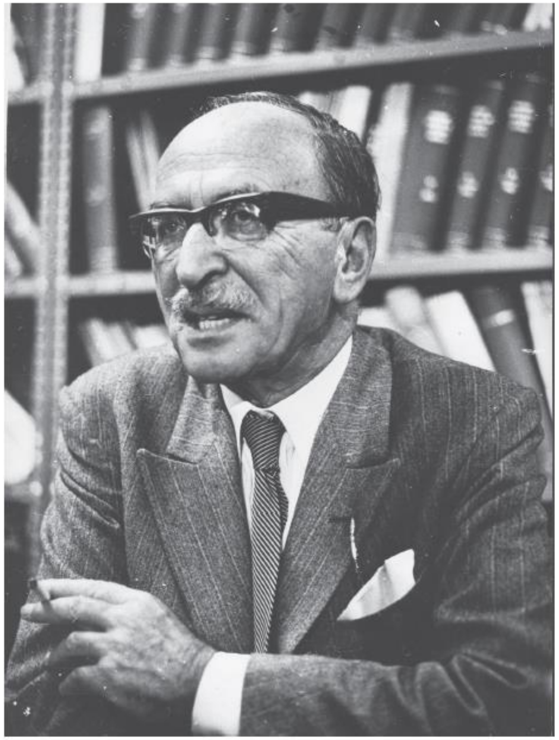
Vertical Cavity Surface Emitting Lasers (VCSELs)

This VCSEL diode provides a single transverse mode emission 795 nm. The spectral width is less than 100 MHz, and the output power is 0.15 mW at 2 mA. (Courtesy of Vixar Inc.)

Sketch of the VCSEL in Kenichi Iga's laboratory book (1997). Professor Iga was at the Tokyo Institute of Technology at the time. (See K. Iga, *Jpn J. Appl. Phys*., *47*, 1, 2008) (Courtesy of Professor K. Iga)

Kenichi Iga, currently (2012) the President of the Tokyo Institute of Technology, was first to conceive the VCSEL, and played a pioneering role in the development of VCSELs. (Courtesy of Professor K. Iga)

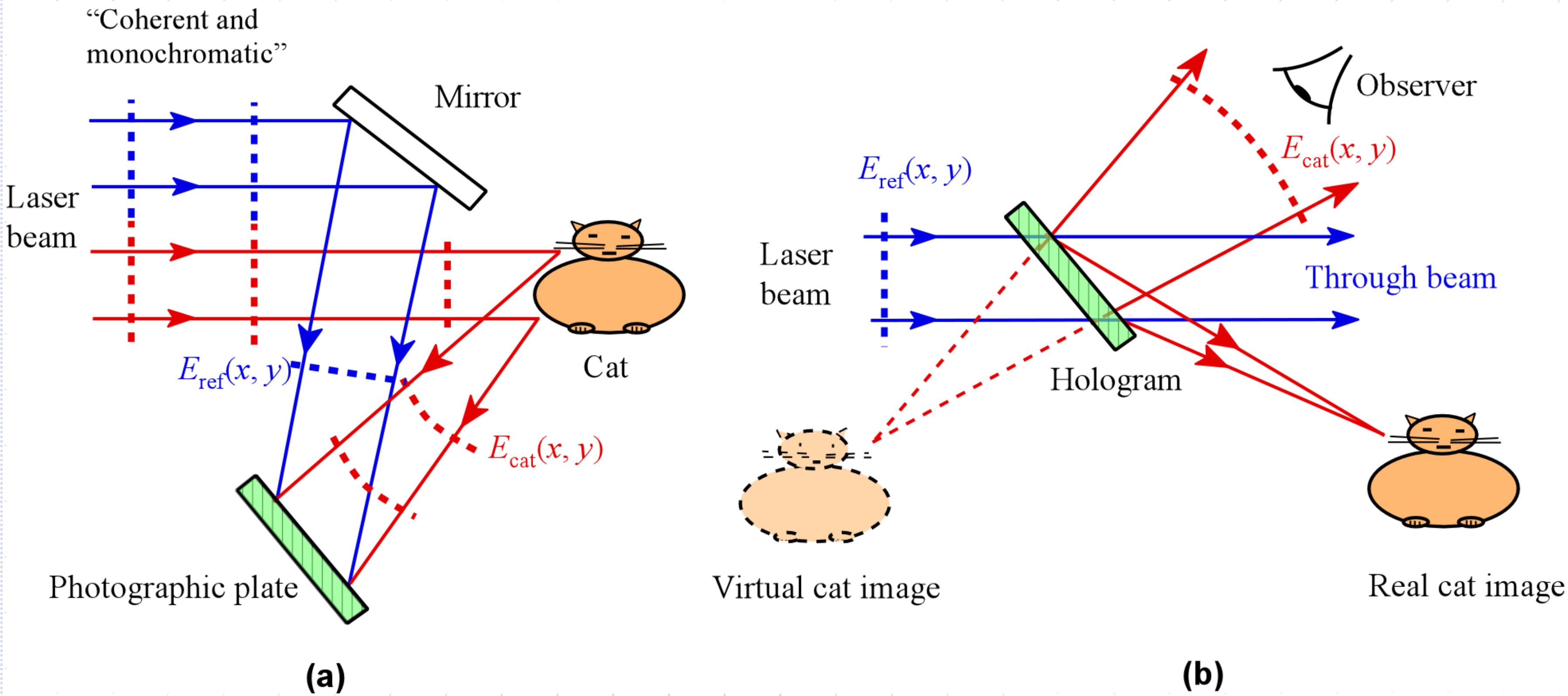
Holography



Dennis Gabor (1900 - 1979), inventor of holography, is standing next to his holographic portrait. Professor Gabor was a Hungarian born British physicist who published his holography invention in *Nature* in 1948 while he was at Thomson-Houston Co. Ltd, at a time when coherent light from lasers was not yet available. He was subsequently a professor of applied electron physics at Imperial College, University of London
(© *Linh Hassel/AGE Fotostock.*)

Holography

Wavefront Reconstruction

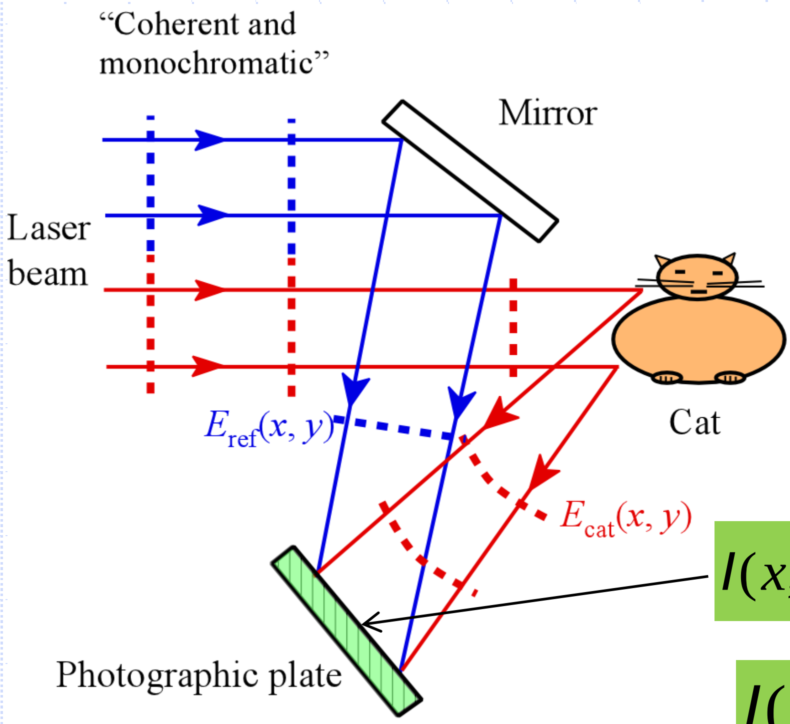


A highly simplified illustration of holography. (a) A laser beam is made to interfere with the diffracted beam from the subject to produce a hologram. (b) Shining the laser beam through the hologram generates a real and a virtual image.

Dr. Ahmed Farghal

Holography

Wavefront Reconstruction



Reference beam wavefront

$E_{ref}(x,y) = U_r(x,y)e^{j\omega t}$

Wavefront reflected from the cat

$E_{cat}(x,y) = U(x,y)e^{j\omega t}$

These interfere and form a hologram

$$I(x,y) = \left|E_{ref} + E_{cat}\right|^2 = \left|U_r + U\right|^2 = (U_r + U)(U_r^* + U^*)$$

$$I(x,y) = UU^* + U_r U_r^* + U_r^* U + U_r U^*$$

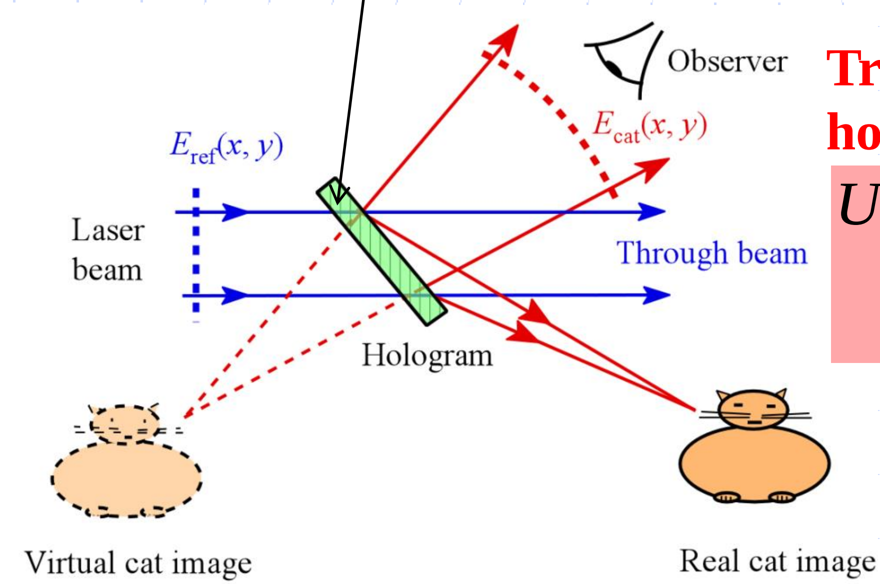
Intensity pattern on the hologram

Holography

Wavefront Reconstruction

$$I(x,y) = UU^* + U_r U_r^* + U_r^* U + U_r U^*$$

Intensity pattern on the hologram



Transmitted intensity through the hologram

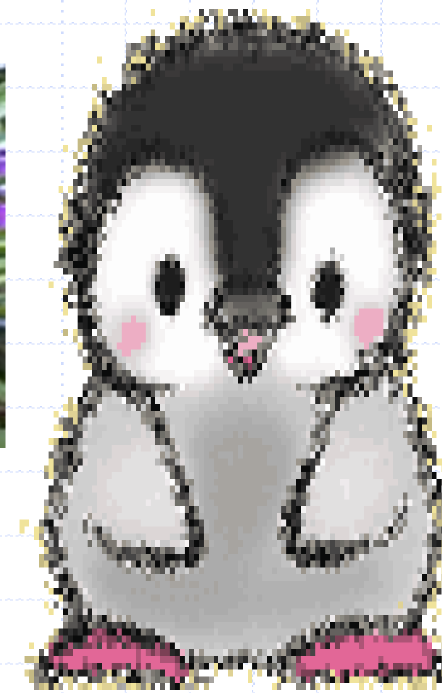
$$U_t \propto U_r I(x,y)$$
$$= U_r[UU^* + U_r U_r^* + U_r^* U + U_r U^*]$$

$$U_t \propto a + bU(x,y) + cU^*(x,y)$$

Virtual image

Real image
(Conjugate image)

Thank you



Have a nice day.