http://www.wiretechworld.com/the-future-of-optical-fibres/
Optical Sources (Optical Emitters)

The optical source is the active component in an optical fiber communication system.

Three main types of optical sources are
- Wideband “continuous spectra” sources (e.g., incandescent lamps)
- Monochromatic incoherent sources (e.g., light emitting diodes; LEDs)
- Monochromatic coherent sources (e.g., lasers)

Major requirements for optical fiber emitters:
- Light output is directional
- Accurately track the electrical input (minimize distortion and noise)
- Emits light at the wavelength of lowest fiber loss and dispersion
- Capable of signal modulation over wide bandwidth
- Have sufficient optical power to meet system requirements
- Should have very narrow optical bandwidth (meaning linewidth)
- Must maintain stable operation
- Of course, it must be reliable and low cost

From: Chapter 6, Section 6.1 of Senior
Some General Comments on Optical Sources

The first generation of optical fiber communication systems operated between 800 and 900 nm from early semiconductor laser sources.

Then with graded index multi-mode fibers it became possible to use broad linewidth LEDs which emitted in the 800 to 900 nm region. This was attractive because IR LEDs are simple and generally trouble free in their operation and inexpensive.

When single-mode fiber was introduced the development of the narrow linewidth semiconductor laser was required. Recall that with single-mode fibers the LED is not a good fit because of the difficulty in focusing enough light into the fiber and the wide spectra that accompanies the LED. More recently, advanced LEDs have been developed that allow for greater power to be coupled into a fiber.

This lecture will mostly address the operation of the laser.

**LASER stands for Light Amplification by Stimulated Emission of Radiation**

From: Chapter 6, Section 6.1 of Senior
The Nature of Photons (Quanta)

Waves as particles and particles as waves! That’s quantum mechanics.

Quanta of light, called photons, must travel at the speed of light ($c = 3 \times 10^8$ meters/sec). The fundamental relationships pertaining to photons are

$$E = |p|c \quad \text{and} \quad E = hf$$

where $h$ is Planck’s constant ($h = 6.626 \times 10^{-34}$ joule-second).

We can’t picture them in a classical way because of the Heisenberg Uncertainty Principle governs in the quantum world.
Atoms Possess Discrete Energy States (Sodium Atom)

Absorption and Emission of Radiation

The interaction of light with matter takes place in discrete packets of energy or quanta.

Atoms possess discrete levels of energy in which light is either absorbed or emitted, causing the atom to change energy states commensurate to the levels involved.

\[ E = E_2 - E_1 = hf \]

where \( h \) is Planck’s constant (\( h = 6.626 \times 10^{-34} \text{ Joule-second} \)).

Photon Examples: Photoelectric effect, blackbody radiation, Bohr model of hydrogen, etc.
Absorption and Emission of Radiation

Initial state

Final state

Absorption

Spontaneous emission

Stimulated emission

\[ E = E_2 - E_1 = hf \]

From: Chapter 6, Section 6.2.1 of Senior; page 298
The Einstein Relations

Two energy levels shown

\[ E_2 \quad \frac{N_1}{N_2} = \frac{g_1 \cdot \exp(-E_1 / kT)}{g_1 \cdot \exp(-E_2 / kT)} = \frac{g_1}{g_2} \exp\left(\frac{E_2 - E_1}{kT}\right) \]

\[ E_1 \quad \frac{N_1}{N_2} = \frac{g_1}{g_2} \exp\left(\frac{hf}{kT}\right) \quad \text{since} \quad E_2 - E_1 = hf \]

where \( N_1 \) and \( N_2 \) represent the density of atoms at energy levels \( E_1 \) and \( E_2 \), respectively. Also, \( g_1 \) and \( g_2 \) represent the degeneracies of the levels, \( k \) is Boltzmann’s constant and \( T \) is absolute temperature.

The number density of atoms in state \( E_1 \) is \( N_1 \). We now want to find an expression for the rate of transitions from level 1 to level 2 is denoted by \( R_{12} \) (i.e., absorption rate)

\[ R_{12} = N_1 \rho_f B_{12} \]

where \( \rho_f \) is the spectral density of radiation and \( B_{12} \) is Einstein’s coefficient of absorption.

From: Chapter 6, Section 6.2.2 of Senior
The Einstein Relations (continued)

where \( N_1 \) and \( N_2 \) represent the density of atoms in energy levels \( E_1 \) and \( E_2 \), respectively.

Atoms in the higher state \( E_2 \) undergo transitions from level 2 to level 1 – these can be either spontaneous emissions or stimulated emissions.

The time an electron exists in the excited state \( E_2 \) before transition \( 2 \rightarrow 1 \) is the “spontaneous lifetime” \( \tau_{21} \). Using the density of atoms in state 2 (denoted by \( N_2 \)) the spontaneous emission rate is given by

\[
N_2 \frac{1}{\tau_{21}} = N_2 A_{21} \quad \Rightarrow \quad A_{21} = \frac{1}{\tau_{21}}
\]

where \( A_{21} \) is Einstein’s coefficient of spontaneous emission. The rate of stimulated emission for the transition \( 2 \rightarrow 1 \) is

\[
\text{Rate} = N_2 \rho_{1} B_{21}
\]

where \( B_{21} \) is Einstein’s coefficient of stimulated emission.

From: Chapter 6, Section 6.2.2 of Senior
The Einstein Relations (continued)

The total transition rate from level 2 to level 1 is the sum of the spontaneous rate plus the stimulated rate:

\[ R_{21} = N_2 A_{21} + N_2 \rho_f B_{21} \]

In thermal equilibrium the up (1 → 2) and down (2 → 1) transition rates are equal.

\[ R_{12} = R_{21} \]

Therefore, we can write,

\[ N_1 \rho_f B_{12} = N_2 A_{21} + N_2 \rho_f B_{21} \]

Solving for \( \rho_f \) gives

\[ \rho_f = \frac{N_2 A_{21}}{N_1 B_{12} - N_2 B_{21}} = \frac{(A_{21} / B_{21})}{\left(\frac{N_1 B_{12}}{N_2 B_{21}}\right) - 1} \]

From: Chapter 6, Section 6.2.2 of Senior
The Einstein Relations (continued)

At thermal equilibrium the density of radiation is equal to the blackbody radiation as derived by Max Planck,

\[ \rho_f = \frac{8\pi hf^3}{c^3} \left[ \frac{1}{\exp(hf / kT) - 1} \right] \]

Comparing, we note the relations

\[ B_{12} = \left( \frac{g_2}{g_1} \right) B_{21} \quad \text{and} \quad \frac{A_{21}}{B_{21}} = \frac{8\pi hf^3}{c^3} \]

If the degeneracies of the two levels are equal \((g_1 = g_2)\), then \( B_{12} = B_{21} \)

\[ \frac{\text{stimulated emission rate}}{\text{spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{\exp(hf / kT) - 1} \]

Next, consider Example 6.1 (page 301)

From: Chapter 6, Section 6.2.2 of Senior
Example 6.1 – page 301

Calculate the ratio of the stimulated emission rate to the spontaneous emission rate.

We have a lamp with an operating temperature of \( T = 1000 \) K. Consider the wavelength \( \lambda \) to be 650 nm (not 0.5 \( \mu \)m = 500 nm as assumed in the book).

First, determine the frequency associated with a wavelength of 650 nm.

\[
\text{frequency } f = \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m/sec}}{0.650 \times 10^{-6} \text{ m}} = 4.62 \times 10^{14} \text{ Hz}
\]

\[
\frac{B_{21}\rho_f}{a_{21}} = \frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{1}{\exp \left( \frac{hf}{kT} \right) - 1}
\]

\[
\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{1}{\exp \left(6.626 \times 10^{-34} \cdot 4.62 \times 10^{14}\right) - 1}
\]

\[
= \frac{1}{\exp(22.1445) - 1} = \exp(-22.1445) = 2.414 \times 10^{-10}
\]

A very, very small number

From: Chapter 6, Section 6.2.2 (page 301) of Senior
Example 6.1 (continued)

How do we interpret the result on the last slide?

The stimulated emission event is negligible compared to the spontaneous emission of radiation. The source is incoherent. **With a two-level system we can never achieve population inversion**, namely

![Diagram]

Equilibrium

Nonequilibrium “Population Inversion”

Boltzmann Distribution

This is what we need to make a laser

From: Chapter 6, Section 6.2.2 (Figure 6.2 on page 302) of Senior
Achieving Population Inversion

1. To achieve optical amplification it is necessary to create a nonequilibrium distribution of the atomic states (upper energy level must have a greater occupation count than the lower energy level). This is called population inversion.

2. Population inversion cannot be created in a two-level system. Instead it requires either a three-level or a four-level system. One or more levels needs to be a "metastable" level (i.e., very slow decay).

3. "Pumping" is required to achieve population inversion. Pumping is often the application of intense radiation, or current across the lasing material.

From: Chapter 6, Section 6.2.3 of Senior
Population Inversion (Three-Level System)

Three-level System:

E_3 → Rapid decay → Metastable level → E_2 → Pumping → Stimulated emission → E_1

Energy Levels:
- E_3
- N_3
- E_2
- N_2
- E_1
- N_1

From: Chapter 6, Section 6.2.3, Figure 6.3(a) of Senior
Population Inversion (Four-Level System)

Four-level System:

- **Energy Levels**:
  - $E_4$
  - $E_3$
  - $E_2$
  - $E_1$

- **Population Inversion**:
  - $N_4 > N_3$
  - $N_2 < N_1$

- **Pumping and Rapid Decay**:
  - $E_4$ to $E_3$ (Pumping)
  - $E_3$ to $E_2$ (Rapid decay)
  - $E_2$ to $E_1$ (Rapid decay)

- **Stimulated Emission**:
  - $E_3$ to $E_2$

- **Energy Diagram**:
  - $E_4$ to $E_3$ to $E_2$ to $E_1$
  - Metastable level $E_3$

**Prototypical Ne-He Laser**

- 1150 nm

*From: Chapter 6, Section 6.2.3, Figure 6.3(b) of Senior*
Optical Feedback and Laser Oscillation

A reflecting optical cavity provides optical feedback to form a resonator in laser devices.

We must contain the photons sufficiently long within the lasing medium and also maintain coherence. This is achieved by reflecting the beam back and forth between reflecting mirrors located at each end of the optical cavity. Multiple passes provide amplification of the radiation by repeated stimulated emission of radiation. This forms a Fabry-Pérot resonator.

The mirror at right end of the cavity is a partially transmitting reflector. That is how we extract radiation for injection into the end of an optical fiber.

From: Chapter 6, Section 6.2.4, Figure 6.3 (page 304) of Senior
Optical Cavities In General

R₁ = radius

https://perg.phys.ksu.edu/vqm/laserweb/Ch-8/F8s1t1p1.htm

Laser Oscillation and Stable Output

A stable output is obtained under “saturation” conditions meaning the optical gain is exactly matched by the optical loss within the laser medium.

Loss mechanisms include:

1) Absorption and scattering within the amplifying medium
2) Absorption, scattering and diffraction at the cavity mirrors, and
3) Unused transmission through the mirrors (not coupled to the fiber itself)

Oscillations occur in the laser cavity over a small range of wavelengths where there is sufficient cavity optical gain to overcome the losses. Result: The laser is not perfectly monochromatic.

Broadening processes:

1) Thermal motion of atoms giving rise to Doppler shift broadening
2) Atomic collisions
3) Atomic vibrations from the thermal environment
Standing Waves in Laser Cavity

Standing waves exist only at frequencies for which the distance between the mirrors is an integer number $q$ of half wavelengths.

The resonance condition ($L$ distance between the mirrors) is given by

$$L = \frac{\lambda q}{2n}$$

where $\lambda$ is the emission wavelength and $n$ is the index of refraction of the laser medium. The emission frequency is defined by

$$f = \frac{qc}{2nL} \quad (2.13)$$

From: Chapter 6, Section 6.2.4, (pages 304-307) of Senior
Longitudinal Modes Set By Cavity Length

The frequencies generated by $f = \frac{qc}{2nL}$ are longitudinal modes.

These modes are separated by an interval $\delta f$ calculated from

$$\delta f = \frac{c}{2nL} \quad (2.14)$$

The mode separation with respect to wavelength $\lambda$, assuming $\delta f \ll f$, and using $f = c/\lambda$, is

$$\delta \lambda = \frac{\lambda \delta f}{f} = \frac{\lambda^2}{c} \delta f \quad (2.15)$$

Therefore, mode spacing is

$$\delta \lambda = \frac{\lambda^2}{2nL} \quad (2.16)$$

This will be used to determine the laser’s linewidth as a function of $\lambda$.

From: Chapter 6, Section 6.2.4, (pages 304-307) of Senior
The first laser demonstrated by Theodore Maiman at Hughes Research Laboratories (announced July 7, 1960). It was a ruby laser operating at 694.3 nm and was chromium doped corundum. Suppose that the ruby cylindrical crystal with a refractive index of 1.78. Assuming a wavelength of 694.3 nm (not the 550 nm cited in Senior), determine the number of longitudinal modes and their frequency separation.

Corundum is extremely hard aluminum oxide, used as an abrasive. Ruby and sapphire are varieties of corundum.


https://www.semanticscholar.org/paper/Fifty-years-of-ophthalmic-laser-therapy-Palanker-Blumenkranz/8f5c7e1d1c290d76c1a206fe373fffb490e863af9/figure/0
Example 6.2 (Page 306 in Senior) – 2

Solution:
The number of longitudinal modes supported within the structure may be calculated from equation (6.13)

\[
f = \frac{qc}{2nL} \quad \Rightarrow \quad \frac{f}{c} = \frac{1}{\lambda} = \frac{q}{2nL}
\]

\[
\therefore \quad q = \frac{2nL}{\lambda} = \frac{2 \times 1.78 \times 0.04 \text{ μm}}{0.6943 \times 10^{-6} \text{ μm}} = 2.051 \times 10^5
\]

Using equation (6.14) the frequency separation of the modes is

\[
\delta f = \frac{c}{2nL} = \frac{3 \times 10^8 \text{ m/sec}}{2 \times 1.78 \times 0.04 \text{ m}} = 2.106 \text{ GHz}
\]

Although this is a huge number of modes, the spectral output of the laser is limited by the gain curve of the cavity size and levels involved in the laser operation.
Gain Curve in Lasers (aka Gain-Bandwidth)

Gain in a laser requires population inversion. The laser gain curve depends upon the transition levels in the lasing medium involved in the population inversion between these two levels.

Note: The bandwidth Is set by cavity losses.

https://physics.stackexchange.com/questions/355223/laser-gain-curve
Combining Longitudinal Modes & Laser Gain Bandwidth


Gain threshold not yet shown
Gain Curve & Longitudinal Modes With Gain Threshold Included

Multi-mode Operation

https://www.semanticscholar.org/paper/Measuring-the-speed-of-light-using-beating-modes-in-D%27Orazio-Smith/c24b66221c2c8d15c95bb4400b18561bef34c7c5/figure/0
Transverse Modes in Laser Cavity

Laser Modes (a) An off-axis transverse mode is able to self-replicate after one round trip. (b) Wavefronts in self-replicating wave. (c) Four low order transverse cavity modes and Their fields. (d) Intensity patterns in the modes shown in part (c).

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https://www.networxsecurity.org/members-area/glossary/t/transverse-mode.html
Gain Threshold of Laser Cavity

Let $\tilde{\alpha} \, (\text{cm}^{-1})$ be the loss coefficient per unit length.

Then, the fractional loss can be written as

$$\text{Fractional loss} = (r_1 r_2) \cdot \exp(-2\tilde{\alpha}L)$$

The increase in beam intensity from stimulated emission is exponential (we simply state this and do not prove it).

From: Chapter 6, Section 6.2.5 of Senior
Gain Threshold of Laser Cavity

Let $\tilde{g}$ (cm$^{-1}$) be the gain coefficient per unit length. Then the fractional gain is given by

$$\text{Fractional gain} = \exp(2\tilde{g}L)$$

Hence, when the gain balances the losses, we write

$$\exp(2\tilde{g}L) \times (r_1 r_2) \cdot \exp(-2\tilde{\alpha}L) = 1$$

$$\left( r_1 r_2 \right) \cdot \exp\left[ 2(\tilde{g} - \tilde{\alpha})L \right] = 1$$

The threshold gain per unit length is found to be

$$\tilde{g} = \tilde{\alpha} + \frac{1}{2L} \log_e \left( \frac{1}{r_1 r_2} \right)$$

From: Chapter 6, Section 6.2.5 of Senior
We are given a semiconductor laser diode with cavity losses of 30 cm$^{-1}$ and a reflectivity for both mirrors (polished edges) of 30% (assume $r_1 = r_2 = r$). If the cavity is 600 μm (= 0.06 cm) long, calculate the gain coefficient per centimeter $\tilde{g}_{th}$ needed to meet the laser’s gain threshold (gain – loss = unity).

Solution:

\[ \tilde{g}_{th} = \tilde{\alpha} + \frac{1}{2L} \log_e \left( \frac{1}{r_1 r_2} \right) = \tilde{\alpha} + \frac{1}{2L} \log_e \left( \frac{1}{r} \right)^2 = \tilde{\alpha} + \frac{1}{L} \log_e \left( \frac{1}{r} \right) \]

\[ \tilde{g}_{th} = 30 \left[ \text{cm}^{-1} \right] + \frac{1}{0.06 [\text{cm}]} \times \log_e \left( \frac{1}{0.3} \right) \]

\[ \tilde{g}_{th} = 30 + \frac{1.2040}{0.06} = 30 + 20.07 = 50 \left[ \text{cm}^{-1} \right] \]
Summary of What We Have Presented in This Lecture

He-Ne LASER: MODES

(a) Optical gain vs. wavelength characteristics (called the optical gain curve) of the lasing medium. (b) Allowed modes and their wavelengths due to stationary EM waves within the optical cavity. (c) The output spectrum (relative intensity vs. wavelength) is determined by satisfying (a) and (b) simultaneously, assuming no cavity losses.

https://slideplayer.com/slide/7452547/
Spectral Linewidth for LED and Laser Sources $\sigma_\lambda$

From Lecture 6 (September 9, 2019)

<table>
<thead>
<tr>
<th>Source</th>
<th>Linewidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEDs</td>
<td>20 nm to 100 nm</td>
</tr>
<tr>
<td>Semiconductor laser diodes</td>
<td>1 nm to 5 nm</td>
</tr>
<tr>
<td>Nd:YAG solid-state lasers</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>NeHe gas laser</td>
<td>0.002 nm</td>
</tr>
<tr>
<td>Single Mode Laser</td>
<td>$10^{-4}$ nm</td>
</tr>
</tbody>
</table>

For an LED if center frequency is 850 nm, then a 50 nm spectral spread is 6% linewidth.
https://www.skipprichard.com/ask-questions-to-improve-your-leadership/