CHAPTER 2

THEORY AND LITERATURE REVIEW

Chapter 2 covers the theory of laser, laser attenuation, laser emission, laser absorption, properties of laser beam, types of laser, light extinction and light scattering. Explanation on the classes of laser and the related safety matters are also discussed in this chapter.

2.1 Principle of Operation

The fundamentals of laser attenuation can be found in various books and other references such as Mathieu (1975). When a body is crossed by a radiation beam, an amount of the incident flux (Φ_i) is reflected at the entrance and exit surfaces while another amount of Φ_i is absorbed and the remainder is transmitted. The reflected flux is denoted by Φ_r while absorbed flux and transmitted flux are denoted by Φ_a and Φ_t respectively. The ratio of $A = \Phi_a / \Phi_i$ gives the information on the extinction of the body or the absorption factor if the absorption is a predominant phenomenon Φ_r, Φ_a and Φ_t are proportional to Φ_i. The classical equation of the Beer-Lambert law based on the above fundamental which has been used in the laser attenuation experiment is given by

$$\frac{I}{I_o} = \exp\left(-N_d \sigma_e L\right) \tag{2.1}$$

where I_o *and* I are the light intensities detected by the power meter before and during the expansion process respectively, N_d is the droplet number density, L is the length of path and σ_e is the extinction cross section for visible frequencies. Figure 2.1 shows the laser attenuation process.

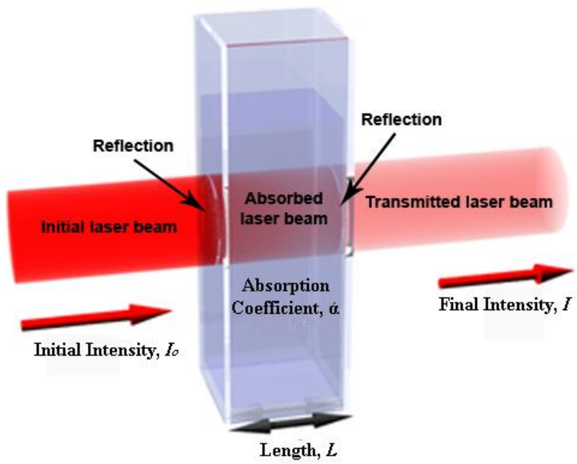

Figure 2.1: The process of laser attenuation (Wikipedia, 2008)

Bachalo (1991) defined the extinction cross section as

$$\sigma_e = \frac{\pi}{4}\overline{Q}_e D_{20}^2 \tag{2.2}$$

where $\overline{Q}_e$ is the mean extinction efficiency and he used $\overline{Q}_e = 2$ for the particles of D_{20} between 5 to 50 microns. D_{20} is defined as the surface mean diameter. It represents the average diameter with a surface area is equal to the mean surface area of the droplets. This relation is given in Equation 2.3 where n_i is the number of droplets within a centered range on diameter D_i and k is the number of ranges (Lefebvre, 1989)

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{k} n_i D_i^2}{\Sigma n_i}} \tag{2.3}$$

Marquez (2003) conducted an input-output calibration by using Absorptive Neutral Density filters of known attenuation. The result of the calibration is shown in Figure 2.2. The figure shows a linear relation between the normalized response voltage of the laser and the normalized intensity of the laser beam detected by the power meter. The linear relation between the response voltage and intensity of laser beam is given by

$$\frac{I}{I_o} = \frac{\left(\frac{V}{V_o} + 0.0279\right)}{1.0483} \tag{2.4}$$

where V_o and I_o are the maximum voltage and laser intensity obtained before any introduction of suspended particles while V and I are the instantaneous values of voltage and laser intensity at a certain time. The ratio of (V/V_o) is obtained from the experiment. The droplet number density N_d can be calculated by using Equation 2.5

$$N_d = -\frac{\ln(I/I_o)}{\sigma_e L} \tag{2.5}$$

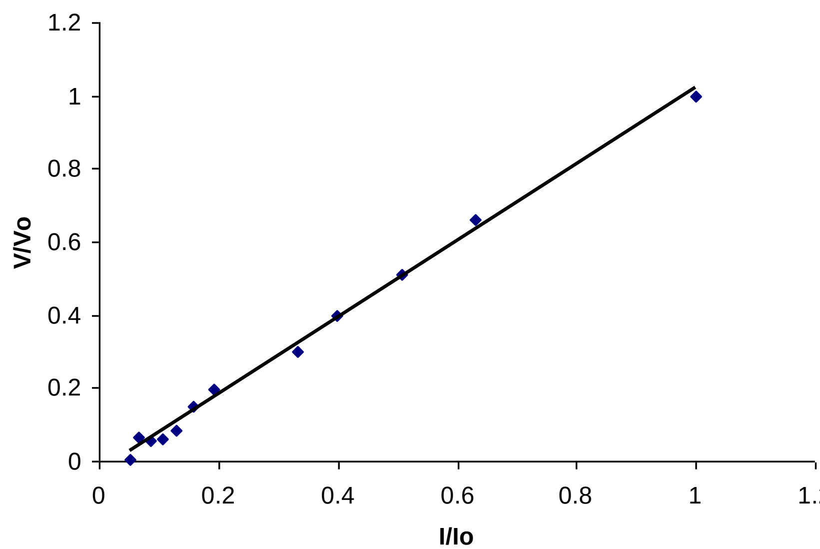

Figure 2.2: Input-output calibration curve for laser power meter, using neutral density filters of known attenuation (Marquez, 2003)

2.2 Laser Emission and Absorption

Laser has become an increasingly important part of modern technology. It is used in the aiming devices, range finders, optical storage devices, fiber-optic communication, laser spectroscopy, manufacturing and surgery. The fundamental of laser starts with the explanation on the emission and absorption phenomenon. The types of emission are spontaneous and stimulated. Svelto (1998) considered two levels of energy, 1 and 2, of some atom or molecule of a given material with energies of E_1 and E_2 $(E_1 < E_2)$. He assumed that level 1 is the ground level and initially the atom is at level 2. Since $E_1 < E_2$, the atom tends to decay to level 1 and the energy difference $E_2 - E_1$ is released by the atom. The process is called spontaneous or radiative emission when the energy is delivered in the form of electromagnetic (EM) wave as shown in Figure 2.3(a). The frequency v_0 of the radiated wave is given by Equation 2.6

$$v_0 = \frac{E_2 - E_1}{h} \tag{2.6}$$

where h is Planck's constant. Spontaneous emission is characterized by the emission of photon energy $hv_0 = E_2 - E_1$ when the atom decays from level 2 to level 1. However, the decay can also occur in non-radiative way and the energy difference is delivered in another form of energy such as kinetic energy.

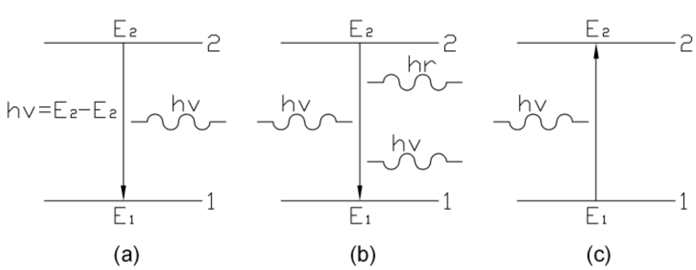

Figure 2.3: Schematic illustration of: (a) spontaneous emission, (b) stimulated emission, and (c) absorption (Svelto, 1998)

Initially, the atom is at level 2 and an EM wave of frequency $v = v_0$ is incident on the material. Since this wave has the same frequency as the atomic frequency, there is a finite probability that this wave forces the atom to undergo the transition from level 2 to level 1. The energy difference $E_2 - E_1$ is delivered in the form of EM wave that adds to the incident wave. This phenomenon is called stimulated emission and it is illustrated in Figure 2.3(b).

Svelto (1998) also explained the difference between spontaneous and stimulated emission. In spontaneous emission, atoms emit an EM wave that has no definite phase relation to that emitted by another atom and the wave is emitted in any direction. In stimulated emission, the emission of any atom adds in phase to that of the incoming wave and in the same direction.

Furthermore, he assumed that the atom is initially at level 1 and an EM wave of frequency $v = v_0$ is incident on the material; there is a probability that the atom will be raised to level 2. The energy difference $E_2 - E_1$ required by the atom to undergo the transition is obtained from the energy of the incident EM wave and this phenomenon is called absorption. Figure 2.3(c) illustrates the absorption process.

2.3 Properties of Laser Beam

2.3.1 Monochromatic

Monochromatic occurs due to these circumstances: (1) only an EM wave of frequency, v, given in Equation 2.6 can be amplified, and (2) since a two-mirror arrangement forms a resonant cavity, oscillation can occur only at the resonance frequencies of this cavity. The second circumstance leads to an often narrower laser line-width than the usual line-width of the transition $2 \rightarrow 1$, as observed in spontaneous emission.

2.3.2 Coherence

Coherence can be explained into two concepts: spatial coherence and temporal coherence. Svelto (1998) assumed that two points of P_1 and P_2 at time of $t = 0$ lie on the same wave front of given EM wave and let $E_1(t)$ and $E_2(t)$ be the corresponding electric fields at these two points. He defined the difference between phases of the two fields at time $t = 0$ is zero. If the difference remains zero when time $t > 0$, then it is a perfect coherence. If that perfect coherence occurs for any two points of EM wave front, then it can be said that the wave has perfect spatial coherence. P_1 and P_2 must lie within some finite area around P_1 to have good phase correlation and in this case the wave has partial spatial coherence.

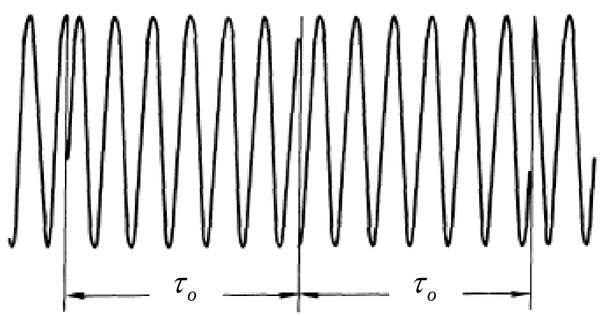

Figure 2.4: Electromagnetic wave with a coherence time of τ_0 (Svelto, 1998)

To define the temporal coherence, he considered the electric field of EM wave (at a given point P) at times t and $t+\tau$. If, for a given time delay τ, the phase difference between the two field remains the same for any time t then it is called temporal coherence over a time τ. If this occurs to any value of τ, then the EM wave is said to have perfect temporal coherence but if it occurs for a time delay τ such that $0 < \tau < \tau_0$ then the wave has partial temporal coherence. Figure 2.4 shows the example of a sinusoidal electric field undergoing phase jumps at time intervals equal to τ_0.

2.3.3 Directionality

Directionality can be defined as a direct consequence when an active medium is placed in resonant cavity. The propagation of wave in the orthogonal direction to the mirrors which can be sustained in the cavity is shown in Figure 2.5. Directionality can be separated in two types of case: perfect spatial coherence and partial spatial coherence.

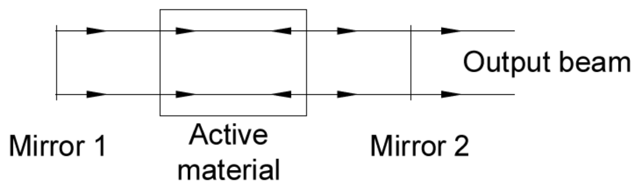

Figure 2.5: Scheme of a laser (Svelto, 1998)

In perfect spatial coherence, a beam of finite aperture has unavoidable divergence due to diffraction. Figure 2.6 shows a beam of uniform intensity and plane wave front is assumed to be incident on a screen S containing an aperture D. According to Huyghen's principle, the wave front at some plane P behind the screen can be obtained by the superposition of the elementary waves emitted by each aperture. Thus, on account of the finite size D of the aperture, the beam has a finite divergence θ_0. Its value can be determined by using diffraction theory. For an arbitrary amplitude distribution, θ_d is obtained by

$$\theta_d = \frac{\beta\lambda}{D} \tag{2.7}$$

where λ and D are the wavelength and diameter of the beam, respectively. The factor β is a numerical coefficient of the order of unity whose value depends on the shape of the amplitude distribution and how both the divergence and beam diameter are defined. The divergence of beam expressed in Equation. 2.7 is referred to as diffraction-limited.

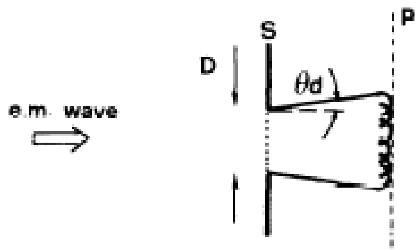

Figure 2.6: Divergence of a plane electromagnetic wave due to diffraction (Svelto, 1998)

If the wave has only partial spatial coherence, its divergence is greater than the minimum value set by diffraction. For any point P' of the wave front, Huyghen's argument (Figure 2.6) can be applied only for the points lying within the coherence area S_c around point P'. Thus, the coherence area acts as a limiting aperture for the coherent superposition of elementary wavelets. Now, the beam divergence can be written as

$$\theta = \frac{\beta\lambda}{(S_c)^{0.5}} \tag{2.8}$$

where β is a numerical coefficient of the order of unity whose exact value depends on how both the divergence, θ and coherence area, S_c are defined.

2.4 Types of Laser

Various types of laser are developed nowadays with a wide range of physical and operating parameters. Solid-state, liquid or gas laser are the lasers which characterized by the physical state of the active material. A special case is where the active material consists of free electros at relativistic velocities passing through a spatially period magnetic field (free-electron lasers). If the lasers are characterized by the wavelength of emitted radiation, they are referred as infrared lasers, visible lasers, ultraviolet lasers and x-ray lasers.

The wavelength is within the range of 1mm to 1nm and the wavelength span can be a factor of 10^6. The output power covers an even greater range of values. For continuous-wave

(CW) lasers, the power is from a few mW used for signal sources to a few MW used in the military applications.

2.5 Factors Affecting Light Extinction

There are three factors which affect the result of the laser attenuation. The factors are field of view (fov), droplet size and optical length. Wind and Szymanski (1978) explained why light scattering is a problem to laser attenuation. The forward scattered light flux superimposes on the transmitted light flux and this phenomenon yields an error in the measurement results. According to Deepak and Box (1978), the scattering effect depends on the geometry of the measuring system and optical depth.

Wind and Szymanski (1978) presented in their work that if fov is small then the scattering is negligible. The term light scattering refers to all the physical processes that move photons apart in different directions. Deepak and Vaughan (1978) suggested that by using the lens and pinhole, the forward scattering effect can be minimized. They also added that there would always be scattering effect especially when the droplet size is larger than the laser wavelength (λ).

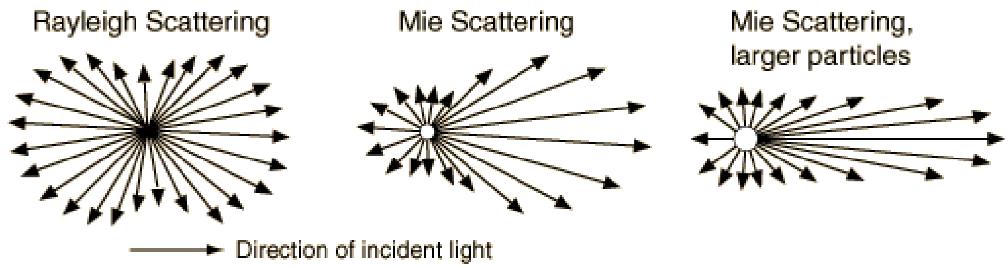

Figure 2.7: Modes of light scattering (Nave, 2000)

Figure 2.7 shows the types of light scattering. It explains the reason why larger droplet size causes significant correction factor. Larger particles experience a sharper and more intense forward lobe of Mie scattering thus it may cause higher measured light intensity than expected.

2.6 Light Scattering

Referring to Sharma (2003), the term light scattering refers to all the physical processes that move photons apart in different directions. He explained that this phenomenon is often caused by local variations of the refractive index within a heterogeneous medium. Other scattering processes, as for instance the Raman effect and the Brillouin scattering, also change the wavelength of the incident photon but these phenomena are rare in nature. Figure 2.8 shows the average absorption of an infinitely thin slice under diffuse illumination is related to the average path of the light in the medium

He studied the scattering caused by small particles that are dispersed in a homogeneous medium. He considered a thin slice of thickness of this scattering medium, as shown in Figure 2.9. The variation $(d\phi)$ of the collimated light flux that crosses this slice is proportional to the flux intensity (ϕ) of the light beam and to the thickness (dx) of the slice. Equation 2.9 below gives the relation between $d\phi$, ϕ and dx.

$$d\phi = -\beta(\lambda)\phi dx \tag{2.9}$$

where λ is the light wavelength and $\beta(\lambda)$ is the scattering coefficient of the medium.

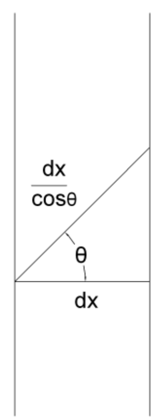

Figure 2.8: The average absorption of an infinitely thin slice under diffuse illumination is related to the average path of the light in the medium (Sharma, 2003)

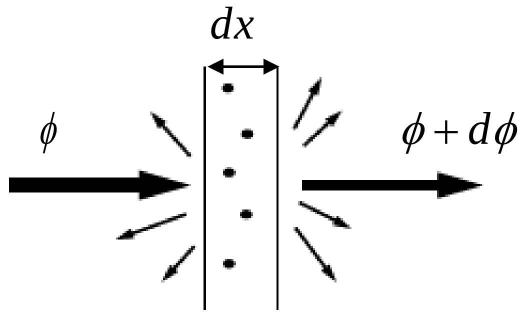

Figure 2.9: Light scattered by an infinitely thin layer containing light-scattering particles at a concentration c (Sharma, 2003)

Then, he introduced molar decadic scattering extinction coefficient $(\sigma(\lambda))$ which can be interpreted as the scattering cross-section area of a mole of particles of radius (r). Equations 2.10 and 2.11 show the relation of scattering coefficient.

$$\beta(\lambda) = \sigma(\lambda) c \ln(10) \tag{2.10}$$

$$\sigma(\lambda) = \frac{N_A}{\ln(10)} \pi r^2 \chi_{SC}(\lambda) \tag{2.11}$$

where c is the concentration of the particles, $N_A = 6.022 \times 10^{23}$ is the Avogadro's number and $\chi_{SC}(\lambda)$ is the scattering efficiency of the particles.

The total extinction coefficient $(\varepsilon_T(\lambda))$ of a particle that has both a scattering and an absorbing behavior corresponds to the sum of the scattering and absorbing cross-section areas is shown below in Equation 2.12.

$$\varepsilon_T(\lambda) = \varepsilon(\lambda) + \sigma(\lambda) = \left[\pi r^2 \chi_{abs}(\lambda) - \pi r^2 \chi_{SC}(\lambda)\right] \frac{N_A}{\ln(10)} \tag{2.12}$$

2.7 Laser Safety

According to Livemore (1987), laser safety has been controversial since laser began appearing in the laboratories. The two major concerns are exposure to the beam (which presents much more danger to the eyes than to the rest of the body) and high voltages within the laser and power supply. Many standards have been developed covering either the performance of laser equipment or the safe use of lasers; some developed by government agencies have legal status, while others are recommendations by voluntary organizations.

High-power laser beams can burn the skin but the most important hazards of laser beams are to the eyes, which are the part of the body most sensitive to light. Like sunlight, laser light arrives in parallel rays which the eye focuses to a point on the retina, the layer of cells that responds to light. Just as staring at the sun can damage vision, exposure to a laser beam of sufficient power can cause permanent eye damage.

Classification of laser depends on its capabilities to produce injury to people. The classification ranges from Class I lasers (harmless) to Class IV lasers (extremely harmful). The manufacturers are required to label Class II, III or IV lasers with a warning label which will also have the classification of laser printed on it. The explanation on the classification of laser is obtained from Schlenker (2006) of University of Kentucky.

Class I is a low-powered laser which considered safe from causing potential hazards. The examples of Class I laser are such as laser printers, CD ROM devices, geological survey equipments and laboratory analytical equipments. No injury to the people is expected from Class I laser although the eyes or skin is exposed to the laser beam.

Next, Class II is a low-powered laser (less than $1mW$) and it is a visible light laser that possibly causes damage to the eyes. The examples of Class II laser are such as laser pointers, aiming devices and range finding equipment. The eyes can be damaged if class II laser beam is directly viewed for long periods of time $(>15\min)$. The steps that must be strictly followed are avoid looking at the laser beam for a long period, avoid viewing the laser beams with the telescopic devices and do not point the laser beam into the eyes.

Class IIIa is a continuous-wave (CW) laser with intermediate power from 1mW to 5mW. This class of laser is used as laser pointer in the class and also in laser scanner. Directly look at the laser beam can be hazardous to the eyes and the precautious steps are the same as Class II laser.

Then, Class IIIb is an upper intermediate power laser with the power ranging from 5mW to 500 mW for CW laser and 10J/cm^2 for pulsed laser. The applications of this laser are such as in stereolithography, spectrometry and entertainment light performance. Direct viewing of the Class IIIb laser beam is hazardous to the eye and the diffuse reflections of the beam can also be hazardous to the eye. The steps that must be strictly followed are avoid looking at the laser beam for a long period, avoid viewing the laser beams with the telescopic devices, do not point the laser beam into the eyes and wear the proper eye protection.

Finally, any laser classified with Class IV is extremely hazardous to the eyes and skin. The power of this laser is ranging more than 500mW for CW laser and more than 10J/cm^2 for pulsed laser. Commonly, this type of laser is used in drilling, cutting, welding, micromachining and surgery. The laser beam and diffuse reflections are hazardous to the eyes and skin. It is also a fire-hazard rated laser because it ignites fire when it strikes the target but it depends on the reaction with the target. Thus, greater control measure is required when using this laser and precautious steps such as wearing proper eye protection, keeping away any reflective material from the laser beam and keeping the hands or other body parts from the laser beam.

The suitable class of laser for this project is either II or IIIa because this project does not require either a lower class or higher class of laser. The initial design of this project is only meant for low power input and output only.