LASER

INTRODUCTION TO LASER: Laser Chart- Einsten's Coefficient's- Its Significance- Population Inversion- NdYAG- He- Ne, CO_2 LASER- Holography-Recording And Reconstruction

Source of LASER

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" originated as an acronym for "**light amplification by stimulated emission of radiation**". The first laser was built in 1960 by Theodore H. Maiman at Hughes Research Laboratories, based on theoretical work by Charles Hard Townes and Arthur Leonard Schawlow. A laser differs from other sources of light in that it emits light *coherently*. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single color of light. Temporal coherence can be used to produce pulses of light as short as a femto-second.

Among their many applications, lasers are used in optical disk drives, laser printers, and barcode scanners; DNA sequencing instruments, fiber-optic and free-space optical communication; laser surgery and skin treatments; cutting and welding materials; military and law enforcement devices for marking targets and measuring range and speed; and laser lighting displays in entertainment.

LASER CHART-

Light Amplification by Stimulated Emission of Radiation, commonly referred to as "Laser" describes a wide range of devices. The lasers can function as oscillators (sources of light) and as amplifiers. Lasers have revolutionized various fields of science and technology, and are being used in a wide range of applications in medicine, communications, defense, measurement, and as a precise light source in many scientific investigations. Commercially available lasers can be categorized based on the characteristics:

Wavelength: Lasers span the entire light spectrum from infrared to ultraviolet.

Power: The power output from a laser ranges from a milliwatt to millions of watts.

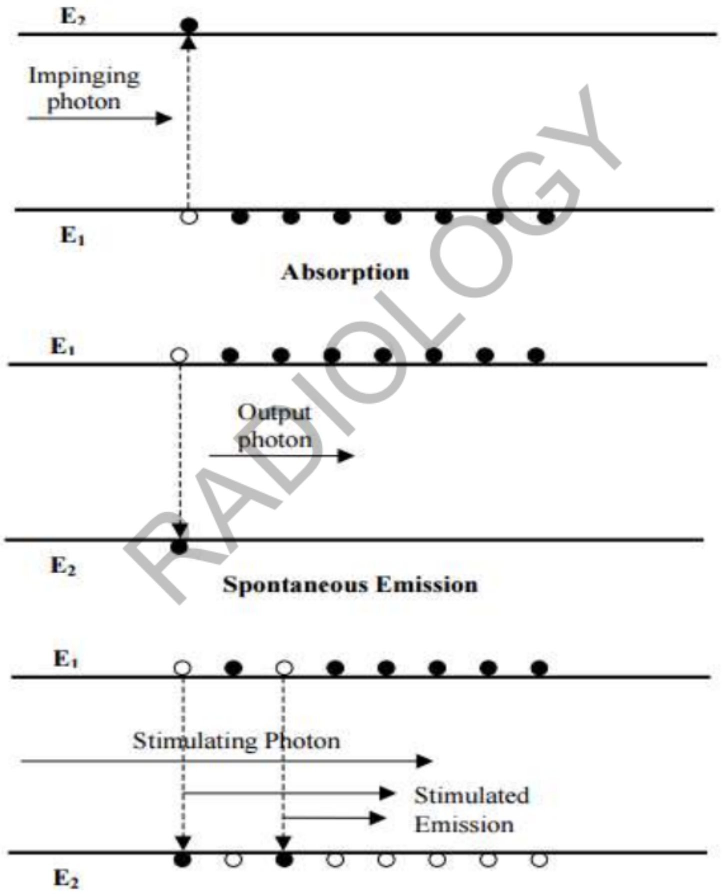
Output beam: The laser output may be a continuous wave, where the lasers emit light in a continuous manner or it might be pulsed, where the lasers emit light in short bursts.

Principle of operation:

The principle of operation remains the same though there is a wide range of lasers. Laser action occurs in three stages: photon absorption, spontaneous emission, and stimulated emission. The above three processes where E1 is the ground-state or lower energy level and E2 is the excited-state or higher energy level. The particle of the material, which undergoes the process of excitation, might be an atom, molecule, or ion depending on the laser material.

Photon absorption:

In any material, during thermal equilibrium the number of particles in the excited state is very small and is negligible. When the number of particles in the excited state is greater than the number of particles in the ground state, the material is in a state of "Population Inversion". Population inversion is a prerequisite for laser action. Energy can be transferred into a laser medium to achieve population inversion by several mechanisms including absorption of photon, collision between electrons (or sometimes ions) and species in the active medium, collisions among atoms and molecules in the active medium, recombination of free electrons with ionized atoms, recombination of current carriers in a semiconductor, chemical reactions producing excited species, and acceleration of electrons. In photon absorption, the laser material is optically excited to achieve population inversion based on Planck's law. According to Planck's law, the change of energy level from E1 to E2 or vice versa, results in the absorption or emission of photon respectively.



STIMULATED EMISSION

Spontaneous emission:

The excited particles resulting from population inversion are unstable. They release their excess energy by non-radiative process, such as collisions with other excited particles or by photon emission (Planck's law), and return to the stable ground state. The emission of a photon can be spontaneous or stimulated. Spontaneous emissions occur without any external stimulus, when the laser material drops to its ground state after a characteristic delay time. Spontaneous emissions are random and isotropic in nature.

Stimulated emission:

The excited particles can be made to return to the ground-state through an external stimulation. When an external photon having the same energy as the energy difference between the ground state and excited state, impinges on the excited laser material, the particles will drop to the ground-state and emit a photon. A photon having the exact energy necessary to cause stimulated emission is made available by the spontaneous emission. These photons from spontaneous emission trigger stimulated emission of other photons resulting in a cascade of stimulated emission.

The photons due to stimulated emission are

1. Highly monochromatic (single wavelength),

2. Coherent (all the waves have the same phase), and

3. Collimated (parallel rays) or appear to originate from a point source If during the process of stimulated emission, the population inversion is maintained by continuous pumping of energy, the laser action continues indefinitely and the result is a continuous wave laser. On the other hand, if the pumping cannot be maintained the output is a pulsed laser.

Construction of a laser:

A laser consists of an active laser material, a source of excitation energy, and a resonator or feedback mechanism to perform the three stages of laser action.

Laser material:

The lasing material can be a solid (Ruby, YAG and glass lasers), liquid (Dye lasers), gas (Helium-neon, argon and carbon dioxide) or a semi-conductor (InGaAlP). A material is said to be in "Normal State" if the number of atoms in the lower energy level is more 17 than the number of atoms in the higher energy level.

LASER CHART:

Common Lasers and Their Wavelengths

LASER TYPE	WAVELENGTH (Nanometers)
Argon Fluoride	193
Xenon Chloride	308 and 459
Xenon Fluoride	353 and 459
Helium Cadmium	325 - 442
Rhodamine 6G	450 - 650
Copper Vapor	511 and 578
Argon	457 - 528 (514.5 and 488 most used)
Frequency doubled Nd:YAG	532
Helium Neon	543, 594, 612, and 632.8
Krypton	337.5 - 799.3 (647.1 - 676.4 most used)
Ruby	694.3

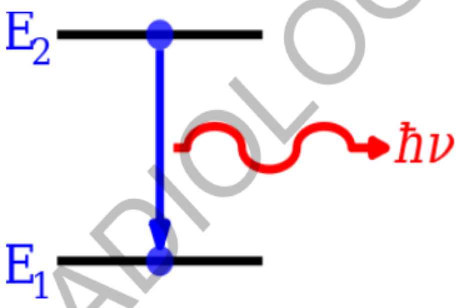
Laser Diodes	630 - 950
Ti:Sapphire	690 - 960
Alexandrite	720 - 780
Nd:YAG	1064
Hydgrogen Fluoride	2600 - 3000
Erbium:Glass	1540
Carbon Monoxide	5000 - 6000
Carbon Dioxide	10600

EINSTEN’S COEFFICIENT’S-

EINSTEIN’S COEFFICIENTS AND ITS SIGNIFICANCE:

In 1916, Albert Einstein proposed that there are three processes occurring in the formation of an atomic spectral line. The three processes are referred to as spontaneous emission, stimulated emission, and absorption. With each is associated an Einstein coefficient which is a measure of the probability of that particular process occurring. Einstein considered the case of isotropic radiation of frequency v, and spectral energy density ρ (v).

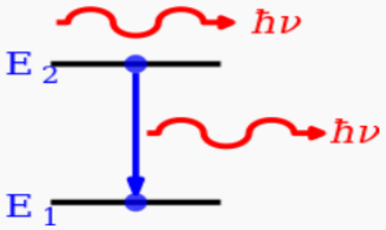
Spontaneous emission



Spontaneous emission is the process by which an electron "spontaneously" (i.e. without any outside influence) decays from a higher energy level to a lower one. The process is described by the Einstein coefficient A_{21} (s^{-1}) which gives the probability per unit time that an electron in state 2 with energy will decay spontaneously to state 1 with energy , emitting a photon with an energy $E_2 - E_1 = hv$. Due to the energy-time uncertainty principle, the transition actually produces photons within a narrow range of frequencies called the spectral line width. If is the number density of atoms in state i then the change in the number density of atoms in state 2 per unit time due to spontaneous emission will be:

$$\left(\frac{dn_2}{dt}\right)_{\text{spontaneous}} = -A_{21} n_2 \, .$$

Stimulated emission



Schematic diagram of atomic stimulated emission

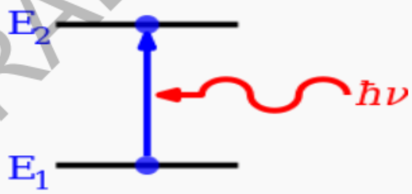
Stimulated emission (also known as induced emission) is the process by which an electron is induced to jump from a higher energy level to a lower one by the presence of electromagnetic radiation at (or near) the frequency of the transition. From the thermodynamic viewpoint, this process must be regarded as negative absorption. The process is described by the Einstein coefficient B_{21} (J^{-1} m^{3} s^{-2}), which gives the probability per unit time per unit spectral energy density of the radiation field that an electron in state 2 with energy will decay to state 1 with energy , emitting a photon with an energy $E_2 - E_1 = h\nu$. The change in the number density of atoms in state 1 per unit time due to induced emission will be:

$$\left(\frac{dn_1}{dt}\right)_{\text{neg absorb}} = B_{21} n_2 \rho(\nu)$$

Where B_{21} denotes the spectral energy density of the isotropic radiation field at the frequency of the transition

The fundamental processes that led to the development of the laser. Laser radiation is, however, very far from the present case of isotropic radiation.

Photon absorption



Schematic diagram of atomic absorption

Absorption is the process by which a photon is absorbed by the atom, causing an electron to jump from a lower energy level to a higher one. The process is described by the Einstein coefficient B_{12} (J^{-1} m^{3} s^{-2}), which gives the probability per unit time per unit spectral energy density of the radiation field that an electron in state 1 with energy E_1 will absorb a photon with an energy $E_2 - E_1 = h\nu$ and jump to state 2 with energy E_2 . The change in the number density of atoms in state 1 per unit time due to absorption will be:

$$\left(\frac{dn_1}{dt}\right)_{\text{pos absorb}} = -B_{12} n_1 \rho(\nu)$$

Detailed balancing:

The Einstein coefficients are fixed probabilities per time associated with each atom, and do not depend on the state of the gas of which the atoms are a part. Therefore, any relationship that we can derive between the coefficients at, say, thermodynamic equilibrium will be valid universally.

At thermodynamic equilibrium, we will have a simple balancing, in which the net change in the number of any excited atoms is zero, being balanced by loss and gain due to all processes. With respect to bound-bound transitions, we will have detailed balancing as well, which states that the net exchange between any two levels will be balanced. This is because the probabilities of transition cannot be affected by the presence or absence of other excited atoms. Detailed balance (valid only at equilibrium) requires that the change in time of the number of atoms in level 1 due to the above three processes be zero:

$$0 = A_{21} n_2 + B_{21} n_2 \rho(\nu) - B_{12} n_1 \rho(\nu)$$

Along with detailed balancing, at temperature *T* we may use our knowledge of the equilibrium energy distribution of the atoms, as stated in the Maxwell–Boltzmann distribution, and the equilibrium distribution of the photons, as stated in Planck's law of black body radiation to derive universal relationships between the Einstein coefficients.

Essential Components of a Laser

1) Lasing medium
   Gas, Dye, Semiconductor
2) Pumping source
   Optical pumping, electric pumping
3) Cavity

Types of Laser

Based on the mode of operation
- (i) Pulsed Laser systems
- (ii) Q-switched systems
- (iii) Continuous wave Laser systems

Based on the mechanism in which Population Inversion is achieved
- (i) Three level lasers
- (ii) Four level lasers

Based on state of active medium used
- i. Gas Laser: He-Ne, Argon ion and CO_2
- ii. Solid state Laser : Ruby, Nd:YAG, Nd:glass
- iii. Semiconductor Laser
- iv. Tunable dye Laser

Neodymium based lasers

- Nd:YAG laser (yttrium aluminium garnet) and Nd:glass laser are important Solid state lasers
- Energy levels of the Neodymium ion takes place in lasing action
- Both are 4 level laser systems
- YAG and glass are hosts in which Neodymium ions are used

Nd:YAG laser:

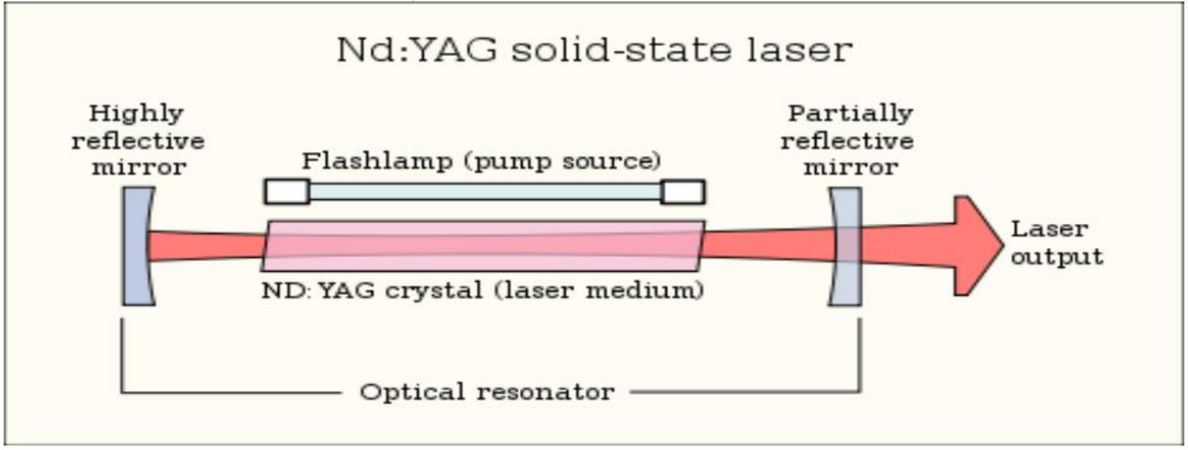
- For continuous or very high pulse rate operation – Nd:YAG preferred
- Nd:YAG laser – emission at 1.06 µm
- Pump band for excitation are 0.81 µm and 0.75 µm
- Spontaneous lifetime of the laser transition is ~ 550 µs
- Has a much lower threshold of oscillation than a ruby laser
- Output energy in the order of 100mJ per pulse
- Used in resistor trimming, scribing, micromachining operations, welding Hole drilling etc…..

Nd:glass laser

- Four level system
- Various silicate and phosphate ions are used as the host material
- Spontaneous lifetime of the laser transition is ~ 300 µs
- More suitable for high energy pulsed operation
- Output energy is in the order of several kilojoules
- Used widely in welding and drilling operations

Advantages of Nd ions in a YAG or glass host:

- In glass, the linewidth is larger than in YAG, and hence in glass the Laser threshold is higher
- In Nd:glass lasers Mode locking phenomena can be used to achieve Ultrashort Pulses of narrow pulsewidth
- Larger linewidth in Nd:glass allows to store a larger amount of power or Energy before saturation when used along with Q switches
- Excellent optical quality and excellent uniformity of doping in glass host
- Compared to YAG, glass has lower thermal conductivity
- Optical distortion is higher in glass host



He-Ne laser

- Laser medium is mixture of Helium and Neon gases in the ratio 10:1

- Medium excited by large electric discharge, flash pump or continuous high power pump
- In gas, atoms characterized by sharp energy levels compared to solids
- Actual lasing atoms are the Neon atoms

Pumping action:

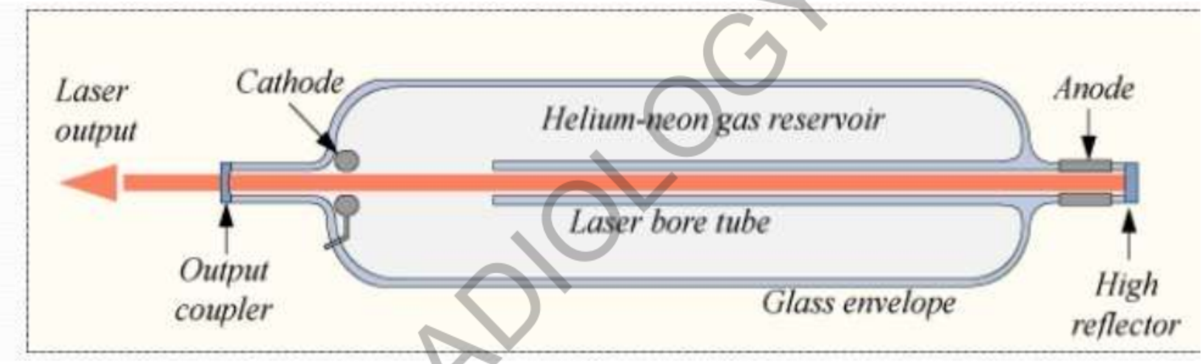
Electric discharge is passed through the gas

Electrons are accelerated, collide with He and He atoms and excite them to higher energy levels

- Helium atom accumulates at levels F2 and F3
- Levels E4 and E6 of neon atoms have almost same energy as F2 and F3
- Excited Helium ions collide with Neon atoms and excite them to E4 and E6

Transitions:

- ✓ Transition between E6 and E3 produce 6328 A line output
- ✓ From E3 to E2 spontaneous emission takes place – 6000 A
- ✓ E2 – metastable state – tends to collect atoms
- ✓ From E2 atoms relax back to ground level
- Other important wave lengths:
- E6 to E5 – 3.39 µm ; E4 to E3 – 1.15µm
- Both share the same lasing level (E6)



(Construction of Helium and Neon - diagram)

Difficulties:

- Gain at 3.39 µm is much higher than that at 0.6328 and hence Oscillations will tend to occur at 3.39 µm.
- This prevents further build up of population in E6 difficult
- Atoms in level E2 tend to re-excite to E3 by absorbing the spontaneous emitted radiation between E3 and E2.
- This alters inversion between E6-E3

***The CO2 LASER*:**

- Lasers discussed above – use transitions among various excited electronic states of an atom or ion
- CO2 laser – uses transition between different vibrational states of CO_2 molecule
- One of the earliest Gas lasers
- Highest power continuous wave laser currently available
- The filling gas within the discharge tube consists primarily of:

    Carbon dioxide

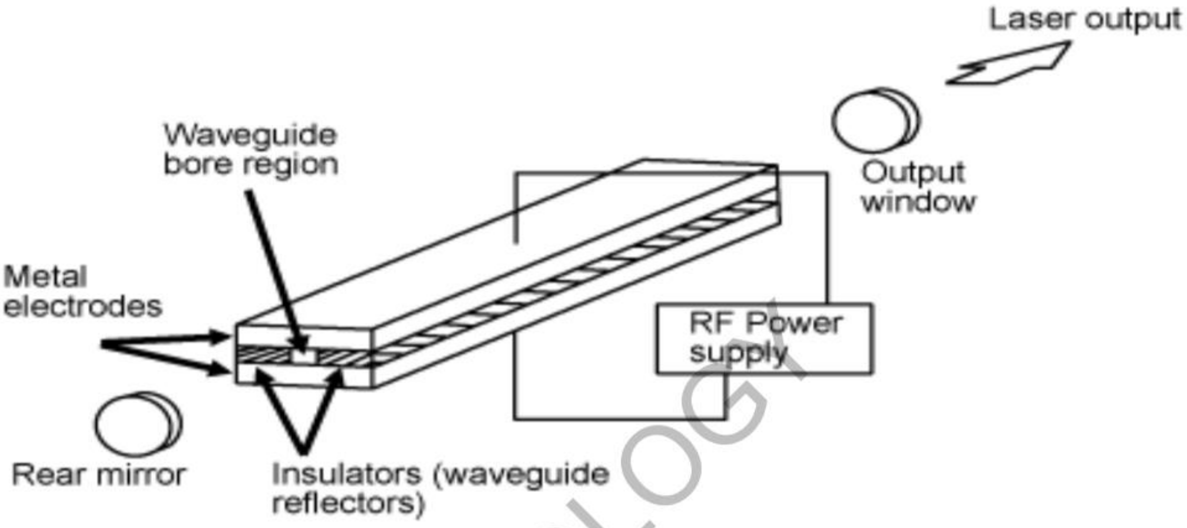
    Hydrogen

Nitrogen

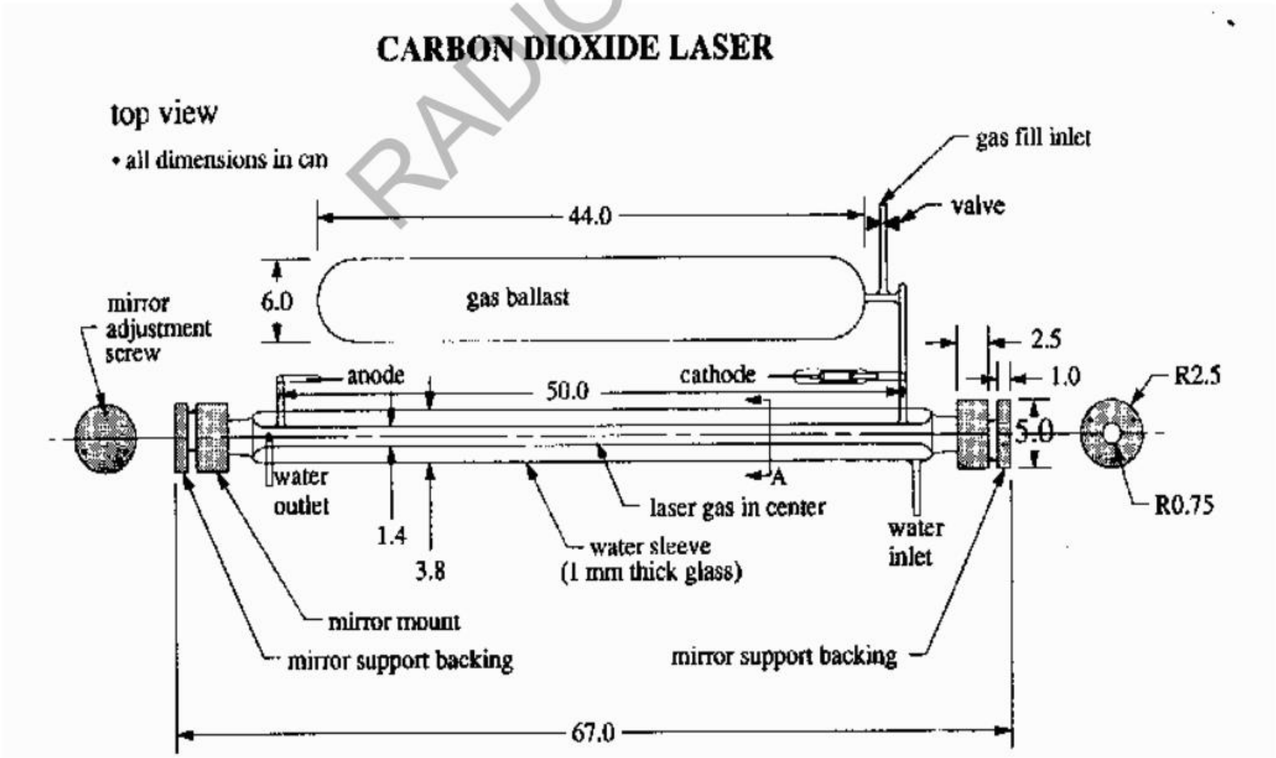
Helium

(Proportions vary according to a specific laser)

- Electron impact excites vibrational motion of the nitrogen.
- Collision energy transfer between the nitrogen and the CO2 molecule causes vibrational excitation of the carbon dioxide
- Excite with sufficient efficiency to lead to the desired population inversion necessary for laser operation.
- Laser transition occurs at 10.6μm



CO_2 laser



- CO2 laser possesses an extremely high efficiency
- *Atomic quantum efficiency* – Ratio of energy difference corresponding to the laser transition to the energy difference of the pump transition
- Atomic quantum efficiency is very high for a CO2 laser
- Large portion of input power is converted into useful output power
- Output power of several watts to several kilowatts can be obtained

Holography

Holography is a technique that enables a light field, which is generally the product of a light source scattered off objects, to be recorded and later reconstructed when the original light field is no longer present, due to the absence of the original objects.

Laser

In laser holography, the hologram is recorded using a flash of laser light that illuminates a scene and then imprints on a recording medium, much in the way a photograph is recorded. In addition, however, part of the light beam must be shone directly onto the recording medium - this second light beam is known as the reference beam. A hologram requires a laser as the sole light source. Lasers can be precisely controlled and have a fixed wavelength, unlike sunlight or light from conventional sources, which contain many different wavelengths. To prevent external light from interfering, holograms are usually taken in darkness, or in low level light of a different color from the laser light used in making the hologram. Holography requires a specific exposure time (just like photography), which can be controlled using a shutter, or by electronically timing the laser.

Apparatus

A hologram can be made by shining part of the light beam directly into the recording medium, and the other part onto the object in such a way that some of the scattered light falls onto the recording medium.

A more flexible arrangement for recording a hologram requires the laser beam to be aimed through a series of elements that change it in different ways. The first element is a beam splitter that divides the beam into two identical beams, each aimed in different directions:

- One beam (known as the *illumination* or *object beam*) is spread using lenses and directed onto the scene using mirrors. Some of the light scattered (reflected) from the scene then falls onto the recording medium.
- The second beam (known as the *reference beam*) is also spread through the use of lenses, but is directed so that it doesn't come in contact with the scene, and instead travels directly onto the recording medium.

Several different materials can be used as the recording medium. One of the most common is a film very similar to photographic film (silver halidephotographic emulsion), but with a much higher concentration of light-reactive grains, making it capable of the much higher resolution that holograms require. A layer of this recording medium (e.g., silver halide) is attached to a transparent substrate, which is commonly glass, but may also be plastic.

Process

When the two laser beams reach the recording medium, their light waves intersect and interfere with each other. It is this interference pattern that is imprinted on the recording medium. The pattern itself is seemingly random; as it represents the way in which the scene's light *interfered* with the original light source — but not the original light source itself. The interference pattern can be considered an encoded version of the scene, requiring a particular key — the original light source — in order to view its contents.

This missing key is provided later by shining a laser, identical to the one used to record the hologram, onto the developed film. When this beam illuminates the hologram, it is diffracted by the hologram's surface pattern. This produces a light field identical to the one originally produced by the scene and scattered onto the hologram.

Holography Vs. photography

Holography may be better understood via an examination of its differences from ordinary photography:

- A hologram represents a recording of information regarding the light that came from the original scene as scattered in a range of directions rather than from only one direction, as in a photograph. This allows the scene to be viewed from a range of different angles, as if it were still present.
- A photograph can be recorded using normal light sources (sunlight or electric lighting) whereas a laser is required to record a hologram.
- A lens is required in photography to record the image, whereas in holography, the light from the object is scattered directly onto the recording medium.
- A holographic recording requires a second light beam (the reference beam) to be directed onto the recording medium.
- A photograph can be viewed in a wide range of lighting conditions, whereas holograms can only be viewed with very specific forms of illumination.
- When a photograph is cut in half, each piece shows half of the scene. When a hologram is cut in half, the whole scene can still be seen in each piece. This is because, whereas each point in a photograph only represents light scattered from a single point in the scene, *each point* on a holographic recording includes information about light scattered from*every point* in the scene. It can be thought of as viewing a street outside a house through a 120 cm × 120 cm (4 ft × 4 ft) window, then through a 60 cm × 60 cm (2 ft × 2 ft) window. One can see all of the same things through the smaller window (by moving the head to change the viewing angle), but the viewer can see more *at once* through the 120 cm (4 ft) window.
- A photograph is a two-dimensional representation that can only reproduce a rudimentary three-dimensional effect, whereas the reproduced viewing range of a hologram adds many more depth perception cues that were present in the original scene. These cues are recognized by the human brain and translated into the same perception of a three-dimensional image as when the original scene might have been viewed.
- A photograph clearly maps out the light field of the original scene. The developed hologram's surface consists of a very fine, seemingly random pattern, which appears to bear no relationship to the scene it recorded.

RECORDING OF HOLOGRAPH

To make a hologram, the following are required:

- a suitable object or set of objects
- part of the laser beam to be directed so that it illuminates the object (the object beam) and another part so that it illuminates the recording medium directly (the reference beam), enabling the reference beam and the light which is scattered from the object onto the recording medium to form an interference pattern
- a recording medium which converts this interference pattern into an optical element which modifies either the amplitude or the phase of an incident light beam according to the intensity of the interference pattern.
- a laser beam that produces coherent light with one wavelength.
- an environment which provides sufficient mechanical and thermal stability that the interference pattern is stable during the time in which the interference pattern is recorded[25]

These requirements are inter-related, and it is essential to understand the nature of optical interference to see this. Interference is the variation in intensity which can occur when two light waves are superimposed. The intensity of the maxima exceeds the sum of the individual intensities of the two beams, and the intensity at the minima is less than this and may be zero. The interference pattern maps the relative phase between the two waves, and any change in the relative phases causes the interference pattern to move across the field of view. If the relative phase of the two waves changes by one cycle, then the pattern drifts by one whole fringe. One phase cycle corresponds to a change in the relative distances travelled by the two beams of one wavelength. Since the wavelength of light is of the order of 0.5 μm, it can be seen that very small changes in the optical paths travelled by either of the beams in the holographic recording system lead to movement of the interference pattern which is the holographic recording. Such changes can be caused by relative movements of any of the optical components or the object itself, and also by local changes in air-temperature. It is essential that any such changes are significantly less than the wavelength of light if a clear well-defined recording of the interference is to be created.

The exposure time required to record the hologram depends on the laser power available, on the particular medium used and on the size and nature of the object(s) to be recorded, just as in conventional photography. This determines the stability requirements. Exposure times of several minutes are typical when using quite powerful gas lasers and silver halide emulsions. All the elements within the optical system have to be stable to fractions of a μm over that period. It is possible to make holograms of much less stable objects by using a pulsed laser which produces a large amount of energy in a very short time (μs or less). These systems have been used to produce holograms of live people. A holographic portrait of Dennis Gabor was produced in 1971 using a pulsed ruby laser.

Thus, the laser power, recording medium sensitivity, recording time and mechanical and thermal stability requirements are all interlinked. Generally, the smaller the object, the more compact the optical layout, so that the stability requirements are significantly less than when making holograms of large objects.

Another very important laser parameter is its coherence. This can be envisaged by considering a laser producing a sine wave whose frequency drifts over time; the coherence length can then be considered to be the distance over which it maintains a single frequency. This is important because two waves of different frequencies do not produce a stable interference pattern. The coherence length of the laser determines the depth of field which can be recorded in the scene. A good holography laser will typically have a coherence length of several meters, ample for a deep hologram.

The objects that form the scene must, in general, have optically rough surfaces so that they scatter light over a wide range of angles. A specularly reflecting (or shiny) surface reflects the light in only one direction at each point on its surface, so in general, most of the light will not be incident on the recording medium. A hologram of a shiny object can be made by locating it very close to the recording plate.

RECONSTRUCTION OF HOLOGRAPH

When the hologram plate is illuminated by a laser beam identical to the reference beam which was used to record the hologram, an exact reconstruction of the original object wave front is obtained. An imaging system (an eye or a camera) located in the reconstructed beam 'sees' exactly the same scene as it would have done when viewing the original. When the lens is moved, the image changes in the same way as it would have done when the object was in place. If several objects were present when the hologram was recorded, the reconstructed objects move relative to one another, i.e. exhibit parallax, in the same way as the original objects would have done. It was very common in the early days of holography to use a chess board as the object and then take photographs at several different angles using the reconstructed light to show how the relative positions of the chess pieces appeared to change.

A holographic image can also be obtained using a different laser beam configuration to the original recording object beam, but the reconstructed image will not match the original exactly.[43] When a laser is used to reconstruct the hologram, the image is speckled just as the original image will have been. This can be a major drawback in viewing a hologram.

White light consists of light of a wide range of wavelengths. Normally, if a hologram is illuminated by a white light source, each wavelength can be considered to generate its own holographic reconstruction, and these will vary in size, angle, and distance. These will be superimposed, and the summed image will wipe out any information about the original scene, as if superimposing a set of photographs of the same object of different sizes and orientations. However, a holographic image can be obtained using white light in specific circumstances, e.g. with volume holograms and rainbow holograms. The white light source used to view these holograms should always approximate to a point source, i.e. a spot light or the sun. An extended source (e.g. a fluorescent lamp) will not reconstruct a hologram since its light is incident at each point at a wide range of angles, giving multiple reconstructions which will "wipe" one another out.

White light reconstructions do not contain speckles.

Fidelity of the reconstructed beam

Reconstructions from two parts of a broken hologram. Note the different viewpoints required to see the whole object

To replicate the original object beam exactly, the reconstructing reference beam must be identical to the original reference beam and the recording medium must be able to fully resolve the interference pattern formed between the object and reference beams. Exact reconstruction is required in holographic interferometry, where the holographically reconstructed wave front interferes with the wave front coming from the actual object, giving a null fringe if there has been no movement of the object and mapping out the displacement if the object has moved. This requires very precise relocation of the developed holographic plate.

Any change in the shape, orientation or wavelength of the reference beam gives rise to aberrations in the reconstructed image. For instance, the reconstructed image is magnified if the laser used to reconstruct the hologram has a shorter wavelength than the original laser. Nonetheless, good reconstruction is obtained using a laser of a different wavelength, quasi-monochromatic light or white light, in the right circumstances.

Since each point in the object illuminates all of the hologram, the whole object can be reconstructed from a small part of the hologram. Thus, a hologram can be broken up into small pieces and each one will enable the whole of the original object to be imaged. One does, however, lose information and the spatial resolution gets worse as the size of the hologram is decreased — the image becomes "fuzzier". The field of view is also reduced, and the viewer will have to change position to see different parts of the scene.