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LASER AND NONLINEAR OPTICS: AN OVERVIEW

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LASER AND NON-LINEAR OPTICS

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Abstract

The purpose of this project is to see the different nature and types of laser and non-linear optics. Both laser and non-linear optics are the fruits of nineteenth century.

Generally, this paper summarizes the operation and application of laser and non-linear optics. Upon irradiation with laser light of specific wavelengths and intensities optical fibers and bulk glasses undergo relatively slow (minutes to hours) changes, which result in new optical phenomena that were not present before irradiation. One of these phenomena is Second Harmonic Generation.

Particularly in the first part of this project, from the meaning of laser to the type and uses of laser is going to be investigated.

In the second part, the non-linear optics, which is entirely related, to laser will be examined.

Some Important Terminologies

1. Monochromatic: Single color [1].
2. LASER: An acronym of Light Amplification by Stimulated Emission of Radiation [1].
3. Coherent light: The emitted light waves are in phase with one anther and are so nearly parallel that they can travel for a long distance with out spreading and have the same wave length means that the same frequency and so that they have the same energy [11].
4. To lase: Means to produce coherent light.
5. Meta-stable state: Is an excited state with higher lifetime than other state.
6. Optics: It means appearance or look in Greek.
7. Optics: Is a branch of physics that describes the behavior and properties of light and the interaction of light with matter.
8. Light: Is an electromagnetic radiation with a wavelength that is visible to the eye. It is quantized and may be represented by photons [10].
9. Non-linear optics (NLO): Is a branch of optics that describes the behavior or property of light in non linear media, that is, media in which polarization P represents non-linearly to the electric field E of the light. This non-linearity is typically only observed at a very high light intensity such as light provided by pulsed LASERS [9].

Introduction

One of the greatest achievements of the nineteenth century in physics is the discovery of laser. It was 1960 in which the first laser introduced by Theodore H. Maiman. After that, lots of efforts forwarded in the creation of different kinds of lasers. Oxford dictionary defines laser as a piece of equipment that produces a very strong beam of light. Laser beams are used in weapons and medical operations and it is the result of interaction of photons with matter.

According to laws of nature, entities (particles, electrons, photons) need the lowest state. That means more number of particles prefer to be in lower state or ground state. But the reverse may occur which is called population inversion, which is the necessary condition for the formation of laser light.

Many of the most dramatic advances in the field of optics in the last decade or two have been directly stimulated by or originated through progress in electrical engineering and its branch of communication sciences, microwave electrons, and radio astronomy. Among the most noteworthy similarities are: The operational Fourier transform treatment of optical image forming processes and of spectroscopy, the introduction of resonant structures and of optical feedback control (for example in laser, in fiber optics, and in interferometeric control of machines).

Non-linear optics presents another important example of the close similarities of basically comparable theory and techniques throughout broad ranges of the electromagnetic domain.

The maser, non linear optics, optical computers, interferometer gratings, lens-less photography, optical filters, and automatic reading systems, to mention only a few, were predicted and worked out ‘almost entirely on the basis of theoretical ideas of a rather complex and abstract nature’.

It is known that glasses are used as optical materials for a wide variety of applications ranging from lenses to optical fibers for communications. In most of these applications, the glass serves as a transmission medium with its optical properties being described by the absorption coefficient and the refractive index, which are contained in the real and imaginary

part of the linear optical susceptibility. The linear susceptibility is sufficient to describe the optical properties of a material when the light intensities are relatively low.

However, when the light intensity increases above a certain material-dependent value, processes that depend non-linearly on the light intensity start to become important and new non-linear optical phenomena can be observed. Examples of such processes are second and third harmonic generation, two-photon absorption, intensity dependent refractive index effects and stimulated Raman and Brillouin scattering.

The dissertation of the project is organized as follows. In chapter one of laser topic, the historical background of laser is going to be investigated. In chapter two the proposal of Einstein calculation for the stimulated and spontaneous emission is going to be examined in detail. In next chapter we are going to see how laser works. In chapter four I try to mention the different types of lasers and their feature. In the fifth chapter the problems, which the world face due to the progress in laser technology, will be seen. In the sixth chapter some thing will be mentioned about laser safety. In the next chapter recent development of laser technology will be examined. In the final chapter of this sub topic applications of laser will be treated [1], [2].

In the first chapter of, the second part of this project I am trying to mention the origin of non-linear optics. In the second chapter linear and non-linear optics will be compared. In the next chapter non-linear optics will be seen independently. In chapter four I try to answer the question: Is optical property of a medium depends on the intensity of light? In the fifth chapter we will see how frequency of light can be mixed. In the sixth chapter some non-linear optical process will be examined. In the next chapter Self focusing phenomena in non-linear optics will be treated in detail. In the next four chapters optical related process, some second harmonic generation material, application of the non-linear optics and some non-linear crystalline materials would be seen respectively [5].

PART A: LASER

CHAPTER ONE

History

This section will look the question when and who is the creator and founder of laser and also we will look the application of laser in holography. In 1916 Albert Einstein laid the foundation for the invention of the LASER and its predecessor, the MASER which is an abbreviation of Microwave Amplification by Stimulated Emission of Radiation, in a ground breaking re-derivation of Max Planck's law of radiation based on the concept of spontaneous and stimulated emission.

MASER, which is the earliest stimulated emission device to be developed, first demonstrated in 1945. For its development, the noble prize in physics was awarded jointly in 1964 to the U.S scientist, Charles H. Towens, at the institute of technology in Cambridge, Massachusetts, and to the Soviet scientists, A.M. Prokovov and N. Bosov, both at the Lebedev institute in Moscow. Following the success of the MASER, many workers endeavored to extend its uses from microwave to light wavelength.

Theodore H. Maiman made the first working laser in 1960 at Hughes Research Laboratories in Malibu, California.

Maiman used a solid-state flash lamp-pumped synthetic ruby crystal to produce red laser at 694nm wavelength. Later in the same year, the Iranian physicist Ali Javan together with Willian Bennet and Donald Herriot made the first gas laser using Helium and Neon. Javan later received the Albert Einstein award in 1993.

The concept of semiconductor laser was proposed by Basov and Javani and the first diode was demonstrated by Robert N. Hall in 1962 [1], [4], [6].

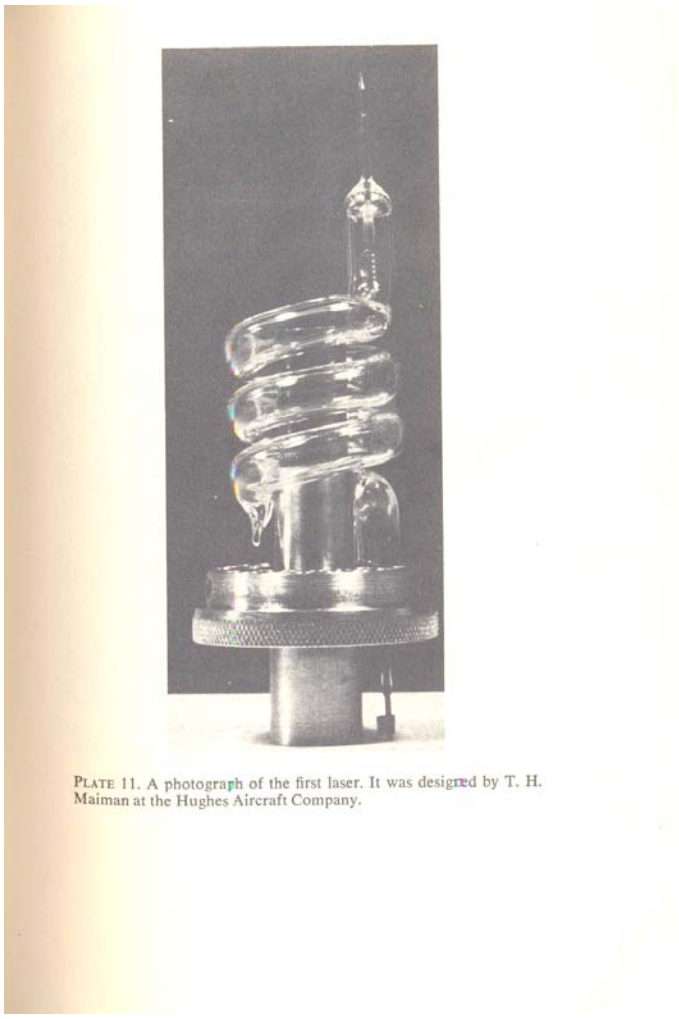


PLATE 11. A photograph of the first laser. It was designed by T. H. Maiman at the Hughes Aircraft Company.

Fig (1) A Photograph of the first laser [7].

Note: T.H. Maiman at the Hughes Aircraft Company designed it.

Holography, like photography is away of recording on film a scene we see with our eyes. But the means by which the two processes accomplish this, and the kinds of images that results, are vastly different. While the photograph collapses into one plane all the scenic depth we perceive, the hologram captures the entire message of the scene in all its visual properties, including the realism of three dimensions. To see around an object in a hologram, the viewer has to move his head to left or right.

Although the idea of holography existed in 1947, it had to wait until a special kind of single frequency light becomes available [7]. In this section we discussed about the inventor of laser. Now let us see the meaning of laser using the concept of Einstein A, B coefficients.

CHAPTER TWO

Einstein A, B Coefficients

Here we consider the transitions in order to get some idea of the laser. We recall that there are two kinds of transition. These are absorption and emission. In the case of emission it can be spontaneous or stimulated but in the case of absorption there should be stimulation.

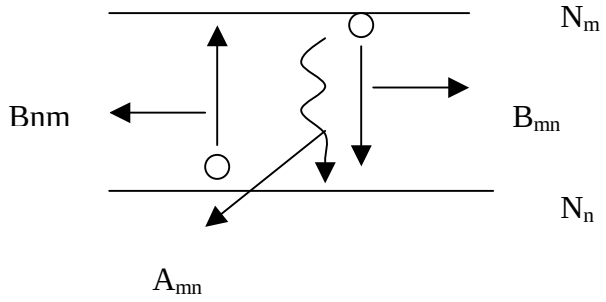


Figure (2) Probabilities of emission and absorption

Where B_{nm} is probability of stimulated absorption.

B_{mn} is probability of stimulated emission.

A_{mn} is probability of spontaneous emission.

Since radiation is characterized by density (ρ), the number of upward transition would proportional to $\rho(\nu_{nm})$ and to the number of electrons in n-level.

I.e. number of upward transition α Nn $\rho(\nu_{nm})$

I.e. number of up ward transition = $B_{nm}\ N_n\ \rho(\nu_{nm})$……..... (1)

Where: the proportionality constant gives the strength of the gap, which is entirely related to number of stimulated emission and stimulated absorption.

Similarly, number of down ward transition = $B_{mn}\ N_m\ \rho(\nu_{mn})$……..…… (2)

And also the number of spontaneous emission = $N_m A_{mn}$……..…….…… (3)

At equilibrium the number of upward transition is equal to the number of down ward transition.

I.e. $B_{nm} N_n \rho(\nu_{nm}) = B_{mn} N_m \rho(\nu_{mn}) + N_m A_{mn}$…….. (4)

Note:

1. The number of stimulated emission is equal to the number of stimulated absorption because they need the same amount of energy.

I.e. $B_{nm}=B_{mn}$…….....….. (5)

2. When electromagnetic radiation in a cavity is in thermal equilibrium at absolute temperature T, the distribution of radiation density follows Planck's distribution function and given by:

$$\rho(\nu_{mn})=\frac{16\pi\eta\nu_{mn}^{3}}{c^{3}}\frac{1}{\exp(\frac{2\eta\nu_{mn}}{KT})-1} \quad \text{……..…….. (6)}$$

Where η = h/2 (h is Planck's constant)

Dividing equation (4) by N_n we obtain

$B_{nm} \rho(\nu_{nm}) = B_{mn} N_m/N_n \rho(\nu_{mn}) + N_m /N_n A_{mn}$……. (7)

Dividing equation (7) by B_{nm} we obtain

$\rho(\nu_{nm})= (B_{mn} /B_{nm}) (N_m/N_n) \rho(\nu_{mn}) + (N_m /N_n) (A_{mn}/B_{nm})$…… (8)

But from equation (5) $B_{mn}=B_{nm}$, so that equation (8) becomes

$\rho(\nu_{nm})= (N_m/N_n) \rho(\nu_{mn}) + (N_m /N_n) (A_{mn}/B_{nm})$…….…….....…… (9)

Solving for $\rho(\nu_{nm})$ we obtain

$$\rho(\nu_{nm}) = \frac{\frac{A_{mn}}{B_{nm}}(\frac{N_m}{N_n})}{1-(\frac{N_m}{N_n})} \quad \text{..... (10)}$$

But $\frac{N_m}{N_n} = \exp(-\frac{2\pi\eta\nu_{mn}}{KT})$ ..... (11)

Substituting equation (11) in equation (10) we get

$$\rho(\nu_{nm}) = (\frac{A_{mn}}{B_{nm}})(\frac{1}{\exp(\frac{2\pi\eta\nu_{mn}}{KT}-1)}) \quad \text{..... (12)}$$

Since thermal equilibrium is maintained with in the cavity by means of radiation whose spectral distribution is governed by Planck's law and it is given by

$$\rho d\rho = \frac{16\pi\eta\nu^3}{c^3}(\frac{d\rho}{\exp(\frac{2\pi\nu\eta}{KT})-1}) \quad \text{..... (13)}$$

Comparing equation (12) and (13) we get

$$\frac{A_{mn}}{B_{nm}} = \frac{16\pi\eta\nu^3}{c^3} \quad \text{..... (14)}$$

After obtaining this result, Einstein postulates that '' the probability for spontaneous emission A is related to the probability of stimulated emission B'' and is given by:

$$\frac{A}{B} = \frac{16\pi\eta\nu^3}{c^3} \quad \text{..... (15)}$$

Rearranging equation (12) we obtain (by dropping subscripts)

$$\frac{A}{B\rho} = \exp(\frac{2\pi\nu\eta}{KT}) - 1 \quad \text{..... (16)}$$

Since $\omega = 2\pi\nu$ ..... (17)

Equation (16) becomes

$$\frac{A}{B\rho} = \exp(\frac{\eta\omega}{KT}) - 1 \quad \text{..... (18)}$$

Let as see what happens to the probabilities for spontaneous emission A and stimulated emission B in two cases [1], [8].

Case 1

If $\omega << \frac{KT}{\eta}$, which means for high temperature,

$$\text{Exp}\,(\frac{\eta\omega}{KT}) = 1 + \frac{\eta\omega}{KT} + \left(\frac{\eta\omega}{KT}\right)^2 + \ldots$$

$$\cong 1 + \frac{\eta\omega}{KT}$$

There fore $\frac{A}{B\rho} = 1 + \frac{\eta\omega}{KT} - 1$,

$$\frac{A}{B\rho} = \frac{\eta\omega}{KT}$$

But $\frac{\omega}{KT/\eta} << 1$

$\frac{A}{B\rho} << 1$ For constant density this equation becomes

$\frac{A}{B} << 1$ Which means A<<B.

Therefore one can conclude that for high temperature, the probability of spontaneous emission is much less than the probability of stimulated emission. But this situation happens if the temperature is of the order of $10{,}000^0$K in which all-material melt. Therefore, the proposal of Einstein was not successful.

Case 2

If $\omega >> \frac{KT}{\eta}$ that means for low temperature

$\frac{A}{B\rho} = \exp(\frac{\eta\omega}{KT}) - 1$ becomes,

$\frac{A}{B\rho} = \exp(\frac{\eta\omega}{KT})$, and much grater than one.

Therefore $\frac{A}{B\rho} >> 1$, for constant density,

$\frac{A}{B} >> 1$ Which means A>>B

The conclusion is for low temperature, the probability of spontaneous emission is much greater than the probability of stimulated emission. Therefore there is no laser formation for low temperature [1], [2].

CHAPTER THREE

Detail of Laser

In this section I am trying to answer questions like: What is laser? What are the different features of laser light? What are the criteria to accomplish for the formation of laser light and like?

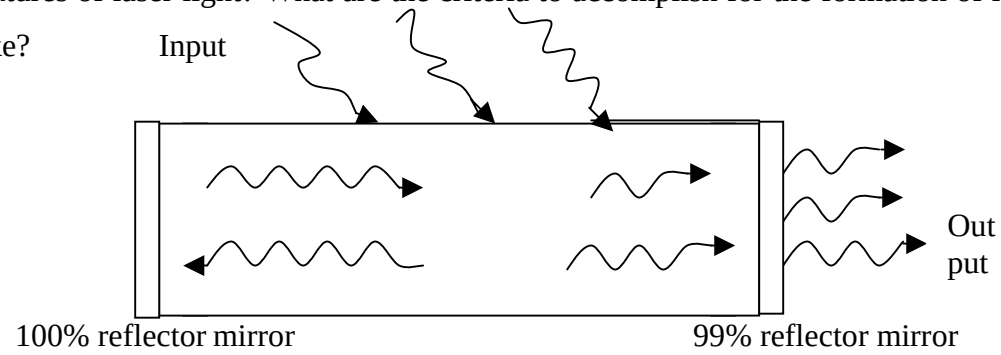


Figure (3) Schematic diagram of laser

Electrons normally reside in the lowest available energy state. That means, the natural tendency of an electrons is to move to wards equilibrium and /or to ground state. Therefore they are elevated to excited state by absorption alone. But both spontaneous emission and stimulated emission will bring them back down, and also the lifetime of a typical excited state is 10*Exp (-8) seconds. So in practical terms, the electrons drop back down by photon emission about as fast as you can pump them up to the upper level. Therefore the main problem in the construction of laser is the creation and maintenance of population inversion. We recall that, laser with out population inversion cannot be created.

Absorption and stimulated emission require photon energy, which is equal to the energy gap between the two successive states.

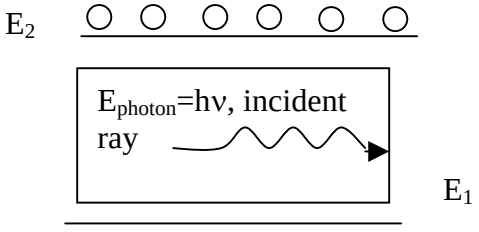


Figure (4) If a significant population inversion exists then stimulated emission can produce significant light amplification.

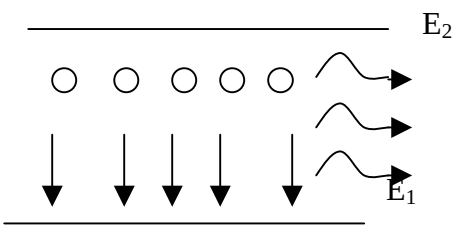


Figure (5) Photons produced by stimulated emission have a definite phase relation ship and produce coherent light. This means, the stimulated emission of light is the crucial quantum process necessary for the operation of laser.

Principal components of laser are

1. Active laser medium
2. Laser pumping energy
3. Total reflacting mirror
4. Partial reflecting mirror
5. Laser beam

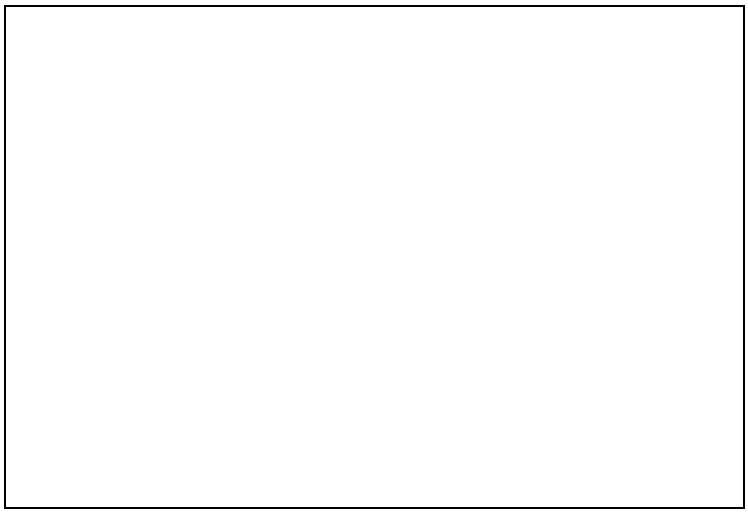


Figure (6) Schematic diagram of laser resonator

3.1 **Properties of Laser Radiation**

We have seen what laser mean and its main components. Now let us see the properties of laser light by comparing with ordinary light.

The energy of photon that is emitted in stimulated emission process is identical to the energy of out going photon.

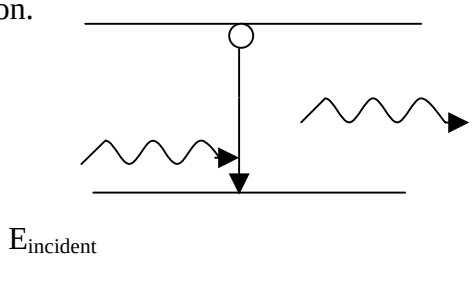


Figure (7) Incidence and outgoing photon

Radiations of laser have:

1. Identical wavelength (and thus frequencies) - Monochromaticity
2. Identical directions in space-Directionality
3. Identical phase – Coherence
4. High intensity than ordinary light radiation

These are the main properties of laser radiation. But if we consider the radiation of ordinary light source such as bulb, the radiation diffuses in all directions, has large line width and low focussability [9]. Let us see these differences using diagram.

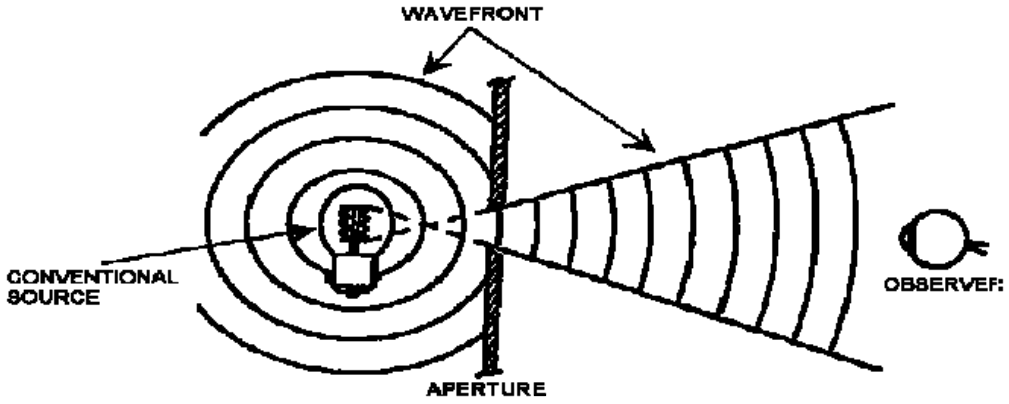


Figure (8) Divergence of conventional light source

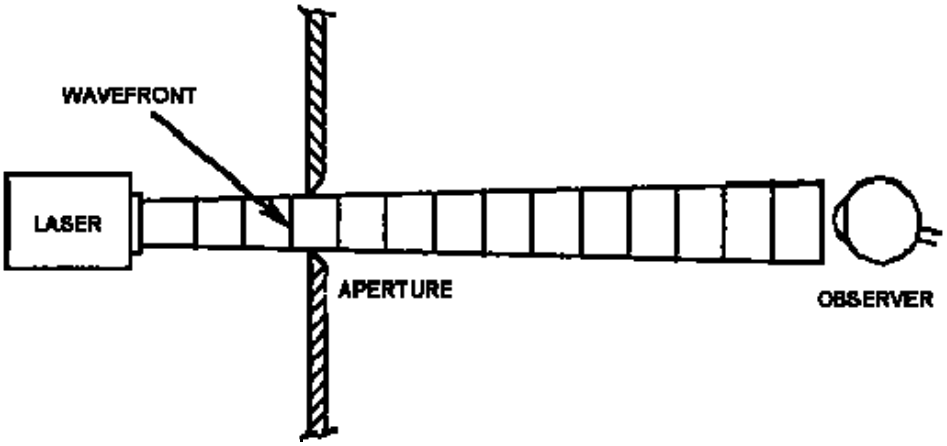


Figure (9) Divergence of laser light source

Laser Gain (G)

The factor by which an input beam is amplified by a medium is called gain and denoted by G. It shows the magnitude of amplification.

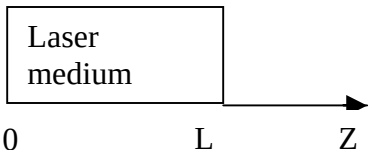


Figure (10) Diagram of laser medium

Neglecting spontaneous emission

$$\frac{dI}{dz} = c\frac{dI}{dz}\alpha BN_2 I - BN_1 I$$

……...……. (19)

$$\alpha B(N_2 - N_1)I$$ ……..……...…….. (20)

Integrating the above equation over the length of the medium we obtain

$$\int \frac{dI}{I} = \int \sigma(N_2 - N_1)dz$$ ……..…….. (21)

Finally we obtain

$$I(z) = I(0)\exp(\sigma(N_2 - N_1)L$$ ……..……...…….. (22)

$$= I(0)G \quad \text{Where } G = \exp(\sigma(N_2 - N_1)L)$$ ……..…….. (23)

If $N_2 < N_1$, G is less than one. If $N_2 > N_1$, G is greater than one. This means in order to get amplification there should be inversion.

In previous section we looked the difference between laser light and ordinary light radiation. In the next chapter let us see what spectral broadening mean.

3.1.1 What is Spectral Broadening?

Spectral Broadening

In this particular section our aim is to investigate the different mechanism for special broadening of laser beam and its infulence in different applications.

The band-width of the Doppler signal depends partly upon technical factors, partly upon the actual range of blood-flow velocities present within the sample volume. Ideally, the Doppler frequency shift should be zero in the absence of flow. The emitted ultrasound pulse in pulsed Doppler ultrasound does not contain a single frequency, however; it has a range of frequencies. This variation in emitted frequency introduces a variation in the echo frequency as well. The result is spectral broadening of the Doppler signal.

A similar effect on the Doppler frequency shift (or velocity) spectrum is caused by the transient presence of the ultrasound scatterers in blood. The scatterers (i.e. the red blood cells) enter and leave the sensitive volume of a continuous wave (CW) Doppler or the sample volume of a pulsed Doppler instrument, and in doing so, their back scattered echoes increase and fade. The beginning and end of each echo is interpreted by the spectrum analyser as differences in frequency. The artificial spectral broadening thus introduced is called transit-time broadening. The phenomenon is also known as geometric or intrinsic spectral broadening.

In clinical situations, spectral broadening is encountered whenever there is an increase in the range of blood-flow velocities present within the sample (or sensitive) volume. Typically, spectral broadening is found in vessel stenoses and in the presence of turbulence. Generally, the range of blood-flow velocities being measured is dependent upon the velocity profile in the vessel and the size of the sample volume compared to the size of the vessel lumen.

The spectral broadening encountered in vessel stenoses is illustrated in Figiure(11). A small sample volume is placed centrally in a vessel having a parabolic velocity profile (top, left). Only the highest velocities are thus being sampled, and the resulting time-velocity spectrum is narrow (bottom, left). In the vessel stenosis, the sample volume covers the entire vessel lumen (top, middle), and all velocities from zero at the wall to maximum in the centre are measured. As well as increased maximum velocity being shown, the time-velocity spectrum is also broadened, with filling - in of the "window" under the spectral curve (bottom, middle). In the poststenotic region (top, right), flow breaks up into vortices due to

the sudden increase in vessel lumen. An irregular flow pattern with spectral broadening is seen (bottom, right), despite the fact that only the central part of the vessel lumen is sampled.

Pulsed Doppler time - velocity spectra from a small sample volume placed within a tight vessel stenosis (middle), as well as upstream (left) and downstream (right) of the stenosis.

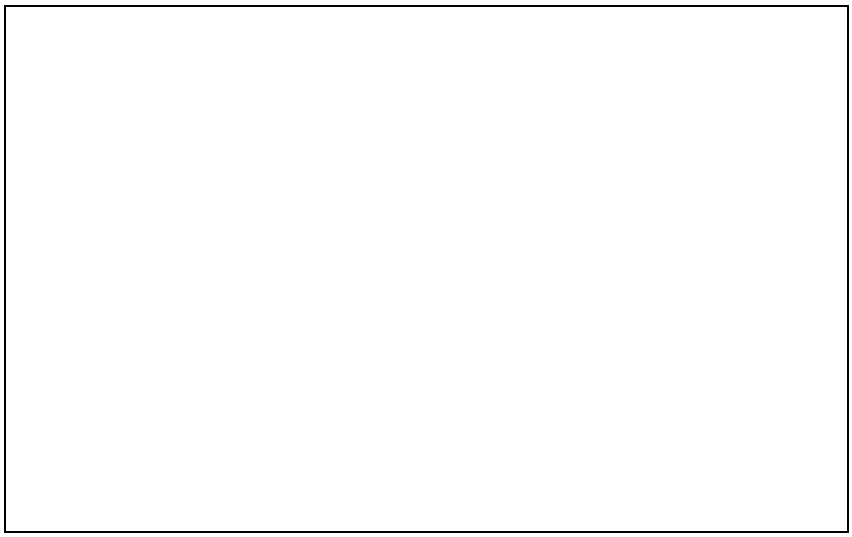


Figure (11) Spectral line width diagram

Spectral line

Let us see what spectral line of light look like.

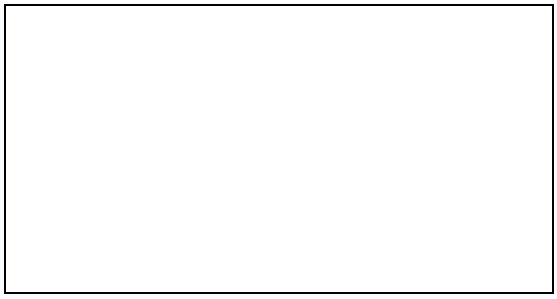


Figure (12) Absorption lines in the spectrum of the sun

Wavelength decreases as if reading a book: left to right, then top to bottom. The dark areas are the absorption lines.

A spectral line is a dark or bright line in an otherwise uniform and continuous spectrum, resulting from an excess or deficiency of photons in a narrow frequency range, compared with the nearby frequencies.

Spectral lines are the result of interaction between a quantum system (usually atoms, but sometimes molecules or atomic nuclei) and single photons. When a photon has exactly the right energy to allow a change in the energy state of the system (in the case of an atom this is usually an electron changing orbitals), the photon is absorbed. Then it will be spontaneously re-emitted, either in the same frequency as the original or in a cascade, where the sum of the energies of the photons emitted will be the same as the energy of the one absorbed. The direction of the new photons will not be related to the direction of travel of the original photon.

Depending on the geometry of the gas, the photon source and the observer, an emission line or an absorption line will be produced. If the gas is between the photon source and the observer, a decrease in the intensity of light in the frequency of the incident photon will be seen, as the re-emitted photons will mostly be in directions different from the original one. This will be an absorption line. If the observer sees the gas, but not the original photon source, then the observer will see only the photons re-emitted in a narrow frequency range. This will be an emission line. Absorption and emission lines are highly atom-specific, and can be used to easily identify the chemical composition of any medium capable of letting light pass through it (typically gas is used). Several elements were discovered by spectroscopic means : helium, thallium, cerium, etc. Spectral lines also depend on the physical conditions of the gas, so they are widely used to determine the chemical composition of stars and other celestial bodies that cannot be analyzed by other means, as well as their physical conditions. Isomer shift is the displacement of an absorption line due to the absorbing nuclei having different electron densities from that of the emitting nuclei.

Mechanisms other than atom-photon interaction can produce spectral lines. Depending on the exact physical interaction (with molecules, single particles, etc.) the frequency of the

involved photons will vary widely, and lines can be observed across all the electromagnetic spectrum, from radio waves to gamma rays.

Spectral Line Broadening and Shift

Here let us see the different kinds of broadening. A line extends over a range of frequencies, not a single frequency. In addition its center may be shifted from its nominal central wavelength. There are several reasons for this broadening and shift:

- **Natural broadening**: The Uncertainty principle relates the life of an excited state with the precision of the energy, so the same excited level will have slightly different energies in different atoms. This broadening effect is described by a Lorentzian profile and there is no associated shift.

- **Thermal Doppler broadening**: Atoms will have different thermal velocities, so they will see the photons red or blue shifted due to the Doppler effect, absorbing photons of different energies in the frame of reference of the observer. The higher the temperature of the gas, the larger the velocity differences (and velocities), and the broader the line. This broadening effect is described by a Doppler profile and there is no associated shift.

- **Pressure broadening**: the presence of nearby particles will affect the radiation emitted by an individual particle. There are two limiting cases by which this occurs:

- Impact pressure broadening: The collision of other particles with the emitting particle interrupts the emission process. The duration of the collision is much shorter than the lifetime of the emission process. This effect depends on both the density and the temperature of the gas. The broadening effect is described by a Lorentzian profile and there may be an associated shift.

- Quasistatic pressure broadening: The presence of other particles shifts the energy levels in the emitting particle, thereby altering the frequency of the emitted radiation. The

duration of the influence is much longer than the lifetime of the emission process. This effect depends on the density of the gas, but is rather insensitive to temperature. The form of the line profile is determined by the functional form of the perturbing force with respect to distance from the perturbing particle. There may also be a shift in the line center. The Lévy skew alpha-stable distribution has been found to be a useful generalization describing a quasistatic line profile. Pressure broadening may also be classified by the nature of the perturbing force.

- **Linear Stark broadening**: occurs via the linear Stark effect which results from the interaction of an emitter with an electric field, which causes a shift in energy which is linear in the field strength. ($\Delta E \sim 1/r^2$)
- **Resonance broadening**: occurs when the perturbing particle is of the same type as the emitting particle, which introduces the possibility of an energy exchange process. This broadening effect is described by a Lorentzian profile in both the impact and the quasistatic case. ($\Delta E \sim 1/r^3$)

- **Quadratic Stark broadening**: occurs via the quadratic Stark effect which results from the interaction of an emitter with an electric field, which causes a shift in energy which is quadratic in the field strength. ($\Delta E \sim 1/r^4$)
- **Van der Waals broadening**: occurs when the emitting particle is being perturbed by Van der Waals forces. For the quasistatic case, a Van der Waals profile is often useful in describing the profile. The energy shift as a function of distance is given in the wings by e.g. the Lennard-Jones potential ($\Delta E \sim 1/r^6$)

- **Opacity broadening**: Considerable re-absorption of emission line photons, an effect known as opacity, often causes line broadening. The line is broadened since photons at the line wings have a smaller re-absorption probability than photons at the line center. Indeed, the absorption near line center may be so great as to cause a self reversal in which the intensity at the center of the line is less than in the wings. This type of broadening is different from the

above mentioned broadening mechanisms because it depends upon the conditions along the entire path taken by the radiation, rather than simply upon conditions that are local to the emitting particle.

These mechanisms can act in isolation or in combination. Assuming each effect is independent of the other, the combined line profile will be the convolution of the line profiles of each mechanism. For example, a combination of thermal Doppler broadening and impact pressure broadening will yield a Voigt profile[28],[29],[30].

3.1.2 What are Mechanisms for Optical Spectral Broadening?

In this section we will try to see the methods in which optical spectral broadening occur. Super continuum generation is a process where light with very broad spectral bandwidth (i.e. low temporal coherence) and usually at the same time high spatial coherence is generated. This is usually obtained by propagating optical pulses through a strongly non-linear device as e.g. an optical fiber. Of special interest are photonic crystal fibers, mainly due to their unusual dispersion characteristics, which can allow a strong non-linear interaction over a significant length of fiber. Even with quite moderate input powers, very broad spectra are achieved (→ a kind of "laser rainbow"). In some cases, tapered fibers can also be used.

Applications of super-continua include coherence tomography, the characterization of optical devices, and the generation of multiple carrier waves in optical fiber communications systems, and the measurement of the carrier-envelope offset frequency of frequency combs.

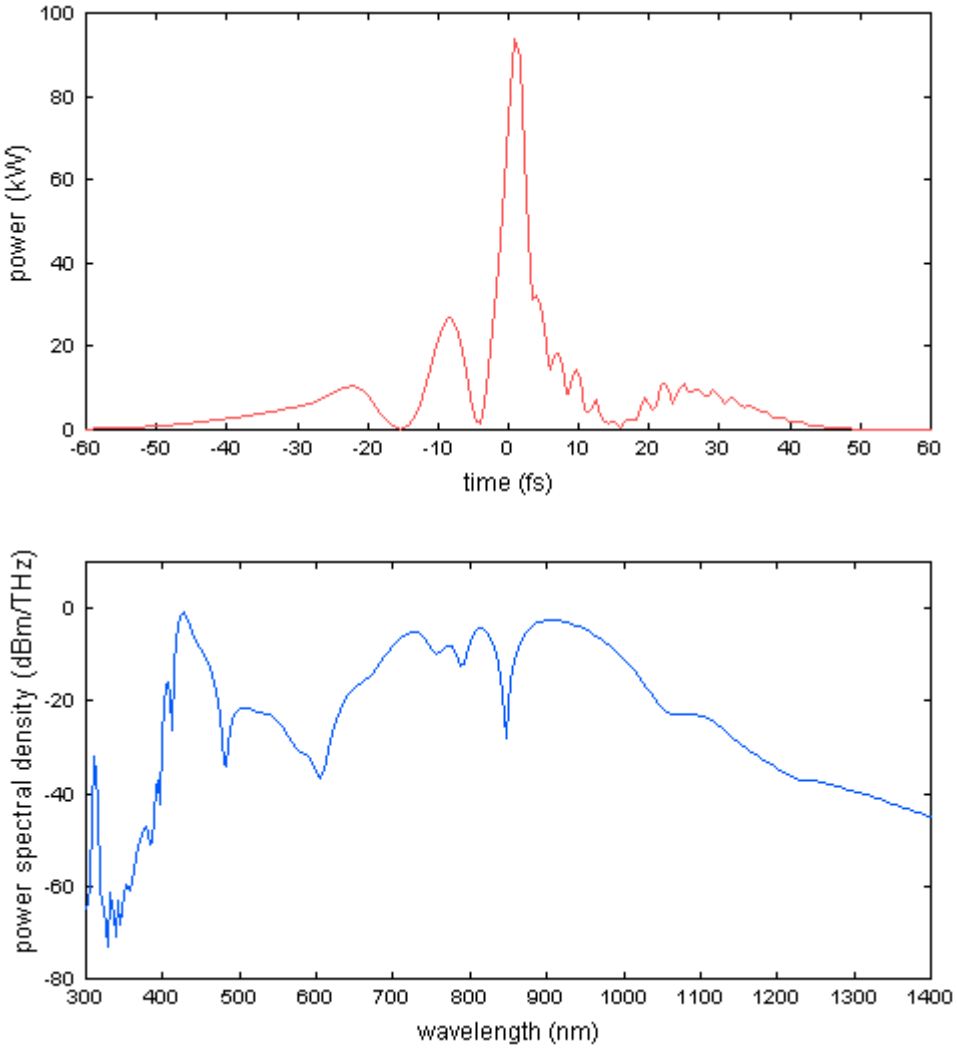


Figure (13) Super continuum, simulated with the program Pro Pulse by R. Paschotta, assuming that 20-fs laser pulses propagate through a 2-mm long photonic crystal fiber. The time domain (upper graph) exhibits a complicated multi-peak structure, while the spectrum (lower graph, with logarithmic scale) has a significant power spectral density over more than one optical octave. The simulation took into account dispersion, the Kerr nonlinearity (leading to self-phase modulation and four-wave mixing) with self-steepening, and Raman scattering.

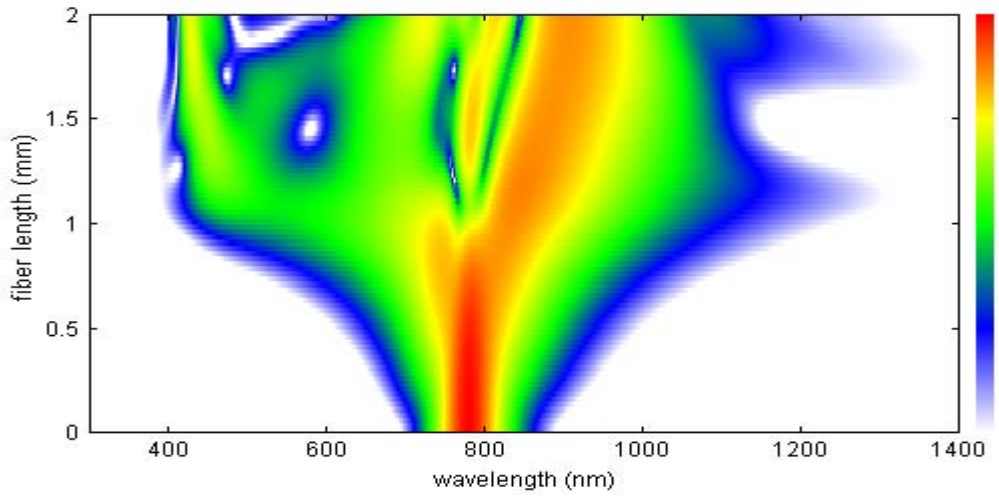


Figure (14) Evolution of the spectrum along the fiber (vertical axis).

After about 1 mm propagation distance, further spectral broadening is weak because the peak power has decreased a lot. Note that the intensity color scale (bar on the right side) is logarithmic.

Understanding Super Continuum Generation

The processes behind super continuum generation in fibers can be very different, depending particularly on the dispersion, the pulse duration and the peak powers. When femto second pulses are used, the spectral broadening can be dominantly caused by self-phase modulation. For pumping with Pico-second or nanosecond pulses, or even with continuous-wave beams, the Raman scattering and four-wave mixing can be rather important. The noise properties of the generated continua can accordingly be very different.

The strongly non-linear nature of super continuum generation makes it hard to intuitively understand all the details of the interaction, or to predict relations with analytical tools. Therefore, numerical pulse propagation modeling is required to analyze such processes. Intuitive pictures or analytical guidelines can be tested by comparison with results from such numerical models.

Coherence Properties

It is worth spending some thoughts on the coherence properties of supercontinua. The spatial coherence is usually very high, particularly when the source involves a single-mode fiber. On the other hand, the high spectral bandwidth suggests a very low temporal coherence. However, supercontinua generated from periodic pulse trains can still have a high temporal coherence in the sense that there can be strong correlations between the electric fields corresponding to different pulses, if the spectral broadening mechanism is highly reproducible. This kind of coherence is in fact very important for the generation of frequency combs in photonic crystal fibers, and it may or may not be achieved depending on parameters like the seed pulse duration and energy, fiber length, and fiber dispersion.

The initially surprising discrepancy between high bandwidth and high temporal coherence can be resolved by realizing the shape of the field correlation function: it has a very narrow peak around zero time delay (with a width of e.g. a few femtoseconds), but there are also additional peaks with comparable height at time delays corresponding to integer multiples of the pulse period. So there is low temporal coherence in the sense of vanishing correlations for most time delays, but high temporal coherence in the sense of strong correlations for some large time delays [31].

3.1.3 What Influences Spectral Line Width?

In this section I try to see the factors that affect the spectral line width. In condensed phase there are a number of complications. Imagine a molecule in solution. Molecules are surrounded by solvents and the arrangement of the solvent around the molecules is continuously changing. The rate of this change is determined primarily, by the temperature. At higher temperature the rate of change is the greatest. If you were to take a snapshot the molecules would have a number of different environments. These molecules would all have slightly different environments and they themselves are moving. This would result in slightly different transition energies for the various molecules. This is inhomogeneous broadening. This difference in environment is inhomogeneous and affects the breadth of transitions. As

we know from Statistical Mechanics energy is partitioned amongst the various degrees of freedom, translational, rotational, vibrational and electronic. So the starting ensemble of molecules may not in the ground vibrational state in solution. In order to simplify the discussion of the breadth or line width of transitions effects due to environment need to be removed. The conceptually easiest way of doing this is by thinking of an ensemble of gas phase molecules. Imagine a stationary isolated molecule in its vibrational and rotational ground state. What causes the width of transitions?

1. Lifetime Broadening

The answer actually arises out of the Heisenberg uncertainty principle. Recall that there are special pairs of linked observables. One such pair is frequency and time. The consequence of this is that if an electronic state exists for a definite period or lifetime τ, then the energy levels of that state have an uncertainty in their energy of: $\delta E = \frac{\hbar}{\tau}$

Or in wave numbers:

$$\delta\nu \approx \frac{5.31 cm^{-1}}{\tau / ps}$$

A state with a 1 Pico second lifetime would have a 5.31 cm^{-1} line width.

A state with a 1 nanosecond would give a line width of 0.00531 cm^{-1}.

Higher energy states are by definition shorter lived and are most prone to lifetime broadening. This makes sense in the fact that having too much excess energy is unnatural and thus the more energy the molecule has the more likely is it to emit a photon and return to its natural state. In the absence of other effects this lifetime broadening is called homogeneous broadening. No state has an infinitely long lifetime so some measure of lifetime or uncertainty broadening is present in all forms of spectroscopy.

When a molecule is in an excited state it can undergo a number of fates.

- It can spontaneously emit a photon.
- It can relax via non-radiative pathways within the molecule itself.

These non-radiative mechanisms actually reduce the lifetime of the molecule. This will of course lead to a spectral broadening for the reasons outlined above.

One other way that accelerates these processes is by collisional deactivation. Clearly the denser the material and the higher the temperature, the more likely are such processes. This is sometimes known as pressure broadening for gas phase samples. Reducing the pressure can minimize such effects. However there is a trade off. You need enough samples to measure. Another fate of an excited state is chemical reaction. If this is fast compared to the excited state natural lifetime then a broadening can also be introduced here. A stationary molecule is not a very common state of affairs. As you know depending upon the temperature an ensemble of molecules has a distribution of velocities. This means that they are moving in all directions and at a variety of speeds. This may have an effect on how broad a line-width is actually observed.

2. The Doppler Effect

When you are sitting in a car and you here a police siren how do you know whether it is coming towards you or going away from you?

You make a spectroscopic measurement with your ears! If it is traveling towards you it appears to be increasingly high pitched. Once it has passed you it sounds deeper. Therefore you as an observer are making a relative measurement. This is known as the Doppler Effect.

So if a spectroscopic measurement is made on an ensemble of molecules the velocity of each given molecule affects how the frequency is "perceived" by the molecule. If the

molecule is moving toward a monochromatic light source the relative frequency of any radiation is given by:

$$\nu'' = \frac{\nu}{1 - v/c}$$

And one moving away is given by:

$$\nu' = \frac{\nu}{1 + v/c}$$

Where v is the velocity, c is the speed of light,ν is the actual frequency,**ν** and **ν** ' are the measured frequencies. Given that there is a temperature dependent distribution of velocities there will therefore be a temperature determined line width.

In practice at room temperature the spectra of most gas phase molecules have line widths that are determined by Doppler broadening. This phenomenon is used in a very large number of situations. One example is in determining the relative velocities of galaxies and getting an estimate for things like the Hubble constant. We know from terrestrial measurements at which frequency a given optical transition is. By making a spectroscopic measurement of a star that is moving away from us and analyzing the measured position of the spectral peaks we can calculate our relative velocity at the time when the light was emitted. The observed line width is therefore a combination of the natural line width as defined by the rate of spontaneous emission and non-radioactive pathways, the line width due to the collisional broadening, Doppler effects and any inhomogeneous broadening due to differing environments. Of course if several transitions are close in energy then they may overlap. Light sources have their own spectral width. If this is not sufficiently narrow then the observed line width will be a convolution of the true line width and that of the light source as shown figure (15) below:

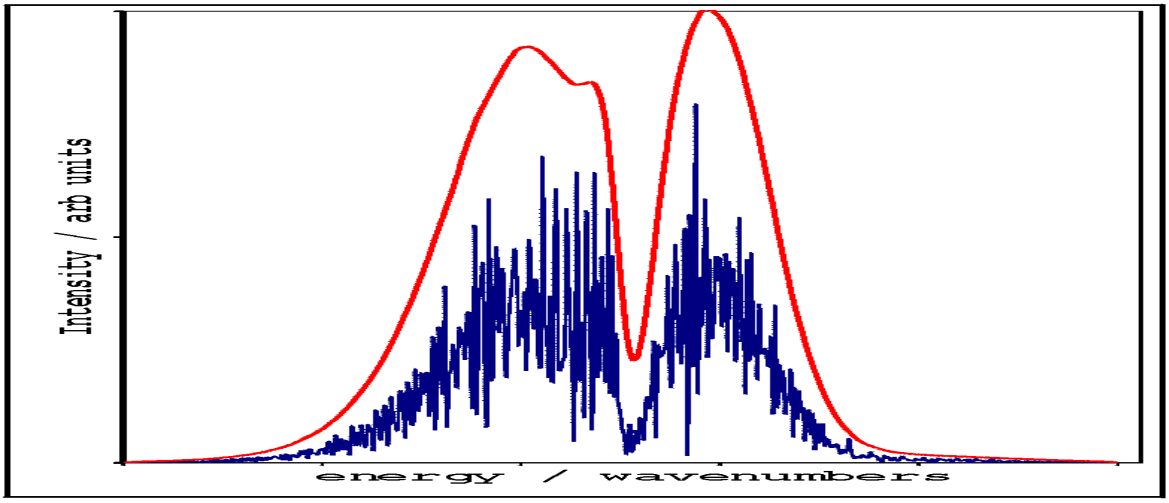


Figure (15) The graph of line width verses intensity

Note: The red curve has a resolution or laser line width that is ten times greater than that of the blue curve. Clearly a lot of information is missing in the red curve!

3.2 Rate Equations

Here we will deal whether there is population inversion, which is the basic necessity of laser or not using rate equation. Rate equation shows that whether there is population inversion or not.

A. Rate Equation for Two Level Systems

Where w_{21} and w_{12} probabilities of spontaneous (A) and stimulated (B) emission respectively

Figure (16) Two level atomic systems

Rate equation for the densities of two states is given by

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2 \quad \text{..... (24)}$$

Here I denotes the intensity.

$B(N_1 - N_2)$ is the total number of stimulated emission.

Again

$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2 \quad \text{..... (25)}$$

Let $\Delta N = N_1 - N_2$, so that $2N_2 = N - \Delta N$

There fore

$$\frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2 \quad \text{..... (26)}$$

This means $\frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$

In steady state $\frac{d\Delta N}{dt} = 0$

Therefore, equation (25) becomes $0 = -2BI\Delta N + AN - A\Delta N$

Rearranging terms, we obtain

$$\Delta N = \frac{N}{1 + \frac{I}{I_{sat}}} \quad \text{..... (27)}$$

Where $I_{sat} = \frac{A}{2B}$ called saturation intensity which plays a key role in laser theory.

From equation (27) one can say that ΔN is always positive, no matter how high I is!

I.e. if $\Delta N > 0$

$N_1 - N_2 > 0$

$N_1 > N_2$

Therefore it is impossible to achieve population inversion in a two level system which means that we can't make laser in two level systems.

B.Rate Equations for a Three Level Systems

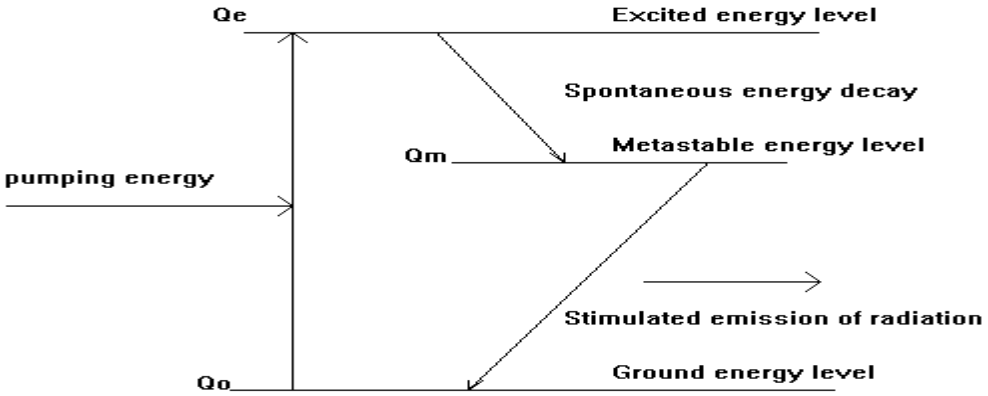


Figure (17) Three level laser energy diagrams [2]

Let N_1, N2, N3 are the number of particles in first, second and third excited states respectively.

$$\frac{dN_2}{dt} = BIN_1 - AN_2 \quad \text{..... (28)}$$

$$\frac{dN_1}{dt} = -BIN_1 + AN_2 \quad \text{..... (29)}$$

Since the decay is fast for level three, N_3 is equal to zero. Let and $\Delta N = N_1 - N_2$ and $N = N_1 + N_2$

Therefore $\frac{d\Delta N}{dt} = -2BIN_1 + 2AN_2$

And it is equal to $\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$ ..... (30)

In a steady state $\frac{d\Delta N}{dt} = 0$

After substituting this in equation (30) and then rearranging terms we obtain

$$\Delta N = \frac{AN - BNI}{A + BI} \quad \text{..... (31)}$$

and finally we obtain

$$\Delta N = \frac{N(1-\frac{I}{I_{sat}})}{(1+\frac{I}{I_{sat}})} \quad \text{..... (32)}$$

Where $I_{sat} = \frac{A}{B}$, ΔN can be positive negative or zero. There fore population inversion is possible for three level systems. That means laser formation is possible for the case of three level systems.

C. Rate Equation for Four Level Systems

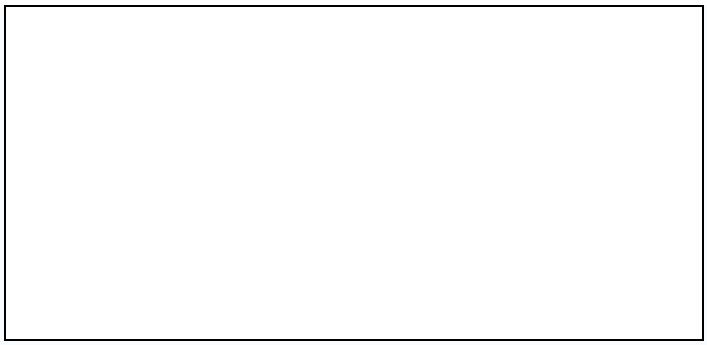


Figure (18) A four-level laser energy diagram [2]

Let $N = N_1 + N_3$

$$\frac{dN_3}{dt} = BIN_1 - AN_3 \quad \text{..... (33)}$$

$$\frac{dN_3}{dt} = BI(N - N_3) - AN_3 \quad \text{..... (34)}$$

Because $N_2 \cong 0$, (due to fast decay)

$\Delta N \cong -N_3$, because $\Delta N = N_2 - N_3$

Equation (34) becomes

$$\frac{-d\Delta N}{dt} = BNI + BI\Delta N + A\Delta N \quad \text{..... (35)}$$

At steady state $\frac{d\Delta N}{dt} = 0$, equation (35) become

$$0 = BIN + BI\,\Delta N + A\,\Delta N \quad \text{..... (36)}$$

Rearranging equation (35) and solving for ΔN, we obtain

$$\Delta N = -\frac{NBI}{BI + A} \quad \text{..... (37)}$$

And finally we obtain

$$\Delta N = -\frac{N\,\dfrac{I}{I_{sat}}}{1 + \dfrac{I}{I_{sat}}} \quad \text{..... (38)}$$

Where $I_{sat} = \dfrac{A}{B}$

Therefore ΔN is always negative which means population inversion occurs for all four level systems. There fore laser formation is possible for all four level systems [1], [10].

3.3 Laser Theory and Operations

In this section we will deal on question like when radiation is emitted? And we will look the connection of color with wavelength.

The color of light is determined by its frequency or wavelength. The shortest wavelengths are the ultraviolet and the longer wavelengths are the infrared.

Electromagnetic radiation is emitted whenever a charged particle such as electron gives up energy. This happens every time when an electron drops from higher energy state, Q_2, to a lower energy state, Q_1.

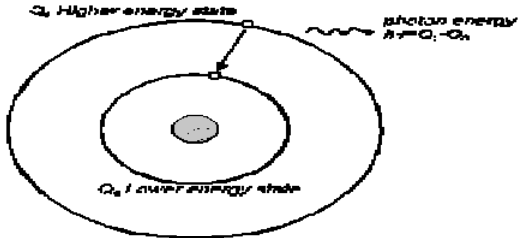


Figure (19) Emission of radiation from an atom by transition of an electron from a higher energy level to a lower energy level [11]

The energy of emitted photon is given by

$E = 2\pi\eta\nu$ …….. (39)

But $\lambda = \frac{c}{\nu}$

Therefore $E = \frac{2\pi\eta c}{\lambda}$ ……..……..……...…… (40)

The difference in energy levels across which an excited electron drops determines the wavelength of the emitted light.

3.4 **How Laser Works?**

In this section we will see the mechanism how laser light is created. The basic requirements for any laser are similar and they all comprise of an active laser medium (gain medium) with a suitable set of energy levels to support laser action. The external energy source can be electricity.

The pump energy is absorbed by the medium, producing excited states. When the number of particles in one excited states exceeds the number of particles in some lower state, population inversion is achieved. In this condition, an optical beam passing through the medium produces more stimulated emission than the stimulated absorption so the beam is amplified. An excited laser medium can also function as an optical amplifier.

1. High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of the atoms in the Ruby crystal to higher energy levels [12], [13].

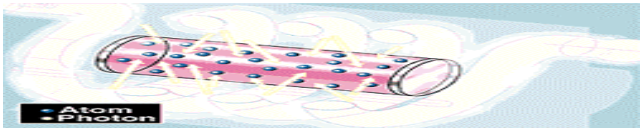


Figure (20) Emission of light in resonator

2. At a specific energy level, some atoms emit particles of light called photons. At first the

photons are emitted in all directions. Photons from one atom stimulate emission of photons from other atoms and the light intensity is rapidly amplified.

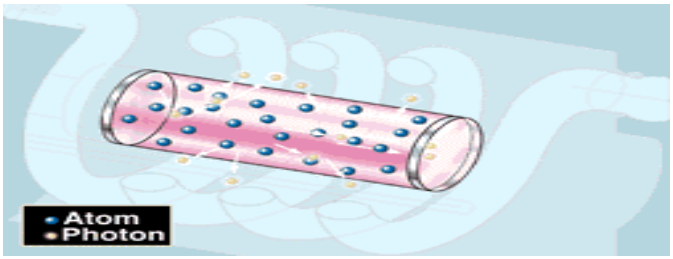


Figure (21) Movement of electrons in resonator

3. Mirrors at each end reflect the photons back and forth, continuing this process of Stimulated emission and amplification.

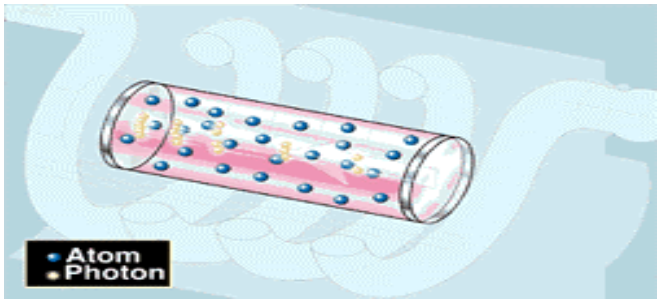


Figure (22) Movement of electrons in resonator

4. The photons leave through the partially silvered mirror at one end. This is laser light.

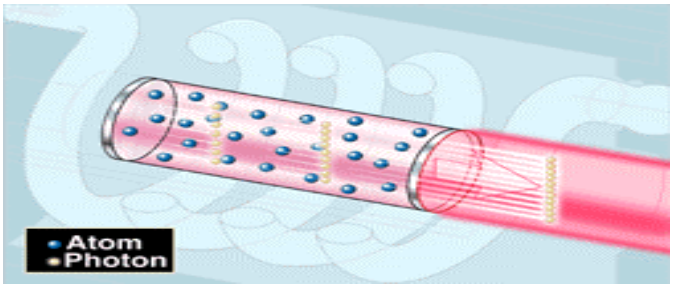


Figure (23) Movement of electrons in resonator

The striking things in laser are:

1. light of single color can enter a transparent substance.
2. different color emerges on the other side.

In the previous section we have seen the way in which laser light is created and its nature. In the coming section let us see the different types of laser with their features.

3.5 Types of Laser

Now let us try to see the different types of lasers and their main features. Depending on the active (lasing) medium there are different kinds of lasers. These are Solid-state laser, Liquid laser, Gas laser, Semi-conductor laser and Excimer laser, Free electron laser [14]. Let us see one by one in detail by starting form the first created laser.

3.5.1 Solid State Laser

Ruby laser, The Nd-YAG laser, The National Ignition Facility (NIF) laser are some of the solid-state lasers [12].

3.5.1.1 Ruby Laser

It is the first working laser to be demonstrated in 1960 by the person called Theodore H. Maiman. It emits short pulse laser light and it is a three level system laser. It also produces the most powerful light pulses.

Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with Chromium atoms. Chromium gives Ruby its characteristic red color and is responsible for the lasing behavior of the crystal. Chromium atoms absorb green and blue light and emit or reflect only red light.

The active medium is a cylindrical crystal of synthetic sapphire (Al_2O_3). It is doped with roughly 0.05%, by weight, Cr_2O_3. With out the Chromium, the crystal is known as Sapphire. The ordinary physical properties of Sapphire and Ruby are identical with the exception of the spectroscopic properties.

Some physical properties of Sapphire and Ruby

Density…….……....3.98g/cm^3

Melting point…….....2040^0c

-

Specific heat

at 20^0c…….0.18cal/g^0c

at 77^0K……0.25cal/g^0c

Thermal conductivity

at 20^0c…….0.092cal/cm^0c.sec

at 77^0K……2,3cal/cm^0c.sec

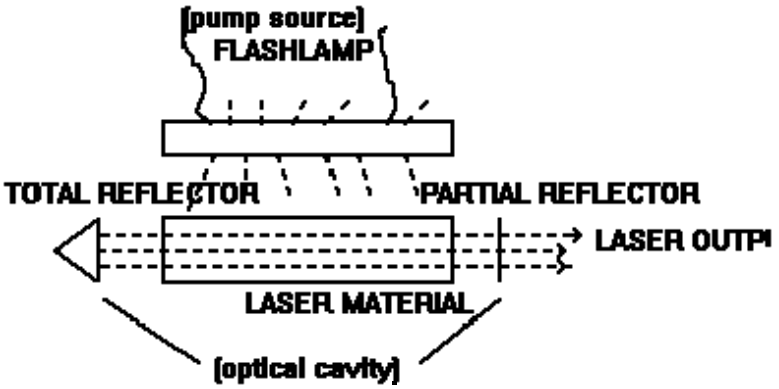


Figure (24) Diagram solid state laser [15]

Note

a. The ends of the rod are polished, flat and parallel. The flatness over the entire end face should vary by no more than a quarter of a wavelength ($\frac{\lambda}{4}$) and both surfaces should be parallel to with in a few seconds of arc.

b. Ruby laser provides the highest out put power of all laser type.

c. Generally preparation of solid laser material is time consuming and expensive.

3.5.1.2 The Nd-YAG Laser

It is an acronym for Neodymium- doped Yttrium Aluminum Garnet. The host material is a crystal of Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$), doped with 0.7% by weight of Neodymium (Nd^{+3}) ions.

Here laser emission takes place at 1.064μm (infrared region). Higher power has been obtained from this laser compared to any other four level materials. At present it is the most widely used solid-state laser [16].

The development of pulsed solid-state laser for industrial applications

The main industrial applications for pulsed solid-state lasers are welding, drilling and cutting. These processes all depend on the sample focusing of a laser beam onto a working piece inorded to cause local melting or vaporization.

3.5.2 Liquid Laser

The use of liquids and gases makes the cooling of the active medium quite simple compared to the cooling of solid lasers, because fluids may be circulated.

A minor disadvantage of liquids as laser materials is their large coefficient of thermal expansion. The linear coefficient of thermal expansion of the liquids suitable for lasers is of the order of one part in one thousand per degree centigrade.

In order to control this expansion we confine the liquid between moveable pistons or attach a coolant.

There are three types of liquid laser. These are Rare-earth chelate laser, Neodymium-Selenium Oxychloride laser and Dye laser.

3.5.2.1 Rare-Earth Laser

The chelates are metallo-organic compounds. A typical chelate is formed when benzolacetonate ions enter in to a combination with a trivalent metal ion.

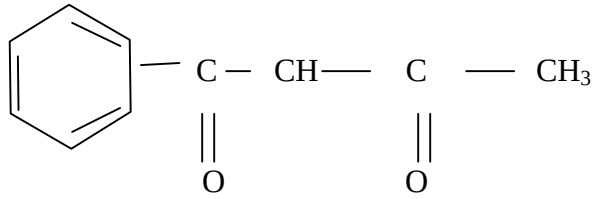


Figure (25) The structure of benzoylacetonate

Chalet lasers have an active material diameter of the order of 1mm. They are excited by a flash in a manner similar to that used for Ruby. An experimental arrangement for the flash excitation of a chelate laser is shown in the figure below.

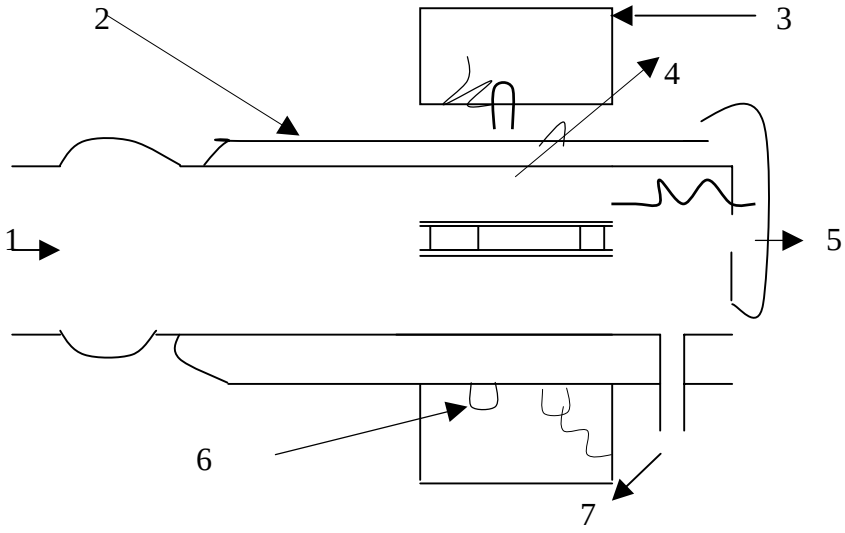


Figure (26) Diagram of chelate laser

The name of the label components of chelate laser are:

1. Coolant gas
2. Vacuum
3. External housing
4. Cell
5. Laser output
6. Gas output
7. Helical flash tube

3.5.2.2 Neodymium-Selenium Oxychloride Laser

Heller and coworkers solved the problem of creating an efficient liquid laser by dissolving Nd in a liquid system, which contains no atoms lighter than oxygen. Liquid neodymium lasers have good efficiency and comparatively low threshold.

A serious disadvantage of this laser is that its solvent is a very dangerous material. It is highly corrosive and very toxic; on contact with the skin it will cause burns and poisoning.

3.5.2.3 Dye Laser

Here the gain medium (active laser medium) is an organic dye molecule that is dissolved in a solvent. Therefore, it is unique laser. The wide gain spectrum of available dyes allows these lasers to be highly tunable, or to produce very short duration pulses (on the order of a few femto seconds).

It is an ideal four level system and a given dye will lase over a range of 100nm. It is very bad for eyes. Dye lasers produce a broad and almost continuous range of colors, most of them in the visible part of the spectrum [17].

How to Design Dye Laser?

The dye laser consisted of a 1cm long quartz glass tube filled with solutions of organic dye such as rhodamine. The dye cell is usually inside a cavity consisting of a partially reflective mirror on the front and a diffraction grating at the rare. In order to vary the wavelength a grating is typically placed in the cavity. A source light is focused on to the dye to excite it and stimulate laser action. The dye lasers provide 3nsec pulses in the spectral range of 360nm to 950nm. Dye laser peak power depends on which dye is used, but typical peak powers are on the order of about 10KW to 20KW.

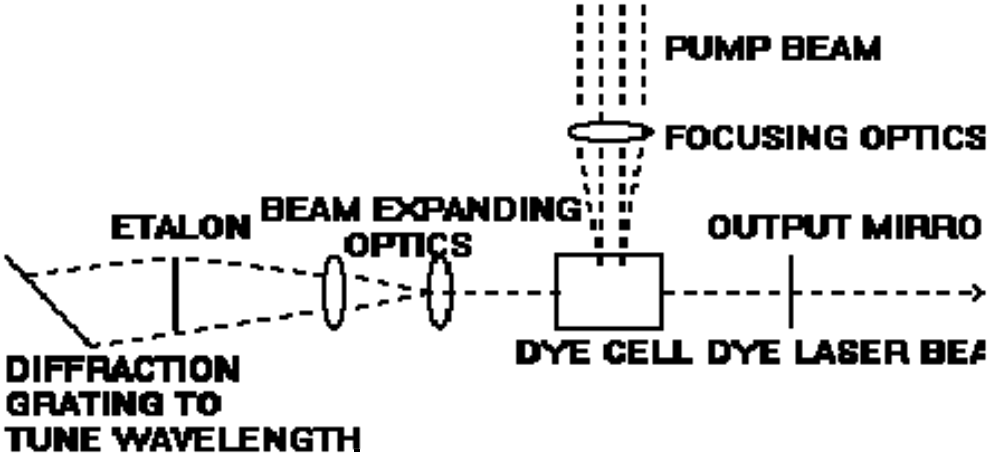


Figure (27) Common dye laser diagram

Energy to excite the dye laser is supplied by a strong light source, either a flash lamp or another laser. The dye will absorb those wavelengths of light that are shorter than those which it emits, since some input energy will always be absorbed in the form of vibrations or heat. The energy absorbed by the dye creates a population inversion, moving the electrons in to an excited state [17].

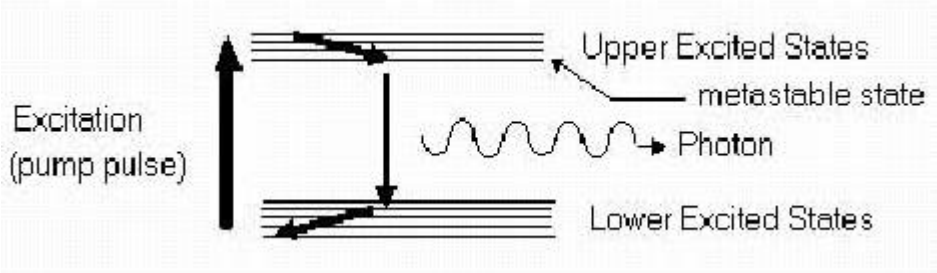


Figure (28) Energy level diagram of a dye laser [17]

Applications of Dye Laser

Dye lasers are particularly well suited for applications in which a precise color is required. Organic dye lasers are becoming increasingly important in spectroscopy, holography, and bi-medical applications. A recent important application of dye lasers involves isotope separation.

3.5.3 Gas Laser

Because gas lasers provide excellent coherence, they are lasers most commonly used in making holograms. But even here some gas lasers are better than others.

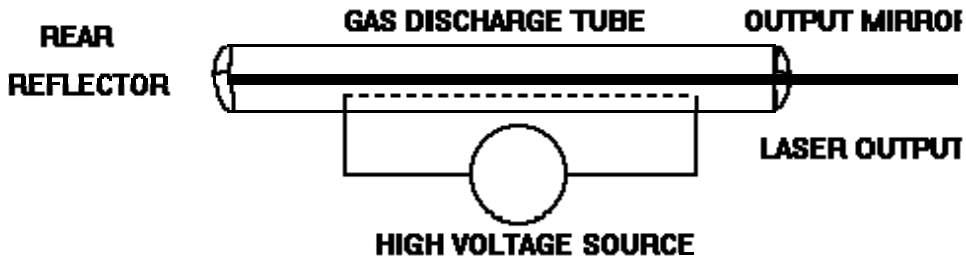


Figure (29) Diagram of gas laser

He-Ne laser, argon-ion laser, carbon dioxide laser, carbon monoxide laser and chemical laser are some of the examples of gas laser [18].

3.5.3.1 The He-Ne Laser

The Iranian physicist Ali Javan together with William Bennet and Donald Herriot invented it in 1960. It is the second working laser system to be demonstrated and it is the first gas laser to produce a continuous out put beam. The active laser medium is a gaseous mixture of He and Ne atoms, in roughly 10:1 proportion.

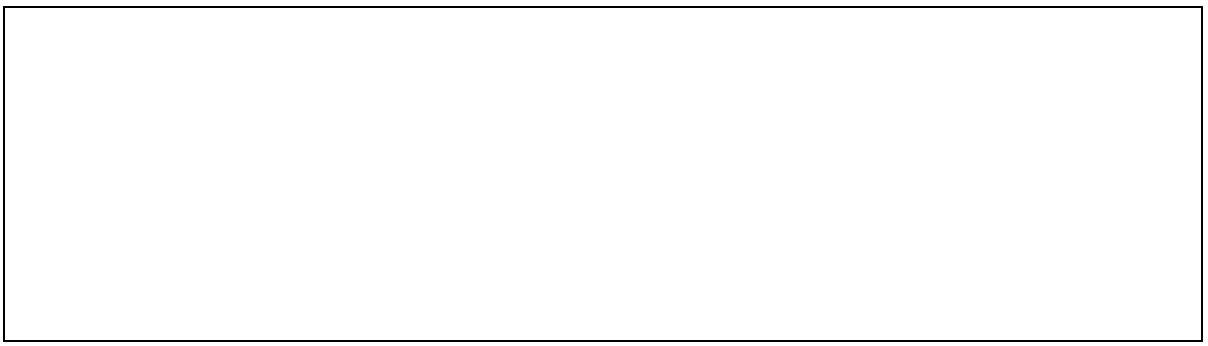


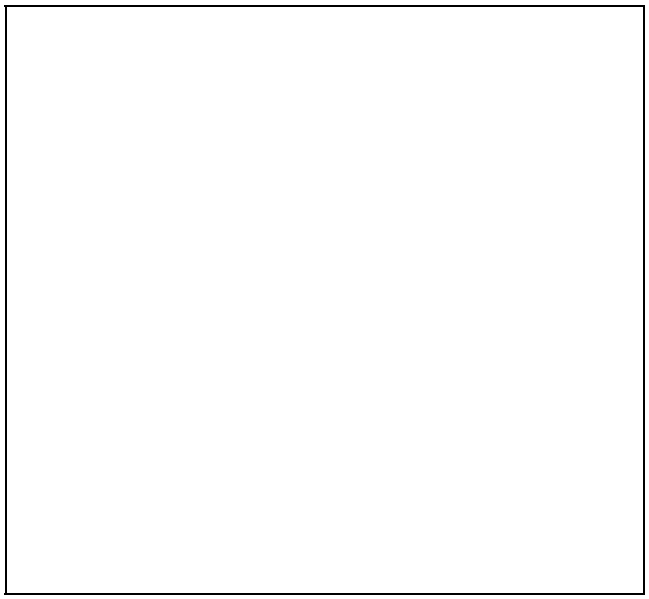
Figure (30) Schematic diagram of a helium-neon laser [12]

The He-Ne laser emittes light with the following properties:

- Wavelength of 633nm (red range).
- Powers in the range of 0.5 to 50mW.
- Beam of divergence about 1m rad.

The He-Ne laser is a four level system laser and very common in education because of its low cost.

Figure(31) A He-Ne laser demonstrated at the Kastler-Brossel Laboratory at Univ. Paris [15]



Figure(32) Energy level diagram of a He-Ne laser [15]

3.5.3.2 The Argon Ion Laser

Unlike the He-Ne laser, the active medium in the argon laser is plasma of excited ions. William Bridges invented it in 1964 at Hughes aircraft and it is one of a family of ion laser that use a noble gas as the active medium. An electron discharge is created in a narrow tube of gaseous argon.

Due to the high energy required to ionize and excite the argon atoms very high current densities are needed of the order of $1Amm^{-2}$.

It emits a light of wavelength 458nm, 488nm or 514.5nm. This laser is used in many applications such as

1. Forensic medicine: This is used to examine the cause of death.
2. Entertainment: For musical concert.
3. General surgery
4. Ophthalmic surgery
5. Holography
6. Optical ‘pumping’ source

3.5.3.3 The Carbon Dioxide Laser

The principal CO_2 laser emits light of wavelength 10.6μm. This is in the far infrared region of spectrum. This laser is favored choice for material processing applications such as cutting, welding and annealing. Unlike most other gas laser, the CO_2 laser has appreciably high efficiency, typically 10 to 15%.

The Carbon Dioxide Laser Resurfacing

How does it work?

Carbon dioxide laser has been used for many years to treat different benign and malignant skin conditions. A new generation of carbon dioxide lasers use very short pulsed light energy (ultra pulsed) or continuous light beams that are delivered in a scanning pattern to very precisely remove thin layers of skin with minimal heat damage to the surrounding structures. These lasers have been successfully used to treat wrinkles and scars as well as other benign skin growths such as warts, linear epidermal nevi (enlarged oil glands on the nose), and other skin conditions.

The field carbon dioxide laser resurfacing is rapidly changing and improving. The ability to rejuvenate sun-damaged, wrinkled skin has been revolutionized by this new technology. Carbon dioxide laser resurfacing is yet another tool in our treatment options, which include Retin-A products, vitamin C lotion, alpha hydroxy acids, chemicals peels, dermabrasion, collagen or fat augmentation, and botulinum toxic for decreasing facial lines and scars. Patients are encouraged to seek out surgeons with documented training and experience in laser surgery [12].

3.5.3.4 The Carbon Monoxide Laser

The potential usefulness of carbon monoxide (CO) laser in aerospaces science and technology is demonstrated by the fact that it is comparable with the argon ions laser in power and better than the carbon dioxide laser in efficiency.

In view of the unique operational requirements of the CO laser, the newly proposed electric field beam excited CO gas dynamic laser seems to be the optimum design for a high power laser since it possesses the potential of having both the high efficiency of an electrically excited CO laser and the high power of a thermally pumped CO laser. There exist many lines of a CO laser that have equal or better transmittance than those of CO_2 laser. Therefore, the CO laser may prove to be a close competitor for the CO_2 laser if, in the future, its output power would match that of the CO_2 laser.

Efficacy of CO Laser in Selectively Intimal Thermal Welding- Implications for Laser Balloon Angioplasty

Excessive vascular damage causes excessive vascular repair, which results in restenosis. To limit the thickness of the coagulation layer in laser balloon angioplasty, we used a carbon monoxide (CO) laser, which has high tissue absorption, as a therapy laser source instead of a Nd: YAG laser. To investigate the benefit of short-penetration CO laser light to vascular tissue, excised human abdominal aorta was irradiated with a CO laser through a 30microns polyethylene membrane. The temperature of vascular tissue was continuously monitored during irradiation. Microscopic examination of aorta, which had been intermittently, irradiated duty ratio 1:2 showed thermal coagulation localized within the intima and a flattened intima surface. These results suggest that intermittent laser irradiation with a CO laser can be used to limit the depth of thermal coagulation, and can selectively weld intima with out excessive thermal damage. Laser balloon angioplasty using a CO laser may help to prevent restenosis.

3.5.3.5 Chemical Laser

The term ‘chemical laser’ describes a device in which population inversion is established as a direct result of a chemical reaction. That means it is powered by a chemical reaction and can achieve high powers in continuous operation. Some of chemical lasers are:

a. Chemical Oxygen Iodine Laser (COIL)

b. Hydrogen Fluoride Laser (2700-2900nm)

c. Deuterium Fluoride Laser (3800nm)

d. All Gas Phase Iodine Laser (AGIL)

a. Chemical Oxygen Iodine Laser (COIL)

It is an infrared chemical laser. It is capable of output power scaling up to mega watts in continuous mode. Its out put wavelength is 1.315μm, the wavelength of transition of atomic iodine. The laser is fed with gaseous chlorine, molecular iodine, and an aqueous mixture of hydrogen peroxide and potassium hydroxide.

The US air force develops it in 1977, for military purposes. However, its properties make it useful for industrial processing as well; the beam is focusable and can be transferred by an optical fiber. COIL is likely to be the laser of choice for the military 'airborne laser' and advanced tactical laser programs.

b. Hydrogen Fluoride Laser

Hydrogen fluoride laser is an infrared chemical laser. It is capable of delivering continuous output power in mega watt range. Hydrogen fluoride laser operates at the wavelength of 2.7-2.9μm. This wavelength is absorbed by the atmosphere, effectively attenuating the beam and reducing its reach unless used in the vacuum [15].

c. Deuterium Fluoride Laser

This laser is different form previous laser only because, hydrogen is replaced by deuterium and it becomes Deuterium Fluoride Laser. It is slightly heavier than hydrogen fluoride laser and it lases at the wavelength of about 3.8μm. This makes the deuterium fluoride laser usable for terrestrial operations.

Deuterium fluoride lasers have found military applications: The miracle laser, the pulsed energy projectile and the tactical high energy lasers are some examples of deuterium fluoride laser.

d. All Gas Phase Iodine Laser (AGIL)

All gas phase iodine laser (AGIL) is a chemical laser using gaseous iodine as a lasing medium. Like the chemical oxygen iodine laser (COIL), it operates at the 1.35μm wavelength. AGIL was developed in order to eliminate the problems with aqueous chemistry of the COILs. AGIL uses a reaction of chlorine atoms with gaseous hydrozic-acid, resulting in excited molecules of nitrogen chloride (NCl), which then pass their energy to the iodine atoms which like the triplet oxygen does in COIL. The iodine atoms then emit the laser radiation itself.

AGIL has numerous advantages over COIL. In the former laser the chemicals are all in gaseous phase, therefore it is easier to work with gases than liquids, especially in micro gravity conditions. The chemicals are also lighter, which is a significant advantage in aerospace applications.

Note: All gas phase iodine laser (AGIL) has a similar construction using all gas reagents, and it is more suitable for aerospace applications [19], [20].

3.5.4 Semi-conductor (Injection) Laser

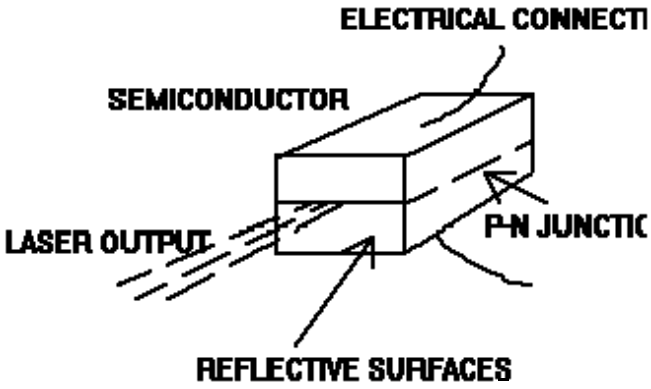


Figure (33) Semiconductor laser diagram

It is some times called light emitting diode laser. Here Silicon and Germanium are not efficient producers of light, rather compounds of semiconductors are better such as GaAs, GaP, and GaAlAs.

It is the third form of laser to be developed. It is similar to the ruby and gas laser except that it employs as its active substance a tiny piece of semi-conductor material.

Semi-conductor laser diodes are formed from heavily doped, pn-junctions and based on modified light emitting diode structure. In order to get laser action, need to ensure high concentration of electron-hole pairs available for recombination. This is achieved by high doping concentrations across junction [21].

Note: A semi-conductor is a material, which is neither a good conductor of electricity nor a perfect insulator.

Semi-conductor (Injection) laser materials and their wavelength

Material	Wavelength (μm)
GaAs	0.84
Ga(AsP)	0.64-0.84
(Ga, In) As	0.84-3.11
(Ga, Al) As	0.64-0.84
InAs	3.11
In (As, P)	0.9-3.11
InP	5.18
InSb	3.11-5.18
GaSb	1.56
PbS	4.32
PbTe	6.5 (at 12^0K)
PbSe	8.5 (at 12^0K)
PbSe	39 (at 77^0K)
(Pb, Sn)Te	6.28
(Pb, Sn)Se	8.31

3.5.5 Excimer Laser

Excimer laser is a shortened form of ‘excited dimmer’, denoting the fact that the lasing medium in this type of laser is an excited diatomic molecule. The excimers used are typically

those formed by rare gases and halogens in electron-excited gas discharges. Molecules like Xe, F are stable only in their excited states and quickly dissociate when they make the transition to their ground state. This makes possible large population inversion because the ground state is depleted by this dissociation. However, the excited states are very short-lived compared to other laser metastable states, and lasers like the XeF excimer laser require high pumping rates. Excimer lasers typically produce high power pulse out puts in the blue or ultraviolet after excitation by fast electron beam discharges [23].

XeF Excimer Laser

The rare gas Xenon and the highly active Fluorine seem unlikely to form a molecule, but they do in the hot plasma environment of an electron beam initiated gas discharge. They are only stable in their excited states, if ‘’stable’’ can be used for molecules, which undergo radioactive decay in 1 to 10 nanoseconds. This is long enough to achieve pulsed laser action in the blue green over a brand from 450 to 510nm, peaking at 486nm.

3.5.6 Free Electron Laser (FEL)

Free electron lasers are based up on stimulated radiation generated by electrons moving at relativistic velocities. Two main types can be distinguished:

a. The electromagnetic wave interacts with individual charges in the Stanford FEL or in Smith Purcell effect FEL.

b. The electromagnetic wave interacts with a propagating space-charge wave. The important characteristics and possible performance data are summarized in the following table [9].

In the case of free electron lasers:

1. Operating frequency does not depend upon bound energy levels of atoms or molecules.
2. Frequency tunable by variation of electron energy by periodicity of electron oscillation frequency.
3. High average output power (>10KW).
4. High efficiency (>10%).
5. Radiation generated over EM spectrum from $100A^0$ to ~ 1mm.
6. Generating mechanism is reversible from laser to electron acceleration.

7. Miniaturization inside crystal should be possible eventually.

We have seen the different types of laser and their difference among them. Now let us see how the advancement of laser brings some challenge to the world.

3.6 Applications of Laser

Lasers now make up a large part of the technology in today's world. They can be used in an enormity of ways and to this day, new lasers are being developed for a variety of different uses. The main uses of lasers are listed below [23].

- In guidance system: for example in aircraft.
- In data transmission, reception and processing.
- In telecommunication.
- In industry such as for welding, drilling and cutting materials.
- In medicine for surgery.
- In education for the presentation.
- To construct airborne laser which destroy other plane and change to ash.
- It used for visual effects during a musical performance.
- It used to store and retrieve data from compact discs (CD) and DVD's.
- It used to measure distances and velocities with extremely high accuracy.
- To detect internal stresses.
- To detect defects in the framework of non-destructive structural control techniques.
- To detect weak under ground shocks.
- To measure drift of continents.
- To separate isotope.
- To treat different benign and malignant skin conditions [9].

Note: LASIK is a type of laser surgery that can correct certain types of "refractive errors" — the reduced ability to focus (or "refract") light. The letters L-A-S-I-K are shorthand for the full name of the operation, which is Laser Assisted in Situ Keratomileusis. While LASIK isn't a cure-all, it is the state-of-the-art treatment for certain types and degrees of vision correction [24].

CHAPTER FOUR

Laser Safety, Problems in Near Future and Recent Development and Activities in Laser

As science progresses, laser technology achieves a remarkable development. As laser technology progresses, the incident of the human body exposed to the danger of the laser beams is increasing. First, Yamamoto Kogaku has developed laser safety goggles and glasses for workers associated with the operation of laser instrument. In addition to the above, it has also developed a "Laser Eye Safety" series which comprise 3 types of shapes, that is, (1) Box type (2) Movable panel type (3) Closed room type, and "Laser Barrier Curtain" made from the unique carbon fiber as safety zone measure products associated with laser processing with making direct radiation of high power lasers and equipment laboratory test in the academic institute.

In the coming section we will see the disadvantage of laser. The fields to which lasers make a significant contribution are growing in parallel with the progress in the domain of laser technology. In some fields lasers already have a high standing, in other areas only first applications have appeared, while in still other ones the possibilities of their application are only at the appraisal stage.

One of the most pressing and important problems, and one that is being solved now, is that of controlled nuclear fusion. Very serious arguments point to the possibility of successful solution of this problem if super powerful laser pulses are used. This approach is under scrutiny in the USSR, USA, and other countries.

Anther important problem is connected with the need to increase the speed of operation and the memory capacity of computers. This is demanded by the needs of scientific and industrial progress, and by the necessity to manage industry and economy of the country as a whole [4]. The spectroscopy group at the Materials Physics Laboratory has a long experience on applying non-linear laser methods to basic research on atomic and molecular physics as well as on studies of more applied nature. For several years, the main topic of

research in the group was work on laser diagnostics of combustion processes. Particular attention was paid to developing sensitive resonance methods for molecular trace species detection in the flame field with high spatial resolution. The group made pioneering work on applying the methods of polarization spectroscopy and forward four-wave mixing to studies of trace concentrations of real combustion products, such as short-lived radicals in flame environments. Among these techniques, polarization spectroscopy has recently gained considerable attention in the literature as a viable method of combustion diagnostics. During the past year our activity in flame studies has been geared down with our expert in diagnostic techniques, Dr. Kaj Nyholm, moving to work at the Combustion Centre, Lund University, Sweden. In 1996, the research in the spectroscopy group concentrated on the realization of a pulsed laser mirror for thermal atomic beams. At the same time, preparations for a new major research initiative on nano-optics were intensified. Also, the work on the development of polymer-host based solid-state dye lasers and on the preparation of photo luminescent porous silicon was continued.

The study of laser-induced porous Silicon structures initiated in 1995 has been pursued in collaboration with V. Svrcek on a visit from Comenius University, Bratislava (now at the University of Innsbruck). This project has benefited from the student exchange programme IAESTE. Photo luminescent and electroluminescent porous Silicon has attracted much interest because of its potential applications as a new material for optoelectronics. However, the fabrication procedures of this material, usually prepared by electrochemical or photo-assisted etching, have suffered from a lack of precise control of the process parameters. We have experimentally studied the creation of porous structures in n-type doped monocrystalline Si wafers using purely laser-induced photo-etching in hydrofluoric acid, in contrast to conventional techniques based on external current sources. This investigation included the dynamics of induced photocurrent and a comparison of the photo-etching efficiency at various laser wavelengths, as well as the photoluminescence properties and spectral characteristics of the resulting porous structures. Purely laser-based etching may provide new insight into the formation process and a step towards improved spectral homogeneity and a

more accurate parameter control. Further progress in porous silicon preparation should bring this material closer to applications in optoelectronics micro components [26].

Nano-carbon as lighting source is demonstrated in this paper. The characterized nano-radiation from nano-carbon, excited by different lasers in vacuum, is observed when laser intensity is over a threshold. With lower excitation threshold and smaller white light source, nano-carbon is more applicable to be as lighting system than the others in scientific experiments. White light emission of nano-carbon induced by more practicable electromagnetic excitation (microwave) is also demonstrated, which is caused by the faradic heating of the metal substrates, with molecular spectra and better color rendering. Lighting systems comprised of nano-carbon may become one of the considerable directions in optics [27].

PART B: NON-LINEAR OPTICS

CHAPTER ONE

1.1 What is the Origin of the Term Non-Linear Optics?

In this section we will see from where the word linear and non-linear optics came. If the laser radiation is sufficiently intensive (so that optical characteristics are functions of light intensity), susceptibility χ stops being constant and becomes a function of field strength E in the light wave.

Theory shows that in the first approximation of this function can be expressed as a sum.

I.e. $\chi(E) = \chi_0 + \chi_1 E + \chi_2 E^2 + ...$ ..... (41)

Where χ_0, χ_1, χ_2..... are parameters of a medium characterizing its polarizability.

Note that all optical characterization of the mediums not only susceptibility but also dielectric permittivity and refractive index become functions of field strength in sufficiently intensive light fields.

We recall that polarization is given by

$P = \chi E$ ..... (42)

Substituting equation (41) in to (42), we obtain

$P = \chi_0 E + \chi_1 E^2 + \chi_2 E^3 + ...$ ..... (43)

Equation (43) shows nonlinear with respect to field strength in the light wave. Hence the term non-linear optics.

If the field of strength in the light field is sufficiently low, only the first term can be retained and equation (43) becomes

$P = \chi_0 E$ ..... (44)

This situation precisely corresponds to the pre-laser optics. Polarization of the medium is described by a linear formula given by equation (44).

Hence the term linear optics.

The relation between wave field strength and polarization of the medium is therefore linear if the light wave strength is relatively low; the medium's polarizability is represented then by the parameter χ_0 called the linear susceptibility. If, however, the light field strength in the laser beam is sufficiently high, the relation in question becomes non linear; additional parameters (χ_1, χ_2.....) referred to as nonlinear susceptibility and then required to describe polarizability of the medium [4].

Non-Linear Polarization of the Medium Allows Mixing of Frequency

Let the polarization of a non-linear medium be

$$P = \chi_0 E + \chi_1 E^2 \text{..... .....……. (45)}$$

We assume that two coherent light waves with unequal frequencies are incident on the medium; $E_1 \cos(2\pi\nu_1 t)$ and $E_2 \cos(2\pi\nu_2 t)$. If the sum of these waves

$E = E_1 \cos(2\pi\nu_1 t) + E_2 \cos(2\pi\nu_2 t)$ is substituted in equation (45), the final expression for the polarization of the medium will contain a term

$$P_{1,2} = 2\chi_1 E_1 E_2 \cos(2\pi\nu_1 t)\cos(2\pi\nu_2 t) \text{ ……. (46)}$$

Making use of relation $2\cos\alpha\cos\beta = \cos(\alpha+\beta) + \cos(\alpha-\beta)$, we transfer equation (46) to the following

$$P_{1,2} = \chi_1 E_1 E_2 \cos(2\pi(\nu_1+\nu_2)t) + \chi_1 E_1 E_2 \cos(2\pi(\nu_1-\nu_2)t) \text{ ……..…… (47)}$$

The fact that the expression for non-linear polarization of the medium contains the term (47) means that light can be re-emitted at the frequency $\nu_1 + \nu_2 and \nu_1 - \nu_2$.

Hence, non-linear mediums make it possible to realize summation and subtraction of light wave frequencies. Here we saw what non-linear and linear optics mean. In the coming section we try to compare the linear and non-linear optics.

1.2 Comparison of Linear Optics (LO) and Non-Linear Optics (NLO)

Here let us try to compare linear and non-linear optics using table.

Linear optics	Non linear optics
$P=\varepsilon\chi_{ij}^{(1)} Ej$, Where: ε is permitivity of free space $\chi_{ij}^{(1)}$ is linear susceptibility.	Using power series, polarization can be expanded as $P= \varepsilon(\chi^{(1)} E+ \chi^{(2)} E.E+ \chi^{(3)} E.E.E\ldots.)$ Where $\chi^{(1)}$, $\chi^{(2)}$, $\chi^{(3)}\ldots.$ are n^{th} orders of non-linear susceptibility.
The magnitude of the electric field is small.	The magnitude of the electric field is large.

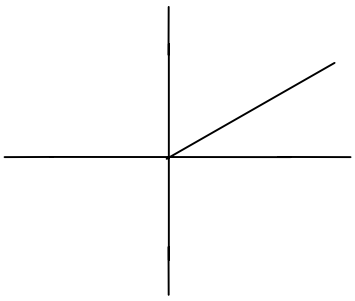
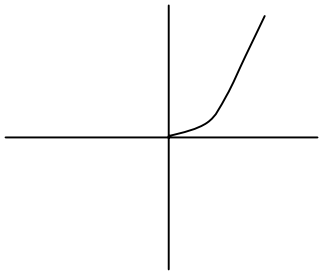
 The graph of polarization(Vertical Axis) (Horizontal Axis) in case of LO.	 The graph of polarization (Vertical Axis) versus electric field (Horizontal Axis) in case of NLO

Table (1) Comparison of LO and NLO

1.3 Can the Optical Properties of a Medium Depend Up on the Intensity of the Radiation?

Let us see the relation between the optical property of a medium and the intensity of radiation. The electric field of light waves is ‘’gaining strength’’. Nothing was said until now about optical characteristics of the medium as function of the light wave intensity. Before the advent of the laser, incoherent optics correctly assumed that optical parameters of mediums are independent of the intensity of the light propagating in these mediums. The essential fact is that the electric fields strength in fields emitted by non laser light sources is always much

smaller than field strengths of interatomic and atomic electric fields. Non-laser light sources generate fields with electric field strength not exceeding 10*Exp (3) v/cm, while atomic fields are characterized by field strengths of the order of 10*Exp (7) to 10*Exp (10) v/cm. It is only natural that with this ratio of field strengths, the light wave is not intensive enough to affect atomic fields and with them the optical parameters.

It has been necessary therefore, to take account of the dependence of optical characteristics of the medium on the intensity of light wave propagating in it. This necessity forms something of a ‘’watershed’’ between the old (pre-laser) and the new (laser) optics. It is customary to refer to the former as the linear, and to the later as the non-linear optics. It must be emphasized that dependence of optical parameters of the medium on the intensity of the light wave constitutes the most characteristics feature of nonlinear optics, one that distinguishes it from the linear optics [4].

CHAPTER TWO

Frequency Mixing Processes

These are processes in which obtaining different kind of light by mixing frequency of light in different ways. These processes are Sum Frequency Generations (SFG), Difference Frequency Generation (DFG), Parametric Amplification, Parametric Oscillation, Parametric Generation, Spontaneous Parametric Down Conversion (SPDC) and Optical Rectification.

- **Sum Harmonic Generation (SHG)**

This is the generation of light with a frequency that is the sum of two other frequencies. One of the most commonly used sum frequency generation is frequency doubling (halved the wavelength) or Second Harmonic Generation (SHG). With this technique, the 1064nm out put from Nd: YAG lasers (it is an acronym for Neodymium-doped Yttrium Aluminum Garnet) or 800nm out put from Ti: Sapphire lasers which emits near infrared light can be converted to visible light, with wavelength of 532nm (green) or 400nm(violet) respectively.

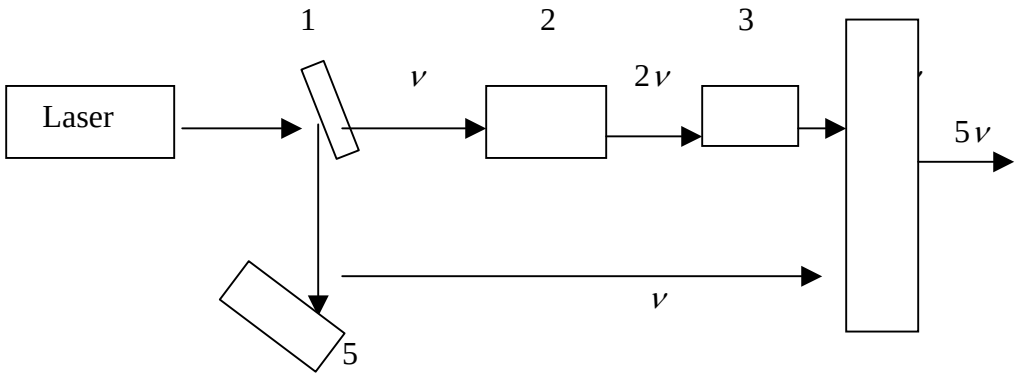


Figure (34) Diagram of sum harmonic generation [3]

The numbers in the figure (34) represent

1. Semitransparent Mirror
2. Second Harmonic Oscillator
3. Second Harmonic Oscillator
4. Frequency Oscillation Converter
5. Mirror

Laser emits a wave with frequency ν. After passing the wavelength through two-second harmonic oscillators we obtain a wave with frequency 4ν that is the fourth optical harmonic. Mixing this harmonic with initial signal (i.e. summing up $4\nu + \nu = 5\nu$) we obtain the fifth optical harmonic [4].

- **Difference Frequency Generation (DFG)**

It is the generation of light with frequency that is the difference between two other frequencies.

- **Parametric Amplification**

It is the amplification of signal input in the presence of a higher frequency pump wave, at the same time generating an idler wave.

- **Parametric Oscillation**

It is the generation of signal and idler wavelength using a parametric amplifier in a resonator (with no signal input). Let us see using diagram.

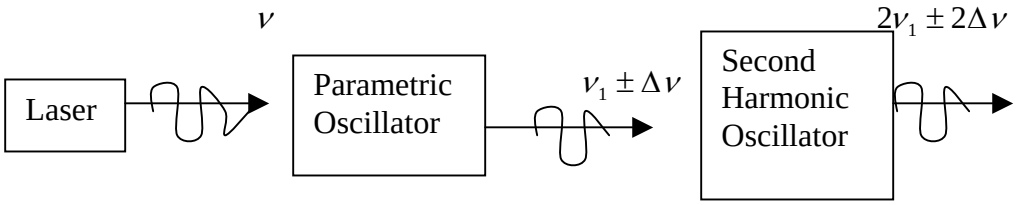


Figure (35) parametric oscillation

A laser emits a coherent light wave with frequency ν. This wave is used to pump the parametric oscillators, which emits radiation than can be continuously tuned in some frequency range, form $\nu_1 - \Delta\nu$ to $\nu_1 + \Delta\nu$. The out put of the second harmonic oscillator; the final result is a coherent radiation with frequency continuously tunable from $2\nu_1 - 2\Delta\nu$ to $2\nu_1 + 2\Delta\nu$ [4].

- **Parametric Generation**

It is like parametric oscillation but with out resonator, using a very high gain instead.

- **Spontaneous Parametric Down Conversion**

This is the amplification of the vacuum fluctuations in the low gain regime.

- **Optical Rectification**

This is the generation of quasi-static electric fields [23].

2.1 Theory

A number of non-linear optical phenomena can be described as frequency mixing processes. If the induced dipole moments of the material respond to applied electric fields, the dielectric polarization (dipole moment per unit volume) P at a time t in a medium can be written as a power series in the electric field,

$$P(t) \alpha \chi^{(1)} E(t) + \chi^{(2)} E^2(t) + \ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (48)$$

Here, the coefficients $\chi^{(n)}$ are the n^{th} order susceptibilities of the medium. For any wave mixing processes, the second order term is crucial: it is the only nonzero in media that have broken inversion symmetry.

If we write $E(t) = E_1 \exp(i\omega_1 t) + E_2 \exp(i\omega_2 t) + C.C$ ...……...……..... (49)

Where $C.C$ denotes complex conjugate of $E_1 and\ E_2$,

$E_1 and E_2$ are the incident beams of interest.

The second order term of polarization will be

$$P^{(2)} \alpha \sum_{n_0, n_1, n_2, m, m_2, l} \chi^{(2)} n_0 E_1^{n_1} E_2^{n_2} (c.c)^l \operatorname{Exp} i(m_1 \omega_1 + m_2 \omega_2) t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (50)$$

Where the summation is over

$$(n_0, n_1, n_2, m_1, m_2, l) = (1,2,0,2,0,0), (1,0,2,2,0), (2,1,0,1,0,1), (2,0,1,0,1,1), (1,0,0,0,0,2), (2,1,1,1,1,1)$$

The six combinations (n_x, m_x) correspond, respectively, to the second harmonic of E_1, the second harmonic of E_2, the optical rectified signals of E_1 and E_2, the difference frequency, and the sum frequency. A medium that is thus pumped by the fields E_1 and E_2 will radiate a field E_3 with an angular frequency $\omega_3 = m_1 \omega_1 + m_2 \omega_2$[9].

2.2 Phase Matching

The above electric field expression ignores the position dependence of the electric fields. In typical situation, the electric fields are traveling waves and described by:

$E_j(\omega,t) = \exp(i(\omega_j t - K_j x)$, at a position x, with the wave vector $K_j = \frac{n(\omega_j)\omega_j}{c}$, where c is the speed of light, $n(\omega_j)$ the index of refraction of the medium. At angular frequency ω_3 the second order term of the polarization can be written as

$$P^{(2)}(x,t) \alpha E_1^{n_1} E_2^{n_2} (\exp(i(\omega_3 t - (m_1 K_1 + m_2 K_2).x))) \quad \text{..... (52)}$$

at each position x, the oscillation second order polarization radiates at angular frequency ω_3 and a corresponding wave vector is given by

$$K_3 = \frac{n(\omega_3)\omega_3}{c} \quad \text{..... (53)}$$

Constructive interference, and therefore a high intensity ω_3 field, will occur only if

$$K_3 = m_1 K_1 + m_2 K_2 \quad \text{..... (54)}$$

The above equation is known as the phase matching condition [23].

2.3 Optical Phase Conjugation

Comparison of phase conjugate mirror with a conventional mirror

With the phase conjugate mirror, the image is not deformed when passing through an aberrating element twice. It is possible, using non-linear optical processes to exactly reverse the propagation direction and phase variation of a beam of light. The reversed beam is called a conjugate beam, and thus the technique is known as optical phase conjugation also called time reversal, wave front reversal and retroreflection.

A retroreflectior is a device that sends light or other radiation back to where it comes from regardless of the angle of incidence, unlike a conventional mirror, which does that only if the mirror is exactly perpendicular to the light beam.

2.4 Application of Phase Conjugate Optics

1. Phase distortion correction
2. Group velocity dispersion correction; channel dispersion and pulse broading in fibers.

3. Real time holography and data processing

4. Pulse shaping and grating.

2.5 Common Second Harmonic Generation (SHG) Materials

Material	Wavelength	Chemical name
$LiIO_3$	806nm	Lithium Iodate
$KNbO_3$	806nm	Potassium Neobdate
$KNbO_3$	980nm	Potassium Neobdate
KDP	1064nm	Potassium Diphospate

Table (2) Common second harmonic generation materials

CHAPTER THREE

3.1 Other Non-Linear processes

a. Optical Kerr effect

b. Raman Scattering

c. Brillouin scattering

a. Optical Kerr Effect

John Kerr, a Scottish Physicist, discovered the Kerr effect in 1875. Here the intensity dependent refractive index exists. The Kerr effect or the quadratic electro-optic effect is a change in the refractive index of a material in response to an electric field. It is distinct from the Pockels effect in that the induced index change is directly proportional to the square of the electric field instead of the magnitude of the field. All material shows a Kerr effect, but certain liquids display the effect more strongly than other materials do.

b. Raman Scattering

It is also called Raman Effect. It is the in elastic scattering of a photon, which creates or annihilates an optical phonon.

When light is scattered from an atom or molecule most photons are elastically scattered (Rayleigh scattering). The scattering photons have the same energy, which means the same frequency and therefore, wavelength as the incident photons. However, a small fraction of light (approximately 1 to 10^7 photons) is scattered at optical frequencies different from incident photon and usually lower than the frequency of the incident photon.

c. Brillouin Scattering

Here there is interaction of photons with acoustic photons. This occurs when light in a medium (such as water or crystal) interacts with density variations and changes its path. The density variation may be due to acoustic modes such as photons, or temperature gradients. As described in classical physics, when the medium is compressed its index of refraction changes and the light's path necessary bends.

3.2 Self Focusing Phenomena in Non-Linear Optics

Definition: focusing of a beam, caused by the beam itself through a nonlinear process

Due to a Kerr lens, an intense optical pulse propagating in a nonlinear medium can experience self-focusing: the beam diameter is decreased compared to that of a weak pulse. This can have important consequences:

As the decrease of the beam diameter further increases the strength of the Kerr lens, there may be total collapse of the beam size, leading to very high optical intensities which can

easily destroy the optical medium (→ optical damage). This typically occurs when the nonlinear phase shift on the beam axis (called the B integral) significantly exceeds 1 rad.

The reduction of beam size for high intensities can be used for Kerr lens mode locking of a laser, when it leads to a better overlap of laser and pump beam, or to reduced losses at some aperture.

3.3 Related Processes

In these processes, the medium has a linear response to the light, but the properties of the medium are affected by the other cases:

- Pockel's effect: Here the refractive index is affected by a static electric field, used in electro optics modulator.
- Acousto-optics: Here the refractive index is affected by acoustic wave (ultrasound); used in acousto-optic modulator.

Pockel's Effect

This is the production of bi-refringence in an optical medium induced by a constant or varying electric field. It is distinguished from the Kerr effect by the fact that the bi-refringence is proportional to the electric field, where as in the Kerr effect it is quadratics in the fields. The Pockel's effect occurs only in crystal that lack inversion symmetry, such as Lithium Niobate or Gallium Arsenide.

3.4 What are Non-Linear Materials?

We are concerned with the investigation and development of nonlinear optical (NLO) materials, primarily for two material categories:

1. NLO crystals for laser sources and
2. Electro-Optic (EO) films for guided-wave photonics.

Our approach to research and development is to use our in-house team to identify and screen new materials for development. Contractors perform actual development with critical technical support seamlessly provided by our in-house scientists. In this way, the technology ultimately resides in the commercial sector. NLO crystals allow us to efficiently convert light from well-established lasers to light with a longer or shorter wavelength, chosen to satisfy the specific application. Due to a number of diverse applications, several classes of NLO materials are being addressed. However, our program primarily focuses on the mid- and far-infrared regions since our foremost concern is to enable infrared countermeasures for protecting aircraft and laser radar systems for the remote detection of chemical and biological agents. We have had a number of successes, the most important being highly transparent zinc germanium phosphide for mid-IR applications. Additional successes include extending the transparency range and laser-damage resistance of the potassium titanyl phosphate family of compounds for visible through mid-IR uses and significantly improved cadmium germanium arsenide for far-IR utility.EO films are required to enable photonic technology for optical data links between satellites and for advanced data-handling architectures on satellites and aircraft. The same materials also enable the photonic control of phased-array radar and phased-array antennas that promise weight, space, and power savings as compared with electronic approaches. The nearer-term solution is EO polymers for which the program's emphasis is on developing material processing techniques and material structures that will enable the fabrication of high-performance optical modulators. Our researchers hold patents and have authored the first publications for optical waveguide structures utilizing conducting cladding layers, a concept that has been demonstrated to provide the highest electric-field poling efficiency known in a multi-layer structure and that promises reduced operating voltages by more than an order of magnitude. Longer-term solutions include electro-optic nano composites with which one of our scientists was the first to experimentally demonstrate a significant enhancement of the electro-optic coefficient [32].

3.5 Some Non-Linear Optical Materials

Chemical formula	Chemical name

$Bi_4Ge_3O_{12}$	Bismuth germinate
$CsLiB_6O_{10}$	Cesium lithium borate
$K_2Al_2B_2O_7$	Potassium Aluminum
$LiNbO_3$	Lithium borate
$LiTAO_3$	Lithium tantalate
KH_2PO_4	Monopotassium phosphate
Nd: YAB (YAl_3 (BO_3) $_4$)	Yttrium aluminum borate
Nd: YCOB	Yttrium cobalt borate
$C_6H_5NO_2$	Nitrogen benzene
$KTiPO_4$	Potassiumtitanyl phosphate
TeO_2	Tellurium dioxide
Y_3Fe_2 (FeO_4) $_3$	Yttrium ion garnet
ZnTe	Zinc telluride

Table (3) Some NLO materials

3.6 Applications of Non-Linear Optics

Non-linear optics allows us to

- Change the color of light beam.
- Change the shape of light in space and time.
- Create the shortest events ever made by man.
- To produce a coherent light.

- Industry
- Medicine
- Entertainment
- Remote sensing and analysis
- Basic research
- Others, including instrumentation, image recording, inspection, military, optical data storage, and Laser Radar (LIDAR)
- Telecommunications

Actually, the applications of non-linear optical materials can be divided into two main categories, which include all the applications listed above:

-Electro-optics and lasers-it includes industry, medicine, entertainment, remote sensing, basic research, and "others"

-Telecommunication [25].

3.7 What are Non-Linear Crystalline Materials?

Transparent crystalline crystal materials can exhibit different kinds of optical nonlinearities which are resulting from a nonlinear polarization. For example, media with a $\chi^{(2)}$ nonlinearity are mainly used for parametric nonlinear frequency conversion (e.g. in frequency doublers and optical parametric oscillators) and for electro-optic modulators, while $\chi^{(3)}$ nonlinearities lead to the Kerr effect, the Raman effect, and four-wave mixing.

Relevant Properties of Nonlinear Crystal

Considering $\chi^{(2)}$ media, a lot of different properties of nonlinear crystals are of importance for applications. The most basic ones are:

- the magnitude of the nonlinear coefficients d_{ijk}: important particularly if the achievable optical intensities are low

- the dispersion and birefringence properties: together with the nonlinear tensor components, these determine possibilities for phase matching and the phase-matching bandwidth, angular acceptance (for critical phase matching), etc.
- the wavelength range with good optical transparency for all involved wavelengths

However, additional properties can be relevant for a comparison:

- the material's potential to be periodically poled to achieve quasi-phase matching
- the resistance against optical damage (e.g. gray tracking) (often quantified as a damage threshold, e.g. in terms of a maximum optical intensity for a given wavelength and pulse duration, although short-wavelength light may also induce long-term damage without a well-defined damage threshold)
- the resistance against photorefractive effects (which are often called "photorefractive damage", even though this is usually reversible)
- the availability of crystals with consistently good quality, large size and a reasonable price
- the ease of fabricating high-quality anti-reflection coatings on the crystals
- the chemical durability; e.g., some crystal materials are hygroscopic, others undergo chemical changes when heated in a vacuum chamber for application of a dielectric coating

Frequently Used $\chi^{(2)}$ Nonlinear Crystal Materials

- lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$): materials with a relatively large nonlinearity; often used for nonlinear frequency conversion and for electro-optic modulators; available in congruent and in stoichiometric form; periodic poling possible; low damage threshold; tendency for photorefractive effects (annoying for frequency conversion, but used e.g. for holographic data storage in Fe-doped $LiNbO_3$ crystals, and reduced photorefractive tendency with MgO doping and/or stoichiometric composition)

- borates like lithium triborate (LiB_3O_5 = LBO), cesium lithium borate (CLBO, $CsLiB_6O_{10}$), beta barium borate (beta-BaB_2O_4 = BBO, strongly hygroscopic, often used in Pockels cells), strontium beryllium borate (SBBO, $Sr_2Be_2B_2O_7$), cesium borate (CBO), yttrium calcium oxyborate (YCOB, also available as laser gain medium), and BiB_3O_6 = BIBO: good media for green and blue laser sources, UV generation (good transparency at short wavelengths and suitable phase-matching options), broadly tunable optical parametric oscillators and optical parametric chirped-pulse amplification
- potassium titanyl phosphate (KTP, $KTiOPO_4$), which may be flux-grown (cheaper) or hydrothermal (better for high powers, lower tendency for gray tracking); periodic poling possible
- similar materials (also belonging to the "KTP family") are KTA ($KTiOAsO_4$), RTP ($RbTiOPO_4$) and RTA ($RbTiAsPO_4$); relatively high nonlinearities; periodic poling possible
- potassium dihydrogen phosphate (KDP, KH_2PO_4) and potassium dideuterium phosphate ($KD*P$, KD_2PO_4): available in large sizes at low price; good homogeneity; high damage threshold; hygroscopic
- potassium niobate ($KNbO_3$): very high nonlinearity; used e.g. for frequency doubling to blue wavelengths and in piezoelectric applications
- Zinc germanium diphosphide (ZGP, $ZnGeP_2$), silver gallium sulfide and selenide ($AgGaS_2$ and $AgGaSe_2$), and cadmium selenide (CdSe): used for mid-infrared and (partially) for terahertz generation [33].

Conclusion

In the first part of this conclusion, I try to summarize the development of laser, how this technology has a great role on the world. In the second part of the conclusion, I try to mention the importance of non-linear optics for the production of laser and the connection of non-linear optics with laser.

In order to obtain highly coherent optical radiation, it is necessary, first, to excite active centers and produce an inverted population of lasing levels, and second, to create selectively for photon states. The inverted population of the lasing levels of active centers is required in order that stimulated emission predominates over absorption. And selectively is required for the effect of stimulated emission to be significant only for a few photon states (otherwise no sufficiently coherent radiation can possibly be obtained).

A laser is an optical source that emits photons in a coherent beam and its light is typically near monochromatic that is consisting of a single wavelength, and emitted in a narrow beam. This is in contrast to common light sources such as bulb, which emit in coherent photons in almost all directions, usually over a wide spectrum of wavelengths. All light, including laser light, is made up of a little packet called photons.

With the beam of light one can shatter a diamond, perform delicate surgery, kill an enemy, send a clear message to a satellite, destroy a missile and also light up the moon.

Non-linear optics produces many exotic (unusual) effects such as second harmonic generation. This means we can create different kind of light by mixing the frequency of different lights.

Non-linear optics can be the source of light which very important to the production of laser. In the case of linear optics the incoming and out going energy are equal in magnitude and super position principle is valid but not in the case of non-linear optics.

When the light intensity is low, the linear susceptibility is sufficient to describe the optical properties. But when the intensity increase above a certain amount nonlinear optical phenomena is very important [1], [2], [3], [4], and [24].

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