Lecture 20
Stimulated Emission Devices- Lasers
- Rate equation*
- Light emitters for optical fiber communications

Semiconductor Detectors - Photodetectors
- Principle of the pn junction photodiode
- Absorption coefficient and photodiode materials
- Properties of semiconductor detectors
  - The pin photodiodes
  - Avalanche photodiodes
Final Presentations

Search for related references and find out the problems, solutions, current status and future applications.

Prepare for a 12 minutes presentation in class. (12 min. presentation + 3 min. questions)

Presentation will be evaluated according to

a. Technical quality (Is the material technically sound?)

b. Clarity (Have you made your point and does everyone understand you?)

c. Organization and presentation (Is the talk well organized and presented?)

d. Handling of questions.

Turn in a copy of your presentation files!
Laser Diode Equation

\[
(N_2 - N_1)_{th} \approx g_{th} \frac{8\pi n^2 v_o^2 \tau_s \Delta \nu}{c^2}
\]
Laser Diode Equation

\[ R_{\text{elect injec}} = R_{\text{spontaneous}} + R_{\text{stimulated}} \]

\[ \frac{I}{eLWd} = \frac{n}{\tau_r} + CnN_{\text{ph}} \]

Radiative lifetime
Einstein Coefficients

Radiative lifetime

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

Spontaneous emission

\[ -\frac{dN_2}{dt} = R_{21} = A_{21}N_2 + B_{21}N_2\rho(\nu) \]

Stimulated emission

\[ N_2 \Rightarrow n \]
Einstein Coefficients

\[
\frac{I}{e L W d} = \frac{n}{\tau_r} + C n N_{ph}
\]

Radiative lifetime

\[
R_{21} = A_{21} N_2 + B_{21} N_2 \rho(\nu)
\]

\[-dN_2/dt \quad \text{Spontaneous emission} \]

\[N_2 \Rightarrow n\]

\[\rho(\nu) \Rightarrow N_{ph}\]
Einstein Coefficients

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

Radiative lifetime

\[
A_{21} = \frac{1}{\tau_r}
\]

\[
R_{21} = A_{21}N_2 + B_{21}N_2\rho(\nu)
\]

\[-dN_2/dt\] Spontaneous emission

\[\rho(\nu) \Rightarrow N_{ph}\]
Laser Diode Equation

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

Radiative lifetime

\[ N_{ph} = 0 \]  
Threshold

\[ \frac{I_{th}}{eLWd} \approx \frac{n_{th}}{\tau_r} \]  
Threshold

\[ P_o = \text{Lasing output power} \propto N_{ph} \]  
Threshold population inversion
Laser Diode Equation

Injected electron concentration = $n$

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

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

Photon cavity lifetime

$$\tau_{\text{th}} = \frac{n}{c\alpha_t}$$

Steady State

Light output = Stimulated

$P_o = \text{Lasing output power} \propto N_{\text{ph}}$

Threshold population inversion
Laser Diode Equation

\[ n_{th} = \frac{1}{C \tau_{ph}} \]

\[ \frac{I_{th}}{eLWd} \approx \frac{n_{th}}{\tau_r} \]

Threshold

General Relation

\[ \frac{I}{eLWd} = \frac{n_{th}}{\tau_r} + Cn_{th}N_{ph} \]

\[ N_{ph} = \frac{\tau_{ph}}{eLWd} \left( I - I_{th} \right) \]
Laser Diode Equation

\[ N_{ph} = \frac{\tau_{ph}}{eLWd} (I - I_{th}) \]

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

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

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

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

\(\Gamma\) = Fraction of the coherent optical radiation within the active region

\(\Gamma = 0.2\) typically (100 nm single mode)

\(\tau_{th} = \frac{n}{c\alpha_t}\)

Photon cavity lifetime
Optical Gain Curve

- **Peak frequency shifts with increasing carrier concentration**
- **Bandwidth increases with increasing carrier concentration**

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 $1 \times 10^{18}$ to $3 \times 10^{18}$ 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.)
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.)
Distributed Bragg Reflectors (DBR) LDs
Distributed Bragg Reflectors (DBR) LDs

DBR section

Gain section

Heat sink
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.

Bragg Wavelength

\[ \lambda_m = \lambda_B \pm \frac{\lambda_B^2}{2nL} (m + 1) \]
Distributed Feedback (DFB) LDs

- HR
- lattice
- corrugated heterostructure
- gain
- AR
- d
Distributed Bragg Reflectors (DBR) & Distributed Feedback LDs

Selected properties of DBR, DFB and external cavity (EC) laser diodes

Note: fm is $10^{-15}$ s; $\delta \nu$ and $\delta \lambda$ are spectral widths (FWHM). SMSR is the side mode suppression ratio, TEC is a thermoelectric cooler.

<table>
<thead>
<tr>
<th>LD</th>
<th>$l_0$ (nm)</th>
<th>$du, dl$</th>
<th>SMSR dB</th>
<th>$P_o$ mW</th>
<th>$I$ mA</th>
<th>$h_{\text{slope}}$ mA</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBRa</td>
<td>1063</td>
<td>2 MHz, 8 fm</td>
<td>45</td>
<td>80</td>
<td>200</td>
<td>0.8</td>
<td>GaAs DBR LD for spectroscopy and metrology, includes monitor current, TEC and thermistor.</td>
</tr>
<tr>
<td>DFBb</td>
<td>1063</td>
<td>2 MHz, 8 fm</td>
<td>45</td>
<td>80</td>
<td>190</td>
<td>0.2</td>
<td>GaAs DFB LD for spectroscopy and metrology, includes monitor current, TEC and thermistor.</td>
</tr>
<tr>
<td>DFBc</td>
<td>1550</td>
<td>10 MHz, 0.08 pm</td>
<td>45</td>
<td>40</td>
<td>300</td>
<td>0.3</td>
<td>Pigtailed to a fiber, includes monitor current, TEC and thermistor. CW output for external modulation. For use in long haul DWDM.</td>
</tr>
<tr>
<td>DFBd</td>
<td>1653</td>
<td>0.1 nm</td>
<td>35</td>
<td>5</td>
<td>30</td>
<td>0.23</td>
<td>Pigtailed to a single mode fiber, includes monitor current, TEC and thermistor. Mainly for fiber optic sensing.</td>
</tr>
<tr>
<td>ECe</td>
<td>1550</td>
<td>50 kHz; 0.4 fm</td>
<td>45</td>
<td>40</td>
<td>300</td>
<td>0.2</td>
<td>Pigtailed. Tunable over $\delta u = 3$ GHz. Mainly for communications.</td>
</tr>
</tbody>
</table>

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*aEagleyard, EYP-DBR-1080-00080-2000-TOC03-0000; \textsuperscript{b}Eagleyard, EYP-DFB-1083-00080-1500-TOC03-0000; \textsuperscript{c}Furukawa-Fitel, FOL15DCWD; \textsuperscript{d}Inphenix, IPDFD1602; \textsuperscript{e}Covega SFL1550S, marketed by Thorlabs.*
Vertical Cavity Surface Emitting Lasers (VCSEL)

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

\[ n_1 d_1 + n_2 d_2 = \frac{1}{2} \lambda \]
VCSEL as a Microlaser

Left: A packaged addressable VCSEL array with 8×8 individually addressable laser devices. The chip is 3 mm × 3 mm. Right: A closer view of the chip. (Courtesy of Princeton Optronics, USA)
Semiconductor Optical Amplifier

Traveling wave (TW) semiconductor optical amplifier:
- Antireflection (AR) coatings at the ends
- The optical cavity is not an efficient optical resonator
- Laser oscillations are therefore prevented.
- As the radiation propagates it becomes amplified

The FP SOA is basically a **regenerative amplifier** in which positive feedback; reflections back into the cavity from the end mirrors.
Covega semiconductor optical amplifier (SOA) for use as a booster amplifier in the O-band (around 1285 nm). The small signal gain is 27 dB and the NF is 7 dB (Courtesy of Thorlabs).

A Semiconductor Optical Amplifier (SOA) for use at 1050 nm.
Fiber Optic Communications

DFB/DBR Lasers
- High threshold
- Non-planar
- Integration
- Slow
- Expensive

Array waveguide grating

Optical-electronic Conversion:
- For switching & routing
- Very expensive
- Time consuming

milimeter size components
**pn Junction Photodiode**

- Photodetector: Converts incident light to an electrical signal (voltage or current)

- Photons generates electron hole pairs -EHP (photogeneration)
- Separates charged carriers (electrons and holes)
- Annular electrode for light to enter
- Antireflection (AR) coatings at the ends
- Highly doped p⁺ region (1 micron thick)
- Depletion zone extends to n-region (few microns)
- Reverse biased (5-20 V) much larger than $V_0=1V$
- Drifting carriers cause photocurrent
Photogeneration inside the SCL generates an electron and a hole.

Both fall their respective energy hills i.e. they drift, and cause a photocurrent $I_{ph}$ in the external circuit.

Photogeneration occurs in the neutral region.

The electron has to diffuse to the depletion layer and then roll down the energy hill i.e. drift across the SCL.