The Laser at 50: Past, present and future

Image credit: Jonathan Ying
Lasers

Mikhail Kats  How Lasers Work

Romain Blanchard  Our Information Age

Ted Feldman  Power for the Future
Light Amplification by Stimulated Emission of Radiation
Laser

Light Amplification by Stimulated Emission of Radiation
Light: electromagnetic wave

Wave properties:
- Crest
- Amplitude
- Wavelength

Electromagnetic spectrum:
- \( \gamma \) rays
- X rays
- UV
- IR
- Microwave
- FM
- AM
- Long radio waves

Increasing Wavelength (\( \lambda \)) →

Visible spectrum

Increasing Wavelength (\( \lambda \)) in nm →

Image source: Wikimedia Commons
Photons: bits of light

- A single packet of light: a photon

Smaller wavelength $\rightarrow$ larger photon energy

- “Wave - particle duality”
- Helps understand interaction between light and atoms

Image source: The Scientific Monthly, 1920
Light Amplification by Stimulated Emission of Radiation
Light Amplification by Stimulated Emission of Radiation

But first... atoms!
Atoms and atomic levels

- Atom: positively charged nucleus surrounded by negatively charged electrons

Simplistic orbit picture

Image source: Wikimedia Commons (modified) and Cornell Astrophysics
Atoms and atomic levels

- Atom: positively charged nucleus surrounded by negatively charged electrons

Simplistic orbit picture

A helpful analogy:
The quantum stepladder
• Simplest model atom

• 2 discrete energy levels - one lower energy, one higher energy
Absorption

Before absorption

incident photon

Electron in ground level

$n=1$ is the lowest energy level.

Rungs correspond to energy levels.

Image source: Wikimedia Commons (modified) and Cornell Astrophysics
Absorption

After absorption

Electron in excited level

$E_1$

$E_2$

Rungs correspond to energy levels.

$n=1$

$n=1$ is the lowest energy level.
Light Amplification by Stimulated Emission of Radiation
Stimulated Emission

- A photon hits an already excited atom...

Electron in an excited level

Rungs correspond to energy levels.

$n=1$ is the lowest energy level.

Image source: Wikimedia Commons (modified)
Stimulated Emission

- The two resulting photons are identical in every way! (wavelength, direction, and they wave in sync)

Electron back to ground level

Image source: Wikimedia Commons (modified)
Light Amplification by Stimulated Emission of Radiation
Light Amplification

- Take a piece of material with many two-level atoms, with all electrons in level 2
- A single photon traveling through this crystal will result in many photons (and put all electrons in the ground level)!

\[ E_1 \rightarrow E_2 \]

\[ \quad \]

\[ \quad \]

\[ \quad \]

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\[ E_1 \rightarrow E_2 \rightarrow \text{many photons} \]
Light Amplification?

- But now... all of the electrons are in the ground level! No more amplification 😞
Constant amplification

- All electrons in our crystal need to constantly be re-excited to level 2
  - How do we get there? Add a third level!
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  - Constant pumping by absorption of a different frequency!

\[ \text{E}_1 \rightarrow \text{E}_2 \rightarrow \text{E}_3 \]
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Fast transition!
Energy lost as heat
Constant amplification

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\[ \text{Fast transition!} \\
\text{Energy lost as heat} \]
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\[ E_1 \rightarrow E_2 \rightarrow E_3 \]

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Fast transition!
Energy lost as heat
Atomic levels: ruby

- Ruby: Sapphire (Al$_2$O$_3$) crystal with 0.5% chrome atoms replacing aluminum

Each chrome atom in the crystal acts like a 3 level system!

(very) simplified energy level diagram

Image source: Wikimedia Commons, contributors Adrian Pingstone and Bkell
• Start with a Ruby with all electrons in the ground state...
• Turn on the pump light!
Laser cavity

- Pump light ensures all electrons are in state 2
Laser cavity

- Pump light ensures all electrons are in state 2
Laser cavity

- Start with just one photon somewhere in the Ruby...

[Diagram showing energy levels $E_1$, $E_2$, and $E_3$.]
Laser cavity

- Stimulated emission!
Laser cavity

- Pumping: Absorption and fast relaxation!
Laser cavity
Laser cavity

- Stimulated emission!
Laser cavity

- Pumping: absorption and fast relaxation!

But now what? How do we get even more photons?
Laser cavity

- Add mirrors! This makes a "laser cavity"
Laser cavity

• Reflection!

Mirror

\[ E_1 \]

\[ E_2 \]

\[ E_3 \]
Laser cavity

Mirror

E₁

E₂

E₃

Mirror
Laser cavity
Laser cavity

- Skipping a few steps!
Laser cavity

- Skipping a few steps!

Does anyone see a problem with this laser?
Laser cavity

- Use a partially reflecting mirror!
Laser cavity

- 50% transmission, 50% reflection!
- Now we have a laser!
The ruby laser

- Ted Maiman’s first laser: 1 ‘Gillette’ of power

Image source: Wikimedia Commons
The ruby laser

Image source: Retrotech on Flickr, reproduced with permission
What’s special about laser light?

- Monochromatic: nearly single frequency
- Coherent: same polarization, phase - all photons in lock step
Brief Timeline

- 1917: stimulated emission explained by Einstein

- 1950s: Charlie Townes, Arthur Shawlow, Alexander Prokhorov and Nikolay Basov work out the theory of lasers

- 1959: Gordon Gould coins the term LASER, patents it

- 1960: Ted Maiman makes first working laser
Thank you!

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Laser cavity

Pumping mechanism

Gain medium

Partially reflecting mirror

100% mirror