Semiconductor Lasers

ECE 162C
Lecture #11
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Read Kasip, Chapters 3, 4
Presentations

• Please prepare a 10 minute presentation (max 10 slides) on a topic of current research.
• The grade is based on your ability to teach your classmates, not how much material can be covered, or how complex your derivation is.
• Schedule next Monday.
• Look at recent OFC proceedings, Optics Express, PTL to see current topics.
• Examples:
  – Quantum communication
  – Single photon transmission/reception
  – Multilevel communication
  – GaInAsNSb lasers
  – Quantum cascade lasers
  – Tunable lasers
• Handout original paper and copies of slides (4/page). Christine can make copies for you.
Laser Requirements

• Confinement of the optical mode
  – Transverse
  – Lateral (rib, strip, gain guided)
  – Longitudinal (cleaved facets, rings, DFB, DBR,…)

• Confinement of carriers
  – Heterojunction, etched, no confinement (implanted, diffused,…)

• Confinement of current
  – Oxide
  – Homojunction
  – PN junction
  – Semi-insulating
Laser Requirements

- Large Bandwidth
- High Modulation efficiency
- Low Intensity Noise
- Large Temperature Range
- Low Distortion
- Low Reflection Sensitivity
- Low Chirp

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Single Mode Lasers

- At least 3 cm\(^{-1}\) of gain difference between the dominant mode and other modes is required.
  - Less gain difference: The laser may lase cw in a single mode, but lases in multiple modes when modulated.
  - More gain difference necessary to achieve 40 dB sidemode suppression under 100% modulation.
Bandwidth Limiting Factors

- Resonance Frequency
  - Current or power limited
- Damping
  - Spectral hole burning or
  - carrier heating limited
- Transport
  - Diffusion or tunneling limited
- Parasitics
  - Capacitance and resistance limited
- Microwave Effects
  - Microwave loss limited
Rate Equations

Neglecting the phase of the optical field, the length dependence of the carrier and photon densities, and the modal dependence; the rate equations for the averaged photon and carrier densities become:

\[
\frac{dS}{dt} = \frac{\Gamma v_g a (N - N_{tr})}{1 + \varepsilon S} S - \frac{S}{\tau_p} + \frac{\beta \Gamma N}{\tau_n}
\]

\[
\frac{dN}{dt} = \eta_i \frac{I}{qV} - \frac{v_g a (N - N_{tr})}{1 + \varepsilon S} S - \frac{N}{\tau_n}
\]
Rate equations:
Small Signal Approximation

Making the usual small signal approximation:

\[ I = I_0 + ie^{j\omega t} \]
\[ S = S_0 + se^{j\omega t} \]
\[ N = N_0 + ne^{j\omega t} \]

We find the small-signal modulation response of the laser:

\[ H(f) = \frac{s(f)}{i(f)} = \frac{s(0)}{i(0)} \frac{f_0^2}{f_0^2 - f^2 + jff_d} \]

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Rate Equation: 
Intrinsic Frequency Response

The damping frequency is:

\[ f_d \approx \frac{\varepsilon S}{2\pi \tau_p} \]

The resonance frequency is at the geometric mean of the photon and carrier lifetimes:

\[ f_0 = \frac{1}{2\pi \sqrt{\tau_p \tau_n^{\text{stim}}}} \]

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The photon lifetime, typically on the order of 1 ps, is given by:

\[
\tau_p = \frac{1}{\nu_g \left( \alpha_i + \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right) \right)}
\]

Far above threshold, spontaneous emission can be neglected, and the stimulated electron lifetime becomes:

\[
\tau_{n,\text{stim}} = \frac{1}{\nu_g aS}
\]
Resonance Frequency

From the previous we get the following expression for the resonance frequency:

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{\nu_g aS}{\tau_p}} = \frac{1}{2\pi} \sqrt{\frac{\nu_g a\eta}{\tau_p}} (I - I_{th}) \]

Note that the peak in modulation response is not at \( f_0 \), but at \( f_p \), given by:

\[ f_p^2 = f_0^2 - \frac{f_d^2}{4} \]

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Modulation Response

The resonance frequency and modulation bandwidth depends on the output power:

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{v_g a S}{\tau_p}} = D\sqrt{P} \]
Bandwidth Relations

Depending on the application, different bandwidths are specified. From the general expression for the modulation response we find:

\[ f_{0dB} = \sqrt{2} f_0 \]
\[ f_{3dB} \approx \sqrt{1 + \sqrt{2} f_0} \]
\[ f_{6dB} \approx \sqrt{3} f_0 \]

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Resonance Frequency Limitations

For most lasers the resonance frequency is limited by the current density due to:

- Leakage currents due to breakdown of p-n junctions or semi-insulating layers
- Conduction across the active layer at high current densities
- Heating (proportional to $I^2R$)

For a given current density higher resonance frequency is obtained with:

- Higher differential gain
- Shorter cavity length
- Small mode volume
Facet Coatings

Can we coat the facets to achieve higher bandwidth?

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{\Gamma \nu_g a \eta_i I}{eV} - \frac{\Gamma \nu_g a \eta_i N_{tr}}{\tau_n} - \frac{\eta_i \nu_g}{\tau_n} \left( \alpha_i + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right)} \]

HR coating increases modulation bandwidth

A. Mar et al., Electron. Lett. 26 (17), 1382 (1990)
Bandwidth Limiting Factors

- **Resonance Frequency**
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  - Capacitance and resistance limited

- **Microwave Effects**
  - Microwave loss limited
Limits to Bandwidth: Damping

Modulation bandwidth is limited by damping due to non-linear gain.

\[ g = \frac{g_0}{1 + \epsilon S} \]

Important causes of non-linear gain are:
- Spectral hole burning
- Carrier heating
Damping

Damping is described by the damping factor $K$, defined as:

$$ f_d = K f_0^2 $$

It can be shown that

$$ K = 4\pi^2 \left( \tau_p + \frac{\varepsilon}{a} \right) $$

Damping limits the maximum bandwidth to:

$$ f_{3dB}^{\text{max}} = \frac{2\pi \sqrt{2}}{K} \approx \frac{8.8}{K} $$

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Bandwidth Limiting Factors

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Transport Effects

Important transport processes in separate confinement heterostructure (SCH) laser

- Diffusion, $\tau_r$
- Thermionic emission, $\tau_e$
- Tunneling, $\tau_t$
- Carrier capture, $\tau_c$
When transport effects are included, the rate equations are modified

\[
\frac{dN_B}{dt} = \frac{I}{qV_{SCH}} - \frac{N_B}{\tau_r} + \frac{N_W(V_W/V_{SCH})}{\tau_e}
\]

\[
\frac{dN_W}{dt} = \frac{N_B(V_{SCH}/V_W)}{\tau_r} - \frac{N_W}{\tau_n} - \frac{v_g a(N_W - N_{tr})S}{(1 + \varepsilon S)}
\]

\[
\frac{dS}{dt} = \frac{\Gamma v_g (N_W - N_{tr})S}{(1 + \varepsilon S)} - \frac{S}{\tau_p} + \frac{\beta \Gamma N_W}{\tau_n}
\]
Transport Effects: Modulation Response

The modulation response and damping factor then become:

\[
R(\omega) = \frac{\omega_0^2}{(1 + j\omega \tau_r)(\omega_0^2 - \omega^2 + j\omega \gamma)}
\]

\[
\omega_0^2 = \frac{\left(\frac{a}{\chi}\right)S}{\tau_p(1 + \varepsilon S)} \quad \chi = 1 + \frac{\tau_r}{\tau_e}
\]

\[
K = 4\pi^2\left(\tau_p + \chi \frac{\varepsilon}{a}\right)
\]

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Transport Effects

Exact numerical solution to rate equations compared to analytical approximation

![Graph showing response in dB against frequency (GHz) with exact and analytical solutions, and a note: Width of SCH = 3000 Å]
Transport Effects
Results from the Model

• Severe roll off in the modulation response due to transport across the SCH region ($\tau_r$). This roll off is independent of:
  - Reduction of differential gain
  - Gain compression
  - Device parasitics

• Transport effects causes reduction of effective differential gain
  $$a \rightarrow \frac{a}{\chi}$$

• Gain compression factor is independent of SCH width
Transport effects

Carrier transport time between two quantum wells in a multiple quantum well (MQW) laser

Transport Effects:
SCH width

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Transport Effects: Cavity Length

Modulation Bandwidth (GHz)

Cavity Length (μm)

1 QW
Bandwidth Limiting Factors

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Laser Parasitics

Device and package parasitics can cause significant reduction in modulation response

- Junction capacitance $C$
- Bond pad capacitance $C_{bp}$
- Series resistance $R_s$
- Bond wire inductance $L$

Example: To achieve 15 GHz bandwidth:

- $C < 2pF$
- $C_{bp} < 2pF$
- $R_s < 4\Omega$
- $L < 0.3nH$
Parasitics

Parasitic limited 3 dB bandwidth contours

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Laser Impedance

Model for laser impedance, consisting of bond-wire inductance, parasitic capacitance and series resistance.

Measurements show microwave characteristics of two mounted laser structures:

- a constricted mesa laser
- a high power dual-channel planar buried heterostructure laser (DCPBH)

Inductance and resistance are determined from measurement of forward biased laser (as shown). Capacitance can be found from reverse biased measurement.
Relative Intensity Noise

- Recombination and generation are stochastic processes -> variations in output power
- Relative Intensity Noise:
  \[ RIN \equiv \frac{\langle \delta P(t)^2 \rangle}{P_0^2} \]
- RIN spectrum related to modulation response:

\[
RIN(\omega) = \frac{2h\nu}{P_0} \left[ \frac{a_1 + a_2 \omega^2}{\omega_R^4} \left| H(\omega) \right|^2 + 1 \right]
\]

RIN
Optical Fiber Communication

- Relative intensity noise cause degradation of Signal-to-Noise Ratio in analog systems, and errors in digital systems
- Analog signal:
  \[ SNR = \frac{2}{m^2} \frac{1}{RIN} \]
- Digital signal, for BER<10^{-9}
  \[ RIN < (11.89)^{-2} \]

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Analog Transmission

- High-speed analog transmission for CATV and wireless communication

- Issues:
  - Noise (RIN)
  - Chirp
  - Linearity

- Non-linearity causes Inter-Modulation Distortion (IMD)
  - Typical system requirement
    - IMD3 < -80dBc

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