Lasers

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Who can use this?

The lecture notes are tailor-made for my students at SBMJCE, Bangalore. It is the fifth of eight chapters in Engineering Physics [06PHY12] course prescribed by VTU for the first-semester (September 2008 - January 2009) BE students of all branches. Any student interested in exploring more about the course may visit the course homepage at *www.satheesh.bigbig.com/EnggPhy*. For those who are looking for the economy of studying this: this chapter is worth 20 marks in the final exam! Cheers ;-)

Syllabus as prescribed by VTU

`Principle and production. Spontaneous and stimulated emission and induced absorption. Einsteins coefficients. Requisites of a Laser system. Condition for Laser action. Principle, Construction and working of He-Ne and semiconductor Laser. Applications of Laser: Laser welding, cutting and drilling. Measurement of atmospheric pollutants. Holography, Principle of Recording and reconstruction of 3-D images. Selected applications of holography`

Reference

- **Leonid Azaroff**, *Introduction to Solids*, TMH Edition, Tata McGraw-Hill Publishing Company Limited, ISBN- 0-07-099219-3.

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1 Introduction

The term LASER is an anachronism for Light Amplification by Stimulated Emission of Radiation. The first working laser was demonstrated in 1960 by Theodore Maiman at Hughes Research Laboratories. Since then, lasers have become a multi-billion dollar industry. By far the largest single application of lasers is in optical storage devices such as compact disc and DVD players. The second-largest application is fiber-optic communication. Other common applications of lasers are bar code readers, laser printers and laser pointers. In manufacturing, lasers are used for cutting precise patterns in glass and metal, and welding metal. Lasers are used by the military for range-finding, target designation, and illumination. Lasers have also begun to be used as directed-energy weapons. Lasers are used in medicine for surgery, diagnostics, to reshape corneas to correct poor vision and therapeutic applications. But we also use lasers as very precise light sources in supermarket checkout lines. In this chapter, we describe the principles behind the lasers and some of its uses.

2 Principle and production

Under normal circumstances when light interacts with matter, electrons in the matter may absorb the light energy and go to the higher energy level and come back to the ground state by emitting the light of the same frequency. But in any given situation the number of electrons in the ground state is more than that in the excited state. The Laser is based on the principle of light amplification by stimulated emission of radiation. This is achieved by having excess concentration of electrons in the higher energy states and stimulating the system by radiation to bring about the de-excitation process.

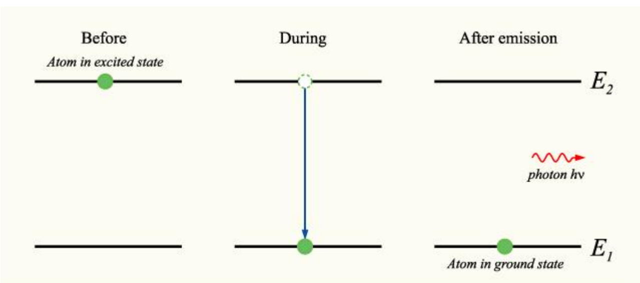
2.1 Induced absorption, spontaneous emission and stimulated emission

An atom in the ground state may absorb a photon of suitable energy and go to an excited state. This is know as the ***induced absorption*** and the process is represented by the following equation.

$$atom + photon \rightarrow atom^*$$

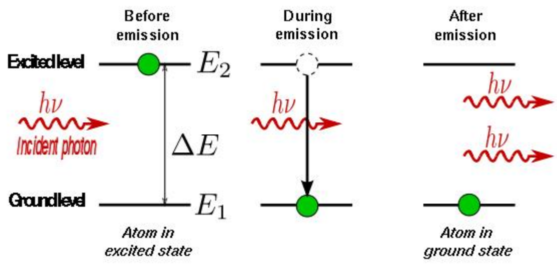
An atom which is already in an excited state will be unstable and it falls back to the ground state by emitting a photon of appropriate energy. This is know as the ***spontaneous emission*** and the process is represented by the following equation.

$$atom^* \rightarrow atom + photon$$



An atom which is already in an excited state will emit a photon on its own while making its transition to the ground state . But by passing a photon of just right energy we can stimulate the excited atom to emit a photon of the same phase, energy and directed in the same direction as that of the introduced one. This is know as the ***stimulated emission*** and the process is represented by the following equation.

$$atom^* + photon \rightarrow atom + photon + photon$$



$$E_2 - E_1 = \Delta E = h\nu$$

2.2 Einsteins coefficients

Consider a system of atoms with two energy states E_1 and E_2 with N_1 and N_2 number of atoms per unit volume in each energy states respectively. The N_1 and N_2 are called the number densities of the atoms. Let a radiation of energy density E_ν of frequency ν be incident on the system.

In the case of induced absorption, an atom in the ground state E_1 goes to an excited state E_2 by absorbing a suitable photon of energy $h\nu = E_2 - E_1$. The number of such absorptions per unit time, per unit volume is called the rate of induced absorption. This depends on the number density N_1 of the ground state and the energy density of the incident radiation E_ν. That is,

$$Rate\ of\ induced\ absorption \propto N_1 E_\nu.$$

By introducing the constant of proportionality B_{12}, we get

$$Rate\ of\ induced\ absorption = B_{12} N_1 E_\nu.$$

In the case of spontaneous emission, an atom in the excited state E_2 makes a transition to the ground state E_1 by by emitting a photon of appropriate energy $h\nu = E_2 - E_1$. The number of such spontaneous emissions per unit time, per unit volume is called the rate of spontaneous emission. This depends only on the number density N_2 of the excited state. That is,

$$Rate\ of\ spontaneous\ emission \propto N_2.$$

By introducing the constant of proportionality A_{21}, we get

$$Rate\ of\ spontaneous\ emission = A_{21} N_2.$$

In the case of stimulated emission, an atom in the excited state E_2 makes a transition to the ground state E_1 upon incidence of a photon of suitable energy $h\nu = E_2 - E_1$, by emitting a photon of same energy. The number of such stimulated emissions per unit time, per unit volume is called the rate of stimulated emission. This depends on the number density N_2 of the excited state and the energy density of the incident radiation E_ν. That is,

$$Rate\ of\ stimulated\ emission \propto N_2 E_\nu.$$

By introducing the constant of proportionality B_{21}, we get

$$Rate\ of\ stimulated\ emission = B_{21} N_2 E_\nu.$$

In the above discussion, the constants of proportionality are called the *Einstein's coefficients*. Under thermal equilibrium,

$$Rate\ of\ induced\ absorption = Rate\ of\ spontaneous\ emission + Rate\ of\ stimulated\ emission$$

that is,

$$B_{12}N_1E_\nu = A_{21}N_2 + B_{21}N_2E_\nu.$$

Taking E_ν terms on to the left hand side, we get

$$B_{12}N_1E_\nu - B_{21}N_2E_\nu = A_{21}N_2,$$

$$(B_{12}N_1 - B_{21}N_2)E_\nu = A_{21}N_2,$$

$$E_\nu = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2}.$$

By rearranging the terms, we get

$$E_\nu = \frac{A_{21}}{B_{21}}\left(\frac{1}{\frac{B_{12}N_1}{B_{21}N_2} - 1}\right).$$

From Boltzmann's law, we know that the ratio of the population densities N_1 and N_2 in the ground state E_1 and excited state E_1 respectively is given by,

$$\frac{N_1}{N_2} = e^{(E_2-E_1)/kT}.$$

But, $E_2 - E_1 = h\nu$, therefore

$$\frac{N_1}{N_2} = e^{h\nu/kT}.$$

Using this in the equation of E_ν, we get

$$E_\nu = \frac{A_{21}}{B_{21}}\left(\frac{1}{\frac{B_{12}}{B_{21}}e^{h\nu/kT} - 1}\right).$$

This equation reminds us of the Planck's law, which is given by

$$E_\nu = \frac{8\pi h\nu^3}{c^3}\left(\frac{1}{e^{h\nu/kT} - 1}\right).$$

By comparing the above two equations, we get

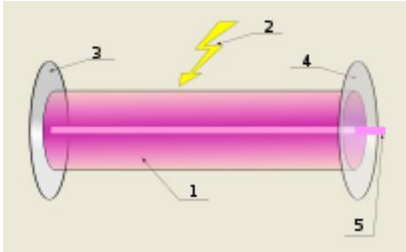
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

and

$$\frac{B_{12}}{B_{21}} = 1 \qquad \Rightarrow \quad B_{12} = B_{21}.$$

The equality $B_{12} = B_{21}$ implies that the probability of induced absorption is equal to that of stimulated emission. Hence we can use simply A and B to denote the Einstein's coefficients. With this our equation for the energy density at thermal equilibrium takes the form,

$$E_\nu = \frac{A}{B\left(e^{h\nu/kT} - 1\right)}.$$



2.3 Requisites of a laser system

The principal components of a laser system are

1. Gain medium or optical medium which supports population inversion
2. Source for pumping action
3. Fully silvered mirror called High reflector
4. A partially transparent mirror called Output coupler
5. Laser beam

A laser consists of a gain medium inside a highly reflective optical cavity, as well as a means to supply energy to the gain medium. The gain medium is a material with properties that allow it to amplify light by stimulated emission. In its simplest form, a cavity consists of two mirrors arranged such that light bounces back and forth, each time passing through the gain medium. Typically one of the two mirrors, the output coupler, is partially transparent. The output laser beam is emitted through this mirror. Light of a specific wavelength that passes through the gain medium is amplified (increases in power); the surrounding mirrors ensure that most of the light makes many passes through the gain medium, being amplified repeatedly. Part of the light that is between the mirrors (that is, within the cavity) passes through the partially transparent mirror and escapes as a beam of light. The process of supplying the energy required for the amplification is called pumping. The energy is typically supplied as an electrical current or as light at a different wavelength.

2.4 Condition for laser action

The two conditions to achieve lasing actions are

1. Population inversion
2. Availability of metastable states

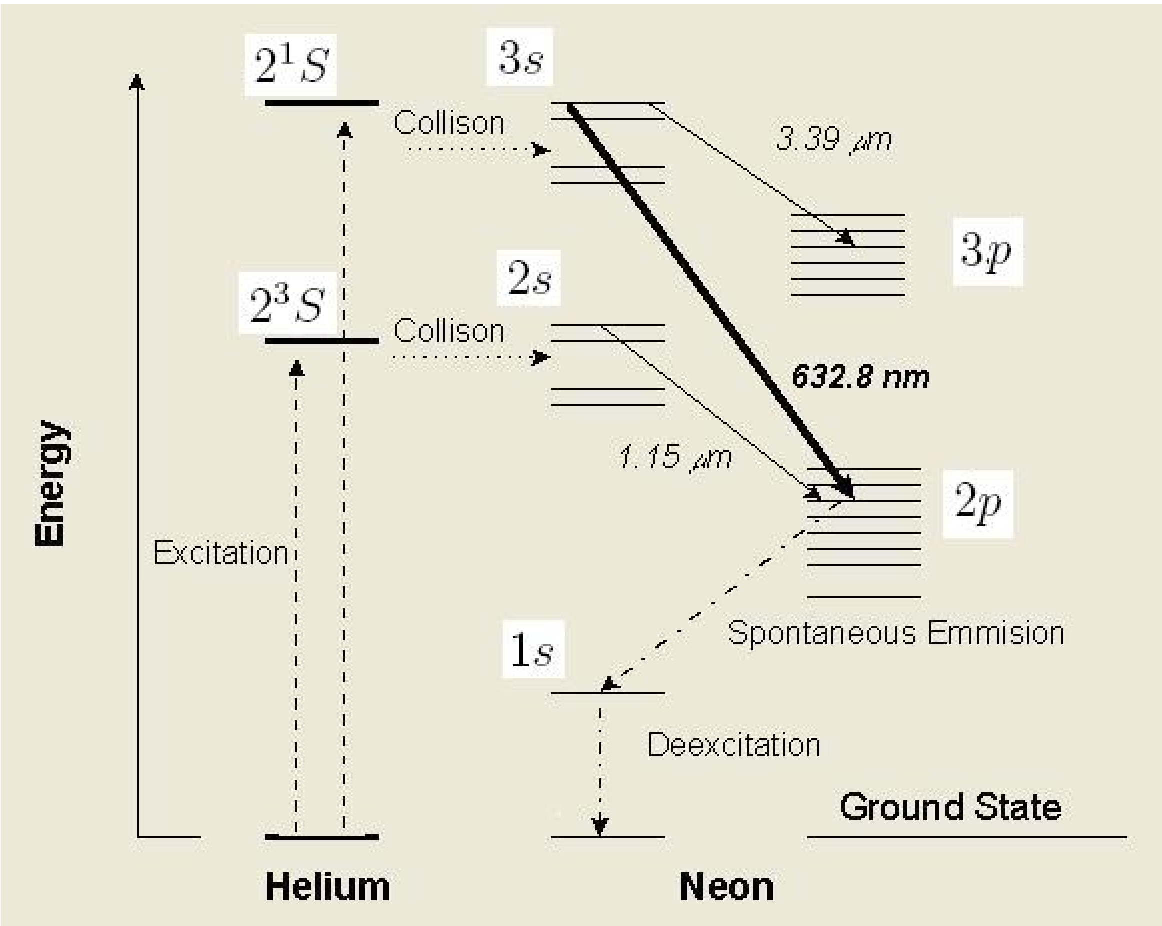
Population inversion is a state of a system in which the population of an excited state is more than that of a ground state. Naturally, we find the number density to be more in the ground state than in the excited one, hence the name. We can achieve population inversion only in those systems which posses a special kind of excited state called ***metastable state***. The electrons will remain only for about $10^{-8}s$ in the excited state and after that they make transitions to the ground state by emission of a photon. Whereas, the electrons can stay in the metastable state as long as $10^{-3}s$. If the excited state happens to be a metastable state, the atoms can stay excited for longer duration resulting in steady increase in the population of the excited or metastable state and one stage we can achieve the population inversion. Once this happens, the number of stimulated emissions outnumber the spontaneous emissions. The photons from stimulated emission will have the same wavelength, phase and direction. Once the intensity of the photons is sufficient to pass through the partially silvered mirror, we get the laser light.

3 Types of Laser

Many thousands of kinds of laser are known, but most of them are not used beyond specialized research. The chief types of lasers are solid state lasers, gas lasers and liquid lasers. A solid, liquid, gas or semiconductor can act as the laser medium. Here we discuss only Helium-Neon and semiconductor lasers.

3.1 Helium-Neon Laser.

A Helium-Neon laser, usually called a He-Ne laser, is a gas laser of operation wavelength is $632.8\,nm$, in the red portion of the visible spectrum. This was invented by Ali Javan, William Bennett Jr. and Donald Herriott at Bell Labs. The gain medium of the laser, as suggested by its name, is a mixture of helium and neon gases, in a 5 : 1 to 20 : 1 ratio, contained at low pressure in a glass tube. The energy or pump source of the laser is provided by an electrical discharge of around $1000\,V$ through an anode and cathode at each end of the glass tube. The optical cavity of the laser typically consists of a plane, high-reflecting mirror at one end of the laser tube, and a concave output coupler mirror of approximately 1% transmission at the other end. He-Ne lasers are typically small, with cavity lengths of around $15\,cm$ up to $0.5\,m$, and optical output powers ranging from $1\,mW$ to $100\,mW$.



The laser process in a He-Ne laser starts with collision of electrons from the electrical discharge with the helium atoms in the gas. This excites helium from the ground state to the 2^3S and 2^1S metastable excited states. Collision of the excited helium atoms with the ground-state neon atoms results in transfer of energy to the neon atoms, exciting neon electrons into the $3s$ and $2s$ levels. This is due to a coincidence of energy levels between the helium and neon atoms. This process is given by the reaction equation:

$$He + electric\ energy \rightarrow He^*$$

$$He^* + Ne \rightarrow He + Ne^*$$

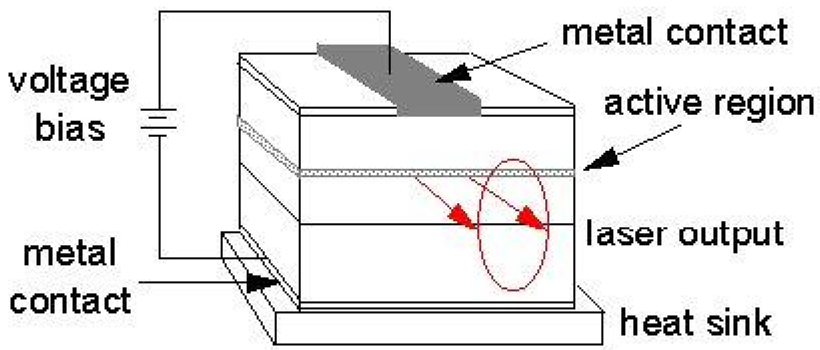
where $*$ represents an excited state. The number of neon atoms entering the excited states builds up as further collisions between helium and neon atoms occur, causing a population inversion. Spontaneous and stimulated emission between the $3s$ and $2p$ states results in emission of $632.82\,nm$ wavelength light. After this, fast radiative decay occurs from the $2p$ to the $1s$ ground state. Because the neon upper level saturates with higher current and the lower level varies linearly with current, the He-Ne laser is restricted to low power operation to maintain population inversion.

With the correct selection of cavity mirrors, other wavelengths of laser emission of the He-Ne laser are possible. There are infrared transitions at $3391.2\,nm$ and $1152.3\,nm$ wavelengths, and a variety of visible transitions. The typical $633\,nm$ wavelength red output of a He-Ne laser actually has a much lower gain compared to other wavelengths such as the $1152.3\,nm$ and $3391.2\,nm$ lines, but these can be suppressed by choosing cavity mirrors with optical coatings that reflect only the desired wavelengths.

It is used in interferometry, holography, spectroscopy, barcode scanning, alignment, optical demonstrations.

3.2 Semiconductor Laser.

A semiconductor laser has the active medium as a semiconductor similar to that found in a light-emitting diode. The most common and practical type of semiconductor laser is formed from a p-n junction and powered by injected electric current.



A semiconductor laser diode, like many other semiconductor devices, is formed by doping a very thin layer on the surface of a crystal wafer. The crystal is doped to produce an n-type region and a p-type region, one above the other, resulting in a p-n junction, or diode. Just as in any semiconductor p-n junction diode, forward electrical bias causes the two species of charge carrier - holes and electrons - to be “injected” from opposite sides of the p-n junction into the depletion region, situated at its heart. Holes are injected from the p-doped, and electrons from the n-doped, semiconductor. The charge injection is a distinguishing feature of semiconductor lasers as compared to all other lasers. When an electron and a hole are present in the same region, they may recombine or annihilate with the result being spontaneous emission i.e., the electron may re-occupy the energy state of the hole, emitting a photon with energy equal to the difference between the electron and hole states involved. In a conventional semiconductor junction diode, the energy released from the recombination of electrons and holes is carried away as phonons rather than as photons.

In the absence of stimulated emission conditions, electrons and holes may coexist in proximity to one another, without recombining for a certain time called the “recombination time”. Then a nearby photon with energy equal to the recombination energy can cause recombination by stimulated emission. This generates another photon of the same frequency, traveling in the same direction, with the same polarization and phase as the first photon. As in other lasers, the gain region is surrounded with an optical cavity. As a light wave passes through the cavity, it is amplified by stimulated emission resulting in a laser beam.

Semiconductor lasers are numerically the most common type of laser. They find wide use in telecommunication, barcode readers, CD players, DVD and Blu-ray technology, material processing, range-finding, laser target designation, surgery, holography and tattoo removal.

4 Applications of Laser

There are many scientific, industrial, military, medical and commercial laser applications. The coherency, high monochromaticity, focussability, directionality and ability to reach extremely high powers are all properties which allow for these specialized applications. We discuss a few of them below.

- **Laser cutting:** In Industry lasers are used for the precise cutting of flat materials. Lasers have the advantage that there is no physical contact with the material so there is no chance of contamination, also there is less chance of the material warping as the laser energy can be focused on a very small area so the whole material is not heated. Even a three dimensional profile can be cut using lasers. Laser cutting is also employed in tailoring industry.
- **Laser welding:** In laser welding, a beam of laser is focused on to the spot to be welded. Due to the heat generated, the material melts over a tiny area and upon cooling the material becomes homogeneous solid structure. Laser welding is a contact-less process and thus no outside material gets into the welded region. Since the heat affected zones are very small, laser welding is ideal for many microelectronic devices.
- **Laser drilling:** Laser drilling of holes is achieved by subjecting the material to powerful laser pulses of about millisecond duration. The intense heat generated over a short duration by the pulses evaporates the material locally leaving a hole. Very fine holes of the dimensions one tenth of millimeter can be drilled. Since there is mechanical stress involved in laser drilling, even the brittle materials can be drilled.
- **Measurement of pollutants in the atmosphere:** There are various types of pollutants in the atmosphere. In the measurement of pollutants, laser is used in the way a radar system is used. Hence it is called LIDAR meaning Light Detection and Ranging. This can evaluate the distance, altitude and angular coordinates of the object.

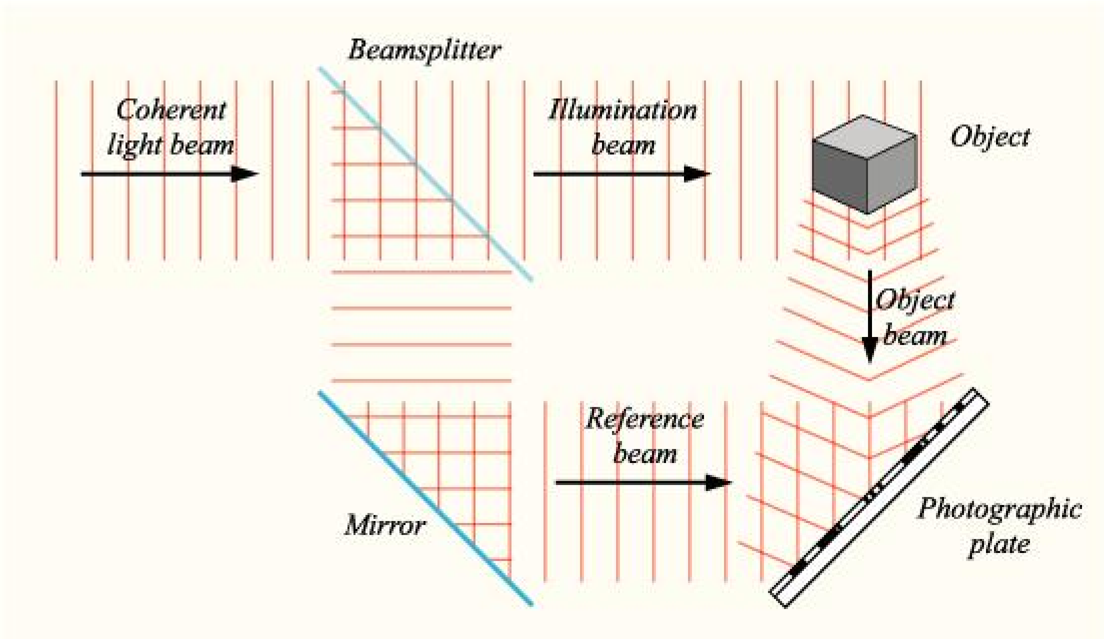
5 Holography

Holography is a technique that allows the light scattered from an object to be recorded and later reconstructed so that it appears as if the object is in the same position relative to the recording medium as it was when recorded. The image changes as the position and orientation of the viewing system changes in exactly the same way as if the object was still present, thus making the recorded image (hologram) appear three dimensional. The technique of holography can also be used to optically store, retrieve, and process information. Holography is commonly used to display static 3-D pictures. Holography was invented in 1947 by Hungarian physicist Dennis Gabor for which he received the Nobel Prize in Physics in 1971.

5.1 Recording of a hologram

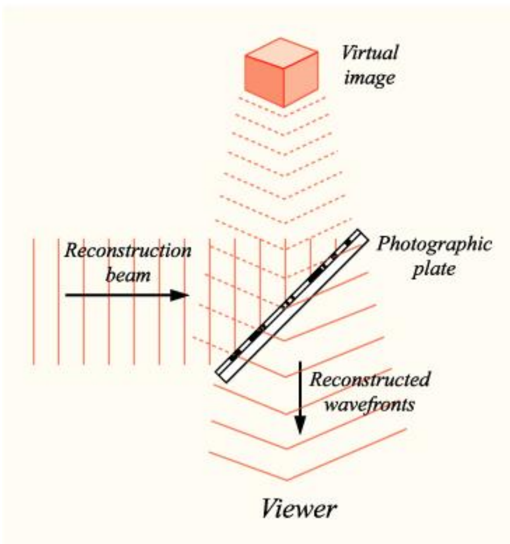
In holography, some of the light scattered from an object or a set of objects falls on the recording medium. A second light beam, known as the reference beam, also illuminates the recording medium, so that interference occurs between the two beams. The resulting light field is an apparently random pattern of varying intensity which is the hologram. There are a variety of recording materials which can be used, including photographic film.

A very simple hologram can be made by superimposing two plane waves from the same light source. One beam (the reference beam) hits the photographic plate normally and the other one (the object beam) hits the plate at an angle θ. The relative phase between the two beams varies across the photographic plate as $2\pi y sin\theta$ where y is the distance along the photographic plate. The two beams interfere with one another to form an interference pattern. The relative phase changes by 2π at intervals of $d = \lambda/sin\theta$ so the spacing of the interference fringes is given by d. Thus, the relative phase of object and reference beam is encoded as the maxima and minima of the fringe pattern.



5.2 Reconstruction of three dimensional image

The process of producing a holographic reconstruction involves the phenomenon of diffraction of light. When the photographic plate is developed, the fringe pattern acts as a diffraction grating and when the reference beam is incident upon the photographic plate, it is partly diffracted into the same angle θ at which the original object beam was incident. Thus, diffraction grating created by the two waves interfering has reconstructed the object beam and when we look into the hologram, we sees the object even though it may no longer be present.



5.3 Applications of holography

Some of the applications of holography are discussed in brief below.

1. **Holographic interferometry:** The most successful application of holography, however, is in interferometry. If two holograms of the same object are recorded on the same plate, then upon reconstruction the two holographic images will interfere. If the object has undergone a deformation between the two recordings, phase differences in certain parts of the two images will result, creating an interference pattern that clearly shows the deformation.

2. **Holographic diffraction gratings:** Holography can be used to make gratings. In this method two laser beams are made to interfere on a recording medium which produces the rulings much more uniformly than any other method.

3. **Holographic storage of digital data:** The digital data can be recorded as bright and dark spots in holographic images. A hologram can contain a large number of 'pages' that are recorded at different angles relative to the plate, thus allowing the storage of a very large amount of data on one hologram. By illuminating the hologram with a laser beam at different angles, the pages can be read out one by one.

4. **Acoustic holography:** It is a method used to estimate the sound field near a source by measuring acoustic parameters away from the source. Measuring techniques included within acoustic holography are becoming increasingly popular in various fields, most notably those of transportation, vehicle and aircraft design.

5. **Security holograms:** They are very difficult to forge because they are replicated from a master hologram which requires expensive, specialized and technologically advanced equipment. They are used widely in many currencies, credit and bank cards as well as books, DVDs and sports equipment.

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