Lecture 13: Semiconductor Laser Diodes

- Semiconductor as a gain medium
- Transition rates for semiconductors in quasi-equilibrium
- Current pumping
- Laser threshold current
- Steady-state laser photon flux
- Power output characteristics
- Direct modulation
- Spatial characteristics
- Spectral characteristics
- Single-mode laser diode structures
- Wavelength tunable laser diodes

Reading: Senior 6.1 – 6.8
Keiser 4.3

Semiconductor lasers

*Some useful characteristics of semiconductor lasers:

1. Capable of emitting *high powers* (e.g. continuous wave ~ W).

2. A relatively *directional* output beam (compared with LEDs) permits high coupling efficiency (~ 50 %) into *single-mode* fibers.

3. A relatively *narrow spectral width* of the emitted light allows operation at high bit rates (~ 10 Gb/s), as *fiber dispersion* becomes less critical for such an optical source.

Laser diodes

- A *laser diode* (LD) is a *semiconductor optical amplifier* (SOA) that has an *optical feedback*.

- A semiconductor optical amplifier is a *forward*-biased *heavily-doped* p^+-n^+ junction fabricated from a *direct*-bandgap semiconductor material.

- The injected current is sufficiently large to provide *optical gain*.

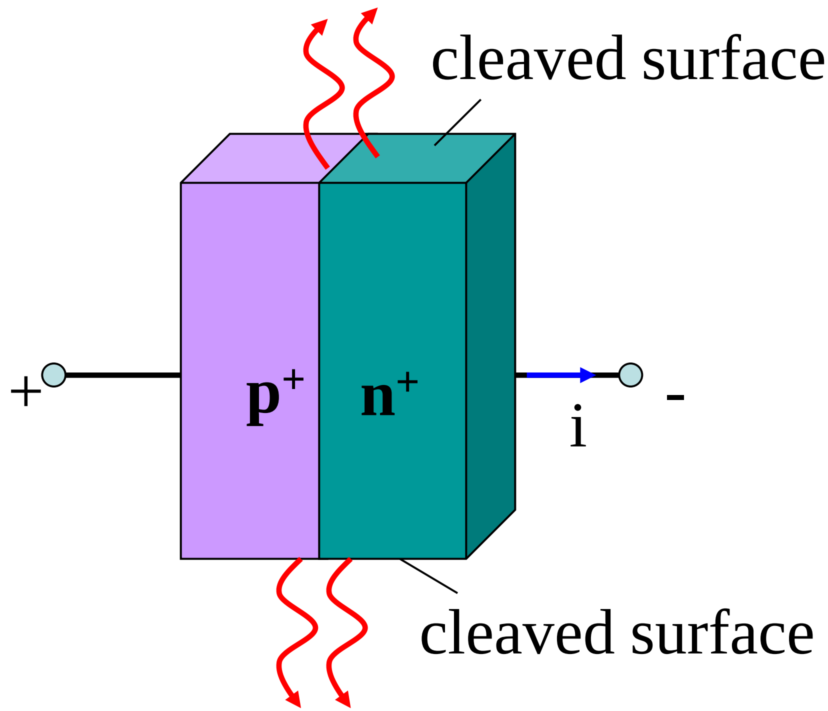
- The optical feedback is usually implemented by *cleaving* the semiconductor material along its crystal planes.

- The sharp refractive index difference between the crystal (~3.5) and the surrounding air causes the cleaved surfaces to act as reflectors.

⇒ The semiconductor crystal therefore in general can act both as a <u>*gain*</u> medium and as a <u>*Fabry-Perot optical resonator*</u>.

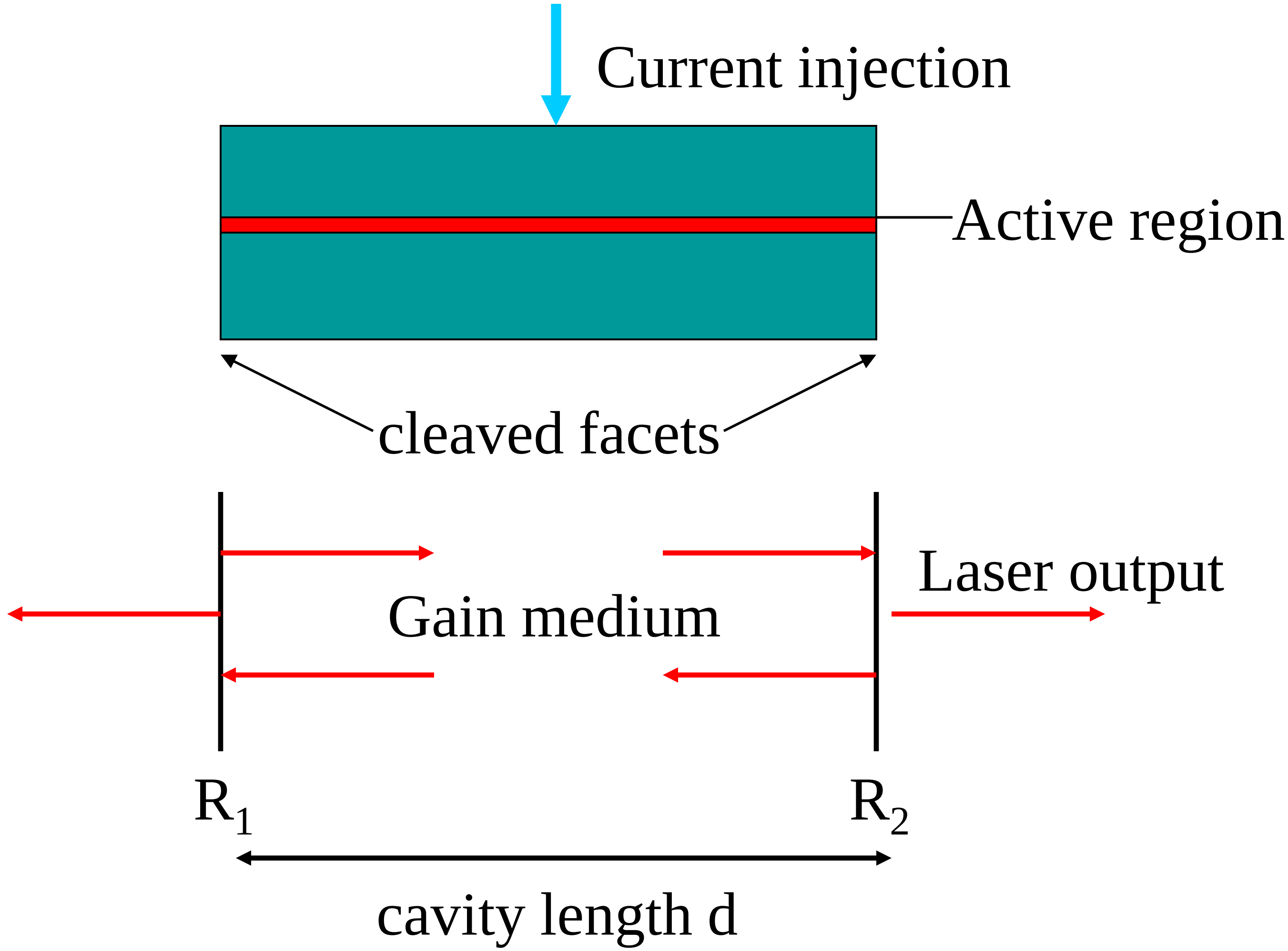
• Provided that the *gain coefficient* is sufficiently large, the feedback converts the optical *amplifier* into an optical *oscillator*, i.e. a laser.

• The device is called a *laser diode* or a *diode laser* or a *semiconductor injection laser*.



Turning semiconductor amplifiers into laser diodes

- In the case of semiconductor lasers, external mirrors are *not* required as the two *cleaved laser facets act as partially reflecting mirrors*



Semiconductor as a gain medium

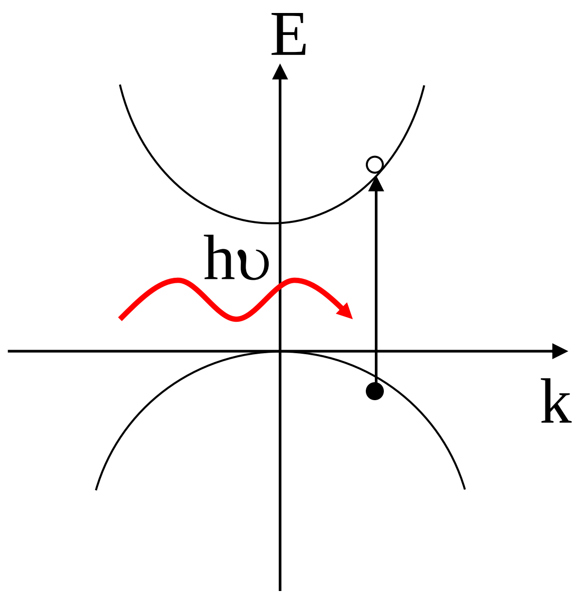
- ***The basic principle***: creation of *population inversion*, *stimulated emission* becomes more prevalent than *absorption*.

- The *population inversion* is usually attained by *electric-current injection* in some form of a p^+-n^+ junction diode (*also possible by optical pumping for basic research*)

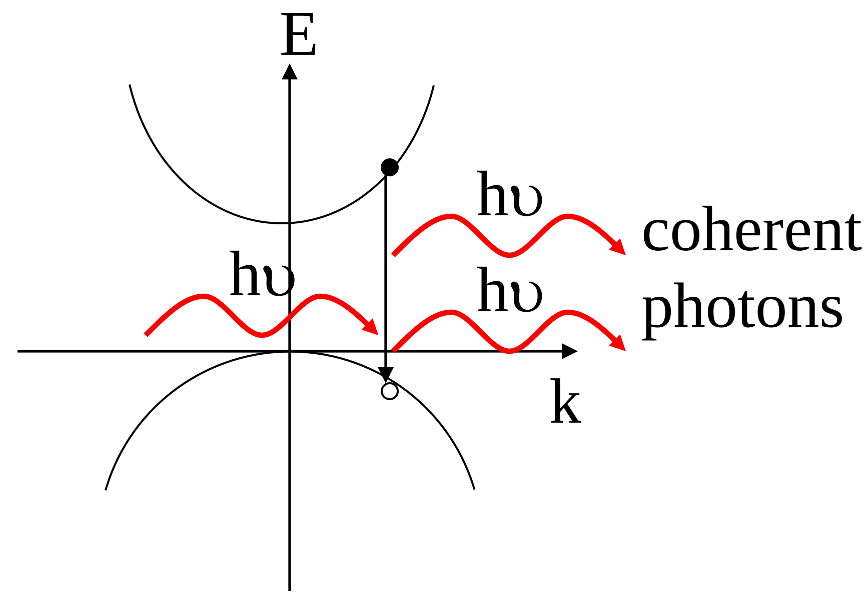
⇒a *forward* bias voltage causes *carrier pairs* to be injected into the junction region, where they *recombine by means of stimulated emission*.

- Here we discuss the semiconductor *gain* and *bandwidth* upon electrical *pumping scheme*.

Absorption and stimulated emission



<u>absorption</u>



<u>stimulated emission</u>

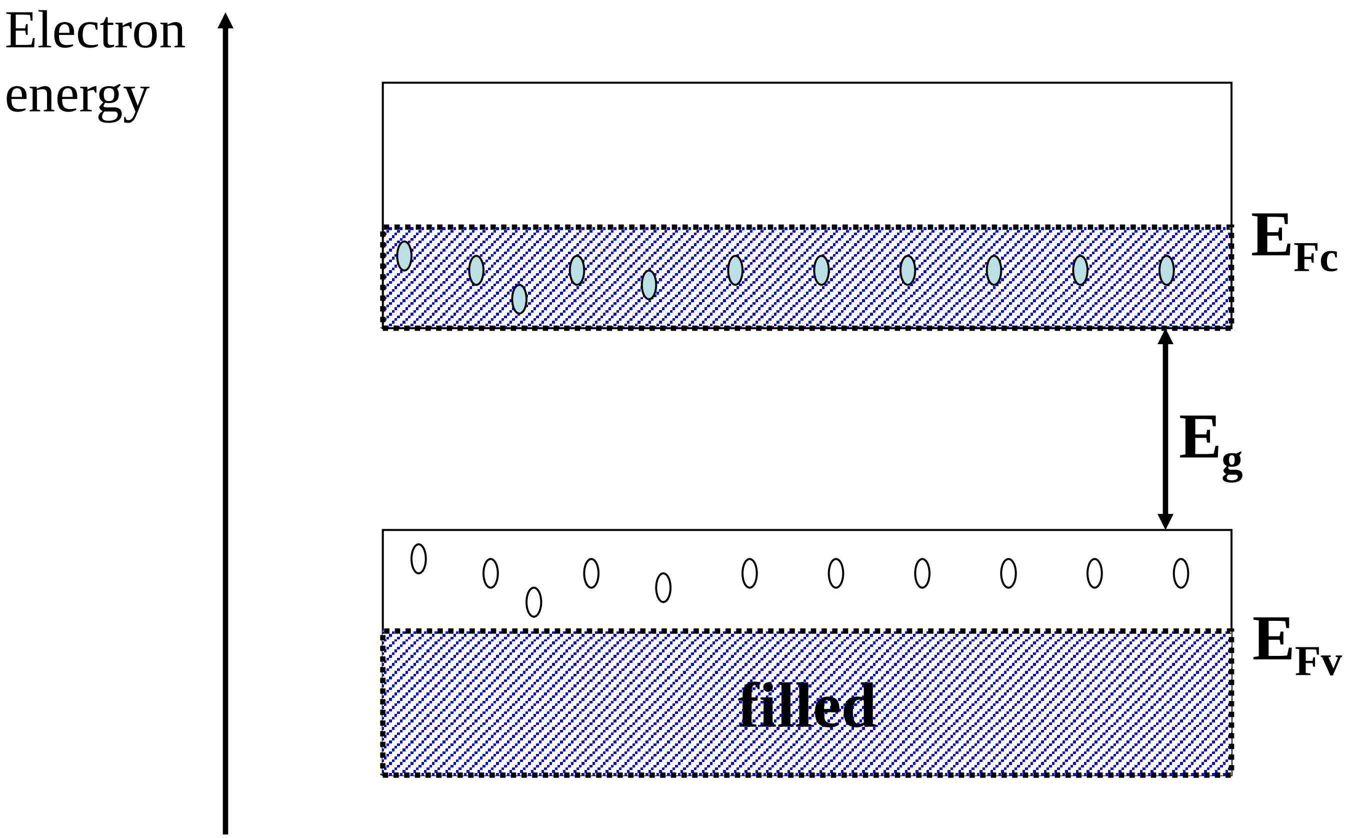
- *When stimulated emission is more likely than absorption*

=> net optical gain (a *net increase in photon flux*)

=> material can serve as a *coherent optical amplifier*.

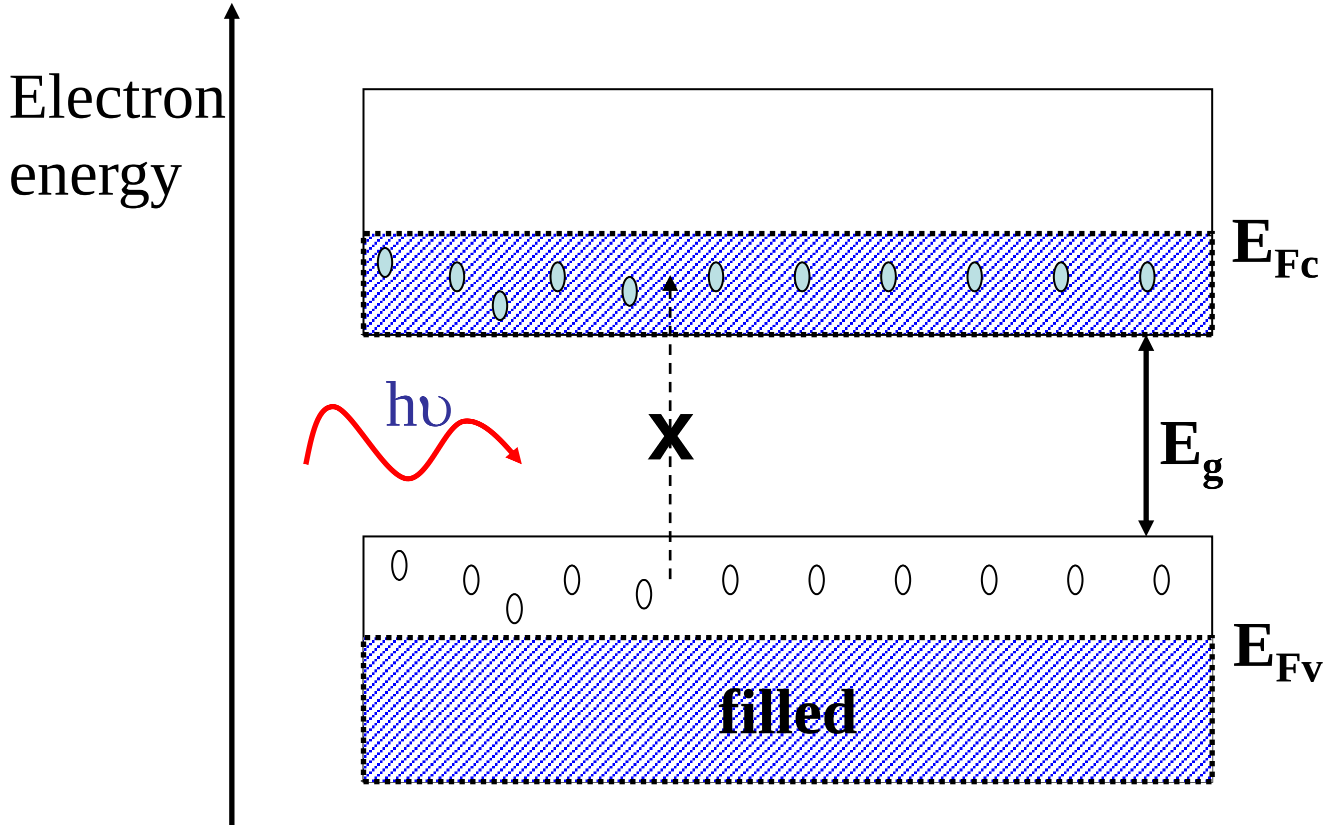
Population inversion by carrier injection

- In a semiconductor, *population inversion* can be obtained by means of *high carrier injection which results in simultaneously heavily populated electrons and holes in the same spatial region*.

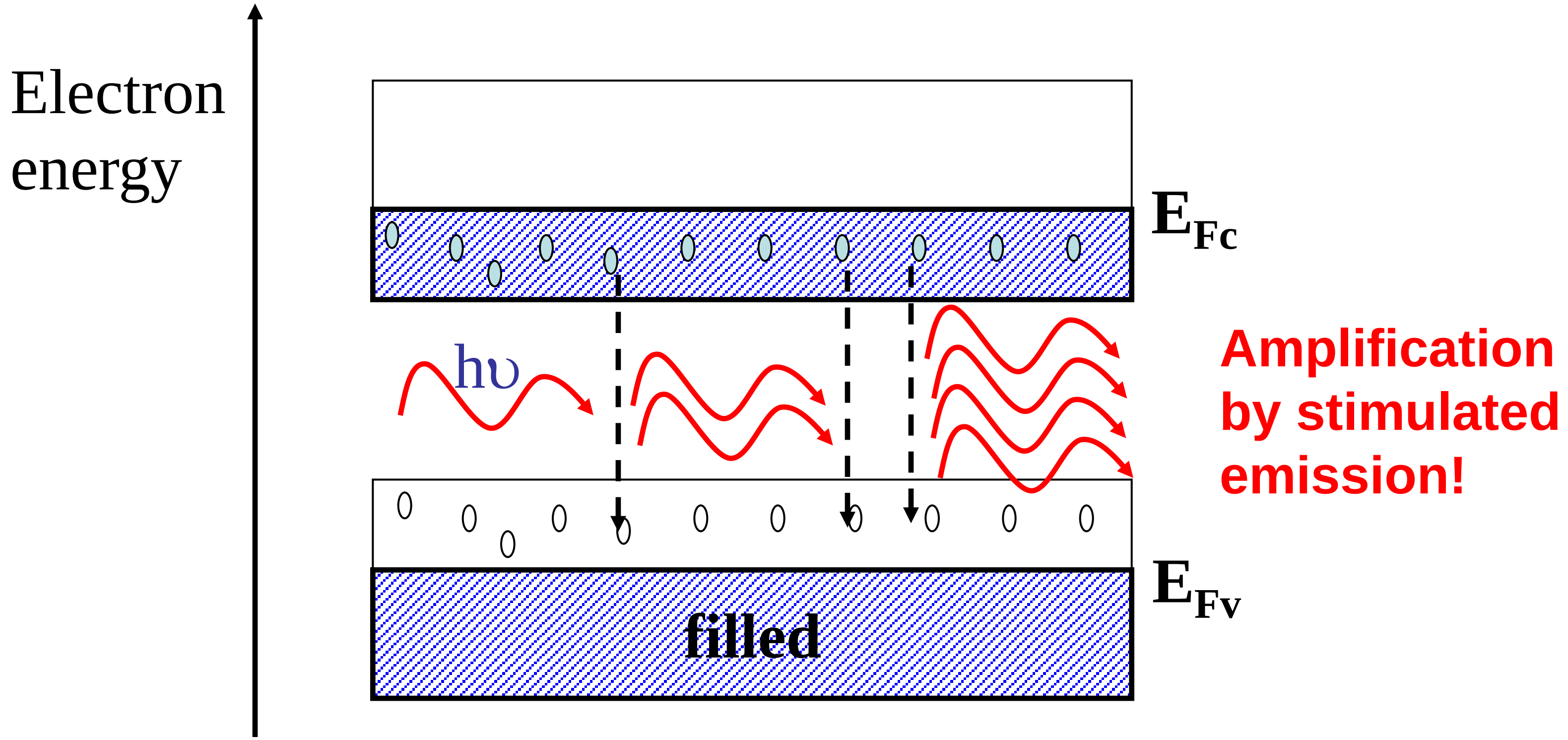


- Incident photons with energy $E_g < h\upsilon < (E_{Fc} - E_{Fv})$ *cannot be absorbed*

because ***the necessary conduction band states are occupied***! (*and the necessary valance band states are empty*)



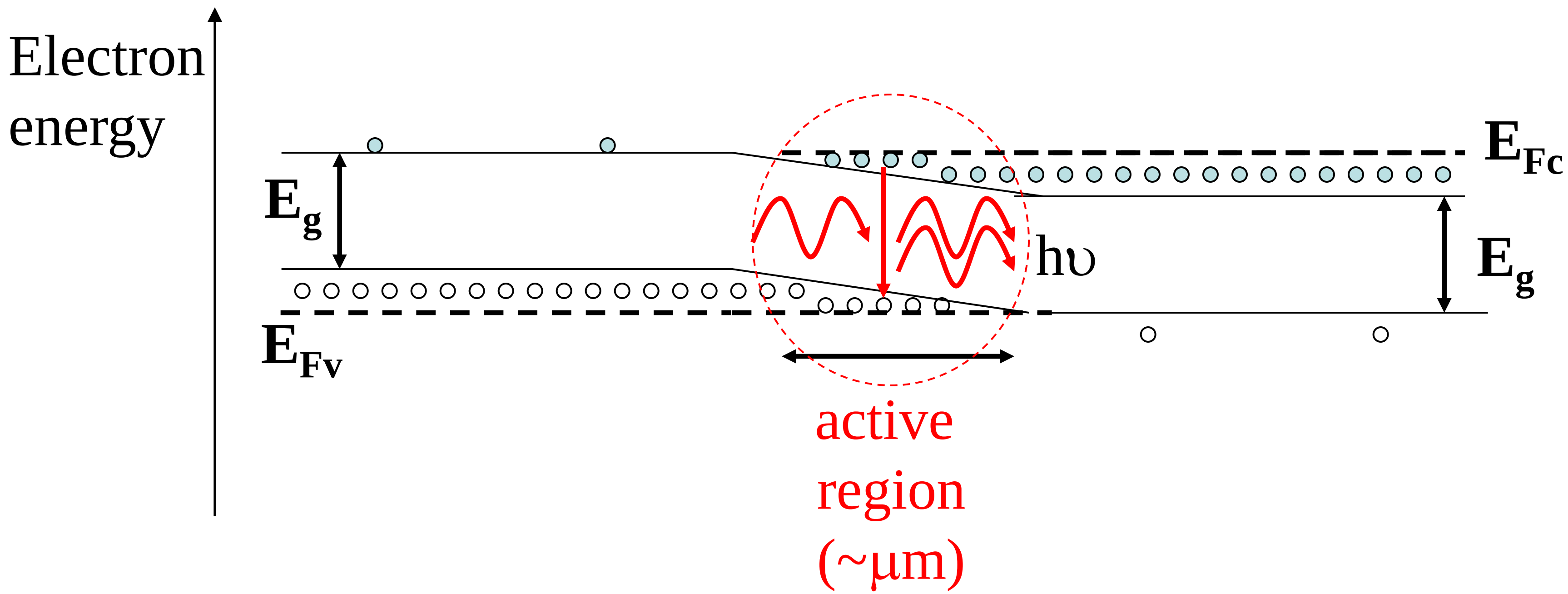
Instead, these photons can ***induce downward transitions*** of an electron from *a filled conduction band state into an empty valence band state*. => **emitting coherent photons!**



The condition for stimulated emission under *population inversion*:

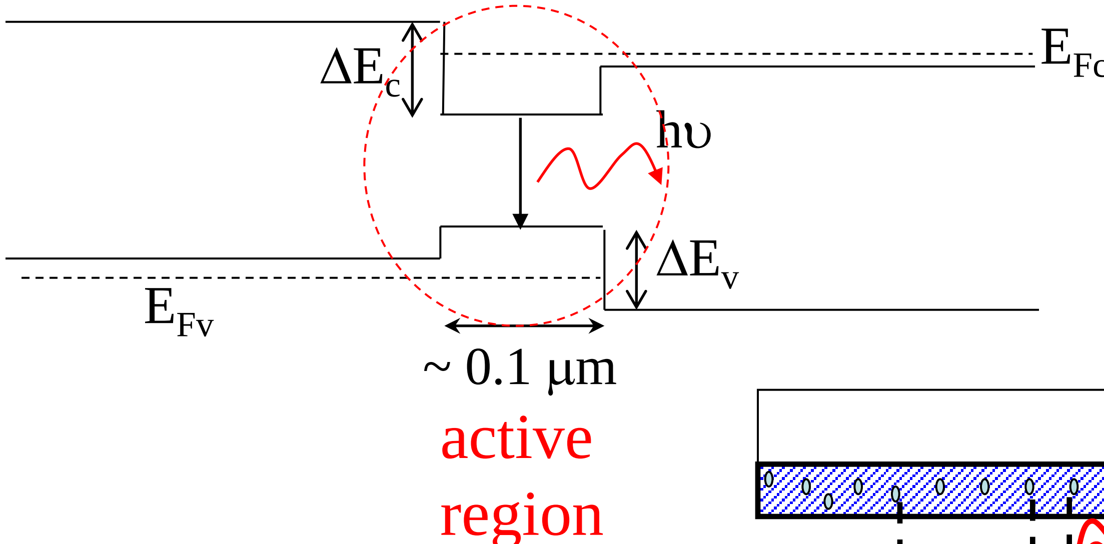
$$E_{Fc} - E_{Fv} > h\upsilon > E_g$$

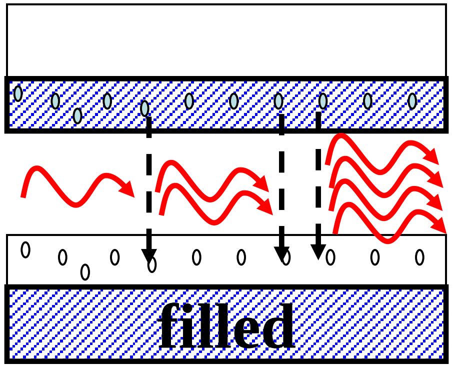
Population inversion in a forward-biased heavily doped p^+-n^+ junction



- Upon *high injection carrier density* in a heavily-doped p^+-n^+ junction there exists an ***active region*** near the depletion layer, which *contains simultaneously heavily populated electrons and holes* – population inverted!

Population inversion in a P$^+$-p-N$^+$ double heterostructure under forward bias (e.g. $Al_xGa_{1-x}As$ system)





- The thin narrow-gap active region of a ***double heterostructure*** *contains simultaneously heavily populated electrons and holes* in a confined active region – population inverted!

Transition rates for semiconductors in quasi-equilibrium

- Recall expressions for the rate of stimulated emission $R_e(\upsilon)$ and the rate of photon absorption $R_a(\upsilon)$:

$$R_e(\upsilon) = B_{21}\, u(\upsilon)\, P_c(E_2)\, [1 - P_v(E_1)]\, \rho(\upsilon) \qquad (m^{-3})$$

$$R_a(\upsilon) = B_{12}\, u(\upsilon)\, P_v(E_1)\, [1 - P_c(E_2)]\, \rho(\upsilon) \qquad (m^{-3})$$

in the presence of an optical radiation field that has a *spectral intensity* $I(\upsilon) = (c/n)\, u(\upsilon)$

$$B_{12} = B_{21} = c^3/(8\pi n^3 h\upsilon^3 \tau_{sp})$$

joint density of states $\rho(\upsilon) = ((2m_r)^{3/2}/\pi\hbar^2)\, (h\upsilon - E_g)^{1/2} \qquad h\upsilon \geq E_g$

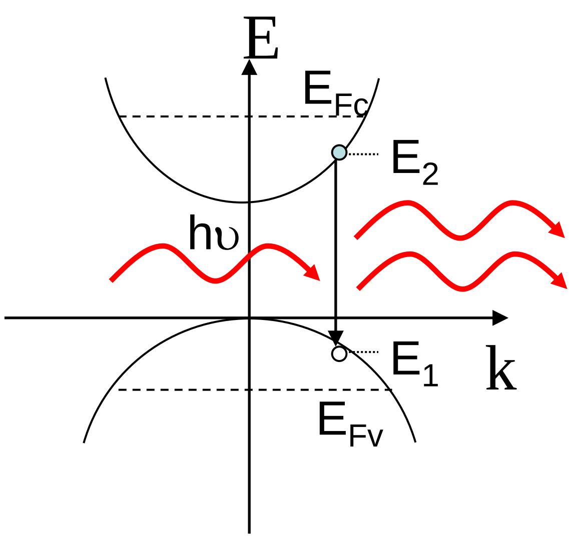
- *Stimulated emission is more prevalent than absorption* when:

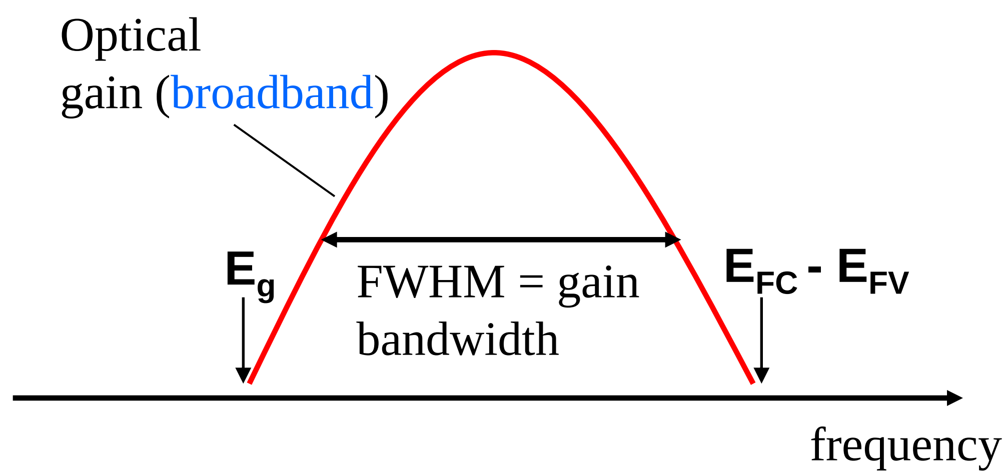
$$R_e(\upsilon) > R_a(\upsilon)$$

$$\Rightarrow P_c(E_2)\,[1 - P_v(E_1)] > P_v(E_1)\,[1 - P_c(E_2)]$$

$$\Rightarrow P_c(E_2) > P_v(E_1) \qquad (E_2 < E_{Fc}\ ,\ E_1 > E_{Fv})$$

- *This defines the **population inversion** in a semiconductor*. The quasi-Fermi levels are determined by the *pumping (injection) level* ($E_{Fc} - E_{Fv} = eV > E_g$, where V is the forward bias voltage).





Gain and absorption coefficients vs. frequency

- Define the ***gain coefficient*** (cm^{-1}) in *quasi*-equilibrium ($P_c(E_2) > P_v(E_1)$, $E_g < h\upsilon < E_{Fc} - E_{Fv}$):

$$g(\upsilon) = (h\upsilon/I(\upsilon))\,[R_e(\upsilon) - R_a(\upsilon)]$$
$$= (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon)\,[P_c(E_2) - P_v(E_1)]$$

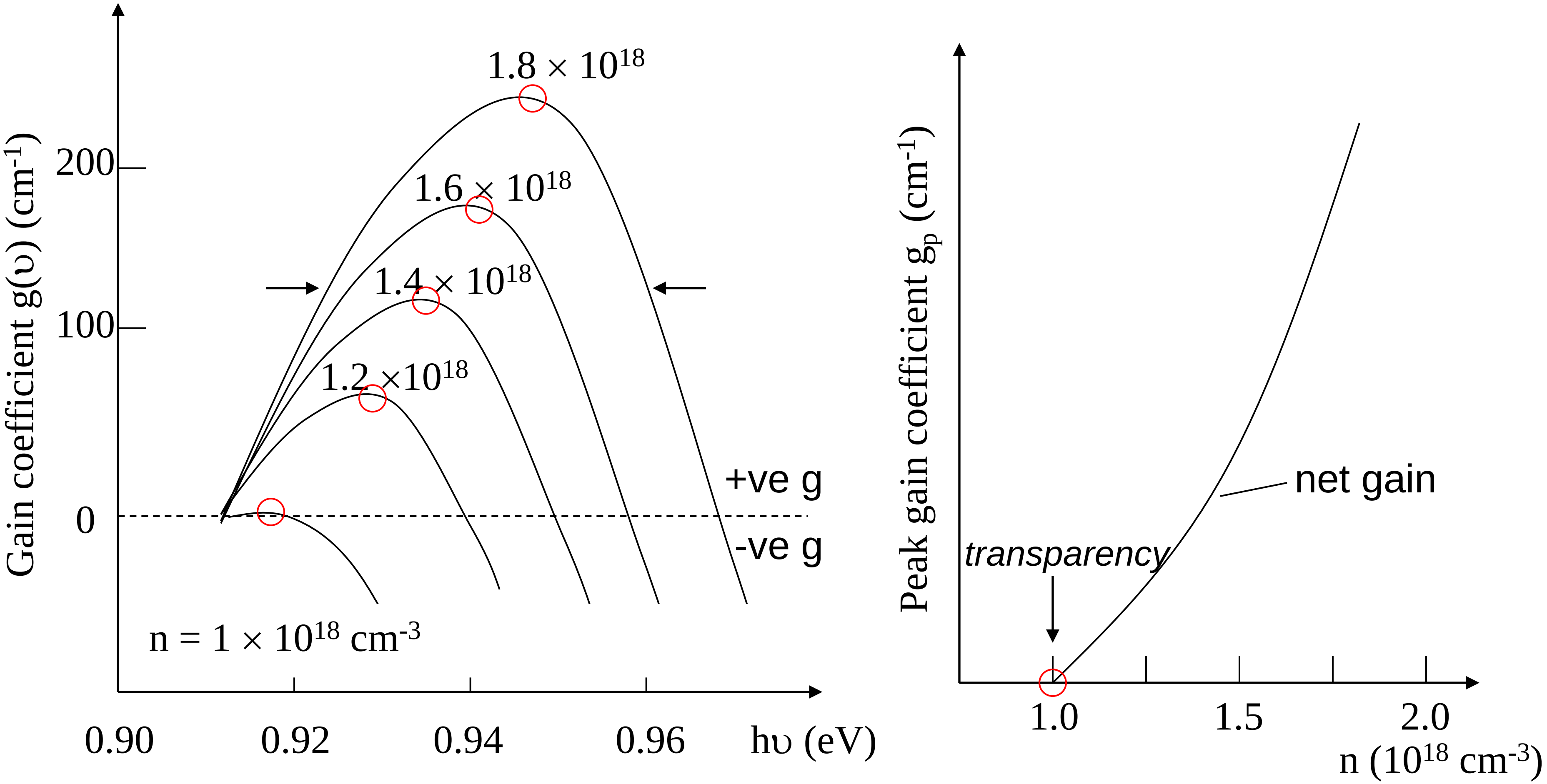
where $I(\upsilon)/h\upsilon = v_g u(\upsilon)/h\upsilon$ is the photon flux per unit *area* *(cm^{-2}).*

- The ***absorption coefficient*** (cm^{-1}) in *thermal* equilibrium (*taking +ve sign*):

$$\alpha(\upsilon) = (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon)\,[P(E_1) - P(E_2)]$$
$$\approx (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon) \quad \text{where } P(E_1) \sim 1,\ P(E_2) \sim 0$$

** The larger the absorption coefficient in *thermal* equilibrium the larger the gain coefficient when pumped ! **

Gain coefficient g(υ) for an InGaAsP SOA



• Both the *amplifier bandwidth* and the *peak value* of the gain coefficient increase with *injected carrier concentration* n. The bandwidth is defined at the FWHM of the gain profile, also called the *3-dB gain bandwidth*.

Material transparency

- The semiconductor material becomes "transparent" (***material transparency***) when the rate of absorption just *equals* the rate of stimulated emission.

  => one incident photon produces *exactly* one photon in the output.

  => the single-pass gain must be unity, i.e. $G = 1$.

  => The material gain upon transparency $g(n_0) = 0$.

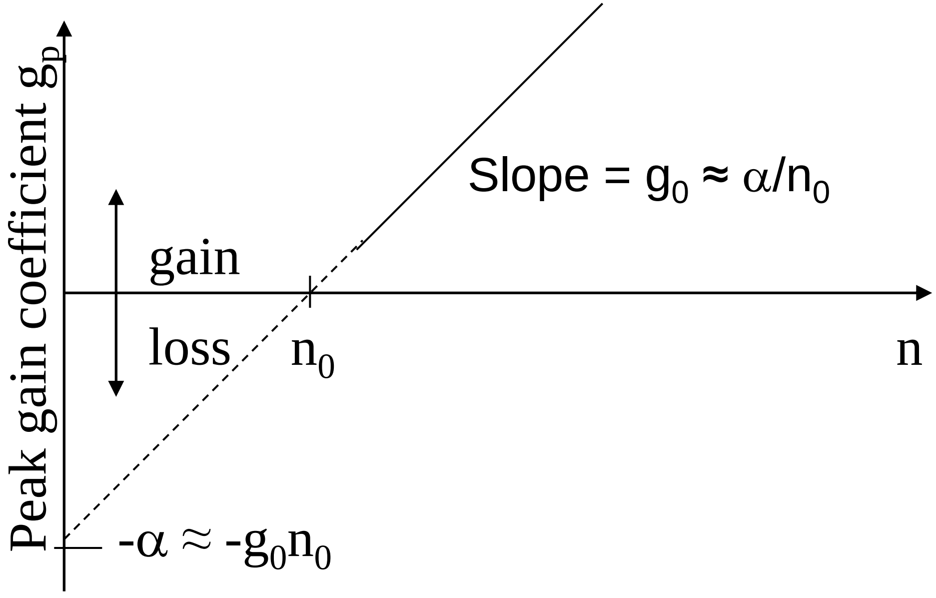
- The ***transparency density*** n_0 (number per unit volume) represents the number of excess conduction band electrons per volume required to achieve transparency.

Differential gain

- The *peak gain coefficient* curves can be approximated by a straight line at n_0 by making a Taylor expansion about the transparency density n_0 to find

$$g_p = g_p(n) \cong g_0(n - n_0) \cong \alpha(n/n_0 - 1)$$

- $g_0 = dg_p/dn$ is typically called the ***differential gain*** **(cm²)**. It has a unit of *cross section*.



- The quantity α represents the *absorption coefficient* in the absence of injection.

- n_0 represents the injected-carrier concentration at which *emission* and *absorption* just balance each other (the *transparency condition*).

- Within the *linear approximation*, the *peak gain coefficient* is linearly related to the *injected current density* J (A cm^{-2})

$$g_p \approx \alpha(J/J_0 - 1)$$

$\Rightarrow$The *transparency current density* J_0 is given by

$$J_0 = (el/\eta_{int}\tau_r)\, n_0$$

where *l* is the active region thickness

- When J = 0, the peak gain coefficient $g_p = -\alpha$ becomes the *absorption coefficient*.
- When $J = J_0$, $g_p = 0$ and the material is *transparent* => exhibits *neither gain nor loss*.
- *Net gain* can be attained in a semiconductor junction *only* when $J > J_0$.

Injected current density

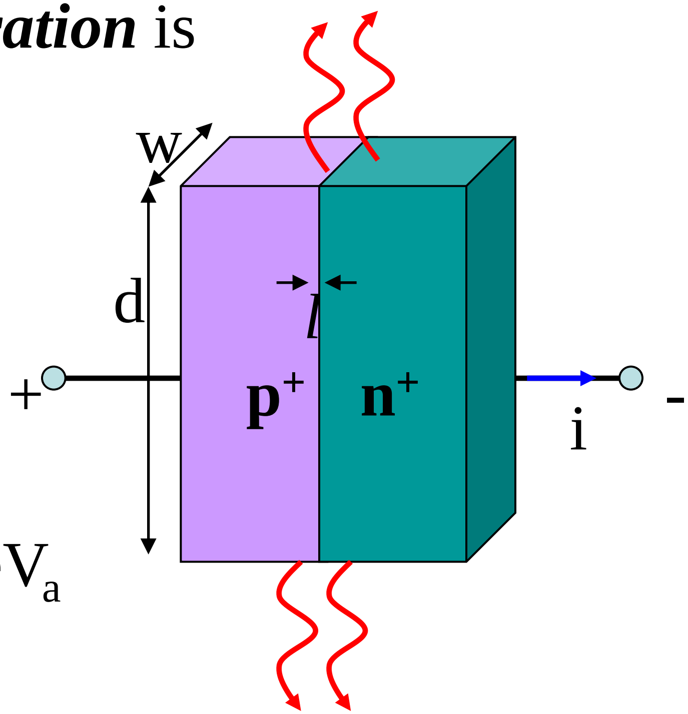
- If an electric current i is injected through an area $A = wd$, into an active region V_a = volume lA (where l is the active region thickness), ⇒the *steady-state carrier injection rate* is $i/elA = J/el$ per second per unit volume, where $J = i/A$ is the *injected current density* ($A\ cm^{-2}$).

⇒The ***steady-state injected carrier concentration*** is (recombination = injection)

$$n/\tau = J/el$$

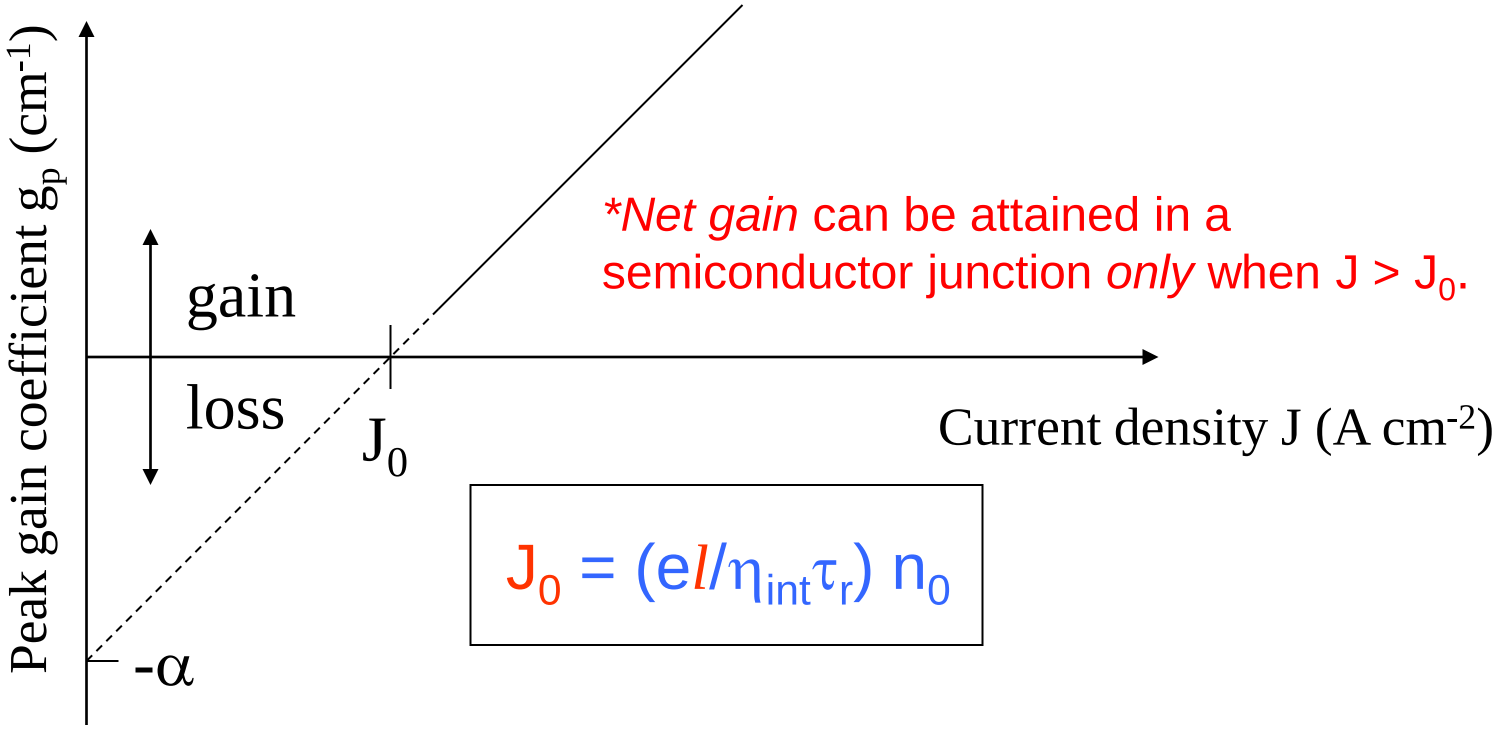
or $$J = (el/\eta_{int}\tau_r)\ n$$

the "pump-current number density" = $\eta_{int}\ i/eV_a$



(τ is the *total* recombination lifetime, τ_r is the *radiative* recombination lifetime, $\eta_{int} = \tau/\tau_r$)

Peak gain coefficient as a function of current density for the approximate linear model



**Net gain* can be attained in a semiconductor junction *only* when $J > J_0$.

$$J_0 = (e l / \eta_{int} \tau_r)\, n_0$$

- Note that J_0 is directly proportional to the junction thickness l => a *lower* transparency current density J_0 is attained by using a *narrower* active-region thickness. (*another motivation for using double heterostructures where l is ~ 0.1 μm*)

e.g. Gain of an InGaAsP SOA

An InGaAsP semiconductor optical amplifier operating at 300° K has the following parameters: $\tau_r = 2.5$ ns, $\eta_{int} = 0.5$, $n_0 = 1.25 \times 10^{18}$ cm^{-3}, and $\alpha = 600$ cm^{-1}. The junction has thickness $l = 2$ μm (not a double heterostructure), length d = 200 μm, and width w = 10 μm.

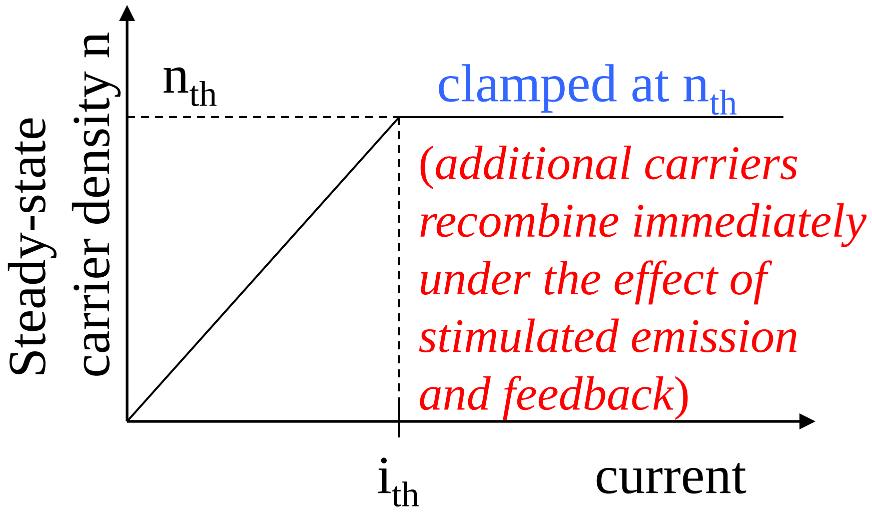
⇒The *transparency current density* $J_0 = 3.2 \times 10^4$ A/cm^2

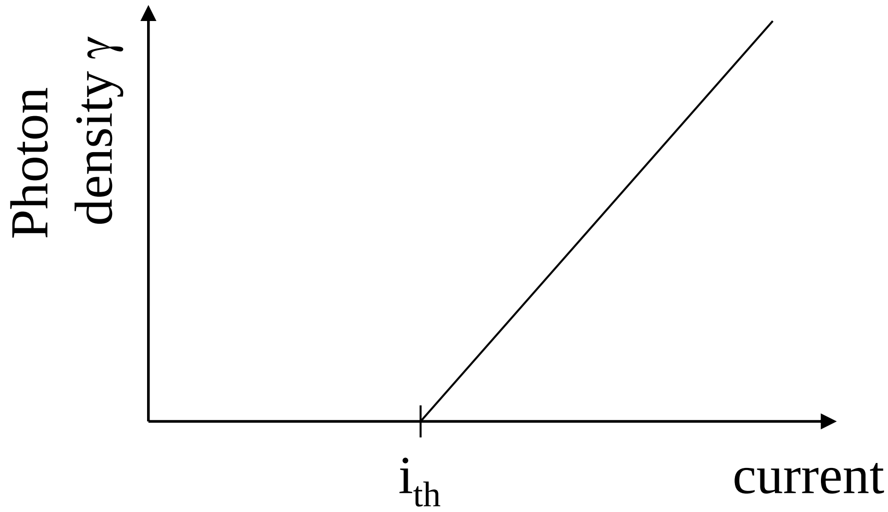
⇒A slightly larger current density $J = 3.5 \times 10^4$ A/cm^2 provides a *peak gain coefficient* $g_p \approx 56$ cm^{-1}.

⇒An *amplifier gain* (i.e. single-pass gain) at the peak gain $G = \exp(g_g d) = \exp(1.12) \approx 3$

However, as the junction area $A = wd = 2 \times 10^{-5}$ cm^2, a rather large injection current $i = JA =$ 700 mA (!) is required to produce this current density.

Steady-state carrier density and photon density as functions of injection current





- *Below threshold*, the laser photon density is *zero*; any increase in the pumping rate is manifested as an increase in the spontaneous-emission photon flux, but there is *no sustained oscillation*.
- *Above threshold*, the steady-state internal laser photon density is directly *proportional to the initial population inversion* (*initial injected carrier density*), and therefore increases with the pumping rate, yet the *gain g(n) remains clamped at the threshold value* ($\simeq g(n_{th})$).

Gain at threshold

- *Above threshold*, the gain does *not* vary much from $g_{th} = g(n_{th})$.
- Recall the ***differential gain*** is the slope of the gain g(n)

$$g_0(n) = dg(n)/dn$$

- For lasing, the differential gain is evaluated at the threshold density n_{th}.
- The lowest order Taylor series approximation centered on the *transparency density* n_0 is

$$g(n) = g_0(n - n_0).$$

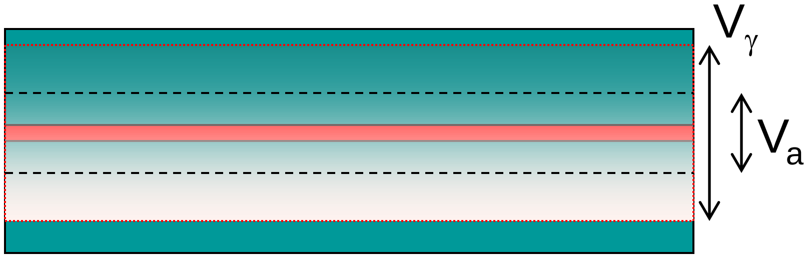
=> The gain at threshold must be

$$g_{th} = g(n_{th}) = g_0(n_{th} - n_0)$$

Optical confinement factor

- The active region (i.e. gain region) has volume V_a, which is *smaller* than the modal volume V_γ containing the optical energy.
- The simplest model assumes that the optical power is uniformly distributed in V_γ and is zero outside the volume.
- The ***optical confinement factor*** Γ specifies the fraction of the optical mode that overlaps the gain region

$$\Gamma = V_a/V_\gamma$$



Threshold current density

- Recall that within the *linear approximation*, the *peak gain coefficient* is linearly related to the injected current density J:

$$g_p \approx \alpha(J/J_0 - 1)$$

where J_0 *is the transparency current density.*

- Setting $g_p = g_{th} = \alpha_r/\Gamma$, the ***threshold injected current density*** J_{th}:

$$J_{th} \approx [(\alpha_r/\Gamma + \alpha)/\alpha]\, J_0$$

$\Rightarrow$The threshold current density is larger than the transparency current density by the factor $(\alpha_r/\Gamma + \alpha)/\alpha$, which is ~ 1 – 2 for good active materials with <u>high gain</u> (large α) in a <u>low-loss cavity</u> (small α_r).

- The ***threshold injected current*** $i_{th} = J_{th}A$ and the *transparency current* $i_0 = J_0A$, where A is the active region cross-sectional area.

Remarks on threshold current density

- The *threshold current density* J_{th} is a key parameter in characterizing the laser-diode performance: *smaller values of J_{th} indicate superior performance.*

- J_{th} can be minimized by ($J_{th} \to J_0$ and minimizing J_0):

  maximizing the internal quantum efficiency η_{int};

  minimizing the resonator loss coefficient α_r,

  minimizing the transparency injected-carrier concentration n_0,

  minimizing the active-region thickness l
  (*key merit of using double heterostructures*)

e.g. Threshold current for an InGaAsP heterostructure laser diode

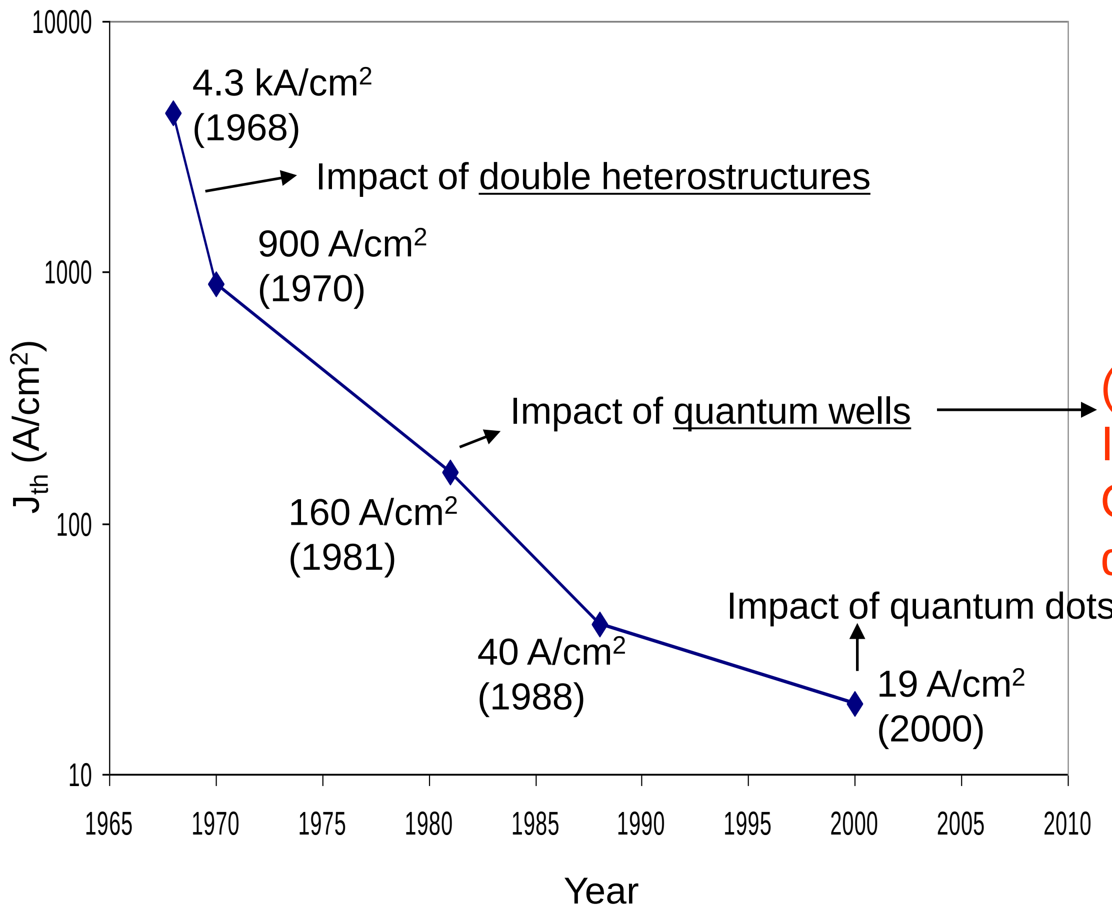
Consider an InGaAsP (active layer) / InP (cladding) double heterostructure laser diode with the material parameters:
$n_0 = 1.25 \times 10^{18}$ cm^{-3}, $\alpha = 600$ cm^{-1}, $\tau_r = 2.5$ ns, n = 3.5, $\eta_{int} = 0.5$ at T = 300° K. Assume that the dimensions of the junction are d = 200 μm, w = 10 μm, and $l = 0.1$ μm. Assume the resonator loss coefficient $\alpha_r = 118$ cm^{-1}. (assume $\Gamma = 1$)

$\Rightarrow$The *transparency current density* $J_0 = 1600$ A/cm^2

$\Rightarrow$The *threshold current density* $J_{th} = 1915$ A/cm^2

$\Rightarrow$ The *threshold current* $i_{th} = 38$ mA. (**Note that it is this reasonably small threshold current that enables continuous-wave (CW) operation of double-heterostructure laser diodes at room temperature*.)

Evolution of the threshold current density of semiconductor lasers



(your lab6 lasers are InGaAsP Multiple Quantum Well (MQW) diode lasers!)

Zhores Alferov, Double heterostructure lasers: early days and future perspectives, IEEE Journal on Selected Topics in Quantum Electronics, Vol. 6, pp. 832-840, Nov/Dec 2000

Laser Diode Rate Equations

- **The relationship between optical output power and diode drive current comes from the rate equations that govern the interaction of photons and electrons in the active region**
- **For a pn junction with a carrier-confinement region of depth d, the rate equations are**

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}}$$

$$= \text{stimulated emission} + \text{spontaneous emission} + \text{photon loss}$$

which governs the number of photons Φ, and

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi$$

$$= \text{injection} + \text{spontaneous recombination} + \text{stimulated emission}$$

which governs the number of electrons *n*.

Note that the two rate equations are coupled via the stimulated emission term. Thus, the equations suggest 2^{nd}-order differential equations in time – oscillation of n and Φ.

Power output of injection lasers

- The *<u>internal</u> laser power* above threshold:

$$P = \eta_{int}\,(hc/e\lambda)\,(i - i_{th}) = (hc/\lambda)\,\eta_{int}\,(i - i_{th})/e$$

- Only part of this power can be extracted through the cavity mirrors, and the rest is dissipated inside the laser resonator.

$\Rightarrow$The *<u>output</u> laser power* if the light transmitted *through <u>both</u> mirrors* is used (assume $R = R_1 = R_2$ => *total mirror loss* $\alpha_m = (1/d)\ln(1/R)$)

$$P_o = \eta_{int}\,(hc/e\lambda)\,(i - i_{th}) \cdot (1/d)\ln(1/R)\,/\,\alpha_r$$

$$= \eta_e\,\eta_{int}\,(hc/e\lambda)\,(i - i_{th}) = \eta_{ext}\,(hc/e\lambda)\,(i - i_{th})$$

extraction efficiency (α_m/α_r)

external differential quantum efficiency

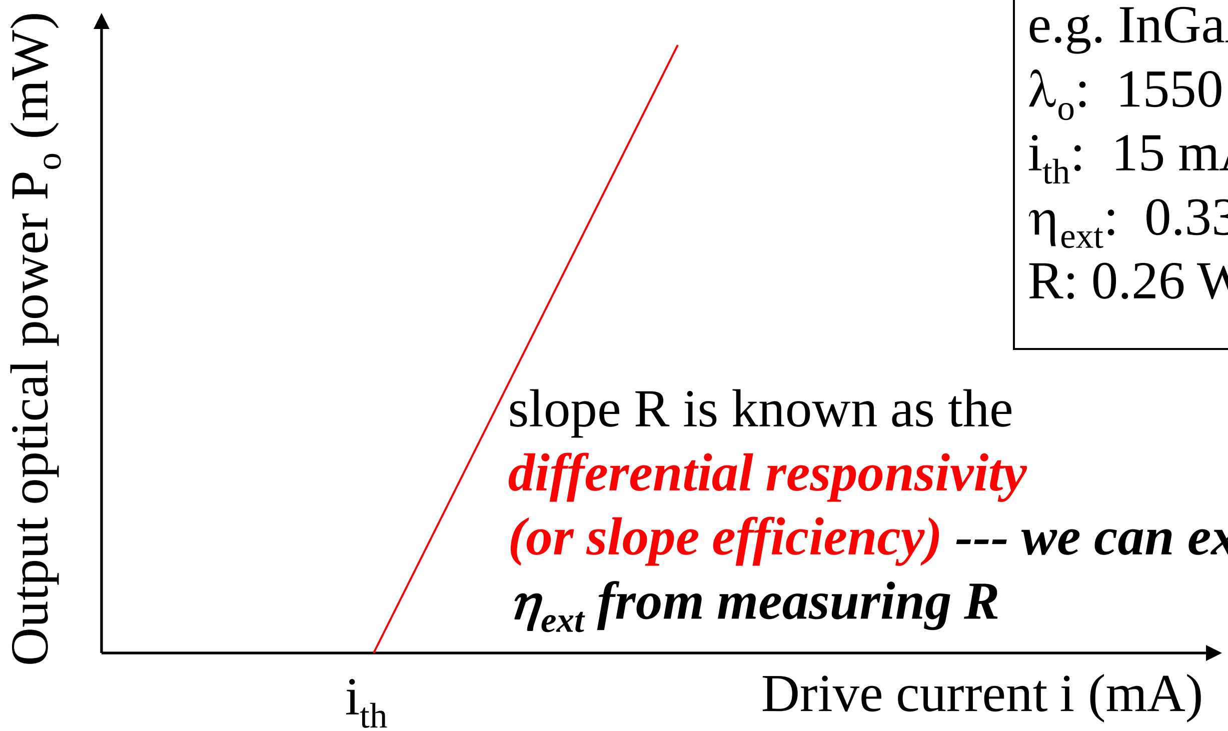
External differential quantum efficiency

- The external differential quantum efficiency η_{ext} is defined as

$$\eta_{ext} = d(P_o/(hc/\lambda)) / d(i/e)$$

$$\Rightarrow \quad dP_o/di = \eta_{ext}\, hc/e\lambda = \eta_{ext}\, 1.24/\lambda \equiv R \qquad (W/A)$$

e.g. InGaAsP/InGaAsP:
λ_o: 1550 nm
i_{th}: 15 mA
η_{ext}: 0.33
R: 0.26 W/A



e.g. Efficiencies for double-heterostructure InGaAsP laser diodes

Consider again an InGaAsP/InP double-heterostructure laser diode with $\eta_{int} = 0.5$, $\alpha_m = 59\ \text{cm}^{-1}$, $\alpha_r = 118\ \text{cm}^{-1}$, and $i_{th} = 38$ mA.

If the light from both output faces is used, the *extraction efficiency* is

$$\eta_e = \alpha_m/\alpha_r = 0.5$$

The *external differential quantum efficiency* is

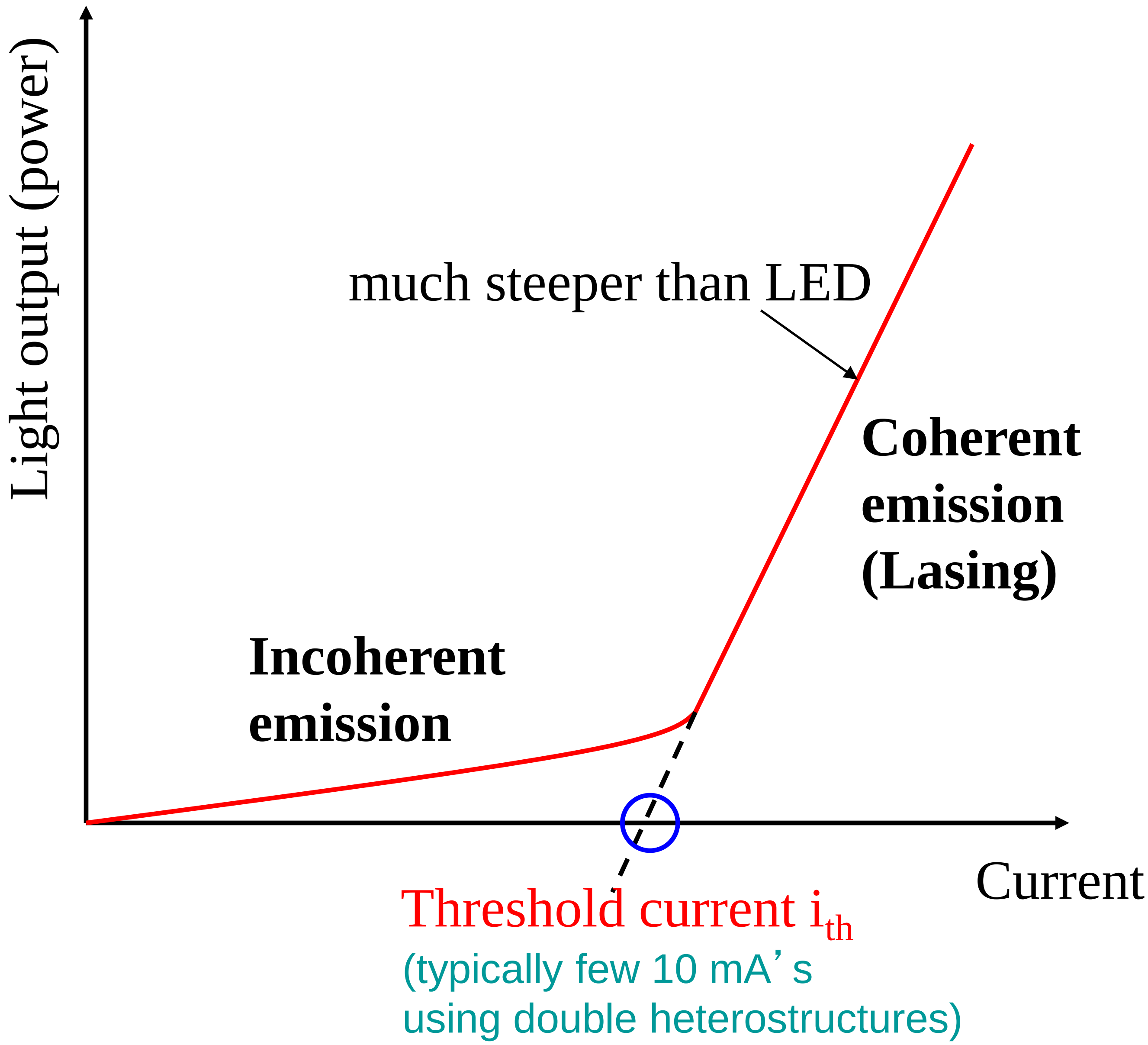
$$\eta_{ext} = \eta_e\, \eta_{int} = 0.25$$

At $\lambda_o = 1300$ nm, the *differential responsivity* of this laser is

$$R = dP_o/di = \eta_{ext}\, 1.24/1.3 = 0.24\ \text{W/A}$$

For i = <u>50 mA</u>, $i - i_{th} = 12$ mA and $P_o = 12 \times 0.24 = \underline{2.9\ \text{mW}}$

Optical output against injection current characteristics



Comparison of LED and LD efficiencies and powers

- When operated *below threshold*, laser diodes produce *spontaneous emission* and behave as light-emitting diodes.

- There is a *one-to-one correspondence* between the efficiencies quantities for the LED and the LD.

- The superior performance of the laser results from the fact that the *extraction efficiency* η_e *for the LD is greater than that for the LED*.

- This stems from the fact that the laser operates on the basis of *stimulated emission*, which *causes the laser light to be concentrated in particular modes* so that it can be more readily extracted.

$\Rightarrow$A laser diode operated above threshold has a value of η_{ext} (10's of %) that is larger than the value of η_{ext} for an LED (fraction of %).

- The ***power-conversion efficiency*** (*wall-plug efficiency*):

$$\eta_c \equiv P_o/iV$$

$$\eta_c = \eta_{ext}\,[(i - i_{th})/i]\,(h\upsilon/eV)$$

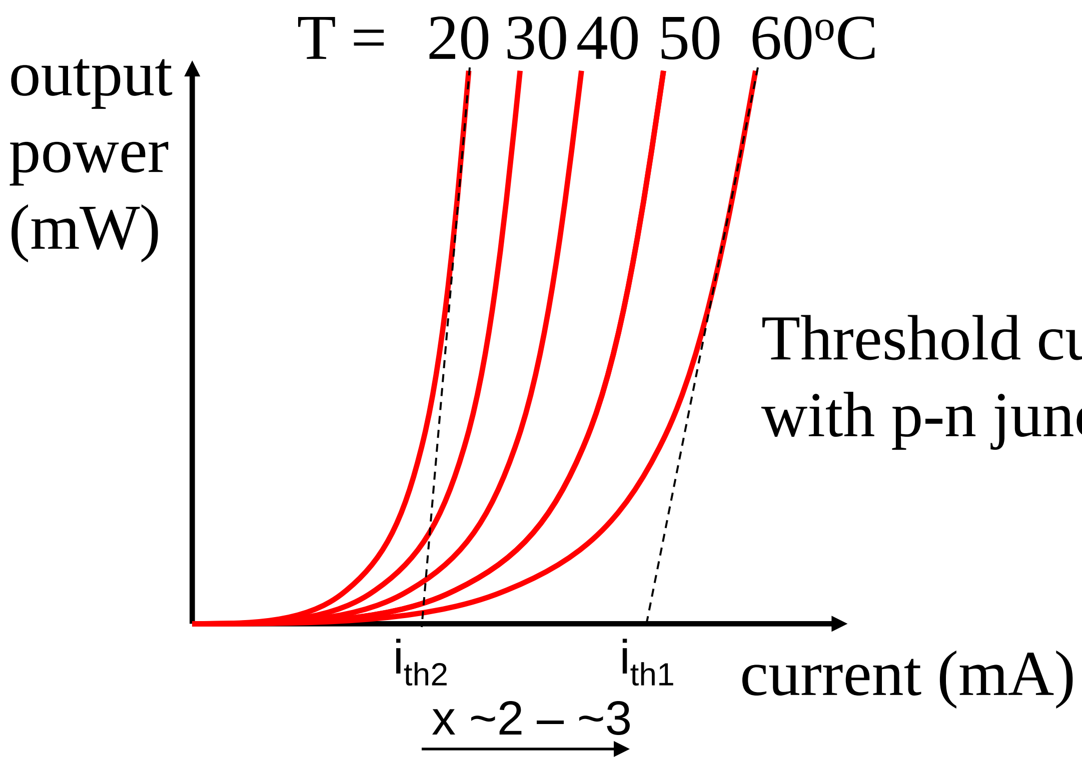
$$@\ i = 2i_{th} \qquad \Rightarrow \quad \eta_c = \eta_{ext}\,(h\upsilon/eV) < \eta_{ext}$$

- Laser diodes can exhibit power-conversion efficiencies in excess of 50%, which is well above that for other types of lasers.

- The electrical power that is not transformed into light is transformed into heat.

- Because *laser diodes generate substantial amounts of heat* they are usually mounted on heat sinks, which help dissipate the heat and stabilize the temperature.

Typical laser diode threshold current temperature dependence



Threshold current increases with p-n junction temperature

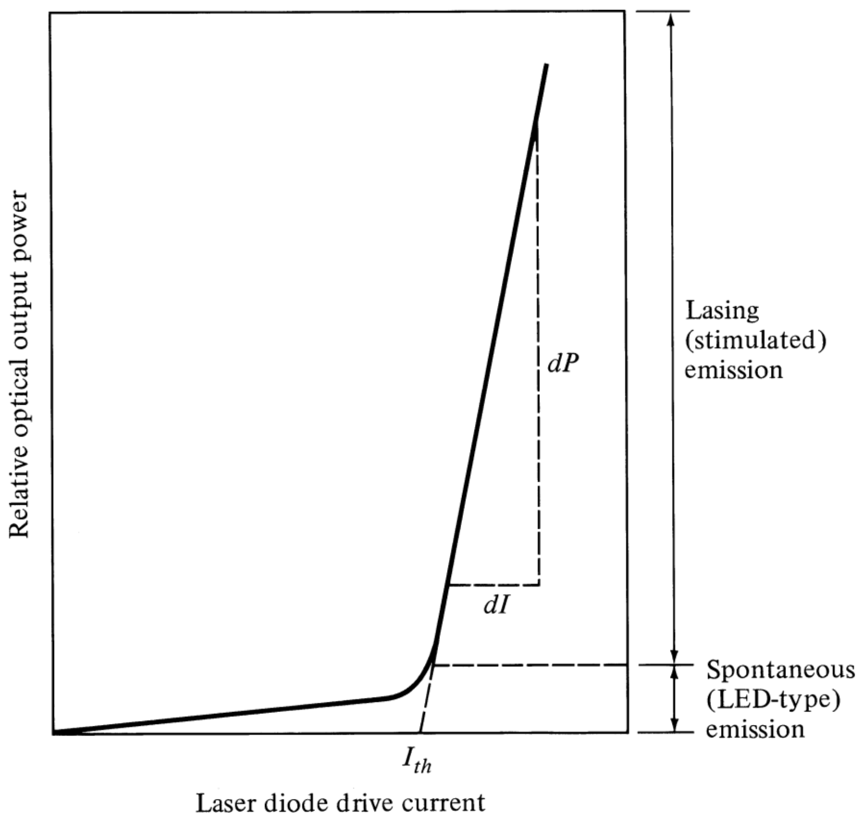
Threshold current: $i_{th} \propto \exp(T/T_o)$ (empirical)

$$i_{th1} = i_{th2} \exp[(T_1 - T_2)/T_0]$$

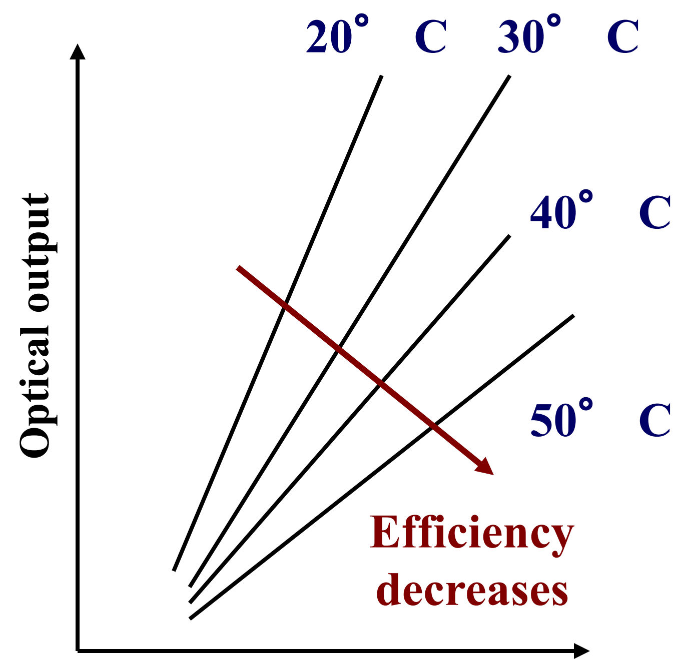
(T_o ~ 40 – 75 K for InGaAsP)

Laser Optical Output vs. Drive Current

Relationship between optical output and laser diode drive current. Below the lasing threshold the optical output is a spontaneous LED-type emission.



Slope efficiency = dP/dI
The laser efficiency changes with temperature:



More on temperature dependence of a laser diode

- As the temperature increases, the diode's *gain decreases*, and so more current is required before oscillation begins (threshold current increases by about 1.5%/^{o}C)

- *Thermal generated carriers* (holes in the n layer and electrons in the p layer) *recombine* with free electrons and holes in the doped regions outside the active layer, reducing the number of charges reaching the active layer, *thereby reducing gain*.

- Reducing in gain leads to an *increase in threshold current*.

Laser diodes temporal response

- ***Laser diodes respond much faster than LEDs***, primarily because the *rise time* of an LED is determined by the natural *spontaneous-emission lifetime* τ_{sp} of the material.

- The rise time of a laser diode depends upon the *stimulated-emission lifetime*.

- In a semiconductor, the spontaneous lifetime is the average time that free charge carriers exist in the active layer before recombining spontaneously (*from injection to recombination*).

- The *stimulated-emission lifetime* is the average time that free charge carriers exist in the active layer before being *induced* to recombine by stimulated emission.

Stimulated lifetime << spontaneous lifetime

- For a laser medium to have gain, the *stimulated lifetime must be shorter than the spontaneous lifetime*.

- Otherwise, spontaneous recombination would occur before stimulated emission could begin, decreasing the population inversion and inhibiting gain and oscillation.

- The faster stimulated-emission process, which dominates recombination in a laser diode, ensures that a laser diode responds more quickly to changes in the injected current than a LED.

Typical LED rise time ~ 2 – 50 ns

Using 3-dB *electrical* bandwidth f_{3dB} = 0.35/rise time

=> 3-dB bandwidth < 0.35 / (2 ns) = 175 MHz

Stimulated emission from **injection lasers** occurs over a much shorter period.

⇒Rise times: ~ 0.1 – 1 ns

⇒3-dB bandwidth < 0.35 / (0.1 ns) = 3.5 GHz

Direct modulation

The **modulation of a laser diode** can be accomplished by changing the drive current.
This type of modulation is known as internal or **direct modulation**.
The intensity of the radiated power is modulated - *intensity modulation*.

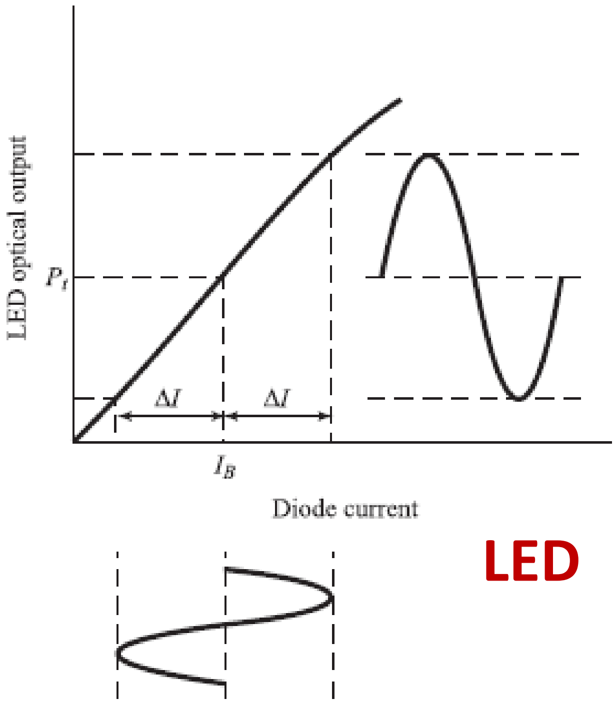
Drawbacks of direct modulation: (1) restricted bandwidth and (2) laser frequency drift (*due to the phase modulation of the semiconductor gain medium upon free-carrier density change*).

*Note: Laser diode direct modulation is now only used for relatively low-speed modulation (~GHz). *For beyond GHz*, we typically employ ***external modulation***, namely, running the diode laser at steady-state (*continuous-wave operation*) and modulate the laser beam with an *external modulator* (which has a bandwidth on the order of 10 GHz).

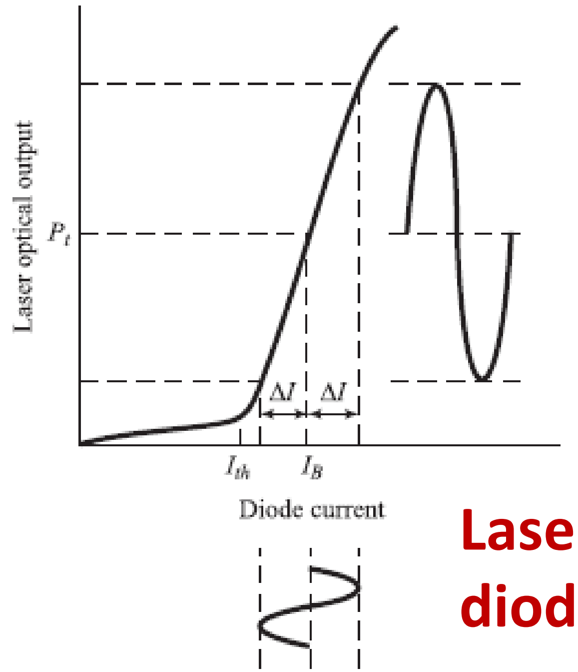
Light Source Linearity

In an analog system, a *time-varying electric analog signal* modulates an optical source directly about a bias current I_B.

•With no signal input, the optical power output is P_t. When an analog signal s(t) is applied, the *time-varying (analog) optical output* is: $P(t) = P_t[1 + m\, s(t)]$, where m = *modulation index*



LED



Laser diode

$$m = \frac{\Delta I}{I'_B}$$

For LEDs $I_B' = I_B$

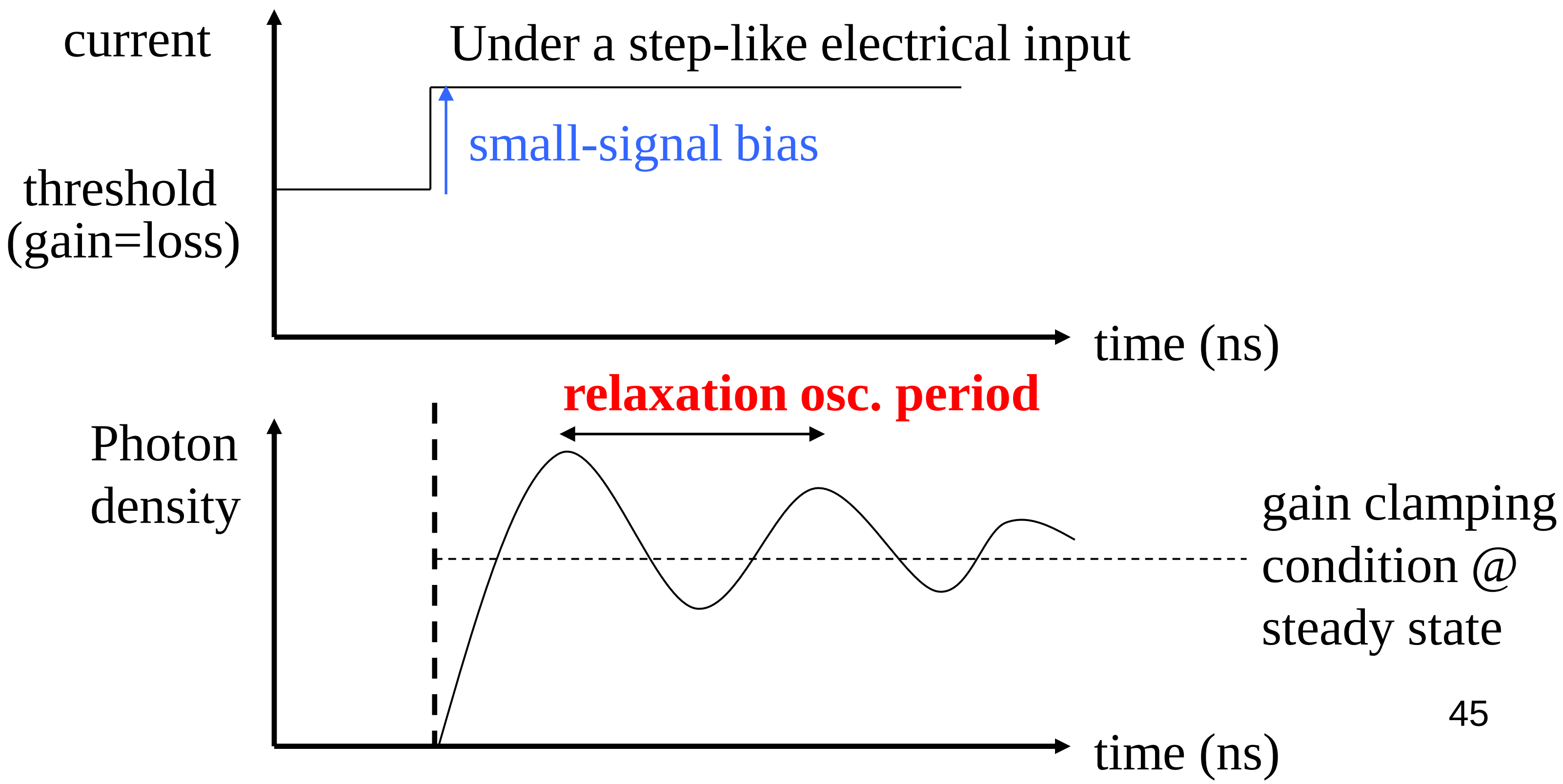
For laser diodes $I_B' = I_B - I_{th}$

- The *coupled rate equations* (*given by the stimulated emission term*)

$\Rightarrow$ laser diode behaves like a *damped oscillator* (2^{nd}-order ODE in $d^2\Phi/dt^2$) before reaching steady-state condition

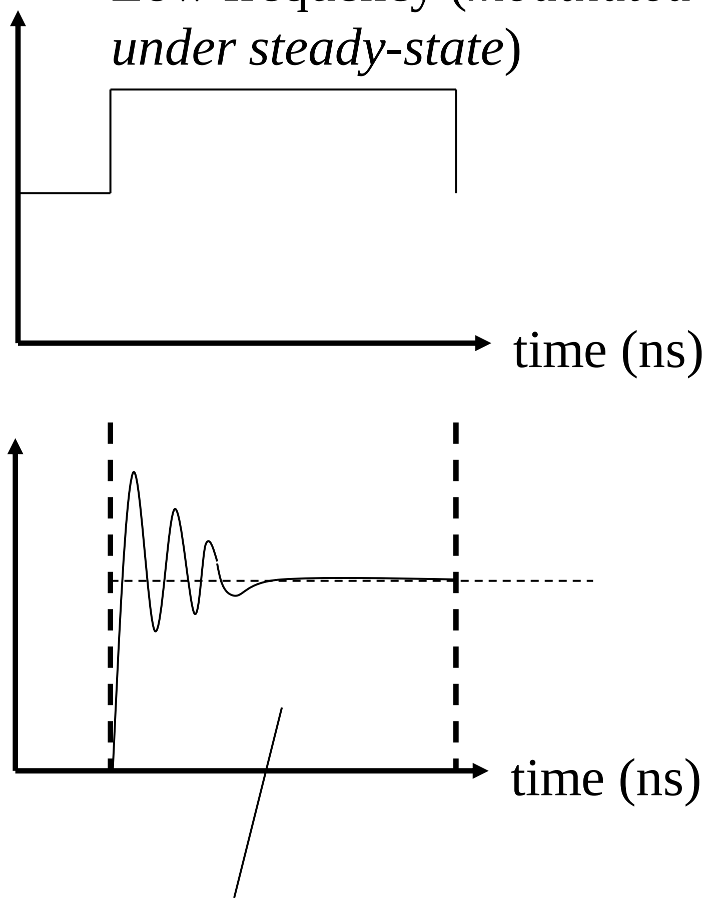
- The direct modulation frequency cannot exceed the laser diode **relaxation oscillation** frequency without significant power drop.

(**Biasing above threshold is needed in order to accelerate the switching of a laser diode from on to off*.)



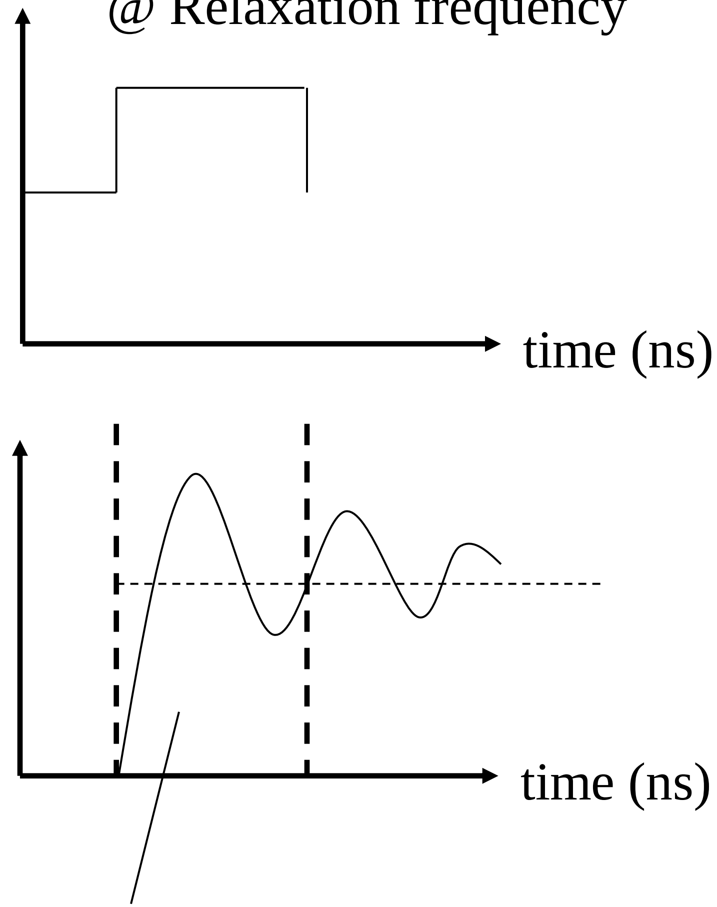
How fast can we modulate a laser diode?

Low frequency (*modulated under steady-state*)



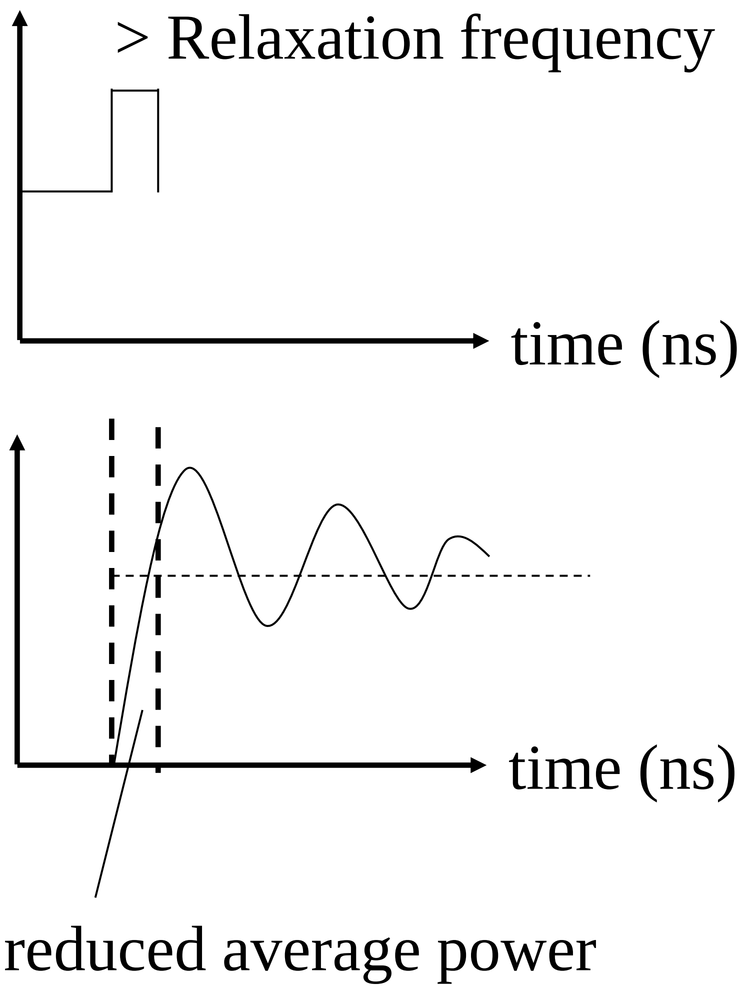
averaged pulse power

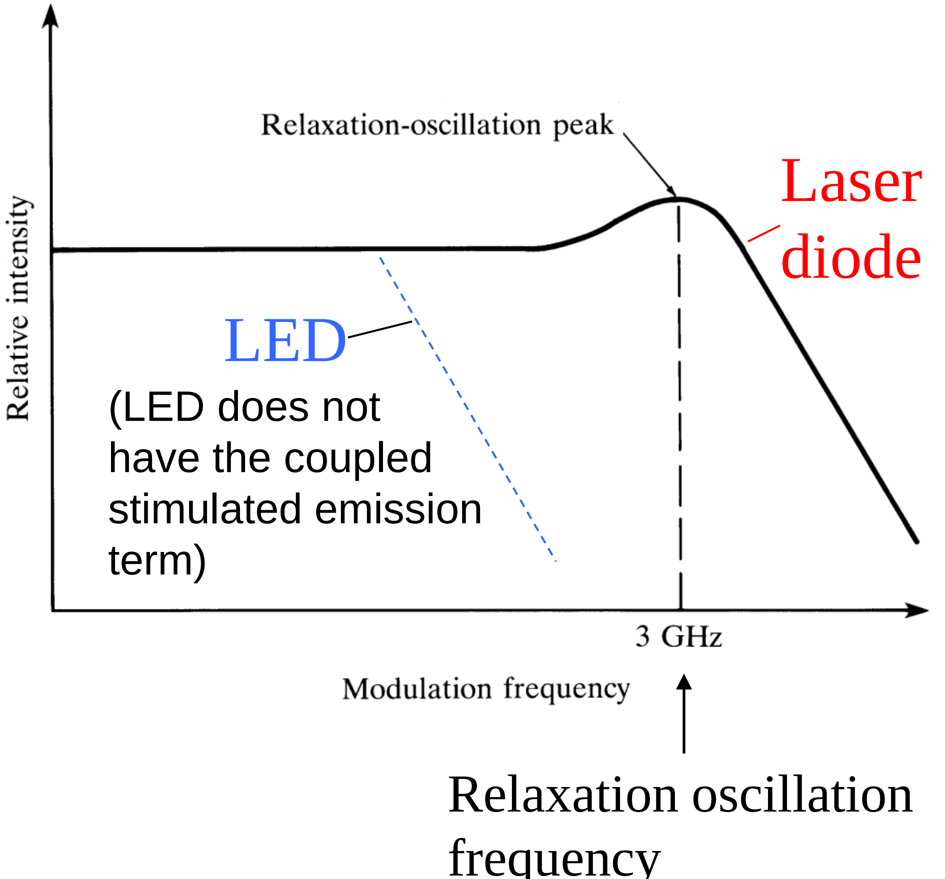
@ Relaxation frequency



1^{st} pulse power only (*highest average power*)

Small-signal modulation behavior





Relaxation oscillation $f \sim (1/2\pi)\,[1/(\tau_{sp}\,\tau_\gamma)^{1/2}]\,(i/i_{th} - 1)^{1/2}$

$(i\uparrow f\uparrow;\ \ \tau_\gamma\downarrow f\uparrow)$

For $\tau_{sp} \sim 1$ ns, $\tau_\gamma \sim 2$ ps for a 300 μm laser

$\Rightarrow$When the injection current ~ $2i_{th}$, the maximum modulation

frequency is a **few GHz**.

LED: $f_{3dB} \approx 1/2\pi\tau_{sp} \sim 100$ MHz

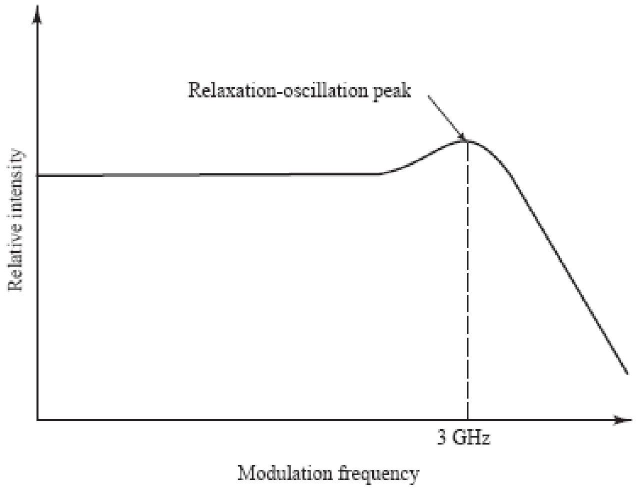
LD: relaxation oscillation $f \approx 1/2\pi(\tau_{sp}\tau_\chi)^{1/2} \sim$ GHz

*For *beyond GHz* modulation, we use <u>external modulation</u>.

Modulation of Laser Diodes

- **For data rates of less than approximately 10 Gb/s (typically 2.5 Gb/s), the process of imposing information on a laser-emitted light stream can be realized by *direct modulation*.**
- **The modulation frequency can be no larger than the frequency of the relaxation oscillations of the laser field**
- **The relaxation oscillation occurs at approximately**

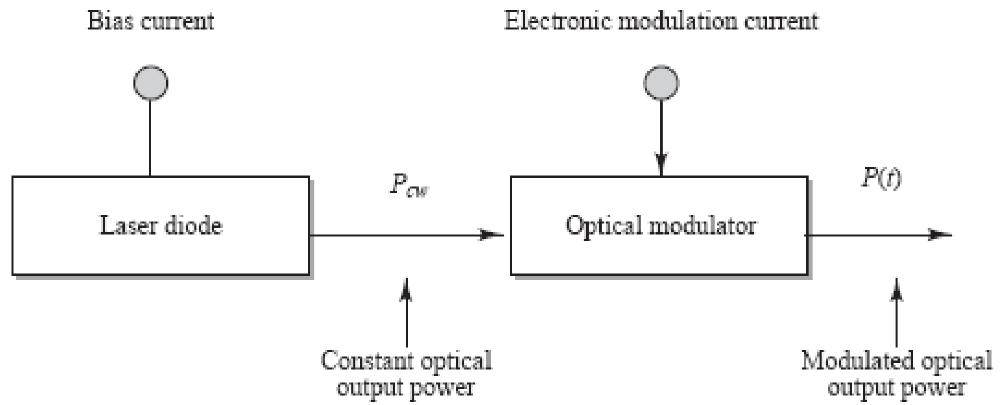
$$f = \frac{1}{2\pi}\frac{1}{(\tau_{sp}\tau_{ph})^{1/2}}\left(\frac{I}{I_{th}} - 1\right)^{1/2}$$

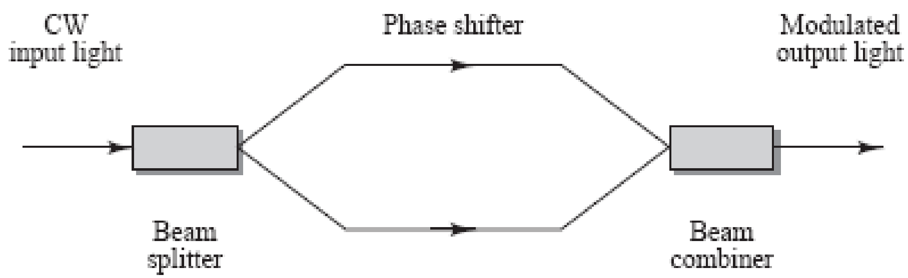


External Modulation

When direct modulation is used in a laser transmitter, the process of turning the laser on and off with an electrical drive current produces a widening of the laser linewidth referred to as *chirp*

The optical source injects a constant-amplitude light signal into an external modulator. The electrical driving signal changes the optical power that exits the external modulator. This produces a time-varying optical signal.





The electro-optical (EO) phase modulator (also called a Mach-Zehnder Modulator or MZM) typically is made of $LiNbO_3$.

Operational concept of an electro-optical lithium niobate external modulator

Spatial characteristics

- Like other lasers, oscillation in laser diodes takes the form of *transverse* and *longitudinal* modes.

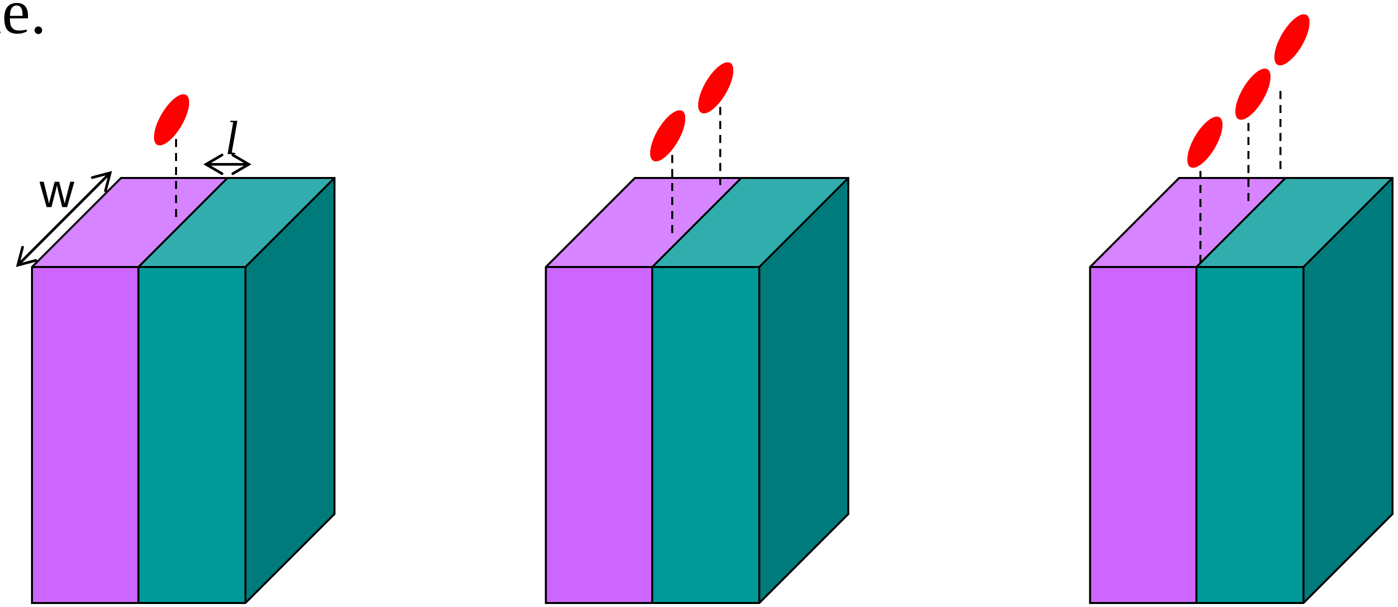
- The *transverse modes* are modes of the *dielectric waveguide* created by the different layers of the laser diode. Recall that the spatial distributions in the transverse direction can be described by the integer mode indexes (p, q).

- The transverse modes can be determined by using the waveguide theory for an optical waveguide with rectangular cross section of dimensions *l* and w.

- If l/λ_o is sufficiently small, the waveguide admits only a single mode in the transverse direction *perpendicular* to the junction plane.

• However, w is usually larger than λ_o => the waveguide will support several modes in the direction *parallel* to the plane of the junction.

• Modes in the direction *parallel* to the junction plane are called ***lateral modes***. The larger the ratio w/λ_o, the greater the number of lateral modes possible.



• Optical-intensity (*near-field*) spatial distributions for the laser waveguide modes (p, q) = (transverse, lateral) = (1, 1), (1, 2) and (1, 3)

Eliminating higher-order lateral modes

- *Higher-order lateral* modes have a *wider spatial spread*, thus less confined and has α_r that is greater than that for lower-order modes.

⇒some of the highest-order modes fail to oscillate; others oscillate at a lower power than the fundamental (lowest-order) mode.

- To achieve *high-power single-spatial-mode* operation, the number of waveguide modes must be reduced by decreasing the dimensions of the active-layer cross section (*l* and w)

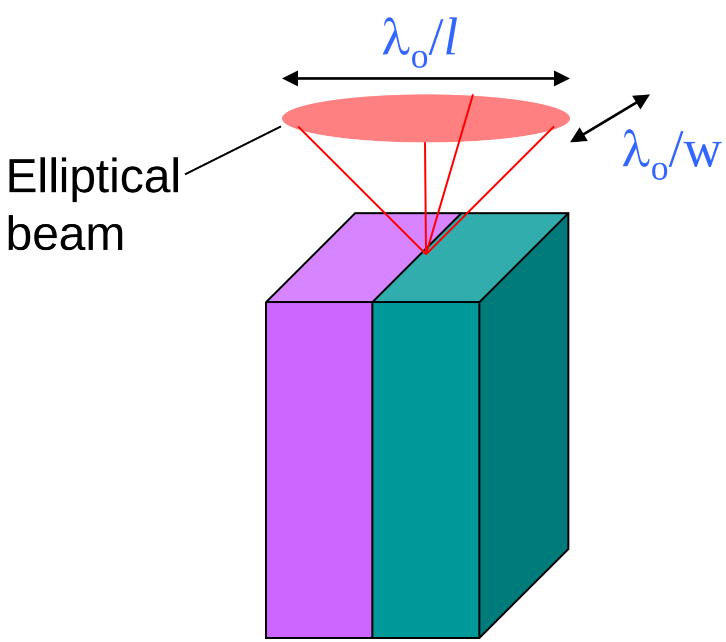
⇒a *single-mode waveguide*; reducing the junction area also *reduces the threshold current*.

- Higher-order lateral modes may be eliminated by making use of *gain-guided* or *index-guided* LD configurations.

Far-field radiation pattern

• A laser diode with an active layer of dimensions *l* and w emits coherent light with *far-field angular divergence* $\approx \lambda_o/l$ (radians) in the plane perpendicular to the junction and $\approx \lambda_o/w$ (radians) in the plane parallel to the junction. The angular divergence determines the *far-field radiation pattern*.

• Due to the small size of its active layer, the laser diode is characterized by an angular divergence larger than that of most other lasers.



e.g. for $l = 2\ \mu m$, $w = 10\ \mu m$, and $\lambda_o = 800$ nm, the divergence angles are $\approx 23^o$ and 5^o.

*The highly asymmetric *elliptical* distribution of laser-diode light can make collimating it tricky!

Spectral characteristics

- The spectral width of the semiconductor gain coefficient is relatively wide (~10 THz) because transitions occur between two energy bands.

- Simultaneous oscillations of *many* longitudinal modes in such homogeneously broadened medium is possible (by ***spatial hole burning***).

- The semiconductor resonator length d is significantly smaller than that of most other types of lasers.

$\Rightarrow$ The frequency spacing of adjacent resonator modes $\Delta\upsilon = c/2nd$ is therefore relatively large. Nevertheless, many such modes can still fit within the *broad bandwidth* B over which the *unsaturated* gain exceeds the loss.

=> The *number of possible laser modes* is $M \approx B/\Delta\upsilon$

e.g. Number of longitudinal modes in an InGaAsP laser diode

An InGaAsP crystal ($n = 3.5$) of length $d = 400\ \mu m$ has resonator modes spaced by

$$\Delta\upsilon = c/2nd \approx 107\ \text{GHz}$$

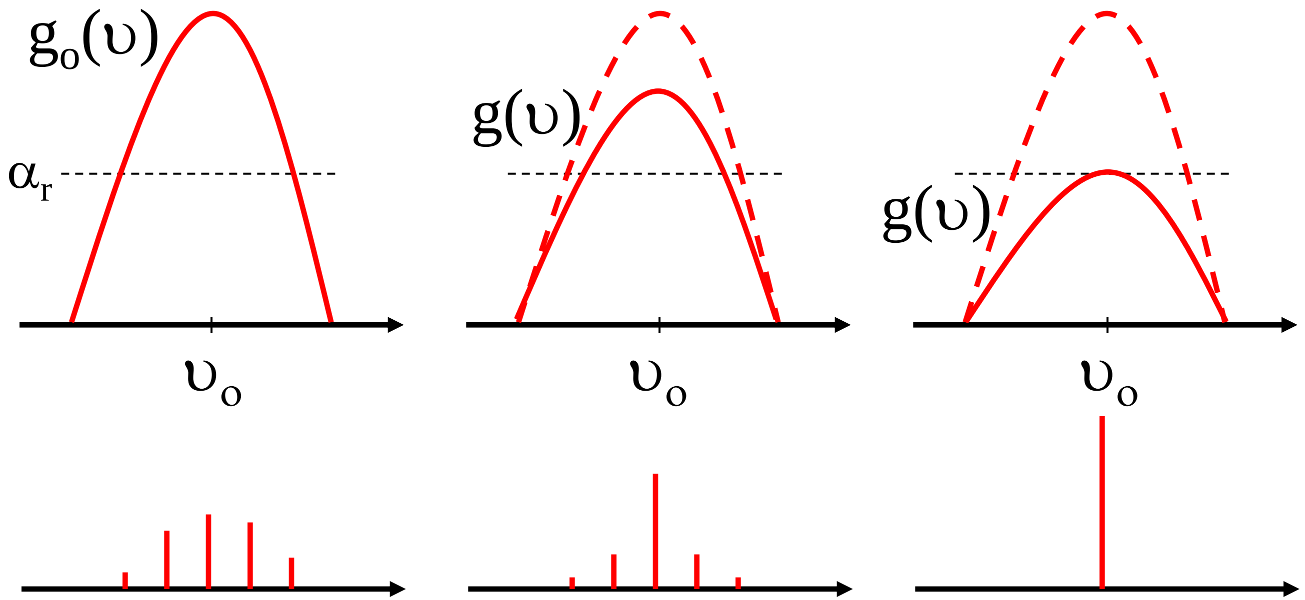
Near the central wavelength $\lambda_o = 1300$ nm, this frequency spacing corresponds to a free-space wavelength spacing

$$\Delta\lambda = \lambda_o^2/2nd \approx 0.6\ \text{nm}$$

If the spectral width $B = 1.2$ THz (a wavelength width $\Delta\lambda = 7$ nm), then approximately $B/\Delta\upsilon \approx 11$ longitudinal modes may oscillate.

*To obtain ***single-mode*** lasing, the resonator length d would have to be reduced so that $B \approx c/2nd$, requiring a cavity of length $d \approx 36\ \mu m$.
(*A shortened resonator length reduces the amplifier gain* $exp(g_p d)$.)

Growth of oscillation in an ideal homogeneously broadened medium



• *Immediately following laser turn-on*, all modal frequencies for which the gain coefficient exceeds the loss coefficient begin to grow, with the central modes growing at the highest rate. After a short time the gain *saturates* so that the central modes continue to grow while the peripheral modes, for which the loss has become greater than the gain, are attenuated and eventually vanish. *Only a single mode survives*.

Homogeneously broadened medium

- Immediately after being turned on, *all* laser modes for which the *initial* gain is greater than the loss begin to grow.

=> photon-flux densities $\phi_1, \phi_2, \ldots, \phi_M$ are created in the M modes.

- Modes whose frequencies lie closest to the gain peak frequency grow most quickly and acquire the highest photon-flux densities.

- These photons interact with the medium and *uniformly* deplete the gain across the gain profile by *depleting the population inversion*.

- The *saturated gain*:

$$g(\upsilon) = g_o(\upsilon)/[1 + \sum_{j=1}^{M} \phi_j/\phi_s(\upsilon_j)]$$

where $\phi_s(\upsilon_j)$ is the saturation photon-flux density associated with mode j.

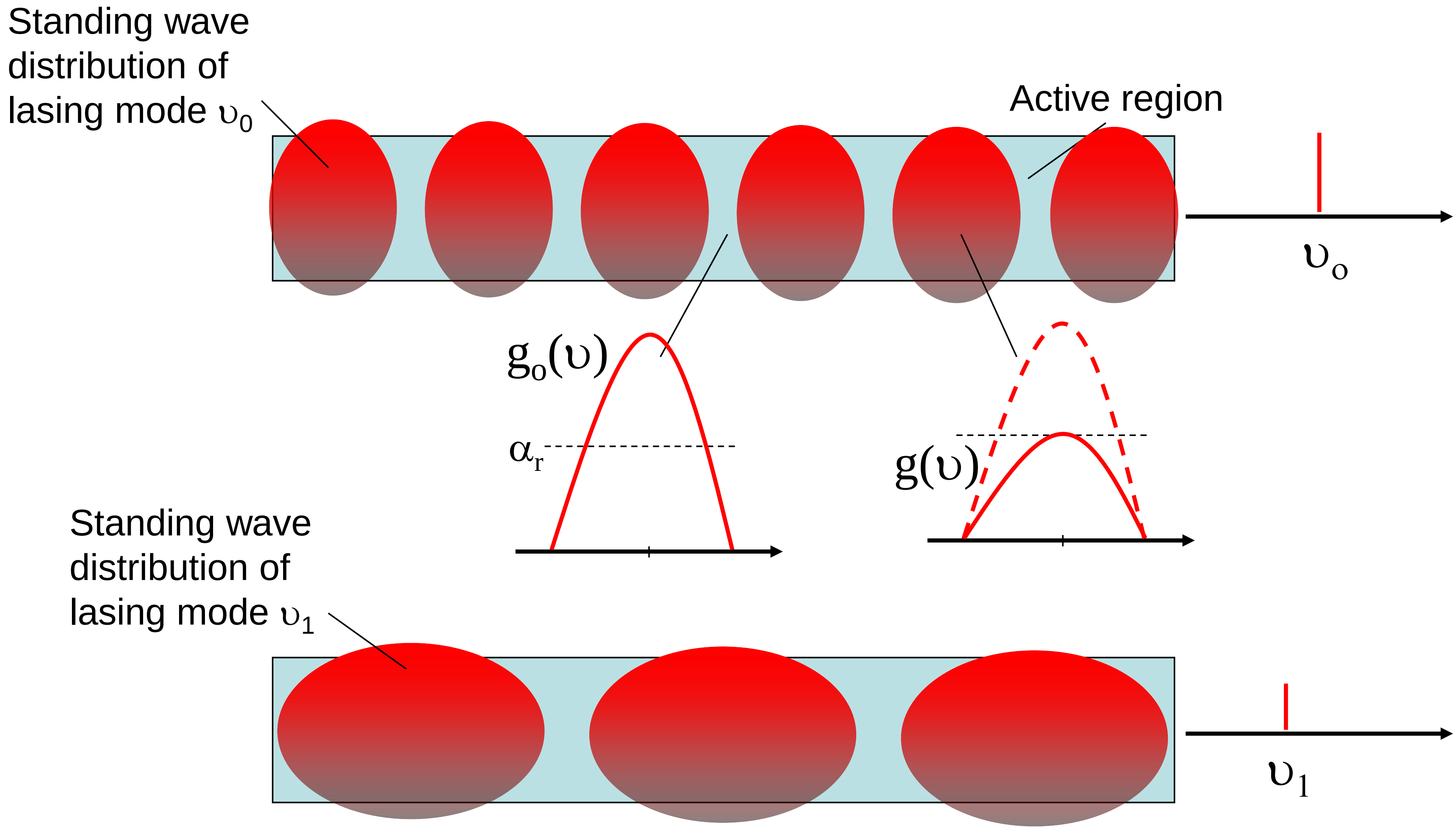
• Under *ideal* steady-state conditions, the surviving mode has the frequency lying *closest* to the gain peak and the power in this preferred mode remains stable, while laser oscillation at all other modes vanishes.

• *Semiconductors tend to be homogeneously broadened* as *intraband* scattering processes are very fast (~0.1 ps). [*So it does not matter which optical transitions (modes) deplete the gain, the carrier distribution within the band quickly, within ~0.1 ps, return to quasi-equilibrium, and the whole gain profile is uniformly depleted*.] => *Suggesting single-mode lasing*

• *In practice*, however, *homogeneously broadened lasers do indeed oscillate on multiple modes* because the *different modes occupy different spatial portions of the active medium*.

=> *When oscillation on the most central mode is established, the gain coefficient can still exceed the loss coefficient at those locations where the standing-wave electric field of the most central mode vanishes*.

Spatial hole burning



Spatial hole burning

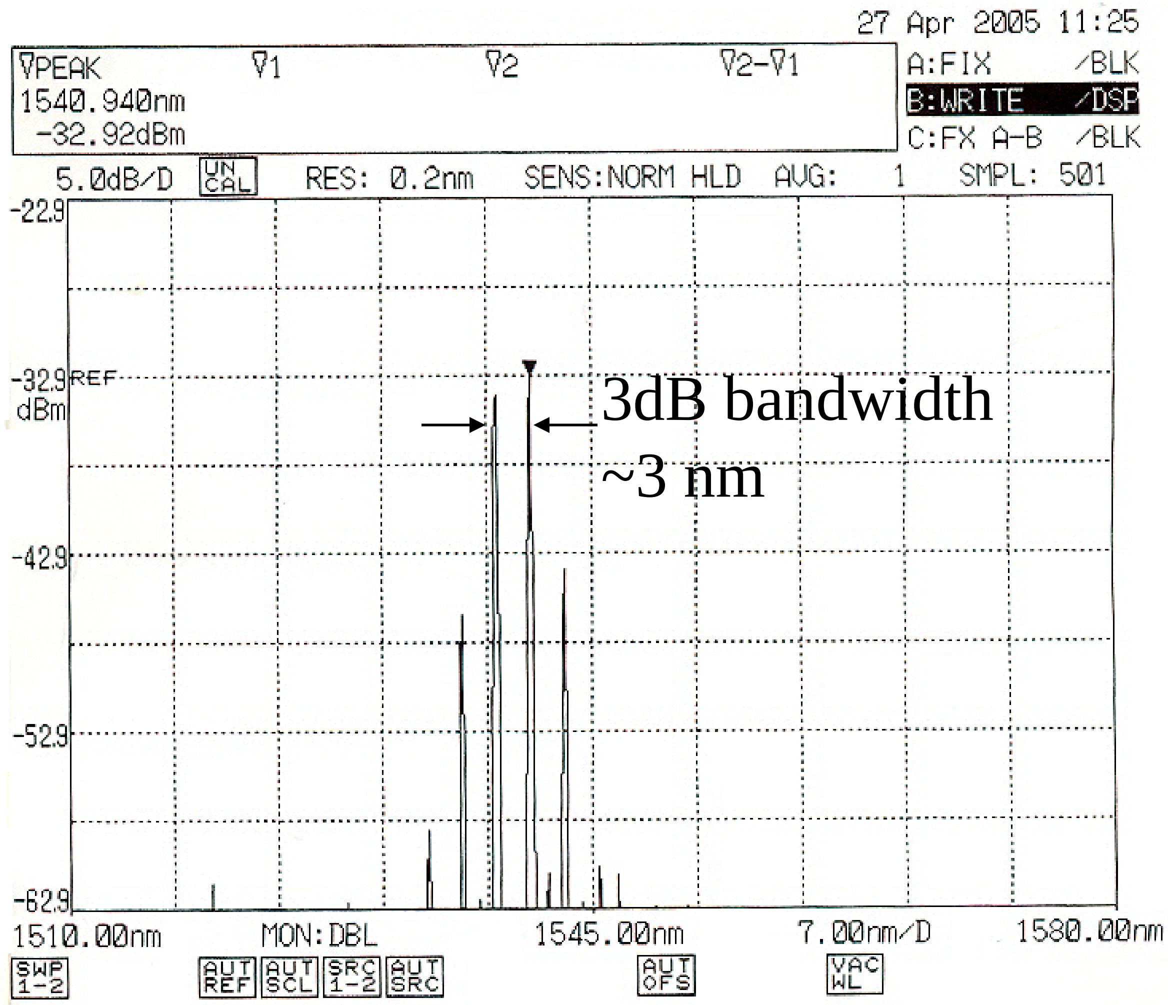
• This phenomenon is known as ***spatial hole burning***. It allows another mode, whose peak fields are located near the energy nulls of the central mode, the opportunity to lase.

⇒permits the *simultaneous oscillation of many longitudinal modes* in a *homogeneously broadened* medium such as a semiconductor.

• Spatial hole burning is particularly prevalent in *short* cavities in which there are *few* standing-wave cycles.

=>permits the fields of different longitudinal modes, which are distributed along the resonator axis, *to overlap less*, thereby allowing *partial spatial hole burning* to occur.

Measured multimode laser spectrum (ELEC 4620 1550 nm laser diode)



(AlGaAs laser diode from Lab 6)

ML725B8F

MITSUBISHI LASER DIODES

DESCRIPTION

ML725B8F is a AlGaAs laser diode which provides a stable, single transverse mode oscillation with emission wavelength of 1310nm and standard continuous light output of 10mW.

ML725B8F is a hermetically sealed device having the photodiode for optical output monitoring.

FEATURES

- Low threshold and operating current
- Built-in monitor photodiode
- MQW* active layer
- High reliability, long operating life

*Multiple Quantum Well

APPLICATION

Laser beam printing, digital copy

ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Conditions	Ratings	Unit
Po	Light output power	-	10	mW
VRL	Reverse voltage (Laser Diode)	-	2	V
VRD	Reverse voltage (Photodiode)	-	20	V
IFD	Forward current (Photodiode)	-	2	mA
Tc	Case temperature	-	-40~+85	°C
Tstg	Storage temperature	-	-40~+100	°C

ELECTRICAL/OPTICAL CHARACTERISTICS (Tc=25°C)

Symbol	Parameter	Test Conditions	Limits			Unit
			Min.	Typ.	Max.	
Ith	Threshold current	CW	-	5	15	mA
Iop	Operating current	CW, Po=5mW	-	20	35	mA
Vop	Operating voltage	CW, Po=5mW	-	1.1	1.5	V
η	Slope efficiency	CW, Po=5mW	0.3	0.5	-	mW/mA
λ c	Center wavelength	CW, Po=5mW	1290	1310	1330	nm
θ //	Beam divergence angle (parallel)	CW, Po=5mW	-	25	-	deg.
θ ⊥	Beam divergence angle (perpendicular)	CW, Po=5mW	-	30	-	deg.
Im	Monitoring output current (Photodiode)	CW, Po=5mW, VRD=1V	0.1	0.5	-	mA
ID	Dark current (Photodiode)	VRD=10V	-	0.01	0.1	μA
Ct	Capacitance (Photodiode)	VRD=10V, f-1MHz	-	10	20	pF

AlGaAs laser diode specifications (lab 6)

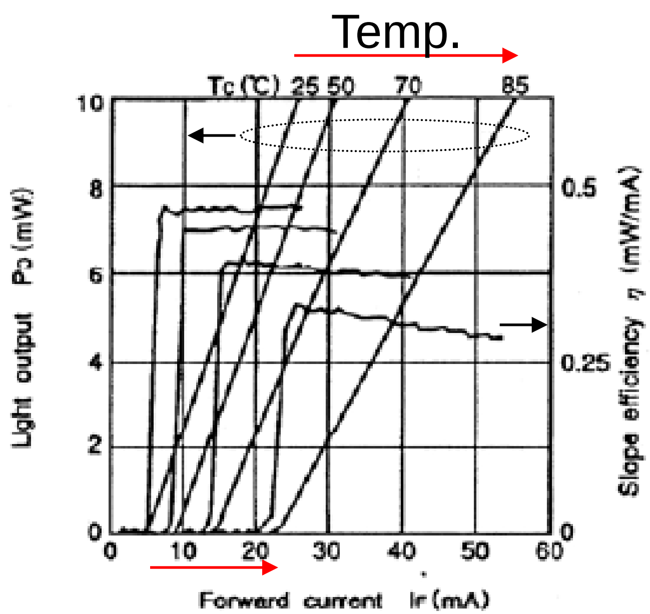


Fig.1 Light output vs. forward current

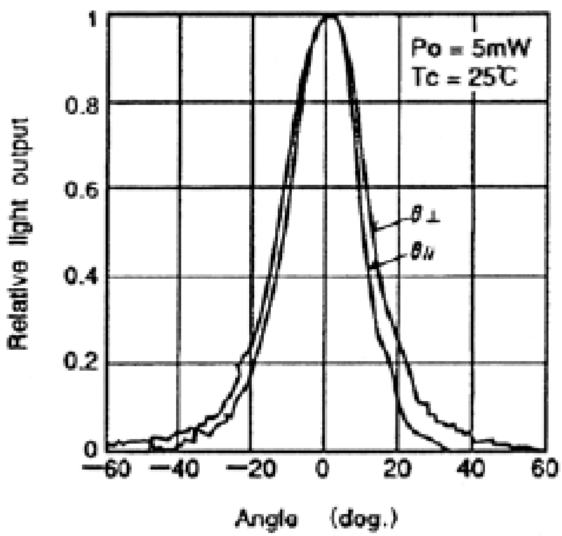


Fig.3 Far field pattern

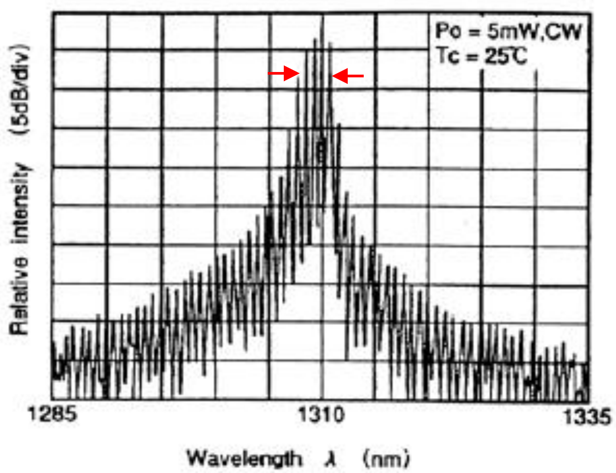


Fig.52 Spectrum

- ~4 nm linewidth
- multimode lasing

(InGaAsP laser diodes from Lab 6)

DESCRIPTION

ML9XX6 series are InGaAsP laser diodes which provides a stable, single transverse mode oscillation with emission wavelength of 1550nm and standard continuous light output of 5mW.

ML9XX6 are hermetically sealed devices having the photodiode for optical output monitoring. This high-performance, high reliability, and long-life laser diode is suitable for such applications as the light sources for long-distance optical communication systems.

FEATURES

- 1550nm typical emission wavelength
- Low threshold current, low operating current
- Wide temperature range operation (Tc = −40 to +85℃)
- High reliability, long operation life
- MQW* active layer

* : Multiple Quantum Well

APPLICATION

Long-distance optical communication system

ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Conditions	Ratings	Unit
P_O	Light output power	CW	6	mW
V_{RL}	Reverse Voltage (Laser diode)	—	2	V
V_{RD}	Reverse Voltage (Photodiode)	—	20	V
I_{FD}	Forward current (Photodiode)	—	2	mA
T_C	Case temperature	—	−40～+85	℃
T_{stg}	Storage temperature	—	−40～+100	℃

ELECTRICAL/OPTICAL CHARACTERISTICS (Tc = 25℃)

Symbol	Parameter	Test conditions	Limits			Unit
			Min.	Typ.	Max.	
I_{th}	Threshold current	CW	—	10	20	mA
I_{OP}	Operating current	CW,Po = 5mW	—	30	50	mA
V_{OP}	Operating voltage	CW,Po = 5mW	—	1.1	1.5	V
η	Slope efficiency	CW,Po = 5mW	0.15	0.25	—	mW/mA
λ_c	Peak wavelength	CW,Po = 5mW	1520	1550	1580	nm
$\Delta\lambda$	Spectral width (RMS)	CW,Po = 5mW	—	1.5	3	nm
$\theta_{//}$	Beam divergence angle (parallel)	CW,Po = 5mW	—	25	—	deg.
$\theta_{\perp}$	Beam divergence angle (perpendicular)	CW,Po = 5mW	—	30	—	deg.
t_r,t_f	Rise and fall times	I_F = I_{th},Po = 5mW,10～90%	—	0.3	0.7	ns
I_m	Monitoring output current (Photodiode)	CW,Po = 5mW,V_{RD} = 1V	0.1	0.5	—	mA
I_D	Dark current (Photodiode)	V_{RD} = 10V	—	0.01	0.1	μA
C_t	Capacitance (Photodiode)	V_{RD} = 10V,f = 1MHz	—	10	20	pF

InGaAsP Fabry-Perot laser diodes (lab 6)

TYPICAL CHARACTERISTICS

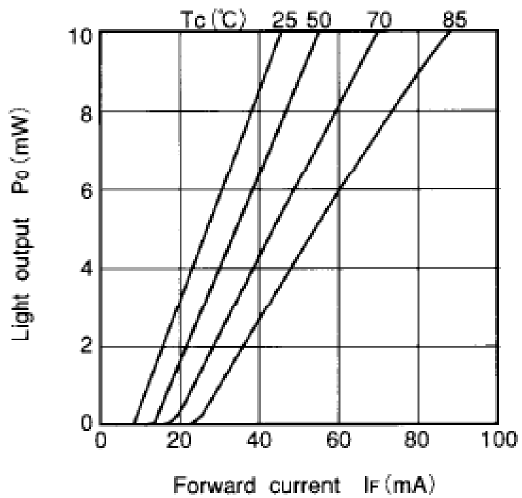


Fig.1 Light output vs. forward current

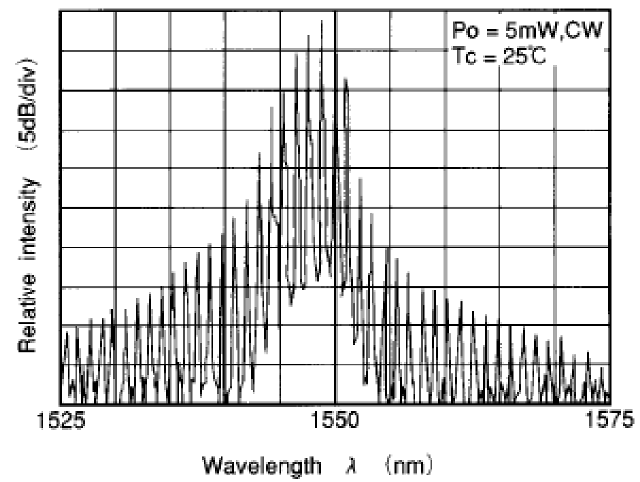


Fig.2 Spectrum

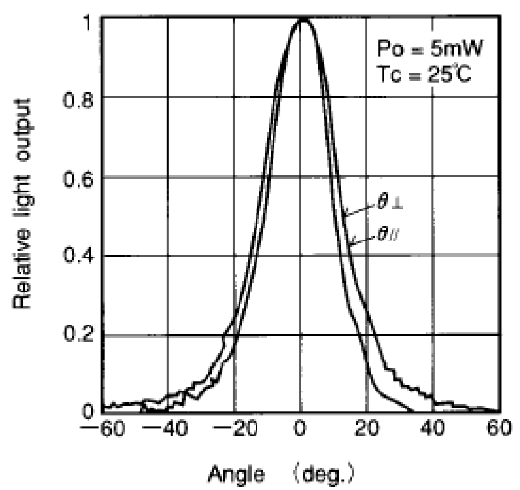


Fig.3 Far field patterns

Single-mode laser diodes

- Essential for **Dense-Wavelength-Division Multiplexing** (DWDM) technology – channel spacing is only 50 GHz in the 1550 nm window (i.e. <u>0.4 nm</u> channel spacing or 64 channels within ~ 30 nm bandwidth of the C-band)

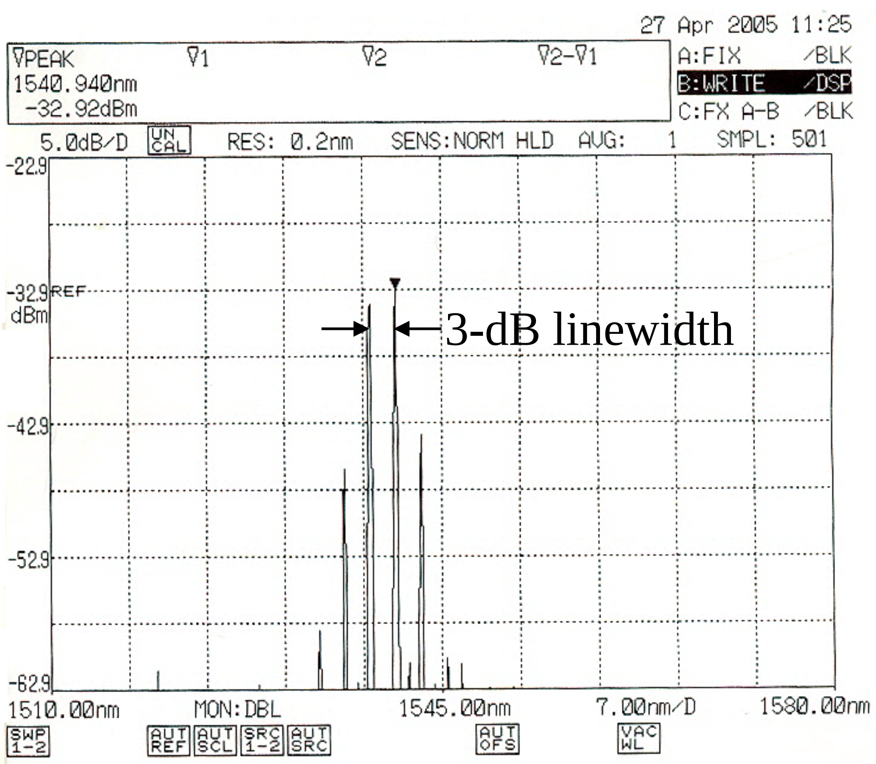
- *Single-mode* laser diodes: eliminate all but <u>one</u> of the longitudinal modes

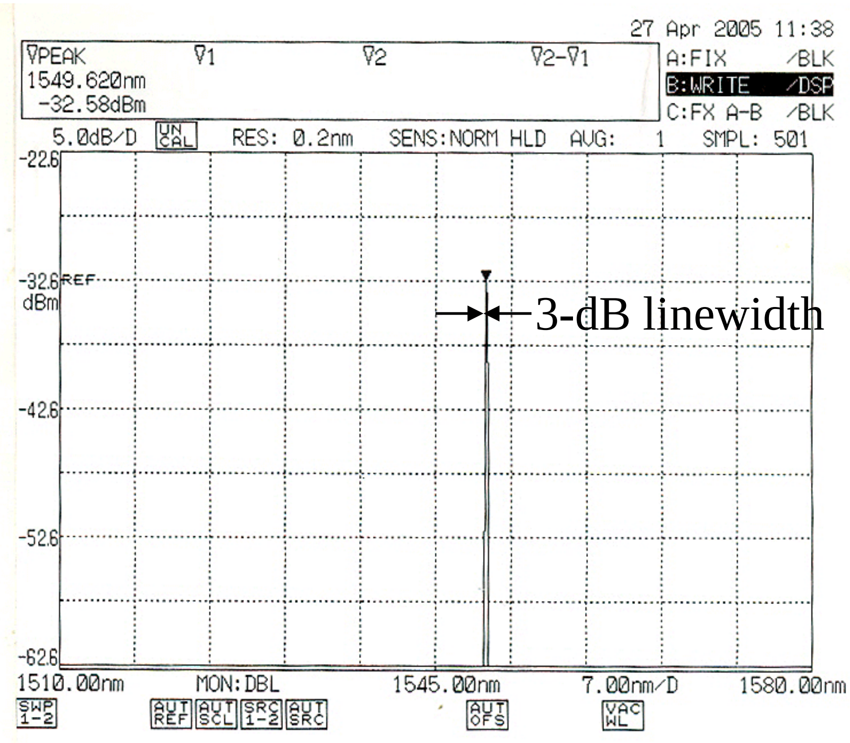
- Recall the *longitudinal mode spacing*: $\Delta\lambda = \lambda^2 / (n\ 2d)$

$\Delta\lambda$ > the gain bandwidth => *only* the single mode within the gain bandwidth lases

But this either imposes <u>very narrow gain bandwidth</u> or <u>very small diode size</u> !

Measured multimode laser spectrum vs. singlemode laser spectrum





Cost: ~HKD2,000

Cost: ~HKD20,000 (for fixed wavelength)

Cost: ~HKD200,000 (for wavelength tunable)

Single longitudinal modes

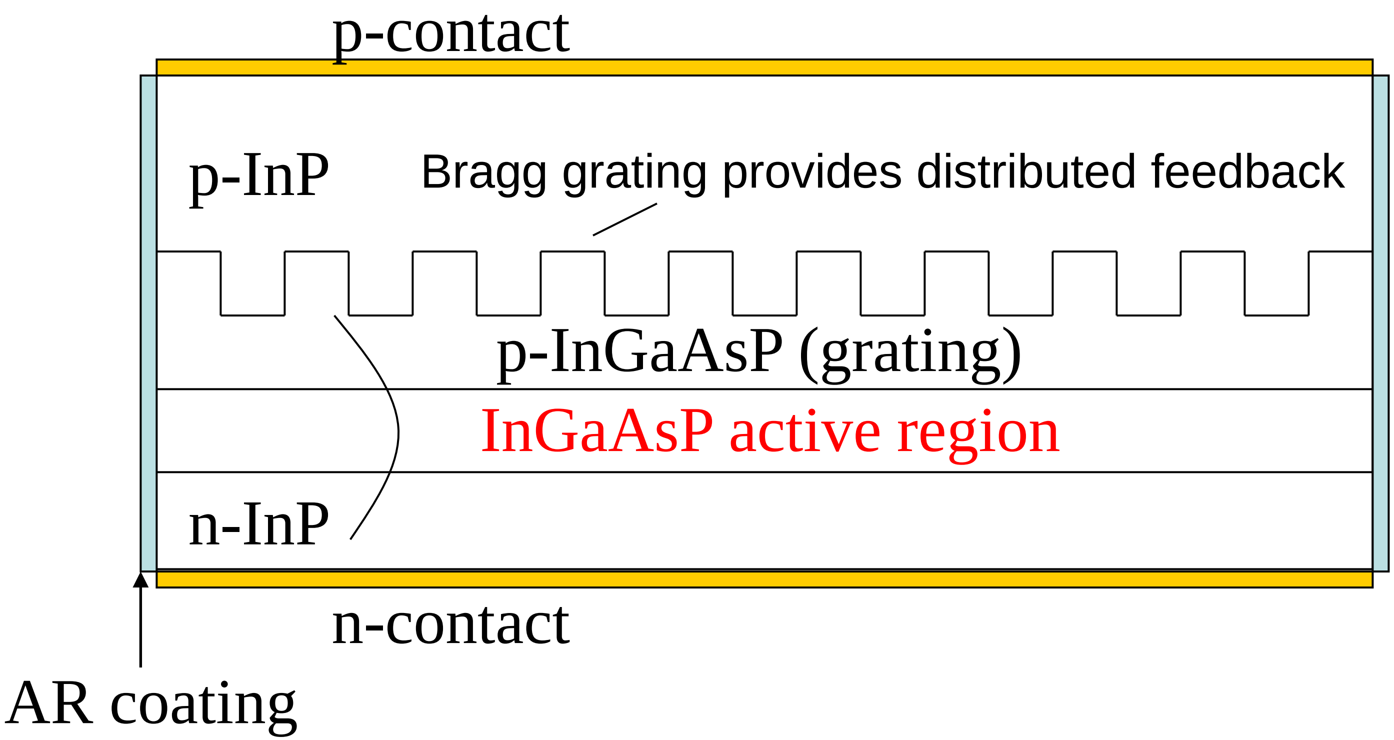
- Operation on a *single longitudinal mode*, which produces a single-frequency output, may be achieved by *reducing the length d of the resonator* so that the frequency spacing between adjacent longitudinal modes exceeds the spectral width of the amplifying medium.

- Better approach for attaining single-frequency operation involves the use of *distributed reflectors* (Bragg gratings) in place of the cleaved crystal surfaces that serve as lumped mirrors in the Fabry-Perot configuration. When distributed feedback is provided, the surfaces of the crystal are *antireflection (AR) coated* to minimize reflections.

e.g. *Bragg gratings* as frequency-selective reflectors can be placed in the plane of the junction (***Distributed Feedback lasers***) or outside the active region (***Distributed Bragg Reflector lasers, Vertical Cavity Surface Emitting Lasers***).

Distributed-feedback (DFB) laser diodes

- The most popular techniques for WDM



The fabricated Bragg grating selectively reflects *only* <u>one</u> wavelength.

The grating in DFB lasers

- The laser has a corrugated structure etched internally just above (or below) the active region.

- The *corrugation forms an optical grating* that selectively reflects light according to its wavelength.

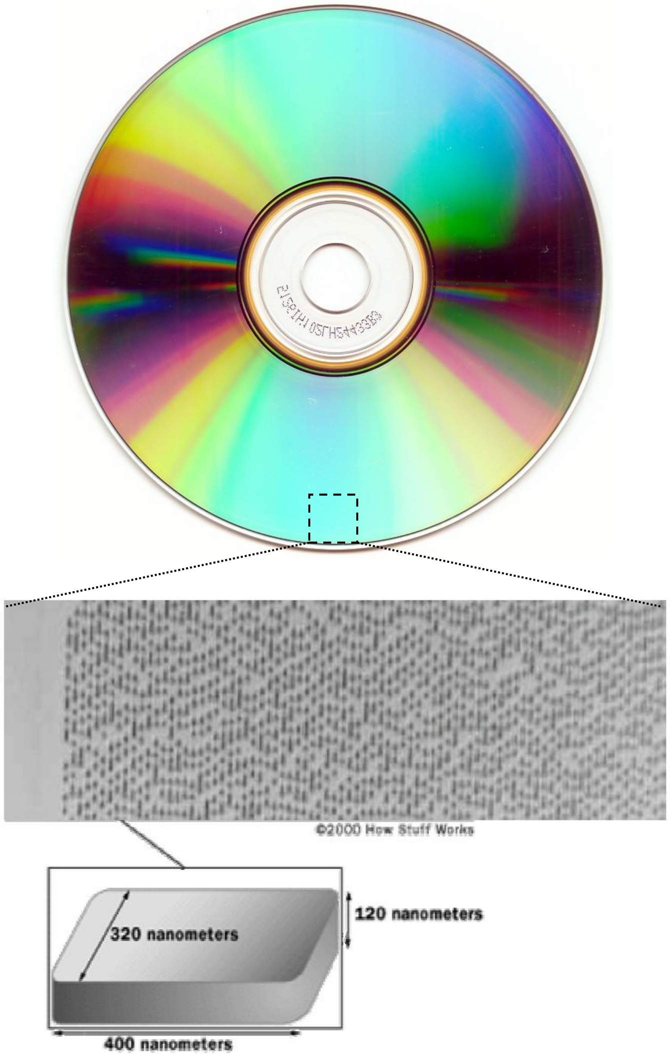
- This grating acts as a *distributed filter*, *allowing only one of the cavity longitudinal modes to propagate back and forth*.

- The *grating interacts directly with the evanescent mode* in the space just above (or below) the active layer.

- The grating is *not placed in the active layer*, because etching in this region could introduce defects that would lower the efficiency of the laser, resulting in a higher threshold current.

Bragg grating in a CD/DVD

- The most common demonstration of Bragg diffraction is the spectrum of colors seen reflected from a compact disc: the closely-spaced tracks on the surface of the disc form a diffraction grating, and the individual wavelengths of white light are diffracted at different angles from it, in accordance with Bragg's law.



120 nm deep pits by injection molding

(extracted from HKUST MSc Photonics EESM510 notes)

Bragg diffraction in nature

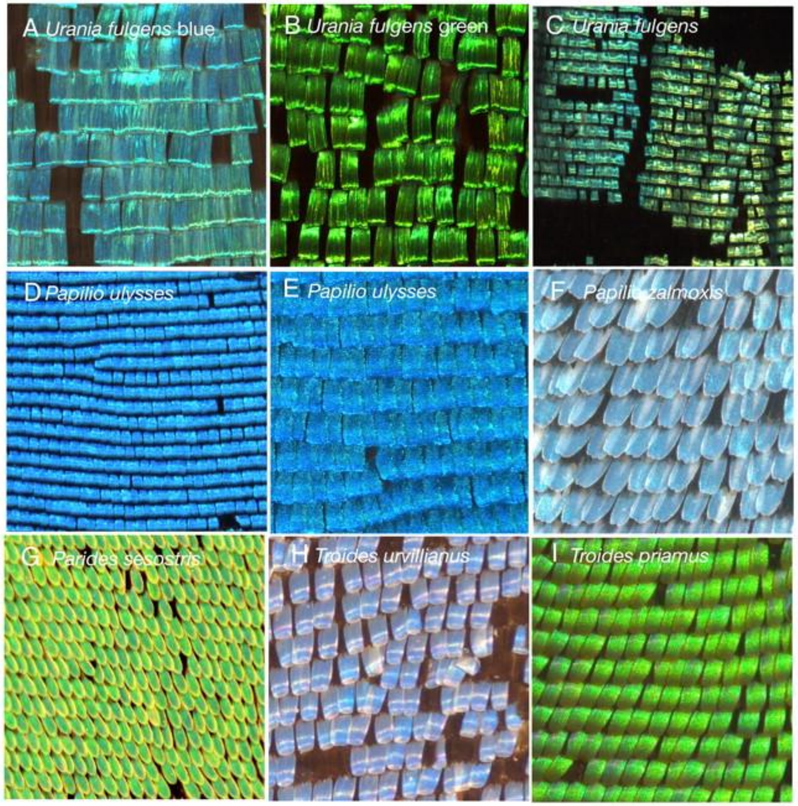
- The structural colors of butterflies (or beetles) are produced by periodic nanostructures of chitin and air in the scales of the wings.
- The wing scales are arranged in a series of rows like shingles on a house
- The structural colors of butterflies and moths have been attributed to a diversity of physical mechanisms, including multilayer interference, diffraction, Bragg scattering, Tyndall scattering and Rayleigh scattering.

(extracted from HKUST MSc Photonics EESM510 notes)

Bragg diffraction in nature

- The structural colors of butterflies are produced by periodic nanostructures of chitin and air in the scales of the wings.
- The wing scales are arranged in a series of rows like shingles on a house
- The structural colors of butterflies and moths have been attributed to a diversity of physical mechanisms, including multilayer interference, **diffraction, Bragg scattering**, Tyndall scattering and Rayleigh scattering.

Light microscope photographs of the structurally colored scales



(extracted from HKUST MSc Photonics EESM510 notes)

Bragg condition

- The operating wavelength is determined from the ***Bragg condition***

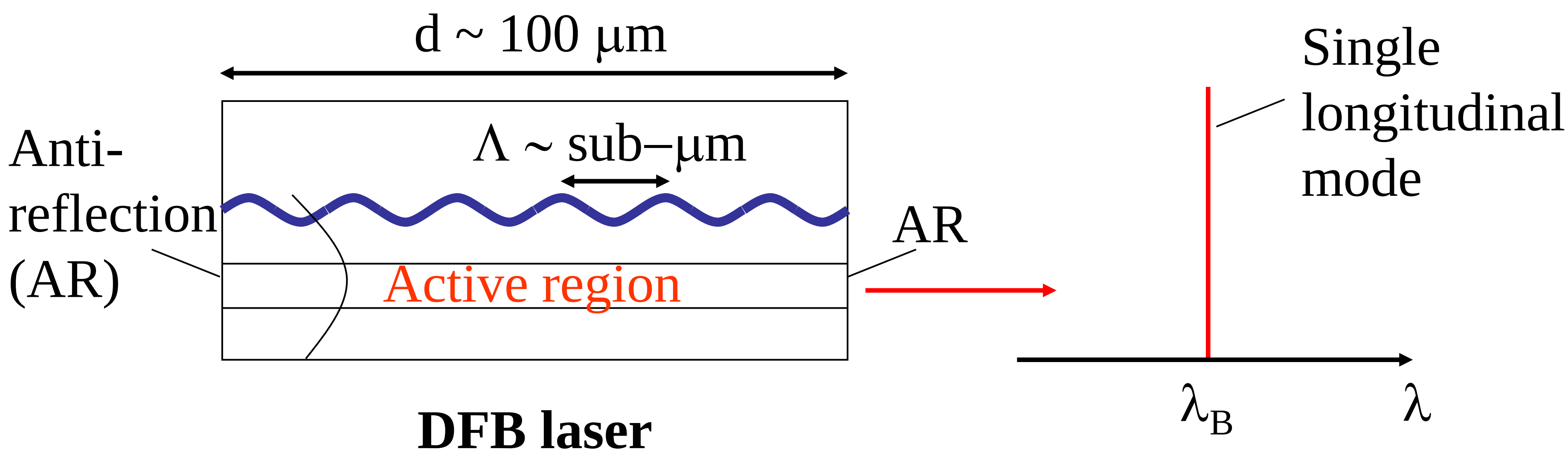
$$\Lambda = m\,(\lambda_o/2n_{eff})$$

Λ is the grating period, λ_o/n_{eff} is the wavelength as measured in the diode as a waveguide, and m is the integer order of the Bragg diffraction. (usually m = 1)

n_{eff} is the *effective refractive index* of the lasing mode in the active layer --- n_{eff} lies somewhere between the index of the guiding layer (the active region of the diode) and that of the cladding layers

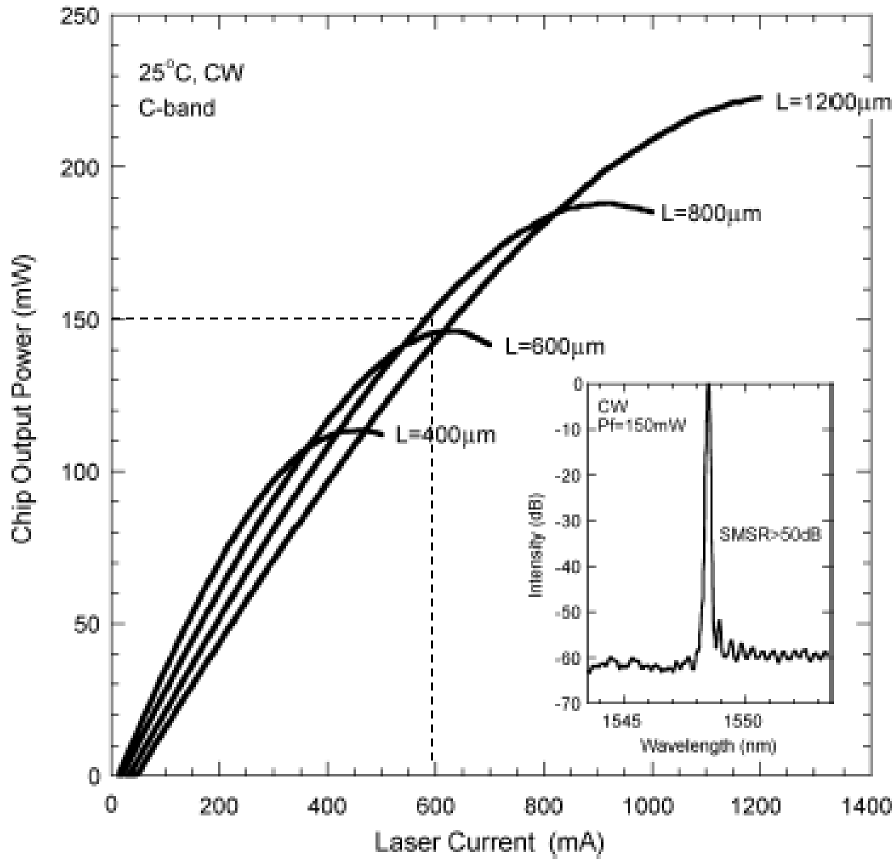
For double-heterostructures, the active region is the higher index narrow-bandgap region (say n ~ 3.5), and the cladding region is the lower-index wide-bandgap region (say n ~ 3.2).

DFB laser radiates only one wavelength λ_B – a single longitudinal mode



For an InGaAsP DFB laser operating at λ_B = 1.55 μm, Λ is about 220 nm if we use the *first*-order Bragg diffraction (m = 1) and n_{eff} ~ 3.2 – 3.5.

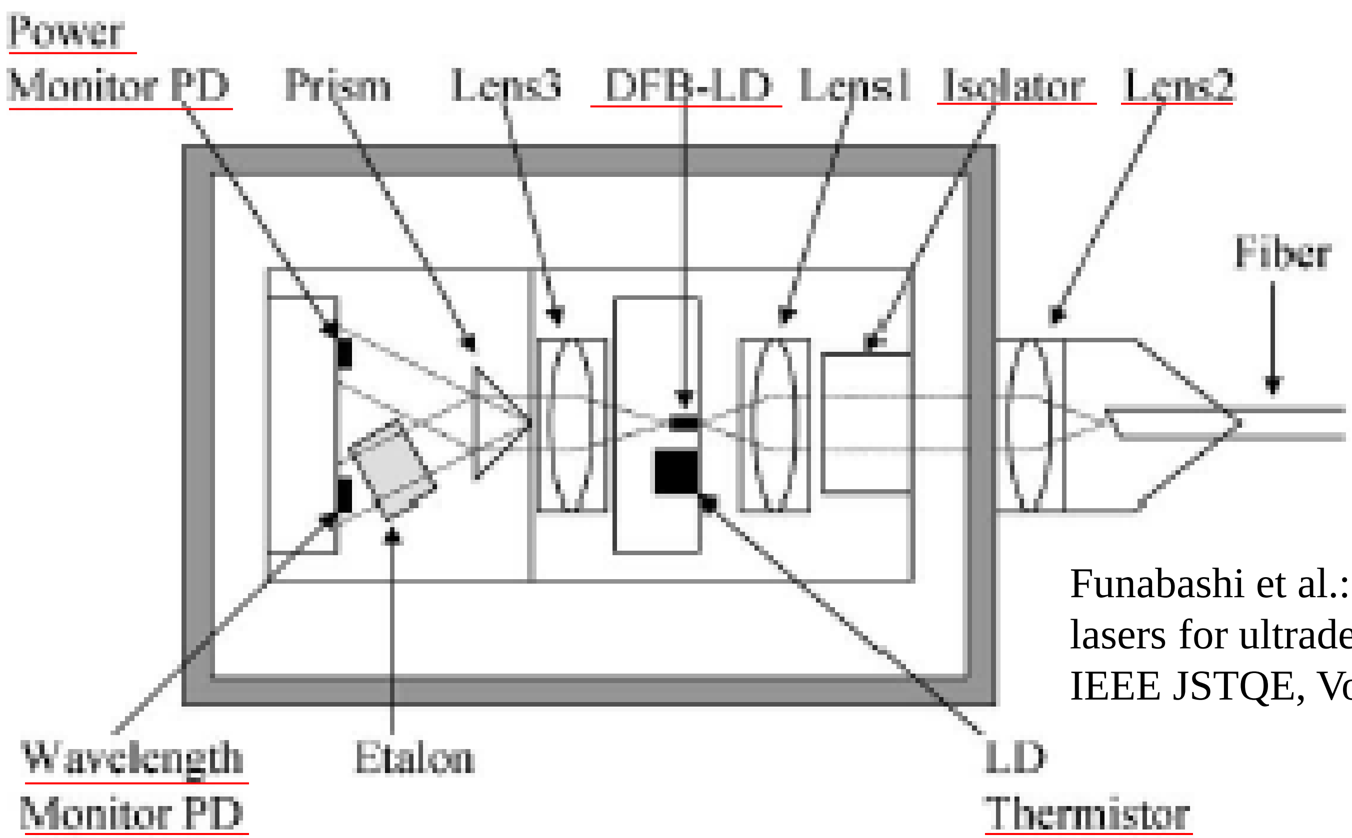
Power-current characteristics of DFB laser diodes



Funabashi et al.: Recent advances in DFB lasers for ultradense WDM applications, IEEE JSTQE, Vol. 10, March/April 2004

Different cavity lengths of 400, 600, 800, and 1200 μm. The inset shows the singlemode laser spectrum from a packaged 800-μm long DFB laser at a fiber-coupled power of 150 mW @ 600 mA.

DFB laser module



Funabashi et al.: Recent advances in DFB lasers for ultradense WDM applications, IEEE JSTQE, Vol. 10, March/April 2004

Fig. 4. Schematic of the DFB laser module with wavelength monitor function integrated in the standard 14-pin butterfly package.

DFB lasers characteristics

- **Narrow linewidths** (typically 0.1 – 0.2 nm), attractive for long-haul high-bandwidth transmission.

- **Less temperature dependence** than most conventional laser diodes

The grating tends to stabilize the output wavelength, which varies with temperature changes in the refractive index. $\Lambda\, n_{eff} = m\, \lambda_o/2$

Typical temperature-induced wavelength shifts are just under 0.1 nm/^{o}C, a performance 3-5 times better than that of conventional laser diodes.

Vertical-cavity surface-emitting laser diodes

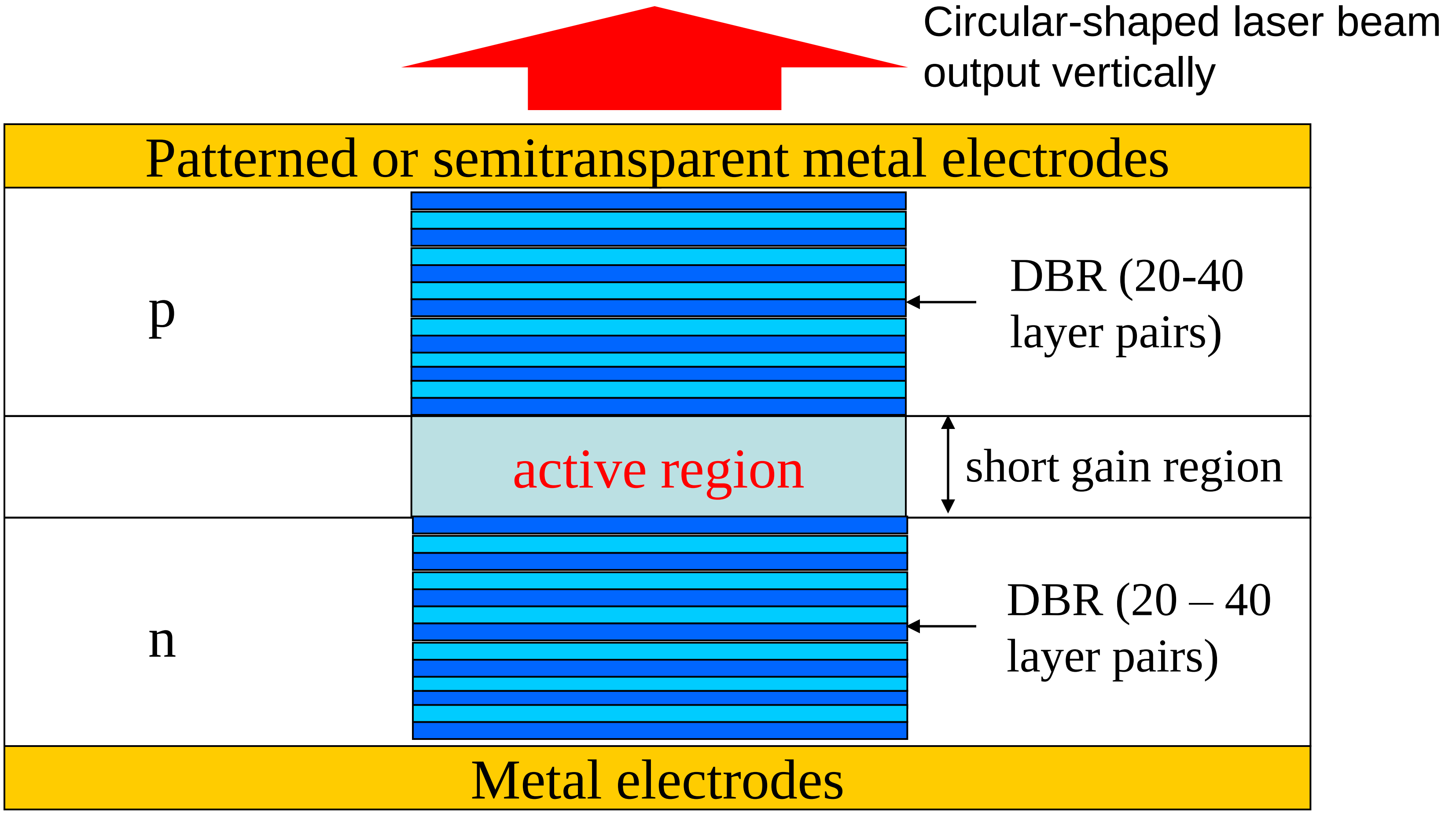
- The vertical-cavity surface-emitting laser (VCSEL) was developed in the 1990s, several decades after the edge-emitting laser diode.

- This diode emits from its surface rather than from its side. The lasing is *perpendicular* to the plane defined by the active layer.

- Instead of cleaved facets, the optical feedback is provided by Bragg reflectors (or distributed Bragg reflectors DBRs) consisting of layers with alternating high and low refractive indices.

- Because of the *very short cavity length* (thereby a short gain medium), very high ($\geq$ 99%) reflectivity are required, so the reflectors typically have 20 to 40 layer pairs.

VCSEL schematic



*The upper DBR is partially transmissive at the laser-output wavelength.

VCSEL merits

- ***Due to the short cavity length***, the longitudinal-mode spacing is large compared with the width of the gain curve.
- *If the resonant wavelength is close to the gain peak*, single-longitudinal-mode operation occurs without the need for any additional wavelength selectivity.
- VCSELs have short cavity lengths, which tend to decrease response times (i.e. *short photon cavity lifetimes* τ_γ). The result is that VCSELs can be modulated at *very high speeds*. (*e.g. 850 nm VCSELs can be operated at well above 10 Gb/s*.)
- The beam pattern is circular, the spot size can be made compatible with that of a single-mode fiber, making the coupling from laser to fiber more efficient (*compared with the elliptical beam from an edge-emitting diode laser*).

VCSEL applications

• VCSELs operating in the *visible* spectrum are appropriate as sources for plastic optical fiber (e.g. for automotive) systems.

• VCSELs are often selected as sources for *short-reach datacom* (LAN) networks operating at 850 nm. Applications include the high-speed Gigabit Ethernet.

• Longer-wavelength VCSELs (emitting in the 1300 and 1550 nm wavelengths) can be considered for high-capacity point-to-point fiber systems.

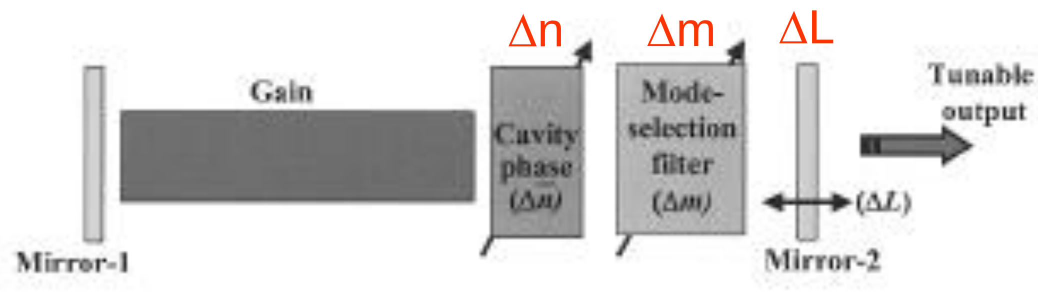
• Because of the geometry, *monolithic (grown on the same substrate) two-dimensional laser-diode arrays can be formed*. Such arrays can be useful in fiber optic-network interconnects and possibly in other communication applications.

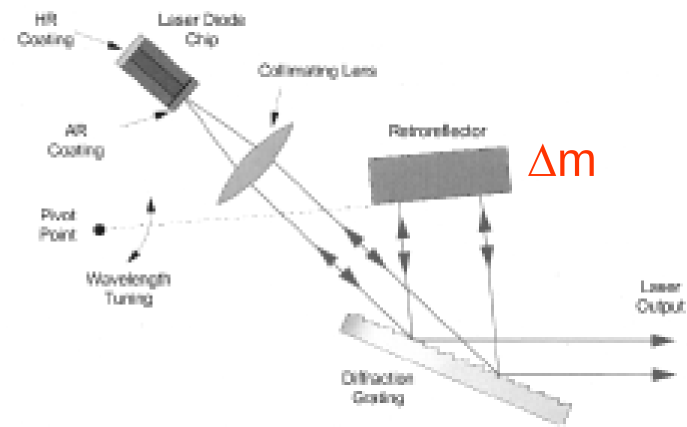
Wavelength tunable laser diodes

- Sources that are precisely tunable to operate at specific wavelengths (e.g. in WDM systems, where wavelengths are spaced by fractions of a nm) --- a wavelength tunable laser diode can serve multiple WDM channels and potentially save cost, think using 64 fixed-wavelength diodes vs. a few wavelength-tunable laser diodes!

- A DFB laser diode can be tuned by changing the temperature or by changing its drive current.
- The output wavelength shifts a few tenths of a nanometer per degree Celsius because of the dependence of the material refractive index on temperature.
- The larger the drive current, the larger the *heating* of the device. Tuning is on the order of 10^{-2} nm/mA. e.g. a change of 10 mA produces a variation in wavelength of only 0.1 nm (less than WDM channel spacing).

Wavelength tunable semiconductor lasers





<u>External-cavity tunable laser</u>

$$m\lambda = 2nL$$

$$\Rightarrow \ \Delta\lambda/\lambda = \Delta n/n + \Delta L/L - \Delta m/m$$

Larry A. Coldren et al., Tunable semiconductor lasers: a tutorial, Journal of Lightwave Technology, Vol. 22, pp. 193 – 202, Jan. 2004

Key mechanisms for semiconductor laser wavelength tuning

- By differential analysis

$$m\lambda = 2nL$$

$$\Delta m \bullet \lambda + m \bullet \Delta\lambda = 2\Delta n \bullet L + 2n \bullet \Delta L$$

$$(\Delta m \bullet \lambda + m \bullet \Delta\lambda)/m\lambda = (2\Delta n \bullet L + 2n \bullet \Delta L)/2nL$$

$$\Delta m/m + \Delta\lambda/\lambda = \Delta n/n + \Delta L/L$$

=> $\Delta\lambda/\lambda = \Delta n/n + \Delta L/L - \Delta m/m$

$\Delta n/n$	$\Delta L/L$	$\Delta m/m$
thermal or electrical injection	cavity length tuning	mode selection filtering

Example: wavelength tuning by varying the refractive index

- The tuning range $\Delta\lambda$ is proportional to the change in the effective refractive index (Δn_{eff}), having cavity length and cavity mode fixed

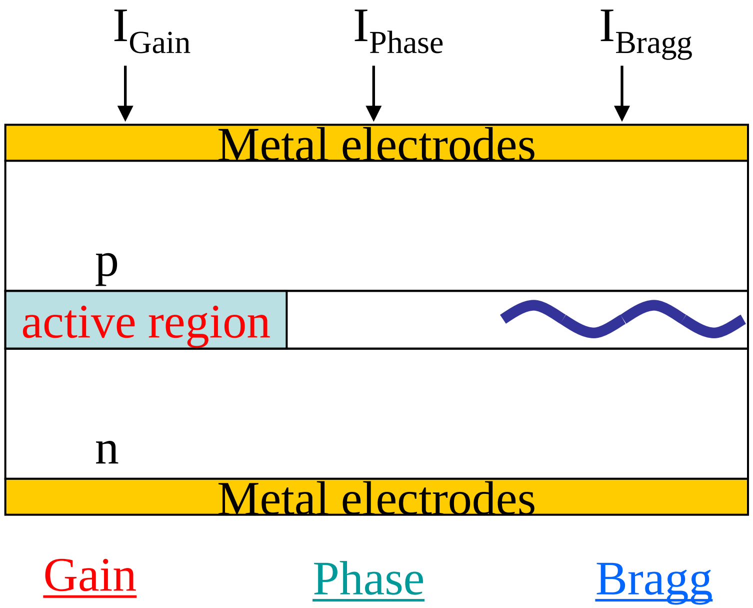
$$\Delta\lambda/\lambda = \Delta n_{eff}/n_{eff}$$

- Consider the maximum expected range of variation in the effective index is 1%. The corresponding tuning range would then be

$$\Delta\lambda = 0.01\ \lambda$$

$\Rightarrow$For $\lambda \sim 1550$ nm, $\Delta\lambda \sim 15$ nm (This is quite decent as it covers about half the C-band!)

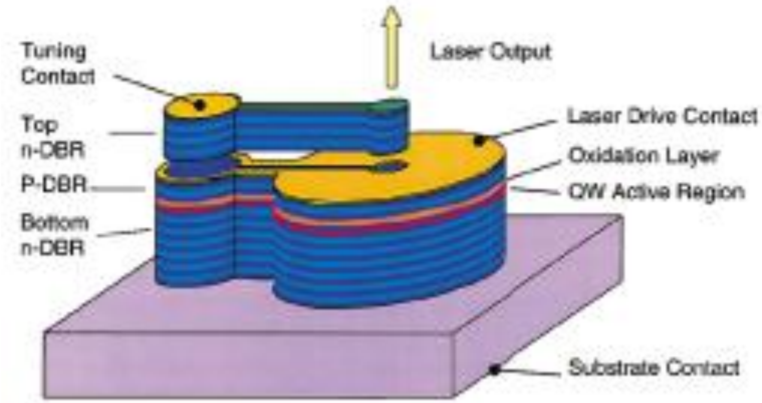
Tunable Distributed-Bragg Reflector (DBR) laser diodes

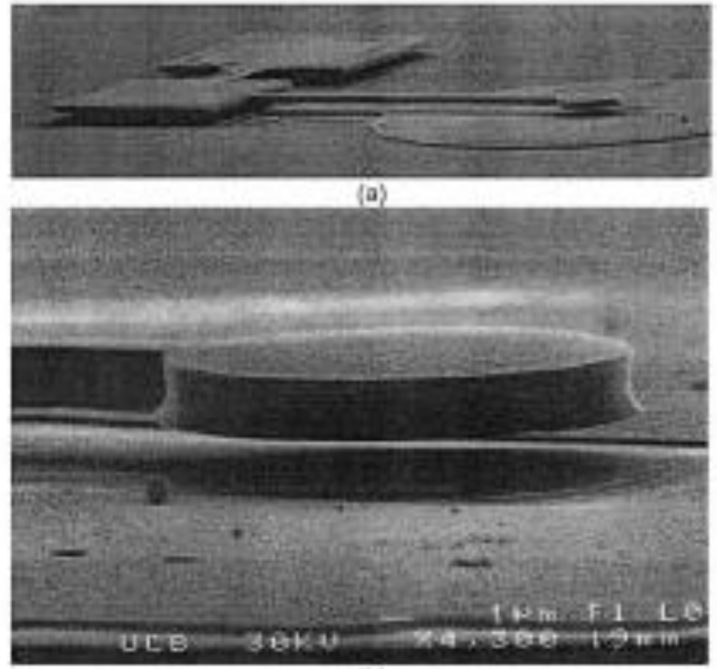


- A separate current controls the Bragg wavelength by changing the temperature in the Bragg region.
- *Heating causes a variation in the effective refractive index of the Bragg region, changing its operating wavelength*.
- From the Bragg condition: $\Lambda\, n_{eff} = m\, \lambda_o/2$

$$\Rightarrow \Delta\lambda/\lambda = \Delta n_{eff}/n_{eff}$$

Wavelength tunable VCSELs



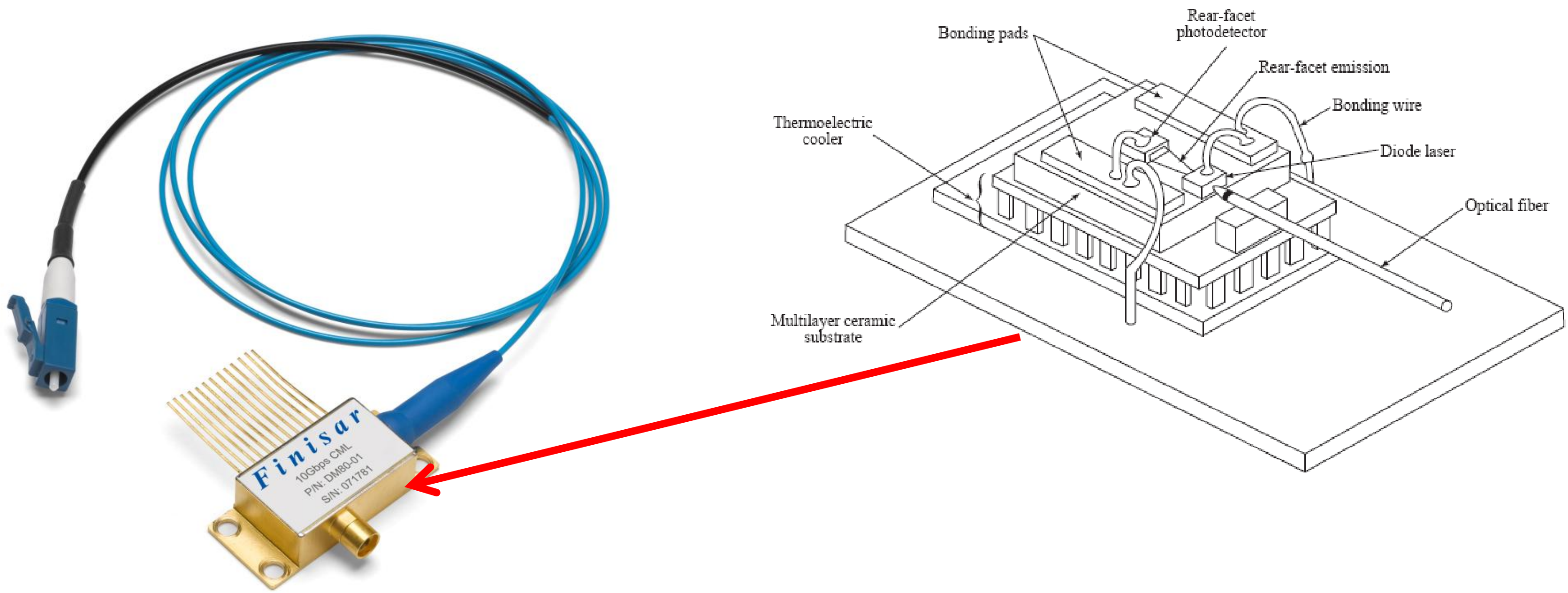


- A tunable cantilever VCSEL. The device consists of a bottom n-DBR, a cavity layer with an active region, and a top mirror. The top mirror, in turn, consists of three parts: a p-DBR, an airgap, and a top n-DBR, which is freely suspended above the laser cavity and supported via a cantilever structure. Laser drive current is injected through the middle contact via the p-DBR. An oxide aperture is formed in the p-DBR section above the cavity layer to provide efficient *current guiding* and *optical index guiding*. A top tuning contact is fabricated on the top n-DBR.

Connie J. Chang-Hasnain, Tunable VCSEL, IEEE Journal on Selected Topics in Quantum Electronics, Vol. 6, pp. 978 – 987, Nov/Dec. 2000

Transmitter Packages

- There are a variety of transmitter packages for different applications.
- One popular transmitter configuration is the *butterfly package.*
- This device has an attached fiber flylead and components such as the diode laser, a monitoring photodiode, and a



Transmitter Packages

Three standard fiber optic transceiver packages

SFP 	• Short and long wavelength WDM use • Datacom applications: Fast/Gigabit Ethernet and 1x,2x,4x Fibre Channel • Telecom applications using OC-3/STM-1, OC-12/STM-4, and OC-48/STM-16 across all distances • Distances from very short links up to 100 km
SFF 	• Short and long wavelength use • Datacom applications for Gigabit Ethernet and 1x,2x,4x Fibre Channel • Telecom applications using OC-3/STM-1, OC-12/STM-4, and OC-48/STM-16 across all distances • Distances from very short links up to 80 km
XFP 	• Short and long wavelength DWDM use • Datacom applications using 10G Ethernet and 10x Fibre Channel • Telecom applications using OC-192/STM-64 • Distances up to 80 km • Supports bit rates up to 11.3 Gb/s