

## Laser Applications and Basics

Objective : To develop a fundamental knowledge of laser theory and operation, as well as its applications.

NJ Standards : 5.2, 5.3, 5.4 and 5.5

- 1) The laser
  - a. Laser Light Amplification by Stimulated Emission of Radiation
  - b. Uses photons generated from excited electron emissions
  - c. Moves at the speed of Light
  - d. Clean accurate light form
  - e. Small divergence over long ranges
  - f. Brief History
  
- 2) Define Light wave, Energy
  - a. Electromagnetic Spectrum
  - b. Wavelength (s)
  - c. Frequency
  - d. Photon Energy
  - e. Excitation of electrons and release of energy
  
- 3) Basic Principals of the Laser
  - a. Monochrome vs ordinary light
  - b. Photon energy is produced via excited electrons
  - c. Spontaneous vs stimulated emission
  - d. Population inversion
  - e. Metastable level
  - f. Coherent vs Incoherent light
  - g. Phase (inphase, out of phase)
  - h. Splitting of beam
  
- 4) Components of a laser
  - a. Materials and their characteristics
    - i. Single element
    - ii. Combinations of elements
    - iii. Solid Crystal, Gas, Dye, Semiconductor Diode
  
  - b. Energy pump
  - c. Mirrors
    - i. Solid
    - ii. Leaky
  - d. Optical Cavity

Will Davis  
MIRTHE RET Module  
July, 2009

5) Types of Lasers

6) Applications

- a. Holograms
- b. Sensors
  - i. Health and environmental
- c. Targeting
- d. Medicine

Teaching tools:

Presentation Slides

- 1) Wave Theory
- 2) Phase, amplitude
- 3) Dangers of Lasers

# **The Fundamentals of Lasers**

**Will Davis**  
**August, 2009**  
**MIRTHE Educational Program**

**Objective:** To develop a fundamental knowledge of laser theory and their operation, as well as its applications

This document will provide an overview of the construction and operation of a laser that can be easily integrated into chemistry or physics lesson plans to assist in meeting several of the New Jersey Core Curriculum Standards .

Lasers have been in existence since the early 1960's and yet have become an important part of our daily lives, seen or unseen. They have the ability to cut through metal or act as a surgical knife for many types of medical procedures, as well as weld detached retinas within the human eye. They are a key component in our telecommunications systems, scan your groceries at the check out and read the music on a compact disc or DVD.

LASER, short for Light Amplification by Stimulated Emission of Radiation, is a device that amplifies light to produce a highly directional, high intensity beam of light by "exciting" the atoms or molecules in a material in a very controlled manner until they emit photons moving the same direction with the crests and troughs of the waves exactly lined up or coherent.

The construction and operation of a laser is relatively simple. The lasing medium is encased in the optical cavity, where energy is pumped into the medium exciting the molecules. There are mirrors at both ends of the optical cavity causing the emitted light amplify by bouncing back and forth. The amplified light exits through one end of the laser where one of the mirrors is semi-transparent.

The laser is an interesting topic that allows an instructor to demonstrate and explain several key areas in Chemistry and Physics:

- Electromagnetic radiation
- Photoelectric effect
- Atomic Spectra and the Bohr atoms
- The Wave Nature of the Electron
- Wave-particle duality
- Atomic Orbitals
- Electron Configurations
- Wavelength, Frequency and Photon Energy

## Learning Standards:

**5.1 Science Practices:** Science is both a body of knowledge and an evidence-based, model-building enterprise that continually extends, refines, and revises knowledge. The four Science Practices strands encompass the knowledge and reasoning skills that students must acquire to be proficient in science.

- A. Understand Scientific Explanations:** Students understand core concepts and principles of science and use measurement and observation tools to assist in categorizing, representing, and interpreting the natural and designed world
- B. Generate Scientific Evidence Through Active Investigations:** Students master the conceptual, mathematical, physical, and computational tools that need to be applied when constructing and evaluating claims.
- C. Reflect on Scientific Knowledge:** Scientific knowledge builds on itself over time.
- D. Participate Productively in Science:** The growth of scientific knowledge involves critique and communication, which are social practices that are governed by a core set of values and norms.

**5.2 Physical Science:** Physical science principles, including fundamental ideas about matter, energy, and motion, are powerful conceptual tools for making sense of phenomena in physical, living, and Earth systems science.

- A. Properties of Matter:** All objects and substances in the natural world are composed of matter. Matter has two fundamental properties: matter takes up space, and matter has inertia.
- B. Changes in Matter:** Substances can undergo physical or chemical changes to form new substances. Each change involves energy.
- C. Forms of Energy:** Knowing the characteristics of familiar forms of energy, including potential and kinetic energy, is useful in coming to the understanding that, for the most part, the natural world can be explained and is predictable.
- D. Energy Transfer and Conservation:** The conservation of energy can be demonstrated by keeping track of familiar forms of energy as they are transferred from one object to another.
- E. Forces and Motion:** It takes energy to change the motion of objects. The energy change is understood in terms of forces.

The word laser is an acronym for **L**ight **A**mplified by **S**timulated **E**mission of **R**adiation.

The laser is a device that concentrates and amplifies photon energy released from an excited electron, into a high intensity beam, which can hold its shape and intensity for long distances. Depending on the lasing material chosen lasers can satisfy any number of purposes from simple pointers in the classroom to an industrial tool that can cut through the strongest materials.

Lasers have been in existence since the early 1960's and yet have become an important part of our daily lives, seen or unseen. They have the ability to cut through metal or act as a surgical knife for many types of medical procedures, as well as weld detached retinas within the human eye. They are a key component in our telecommunications systems, scan your groceries at the check out and read the music on a compact disc or DVD.

Though the idea of a laser is relatively simple it takes special conditions within the laser for amplification to occur, but it is that capability of taking light that would normally radiate from a source in all directions and concentrate that light into a beam traveling in a single direction that make a laser, a laser.

Laser light differs from usual white light sources due to three primary characteristics.

#### Specific vs. multiple wavelengths

The light/color that humans see with the naked eye is generally composed of multiple wavelengths between 350 to 750 nanometers. These wavelengths are part of the visible portion of the electromagnetic spectrum. A good example of this is when white light is passed through a prism and the various colors or wavelengths that make up the beam of light are distinguished.

The light or energy produced by a laser is produced from a very specific wavelength and can range from any point on the electromagnetic spectrum. Depending on the lasing medium used the laser will produce a coherent beam of energy at a specific wavelength.

#### Direction and Intensity

If you visualize a light bulb in a table lamp, the light energy is sent out in all directions. The intensity of the light exponentially diminishing as it flows from the source. Even when ordinary light is concentrated or focused similar to the way a flashlight creates a beam of light to illuminate objects relatively close to the source as the beam widens and the intensity of the beam drops very quickly as it leaves the source.

The laser concentrates light into a single beam. This beam can be pointed in any direction and will maintain its intensity far longer than a standard light source. A beam of laser light can easily travel in a straight line for many miles, as is seen in targeting devices used by the military and optical telecommunications.

The Laser produces a beam of light from a relatively simple set of components. Normally encased in metal are the lasing medium, pumping source and optical cavity, which contains two reflecting mirrors. Fig. 1.

**Lasing Medium** – is the material that is excited by the pumping source causing the electrons within the material to release photon energy. A variety of mediums are used including solid crystals; such as ruby and Neodymium, Gas; Helium-Neon, Carbon Dioxide, semiconductor-diodes and liquid-dye. The choice of medium is generally dependent on the type application the laser will be utilized in.

**Pump Source** – energizes the lasing material by exciting the electrons and causing the spontaneous release of photon energy. Two types of energy sources are used; the flash lamp produce intense light energy as it surrounds the medium or electrical current is run through the medium. Each lasing medium will have a specific excitation energy that must be supplied by the pumping source in order begin the lasing process.

**Optical Cavity** – contains the lasing medium and is bound on each end with reflecting mirrors. The mirrors cause the photons to rebound at  $180^\circ$  along the axis of the cavity, facilitating the feedback mechanism for light amplification. One mirror is fully reflecting and the other is a leaky mirror to allow the amplified light to exit.

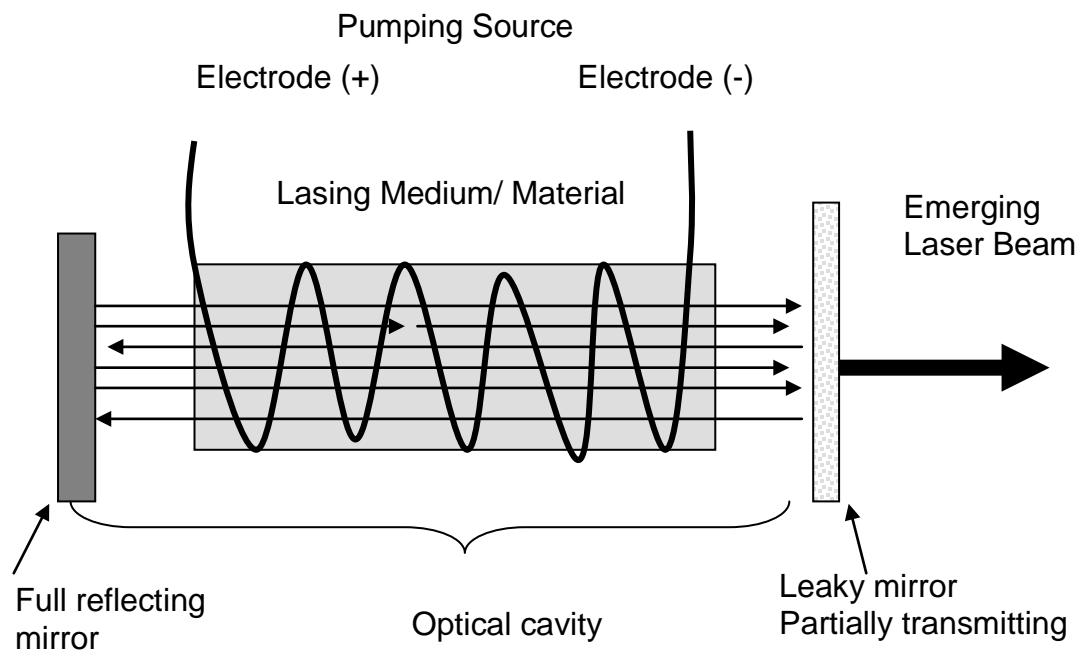


Fig. 1. Basic Components of a laser.

Lasers operate the principle that a photon is generated from the spontaneous emission of energy from an excited electron.

Electrons within an atom will jump to higher energy level after absorbing a specific amount of energy. This causes the electron to be in an unstable state, in order to return to a stable state a photon is emitted and the electron returns to its original ground state. The photon that is released will have a specific wavelength and frequency, which will correspond to a specific point on the electromagnetic spectrum.

Generally within an atom the electrons are in their ground state, an unexcited state. Fig. 2a. When energy is introduced, by some means, the electrons absorb the energy and becomes excited, jumping from ground state  $E_1$  into an excited state  $E_3$  (Fig. 2b). As the unstable electrons fall back to the ground state a photon is emitted.

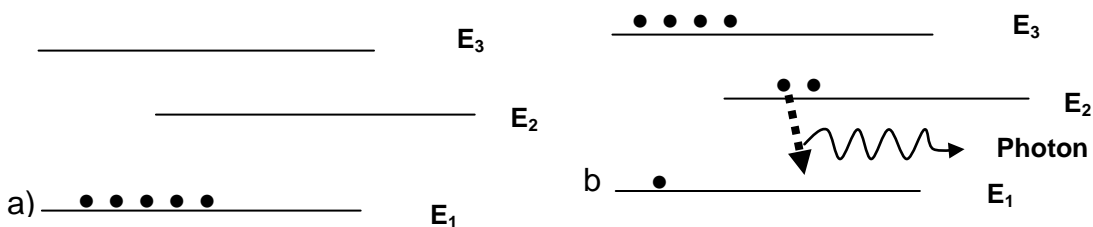


Fig. 2. a) Unexcited State

b) Excited State

As an example, when a hydrogen electron absorbs  $1.64 \times 10^{-18}$  joules, the electron will jump to the second energy level. At this location the electron is in an excited unstable state, as it falls drop back to its stable ground state the absorbed energy will be release in the form of a photon. The energy associated with the photon has a wavelength of 121.5 nanometers and a frequency of  $2.47 \times 10^{15}$  Hz. This wavelength lies in the ultraviolet region of the electromagnetic spectrum.

Spontaneous emission produces one randomly directed photon. The laser uses this basic principal to produces an amplified, concentrated light in a single beam with a very small diameter producing a highly directional, high-intensity beam that most often has a very pure frequency or wavelength (1).

Although the photons generated will have the same wavelength they are not in phase. By not maintaining a fixed phase relation relative to each other the waves are not coherent. Out of phase waves cause interference between the waves and will negate some or all of the energy.

Laser Light is coherent which means that all of the waves are "in phase" in space and time. When many waves are in phase with each other, they do not interfere with one another and the wavelength remains constant as the light travels away from the source.

When waves are in-phase they have the exact same wavelength and frequency and do not interfere with each other and the energy carried in the wave added together, as seen in fig. 3.

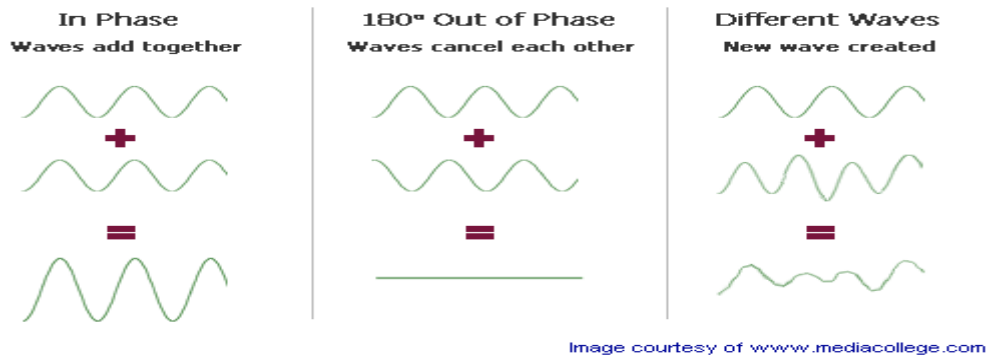


Fig. 3 In-phase and out of phase waves.

In order to produce the concentrated intense beam more photons must be produced. Several factors must be present stimulated emission, population inversion and optical feedback.

In 1917 Einstein determined that atoms in an excited state can be stimulated to jump to a lower energy level when they are struck by a photon of incident light whose energy is the same as the energy-level difference involved in the jump. The electron thus emits a photon of the same wavelength as the incident photon. The incident and emitted photons travel away from the atom in phase. (2).

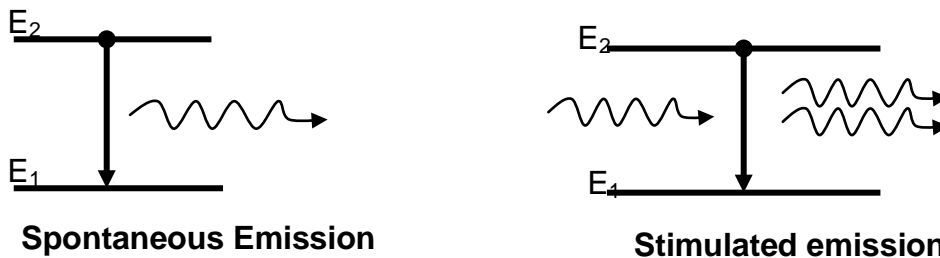


Fig. 4 Emission of photons

The stimulated transition will release energy in the form of photons of light that travel in phase, frequency and polarization at the same wavelength and in the same direction as the incident photon

Stimulated emission occurs in many optical sources, such as light bulbs, but is normally too small to be detected. Einstein demonstrated that for stimulated emission to dominate it was necessary that the photon radiation density and the population density  $N_2$  of the upper energy level must be increased relative to the lower level ( $E_1$  and  $N_1$ ). When  $N_2 > N_1$  there are a greater number of electrons in the excited state rather than in the ground state. This is known as population inversion and is a fundamental condition for stimulated emission. (3)

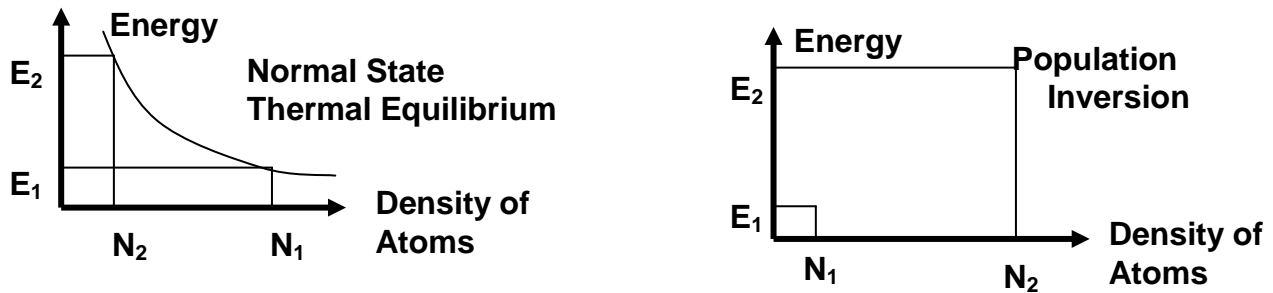


Fig. 5. Normal state vs. Population inversion

In order to produce a large intensity of stimulated emissions there must be a greater number of electrons in the excited state than in the ground state. To create a population inversion the electron must be in a metastable state, this is where the excited electron is unusually stable and the electron in an excited state will fall to a lower energy level and stay in that state for some time before spontaneously falling back to its original ground state.

A lasing medium must have at least one excited metastable state where electrons can be trapped long enough (microseconds to milliseconds) for a population inversion to occur. Although laser action is possible with only two energy levels, most lasers have four or more levels.

In order to generate lasing the majority of the electrons must be pushed to the excited state by the pumping source. Once there most of the electrons on level  $E_3$  will jump to a metastable state  $E_2$  where they are in an unusually stable state and cannot readily return spontaneously to  $E_1$ . This causes a build up of the number of electrons in  $E_2$ , a population inversion relative to the ground state. fig. 6a. If a photon, of energy  $(E_2 - E_1)$ , passes through the atom, it can stimulate a second electron to jump from  $E_2$  to  $E_1$ . The second photon is identical and in phase with the incident photon (fig. 6b). As this process repeats many times the number of photons increases geometrically and the intensity of the light is amplified and lasing will begin.



Figure 6 – Emission of photons from the metastable state.

The combination of population inversion, stimulated and spontaneous emission will create a situation where large number of photons will be produced, but lasing will not occur without the presence of optical feed back.

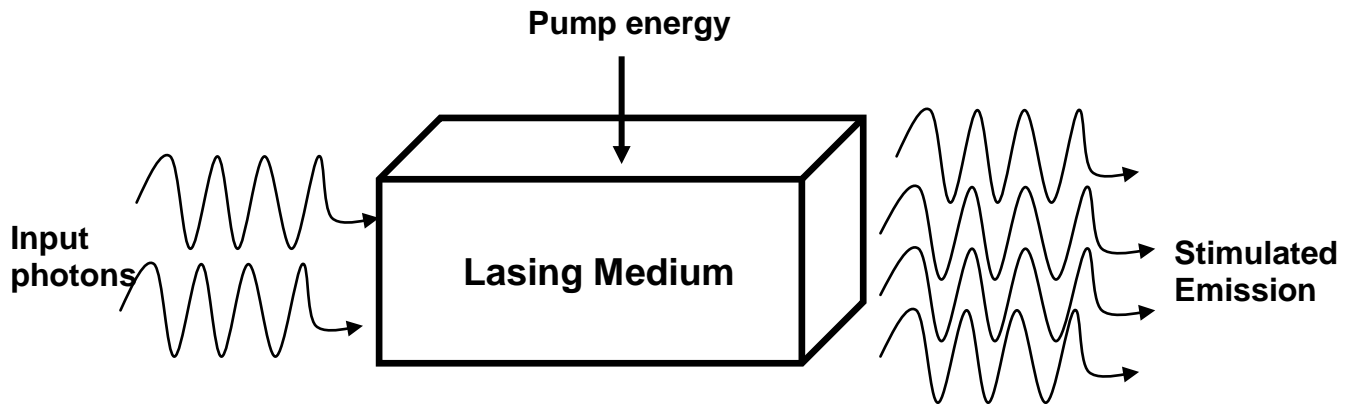


Fig. 7 – Photons increase geometrically in population inversion

Stimulated emission can be seen as optical gain, in that the number of photons out of the lasing medium exceeds the number entering. Feedback is normally achieved using parallel plane mirrors at both ends of the active medium. The fully metalized reflecting mirror encloses one end of the cavity and at the other end is lightly metalized so that it reflects approximately 99 percent of the light, allowing for lasing to occur, seen. Fig. 8.

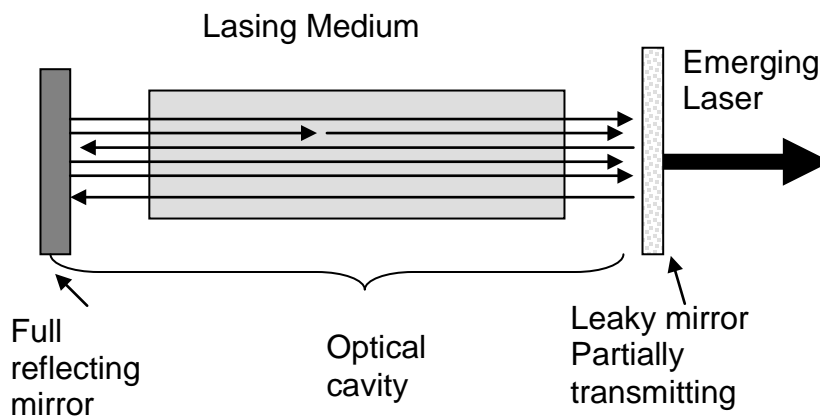


Fig. 8. Two mirrors enclose the lasing medium, making the optical cavity

Within the cavity stimulated emission overwhelms further photon absorption, and so the intensity of the emitted waves grows as they pass through the lasing medium. In a short time, the cavity is filled with coherent waves moving back and forth between the two mirrors, parallel to the center axis of the cavity, resulting in a very intense, monochromatic coherent beam in the cavity, with a small fraction of the coherent beam exiting from the leaky mirror.

Because the energy of each photon is exactly the same the wavelength of the light can be sharply defined. Not only is the beam intense and coherent, but also it is a very thin, straight beam that diverges very little. This fact is of key importance, the laser beams energy does not fan out into space, but it flows into space through a thin cylinder and maintains its intensity over very long distances.

The beam can travel in a straight line for many miles or it can be controlled to pulse fractions of an inch. Laser power may range from milliWatts (in CD-ROM drives and laser pointers) to dozens of Watts (industrial and medical applications) and over trillions of Watts (pulsed lasers in scientific and military applications). (4)

The laser produces a very dependable, definable beam of light that can be used in numerous applications. This is why the laser has become an integral part in the development of new and exciting applications that will help and improve the health of humans and the world.

### **Laser Surgery –**

Laser surgery is a medical procedure that uses laser light to remove diseased tissues or treat bleeding blood vessels. A laser is a light beam that can be precisely focused. It is used to treat tissues by heating the targeted cells until they "burst."

A highly focused laser beam can efficiently vaporize or chip away the living tissue. At the same time, it seals capillaries, small blood vessels, lymphatics, and nerve endings, with significant benefits to both patients and surgeons.

Lasers differ from each other by the wavelength of light they produce. There are several types of lasers, including the carbon dioxide (CO<sub>2</sub>) laser, the YAG (yttrium aluminum garnet) laser, and the pulsed dye laser. Each laser has specific uses. The color of the light beam used is directly related to the type of surgery being performed and the color of the tissue being treated.

The most commonly used surgical laser used in soft tissue surgery is CO<sub>2</sub> laser. The CO<sub>2</sub> laser wavelength (10.6 micrometer) is highly absorbed by water contained in the soft tissues. Because of its outstanding versatility and precision, CO<sub>2</sub> surgical laser is the most efficient and dominant soft tissue surgical laser since the 1960s.

The excimer, or pulsed gas laser, emits an ultraviolet light beam, vaporizing tissue by breaking down molecular tissue bonds in a minute targeted area. This type of laser is used in cosmetic surgeries because it can be focused on a specific depth so as not to damage skin cells below the effected layer. It is called a cold laser because it doesn't produce heat that could have harmful effects to the surrounding tissue. This type of laser begun to be

used as part of balloon angioplasty procedures because treating the area with a laser has been shown to reduce the amount of reclogging after the artery is expanded.

The benefits to the patient are:

Less bleeding - The drastic reduction in bleeding, as it cuts the laser also seals small blood vessels. This has enabled a number of new surgical procedures that are not practical with conventional scalpel.

Less Pain - The CO<sub>2</sub> laser beam seals nerve endings and lymphatics, resulting in less swelling and pain. The patient experiences a far more comfortable post-operative recovery.

Reduction in infection - The laser is unique in that it efficiently kills bacteria in its path, producing a sterilizing effect.

Overall the laser has drastically changed the medical world by improving surgical procedures by making them simpler and reducing the associated risks. The reduction in bleeding provides greater visibility within the surgical field allowing the surgeon to utilize the power and increased precision and control of the laser to adjust the focal spot size of the beam a small fraction of a millimeter to remove one cell at a time or expanded for a much wider coverage for rapid removal of large tissue amounts.

The laser has enabled the development of new procedures and techniques that were previously were not practical with conventional methods.

### **SENSOR – Measurement of concentration, presences, velocity,**

Sensors are devices that monitor or measure a wide range of conditions. Sensors can be classified into several major groups, those that detect movement, measure distance and those that measure the presence or absence of a particular molecule or condition.

The operation of a sensor is relatively simple. A beam of light is pointed toward the sensing device. When molecules pass between the laser and the detector the molecules absorb some of the energy transmitted by the laser. The laser power transmitted through the sample is detected as a function of laser wavelength. This results in a measurement of one part of the absorption spectrum, which is used to identify the specific molecule.

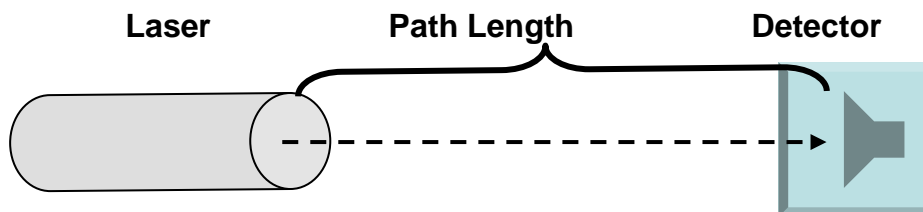


Figure 9 – Basic sensor configuration

To determine the concentration of a specific molecule, the amount of power absorbed at a characteristic wavelength is measured, and divide it by the cross section and by the path length.

The benefit of developing laser sensors is that the output of a laser is a highly monochromatic beam of light that is, it is composed of a single wavelength or color. Also the power of the laser beam can be very low and all the light can be directed through the desired measurement region, and the photons are all the correct color to be absorbed by the molecules. This is usually not the case for non-laser based optical measurements.

The development of low power lasers has lead to the development of many new types of sensors in the mid-infrared region of the absorption spectrum. These lasers are of special interest to the molecular gas sensing community because of the high sensitivity that can be achieved in this region. The efforts focus on achieving room temperature operation and single frequency output through novel device structures.

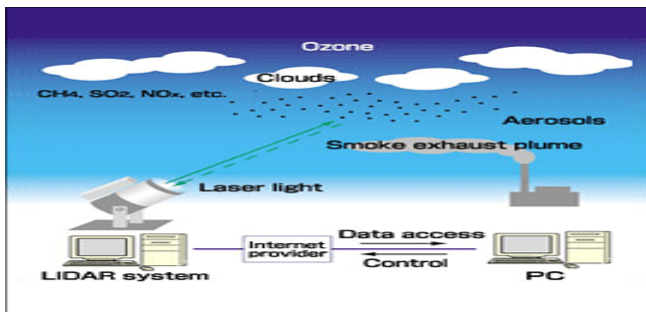
As an example, a sensing instrument has been designed to measure in situ CO<sub>2</sub> concentrations open to the atmosphere at ground level. Because of the ability to tune the wavelength within the mid-infra red regions, absorption lines generated were carefully selected around 2.68 μm. By working in this region the interference from neighboring water vapor and other molecule transitions were minimized.

The laser wavelength depends foremost on the composition and structure of the device. But once a laser has been fabricated, it is possible to tune the output by controlling the laser temperature and current. In practice, it is the current tunability that gives the laser sensor its high sensitivity and fast time response.

The ability to identify molecules outside the standard absorption spectrum has greatly improved the monitoring and measurement of specific molecules that effect our health and environment.

## **LIDAR (Light Detection and Ranging)**

**LIDAR (Light Detection and Ranging)** is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. The prevalent method to determine distance to an object or surface is to use laser pulses.



Like the similar radar technology, which uses radio waves, which is light that is not in the visible spectrum, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal.

The primary difference between lidar and radar is that with lidar, much shorter wavelengths are used, typically in the ultraviolet, visible or near infrared. This allows lidar to be highly sensitive to aerosols and cloud particles.

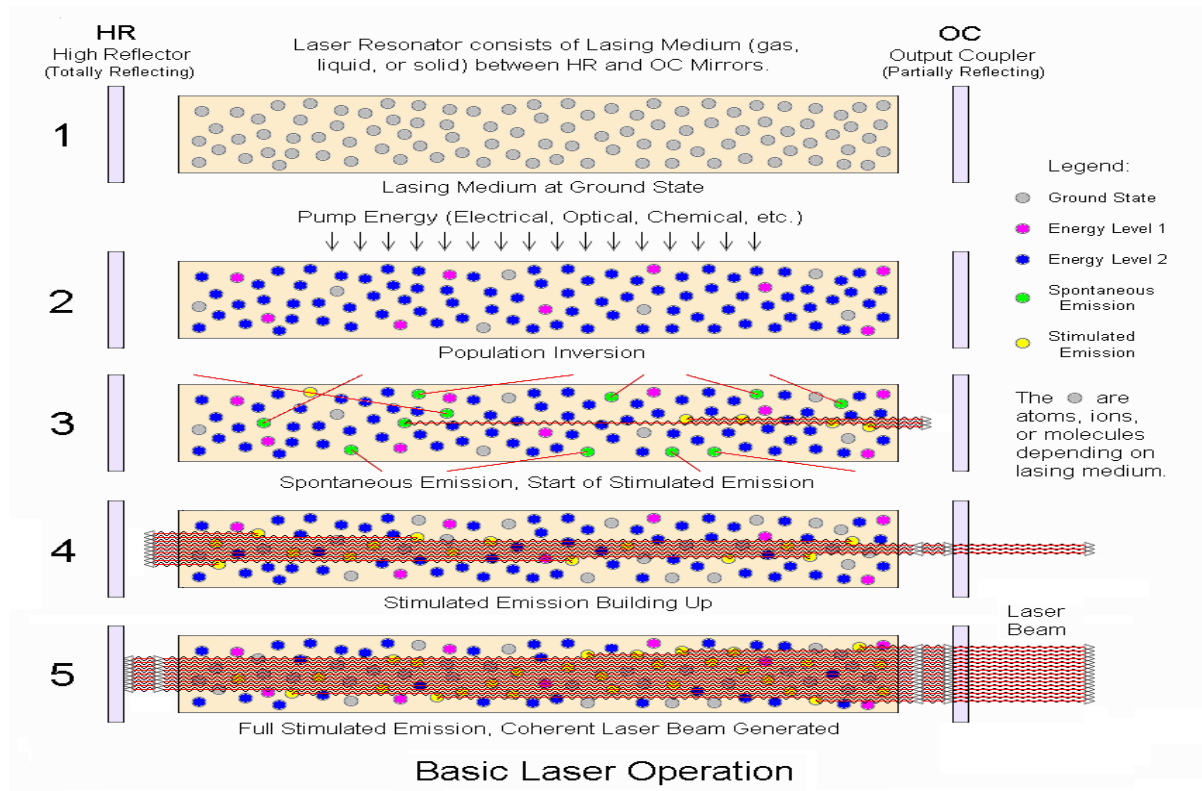
Radar wavelengths are in the microwave or radio spectrum and are very good when a metallic object produces a significant reflection. However non-metallic objects, such as rain and rocks produce weaker reflections and some materials may produce no detectable reflection at all.

Lasers provide one solution to these problems. The beam wavelengths are much smaller than can be achieved with radio systems, and range from about 10 micrometers to the UV (ca. 250 nm). At such wavelengths, the waves are "reflected" very well from small objects. The wavelengths are ideal for making measurements of smoke and other airborne particles, clouds, and air molecules.

A laser typically has a very narrow beam which allows the mapping of physical features with very high resolution compared with radar. In addition, many chemical compounds interact more strongly at visible wavelengths than at microwaves, resulting in a stronger image of these materials.

Lidar has been used extensively for atmospheric research and meteorology. GPS based surveying technology has made airborne surveying and mapping applications possible and practical. Many have been developed, using downward-looking lidar instruments mounted in aircraft or satellites. A recent example is the NASA Experimental Advanced Research Lidar.

## Summary of the basic Operation of a Laser.



Step 1: The lasing material is in a ground state, no energy is being pumped into the medium.

Step 2: The pump energy is increased, electrons begin to jump to higher energy levels, Population inversion begins.

Step 3: Spontaneous emission begin and stimulated emissions follow. The resulting Photons begin to travel within the optical cavity producing more stimulated emissions.

Step 4: The build up of stimulated emission begin and lasing begins.

Step 5: Full inversion and stimulated emission is occurring, coherent beams are generated and sent out.

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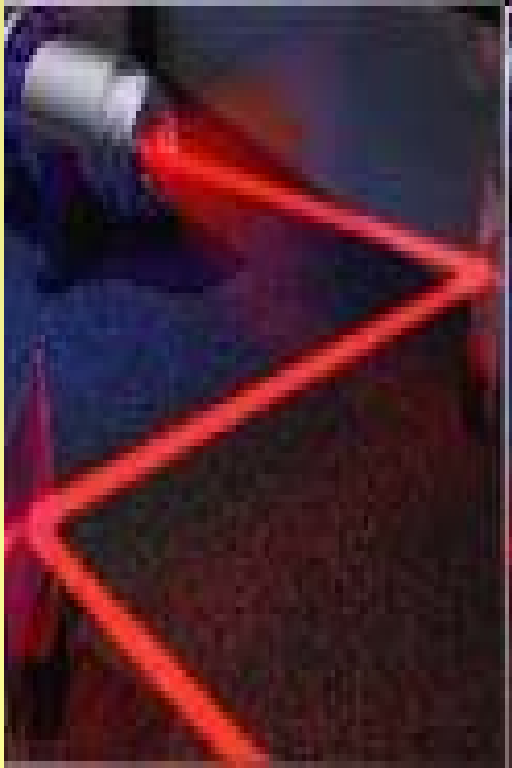
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# ***Laser***

## ***Light Amplified Stimulated Emission of Radiation***



- The laser is a device that concentrates and amplifies photon energy released from an excited electron, into a high intensity beam, which can hold its shape and intensity for long distances.



# *Types of Lasers*

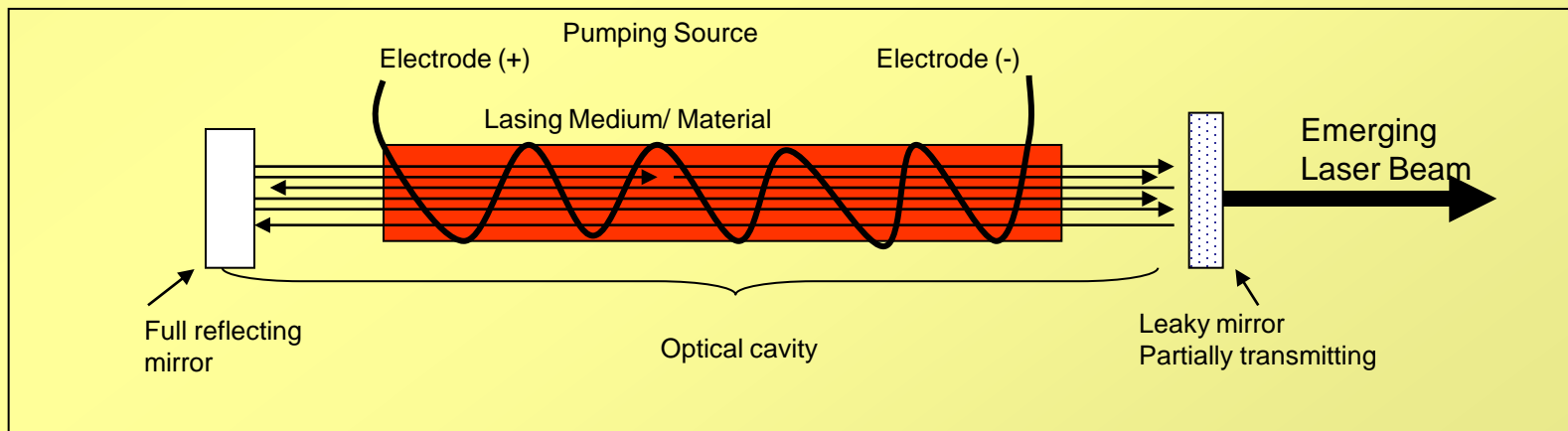
- Solid crystals: ruby and Neodymium,
- Gas: Helium-Neon, Carbon Dioxide,
- Semiconductor-diodes and
- Liquid-dye

The choice of medium is generally dependent on the type application the laser will be utilized in.



# Basic Components of a Laser

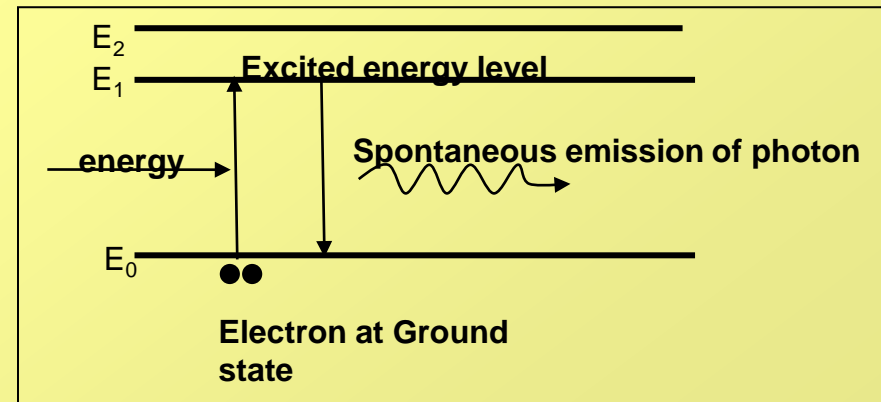
- Lasing Medium
  - the material that is excited by the pumping source causing the electrons within the material to release photon energy
- Pumping source
  - energizes the lasing material exciting the electrons and causing the release of photon energy
- Optical cavity
  - contains the lasing medium and is bound on each end with reflecting mirrors.





# Spontaneous Emission

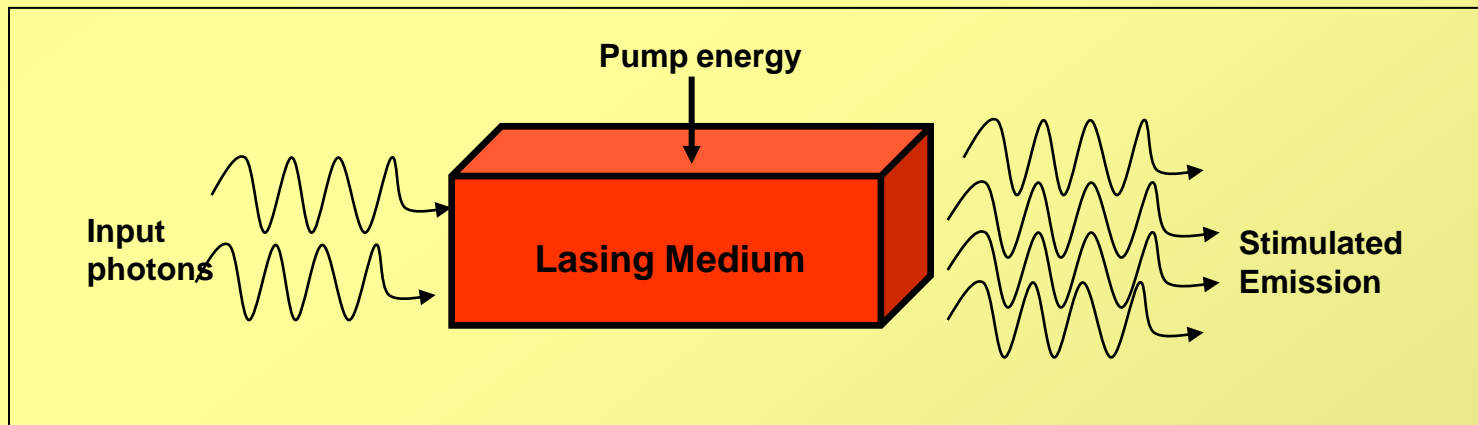
- Lasers operate the principle that a photon is generated from the spontaneous emission of energy from an excited electron.
- Electrons within an atom will jump to higher energy level after absorbing a specific amount of energy.
  - The electron is then in an unstable state,
  - electromagnetic radiation is emitted
  - electron returns to its original ground state.
- The photon that is released will have a specific wavelength and frequency which will correspond to a specific point on the electromagnetic spectrum.





# Basic Principals of Lasers

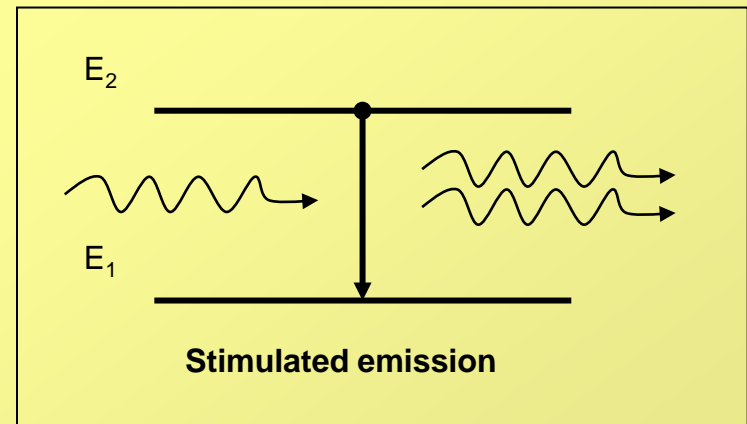
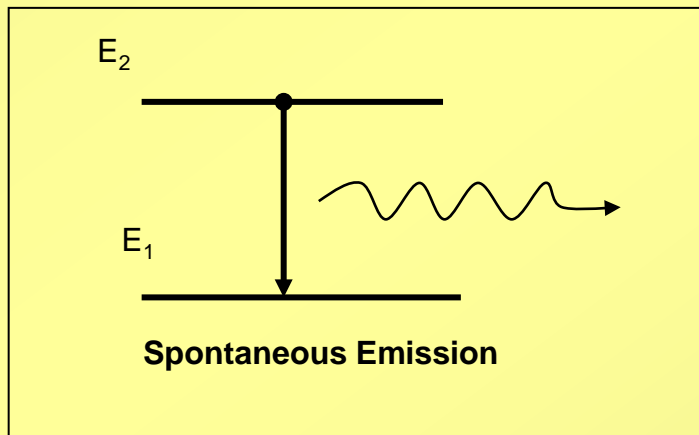
- Lasers produce a high intensity beam, which can hold its shape and intensity for long distances by concentrating and amplifying the photon energy released from excited electrons
- Pumping alone will not produce lasing.
- For lasing to occur you must have,
  - Stimulated emission
  - Population inversion
  - Optical feedback.





# Stimulated Emissions

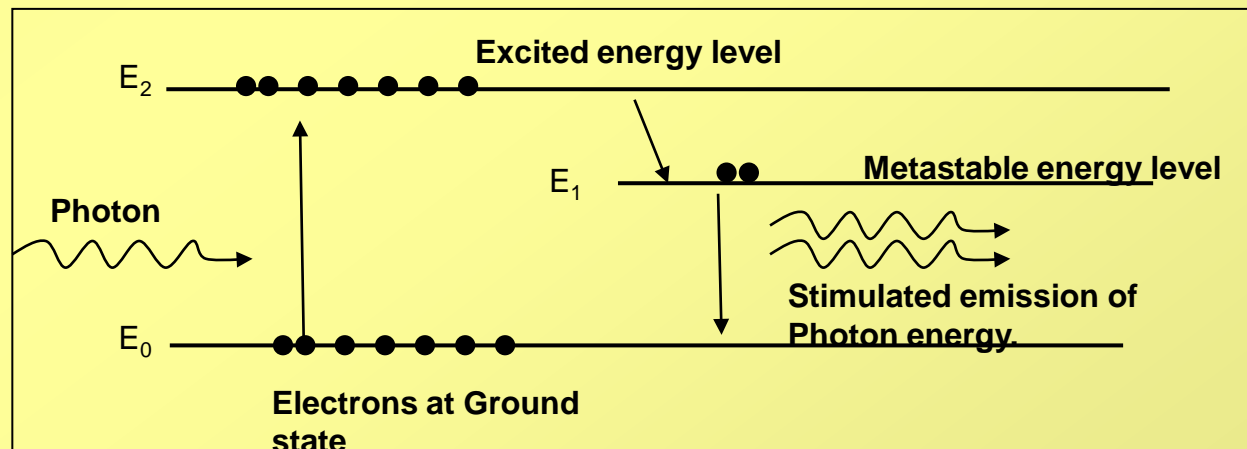
- Spontaneous emission
  - An excited electron transitions from  $E_2$  to  $E_1$ , resulting in the emission of one photon
- Stimulated emission
  - Photon with an energy of  $E_2 - E_1$  interacts with an electron in the upper energy level, causing it to return to the lower state with the emission of a second photon
  - The second photon has the same phase, frequency and polarization as the first





# Population Inversion

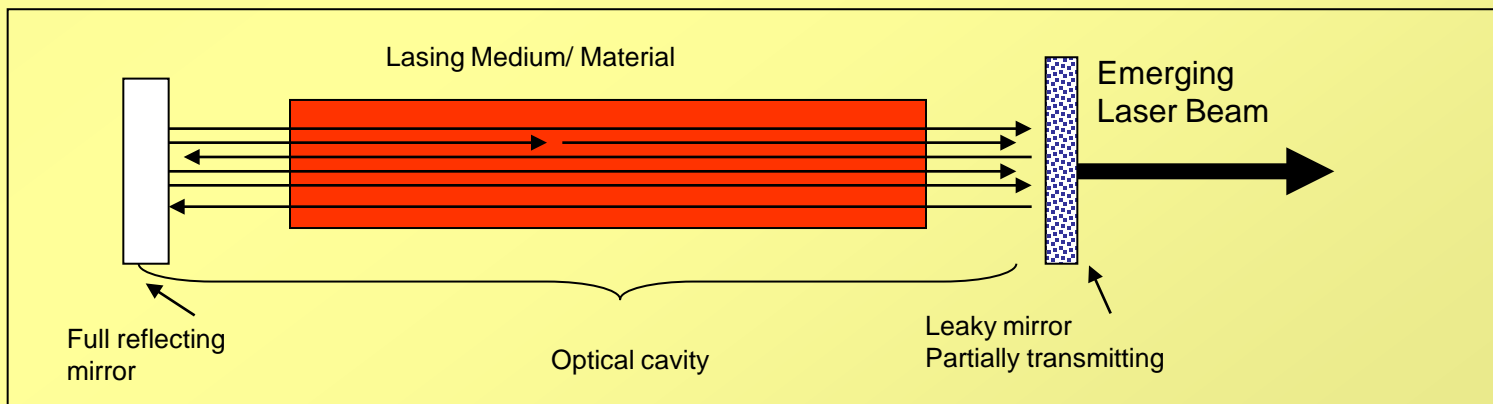
- Population inversion is when the majority of electrons in a material are in the excited state.
- Population inversion occurs when the lasing medium has at least one excited metastable state
  - This is where the excited electron in an unusually stable can be trapped on an upper energy level
  - A photon can cause a second photon, identical to and in phase with an incident photon to be released
  - Photons increase geometrically and the intensity of the light is amplified as the process repeats itself





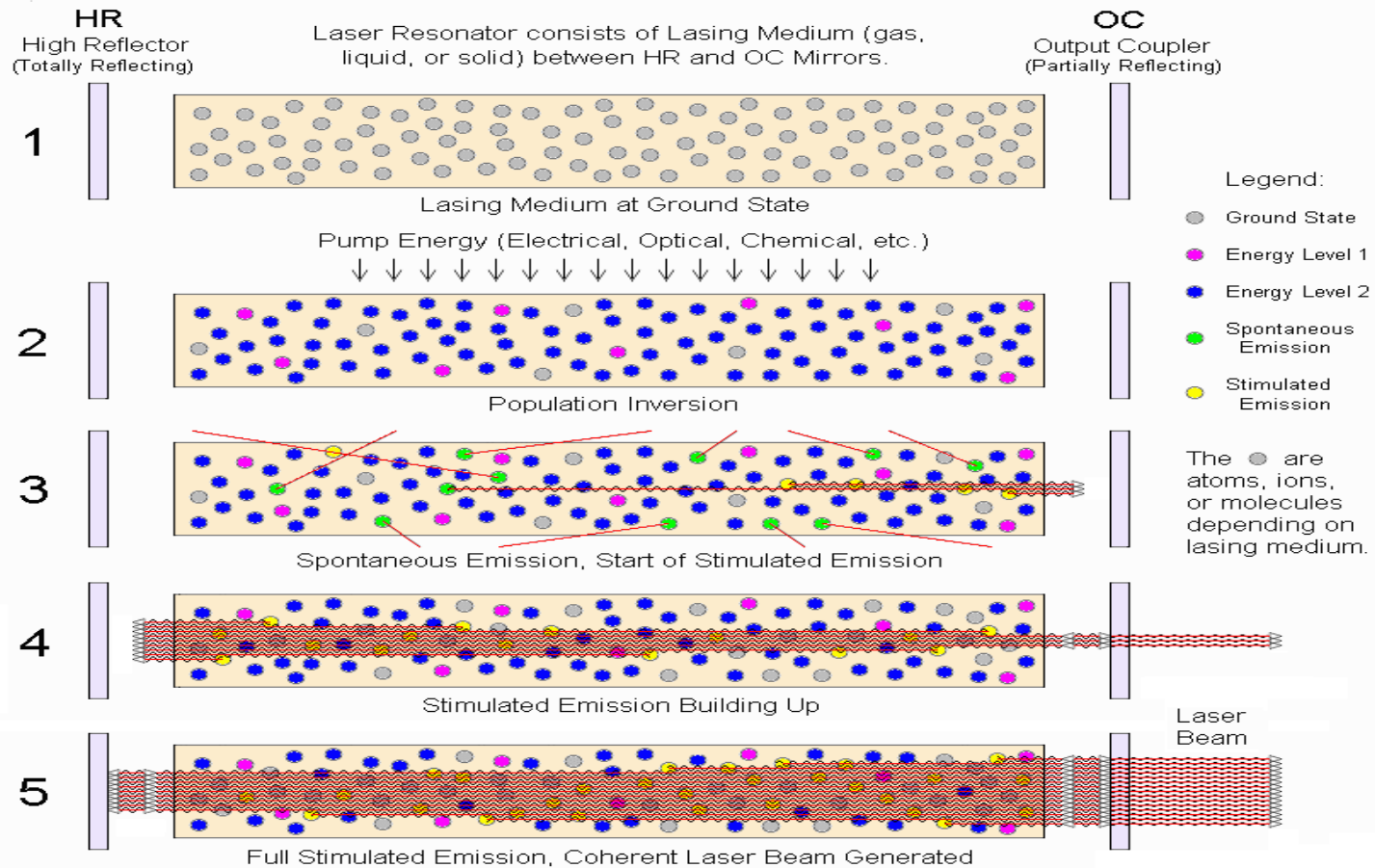
# Optical Feedback

- For lasing to occur population inversion and stimulated emission must take place in the presence of optical feedback.
- Feedback is achieved using parallel plane mirrors at both ends of the active medium.
  - A fully metalized reflecting mirror
  - As lightly metalized mirror that reflects ~99% of the light
  - The laser beam will emerge from the leaky mirror





# Basic Laser Operation



Basic Laser Operation