Chirping, Large Signal Modulation and Single Frequency Lasers

Read: Kasip, 4.10-4.15

Yariv, Chapter 15,16

Coldren/Corzine Chapter 3,5

Agrawal/Dutta Chapter 6,7,8

ECE 162C

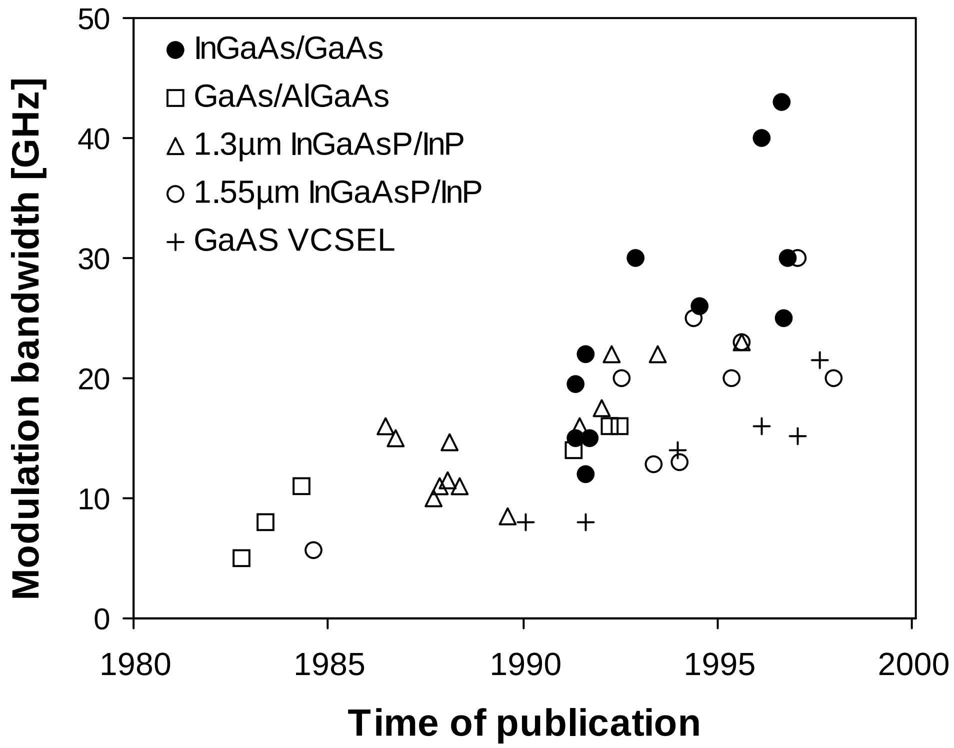
Lecture #12

Prof. John Bowers

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.

Record Modulation Bandwidth



State of the Art: Highest Modulation Bandwidths

Material System	Type	Bandwidth	Reference
GaAs/InGaAs/AlGaAs			
GaAs	Bulk, FP	11 GHz	Lau et al., Appl. Phys. Lett., **45**, 316 (8/84)
GaAs/$Al_{0.35}Ga_{0.65}As$	3 QW, RWG, FP	21 GHz	Dong et al., **PTL-8**, 46 (1/96)
$In_{0.2}Ga_{0.8}As$/GaAs	4 QW, RWG, FP	**48 GHz**	Zhang et al., **J. STQE-3**, 309 (4/97)
InGaAlAs/InGaAsP/InP			
InGaAsP/InP (1.3µm)	Bulk, FP	24 GHz	Meland et al., Electron. Lett., **26**, 1827 (11/90)
InGaAsP/InP (1.3µm)	10 QW, Strain, FP	20 GHz	Lipsanen et al., **PTL-4**, 673, (7/92)
InGaAsP/InP (1.3µm)	Bulk, FE-doped, DFB	18 GHz	Wang et al., **PTL**-1, 258, (9/89)
InGaAsP/InP (1.3µm)	10 QW, Strain, DFB	20 GHz	Chen et al., **PLT-7**, 458, (5/95)
InGaAsP/InP (1.56µm)	Bulk, FP	10 GHz	Blondeau et al., Electron. Lett., **26**, 458 (3/90)
InGaAlAs/InP (1.55µm)	20 QW, strain, FP	30 GHz	Matsui et al., **PTL-9**, 25 (1/97)
InGaAsP/InP (1.55µm)	Bulk, -10 nm detuned, DFB	17 GHz	Uomi et al., Electron. Lett., **25**, 668, (5/89)
InGaAsP/InP (1.52µm)	7 QW, strain,p-doped DFB	22.5 GHz	Morton et al., CLEO ‘94, CWO4, (5/94)

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

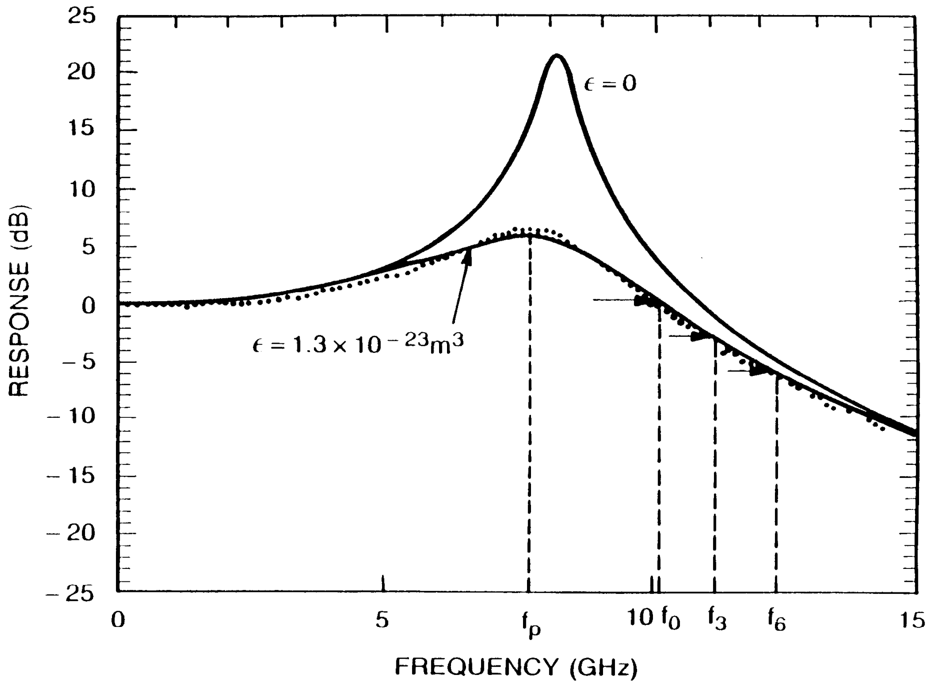
Limits to Bandwidth: Damping

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:

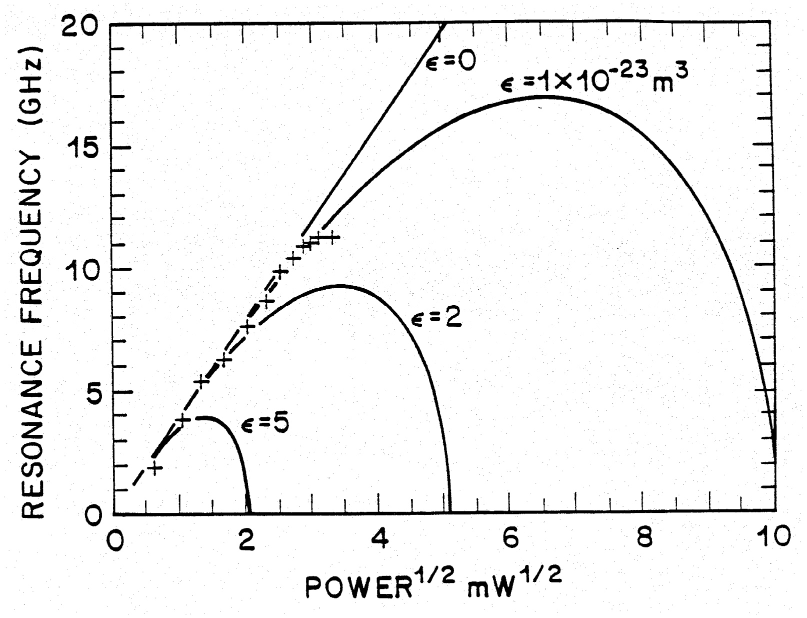
$$f_d = K f_0^2$$

It can be shown that

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

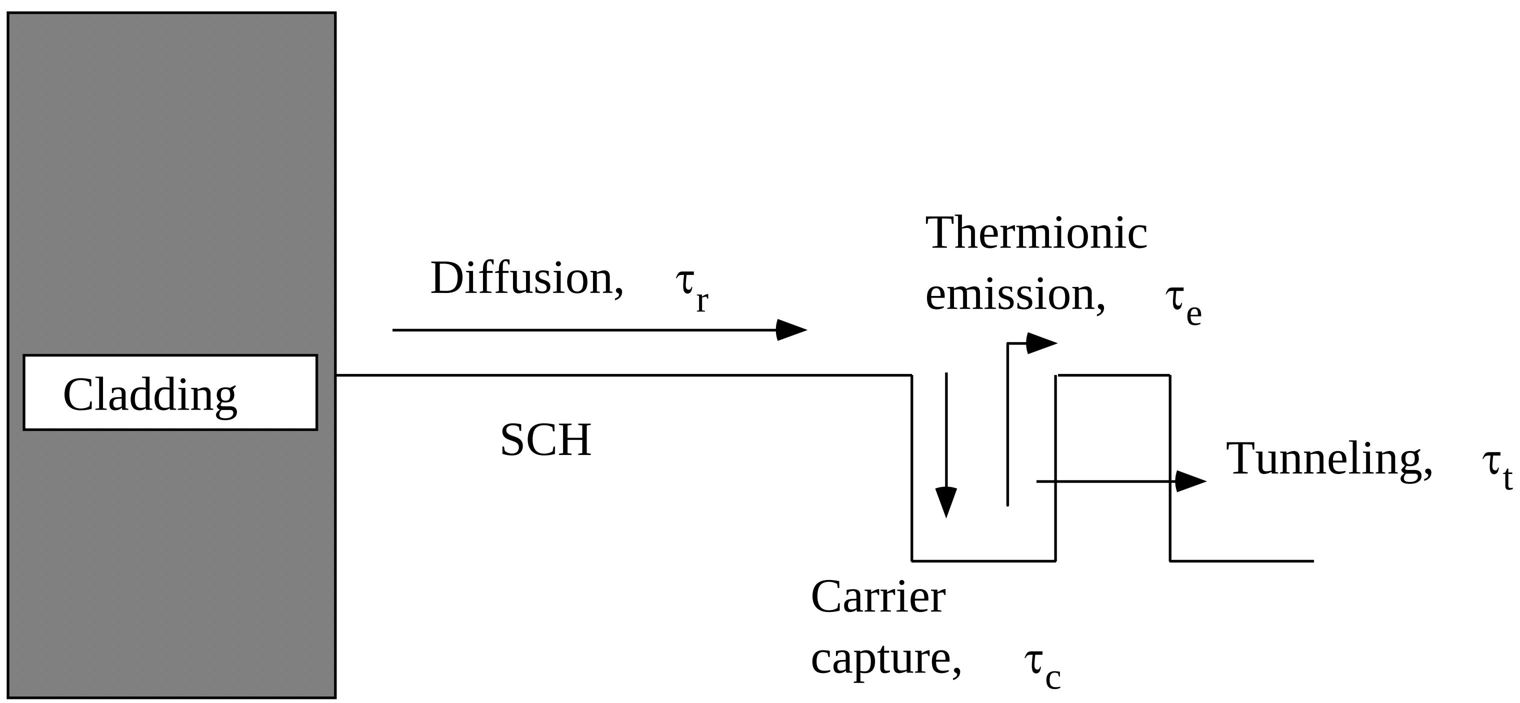
Damping limits the maximum bandwidth to:

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



Transport Effects

Important transport processes in separate confinement heterostructure (SCH) laser



Transport Effects: Modulation Response

The modulation response and damping factor then become:

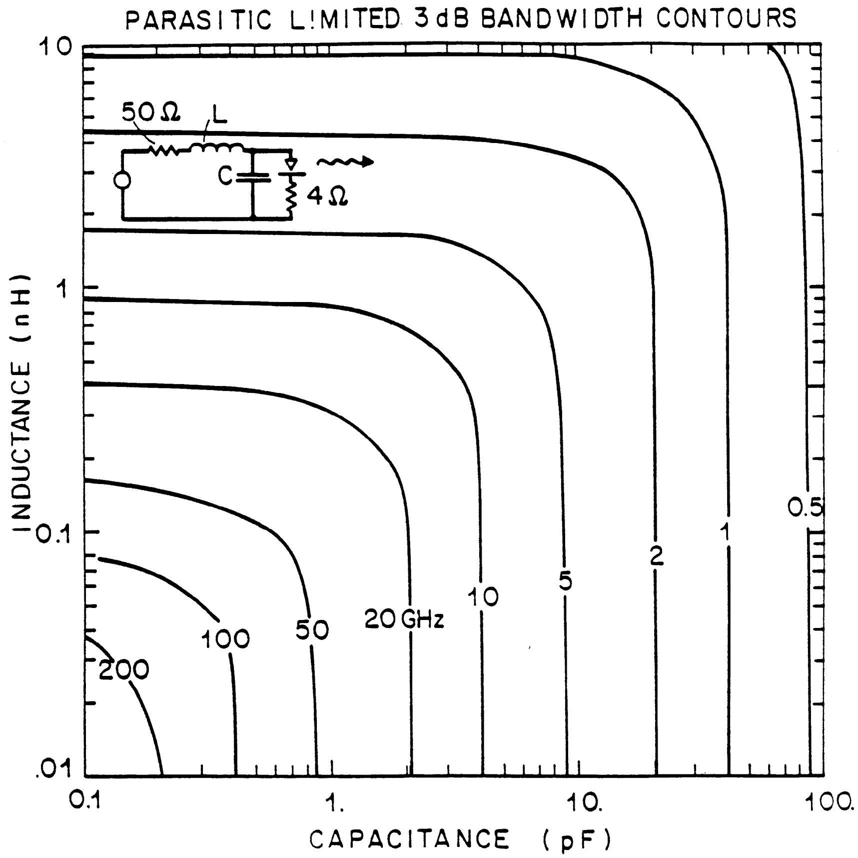
$$R(\omega) = \frac{\omega_0^2}{(1 + j\omega\tau_r)(\omega_0^2 - \omega^2 + j\omega\gamma)}$$

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

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

Parasitics

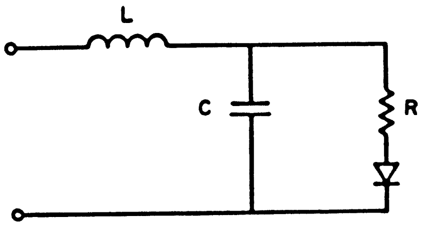
Parasitic limited 3 dB bandwidth contours



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

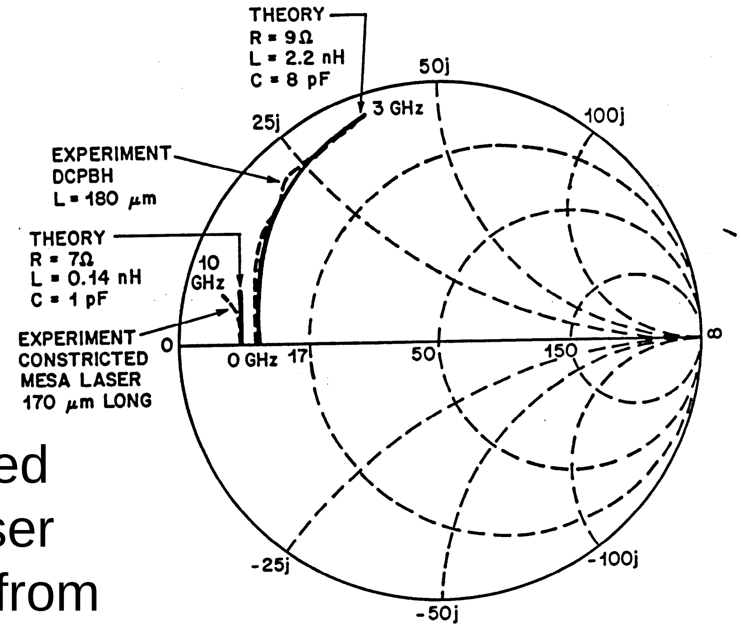
Laser Impedance

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)

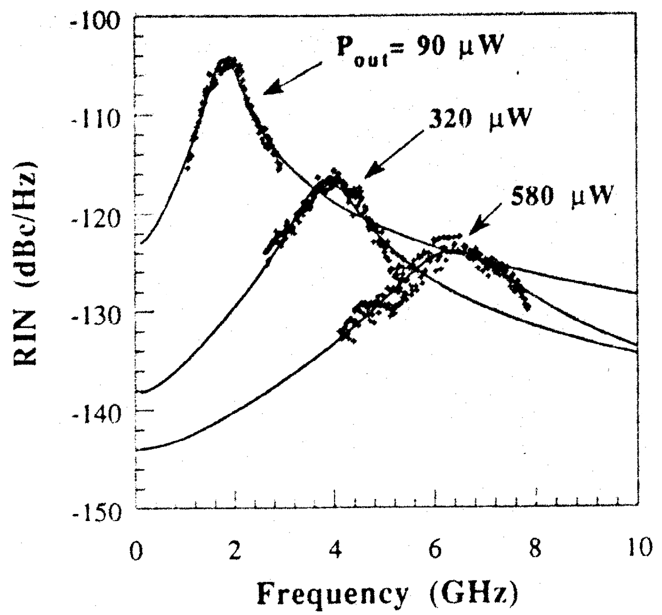


Inductance and resistance are determined from measurement of forward biased laser (as shown). Capacitance can be found from reverse biased measurement

Relative Intensity Noise

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

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



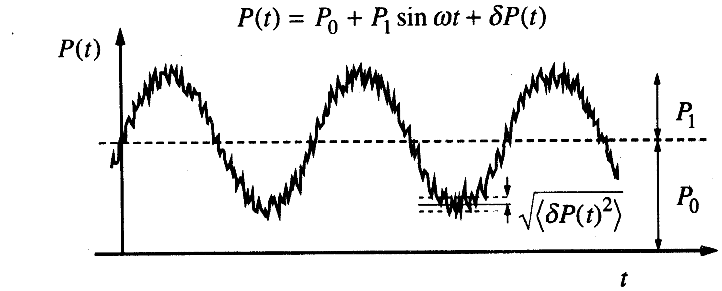
- RIN spectrum related to modulation response:

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

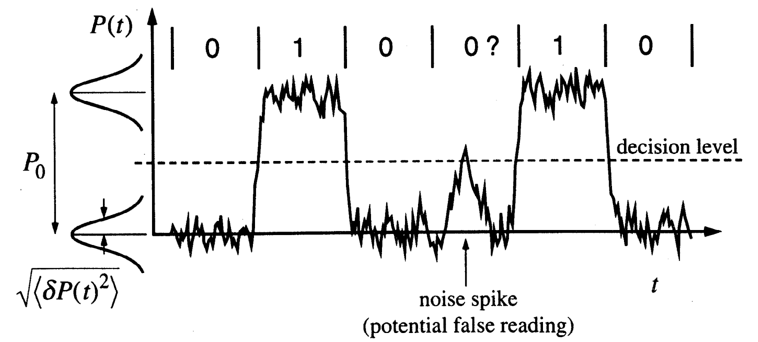
L.A.Coldren and S.W. Corzine, "Diode Lasers and Photonic Integrated Circuits", Wiley and Sons, 1995
D. Tauber et al., Appl. Phys. Lett., vol.62, no.4, 1993, 325-327

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}

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

L.A.Coldren and S.W. Corzine, “Diode Lasers and Photonic Integrated Circuits”, Wiley and Sons, 1995

Large Signal Modulation

The analysis is based on the rate equations:

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

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

For simplicity gain non-linearities are omitted.

With the small-signal approximation no longer valid, the equations must be solved numerically

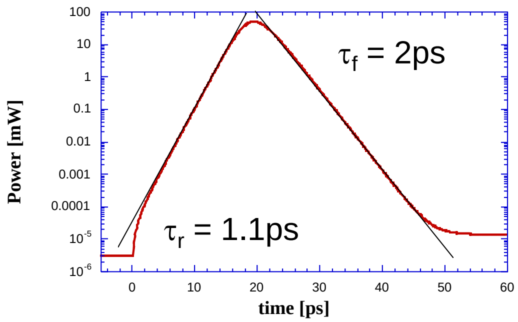
Large Signal Modulation
Impulse Response

Consider a laser with initial carrier density N_i, excited with a charge impulse at t = 0

$$N = \begin{cases} N_i & t < 0 \\ N_i + \dfrac{Q}{qV} & 0 < t < t_{on} \end{cases}$$

Ignoring spontaneous emission we get:

$$\frac{dS}{S} = \left(\Gamma v_g \left(N(t) - N_{tr} \right) - \frac{1}{\tau_p} \right) dt$$



With the solution

$$S = S_0 e^{t/\tau_r}$$

$$\frac{1}{\tau_r} = \Gamma v_g a \left(\frac{Q}{qV} + N_i - N_{tr} \right) - \frac{1}{\tau_p}$$

Large Signal Modulation
Impulse Response

The fall-time depends on how far below threshold the carrier density can be brought. Unless charge is extracted electrically $N > N_{tr}$, which means:

$$\frac{1}{\tau_f} = \frac{1}{\tau_p} - \Gamma v_g a\left(N - N_{tr}\right)$$

$$\frac{1}{\tau_f} < \frac{1}{\tau_p}$$

$$\tau_f > \tau_p \approx 1ps$$

This is best case, more often τ_f is on the order of 10-20 ps

Large Signal Modulation Impulse Response

Example:

$$\Gamma = 0.1$$

$$v_g = 10^8\ {}^{m}\!/_{s}$$

$$a = 3 \cdot 10^{16}\, cm^2$$

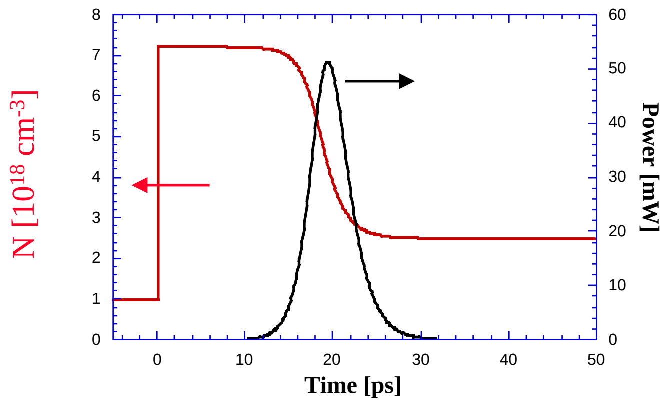
$$V = 300 \cdot 1 \cdot 0.1 \mu m^3 = 30 \mu m^3$$

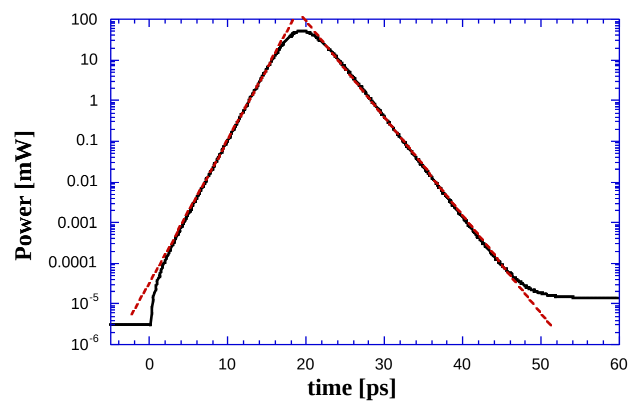
$$N_{tr} = 10^{18} cm^{-3}$$

$$N_i = 10^{18} cm^{-3}$$

$$\tau_p = 1 ps$$

$$Q = 6 \cdot 10^{-11} C$$





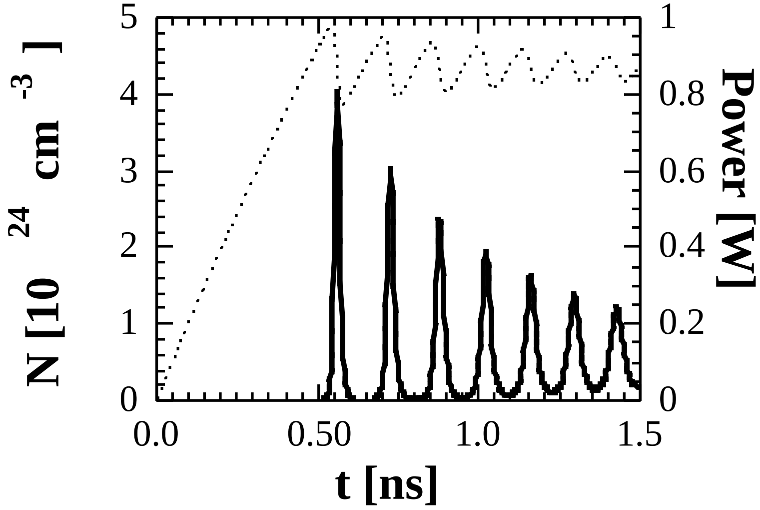
Large Signal Modulation
Step Response

Turn-on delay:

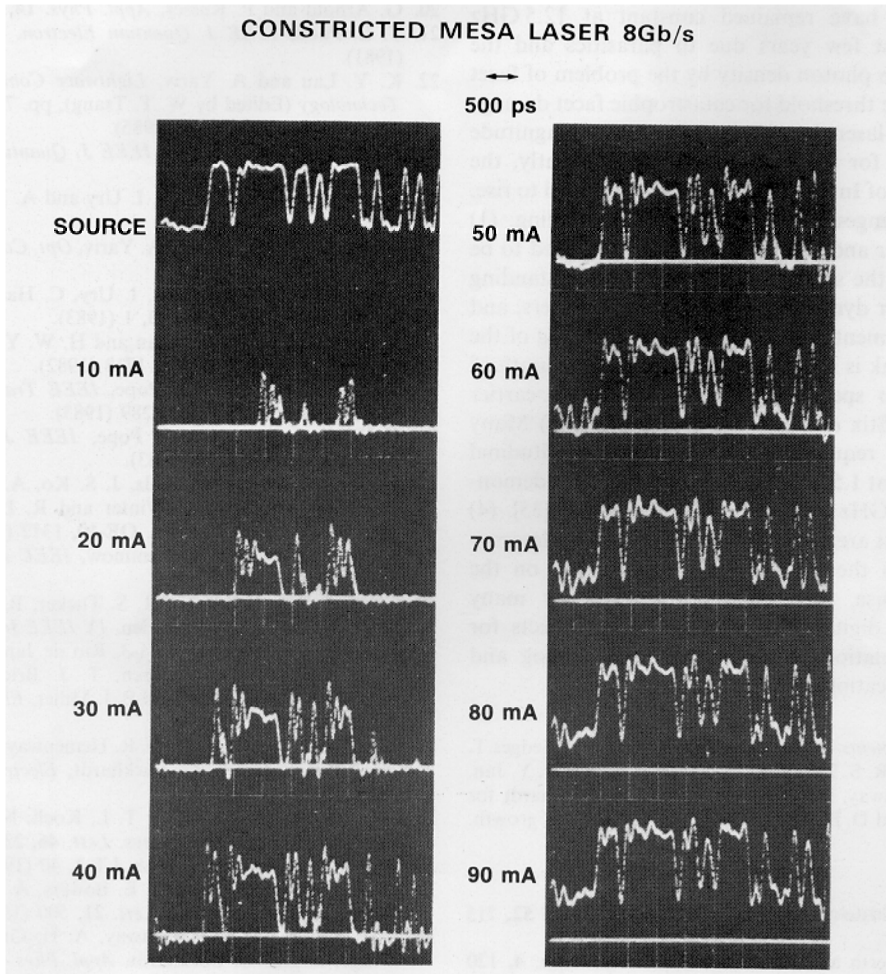
$$\tau_d = \tau_n \ln\left(\frac{I - I_b}{I - I_{th}}\right)$$

Oscillation frequency:

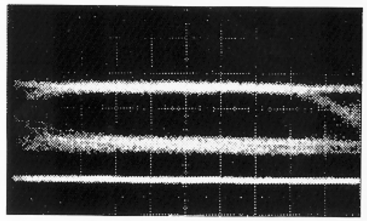
$$f_r = \sqrt{\frac{1 + \Gamma v_g a N_{tr} \tau_p}{\tau_p \tau_n}\left(\frac{I - I_{th}}{I_{th}}\right)}$$

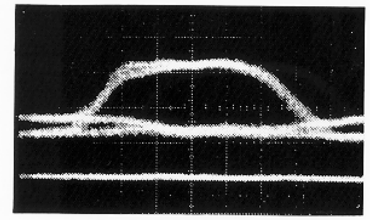


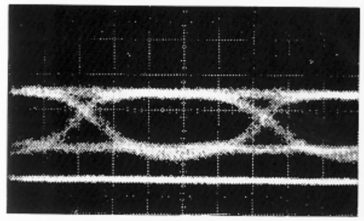
Large Signal Modulation 8 Gbit/s

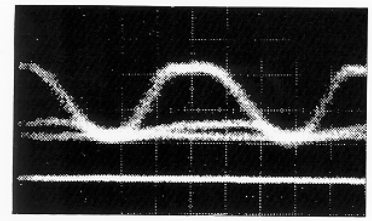


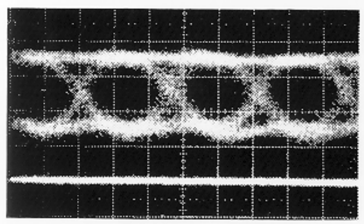
DIGITAL MODULATION OF A CONSTRICTED MESA LASER (50 ps/div, 100 mA DC BIAS)

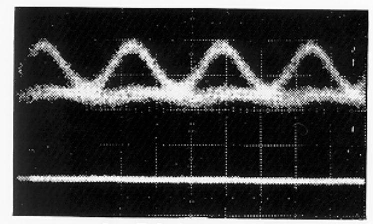

2 Gbit/s NRZ

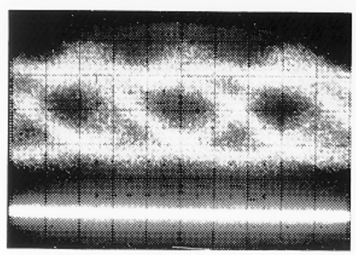

2 Gbit/s RZ


4 Gbit/s NRZ


4 Gbit/s RZ


8 Gbit/s NRZ


8 Gbit/s RZ

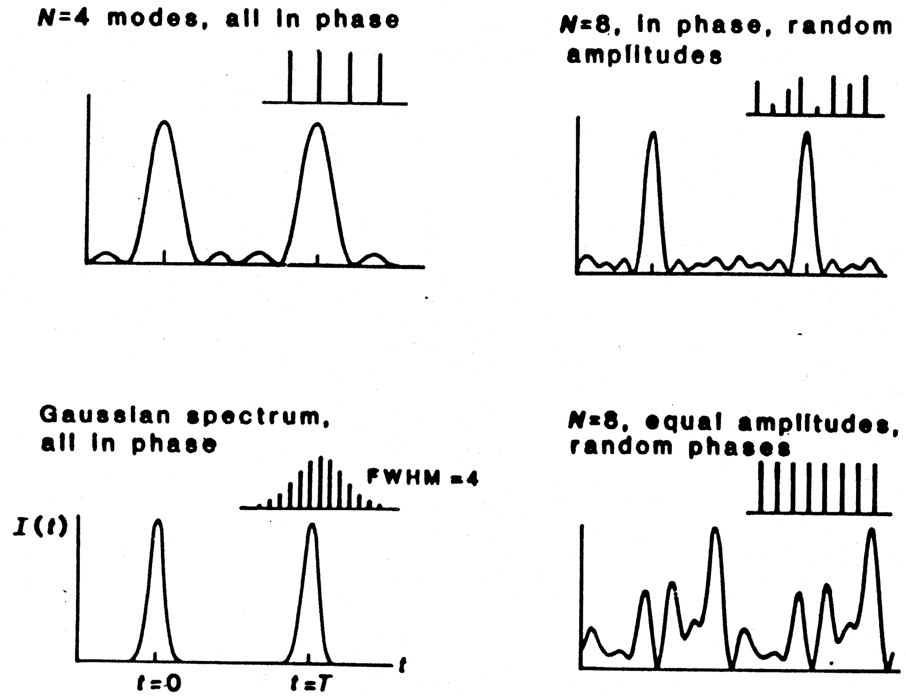

16 Gbit/s NRZ (20 ps/div)

Large Signal Modulation Pulse Generation

- Gain Switching
  - Short electrical pulse
- Q-switching
  - High loss element inside laser cavity increases threshold, making it possible to achieve high inversion. When the loss is decreased again, all the stored energy is released in short, high power pulse
- Mode-Locking
  - Modulation at cavity roundtrip frequency locks the cavity modes in phase, creating short pulses

Pulse Generation : Mode-Locking

- Modulation at cavity frequency phase locks modes
- More modes and better phase lock gives shorter pulses
- Pulse repetition rate determined by cavity length - does not depend on bias conditions

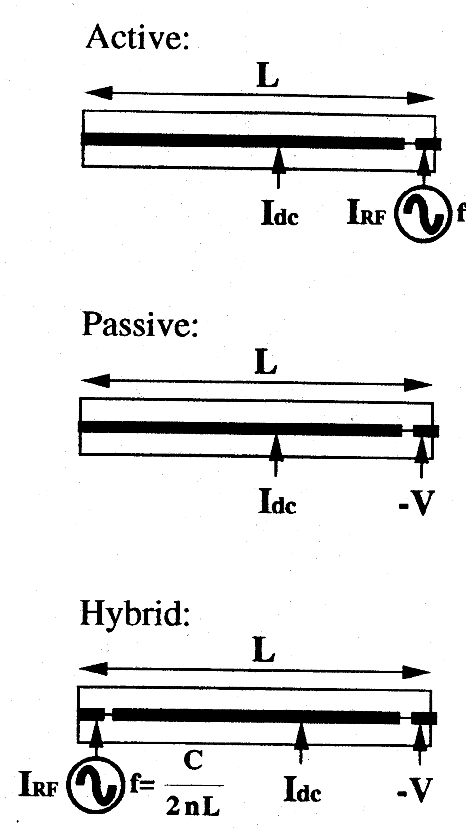


A.E. Siegman, "Lasers", University Press, 1987

Pulse Generation : Mode-Locking

Resonant modulation of roundtrip gain or phase at the cavity frequency

- Active mode-locking
  - modulation signal applied externally
- Passive mode-locking
  - Non-linear element in cavity provide modulation
- Hybrid mode-locking



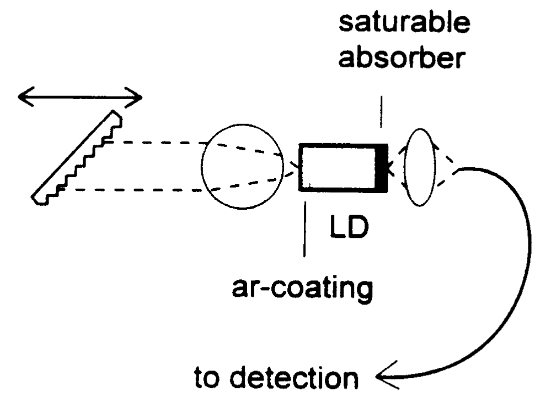
Pulse Generation : Mode-Locking

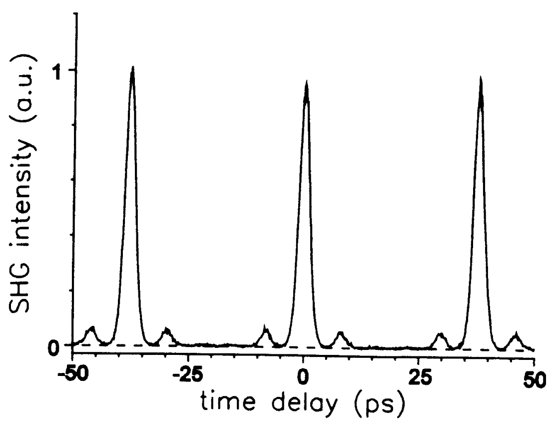
Limits to minimum pulsewidth

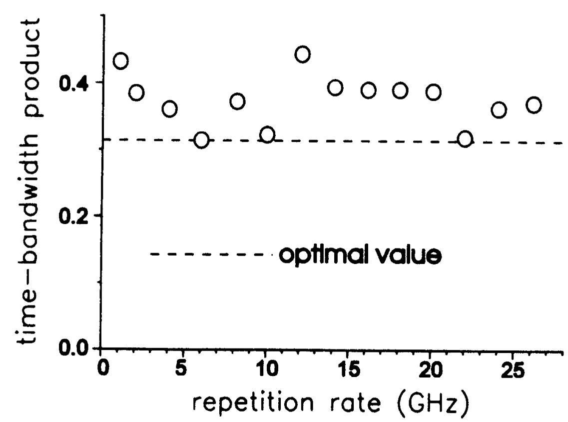
- Gain bandwidth
  - Very wide, potential for pulses <100fs
- Self Phase Modulation
    - refractive index depends on carrier density
  - Spectral width larger than transform limit
  - Generation of chirped pulses
- Dispersion
  - Causes broadening of chirped pulses

Passive Mode-Locking in External Cavity

- Pulsewidth : 1-2 ps
- Repetition rate 1-26 GHz
- Transform limited pulses



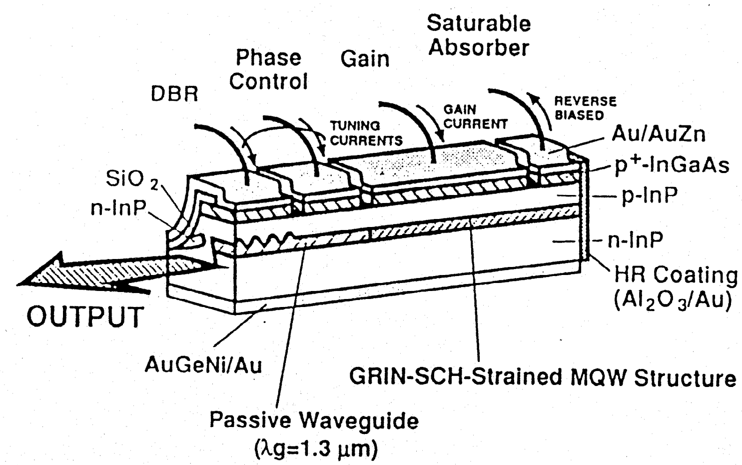


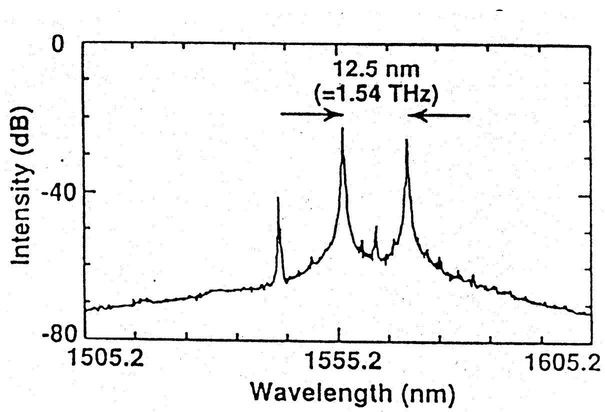


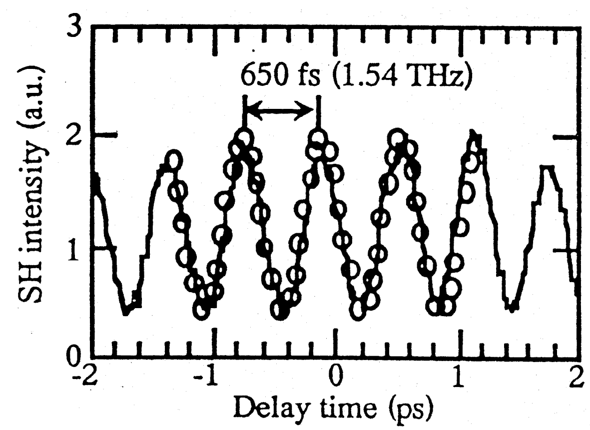
J. Yu et al., IEEE Photon. Technol. Lett., vol. 7, no. 5, 467 (1995)

Passive Mode-Locking Monolithic Cavity

- Mode-locking at 1.54 THz
- Monolithic integrated DBR laser
- Total cavity length 1.1mm (cavity resosnace: 40GHz)
- .55µm
- , 400, THz.







S. Arahira et al., Optics Letters, vol.19, (no.11):834-6 (1994)
Y. Ogawa, International Workshop on Femtosecond Technology FST'95

Chirp

Modulation of injection current causes not only intensity modulation, but also frequency modulation. The linewidth enhancement factor α quantifies this

$$\alpha = \frac{\dfrac{dn}{dN}}{\dfrac{dg}{dN}}$$

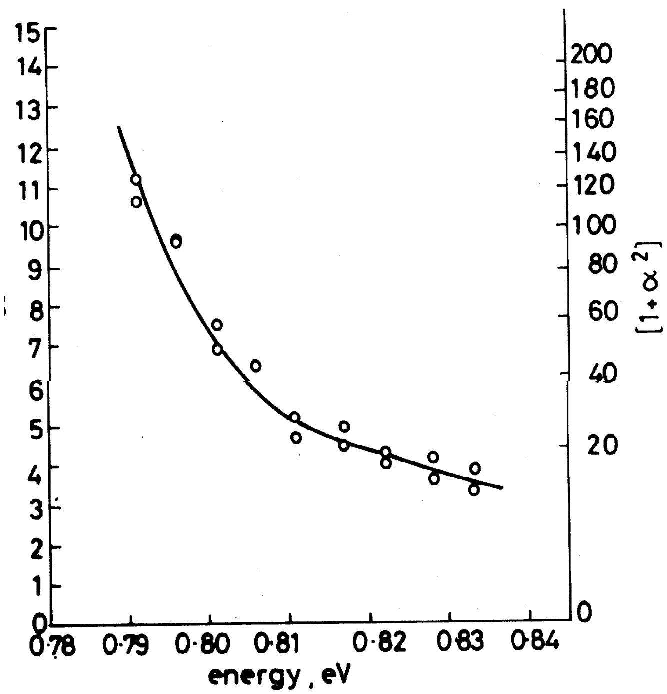
The Chirping is

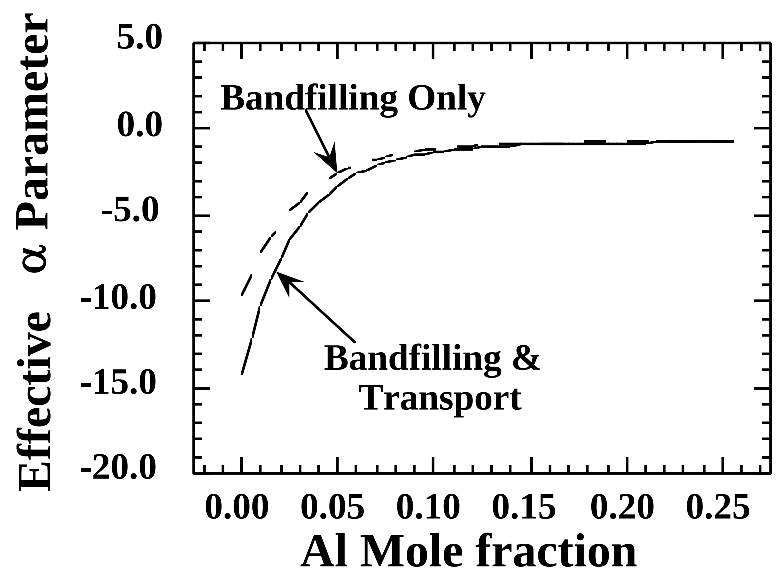
$$\Delta\nu(t) = -\frac{\alpha}{4\pi}\frac{1}{P}\frac{dP}{dT} + 2\frac{\Gamma\varepsilon}{V\eta h\nu}P$$

T. Koch et al., Elec. Lett., vol. 20, no. 25, 1038 (1984)
T. Koch et al., Appl. Phys. Lett., vol. 48., no. 10, 613 (1986)

Chirp

The linewidth enhancement factor changes with wavelength, and can also depend on the structure

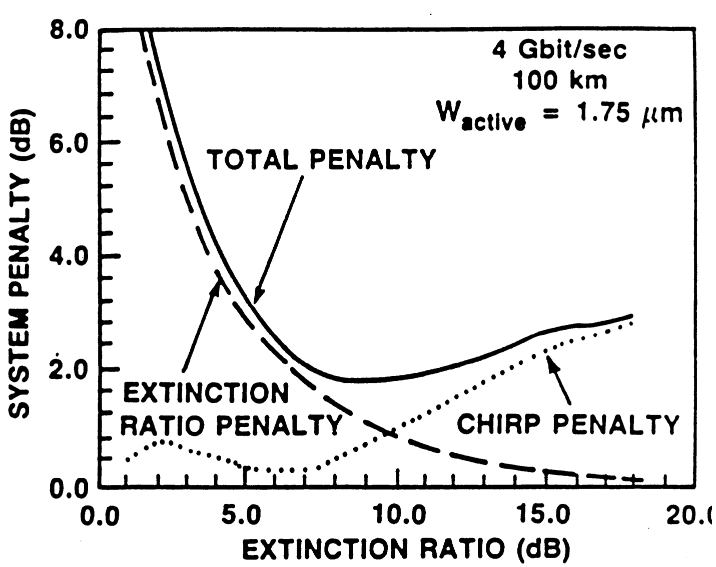




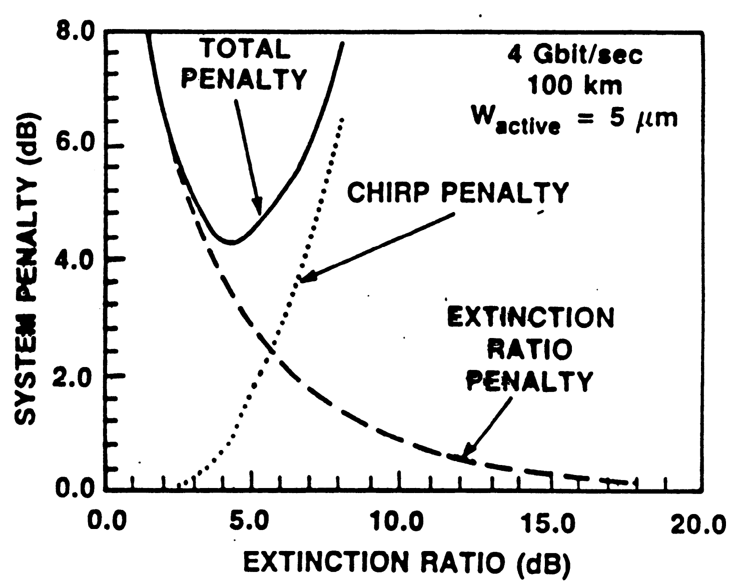
L.D. Westbrook, Electron. Lett., vol. 21, no. 22, 1018 (1984)
R. Nagarajan, J. Quantum Electronics, vol. 29, no. 6, 1601 (1993)

Chirp

Low chirp laser is a requirement to achieve the full potential of an optical communication system



DCPBH Laser



Ridge Waveguide Laser

P.J. Corvini et al., J. Lightwave Technol., vol. LT-5, 1591 (1987)

Single Longitudinal Mode Lasers

- A technique is needed to filter the gain or loss so only one mode reaches threshold.
- Possibilities:
  - Short cavity lasers
  - Coupled cavity lasers (3 or 4 mirror cavities)
  - Grating feedback
    - Distributed feedback (DFB)
    - Distributed Bragg Reflector (DBR)
    - Bulk grating (external cavity)