ECE 536
Integrated Optics and Optoelectronics
TuTh 11:00-12:20, 3020 ECEB
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Office Hours: Tuesday 1:00-2:00 pm
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**Subject to Change**
Today’s Discussion

• Light Output
• LEDs and Lasers
• Waveguides with Gain and Loss
• Assignments
• Topics for Next Lecture
Light Power Output
Photon Density “S”

Above threshold, gain is pinned. As current increases beyond threshold, excess carriers must be converted into photons:

$$\eta_i \frac{J}{qd} = \left( A n_{th} + B n_{th}^2 + C n_{th}^3 \right) + v_g g_{th} S$$

recall at threshold:

$$\eta_i \frac{J_{th}}{qd} = \left( A n_{th} + B n_{th}^2 + C n_{th}^3 \right)$$

therefore:

$$v_g g_{th} S = \eta_i \frac{(J - J_{th})}{qd} \quad \Rightarrow \quad S = \frac{\eta_i (J - J_{th})}{qdv_g g_{th}}$$

The photon lifetime is the loss rate of photons due to absorption and transmission at the end facets:

$$\frac{1}{\tau_p} = v_g \left( \alpha_i + \alpha_m \right) = v_g \Gamma g_{th}$$

Combining this with the expression for S:

$$\frac{S}{\tau_p} = \left( \frac{\eta_i (J - J_{th})}{qdv_g g_{th}} \right) (v_g \Gamma g_{th}) = \eta_i \frac{(J - J_{th})}{qd} \Gamma$$
Light Output Intensity

\[ P_{\text{out}} = \left( \text{Energy of a photon} \right) \left( \text{Photon Density} \right) \left( \text{Effective volume of the optical mode} \right) \left( \text{Escape rate of photons} \right) \]

\[ = (\hbar \omega)(S)(wLd_{\text{op}})(v_g \alpha_m) \]

Since \( d_{\text{op}} = \frac{d}{\Gamma} \) and \( I = wLJ \)

\[ P_{\text{out}} = \eta_i \frac{\hbar \omega}{q} \frac{\alpha_m}{\alpha_i + \alpha_m} (I - I_{\text{th}}) \]

The external quantum efficiency is defined as:

\[ \eta_e = \frac{dP_{\text{out}}}{dI} = \eta_i \frac{\alpha_m}{\alpha_i + \alpha_m} = \eta_i \frac{\ln(1/R)}{\alpha_i L + \ln(1/R)} \]

also

\[ \eta_e^{-1} = \eta_i^{-1} \left[ 1 + \frac{\alpha_i L}{\ln(1/R)} \right] \]

Plotting \( \eta_i^{-1} \) versus \( L \) is a line with a y-intercept of \( \eta_i^{-1} \)

The slope divided by the y-intercept is \( \frac{\alpha_i}{\ln(1/R)} \) and can determine \( \alpha_i \).
**Leakage Current**

**Leakage Current**:
Consider a device with leakage current $I_L$.
For example, this can occur in ridge waveguide lasers.
Current spreads from the p-contact and stimulated emission is weak at the edges since the laser intensity is weaker than at the center. So, the carriers can leak by at the edges (carrier density partially pinned).

$$I = I_A + I_L = JwL + I_L$$

Leakage current causes the threshold current to be larger:

$$I_{th} = J_{th}wL + I_{L@th} = \frac{q n_{th}(wLd)}{\eta_i \tau_e(n_{th})} + I_{L@th}$$

Revised Expression for $P_{out}$:

$$P_{out} = \eta_i \frac{\hbar \omega}{q} \frac{\alpha_m}{\alpha_m + \alpha_i} (I - I_{th} - \Delta I_L)$$
Characteristic Temperatures

Due to the temperature dependence of \( g(\hbar \omega) \) and of many other processes (e.g. Auger recombination), the laser threshold and efficiency vary with temperature.

**Variation with temperature:**

- \( I_{th} \) typically increases with temperature
  \[
  I_{th}(T) = \{\text{constant}\} e^{T/T_0} = I_{th}(T_a) e^{(T-T_a)/T_0}
  \]

- \( \eta_e \) typically decreases with temperature
  \[
  \eta_e(T) = \{\text{constant}\} e^{-T/T_i} = \eta_e(T_a) e^{-(T-T_a)/T_i}
  \]

http://ars.els-cdn.com/content/image/1-s2.0-S0038110199002531-gr1.gif
Saturation of Laser Output Power

- Increasing leakage current
- Junction heating
- Increasing internal absorption $\alpha_i$
LEDs Versus Lasers

Spontaneous Emission and ASE
LEDs for Display Versus Communication

Display

Communication

Critical Angle

http://www.fiberopticproducts.com/Led.ht14.gif
Also: E.F. Schubert, Light Emitting Diodes
"Window" Light:

\[ L_w(\hbar \omega) = \hbar \omega \, r^{\text{spon}}(\hbar \omega) \, w dL \]

Facet Light (ASE):

\[ L_F(\hbar \omega) = \hbar \omega w d \int_{z=0}^{L} r^{\text{spon}}(\hbar \omega) e^{G_n(\hbar \omega)z} \, dz \]

\[ = \hbar \omega w d \, r^{\text{spon}}(\hbar \omega) \left[ \frac{e^{G_n(\hbar \omega)L} - 1}{G_n(\hbar \omega)} \right] \]

where \( G_n(\hbar \omega) = \Gamma g - \alpha_i \)
ASE Versus Window Light

\[
\ln \left( \frac{L_F}{L_w} \right) \propto \ln \left( \frac{e^{G_nL} - 1}{G_n} \right) \sim \left( \Gamma g_n - \alpha_i \right) L
\]

For \( G_n L \gg 1 \)
Carrier Pinning

(a) LED \((T = 25^\circ C)\)

(b) LED \((T = 55^\circ C)\)

Carrier density \(n \left(10^{18} \text{ cm}^{-3}\right)\)

Current \(I\) (mA)

\(I_{th} = 9.7\) mA

\(I_{th} = 21.5\) mA

LD \((T = 25^\circ C)\)

LD \((T = 55^\circ C)\)
ASE and Optical Gain Measurements
Optical Fields in a Fabry - Perot Cavity (revisited)

Initial Field: \( E_{sp}(\lambda) \)

Field After Single Pass: \( E'(\lambda) = E_{sp}(\lambda) + E_{sp}(\lambda)r_1r_2e^{i2kL} \)

General Expression: \( E_{ASE}(\lambda) = E_{sp}(\lambda)\left[1 + r_1r_2e^{i2kL} + (r_1r_2e^{i2kL})^2 + (r_1r_2e^{i2kL})^3 + ... \right] \)

Using the fact that \( \left[1 + a + a^2 + a^3 + ... \right] = \frac{1}{1-a} \)

\( E_{ASE}(\lambda) = \frac{E_{sp}(\lambda)}{1-r_1r_2e^{i2kL}} \) where \( k = k' - i\frac{G_n}{2} = \frac{2\pi}{\lambda} n_e - i\frac{G_n}{2} \) and \( G_n = \Gamma g - \alpha_i \)

\( n_e \) is the effective index, \( G_n = \Gamma g - \alpha_i \) is the net modal gain

ASE Power Spectrum:

\( P(\lambda) \propto \left| E_{ASE}(\lambda) \right|^2 = \left| \frac{E_{sp}(\lambda)}{1-r_1r_2e^{i2kL}} \right|^2 = \frac{\left| E_{sp}(\lambda) \right|^2}{\left(1-A\right)^2 + 4Asin^2(k'L)} \)

\( A = \sqrt{R_1R_2}e^{G_nL} \) where \( R_1 = \left|r_1\right|^2 \) and \( R_2 = \left|r_2\right|^2 \)
Modal Gain from ASE Spectra

\[ P(\lambda) \propto I(\lambda) = |E_{ASE}(\lambda)|^2 = \frac{|E_{sp}(\lambda)|^2}{|1 - r_1 r_2 e^{i2kL}|^2} = \frac{|E_{sp}(\lambda)|^2}{(1 - A)^2 + 4A\sin^2(k'L)} \]

Maximum of ASE Spectrum: \( k'L = m\pi \) and \( I_{\text{max}} = \frac{|E_{sp}(\lambda_{\text{max}})|^2}{(1 - A)^2} \)

Minimum of ASE Spectrum: \( k'L = \left( m + \frac{1}{2} \right)\pi \) and \( I_{\text{min}} = \frac{|E_{sp}(\lambda_{\text{min}})|^2}{(1 + A)^2} \)

Taking the ratio (nearby ASE peaks): \( \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{(1 + A)^2}{(1 - A)^2} \)

Solving for \( A \): \( A = \sqrt{\frac{I_{\text{max}}}{I_{\text{min}}} + 1} - 1 = \sqrt{R_1 R_2} e^{G_n L} \)

Solving for \( G_n \): \( G_n = \frac{1}{L} \ln \left[ \sqrt{\frac{I_{\text{max}}}{I_{\text{min}}} + 1} - 1 + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right] \)

\( G \) is the net modal gain.

Note: \( G_n(\lambda) = \Gamma g(\lambda) - \alpha_i = Q_r + \alpha_m \) where \( Q_r = \frac{1}{L} \ln \left[ \sqrt{\frac{I_{\text{max}}}{I_{\text{min}}} + 1} - 1 \right] \)
Hakki-Paoli Method for Gain Measurement

- Measure ASE spectrum
- Take the ratio of the magnitude of $I_{\text{max}}$ and $I_{\text{min}}$ for the peaks near the $m^{th}$ mode $\lambda_m$
- Calculate the mirror reflectivity and either measure the cavity length or calculate it from the measured mode spacing and the effective index $\eta_e$
- Gain is then calculated using $G_n(\lambda) = Q_r + \alpha_m$
Cassidy’s Method: A Variant of H-P

Based on the Hakki-Paoli method, except that the ratio: $I_{\text{avg}} / I_{\text{min}}$ is computed.

You can show $I_{\text{avg}} = \sqrt{I_{\text{max}} \cdot I_{\text{min}}}$. So, just modify previous derivation to extract the modal gain.

–Main advantage is that $I_{\text{avg}}$ is more accurate to measure than $I_{\text{max}}$, since $I_{\text{max}}$ depends greatly on the instrument’s resolution and its response function.

–Alternatively, you could use the ratio: $I_{\text{max}} / I_{\text{avg}}$ if the data is noisy or if $I_{\text{max}}$ is more accurate than $I_{\text{min}}$.

JAP 56, 3096 (1984)
JQE 41, 532 (2005)

http://scitation.aip.org/content/aip/journal/jap/56/11/10.1063/1.333867
Other Methods to Measure Gain

Method 2:
- Measure spontaneous emission spectra
- Fit to gain relationship using $\Delta F = F_2 - F_1$ as fitting parameter

$$g(\hbar \omega) = \left( \frac{\pi^2 \hbar c^2}{n_r^2 \omega^2} \right) \left( 1 - e^{\frac{\hbar \omega - (F_2 - F_1)}{k_B T}} \right) r^{\text{spont}}(\hbar \omega)$$

Method 3:
- AC modulated probe beam at wavelength near quasi-Fermi separation
- Measure AC induced voltage as wavelength is tuned
- Look for sign change in induced voltage – when induced voltage changes sign the probe laser wavelength is at the transparency energy

Characteristics of the G-λ Plot

- Below the band edge, gain is negligible and \( G_n(\lambda) \) approaches \( -\alpha_i \).
- The peak gain occurs at the laser threshold gain \( G_n(\lambda) = \Gamma g_{th} - \alpha_i = \alpha_m \).

\[
\Delta F = F_n - F_p
\]

\[
\Gamma g_{th} = \alpha_i + \alpha_m
\]
Comparison of Gain Measurement Methods
Assignments
Assignments

• Reading
  – Physics of Photonic Devices (S.L. Chuang)
    • Tues 2/12: §’s 9.6 & 9.7
    • Thurs 2/14: § 10.1
    • Tues 2/19: §’s 7.6 & 10.2
    • Thurs 2/21: § 10.3 in Chuang and § 8.2.5 in C&C
    • Tues 2/26: § ’s 4.5 & 10.4
  – Diode Lasers and Photonic Integrated Circuits (Coldren & Corzine)
    • § 8.2.5
    • Appendix 1, 2, 3, 9 (Supplemental)

• Think about Partner for Project
Topics for Next Lecture
Agenda for Thursday, 2/21

• Continue Scaling Laws
Thank You for Listening!
Course Purpose & Objectives
Course Purpose

- Cover the theory and design of semiconductor devices used in optical communication systems and electronic-photonic integrated circuits
Course Objectives

• Discuss, at a graduate level, key topics in semiconductor physics
• Discuss, at a graduate level, key topics in electromagnetics as applied to photonic devices
• Provide an understanding of active photonic devices used in optical communication systems and photonic integrated circuits
• Provide an understanding of passive photonic devices used in optical communication systems and photonic integrated circuits
Overlap With ECE/PHYS Courses

Quantum Mechanics (PHYS 486/487)

Semiconductor Physics (ECE 488)

E&M (ECE 452/520)

ECE 536
Course Schedule
**Tentative Schedule [1]**

| JAN 15: Course Overview, Intro to Optoelectronics & Communication, Maxwell’s Equations | JAN 17: Semiconductor Electronics |
| JAN 22: Generation and Recombination in Semiconductors | JAN 24: Basic Quantum Mechanics and Square Wells |
| JAN 29: Time-Dependent Perturbation Theory, Fermi’s Golden Rule | JAN 31: Symmetric Optical Waveguides, Dispersion Relations |
| FEB 5: Optical Transitions Using Fermi’s Golden Rule | FEB 7: Interband Absorption and Gain of Bulk Semiconductors and Quantum Wells |

**Subject to Change**
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# Tentative Schedule [3]

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<td>MAY 2: Reading Day (no class) Final Exam: Class Presentations</td>
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**Subject to Change**
Grading, Expectations, and Policies
Determination of Grade

• Homework: 20%
• Exam I: 25%
• Exam II: 25%
• Class Participation & Term Project Presentation: 15%
• Term Project Report: 15%
Homework

• Assigned per posted class schedule on Thursdays, due 1 week later

• TA is Fu-Chen Hsiao, 3211 MNTL
  – Office hours Wednesday from 10-11am, 4034 ECEB
  – TA: good first contact for questions on homework

• Do not copy solutions from others in class or from other sources
Term Project

• Collaborative presentation: teams of 2
• Individual paper
• Details and a list of topics will be provided in early February
Expectations

• Diligence
  – Attend class & participate

• Honesty
  – No cheating on exams or homework
  – Original work on term project
  – Accurate/legitimate representation of any issues affecting homework/exams/project

• Mutual Respect

• Maturity
  – Graduate-level class
Policies

- Where applicable, general university policies on academic affairs will be used.
- Any issues involving homework, exams, semester project, etc. should be disclosed and discussed as soon as the issue is known.
Text Errata
Text Errata

- Text errata provided by Professor Chuang will be posted on the class website
  - I will include additional errata in the lecture slides
- Handout: inside book cover
- Additional errata:
  - Equation 3.2.18 “=“ should be “>”
    - $|z| > L/2$
  - Equation 3.2.23 “=“ should be “<“
    - $|z| < L/2$
  - Equation 3.2.23: “L/2” not “L2” in exponent
1) Equation 1.3.1 should be:
\[ a(A_x B_{1-x} C) = x a(AC) + (1 - x) a(BC) \]
where \( a(AC) \) is the lattice constant of the binary compound AC and...

2) Equation 1.3.2 should be:
\[ E_g(A_x B_{1-x} C) = x E_g(AC) + (1 - x) E_g(BC) - bx(1-x) \]

3) Other printing errors in book - see errata posted on website

Errors in some copies of Second Edition
Errata

• Equation 3.6.15 should be:

\[ a_m^{(0)} (t = 0) = 0 \quad \text{not} \quad a_m^{(0)} (t) = 0 \]
• Pg. 41, top of page, between equations 2.3.3 and 2.3.4
• Current Text is: “0 = Bn_o p_o = e_r”
• Should Be: “0 = Bn_o p_o - e_r”

The consequence of this is that $Bn_o p_o = e_r$ in equilibrium where there is no optical generation or electrical injection of carriers.
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