Optical Fibres and Telecommunications

Lecture 8 – Laser Structures and Modulating Lasers

Introduction

• Where are we?
• Laser structures
• Modulating laser diodes
  – Relaxation oscillations
  – Chirp
Last Time

- Temporal response of an LED.
- Rise time and fall time.
- Modulation bandwidth.
- Laser structures
  - Homojunction
  - Double heterostructure
- Optical confinement
  - Gain guiding
  - Index guiding.
- Next time Fabry-Perot modes, modulating laser diodes.

Fabry-Perot Laser Structures

- The laser structures shown so far are Fabry-Perot structures.
- To form a standing wave pattern, antinodes must be formed at the mirrors.
- Only modes with certain allowed wavelengths can be supported.
- These are the longitudinal modes of the resonator.
Longitudinal Modes

- Longitudinal modes are standing waves.
- For a longitudinal mode to be supported:
  \[ \frac{2L}{\lambda} = N \]
  \( L \) = length of cavity, \( N \) = Integer number

Example: \( \lambda = 1500\text{nm} \), \( L = 0.4\text{mm} \), \( N = 533.333 \) – Not allowed!

Allowed mode: \( \lambda = \frac{2L}{N} = \frac{0.8\text{mm}}{534} = 1498.1\text{nm} \)
BUT: \( \lambda = \frac{0.8\text{mm}}{533} = 1500.9\text{nm} \) is also an allowed mode!

What does this mean?
Longitudinal Modes III

• Laser can generally operate simultaneously in several longitudinal modes.
• Effectively increases bandwidth of the source.

Spacing between adjacent modes $\approx \frac{\lambda}{2L}$

DBR’s and DFB’s

• In most situations want narrow linewidth.
• Implies operation on a single longitudinal mode.
• Simple Fabry-Perot Cavity is not sufficient.
• Need to design a cavity with a very narrow oscillation bandwidth.
• Use Distributed Bragg Reflector (DBR) or Distributed Bragg Feedback (DFB) Cavity.
• Similar to the Fibre Bragg Gratings we met earlier in the course.
Bragg Reflectors

- Portion of the light is reflected at each interface.
- Only for one wavelength can a coherent addition be performed.
- Wavelength satisfying the Bragg Condition, $\lambda_B$: $2\Lambda n_{eff} = \lambda_B$
  - $n_{eff}$ is the effective index of the waveguide core.
  - Very narrow bandwidths are possible.

DBR Lasers

- Active region is terminated by a Bragg Reflector.
- Can use either a single ended grating or have a grating on both ends.
DFB Lasers

- Bragg grating placed in the vicinity of the active region.
- Feedback takes place throughout the laser cavity.
- Bragg condition must be satisfied.
- Narrow linewidth operation.
- Wavelength tuning is possible by heating the grating.

DFB Laser Spectrum

http://photonics.kist.re.kr/Teams/photonic/English/Research_FGG.html
Laser Structures – VCSEL’s

Picture from: http://www.physics.montana.edu/optics/jlc/VCSEL.htm

VCSEL SEM Image

http://www.gerhard-franz.org/title/vcsel-01.jpg
VCSELS II

- Replaces the traditional edge emitting geometry with a surface emitter like the SLED.
- Gives a VERY short cavity length.
- Widely spaced longitudinal modes – well outside the gain bandwidth.
- Single mode operation.
- Current injected through a shaped contact or a transparent Indium Tin Oxide (ITO) contact.
- Small size gives efficient operation and high switching speeds.
- Circular output well matched to fibre.
- On-chip testing possible for cheap production.
- Still difficult to obtain long wavelength operation, but rapidly becoming the most important laser source for datacomms applications.

Laser Diode Characteristics

- Below threshold, device operates as an LED.
- Above threshold, lasing takes place.

Slope Efficiency:
\[ \eta_{se} = \frac{P_2 - P_1}{I_2 - I_1} = \frac{\Delta P}{\Delta I} \text{ } \mu W/mA \]

\[ \eta_{se \text{ laser}} \approx 100 \times \eta_{se \text{ LED}} \]
Quantum Efficiency

- Previously we met $\eta_{\text{int}}$ – the internal quantum efficiency.  
  - Fraction of injected charge carriers that produce photons.

- Also need to consider how efficiently light is coupled out of the device – the light extraction efficiency, $E_{\text{light}}$.  
  - Some light may bounce around and be internally reflected.

- The product of $\eta_{\text{int}}$ and $E_{\text{light}}$ is defined as the external quantum efficiency – $\eta_{\text{ext}}$.  
  - $\eta_{\text{ext}} = \eta_{\text{int}} \times E_{\text{light}}$

- Number of photons escaping from the device (ie. useful light) :  
  - $N_{\text{esc}} = \eta_{\text{ext}} \times N_{\text{carriers}}$

Calculating Slope Efficiency

Let’s consider the case of a diode operating above threshold.

$$P_{\text{out}} = (E_{p} \times N_{\text{esc}})/t$$

$P_{\text{out}}$ = output power, $E_{p}$ = Photon energy $= hc/\lambda$, $N_{\text{esc}}$= Number of photons escaping  

$$N_{\text{esc}} = \eta_{\text{ext}} \times N_{\text{carriers}}$$

$N_{\text{carriers}}$=Number of carriers injected, $\eta_{\text{ext}}$ = External quantum efficiency.  

$$N_{\text{esc}} = \eta_{\text{ext}} \times ((I_{f} \times t) / e)$$

$I_{f}$ = Forward current, $e$ = electron charge.

$$P = (E_{p} / e) \times \eta_{\text{ext}} \times I_{f}$$

Therefore:  

$$\eta_{\text{se}} = \Delta P / \Delta I \approx P/I_{f}$$

$$= (E_{p} / e) \times \eta_{\text{ext}} = (E_{g} / e) \times \eta_{\text{ext}}$$

$E_{g}$=Energy gap of semiconductor.
Modulating Laser Diodes

- Laser diodes can be modulated by switching the current, \( I_F \).
- Modulation takes place around the threshold current \( I_{th} \).
- This is called **Direct Modulation**.
- Most cases modulation is digital.
- Analogue modulation still used in some cable TV systems.
- How fast can lasers be modulated using this method?

Modulating Lasers – A Simplistic Approach.

- Switching the current above threshold causes a population inversion. \( \tau_{pl} \)
- Electron hole pair combine to form a photon. \( \tau_{ehr} \)
- Photon escapes from the laser cavity. \( \tau_{ph} \)
Modulating Lasers – A Simplistic Approach II

• The photon lifetime, $\tau_{ph}$, is the fundamental limit.
• After creation the photon travels through the diode before escaping from the facet.
• Can relate the lifetime to the cavity properties:
  \[ \exp(-t/\tau_{ph}) = \exp(-\alpha x) \] (Loss after travelling for $t$ s is same as for travelling $x$ m)
  
  Now, $x = vt = (c/n_{index}) \times t$
  
  Therefore: $\tau_{ph} = n_{index}/(\alpha c) = n_{index}/(g_{th} c)$
  
  $n_{index} =$ refractive index (3.5), $\alpha =$ loss (1000 m$^{-1}$), $g_{th} =$ threshold gain.
  
  $\tau_{ph} = 0.12$ ps $\rightarrow$ Modulation frequency = 8.3THz
  
  However in reality the limit is much less than this – why?

Modulating Laser Diodes – Relaxation Oscillations

• In order to understand behaviour, necessary to consider rate equations.
  
  \[
  \frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_{sp}} - Dns
  \]
  
  Carriers injected \hspace{1cm} Rate of stimulated emission
  
  Rate of change of electron density \hspace{1cm} Rate of spontaneous emission
  
  \[
  \frac{ds}{dt} = Dns + \frac{\zeta n}{\tau_{sp}} - \frac{s}{\tau_{ph}}
  \]
  
  Stimulated emission photons \hspace{1cm} Photons lost
  
  Spontaneous emission in the right direction
  
  Rate of change of Photon Density
Modulating Laser Diodes – Rate Equations II

Solution to these coupled equations gives a classically damped system.

• These are relaxation oscillations.
• Leads to a finite time before photon can be emitted.
• Represents the limit of diode operation.
Modulating Diodes - Chirp

- There is a problem with direct modulation of diodes.
- A change in light intensity during modulation can change the output frequency of the laser.
- Mechanism is due to change in carrier population causes a change in refractive index – slightly changes the laser output frequency.
- Chirp acts to broaden the laser linewidth. Undesirable and causes chromatic dispersion.
- Have to move to an external modulator geometry to get very high data speeds.

Summary

- Fabry-perot laser structures
  - Longitudinal modes
- Single mode laser operation.
  - DBR lasers
  - DFB lasers
- VCSEL’s
- Modulating laser diodes
  - Relaxation oscillations
  - Chirp