Topic 23

23 Some issues in semiconductor laser diodes

23.1 Introduction

23.2 Semiconductor laser rate equations

Carrier density rate equation

Photon density rate equation

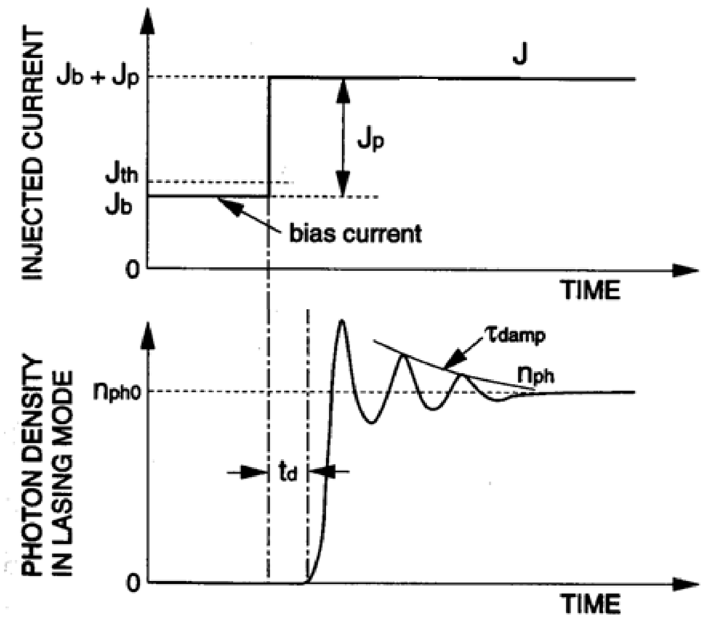
23.3 Laser turn on delay

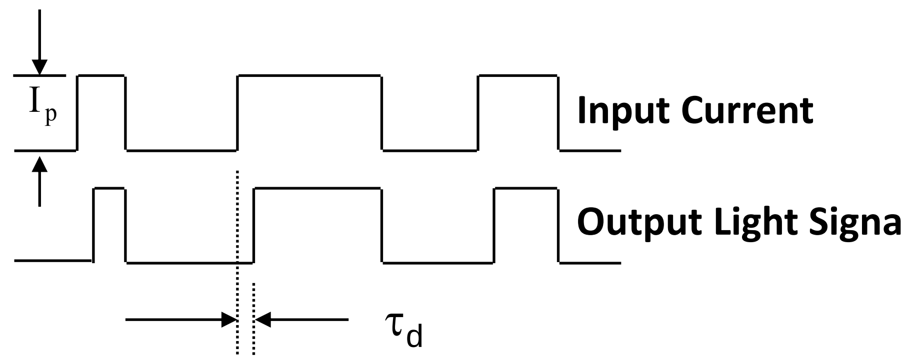
23.4 Dynamic response above threshold

23.5 Frequency modulation response

23.6 Chirp

Introduction



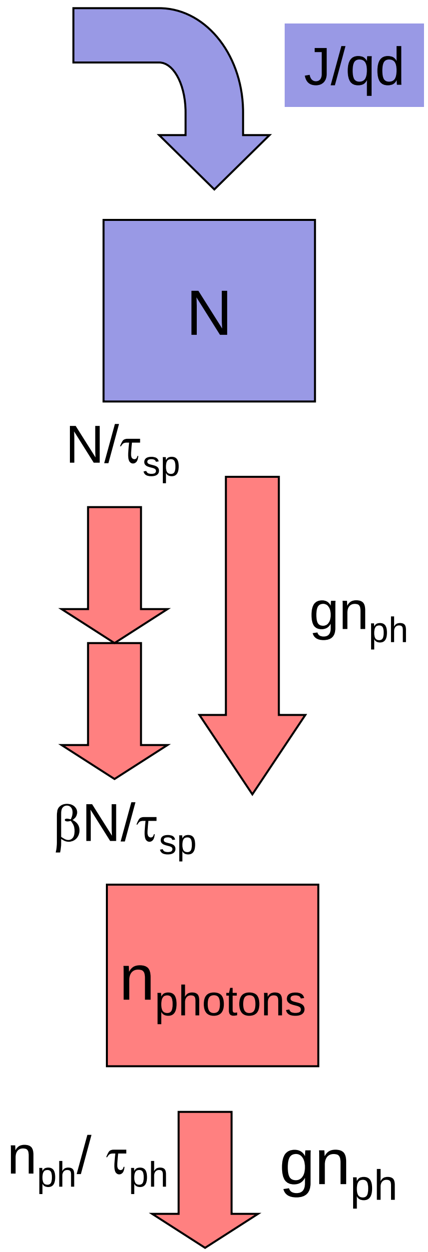


For practical applications, we can often observe:

(1) Laser turn-on delay

(2) Relaxation Oscillation

Schematic Process of Electrical Injection LDs



Injected Carriers

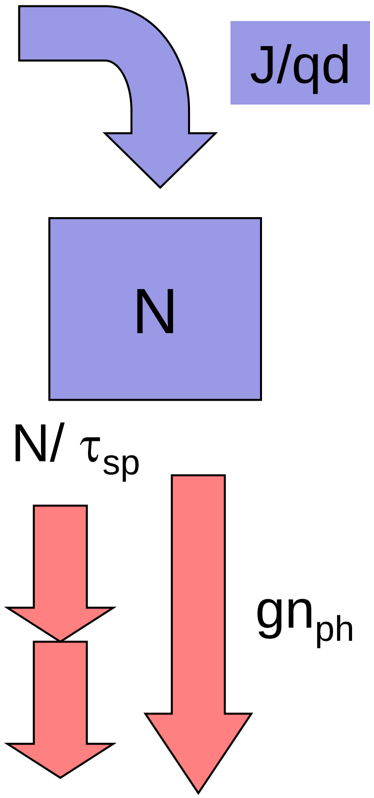
Carrier reservoir

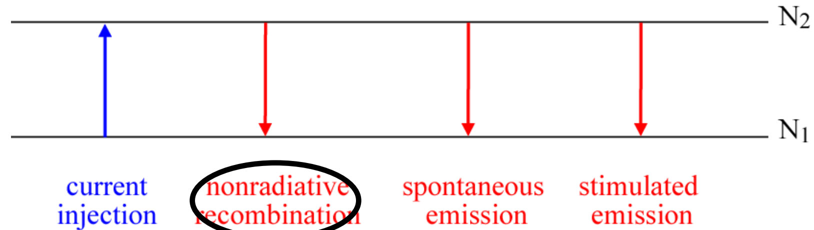
Additions to Photon Population

Photon Reservoir

Lasing Photons Escaping Cavity

Carrier Density Rate Equation





ignore

$$\underbrace{\frac{dN}{dt}}_{\text{carrier rate}} = \underbrace{\frac{J}{qd}}_{\text{current injection}} - \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}} - \underbrace{gN_{ph}}_{\text{stimulated emission}}$$

A change in carrier density is due to

(1) Injection current: (+)

add carriers

(2) spontaneous and stimulated recombination:(-)

remove carriers

(3) non-radiative recombination is ignored

Photon Density Rate Equation

$$\underbrace{\frac{dN_{ph}}{dt}}_{\text{Photon rate}} = -(\underbrace{gN_{ph}}_{\text{stimulated emission}} + \underbrace{\beta\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}}) + \underbrace{\frac{N_{ph}}{\tau_{ph}}}_{\text{loss of photons}}$$

3 channels for a change in photon density

(1) Stimulated recombination: (-)

(2) Spontaneous recombination (-)

(3) Optical loss in gain region (scattering, absorption, etc): (+)

Introducing photon lifetime (τ_{ph}) to describe optical loss:

β_{sp}: percentage of spontaneous emission (~$10E^{-5}$)

Steady State Solution

- Steady state requires: both carrier density and photon density have to remain unchanged

$$\frac{dN}{dt} = 0 \qquad \frac{dN_{ph}}{dt} = 0$$

- From Carrier density rate equation and photon density rate equation:

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_{sp}} - gN_{ph} = 0 \qquad \frac{dN_{ph}}{dt} = -(gN_{ph} + \beta\frac{N}{\tau_{sp}}) + \frac{N_{ph}}{\tau_{ph}} = 0$$

$$\Rightarrow \quad J = qd[\frac{N}{\tau_{sp}} + gN_{ph}] \qquad \Rightarrow \quad gN_{ph} = \frac{N_{ph}}{\tau_{ph}} - \beta\frac{N}{\tau_{sp}}$$

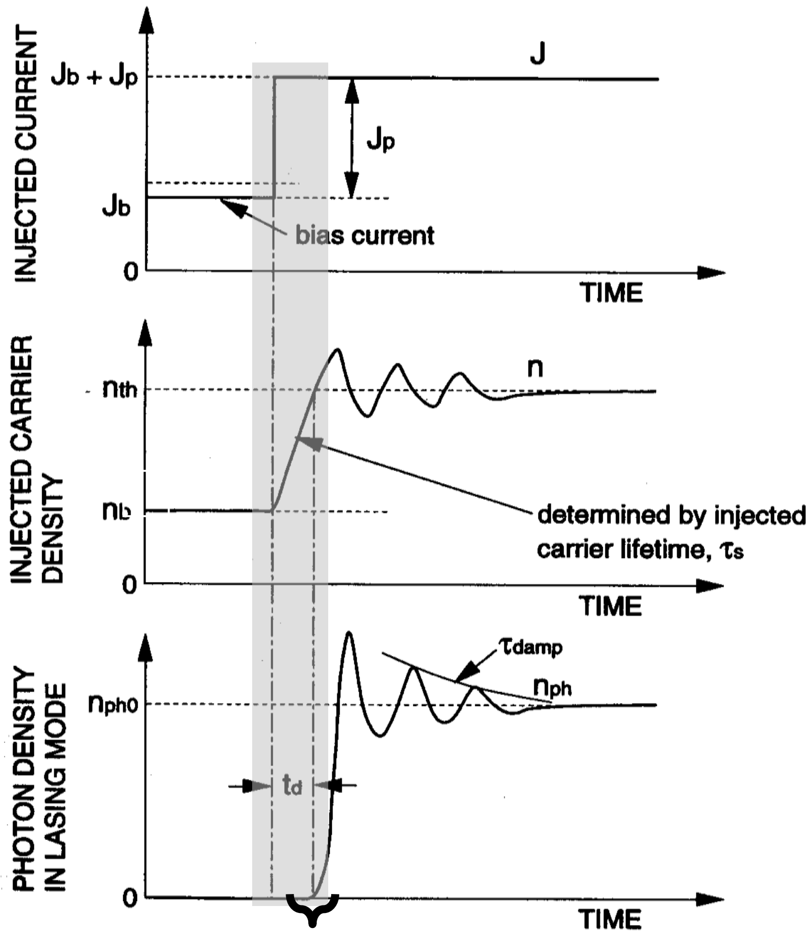
(1) At threshold: Ignore effect of stimulated recombination of carriers

$$J_{th} = \frac{qdN_{th}}{\tau_{sp}}$$

(2) Above threshold: Ignore spontaneous emission into lasing mode

$$g = \frac{1}{\tau_{ph}}$$

Laser Turn on Delay



Laser Turn on

- Initial carrier density (Before onset of stimulated emission)

$$\frac{dN}{dt} = \frac{J}{qd} - \frac{N}{\tau_{sp}}$$

- Rate of increase (dN/dt) is positive : cause an increase in carrier density

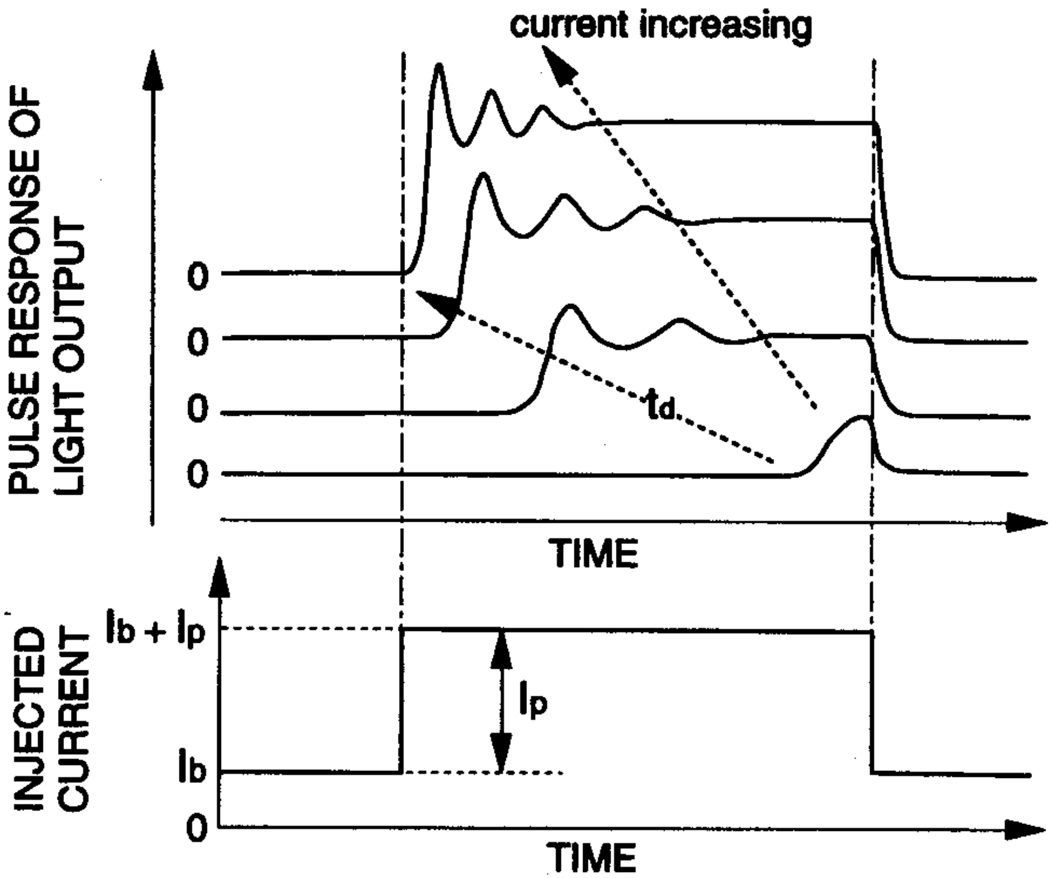
- When $N \geq N_{th}$: lasing starts

- Time delay, t_d given by:

$$t_d = \tau_{sp} \ln\left[\frac{J}{J - J_{th}}\right]$$

Laser Turn on Delay – increasing current

$$\boxed{t_d = \tau_{sp} \ln\left[\frac{J}{J - J_{th}}\right]}$$



Constantly add extra I_{bias} -reduces delay time

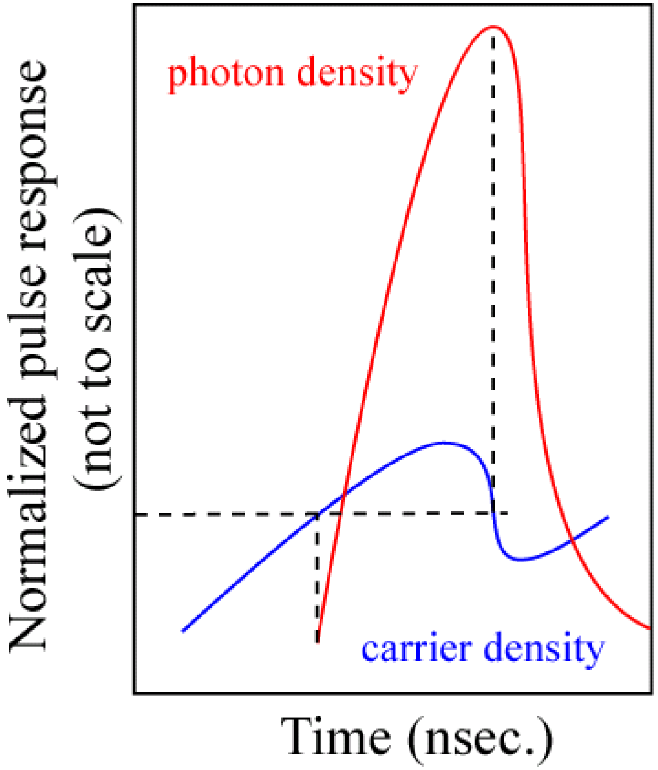
- Use a low threshold laser and make I_p large
- Bias the laser at or above threshold

Above Threshold

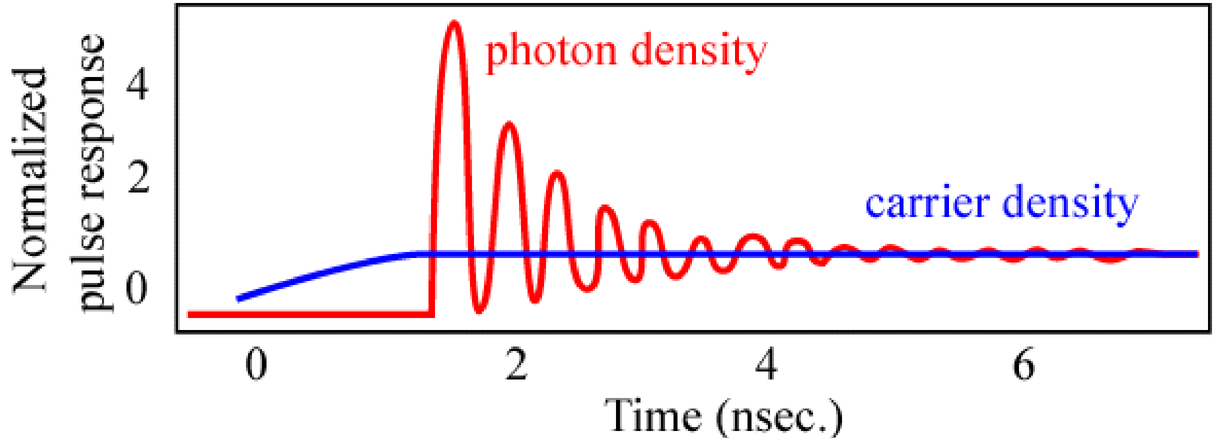
$$\underbrace{\frac{dN}{dt}}_{\text{carrier rate}} = \underbrace{\frac{J}{qd}}_{\text{current injection}} - \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}} - \underbrace{gN_{ph}}_{\text{stimulated emission}}$$

$$\underbrace{\frac{dN_{ph}}{dt}}_{\text{Photon rate}} = -(\underbrace{gN_{ph}}_{\text{stimulated emission}} + \beta \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}}) + \underbrace{\frac{N_{ph}}{\tau_{ph}}}_{\text{loss of photons}}$$

- When $N > N_{th}$:
  - (1) The increase in N_{ph} causes
    - decrease in the dN/dt because the stimulated emission term is negative
  - (2) When N_{ph} reaches a certain value dN/dt becomes negative
    - N starts to decrease



Relaxation Oscillations (RO)



$$\underbrace{\frac{dN}{dt}}_{\text{carrier rate}} = \underbrace{\frac{J}{qd}}_{\text{current injection}} - \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}} - \underbrace{gN_{ph}}_{\text{stimulated emission}}$$

$$\underbrace{\frac{dN_{ph}}{dt}}_{\text{Photon rate}} = -(\underbrace{gN_{ph}}_{\text{stimulated emission}} + \underbrace{\beta\frac{N}{\tau_{sp}}}_{\text{spontaneous s emission}}) + \underbrace{\frac{N_{ph}}{\tau_{ph}}}_{\text{loss of photons}}$$

- When N drops below N_{th}
  - N_{ph} drops quickly, and then N starts increasing again
  - The process repeats itself as a damped oscillation

- After repeating it several times, a steady state can be achieved, and both carrier density and photon density are stable

RO Frequency

$$\underbrace{\frac{dN}{dt}}_{\text{carrier rate}} = \underbrace{\frac{J}{qd}}_{\text{current injection}} - \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}} - \underbrace{gN_{ph}}_{\text{stimulated emission}}$$

$$\underbrace{\frac{dN_{ph}}{dt}}_{\text{Photon rate}} = \underbrace{gN_{ph}}_{\text{stimulated emission}} + \beta \underbrace{\frac{N}{\tau_{sp}}}_{\text{spontaneous emission}} - \frac{N_{ph}}{\underbrace{\tau_{ph}}_{\text{loss of photons}}}$$

- $I = I_0 + I_1 e^{jwt}$; $N = N_0 + N_1 e^{jwt}$; $N_{photon} = N_{photon0} + N_{photon1} e^{jwt}$
- Substitute, remove d.c. components satisfying steady state conditions

$$f = \frac{1}{2\pi} \frac{1}{\left(\tau_{sp}\tau_{ph}\right)^{1/2}} \left(\frac{J}{J_{th}} - 1\right)^{1/2}$$

- Relaxation Oscillations: refers to attempt to return to steady state
- **RO Frequency** -determines the maximum modulation rate of laser diode
- **Turn injected current up** – might destroy the facet if it is too high
- **Decrease photon lifetime** – shorter optical cavity but J_{th} goes up as mirror loss increases

Chirp (1)

•Definition: the modulation of a single mode laser diodes can cause a dynamic shift of the peak wavelength emitted from the device

•Formation mechanisms:

(1) variation carrier density with time

(2) Chang in carrier density leads to a change in refractive index of active region

(3) This results in a change in the (frequency) lasing wavelength

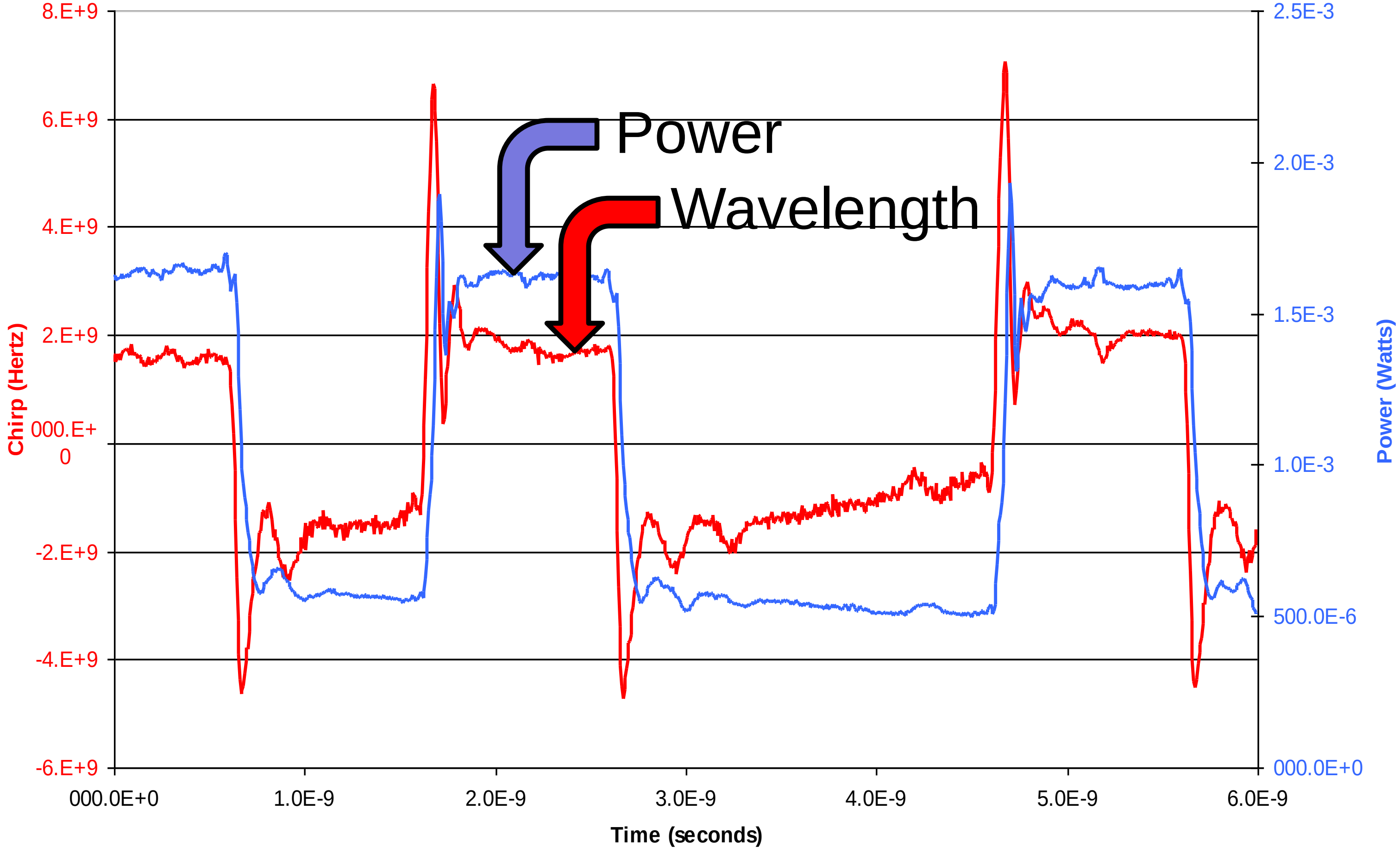
•Only important for single mode lasers – DFBs, WDM systems, etc

•Chirping gets worse at high frequencies

•Relaxation oscillations will produce large dp/dt which leads to large chirping

•Damping of relaxation oscillations will reduce chirp

Chirp (2)



Measurement of DFB wavelength as a function of time

- Change in wavelength is due to a change in refractive index

Summary (1)

- For modulation of a laser diode – set up rate equations for carrier and photon reservoirs
- Solution of rate equations below and above threshold – get turn on delay for modulation from below to above threshold – this is why lasers are modulated *above* threshold
- For modulation above threshold – the maximum modulation rate is determined by the characteristic time it takes for carrier and photon reservoirs to relax to their equilibrium values – the Relaxation Oscillation Frequency

Summary (2)

- A number of strategies exist for increasing the maximum modulation rate (increase photon density, decrease photon lifetime,etc)
- Spontaneous emission into lasing mode - due to relaxation of carrier and photon populations to equilibrium values get noise peak at RO frequency
- Due to change in cavity temperature and carrier density during modulation, refractive index of cavity and hence emission energy (linewidth) changes under modulation (chirp) - deleterious for DWDM, dispersion limited system

Tutorial Questions

T23.1 (Hard! Needs integration skill!) The parasitic recombination rate per unit volume for carriers of density n in the active region of a laser is given by R(n) = n/. Show that the current Ith needed to maintain threshold carrier concentration nth in an active region of volume V is given by Ith = eVnth/. If the current is stepped from a constant value I = Ith/2 to I = 2Ith show that the time delay to lasing is given by td = 0.405.

If the carrier recombination is dominated by spontaneous emission at a rate per unit volume given by R(n) = Bn2 show that Ith = eVB(nth)2 and td = 0.235/(Bnth).

T23.2 The maximum direct modulation rate of a laser is governed by the relaxation oscillation. Describe factors which determine this parameter and strategies for maximising the data transmission rate. Comment on the practicalities of your suggestions.