What is a laser?
Three Atomic Processes
Three Components of Every Laser
Laser Light Characteristics
Units of Laser Spectroscopy
History
Laser Applications

Introduction

ECE 455 Optical Electronics

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ECE Illinois

Contact Information

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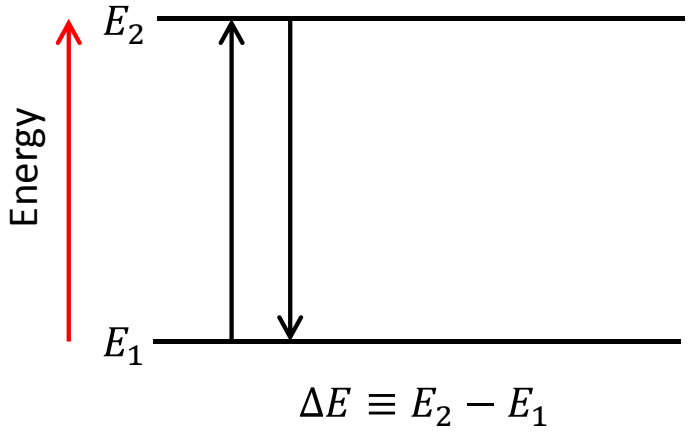
LASER

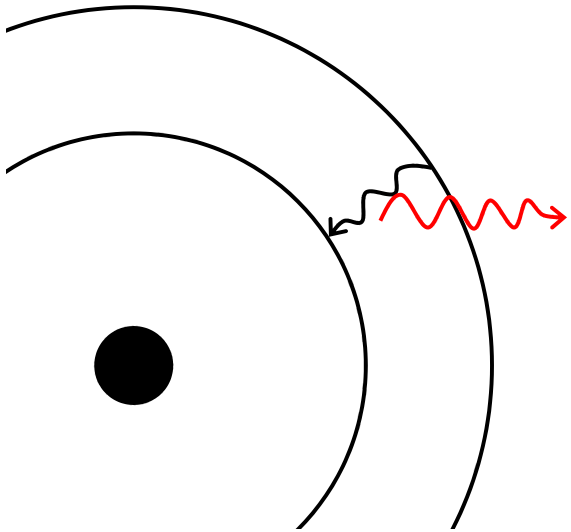
Light
Amplification by
Stimulated
Emission of
Radiation

Atomic Energy Levels

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- Individual atoms have discrete energy levels
- Solids will have energy bands
- Light can cause atoms to transition between energy levels

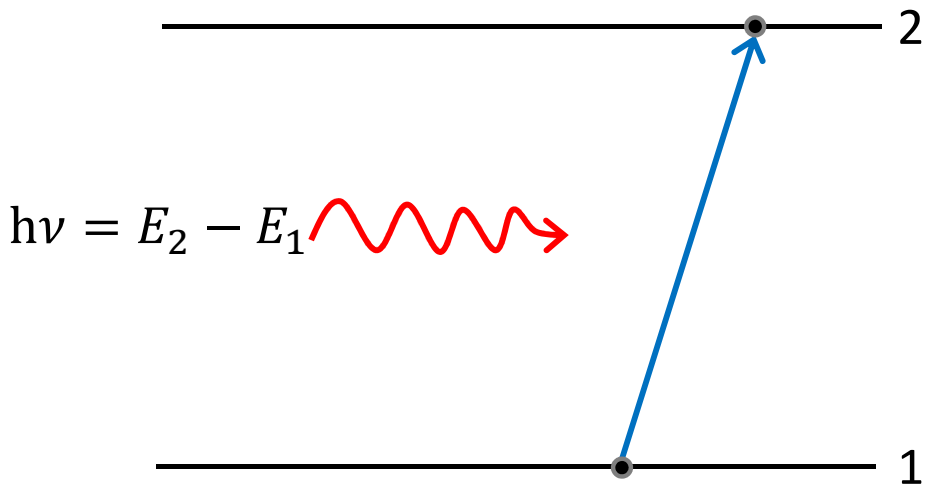




Absorption

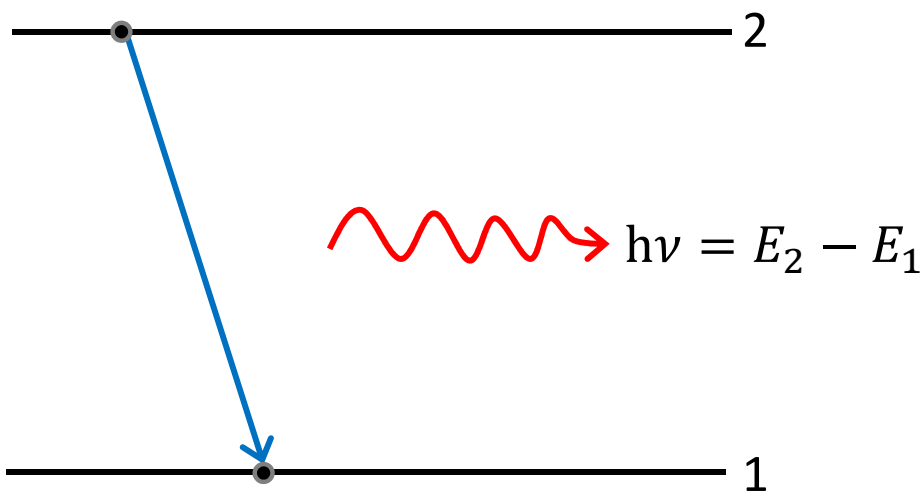
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- When a two-level system absorbs a photon, it is left in an excited state



Spontaneous Emission

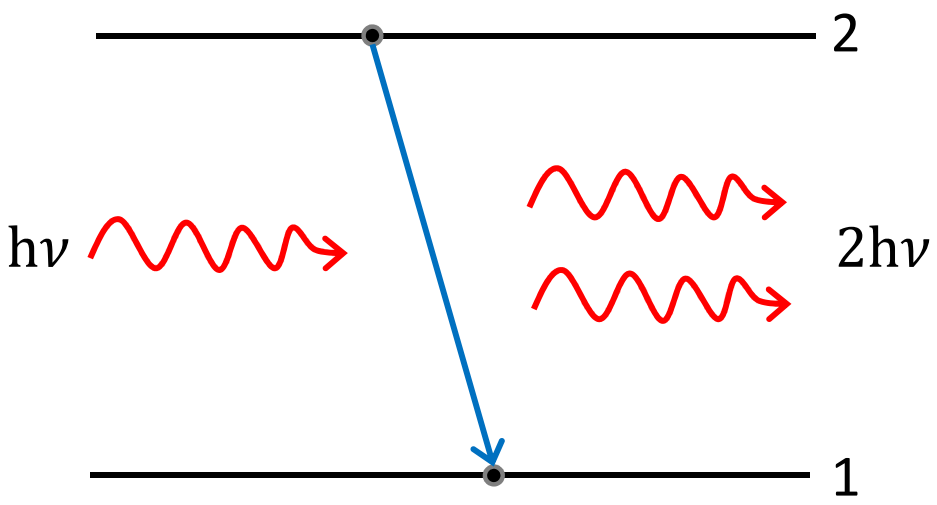
- Two-level system spontaneously decays from a higher energy level to a lower energy level and emits a photon.
- The decay rate is characterized by the **spontaneous emission lifetime** τ
- Emission is uniform in all 4π steradians
- Spontaneous emission can only be explained by QED



Stimulated Emission

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- Photon interacts with two-level system in an excited state
- The system goes to a lower energy level and a photon with the corresponding energy is emitted
- Emitted photon has the same **direction, polarization, phase** and **energy** as the incident photon



Absorption and Stimulated Emission

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- Absorption and stimulated emission are inverse processes.
- The probability for a photon to be absorbed by an atom in its ground state is the same as the probability for the same photon to induce stimulated emission from an atom in its upper state.

To Have Optical Gain...

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In order to have gain, there must be more atoms in the upper energy state than in the lower energy state. This situation is known as **population inversion**.

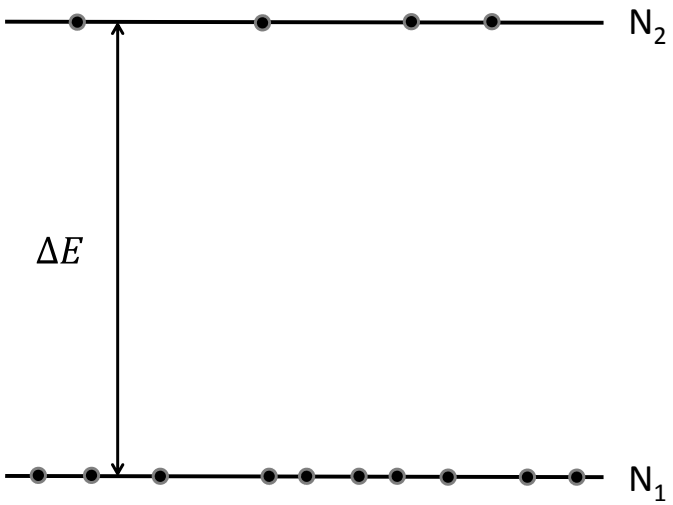


Figure: Net loss will occur

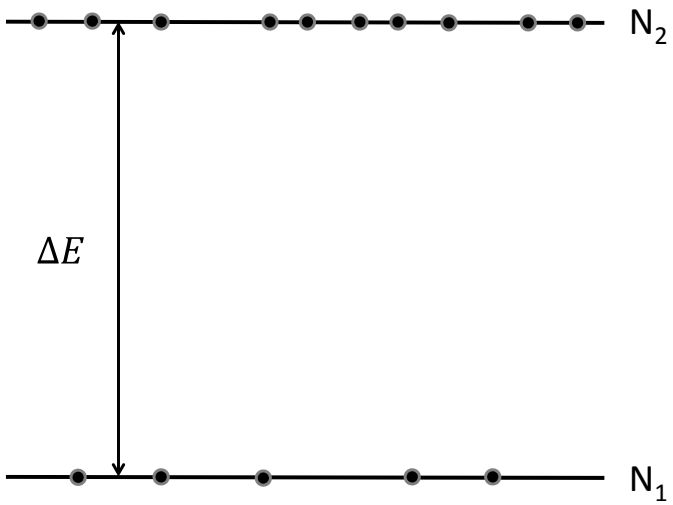
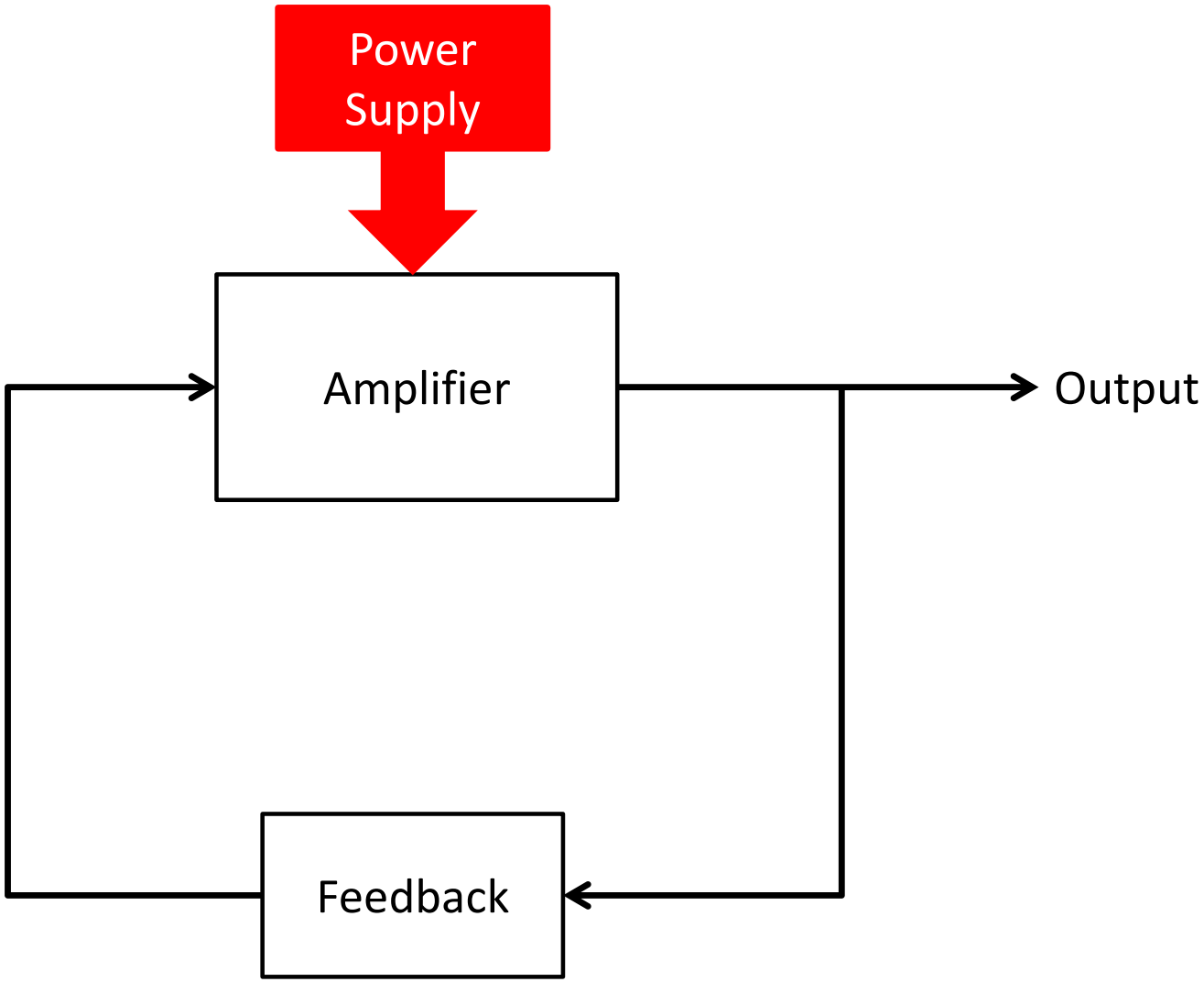


Figure: Net gain will occur

What would happen if the populations of the upper and lower states were equal?

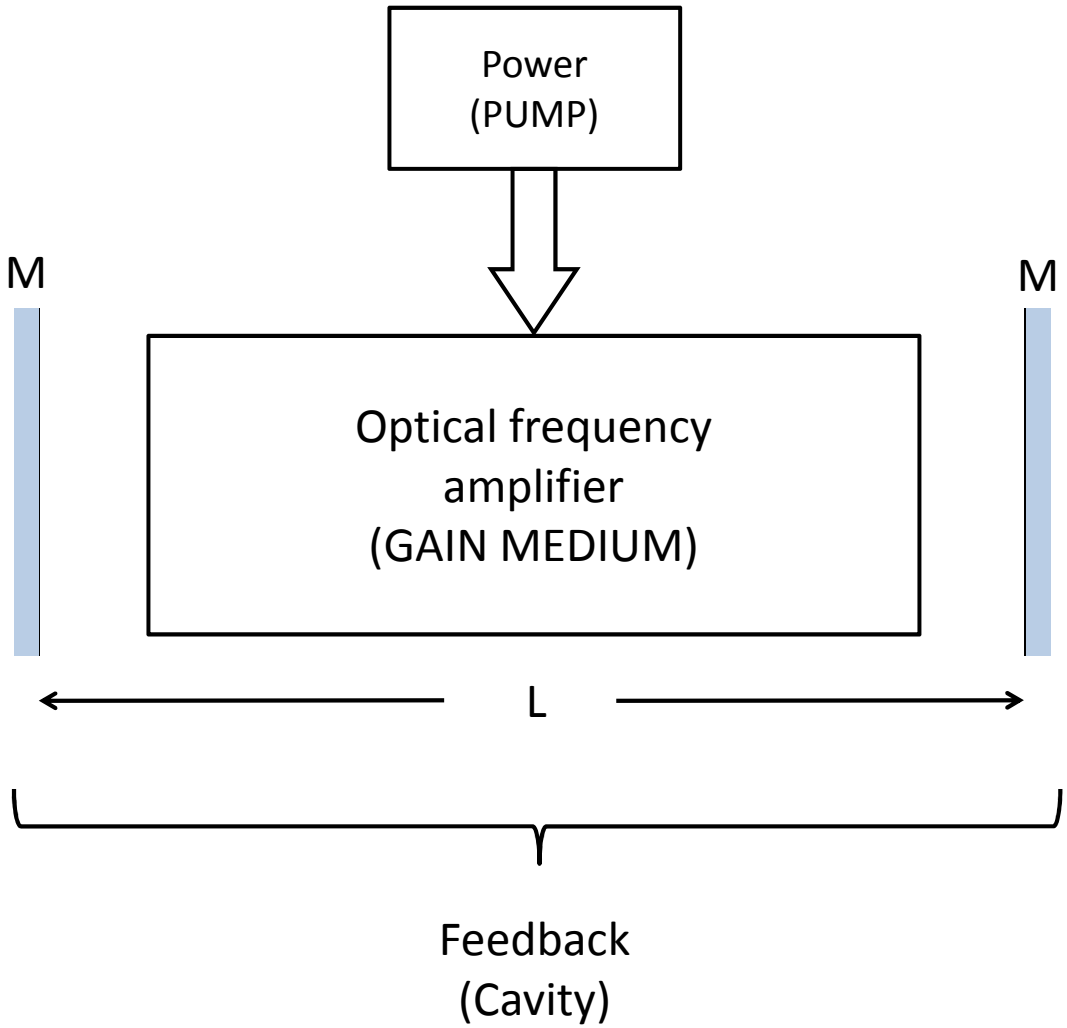
Three Components of Every Oscillator

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Three Components of Every Laser

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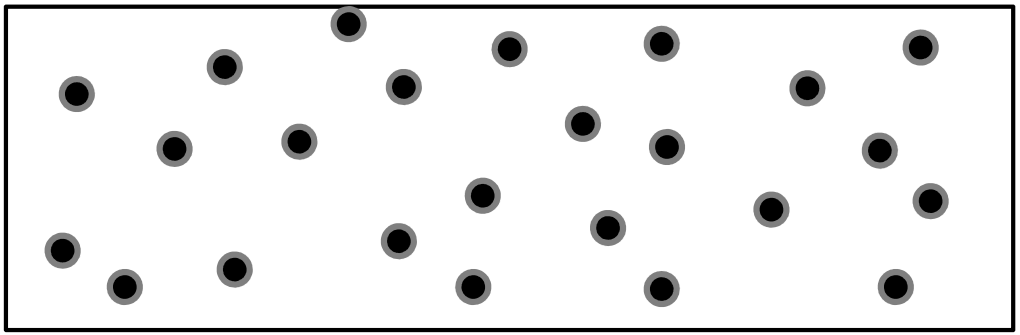
Characteristics of Gain Medium

- Provides optical gain
- Stores energy from the pump
- Energy levels in atomic media are set by nature. It is up to the laser designer to figure out how to use them.
- In semiconductor lasers, designers tweak semiconductor dimensions and composition to adjust the energy levels.
- Examples of gain media
  - Titanium atoms doped into sapphire crystal ($Ti:Al_2O_3$)
  - Neon atoms in a plasma
  - Organic dye molecules in a liquid solution
  - Quantum dots in semiconductor lasers

Gain Medium

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The gain medium by itself is not very exciting.



Ground State Atom
Excited Atom
Photon

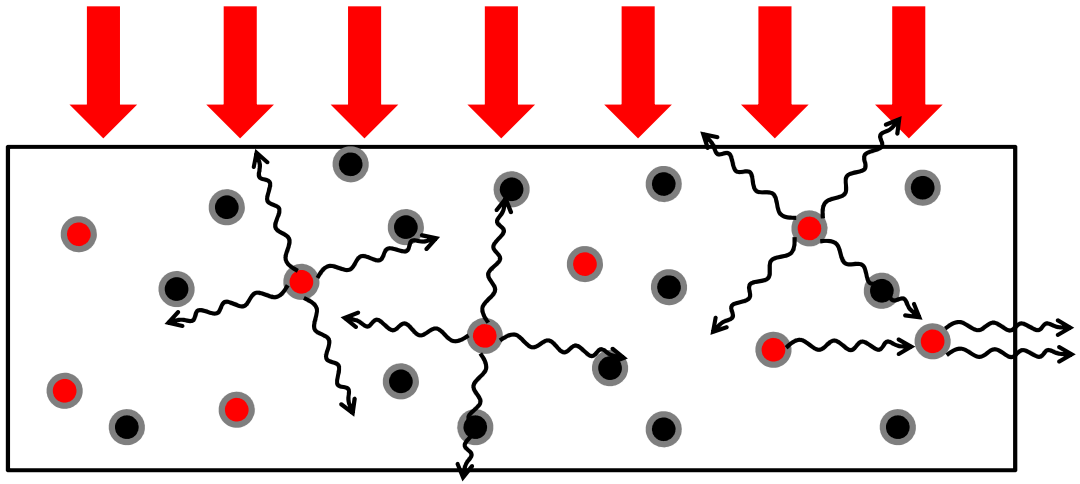
Characteristics of a Pump Source

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- Source of energy for the laser
- Moves the lasing species from its ground state to an excited state, though not necessarily the upper level of the laser transition
- Examples of pumps
  - Flashlamp
  - Another laser
  - Direct electrical pumping (as in a diode laser)
  - Collisional pumping (electron collisions in a plasma)
  - Chemical reactions (reactions do not necessarily leave the product molecule in its ground state)

Gain Medium and Pump

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Ground State Atom
Excited Atom
Photon

Gain Medium and Pump

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- Photons only pass through a fraction of the gain medium before escaping.
- The average distance a photon travels through a gain medium before causing stimulated emission is:

$$L_{opt} = \frac{1}{\sigma_{se}(N_2 - N_1)} \tag{1}$$

  where σ_{se} is a constant and N_1 and N_2 are the population number of the upper and lower states.
- If $L_{gain} \ll L_{opt}$, there will be negligible stimulated emission.
- Excited atoms relax via spontaneous emission
  - Light is emitted equally in all directions
- If a signal is introduced into one end of this device, the gain medium can be used as an **optical amplifier**.

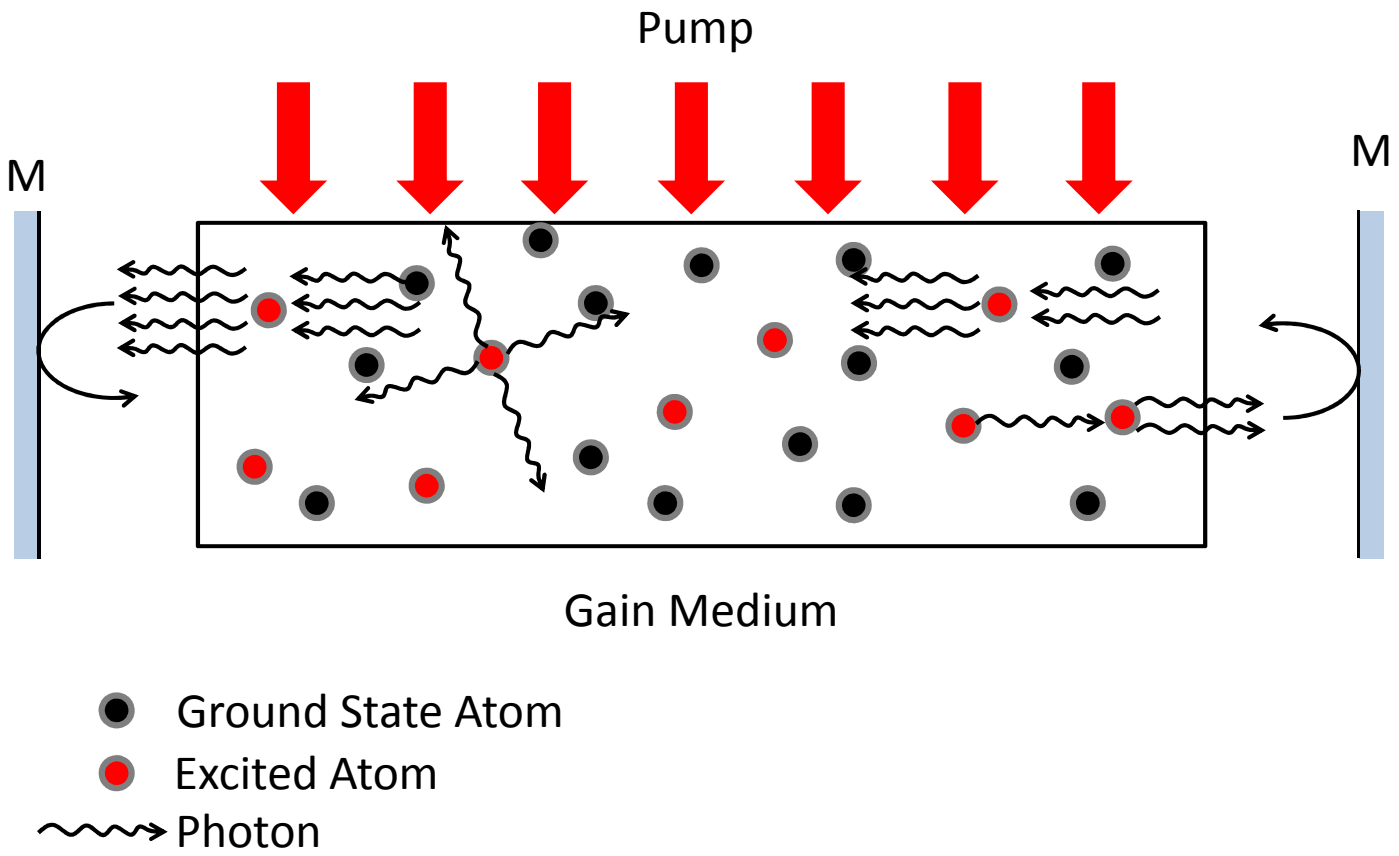
Characteristics of Optical Cavities

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- Provides feedback of the optical field
- Increases the effective length of the gain medium
- Determines the spatial characteristics of the laser beam
- Resonant modes of the cavity determine the exact frequency of oscillation
- Output power strongly influenced by loss of cavity.
- Examples of cavities
  - A pair of high-reflecting mirrors may be placed around a gain medium or form its boundaries
  - Edge-emitting semiconductor lasers receive feedback from reflections at the boundaries of the semiconductor
  - Cavities are not required for all lasers "Mirrorless Lasers")

Gain Medium, Pump and Cavity

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Gain Medium, Pump and Cavity

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- Mirrors force photons to pass through the gain medium several times, increasing the effective length of the gain medium along the axis of the cavity.
- If $L_{gain,eff} \geq L_{opt}$, then on average, each photon causes more than one stimulated emission before it leaves the gain medium and the number of photons grows. A laser is born!
- Note that the effective gain length is only increased on the cavity's axis
- Therefore strong stimulated emission is only observed along the axis of the cavity
- As atoms move to lower states via stimulated emission, spontaneous emission is suppressed (though not completely).

Gain Medium, Pump and Cavity

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- Photons passing through an inverted gain medium experience positive feedback:
  - Each stimulated emission increases the number of photons
  - More photons cause more stimulated emission
- In a laser, the positive feedback is balanced by two factors:
  - Saturation of the gain medium – increased stimulated emission decreases the number of atoms in their upper state
  - Loss of photons from the cavity, both from the laser's output as well as undesirable absorption and scattering

Gain Medium, Pump and Cavity

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- The cavity provides the gain medium with a 'memory'
- Without it, all photons emitted at time $t = 0$ escape by time

$$t = \frac{L_{gain}}{c} \tag{2}$$

- With a cavity, the average photon escapes the cavity in time

$$t = \frac{L_{gain,eff}}{c} \tag{3}$$

  where $L_{gain,eff}$ is the effective length of the laser
- The cavity "traps" light
- But before each photon leaves, it creates other photons with the same **direction, polarization, phase** and **energy** via stimulated emission.
- The net result is to stabilize the output of the laser

How is Laser Light Different From Ordinary Light?

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Laser light is:

- Intense
- Quasi-monochromatic
- Temporally coherent
- Spatially coherent
- Single or few mode

Speckle Demo

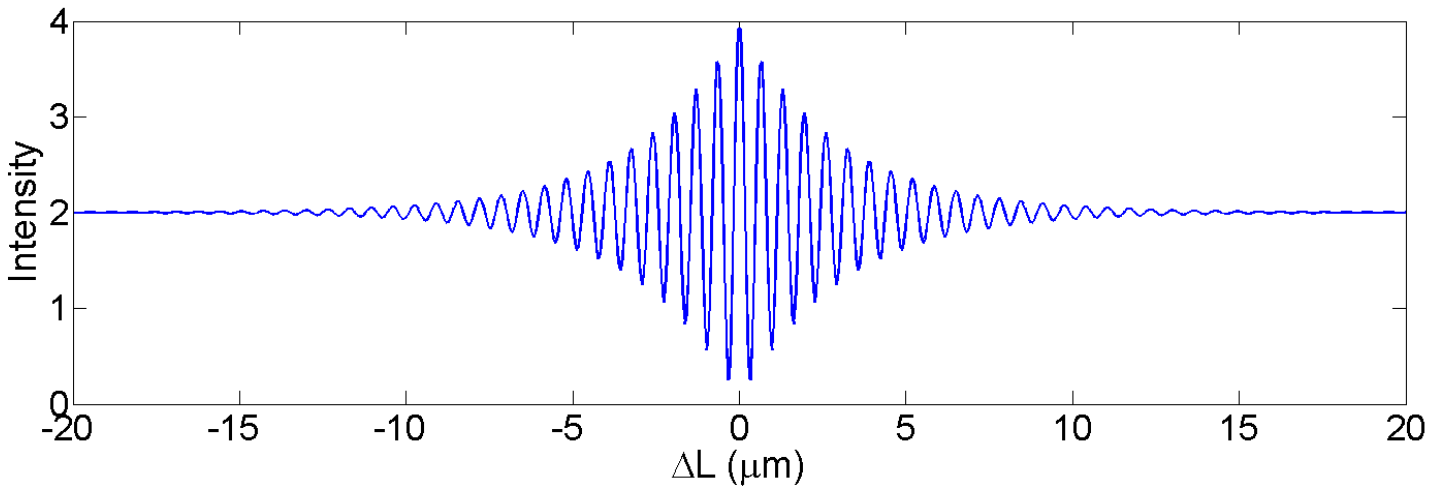
1. Shine laser pointer on screen
2. Observe pattern of spots
3. Place finger $\sim$30 cm in front of face and focus eye on it
4. Speckle pattern in background does not go out of focus

What is Coherence?

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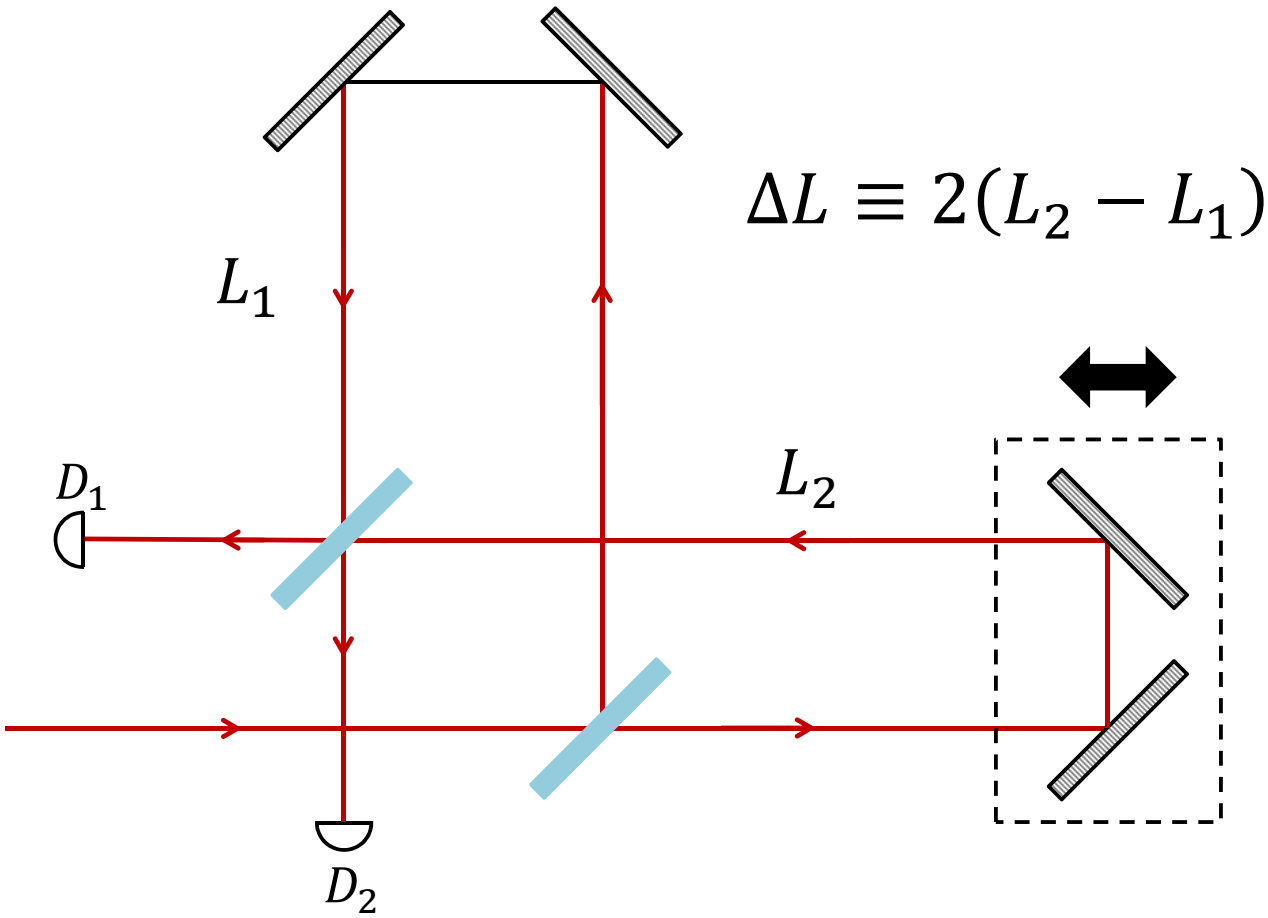
Roughly speaking...

- **Coherence** is the ability to form interference fringes, as shown below.
- **Coherence length** is the characteristic length L_c over which fringes will disappear as ΔL is scanned in a Michelson interferometer.
- **Coherence area** is the square of the characteristic distance (L_A) over which fringes disappear in a Young's Double Slit experiment.



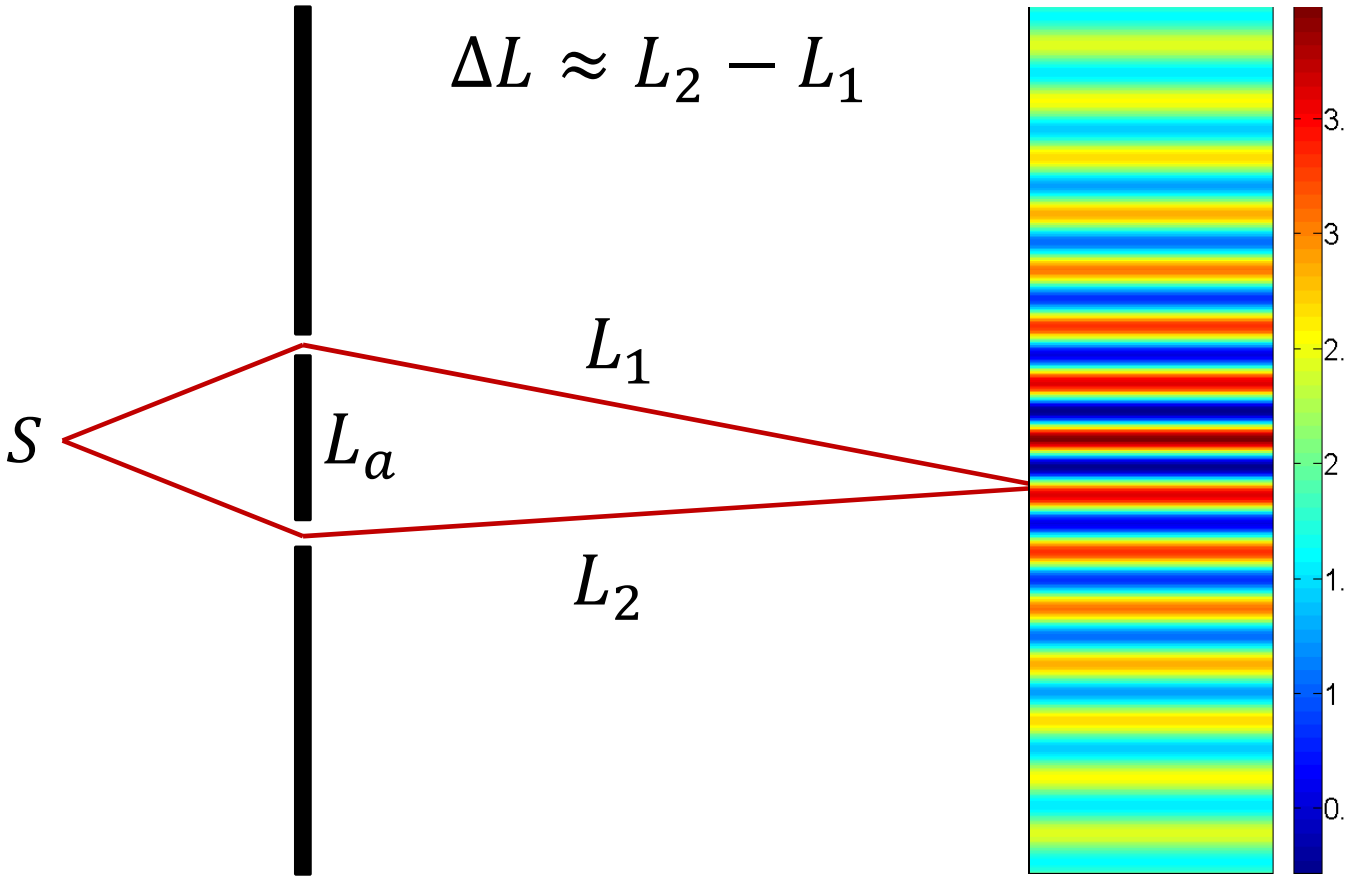
Temporal Coherence: Michelson Interferometer

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Spatial Coherence: Young's Double Slit Experiment

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Colors

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- Human vision extends from 400-700 nm.
- Knowing the correspondence between color and wavelength can be an important safety issue.
- Memorize the chart below:

Wavelength (nm)	Color
Below 400	Ultraviolet (UV)
400-440	Violet
440-490	Blue
490-560	Green
560-590	Yellow
590-620	Orange
620-700	Red
Above 700	Near Infrared (NIR)

- The exact boundaries are not standardized.

Invisible Light I

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- Electromagnetic waves with wavelengths longer than 700 nm are referred to as 'infrared' (IR). Infrared is invisible because it cannot be detected by your retina.
- Electromagnetic waves with wavelengths shorter than 400 nm are referred to as 'ultraviolet' (UV). Ultraviolet light is invisible because it absorbed by your cornea.
- Your eyes do not have a perfectly sharp cutoff. You still may be able to see wavelengths longer than 700 nm or shorter than 400 nm.
- In the literature both IR and UV will be referred to as 'light' and as part of the field of 'optics.'

Invisible Light II

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- Even though it is invisible, IR and UV radiation from lasers may still be dangerous.
  - Although IR light is invisible, it can still focus on and burn the retina.
  - UV light causes cataracts.
- With sufficiently high peak intensities (such as in a regeneratively amplified femtosecond laser), a laser beam may stimulate 2-photon transitions and appear blue.
- A UV laser will typically appear white or blue upon striking a surface due to fluorescence.

Laser Safety

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- Your eye is designed to image light onto your retina.
- Laser light can cause damage at significantly lower powers than other sources because laser beams focus tightly.
- Retinal damage (permanent blind spots) may occur from a 100 ms exposure to a laser with power as low as 10 mW (a typical laser pointer is 5 mW)
- Damage thresholds for pulsed lasers are more complicated
- Beams should be contained to eliminate stray reflections
- Laser safety glasses are your last line of defense
- THIS SLIDE DOES NOT CONSTITUTE LASER SAFETY TRAINING!
- See [1] for more information.

Wavelength

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All wavelength measurements denoted in terms of the meter. The traditional symbol representing wavelength is λ.

Unit	Name	Conversion	Use
Å	Angstrom	10^{-10} m	X-ray through IR wavelengths
nm	nanometer	10^{-9} m	UV through IR wavelengths
μm	micron	10^{-6} m	Visble through IR wavelengths
mm	millimeter	10^{-3} m	Beam Size
cm	centimeter	10^{-2} m	Beam Size
m	meter	1 m	Distance
km	kilometer	1000 m	Radio Waves

Energy and Frequency

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Frequency, energy, and inverse wavelength are all linearly related and used interchangeably in atomic physics.

Unit	**Name**	**Use**
Hz	Hertz	Electromagnetic field frequency
eV	Electron Volts	Photon Energy/Electron Energy Levels
cm^{-1}	Wavenumber	Photon Energy/Electron Energy Levels
J	Joule	Pulse Energy

Conversions and Formulae

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$$\text{Energy } (\text{cm}^{-1}) = \frac{1}{\lambda(cm)} \qquad (\textbf{Note NO } \mathbf{2\pi})$$

$$1 \text{ eV} = 8065 \text{ cm}^{-1} = 1.602\times 10^{-19} \text{ J}$$

$$\lambda \text{ (nm)} \times \text{E (eV)} = 1240 \text{ eV-nm}$$

$$1 \text{ cm}^{-1} = 30 \text{ GHz}$$

$$\lambda\nu = c \Rightarrow \Delta\lambda = \frac{\lambda^2}{c}\Delta\nu$$

$$1\text{eV} = 11600 \text{ K}$$

$$1 \text{ Torr} = 3.22 \times 10^{16} \text{ cm}^{-3}$$

Laser Development Milestones

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- 1914 - Regenerative amplifier/oscillator circuit demonstrated by Edwin Armstrong
- 1917 - Einstein predicts stimulated emission while studying blackbody radiation
- 1954 - First MASER (NH_3) demonstrated by Townes
- 1958 - Townes and Schawlow predict 'optical maser'
- 1960 - First LASER (ruby) demonstrated by Theodore Maiman (Hughes, Malibu)
- 1960 - First CW laser (He-Ne) demonstrated by Ali Javan
- 1962 - Semiconductor lasers created by three independent teams within 1 month
- Post 1962 - You could write several books on all the developments since 1962
- 2010 - 50^{th} Anniversary

Laser Related Nobel Prizes

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Year	Name	Description
1964	Charles H. Townes Nikolai G. Basov Aleksandr M. Prokhorov	Development of the maser and laser
1971	Dennis Gabor	Holography
1981	Nicolaas Bloembergen Arthur Schawlow	Developments in laser spectroscopy
1997	Steven Chu Claude Cohen-Tannoudji William Daniel Phillips	Laser cooling and trapping of atoms with laser light
1999	Ahmed H. Zewail	Femtosecond spectroscopy
2005	John L. Hall Theodor W. Hänsch	Frequency combs
2009	Charles K. Kao	Light transmission in glass fibers

Laser Revenue by Application 2010

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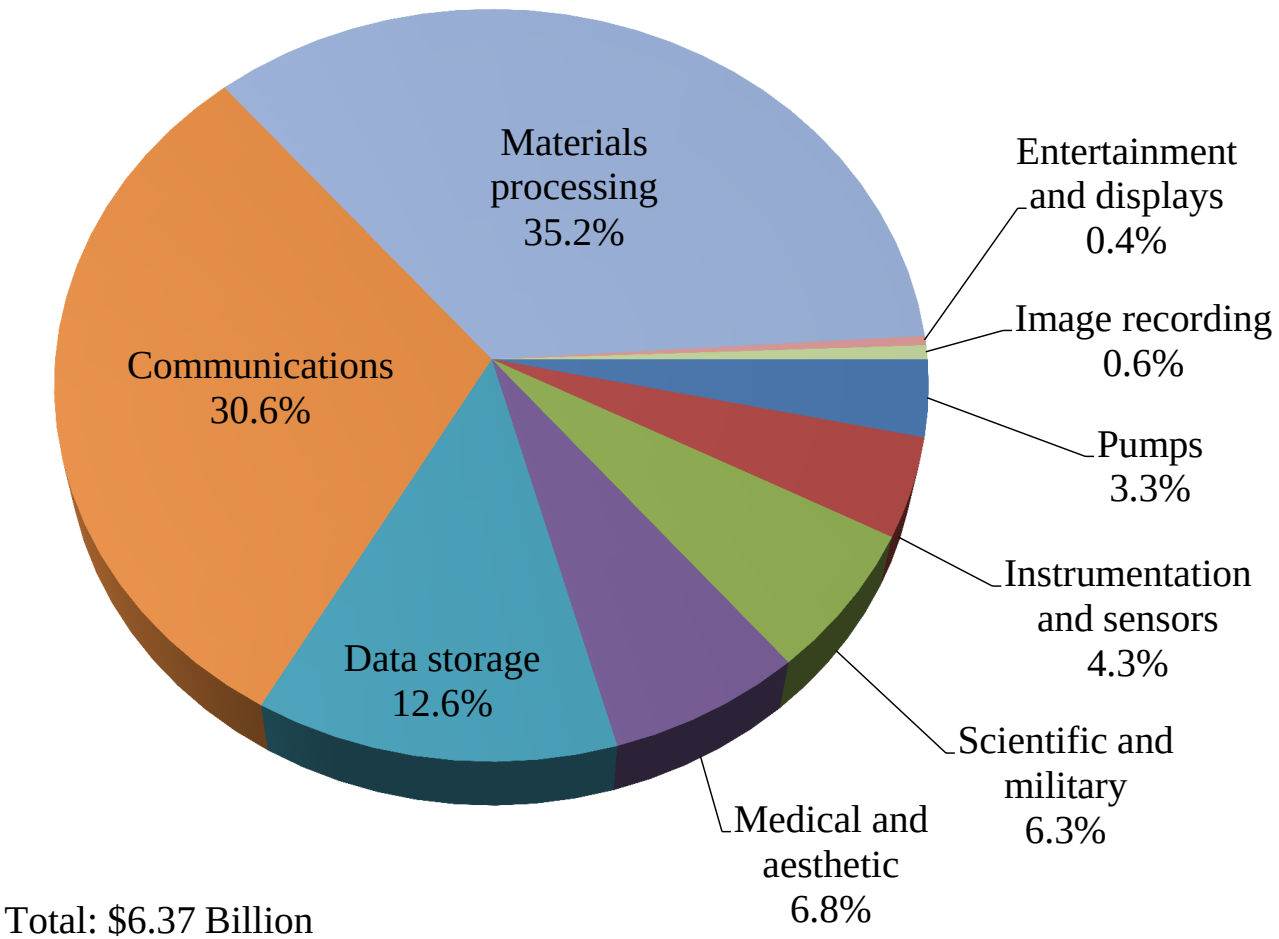


Figure: Source: *Laser Focus World* **47** 1

Death Rays

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- Contrary to popular perception, funding for directed energy weapons is only a small fraction of laser research.
- Clouds and atmospheric turbulence scatter laser beams.
- Storing energy for lasers in a portable format is also challenging.
- There are many military uses for lasers:
  - Laser welding
  - Laser rangefinder
  - Laser-guided bombs
  - The Viper laser confuses heat-seeking missiles



Real Genius (1985)

Single Cell Biological Lasers [2]

- Cells genetically modified to create green fluorescent protein (GFP)
- A high-Q cavity surrounded the cell
- System was pumped with 850 pJ of 465 nm light from an OPO
- Applications in cell sensing and cytometry

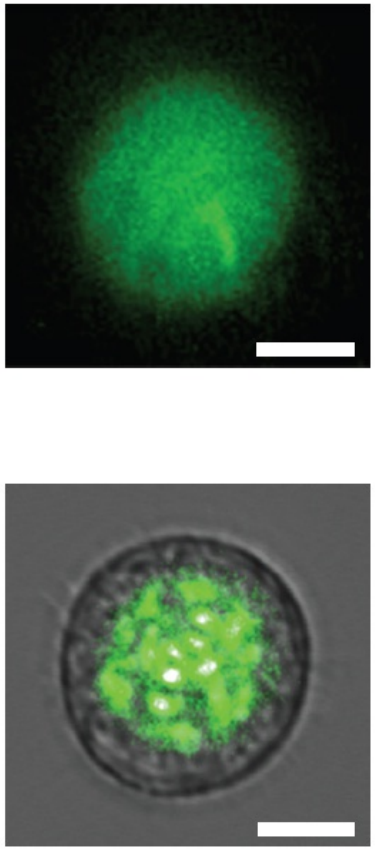


Figure: Images of a living cell as it is pumped above (bottom) and below threshold (top).

National Ignition Facility

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- Built for research into inertial confinement fusion
- 192 beams focus onto a millimeter-sized pellet filled with a mixture of deuterium and tritium
- Expected to produce the first exothermic ICF reaction
- 1.8 MJ pulses
- 500 TW peak power



Figure: One of two laser bays at LLNL. (Source: http://lasers.LLNL.gov)

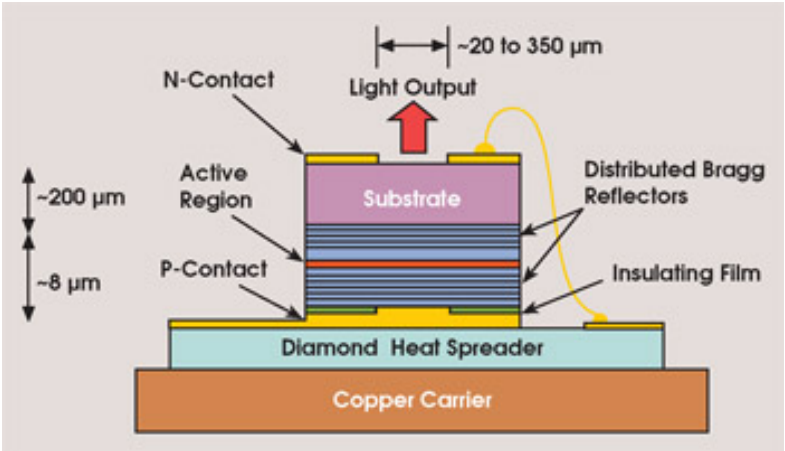
Stimulated Emission in Nature [3, 4]

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- Non-thermal emission spectra of CO_2 are observed in the upper atmospheres of Venus and Mars around 9.4 μm and 10.6 μm.
- The vibrational levels of the CO_2 molecule are pumped to inversion by the Sun.
- Photons traverse enormous atmospheric path lengths.
- Stimulated emission contributes approximately 4% of the photon flux.

Vertical Cavity Surface Emitting Lasers (VCSELS)

- Emission is perpendicular to the wafer, rather than along its edge.
- Cavity length as short as $\lambda/2$
- Cavity volume can be on the order of λ^3
- Used in research to test fundamental aspects of quantum mechanics.
- Commercial use: laser mice, optical data transmission, autonomous vehicles



(Source: www.photonics.com)

The Internet

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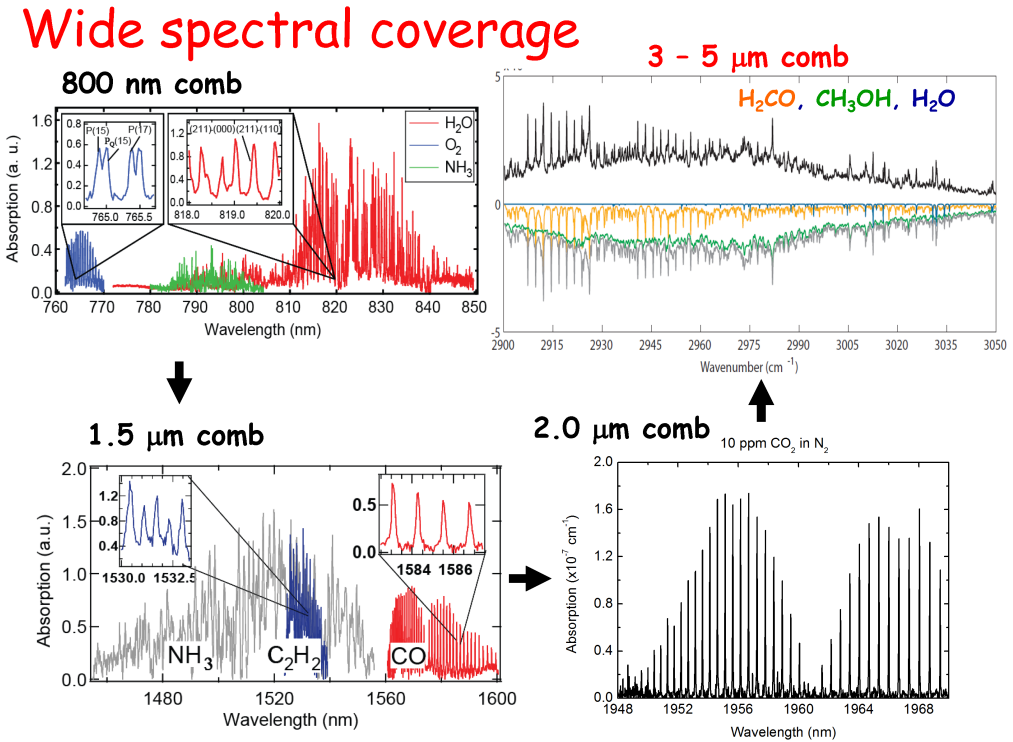
- Fiber optics have been carrying telephone data since the early 1980s.
- Data is transmitted by modulating the output of CW lasers.
- Signals from one or several lasers at different wavelengths may be sent on the same fiber (WDM).
- Er-doped fibers pumped by diode lasers amplify signals without having to convert the signal.
- For history, see [5]

NEED PICTURE

Frequency Combs

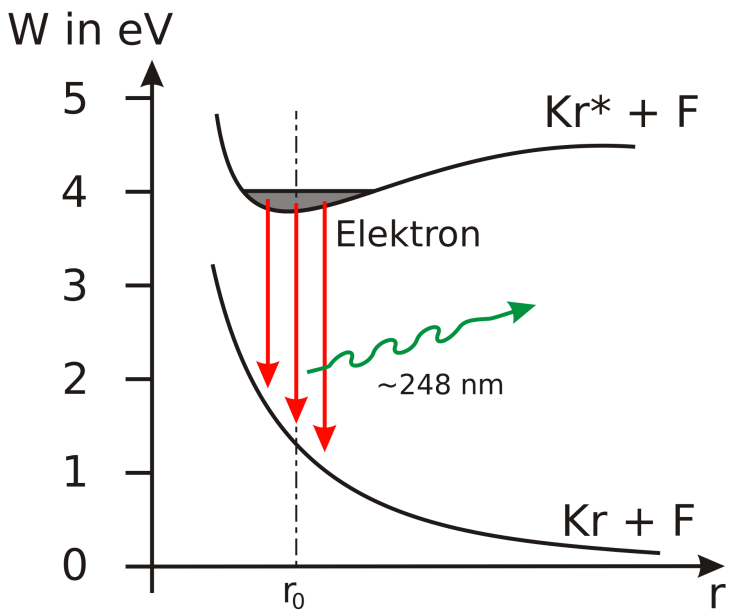
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- Nonlinearities can be exploited to generate lasers with a bandwidth exceeding one octave at optical frequencies.
- Spectrum will consist of uniformly-spaced lines.
- Direct measurement of optical transition frequency
- Key role in the detection of planets around other stars
- Clocks more accurate than today's microwave standards



Excimer ("Excited Dimer")

- Transient molecules, not normally found in nature, created by electron (plasma) or optical pumping
- Molecules split, emit a photon
- Strong absorption and high peak power make excimers ideal sources for ablation in laser eye surgery or materials processing
- Short wavelength and high energy make excimers good light sources for photolithography
  - Minimum feature size scales as: $d \propto \frac{\lambda}{NA}$



(Source: Wikimedia)

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