Lecture 3: Light Sources

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- Types of Light Source
  - LED
  - Laser
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- Comparison
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In order for the light sources to function properly and find practical use, the following requirements must be satisfied:

- **Output wavelength**: must coincide with the loss minima of the fibre
- **Output power**: must be high, using lowest possible current and less heat
- **High output directionality**: narrow spectral width
- **Wide bandwidth**
- **Low distortion**
Light Sources - Types

Every day light sources such as tungsten filament and arc lamps are suitable, but there exists two types of devices, which are widely used in optical fibre communication systems:

- **Light Emitting Diode (LED)**
- **Semiconductor Laser Diode (SLD or LD).**

In both types of device the light emitting region consists of a **pn junction** constructed of a direct band gap III-V semiconductor, which when forward biased, experiences injected minority carrier recombination, resulting in the generation of photons.
LED - Structure

- pn-junction in forward bias,

- Injection of minority carriers across the junction gives rise to efficient radiative recombination (electroluminescence) of electrons (in CB) with holes (in VB)

--- Fermi levels

Homojunction LED
LED - Structure

- Optical power produced by the Junction:

\[ P_0 = I \frac{\eta_{\text{int}}}{q} hf = I \frac{\eta h c}{q \lambda} \]

Where

- \( \eta_{\text{int}} = \) Internal quantum efficiency
- \( q = \) Electron charge \( 1.602 \times 10^{-19} \text{C} \)
LED - External quantum efficiency $\eta_{\text{ext}}$

It considers the number of photons actually leaving the LED structure

$$\eta_{\text{ext}} = \frac{Fn^2}{4n_x^2}$$

Where

- $F$ = Transmission factor of the device-external interface
- $n$ = Light coupling medium refractive index
- $n_x$ = Device material refractive index

**Loss mechanisms that affect the external quantum efficiency:**

1. Absorption within LED
2. Fresnel losses: part of the light gets reflected back, reflection coefficient: $R=\{(n_2-n_1)/(n_2+n_1)\}$
3. Critical angle loss: all light gets reflected back if the incident angle is greater than the critical angle.
LED - Power Efficiency

- Emitted optical power
  \[ P_e = \frac{P_0 F n^2}{4 n_x^2} \]

External power efficiency
  \[ \eta_{ep} = \frac{p_e}{P} \times 100 \% \]

The coupling efficiency
  - MMSF: \[ \eta_c = \frac{N A^2}{2} \]
  - GMMF: \[ \eta_c = \frac{N A^2}{2} \]

The optical coupling loss relative to \( P_e \) is:
  \[ L_c = -10 \log_{10} \frac{P_c}{P_e} \]

Or the power coupled to the fibre:
  \[ P_c (\text{dBm}) = P_e (\text{dBm}) - L_c (\text{dB}) \]
LED- Surface Emitting LED (SLED)

- Data rates less than 20 Mbps
- Short optical links with large NA fibres (poor coupling)
- Coupling lens used to increase efficiency

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**LED- Edge Emitting LED (ELED)**

- Higher data rate > 100 Mbps
- Multimode and single mode fibres

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LED - Spectral Profile

- Intensity
- Wavelength (nm)

- 800-900 nm
- 1300-1550 nm

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Since $P \propto I$, then LED can be intensity modulated by modulating the $I$.
## LED - Characteristics

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>800-850 nm</th>
<th>1300 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Spectral width (nm)</td>
<td>30-60</td>
<td>50-150</td>
</tr>
<tr>
<td>• Output power (mW)</td>
<td>0.4-5</td>
<td>0.4-1.0</td>
</tr>
<tr>
<td>• Coupled power (mW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 100 um core</td>
<td>0.1-2 ELED</td>
<td>0.04-0.08</td>
</tr>
<tr>
<td></td>
<td>0.3-0.4 SLED</td>
<td></td>
</tr>
<tr>
<td>- 50 um core</td>
<td>0.01-0.05 SLED</td>
<td>0.03-0.07</td>
</tr>
<tr>
<td></td>
<td>0.05-0.15</td>
<td></td>
</tr>
<tr>
<td>- Single mode</td>
<td></td>
<td>0.003-0.04</td>
</tr>
<tr>
<td>• Drive current (mA)</td>
<td>50-150</td>
<td>100-150</td>
</tr>
<tr>
<td>• Modulation bandwidth (MHz)</td>
<td>80-150</td>
<td>100-300</td>
</tr>
</tbody>
</table>
LED - Frequency Response

Magnitude (dB)

0

-3

Frequency (MHz)

1 10 100 1000 10,000

800 nm 1300-1550 nm

LED LD

Multimode Single mode
Laser - Characteristics

- The term Laser stands for **Light Amplification by Stimulated Emission of Radiation**.
- Could be mono-chromatic (one colour).
- It is coherent in nature. (I.e. all the wavelengths contained within the Laser light have the same phase). One the main advantage of Laser over other light sources
- A pumping source providing power
- It had well defined threshold current beyond which lasing occurs
- At low operating current it behaves like LED
- Most operate in the near-infrared region
Laser - Basic Operation

Similar to LED, but based on **stimulated light emission**.

Three steps required to generate a laser beam are:

- Absorption
- Spontaneous Emission
- Stimulated Emission
Absorption

When a photon with certain energy is incident on an electron in a semiconductor at the ground state (lower energy level $E_1$) the electron absorbs the energy and shifts to the higher energy level ($E_2$).

The energy now acquired by the electron is $E_e = E_2 - E_1$.  

Plank's law
Spontaneous Emission

• $E_2$ is unstable and the excited electron(s) will return back to the lower energy level $E_1$

• As they fall, they give up the energy acquired during absorption in the form of radiation, which is known as the spontaneous emission process.
Stimulated Emission

• But before the occurrence of this spontaneous emission process, if external stimulation (photon) is used to strike the excited atom then, it will stimulate the electron to return to the lower state level.

• By doing so it releases its energy as a new photon. The generated photon(s) is in phase and have the same frequency as the incident photon.

• The result is generation of a coherent light composed of two or more photons

\[ E_1 \rightarrow E_2 \rightarrow E_1 \]

**Requirement:** \( \alpha < 0 \)

**Light amplification:** \( I(x) = I_0 \exp(-\alpha x) \)
The Rate Equations

Rate of change of photon numbers

\[ \frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}} \]

Rate of change of electron numbers

\[ \frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\phi \]

\( J \) is the current density, \( R_{sp} \) is the rate of spontaneous emission, \( \tau_{ph} \) is the photon rate, \( \tau_{sp} \) spontaneous recombination rate, \( C \) is the constant
Standing wave (modes) exists at frequencies for which

\[ L = \frac{\lambda_i}{2n}, \quad i = 1, 2, .. \]

Modes are separated by

\[ \delta f = \frac{c}{2nL} \]

In terms of wavelength separation

\[ \Delta \lambda = \frac{2nL}{i} - \frac{2nL}{i+1} = \frac{2nL}{i} \quad \text{for } i \gg 1 \]

\[ \Delta \lambda = \frac{\lambda^2}{2nL} = \frac{\lambda^2}{c} \delta f \]
LD - Spectral Profile

Multi-mode
LD - Efficiencies

Internal quantum efficiency

\[ \eta_{\text{int}} = \frac{\text{number of photons generated in the cavity}}{\text{number of injected electrons}} \]

External quantum efficiency

\[ \eta_{\text{ext}} = \frac{P_e}{IE_g} \]

External power efficiency

\[ \eta_{\text{ep}} = \frac{P_e}{P} \]

Where \( P = IV \)
Power Vs. Current Characteristics

- Power vs. Current
  - Power $P_0$ (mW)
  - Current $I$ (mA)

- LED
- Spontaneous emission
- Stimulated emission (lasing)
- Threshold current $I_{th}$

Graph showing the relationship between power and current with key parameters indicated.
LD - Single Mode

- Achieved by reducing the cavity length $L$ from 250 $\mu$m to 25 $\mu$m
- But difficult to fabricate
- Low power
- Long distance applications

Types:

- Fabry-Perot (FP)
- Distributed Feedback (DFB)
- Distributed Bragg Reflector (DBR)
- Distributed Reflector (DR)
Laser - Fabry-Perot

• Strong optical feedback in the longitudinal direction
• Multiple longitudinal mode spectrum
• “Classic” semiconductor laser
  – 1st fibre optic links (850 nm or 1300 nm)
  – Short & medium range links
• Key characteristics
  – Wavelength: 850 or 1310 nm
  – Total output power: a few mw
  – Spectral width: 3 to 20 nm
  – Mode spacing: 0.7 to 2 nm
  – Highly polarized
  – Coherence length: 1 to 100 mm
  – Small NA (→ good coupling into fiber)

Agilent Technology

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Laser - Distributed Feedback (DFB)

• No cleaved faces, uses Bragg Reflectors for lasing
• Single longitudinal mode spectrum
• High performance
  – Costly
  – Long-haul links & DWDM systems
• Key characteristics
  – Wavelength: around 1550 nm
  – Total power output: 3 to 50 mw
  – Spectral width: 10 to 100 MHz (0.08 to 0.8 pm)
  – Sidemode suppression ratio (SMSR): > 50 dB
  – Coherence length: 1 to 100 m
  – Small NA (→ good coupling into fiber)
Laser - Vertical Cavity Surface Emitting Lasers (VCSEL)

• Distributed Bragg reflector mirrors
  – Alternating layers of semiconductor material
  – 40 to 60 layers, each $\lambda / 4$ thick
  – Beam matches optical acceptance needs of fibers more closely

• Key properties
  – Wavelength range: 780 to 980 nm (gigabit ethernet)
  – Spectral width: <1nm
  – Total output power: >-10 dBm
  – Coherence length: 10 cm to 10 m
  – Numerical aperture: 0.2 to 0.3
## Laser diode - Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Multimode</th>
<th>Single Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral width (nm)</td>
<td>1-5</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Output power (mW)</td>
<td>1-10</td>
<td>10-100</td>
</tr>
<tr>
<td>Coupled power (µW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Single mode</td>
<td>0.1-5</td>
<td>1-40</td>
</tr>
<tr>
<td>External quantum efficiency</td>
<td>1-40</td>
<td>25-60</td>
</tr>
<tr>
<td>Drive current (mA)</td>
<td>50-150</td>
<td>100-250</td>
</tr>
<tr>
<td>Modulation bandwidth (MHz)</td>
<td>2000</td>
<td>6000-40,000</td>
</tr>
</tbody>
</table>
# Comparison

<table>
<thead>
<tr>
<th><strong>LED</strong></th>
<th><strong>Laser Diode</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Low efficiency</td>
<td>• High efficiency</td>
</tr>
<tr>
<td>• Slow response time</td>
<td>• Fast response time</td>
</tr>
<tr>
<td>• Lower data transmission rate</td>
<td>• Higher data transmission rate</td>
</tr>
<tr>
<td>• Broad output spectrum</td>
<td>• Narrow output spectrum</td>
</tr>
<tr>
<td>• In-coherent beam</td>
<td>• Coherent output beam</td>
</tr>
<tr>
<td>• Low launch power</td>
<td>• Higher bit rate</td>
</tr>
<tr>
<td>• Higher distortion level at the</td>
<td>• High launch power</td>
</tr>
<tr>
<td>output</td>
<td>• Less distortion</td>
</tr>
<tr>
<td>• Suitable for shorter</td>
<td>• Suitable for longer transmission</td>
</tr>
<tr>
<td>transmission distances.</td>
<td>distances</td>
</tr>
<tr>
<td>• Higher dispersion</td>
<td>• Lower dispersion</td>
</tr>
<tr>
<td>• Less temperature dependent</td>
<td>• More temperature dependent</td>
</tr>
<tr>
<td>• Simple construction</td>
<td>• Construction is complicated</td>
</tr>
<tr>
<td>• Life time $10^7$ hours</td>
<td>• Life time $10^7$ hours</td>
</tr>
</tbody>
</table>
Modulation

The process transmitting information via light carrier (or any carrier signal) is called modulation.

- **Direct Intensity (current)**
  - Inexpensive (LED)
  - In LD it suffers from chirp up to 1 nm (wavelength variation due to variation in electron densities in the lasing area)

- **External Modulation**

![Diagram of Modulation Process]
Direct Intensity Modulation - Analogue

LED

LD

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Direct Intensity Modulation - Digital

LED

Optical power vs. Time

LD

Optical power vs. Time
External Modulation

- For high frequencies 2.5 Gbps - 40 Gbps
- AM sidebands (caused by modulation spectrum) dominate linewidth of optical signal
Modulation Bandwidth

In optical fibre communication the modulation bandwidth may be defined in terms of:

- **Electrical Bandwidth** $B_{ele}$ - (most widely used)
- **Optical Bandwidth** $B_{opt}$ - Larger than $B_{ele}$

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