Four-level systems are the best for lasers

Steady-state conditions:

- threshold
- longitudinal modes

Some laser examples

“The teleforce ray will send concentrated beams of particles through the free air, of such tremendous energy that they will bring down a fleet of 10,000 enemy airplanes at a distance of 250 miles from the defending nation's border and will cause armies of millions to drop dead in their tracks.”

- Nikolai Tesla, 1937
Two-, three-, and four-level systems

Two-level system
At best, you get equal populations. No lasing.

Three-level system
If you hit it hard, you get lasing.

Four-level system
Lasing is easy!

Population inversion: \( \Delta N = -N \frac{I / I_{sat}}{1 + I / I_{sat}} \) always negative
Gain must exceed loss

Having a population inversion (ΔN < 0) isn’t enough. Additional losses in intensity occur, due to absorption, scattering, and reflections. Also there is an output beam...

The laser will lase if the beam maintains its intensity after one round trip, that is, if:

\[ G = \exp(gL) \]

This means: \( I_3 = I_0 \). Here, it means a condition on \( I_3 \):

\[ I_3 = I_0 \exp(gL) \quad R \exp(gL) = I_0 \]

In this expression, we are ignoring sources of loss other than the mirror reflectivity \( R \). This is an approximation, because there are always other sources of loss.
ΔN < 0 is necessary, but not sufficient.

Solving for \( g \), we find:

\[
\Rightarrow \quad g = \frac{1}{2L} \ln(1/R)
\]

This is the minimum value of the gain which is required in order to turn on a laser. This can be thought of as a threshold gain value, \( g_{\text{threshold}} \).

Now, recall that the gain is proportional to the population inversion:

If \( N_2 > N_1 \):

\[
g \equiv [N_2 - N_1] \sigma = -\Delta N \cdot \sigma \quad \text{remember: } \Delta N < 0
\]

for a population inversion, so \( g > 0 \).

Thus, there is a threshold value of the population inversion which is required:

\[
\Delta N_{\text{threshold}} = -\frac{1}{2L\sigma} \ln(1/R)
\]

\( \Delta N < 0 \) is not sufficient to make the laser operate. We need \( \Delta N < \Delta N_{\text{threshold}} \).
A threshold value of pump intensity

Can we estimate the value of $I_{\text{threshold}}$?
**Achieving Laser Threshold in a four-level system**

For a four-level system:

\[
\Delta N = -N \frac{I_{pump}}{1 + I_{pump} / I_{sat}}
\]

If the pump intensity is low (well below the saturation intensity), then this can be approximated by:

\[
\Delta N \approx -N \frac{I_{pump}}{I_{sat}}
\]

i.e., population inversion is negative and proportional to the pump intensity.

→ Even for a four-level system, lasers have a **threshold** pump intensity, in order to achieve sufficient gain to overcome the loss and begin to lase.

\[
I_{th} = \frac{I_{sat}}{2NL\sigma} \ln(1/R)
\]

(valid if the output coupler is the only source of loss)
Lasing behavior above threshold

In most lasers, the product $gL$ is a small number - the gain per pass through the gain medium is small. Then the gain per pass, $e^{gL}$, is approximately equal to: $1 + gL$. The power circulating inside the laser is therefore proportional to the gain $g$.

Thus: $I_{out} = R \cdot I_{circulating} \propto g$ The power emerging from the laser varies linearly with $g$.

So, for low pump intensities (but above threshold), we have:

output power $\propto g \propto -\Delta N \propto$ pump power

As we turn up the pump (from zero), there will be essentially no laser photons until we reach threshold. At that point, the laser turns on.

Then, the output power increases linearly with the pump power.
**Slope efficiency**

Above threshold (but not too far above), the output laser power is proportional to the input pump power.

The slope of this line is called the “slope efficiency” of the laser.

For example, a slope efficiency of 50% means that for every two additional pump photons we add, one additional laser photon is generated.

The concept of slope efficiency only applies for \( I_{th} < I_{pump} < I_{sat} \).

Essentially all lasers exhibit this behavior. Here’s an example: the silicon laser (2005)

In these data, you can see all three regimes: below threshold, above threshold, and saturation.
Another steady-state condition: the phase

In addition to requiring that gain exceed loss, (i.e., that the laser field amplitude must be constant on each round trip) we also require that the phase of the laser field must reproduce itself on each round trip.

\[
\frac{\text{angle}(E_{\text{after}})}{\text{angle}(E_{\text{before}})} = \exp(-j \omega L_{RT} / c) = 1 \quad \Rightarrow \quad \omega_m = \frac{2\pi c}{L_{RT}} \cdot m
\]

Since \( \omega = \frac{2\pi c}{\lambda} \), this is the same as saying that an integer number of wavelengths must fit in the cavity.

Only certain specific frequencies can satisfy this condition and lase.
Longitudinal modes

These are called the axial or longitudinal modes of the laser cavity.

They form a ‘picket fence’, an equally spaced set of discrete frequencies.

\[ \omega_m = \frac{2\pi c}{L_{RT}} \cdot m \]

\(m = \text{an integer}\)

single-mode laser - a laser which lases at only one frequency. Only one longitudinal mode lases.

multi-mode laser - when more than one longitudinal mode lases. Most lasers are multi-mode lasers.
Longitudinal modes

The number of modes oscillating inside a laser depends on the mode spacing $\Delta \nu$, and how it compares to the width of the Lorentzian gain curve. All modes that experience $\text{gain} > \text{loss}$ will lase.

This number can range from one or just a few up to millions.
Mode locking

For a laser with multiple modes lasing simultaneously, the output is the superposition of all of these modes.

If we can “lock” all of these phases together, we get a short pulse!

Techniques for doing this are called “mode locking”. They can be used to generate **absurdly short** pulses (the more modes that are locked, the shorter the pulse).

How short is “absurdly short”? 10 femtoseconds is to one second as one second is to 3.1 million years.
Short optical pulses are the fastest events ever created (or measured)

Charles Shank

Erich Ippen

Mikio Yamashita

Ferenc Krausz
Early history of the laser

In 1953, Charles Townes (Columbia University) built the first MASER, basically a laser at microwave frequencies.

In 1958, Townes and Arthur Schawlow (Bell Laboratories) predicted that the maser concept could be extended into the optical regime.

The acronym LASER is attributed to PhD student Gordon Gould.

At a 1998 party celebrating the 40th anniversary of the laser concept.

Schawlow died in 1999.

Townes was still doing research until his death in January of 2015.

He was 99 years old.
The ammonia maser

Charles Townes and his PhD student Jim Gordon, with the first maser (1953, Columbia University)

Produced a coherent beam of amplified microwave radiation

The nitrogen inversion transition in \( \text{NH}_3 \) has an energy level splitting of

\[
\nu = \frac{\Delta E}{\hbar} \approx 24 \text{ GHz}
\]
1960: The first laser

Ruby: a few chromium ions \(\text{Cr}^{+3}\) in a sapphire crystal

Ruby is a three-level system, so you have to hit it hard to make it lase. Almost nobody uses ruby lasers anymore.
Some types of lasers

Solid-state lasers have lasing material distributed in a solid matrix (such as ruby or neodymium:yttrium-aluminum garnet "YAG"). The Nd:YAG laser emits infrared light at 1064 nm.

Semiconductor lasers, sometimes called diode lasers, are $pn$ junctions. Electrical current is the pump source. Applications: laser printers or CD players.

Dye lasers use complex organic dyes, such as rhodamine 6G, in liquid solution or suspension as lasing media. They are tunable over a broad range of wavelengths.

Gas lasers are pumped by electrical current. Helium-Neon lases in the visible and IR. Argon lases in the visible and UV. CO$_2$ lasers emit light in the infrared (10.6 µm). There is even a water vapor laser that operates in the terahertz range (e.g., at $\lambda = 118$ µm).

Excimer lasers (from the terms excited and dimers) use reactive gases, such as chlorine and fluorine, mixed with inert gases such as argon, krypton, or xenon. When electrically stimulated, a pseudo-molecule (dimer) is produced. Excimers lase in the UV.
The Helium-Neon Laser

Energetic electrons in a glow discharge collide with and excite He atoms, which then collide with and transfer the excitation to Ne atoms, an ideal 4-level system.

A similar idea can be used to excite gaseous cadmium: a HeCd laser. This laser operates in the blue and near UV, and is often used for photolithography.
Carbon Dioxide Laser

The CO$_2$ laser operates analogously. N$_2$ is pumped, transferring the energy to CO$_2$.

CO$_2$ lasers are widely used in high-power applications. Including opening macadamia nuts: United States Patent 4358467 “Method for shelling of nuts with a laser beam”
The Nd:YAG laser

This gain medium consists of a small amount of Nd\(^{3+}\) ions doped into a YAG crystal. YAG stands for “yttrium aluminum garnet”, which is Y\(_3\)Al\(_5\)O\(_{12}\), a synthetic crystal.

The YAG acts as a host, and has little effect on the Nd ions which are almost an ideal 4-level system. The primary lasing transition is at \(\lambda = 1064\) nm.

Nd:YAG lasers are widely used for many different applications, including certain types of eye surgery.

Nd ions can also be doped into other crystalline materials (e.g., yttrium lanthanum fluoride, or YLF) or into various different amorphous glasses.
Dye lasers

Molecular dyes are often ideal four-level systems, and a given dye will lase over a range of ~100 nm.
Dyes cover the visible, near-IR, and near-UV ranges.
Diode Lasers

usually just a $p$-$n$ junction...
Vertical cavity diode lasers

Diode lasers can also be fabricated with vertical cavities. This configuration is known as a VCSEL (pronounced “vixel”), which stands for “vertical cavity surface emitting laser.”

A VCSEL emits a circular beam, rather than a stripe, so it is easy to couple to an optical fiber. Also, due to its surface-emission architecture, it can be tested on the wafer.

a 6-micron tall VCSEL mesa  

VCSEL’s can also be fabricated in the form of arrays.
Some everyday applications of diode lasers

CD burner  Laser Printer
Quantum cascade lasers

In a QC laser, the transitions are all in the conduction band. The valence band does not participate.

This means that one electron can produce hundreds of photons!

Extremely useful for making lasers in the mid and far infrared.
The (formerly) world’s biggest laser

Nova - Lawrence Livermore National Laboratory

Delivers $\sim 10^{14}$ watts in $10^{-9}$ seconds

For that brief instant, Nova produces 200 times as much power as the entire US electrical grid.
Even Bigger

National Ignition Facility

192 shaped pulses
23-nanosecond pulse duration
1.8 MJ total energy on target
(achieved on March 15, 2012)
REALLY Big

Laser bay #2

A mirror for the NIF laser

Target chamber
You may have seen NIF before...
Laser Safety Classifications

**Class I** - These lasers are not hazardous.

**Class IA** - A special designation that applies only to lasers that are "not intended for viewing," such as a supermarket laser scanner. The upper power limit of Class IA is 4 mW.

**Class II** - Low-power visible lasers that emit above Class I levels but at a radiant power not above 1 mW. The concept is that the human aversion reaction to bright light will protect a person.

**Class IIIA** - Intermediate-power lasers (cw: 1-5 mW), which are hazardous only for intrabeam viewing. Most pen-like pointing lasers are in this class.

**Class IIIB** - Moderate-power lasers (~ tens of mW).

**Class IV** - High-power lasers (cw: 500 mW, pulsed: 10 J/cm² or the diffuse reflection limit), which are hazardous to view under any condition (directly or diffusely scattered), and are a potential fire hazard and a skin hazard. Significant controls are required of Class IV laser facilities.
WARNING!
Do not look into laser with remaining eye!