Semiconductor Lasers

ECE 162C
Lecture #11
Prof. John Bowers

Read Kasip, Chapters 3,4

Presentations

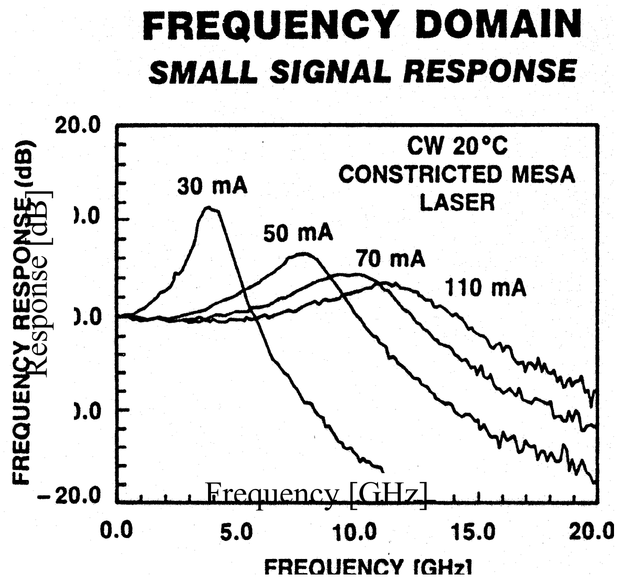
- Please prepare a 10 minute presentation (max 10 slides) on a topic of current research.
- The grade is based on your ability to teach your classmates, not how much material can be covered, or how complex your derivation is.
- Schedule next Monday.
- Look at recent OFC proceedings, Optics Express, PTL 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.

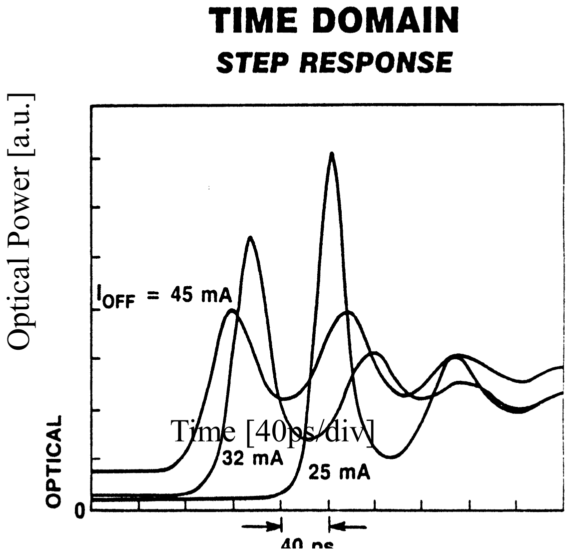
Laser Requirements

- 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



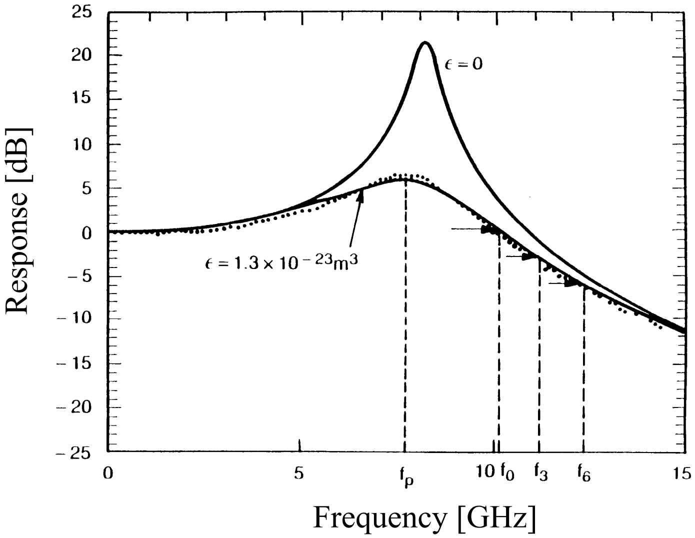


Single Mode Lasers

- 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:

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

$$\frac{dN}{dt}=\eta_i\frac{I}{qV}-\frac{v_g a(N-N_{tr})}{1+\varepsilon S}S-\frac{N}{\tau_n}$$

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:

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

T. Ikegami and Y. Suematsu, Elecron. Comm. Jap. 51-B, **51** (1968)

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:

$$f_0 = \frac{1}{2\pi\sqrt{\tau_p \tau_n^{stim}}}$$

J.E. Bowers, Solid State Electronics, vol. 30, no. 1, pp. 1-11(1987)

Rate Equations: Resonance Frequency

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

$$\tau_p = \frac{1}{v_g\left(\alpha_i + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)\right)}$$

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

$$\tau_n^{stim} = \frac{1}{v_g a S}$$

Resonance Frequency

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

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{v_g a S}{\tau_p}} = \frac{1}{2\pi}\sqrt{\frac{v_g a \eta}{\tau_p}\left(I - I_{th}\right)}$$

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

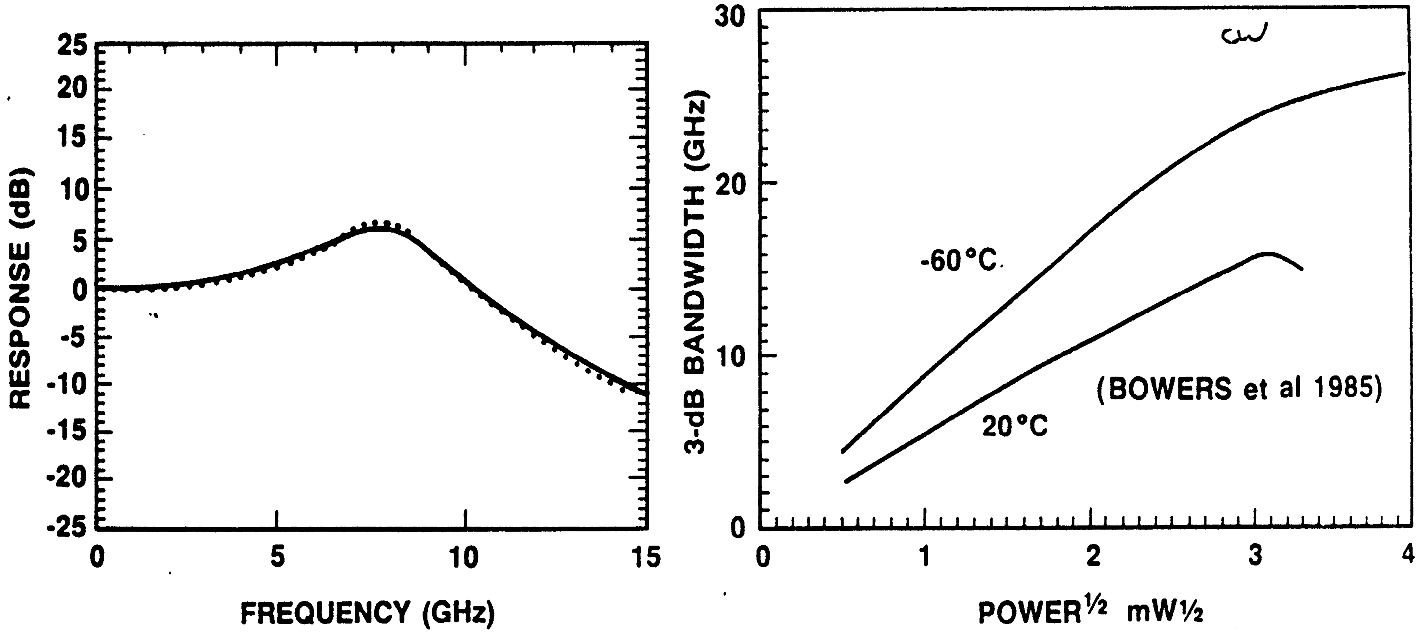
$$f_p^2 = f_0^2 - \frac{f_d^2}{4}$$

J.E. Bowers, Solid State Electronics, vol. 30, no. 1, pp. 1-11(1987)
K.Y. Lau and A. Yariv, IEEE J. Quantum Electron. QE-21, 121(1985)

Modulation Response

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

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{v_g a S}{\tau_p}} = D\sqrt{P}$$



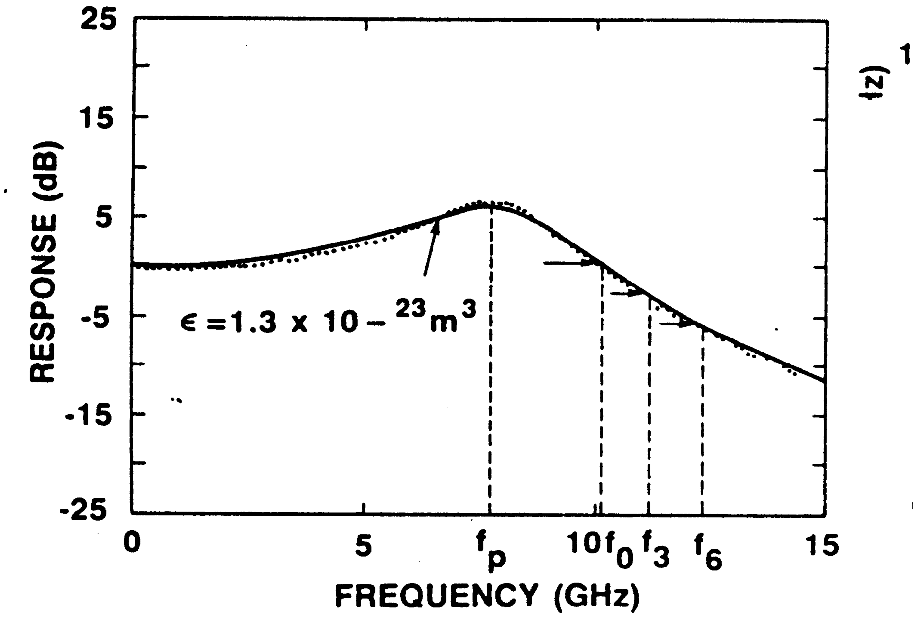
Bandwidth Relations

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

$$f_{0dB} = \sqrt{2}\, f_0$$

$$f_{3dB} \approx \sqrt{1+\sqrt{2}}\, f_0$$

$$f_{6dB} \approx \sqrt{3}\, f_0$$



J.E. Bowers, B.R. Hemenway, A.H. Gnauck and D.P. Wilt, IEEE J. Quantum Electron. QE-22, 833(1986)

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)

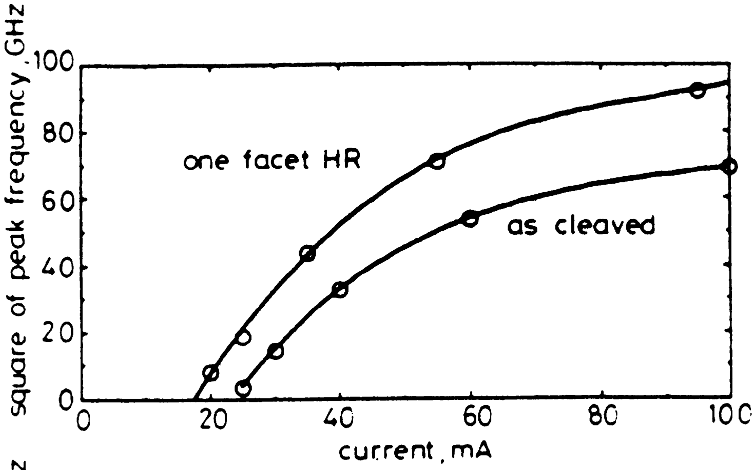
For a given current density higher resonance frequency is obtained with:

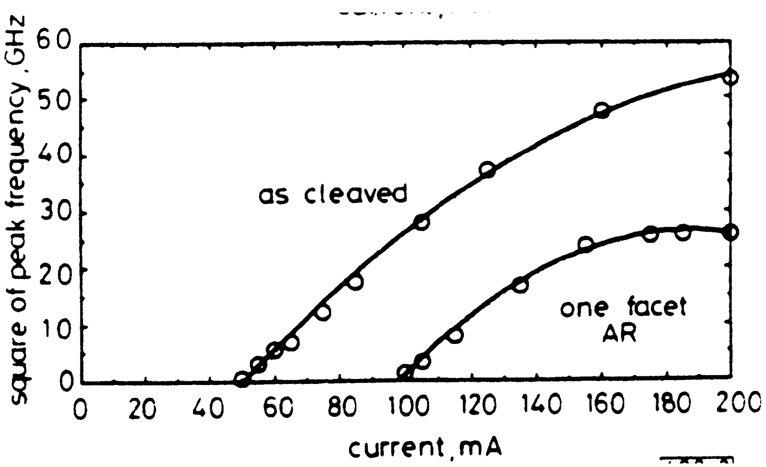
- Higher differential gain
- Shorter cavity length
- Small mode volume

Facet Coatings

Can we coat the facets to achieve higher bandwidth?

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





HR coating increases modulation bandwidth

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

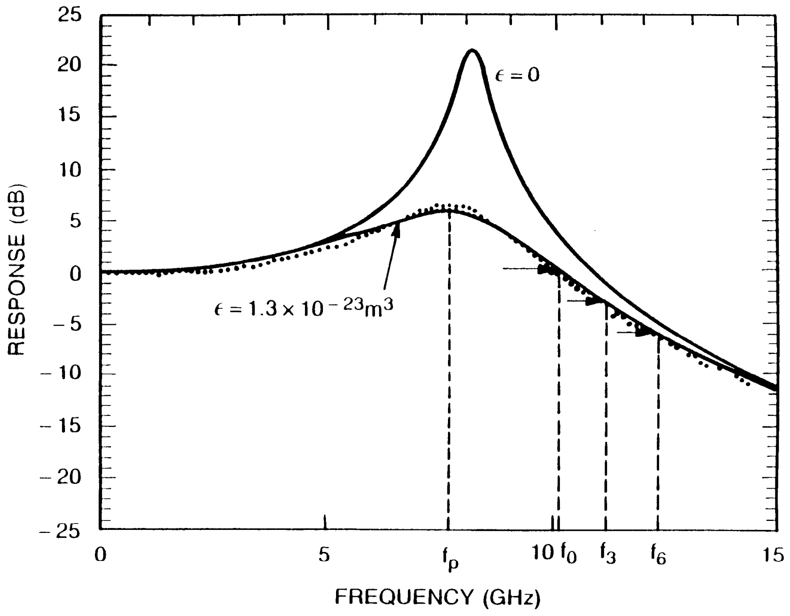
Bandwidth Limiting Factors

- Resonance Frequency
  - 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

Limits to Bandwidth: Damping

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

$$g=g_0/(1+\varepsilon S)$$



Important causes of non-linear gain are:

- Spectral hole burning
- Carrier heating

Damping

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

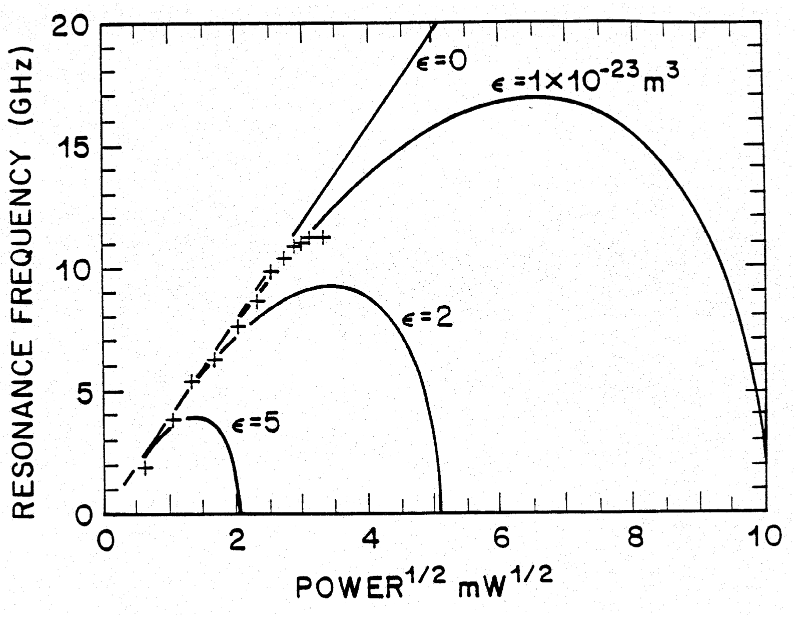
$$f_d = K f_0^2$$

It can be shown that

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

Damping limits the maximum bandwidth to:

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



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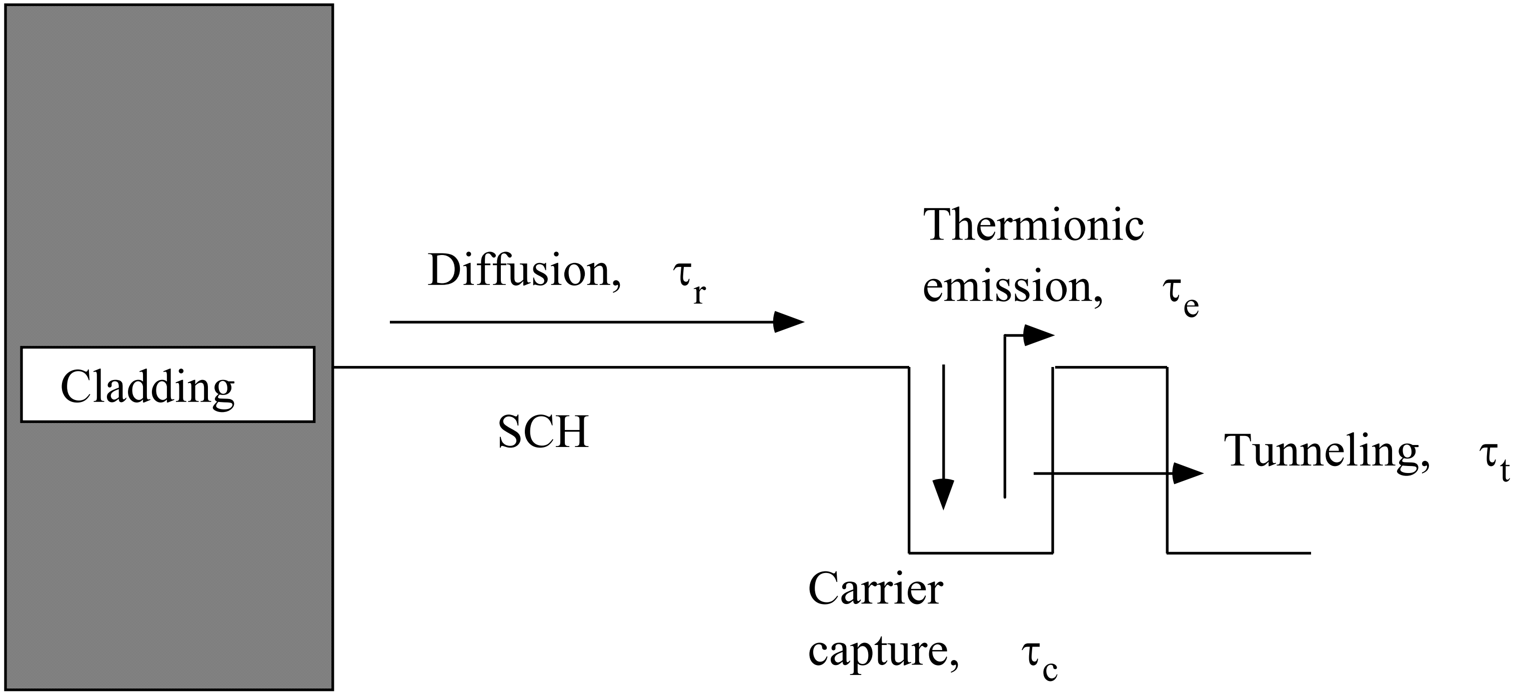
Transport Effects

Important transport processes in separate confinement heterostructure (SCH) laser



Transport Effects : Rate Equations

When transport effects are included, the rate equations are modified

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

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

$$\frac{dS}{dt} = \frac{\Gamma v_g\left(N_W - N_{tr}\right)S}{\left(1+\varepsilon S\right)} - \frac{S}{\tau_p} + \beta\Gamma\frac{N_W}{\tau_n}$$

R. Nagarajan et al., Photonics Tech. Lett., vol. 4, no. 2, 121(1992)

Transport Effects:
Modulation Response

The modulation response and damping factor then become:

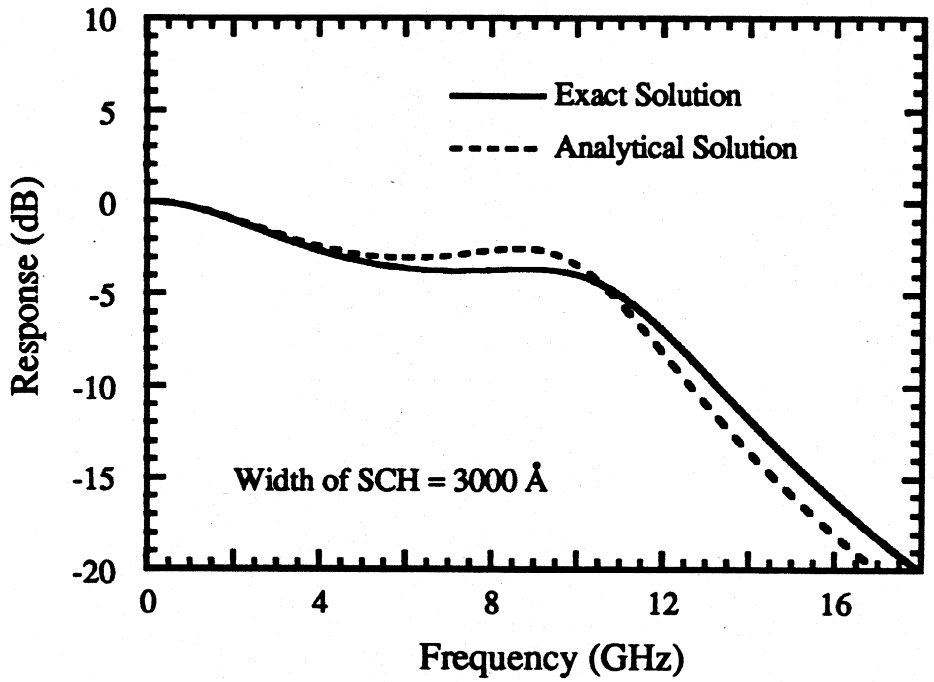
$$R(\omega) = \frac{\omega_0^2}{(1 + j\omega\tau_r)(\omega_0^2 - \omega^2 + j\omega\gamma)}$$

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

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

Transport Effects

Exact numerical solution to rate equations compared to analytical approximation



Transport Effects
Results from the Model

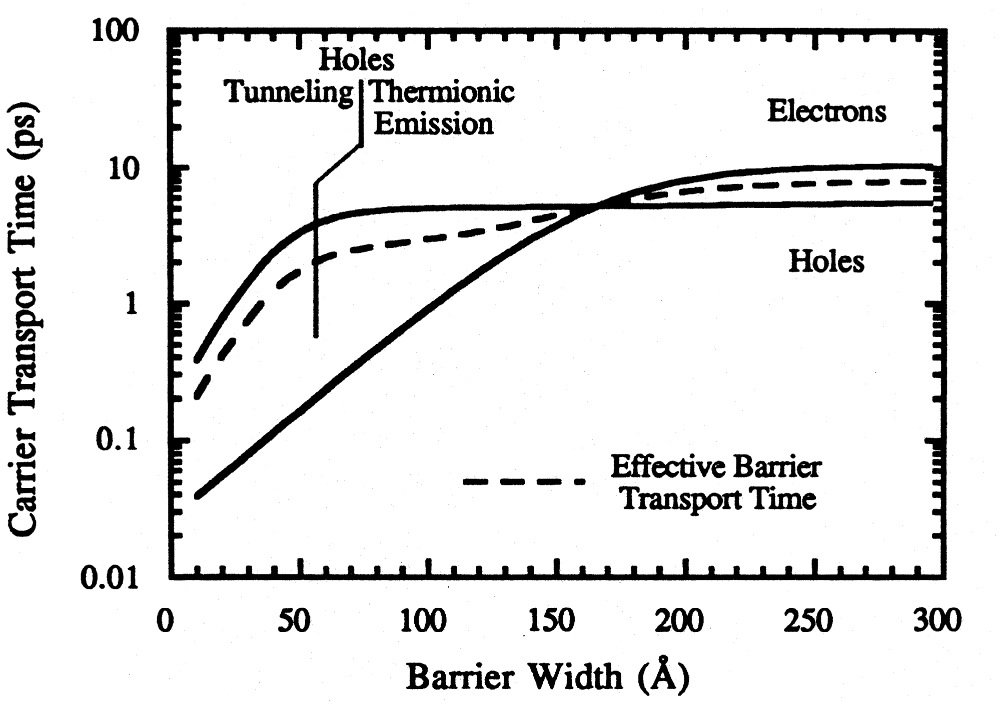
- Severe roll off in the modulation response due to transport across the SCH region (τ_r). This roll off is independent of:
  - Reduction of differential gain
  - Gain compression
  - Device parasitics
- Transport effects causes reduction of effective differential gain

$$a \rightarrow \frac{a}{\chi}$$

- Gain compression factor is independent of SCH width

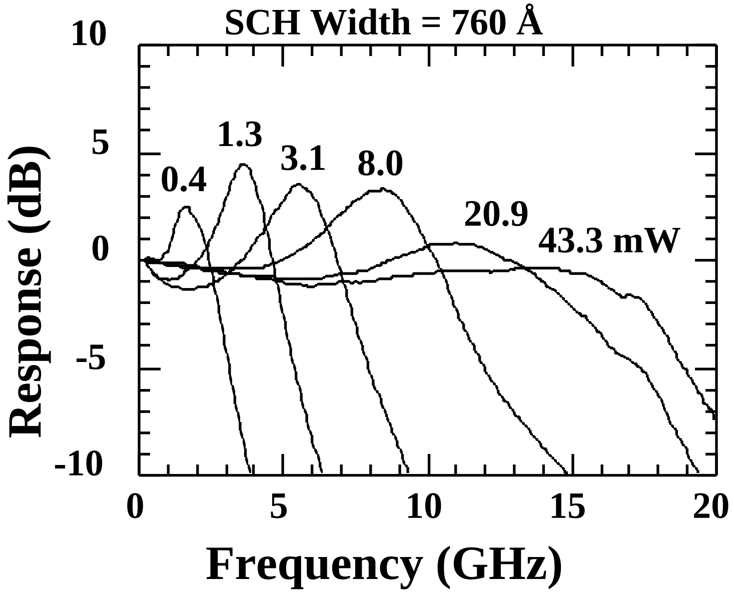
Transport effects

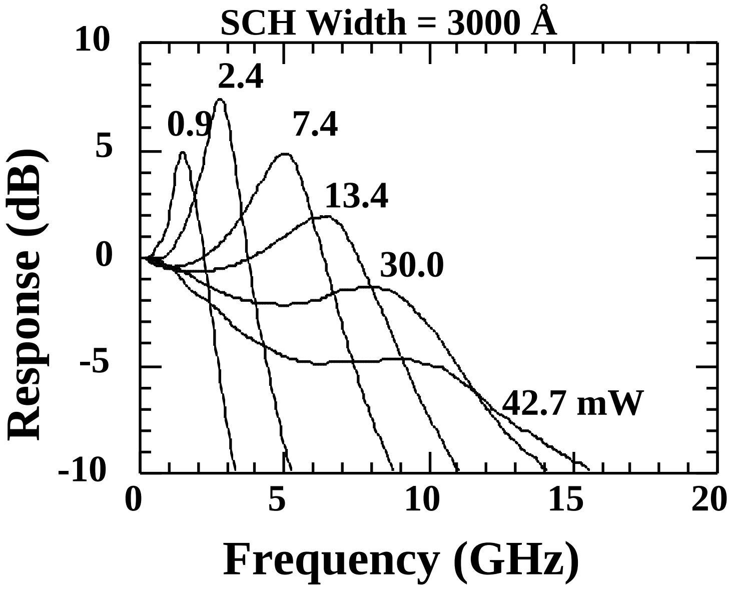
Carrier transport time between two quantum wells in a multiple quantum well (MQW) laser



R. Nagarajan et al., Appl. Phys. Lett. **59** (15), 1835(1991)

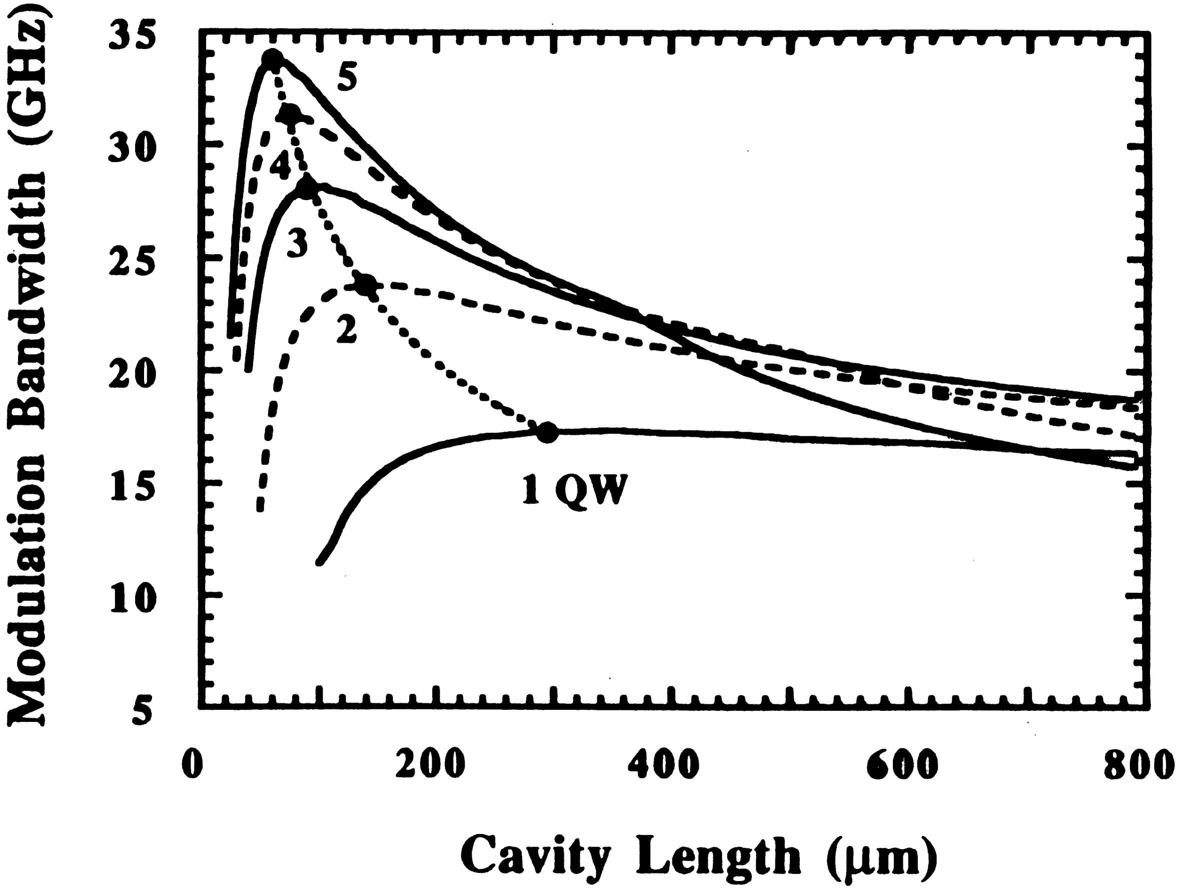
Transport Effects: SCH width





R. Nagarajan et al., Photon. Technol. Lett., vol. 4, no. 2, 121 (1992)

Transport Effects : Cavity Length



R. Nagarajan et al. ,J. Quantum Electronics, vol. 28, no. 10, p.1990 (1992)

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    - **Capacitance and resistance limited**
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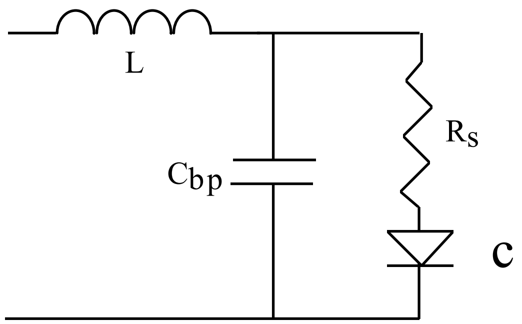
Laser Parasitics

Device and package parasitics can cause significant reduction in modulation response



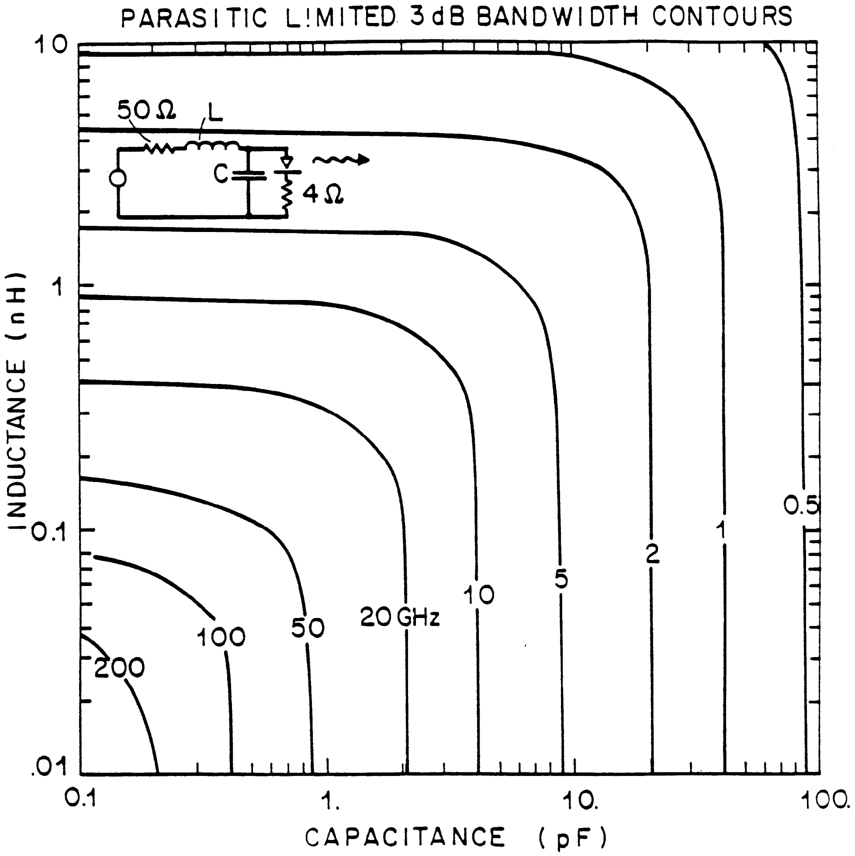
- Junction capacitance C
- Bond pad capacitance C_{bp}
- Series resistance R_s
- Bond wire inductance L

Example: To achieve 15 GHz bandwidth:

$$\begin{aligned} C &< 2\text{pF} \\ C_{bp} &< 2\text{pF} \\ R_S &< 4\Omega \\ L &< 0.3\text{nH} \end{aligned}$$

Parasitics

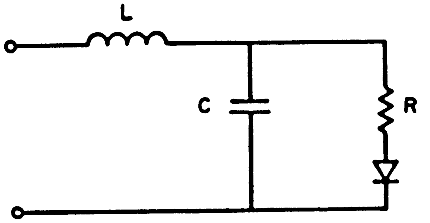
Parasitic limited 3 dB bandwidth contours



J.E. Bowers, Solid-State Electronics, vol. 30, no. 1, 1 (1987)

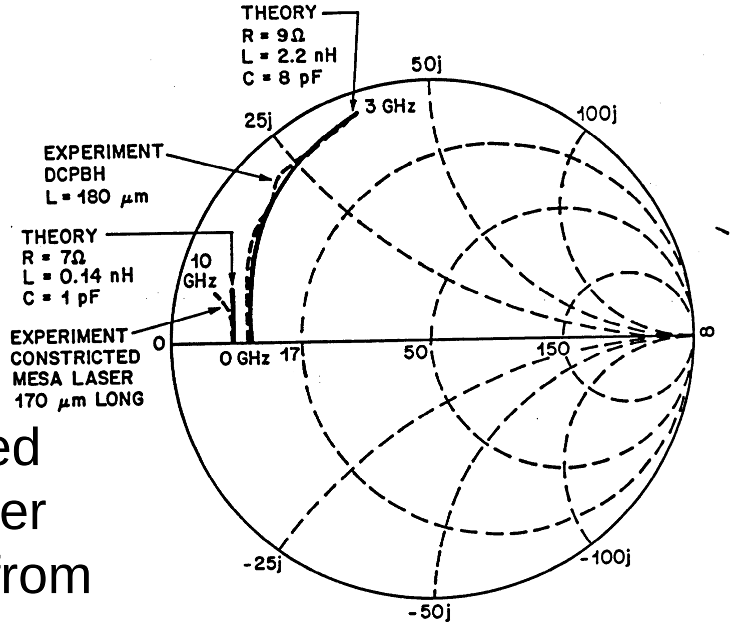
Laser Impedance

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)



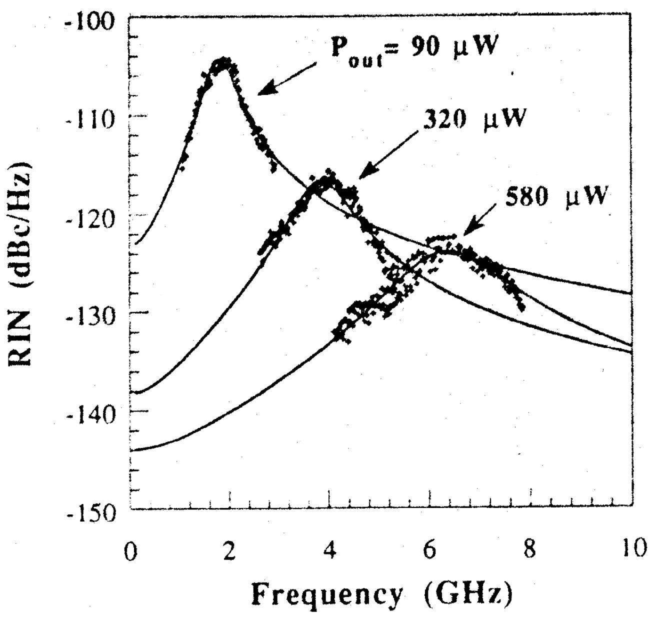
Inductance and resistance are determined from measurement of forward biased laser (as shown). Capacitance can be found from reverse biased measurement

Relative Intensity Noise

- Recombination and generation are stochastic processes -> variations in output power
- Relative Intensity Noise:

$$RIN \equiv \frac{\left\langle \delta P(t)^2 \right\rangle}{P_0^2}$$

- RIN spectrum related to modulation response:



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

L.A.Coldren and S.W. Corzine, "Diode Lasers and Photonic Integrated Circuits", Wiley and Sons, 1995
D. Tauber et al., Appl. Phys. Lett., vol.62, no.4, 1993, 325-327

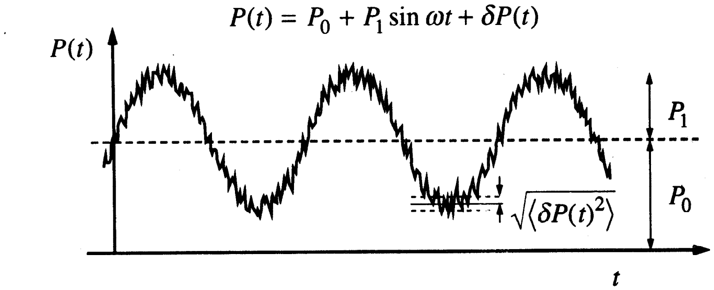
RIN
Optical Fiber Communication

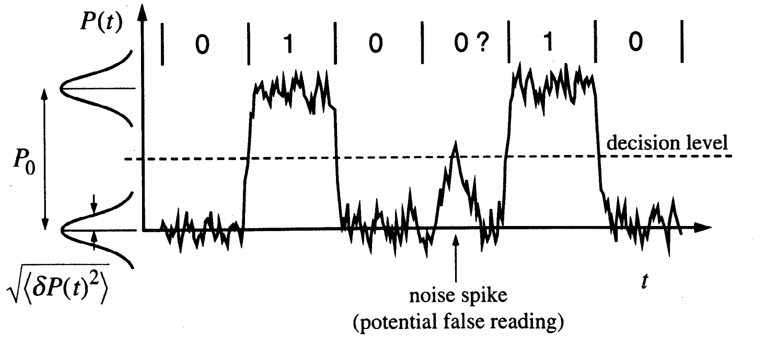
- Relative intensity noise cause degradation of Signal-to-Noise Ratio in analog systems, and errors in digital systems
- Analog signal:

$$SNR = \frac{2}{m^2}\frac{1}{RIN}$$

- Digital signal, for BER<10^{-9}

$$RIN < (11.89)^{-2}$$





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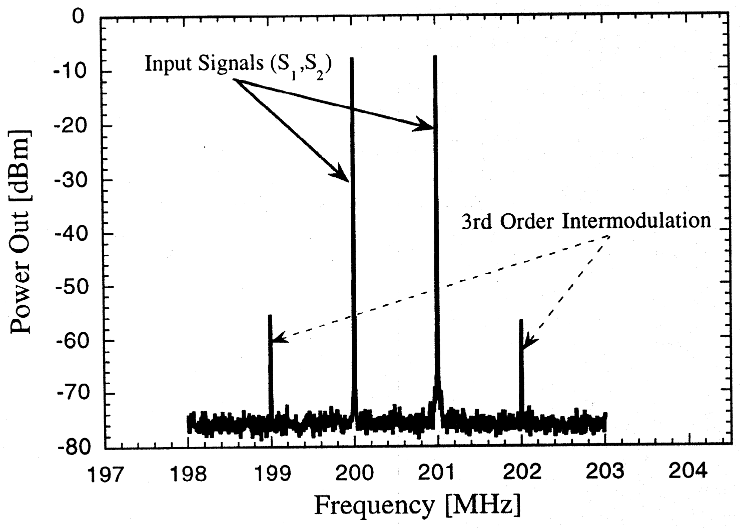
Analog Transmission

- 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



J. Wesselman et al., Applied Physics Letters, vol.72, (no.17),. p.2084-6