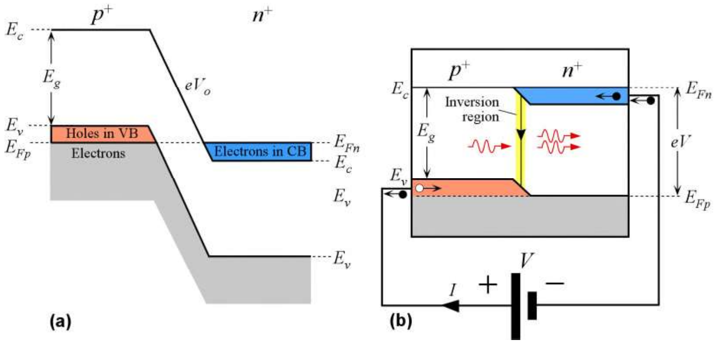
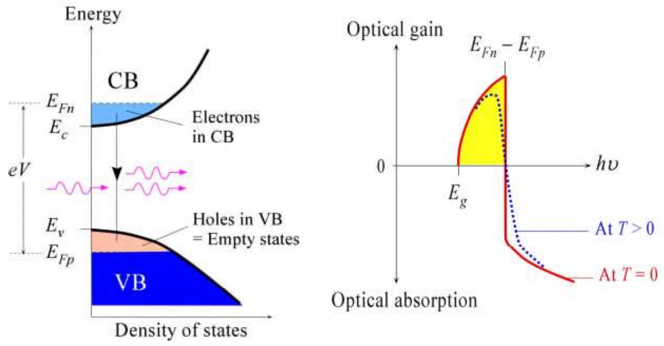
Semiconductor Laser Diode



(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 ($h\upsilon$).

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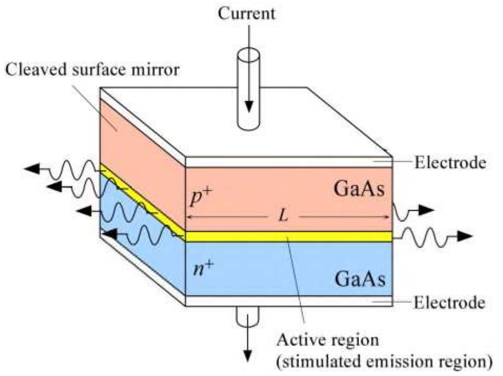
Semiconductor Laser Diode



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

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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)*

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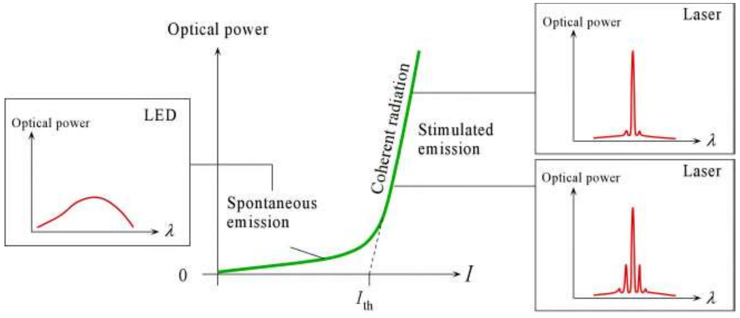
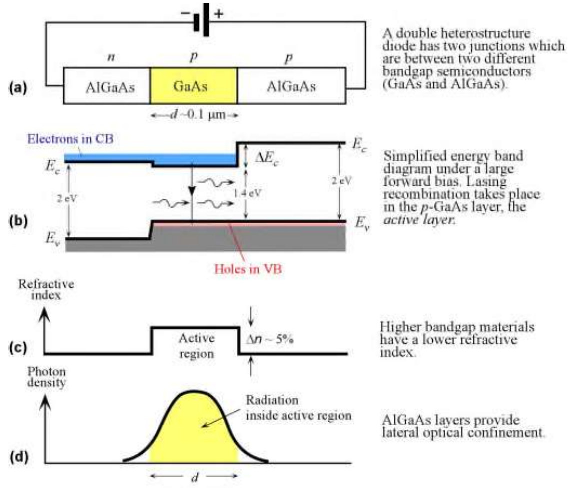
Semiconductor Laser Diode Output



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.

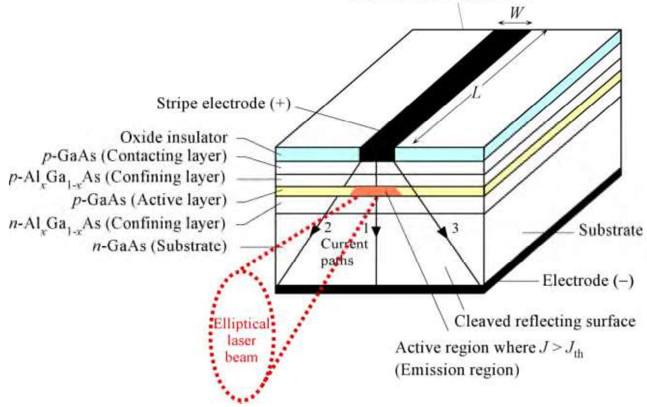
Double Heterostructure Laser Diode



Double Heterostructure Laser Diode

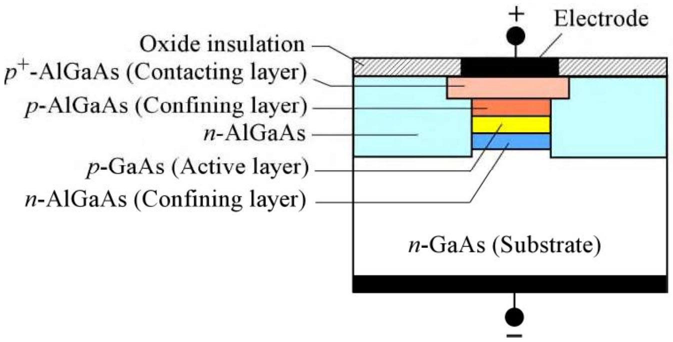
Izuo Hayashi (left) and Morton Panish (1971) at Bell Labs were able to design the first semiconductor laser that operated continuously at room temperature. The need for semiconductor heterostructures for efficient laser diode operation was put forward by Herbert Kroemer in the USA and Zhores Alferov in Russia in 1963. *(Reprinted with permission of Alcatel–Lucent USA Inc.)*

Stripe Geometry Laser Diode



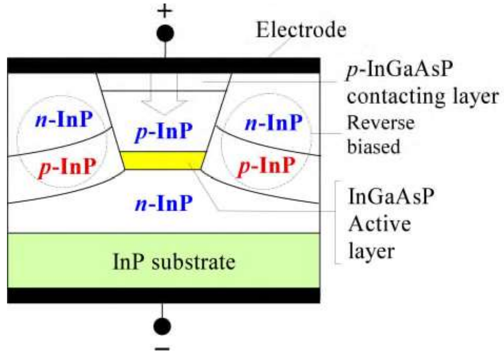
Schematic illustration of the structure of a double heterojunction stripe contact laser diode

Buried Double Heterostructure



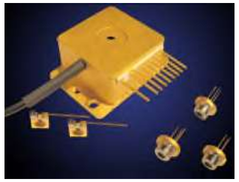
A simplified schematic diagram of a double heterostructure semiconductor laser device that has its active region *buried* within the device in such a way that it is surrounded by low refractive index materials rendering the active region as a waveguide.

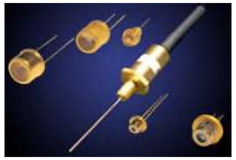
Buried Double Heterostructure



A highly simplified schematic sketch of a buried heterostructure laser diode for telecom applications. The active layer (InGaAsP) is surrounded by the wider bandgap, lower refractive index InP material. Layers are grown on an InP substrate. The InP *np* junction is reverse biased and prevents the current flow outside the central active region.

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.)

EXAMPLE: Modes in a laser and the optical cavity length

Consider an AlGaAs based heterostructure laser diode that has an optical cavity of length 200 μm. The peak radiation is at 870 nm and the refractive index of GaAs is about 3.6. What is the mode integer m of the peak radiation and the separation between the modes of the cavity? If the optical gain vs. wavelength characteristics has a FWHM wavelength width of about 6 nm how many modes are there within this bandwidth? How many modes are there if the cavity length is 20 μm?

Solution

Figure 4.19 schematically illustrates the cavity modes, the optical gain characteristics, and a typical output spectrum from a laser. The wavelength λ of a cavity mode and length L are related by Eq. (4.9.1), $\boldsymbol{m(1/2)(\lambda/n) = L}$, where n is the refractive index of the semiconductor medium, so that

$$m = \frac{2nL}{\lambda} = \frac{2(3.6)(200\times10^{-6})}{(870\times10^{-9})} = 1655.1 \text{ or } 1655 \text{ (integer)}$$

The wavelength separation $\Delta\lambda_m$ between the adjacent cavity modes m and $(m+1)$ in Figure 4.19 is

$$\Delta\lambda_m = \frac{2nL}{m} - \frac{2nL}{m+1} \approx \frac{2nL}{m^2} = \frac{\lambda^2}{2nL}$$

where we assumed that the refractive index n does not change significantly with wavelength from one mode to another. Thus the separation between the modes for a given peak wavelength increases with decreasing L.

EXAMPLE: Modes in a laser and the optical cavity length

Solution (continued)

When L = 200 μm,

$$\Delta\lambda_m = \frac{(870\times10^{-9})^2}{2(3.6)(200\times10^{-6})} = 5.26\times10^{-10}\ \text{m or } 0.526\,\text{nm}$$

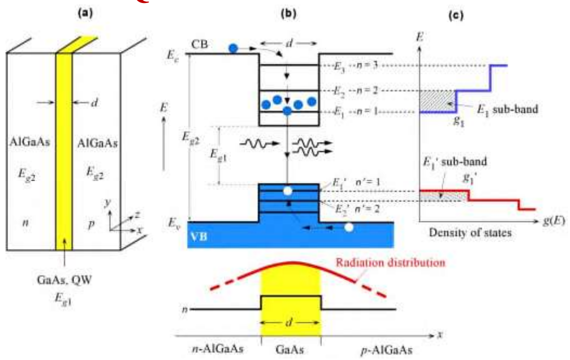
If the optical gain has a bandwidth of $\Delta\lambda_{1/2}$, then there will be $\Delta\lambda_{1/2}/\Delta\lambda_m$ number of modes, or (6 nm)/(0.526 nm), that is 11 modes.

When L = 20 μm, the separation between the modes becomes,

$$\Delta\lambda_m = \frac{(870\times10^{-9})^2}{2(3.6)(20\times10^{-6})} = 5.26\ \text{nm}$$

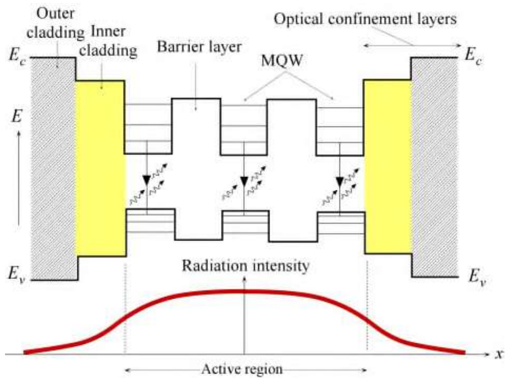
Then $(\Delta\lambda_{1/2})/\Delta\lambda_m$ = 1.14 and there will be one mode that corresponds to about 870 nm. In fact m must be an integer so that choosing the nearest integer, m = 166, gives λ = 867.5 nm (choosing m = 165 gives 872.7 nm) It is apparent that reducing the cavity length suppresses higher modes. Note that the optical bandwidth depends on the diode current.

Quantum Well Lasers



(a) A single quantum well (SQW) of bandgap E_{g1} sandwiched between two semiconductors of wider bandgap E_{g2}, (b) The electron energy levels, and stimulated emission. The electrons and holes are injected from n-AlGaAs and p-AlGaAs respectively. The refractive index variation tries to confine the radiation to GaAs but d is too thin, and most of the radiation is in the AlGaAs layers rather than within d. (c) The density of sates $g(E)$ is a step-like function, and is finite at E_1 and E_1'. The E_1 sub-band for electrons and E_1' sub-band for holes are also shown. The electrons in the E_1 sub-band have kinetic energies in the yz-plane.

Quantum Well Lasers



A simplified schematic diagram of multiple quantum well (MQW) heterostructure laser diode. Electrons are injected by the forward current into quantum wells. The light intensity distribution is also shown. Most of the light is in the active region.

EXAMPLE: A GaAs quantum well

Consider a very thin GaAs quantum well sandwiched between two wider bandgap semiconductor layers of AlGaAs ($Al_{0.33}Ga_{0.67}As$ in present case). The QW depths from E_c and E_v are approximately 0.28 eV and 0.16 eV respectively. Effective mass m_e* of a conduction electron in GaAs is approximately $0.07m_e$ where m_e is the electron mass in vacuum. Calculate the first two electron energy levels for a quantum well of thickness 10 nm. What is the hole energy in the QW above E_v of GaAs, if the hole effective mass $m_h^* \approx 0.50m_e$? What is the change in the emission wavelength with respect to bulk GaAs, for which E_g = 1.42 eV? Assume infinite QW depths for the calculations.

Solution

As we saw in Ch3 (Section 3.12), the electron energy levels in the QW are with respect to the CB edge E_c in GaAs. Suppose that ε_n is the electron energy with respect to E_c in GaAs, or $\varepsilon_n = E_n - E_c$ in Figure 4.40(b). Then, the energy of an electron in a one-dimensional infinite potential energy well is

$$\varepsilon_n = \frac{h^2n^2}{8m_e^*d^2} = \frac{(6.626\times10^{-34})^2(1)^2}{8(0.07\times9.1\times10^{-31})(10\times10^{-9})^2} = 8.62\times10^{-21}\ \text{J or } 0.0538\ \text{eV}$$

where n is a quantum number, 1, 2,…, and we have used $d = 10\times10^{-9}$ m, $m_e^* = 0.07m_e$ and n = 1 to find ε_1 = 0.054 eV. The next level from the same calculation with n = 2 is ε_2 = 0.215 eV.

The hole energy levels below E_v in 4.40(b) are given by $\varepsilon'_{n'} = \dfrac{h^2n'^2}{8m_h^*d^2}$

EXAMPLE: A GaAs quantum well
Solution (continued)

where n' is the quantum number for the hole energy levels above E_v. Using $d = 10\times10^{-9}$ m, $m_h^* \approx 0.5m_e$ and $n' = 1$, we find, $\varepsilon'_1 =$ **0.0075 eV.**

The wavelength of emission from bulk GaAs with $E_g = 1.42$ eV is

$$\lambda_g = \frac{hc}{E_g} = \frac{(6.626\times10^{-34})(3\times10^{8})}{(1.42)(1.602\times10^{-19})} = 874\times10^{-9}\text{ m (874 nm)}$$

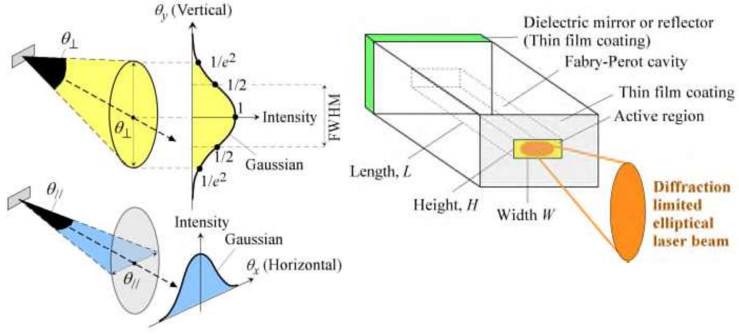
In the case of QWs, we must obey the selection rule that the radiative transition must have $\Delta n = n' - n = 0$. Thus, the radiative transition is from ε_1 to ε_1' so that the emitted wavelength is,

$$\lambda_{QW} = \frac{hc}{E_g + \varepsilon_1 + \varepsilon_1'} = \frac{(6.626\times10^{-34})(3\times10^{8})}{(1.42+0.0538+0.0075)(1.602\times10^{-19})}$$

$$= 838\times10^{-9}\text{ m (838 nm)}$$

The difference is $\lambda_g - \lambda_{QW} = 36$ nm. We note that we assumed an infinite PE well. If we actually solve the problem properly by using a finite well depth, then we would find $\varepsilon_1 \approx 0.031$ eV, $\varepsilon_2 \approx 0.121$ eV, $\varepsilon'_1 \approx 0.007$ eV. The emitted photon wavelength is 848 nm and $\lambda_g - \lambda_{QW} = 26$ nm

Elementary Laser Characteristics



LEFT: The laser cavity definitions and the output laser beam characteristics. RIGHT: Laser diode output beam astigmatism. The beam is elliptical, and is characterized by two angles $\theta_\perp$ and $\theta_{//}$.

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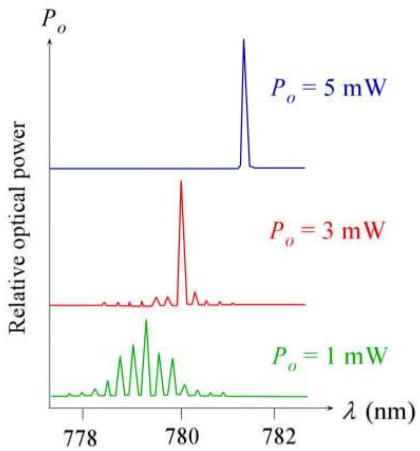
Elementary Laser Characteristics



Output spectra of lasing emission from an index guided edge emitting LD. At sufficiently high diode currents corresponding to high optical power, the operation becomes single mode. (Note: Relative power scale applies to each spectrum individually and not between spectra.)

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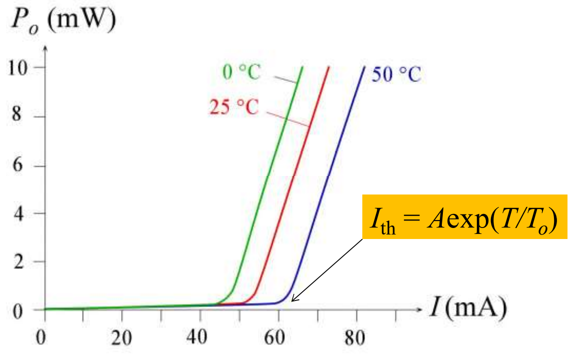
Elementary Laser Characteristics



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

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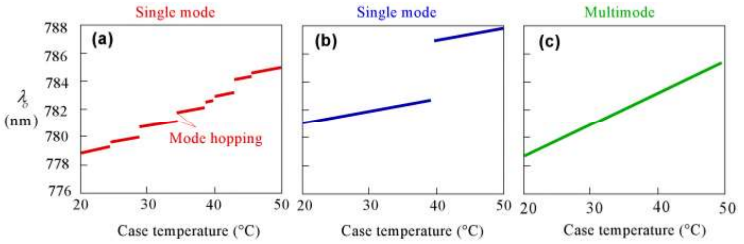
Elementary Laser Characteristics



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 $dn/dT \approx 2.0 \times 10^{-4}$ 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,

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

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 6×10^{-6} K^{-1}.

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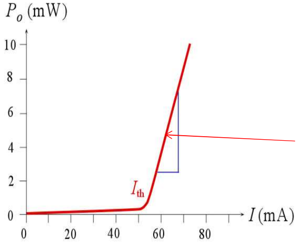
Laser Diode Efficiencies

Slope Efficiency



$$\eta_{\text{slope}} = \left(\frac{\Delta P_o}{\Delta I}\right)_{\text{above threshold}} \approx \frac{P_o}{I - I_{\text{th}}}$$

$$\eta_{\text{slope}} = \frac{\text{Increase in optical output power}}{\text{Increase in input current above threshold}}$$

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Laser Diode Efficiencies

External Quantum Efficiency

$$\eta_{\text{EQE}} = \frac{\text{Number of output photons from the diode per unit second}}{\text{Number of injected electrons into the diode per unit second}}$$

$$\eta_{\text{EQE}} = \frac{P_o / h\upsilon}{I / e} \approx \frac{eP_o}{E_g I}$$

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Laser Diode Efficiencies

External Differential Quantum Efficiency

$$\eta_{\text{EDQE}} = \frac{\text{Increase in number of output photons from diode per unit second}}{\text{Increase in number of injected electrons into diode per unit second}}$$

$$\eta_{\text{EDQE}} = \frac{\Delta P_o / h\upsilon}{\Delta I / e} = \eta_{\text{slope}} \frac{e}{h\upsilon} \approx \left(\frac{e}{E_g}\right) \frac{P_o}{I - I_{\text{th}}}$$

Laser Diode Efficiencies

Internal Quantum Efficiency

$$\eta_{\text{IDQE}} = \frac{\text{Number of photons generated internally per unit second}}{\text{Number of injected electrons into diode per unit second}}$$

$$\eta_{\text{IQE}} = \frac{1/\tau_r}{1/\tau_r + 1/\tau_{nr}}$$

τ_{nr} = Nonradiative recombination time

τ_r = Radiative recombination time

Laser Diode Efficiencies

Internal Differential Quantum Efficiency

$$\eta_{\text{IDQE}} = \frac{\text{Increase in number of photons generated internally per unit second}}{\text{Increase in number of injected electrons into diode per unit second}}$$

If the current increases by ΔI above threshold, increase in the injected electrons is $\Delta I/e$

The increase in the number of photons generated *internally* is then

$$\eta_{\text{IDQE}} \times \Delta I/e$$

Laser Diode Efficiencies

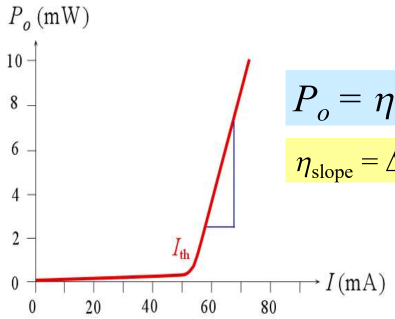
Extraction efficiency

=

(Loss from the exit cavity end) / (Total loss)

$$\eta_{\text{EE}} = (1/2L)\ln(1/R_1) / \alpha_t$$

Laser Diode Efficiencies



$$P_o = \eta_{EE}\eta_{IDQE} h\upsilon (I - I_{th})/e$$

$$\eta_{slope} = \Delta P_o / \Delta I = \eta_{EE}\eta_{IDQE} h\upsilon/e$$

$$\eta_{EDQE} = (\Delta P_o / h\upsilon) / (\Delta I/e)$$
$$= (P_o / h\upsilon) / [(I - I_{th})/e] = \eta_{EE}\eta_{IDQE}$$

Laser Diode Efficiencies

Power Conversion Efficiency

$$\eta_{PCE} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_o}{IV} \approx \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

$$\eta_{PCE} = \frac{P_o}{IV} \approx \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

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Laser Diode Efficiencies

Typical characteristics for a few selected red and violet commercial laser diodes. All LDs are MQW structures and have FP cavities. Violet lasers are based on InGaN/GaN MQW, and red LEDs use mainly AlGaInP/GaInP MQW.

LD	P_o (mW)	λ (nm)	I_{th} (mA)	I (mA)	V (V)	$\theta_\perp$	$\theta_{//}$	η_{slope} (mW/mA)	η_{PCE} %
Red	500	670	400	700	2.4	21°	10°	1.0	30
Red	100	660	75	180	2.5	18°	9°	1.0	22
Red	50	660	60	115	2.3	17°	10°	0.90	19
Red	10	639	30	40	2.3	21°	8°	1.0	11
Violet	400	405	160	390	5.0	45°	15°	1.7	21
Violet	120	405	45	120	5.0	17°	8°	1.6	20
Violet	10	405	26	35	4.8	19°	8.5°	1.1	6.0

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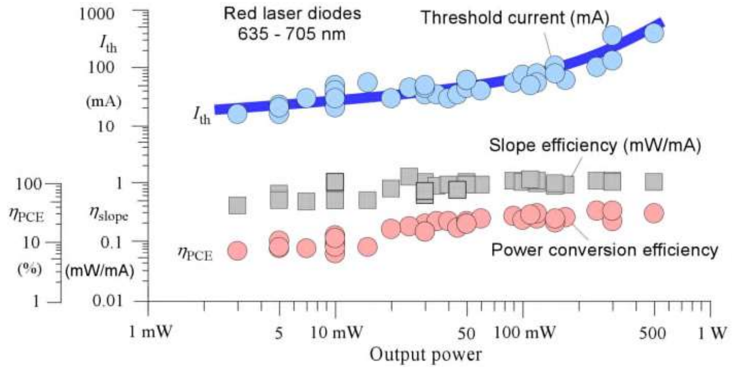
Laser Diode Efficiencies



Typical values for the threshold current I_{th}, slope efficiency (η_{slope}) and power conversion efficiency (η_{PCE}) for 36 commercial red LDs with different optical output powers from 3 mW – 500 mW.

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EXAMPLE: Laser diode efficiencies for a sky blue LD

Consider a 60 mW blue LD (Nichia SkyBlue NDS4113), emitting at a peak wavelength of 488 nm. The threshold current is 30 mA. At a forward current of 100 mA and a voltage of 5.6 V, the output power is 60 mW. Find the slope efficiency, PCE, EQE and EDQE.

Solution

From the definition in Eq. (4.12.2),

$$\eta_{\text{slope}} = P_o / (I - I_{\text{th}})$$
$$= (60\text{ mW}) / (100 - 30\text{ mA}) = \mathbf{0.86\ mW/mA^{-1}}$$

From Eq. (4.12.8), PCE is

$$\eta_{\text{PCE}} = P_o / IV$$
$$= (60\text{ mW}) / [(100\text{ mA})(5.6\text{ V})] = \mathbf{0.11} \text{ or } \mathbf{11\%}$$

We can find the EQE from Eq. (4.12.3) but we need $h\upsilon$, which is hc/λ. In eV,

$$h\upsilon\ (\text{eV}) = 1.24 / \lambda\ (\mu\text{m})$$
$$= 1.24 / 0.488 = 2.54\text{ eV}$$

EQE is given by Eq. (4.12.3)

$$\eta_{\text{EQE}} = (P_o / h\upsilon) / (I / e)$$
$$= [(60\times10^{-3})/(2.54\times1.6\times10^{-19})]/[(100\times10^{-3})/(1.6\times10^{-19})]$$
$$= \mathbf{0.24} \text{ or } \mathbf{24\%}$$

EXAMPLE: Laser diode efficiencies for a sky blue LD
Solution (continued)

Similarly, η_{EDQE} is given by Eq. (4.12.4b) above threshold,

$$\eta_{\text{EDQE}} = (\Delta P_o / h\upsilon) / (\Delta I / e) \approx (P_o / h\upsilon) / [(I - I_{\text{th}})/e)]$$

$$= [(60\times10^{-3})/(2.54\times1.6\times10^{-19})] / [(100\times10^{-3}-30\times10^{-3})/1.6\times10^{-19})]$$

$$= \mathbf{0.34\ or\ 34\%}$$

The EDQE is higher than the EQE because most injected electrons above I_{th} are used in stimulated recombinations. EQE gauges the total conversion efficiency from all the injected electrons brought by the current to coherent output photons. But, a portion of the current is used in pumping the gain medium.

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EXAMPLE: Laser diode efficiencies

Consider an InGaAs FP semiconductor laser diode that emits CW radiation at 1310 nm. The cavity length (L) is 200 µm. The internal loss coefficient $\alpha_s = 20\text{ cm}^{-1}$, $R_1 = R_2 \approx 0.33$ (cleaved ends). Assume that internal differential quantum efficiency, IDQE, is close to 1. The threshold current is 5 mA. What is the output power P_o at $I = 20$ mA? The forward voltage is about 1.3 V. What is the EDQE and conversion efficiency?

Solution

From the definition of IDQE in Eq. (4.12.6), the number of internal coherent photons generated per second above threshold is $\eta_{\text{IDQE}}(I - I_{\text{th}})/e$. Thus,

$$\textbf{Internal optical power generated} = h\upsilon \times \eta_{\text{IDQE}}(I - I_{\text{th}})/e$$

The extraction efficiency η_{EE} then couples a portion of this optical power into the output radiation. The output power P_o is then $\eta_{\text{EE}} \times h\upsilon \times \eta_{\text{IDQE}}(I - I_{\text{th}})/e$. Thus,

$$P_o = \eta_{\text{EE}}\eta_{\text{IDQE}} h\upsilon(I - I_{\text{th}})/e \qquad \textit{Output power vs current} \qquad (4.12.9)$$

The slope efficiency from Eq.(4.12.2) is

$$\eta_{\text{slope}} = \Delta P_o / \Delta I = \eta_{\text{EE}}\eta_{\text{IDQE}}(h\upsilon/e) \qquad \textit{Slope efficiency} \qquad (4.12.10)$$

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EXAMPLE .3: Laser diode efficiencies
Solution (continued)

Further, from the definition of EDQE and Eq.(4.12.9) is

$$\eta_{\text{EDQE}} = (\Delta P_o / h\upsilon) / (\Delta I / e) = (P_o / h\upsilon) / [(I - I_{\text{th}})/e] = \eta_{\text{EE}}\eta_{\text{IDQE}}$$

External differential quantum efficiency (4.12.11)

We can now calculate the quantities needed. The total loss coefficient is

$$\alpha_t = \alpha_s + (1/2L)\ln(1 / R_1R_2)$$

$$= 2000 + (2\times200\times10^{-6})^{-1}\ln(0.33\times0.33)^{-1} = 7543\text{ m}^{-1}$$

The extraction efficiency is

$$\eta_{\text{EE}} = (1/2L)\ln(1/R_1) / \alpha_t = (2\times200\times10^{-6})^{-1}\ln(1/0.33) / (7543)$$
$$= \mathbf{0.37\ or\ 37\%}$$

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EXAMPLE: Laser diode efficiencies
Solution (continued)

Thus, using I = 20 mA in Eq. (4.12.9),

$P_o = (0.37)(1)[(6.62\times10^{-34})(3\times10^{8})/(1310\times10^{-9})][(0.02 - 0.005) / (1.6\times10^{-19})] = \mathbf{5.2\ mW}$

The slope efficiency from Eq. (4.12.10) is

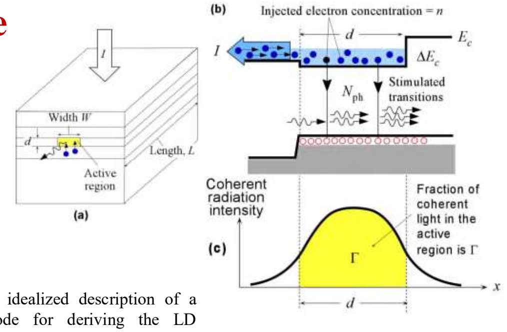
$\eta_{slope} = \Delta P_o / \Delta I = (5.2\text{ mW} - 0) / (20\text{ mA} - 5\text{ mA}) = \mathbf{0.35\ mW\ mA^{-1}}$

The EDQE from Eq. (4.12.11) is

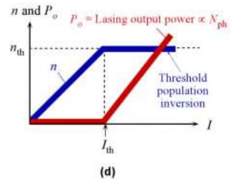
$\eta_{EDQE} = \eta_{EE}\eta_{IDQE} = \mathbf{0.37}$ or $\mathbf{37\%}$

The power conversion efficiency $\eta_{PCE} = P_o / IV$
$= 5.2\text{ mW} / (20\text{ mA} \times 1.3\text{ V})$
$= \mathbf{0.20}$ or $\mathbf{20\%}$

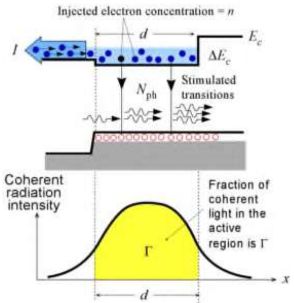
Laser Diode Equation



A highly simplified and idealized description of a semiconductor laser diode for deriving the LD equation. (a) The heterostructure laser diode structure. (b) The current I injects electrons in the conduction band, and these electrons recombine radiatively with the holes in the active region. (c) The coherent radiation intensity across the device; only a fraction Γ is within the active region where there is optical gain. (d) Injected electron concentration n and coherent radiation output power P_o vs. diode current I. The current represents the pump rate.



Laser Diode Equation



$$\frac{I}{eLWd} = \frac{n}{\tau_r} + CnN_{ph}$$

Radiative lifetime

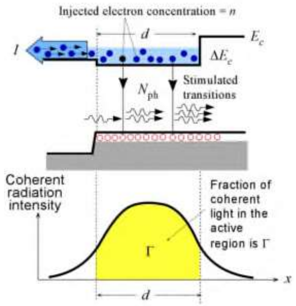
Rate of electron injection by current I
= Rate of spontaneous emissions
+ Rate of stimulated emissions

$$\boxed{\frac{N_{ph}}{\tau_{ph}} = CnN_{ph}}$$

Rate of coherent photon loss in the cavity
= Rate of stimulated emissions

Photon cavity lifetime

Laser Diode Equation



$$\frac{I_{th}}{eLWd} \approx \frac{n_{th}}{\tau_r}$$ **Threshold**

$$n_{th} = \frac{1}{C\tau_{ph}}$$ **Threshold**

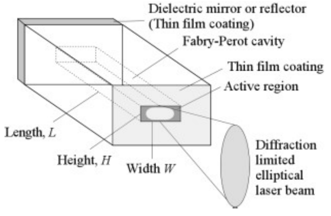
Substitute back into steady state rate equation

$$\frac{I}{eLWd} = \frac{n_{th}}{\tau_r} + Cn_{th}N_{ph} \Rightarrow N_{ph} = \frac{\tau_{ph}}{eLWd}(I - I_{th})$$

Laser Diode Equation

$$N_{\mathrm{ph}} = \frac{\tau_{\mathrm{ph}}}{eLWd}(I - I_{\mathrm{th}})$$

$$P_o = \frac{(\frac{1}{2}N_{\mathrm{ph}})(\text{Cavity Volume})(\text{Photon energy})}{\Delta t}(1-R)$$

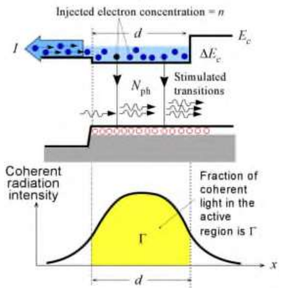


$$P_o = \left[\frac{hc^2\tau_{\mathrm{ph}}(1-R)}{2en\lambda L}\right](I - I_{\mathrm{th}})$$

$$I_o = \left[\frac{hc^2\tau_{\mathrm{ph}}(1-R)}{2en\lambda d}\right](J - J_{\mathrm{th}})$$

Light intensity = P_o / A

Threshold Gain

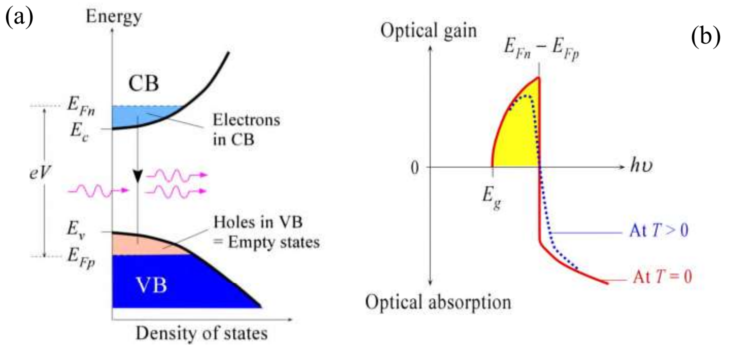


$$\Gamma g_{\mathrm{th}} = \alpha_t = \alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

Γ= Fraction of the coherent optical radiation within the active region

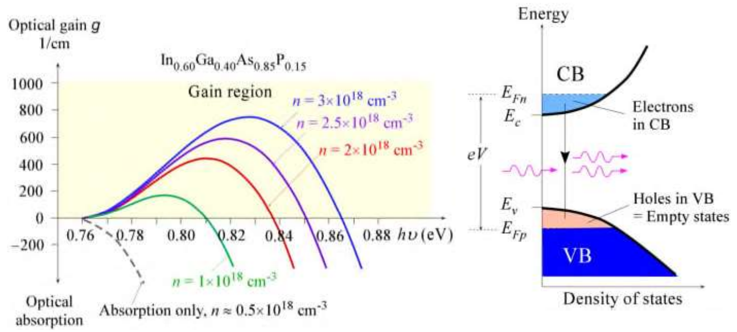
The gain g works on the radiation within the cavity, which means that we must multiply g with Γ to account for less than perfect optical confinement

Optical Gain Curve



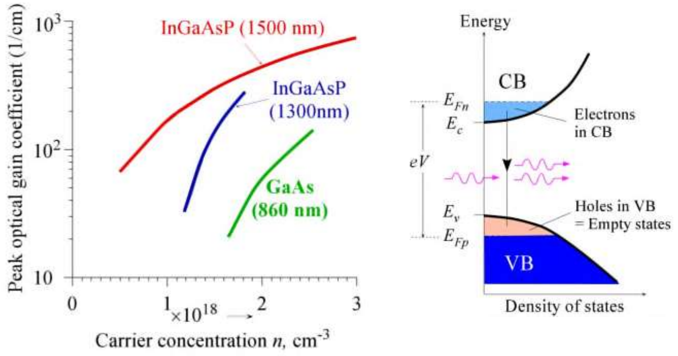
(a) The density of states and energy distribution of electrons and holes in the conduction and valence bands respectively at $T > 0$ in the SCL under forward bias such that $E_{Fn} - E_{Fp} > E_g$. Holes in the VB are empty states. (b) Gain vs. photon energy ($h\upsilon$).

Optical Gain Curve



Optical gain g vs. photon energy for an InGaAsP active layer (in a 1500 nm LD) as a function of injected carrier concentration n from 1×10^{18} to 3×10^{18} cm^{-3}. (The model described in Leuthold *et al*, *J. Appl. Phys.*, *87*, 618, 2000 was used to find the gain spectra at different carrier concentrations.) (Data combined from J. Singh, *Electronic and Optoelectronic Properties of Semiconductor Structures*, Cambridge University Press, 203, p390; N.K. Dutta, *J. Appl. Phys.*, *51*, 6095, 1980; J. Leuthold *et al*, *J. Appl. Phys.*, 87, 618, 2000.)

Optical Gain Curve



The dependence of the peak gain coefficient (maximum g) on the injected carrier concentration n for GaAs (860 nm), $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$ (1300 nm), and $In_{0.60}Ga_{0.40}As_{0.85}P_{0.15}$ (1500 nm) active layers. (Data combined from J. Singh, *Electronic and Optoelectronic Properties of Semiconductor Structures*, Cambridge University Press, 203, p390; N.K. Dutta, *J. Appl. Phys.*, *51*, 6095, 1980; J. Leuthold *et al*, *J. Appl. Phys.*, 87, 618, 2000.)

EXAMPLE: Threshold current and optical output power from a Fabry-Perot (FP) heterostructure laser diode

Consider GaAs DH laser diode that lases at 860 nm. It has an active layer (cavity) length L of 250 μm. The active layer thickness d is 0.15 μm and the width W is 5 μm. The refractive index is 3.6, and the attenuation coefficient α_s inside the cavity is 10^3 m^{-1}. The required threshold gain g_{th} corresponds to a threshold carrier concentration $n_{th} \approx 2\times10^{18}$ cm^{-3}. The radiative lifetime τ_r in the active region can be found (at least approximately) by using $\tau_r = 1/Bn_{th}$, where B is the direct recombination coefficient, and assuming strong injection as will be the case for laser diodes [see Eq. (3.8.7) in Chapter 3]. For GaAs, $B \approx 2\times10^{-16}$ m^3 s^{-1}. What is the threshold current density and threshold current? Find the output optical power at $I = 1.5I_{th}$, and the external slope efficiency η_{slope}. How would $\Gamma = 0.5$ affect the calculations?

Solution

The reflectances at the each end are the same (we assume no other thin film coating on the ends of the cavity) so that $R = (n-1)^2/(n+1)^2 = 0.32$. The total attenuation coefficient α_t and hence the threshold gain g_{th}, assuming $\Gamma = 1$ in Eq. (4.13.9), is

$$g_{th} = \alpha_t = (10\text{ cm}^{-1}) + \frac{1}{(2\times250\times10^{-4}\text{ cm})}\ln\left[\frac{1}{(0.32)(0.32)}\right] = 55.6\text{ cm}^{-1}$$

From Figure 4.48(b), at this gain of 56 cm^{-1}, $n_{th} \approx 2\times10^{18}$ cm^{-3}. This is the threshold carrier concentration that gives the right gain under ideal optical confinement, with $\Gamma = 1$.

EXAMPLE: Threshold current and optical output power from a Fabry-Perot (FP) heterostructure laser diode

Solution (continued)

The radiative lifetime $\tau_r = 1/Bn_{th} = 1/[2\times10^{-16}\text{ m}^3\text{ s}^{-1})(2\times10^{24}\text{ m}^{-3})] =$ **2.5 ns**

Since $J = I/WL$, the threshold current density from Eq. (4.13.4) is

$$J_{th} = \frac{n_{th}ed}{\tau_r} = \frac{(2\times10^{24}\text{ m}^{-3})(1.6\times10^{-19}\text{ C})(0.15\times10^{-6}\text{ m})}{(2.5\times10^{-9}\text{ s})}$$

$= 1.9\times10^7$ A m^{-2} or 1.9 kA cm^{-2} or 19 A mm^{-2}.

The threshold current itself is,

$I_{th} = (WL)J_{th} = (5\times10^{-6}\text{ m})(250\times10^{-6}\text{ m})(1.9\times10^7\text{ A m}^{-2})$
$= 0.024$ A or **24 mA**

The photon cavity lifetime depends on α_t, and is given by

$\tau_{ph} = n/(c\alpha_t) = 3.6 / [(3\times10^8\text{ m s}^{-1})(5.56\times10^3\text{ m}^{-1})]$
$=$ **2.16 ps**

The laser diode output power is

$$P_o = \left[\frac{hc^2\tau_{ph}(1-R)}{2en\lambda L}\right](I - I_{th}) = \frac{(6.626\times10^{-34})(3\times10^8)^2(2.16\times10^{-12})(1-0.32)}{2(1.6\times10^{-19})(3.6)(860\times10^{-9})(250\times10^{-6})}(I - I_{th})$$

EXAMPLE: Threshold current and optical output power from a Fabry-Perot (FP) heterostructure laser diode

Solution (continued)

That is $\boldsymbol{P_o = (0.35\text{ W A}^{-1})(I - I_{th}) = (0.35\text{ mW mA}^{-1})(I - 24\text{ mA})}$

When $I = 1.5I_{th} = 36$ mA,

$P_o = (0.35\text{ mW mA}^{-1})(36\text{ mA}-24\text{ mA}) =$ **4.2 mW**

The slope efficiency is the slope of the P_o vs. I characteristic above I_{th},

$$\eta_{slope} = \frac{\Delta P_o}{\Delta I} = \left[\frac{hc^2\tau_{ph}(1-R)}{2en\lambda L}\right] = \mathbf{0.35\text{ mW mA}^{-1}}$$

We can now repeat the problem say for $\Gamma = 0.5$, which would give $\Gamma g_{th} = \alpha_t$, so that $g_{th} = 55.6$ cm^{-1} / 0.5 = 111 cm^{-1}. From Figure 4.48 (b), at this gain of 111 cm^{-1}, $n_{th} \approx 2.5\times10^{18}$ cm^{-3}. The new radiative lifetime,

$\tau_r = 1/Bn_{th} = 1/[2.0\times10^{-16}\text{ m}^3\text{ s}^{-1})(2.5\times10^{24}\text{ m}^{-3})] = 2.0$ ns

The corresponding threshold current density is

$J_{th} = n_{th}ed/\tau_r = (2.5\times10^{24}\text{ m}^{-3})(1.6\times10^{-19}\text{ C})(0.15\times10^{-6}\text{ m})/(2.0\times10^{-9}\text{ s})$
$=$ **30 A mm^{-2}**

and the corresponding threshold current I_{th} is **37.5 mA**

EXAMPLE: Threshold current and optical output power from a Fabry-Perot (FP) heterostructure laser diode
Solution (continued)

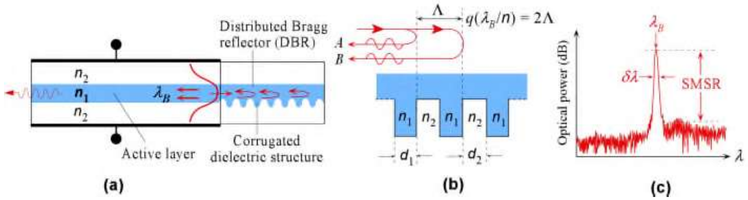
There are several important notes to this problem

• First, the threshold concentration $n_{th} \approx 2\times10^{18}$ cm^{-3} was obtained graphically from Figure 4.48 (b) by using the g_{th} value we need.

• Second is that, at best, the calculations represent rough values since we also need to know how the mode spreads into the cladding where there is no gain but absorption and, in addition, what fraction of the current is lost to nonradiative recombination processes. We can increase α_s to account for absorption in the cladding, which would result in a higher g_{th}, larger n_{th} and greater I_{th}. If τ_{nr} is the nonradiative lifetime, we can replace τ_r by an effective recombination time τ such that , $\tau^{-1} = \tau_r^{-1} + \tau_{nr}^{-1}$ which means that the threshold current will again be larger. We would also need to reduce the optical output power since some of the injected electrons are now used in nonradiative transitions.

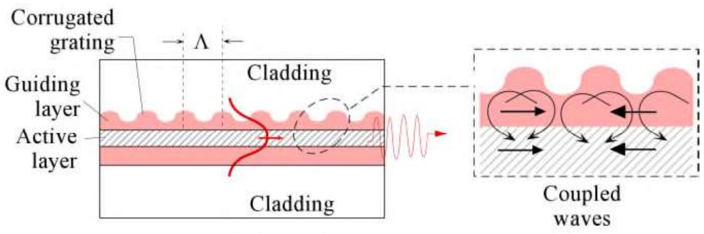
• Third, is the low slope efficiency compared with commercial LDs. η_{slope} depends on τ_{ph}, the photon cavity lifetime, which can be greatly improved by using better reflectors at the cavity ends, *e.g.* ,by using thin film coating on the crystal facets to increase R.

Distributed Bragg Reflector (DBR) LDs



(a) The basic principle of the Distributed Bragg Reflection (DBR) laser. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves *A* and *B* interfere constructively when $q(\lambda_B/n) = 2\Lambda$. (c) Typical output spectrum. SMSR is the side mode suppression ratio.

Distributed Feedback (DFB) LDs

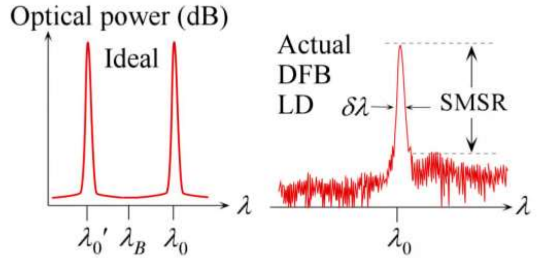


LEFT: Distributed feedback (DFB) laser structure. The mode field diameter is normally larger than the active layer thickness and the radiation spreads into the guiding layer.

RIGHT: There are left and right propagating waves, partial reflections from the corrugation, and optical amplification within the cavity, which has both the active layer and the guiding layer.

Distributed Feedback (DFB) LDs

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1)$$



LEFT: Ideal lasing emission output has two primary peaks above and below λ_B. RIGHT: Typical output spectrum from a DFB laser has a single narrow peak with a $\delta\lambda$ typically very narrow, and much less than 0.1 nm

Distributed Bragg Reflector (DBR) and Distributed Feedback (DFB) LDs

Selected properties of DBR, DFB and external cavity (EC) laser diodes
Note: fm is 10^{-15} s; $\delta\upsilon$ and $\delta\lambda$ are spectral widths (FWHM). SMSR is the side mode suppression ratio, TEC is a thermoelectric cooler

LD	λ_0 (nm)	$\delta\upsilon$, $\delta\lambda$	SMSR dB	P_o mW	I mA	η_{slope} mA	Comment
DBR[a]	1063	2 MHz, 8 fm	45	80	200	0.8	GaAs DBR LD for spectroscopy and metrology, includes monitor current, TEC and thermistor.
DFB[b]	1063	2 MHz, 8 fm	45	80	190	0.2	GaAs DFB LD for spectroscopy and metrology, includes monitor current, TEC and thermistor
DFB[c]	1550	10 MHz, 0.08 pm	45	40	300	0.3	Pigtailed to a fiber, includes monitor current, TEC and thermistor. CW output for external modulation. For use in long haul DWDM.
DFB[d]	1653	0.1 nm	35	5	30	0.23	Pigtailed to a single mode fiber, includes monitor current, TEC and thermistor. Mainly for fiber optic sensing.
EC[e]	1550	50 kHz; 0.4 fm	45	40	300	0.2	Pigtailed. Tunable over $\Delta\upsilon$ = 3 GHz. Mainly for communications

[a]Eagleyard, EYP-DBR-1080-00080-2000-TOC03-0000; [b]Eagleyard, EYP-DFB-1083-00080-1500-TOC03-0000; [c]Furukawa-Fitel, FOL15DCWD; [d]Inphenix, IPDFD1602; [e]Covega SFL1550S, marketed by Thorlabs.

Example: DFB LD wavelength

Consider a DFB laser that has a corrugation period Λ of 0.22 μm and a grating length of 400 μm. Suppose that the effective refractive index of the medium is 3.5. Assuming a first order grating, calculate the Bragg wavelength, the mode wavelengths and their separation.

Solution

The Bragg wavelength is

$$\lambda_B = \frac{2\Lambda n}{q} = \frac{2(0.22\ \mu\text{m})(3.5)}{1} = 1.5400\ \mu\text{m}.$$

and the symmetric mode wavelengths about λ_B are

$$\lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL}(m+1) = 1.5400 \pm \frac{(1.5400\ \mu\text{m})^2}{2(3.5)(400\ \mu\text{m})}(0+1)$$

so that the $m = 0$ mode wavelengths are

λ_0 = 1.53915 or 1.54085 μm.

The two are separated by 0.0017 μm, or 1.7 nm. Due to a design asymmetry, only one mode will appear in the output and for most practical purposes the mode wavelength can be taken as λ_B. Note: The wavelength calculation was kept to five decimal places because λ_m is very close to λ_B.

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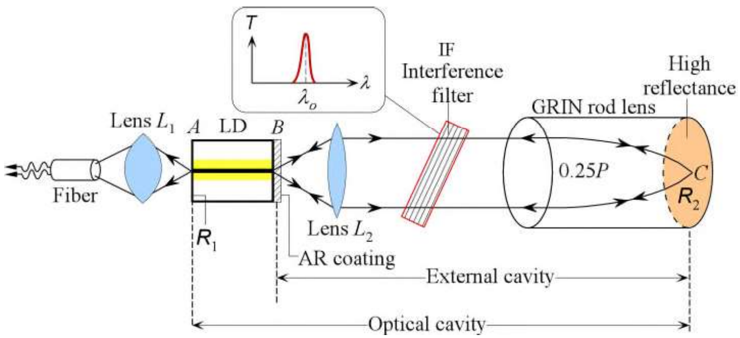
External Cavity Laser Diodes (ECLD)



A simplified diagram of an external cavity diode laser (ECDL), which uses an angled interference filter (IF) to select the wavelength λ_o (depends on the angle of the IF), and the optical cavity has a GRIN lens with one end coated for full reflection back to the LD. The output is taken from the left facet of the LD.

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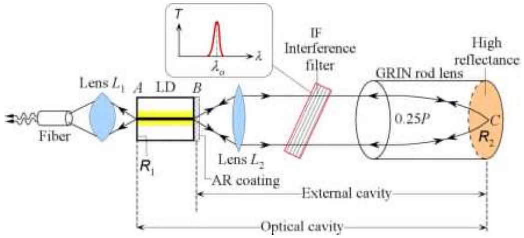
External Cavity Laser Diodes (ECLD)



LEFT: A commercial external cavity diode laser, based on the principle shown on the right. (US Patent 6,556,599, Bookham Technology). The output is a single mode at 785 nm (± 1.5 pm) with a linewidth less than 200 kHz, and coupled into a fiber. The output power is 35 mW, and the SMSR is 50 dB. (ECDL, SWL-7513-P. Courtesy of Newport, USA)

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