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Introduction to Lasers

In the context of measurements, lasers fall in the category of light sources with certain helpful properties. Unlike a material probe (say, a thermocouple), lasers are often called photon probes . The measurement of a flow property may, however, rely on the wave-like nature of light.

Though light propagates as a wave, generation of light from a material is a quantum-mechanical phenomenon. In fact, the subject is one of emission of electromagnetic radiation, with light being EM radiation in the visible range (400-700 nm, wavelength). In a conventional light source, for example a tungsten filament lamp, the metallic wire is electrically heated to a high enough temperature. Under a thermal stimulus, electrons undergo transition to higher energy levels. As they return to the ground state, they emit photons. Transitions occuring closer to the surface to the material result in a net emission of radiation to the environment. If the filament temperature is high enough, photons would be energetic and radiation can fall in the visible range. Unfortunately, such a light source has limited utility in measurements.

The tungsten filament lamp is often called a *conventional light source* , to contrast its behaviour with a laser. Characteristically, the filament emisison is random in time, spatially distributed, and photon energies are distributed over several wavelengths, thus giving rise to polychromatic radiation. The randomness in time ensures that the phases of the wave packets leaving the filament are practically uncorrelated. Further, the emisison is in all directions and intensity diminishes with distance. In contrast, a laser output is

1. monochromatic,

2. intense,

3. directional, and

4. coherent.

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A summary of various commercially available lasers is given in Table 3.1. A helium-neon laser is most popular in measurements. For measurements in liquids and when multiple lines (wavelengths) are required, the Argon-Ion laser is preferred. This is because of its superior coherence at higher power outputs. A CO_2 laser is unsuitable in the measurement context but is preferred in the manufacturing industry where operations such as drilling and cutting are common.

A summary of optical measurement techniques employed in various aplications is provided in Table 3.2. Examples where white light is used are included for completeness.

Table 3.1: Various types of lasers and their overall specification. An ***etalon*** is an optical interferometer contained within the laser that helps improve coherence of the light output.

Medium	phase	mode	wavelength λ, nm	power	energy per pulse	coherence length
He-Ne	gas	continuous	632.8 nm	0.1 - 75 mW	-	20 cm
			(orange-red)			
Argon-Ion	gas	continuous	488 nm (blue)	0.1 - 10 W		5 cm
			514 (green)			2000 cm
						(with etalon)
Krypton	solid	continuous	47-676 nm	0.1-0.9 W		5-18 cm
Ruby	solid	pulsed or	694 nm	0.1 - 1 W	500-2000 mJ	50-500
		continuous				(with etalon)
Nd:YAG	solid	pulsed	1064 nm		0.1 - 100 J	1 cm
COCO_2gas	pulsed or	1062 nm	10 kW	2000 mJ	small	
		continuous				

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Table 3.2: Overview of optical methods suitable for measurement of temperature and species concentration. LDV is laser Doppler velocimetry; PIV is particle image velocimetry; LCT is liquid crystal thermography; CARS is coherent anti-Stokes Raman spectroscopy; and LIF is laser-induced fluorescence. Temperature and concentration are represented as T and C respectively.

Method	physical mechanism	incident light	attribute measured	quantities detected	real-time	spatial extent
interferometry	refractive index	laser beam	intensity	T and C	yes	2D (integrated)
			(via fringes)			
schlieren and	refractive index	laser beam	intensity field	T and C	yes	2D (integrated)
shadowgraph						
rainbow schlieren	refractive index	white light	hue	T and C	yes	2D (integrated)
LDV	elastic scattering	2 laser beams	Doppler shift	u	yes	point
		per dimension				
PIV	Mie scattering	laser sheet	intensity	u	Yes	2D and 3D
LCT	Mie scattering	white light	hue	T and wall shear	yes	2D
LIF	fluorescence	laser sheet	intensity	T and C	yes	2D
CARS	inelastic scattering	2 laser beams	intensity spectrum	T and C	no	point

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Light Sources

Conventional light sources emit radiation by a series of successive spatially distributed random phenomena. These involve atomic excitation followed by emission as electrons in the valence band jump to lower energy levels. This downward transition follows predetermined rules that finally govern the wavelength of the emitted photon. Note that energy emitted e and wavelength λ are related as $e = hc/\lambda$ where h is Planck's constant. The average life of a radiating atom is $1.6 \times 10^{-8} s$ and so the average length of a single train of waves is $CL = cT = 4.8$m. Coherence length of a tungsten filament is at best a few mm. In contrast to this a laser produces a beam whose coherence length is several mm. Further a laser beam is thin and approximates a point source.

We describe briefly the principles involved in the operation of a laser. Laser is an acronym for light amplification by stimulated emission of radiation. Its operation employs the following ideas.

a. Metastable states: Normally valence electrons of an atom can be excited to a higher energy level from which they return to the ground state by emitting a photon. However, for certain materials there exist energy levels beyond the ground state from which the return of electrons to the ground state is considerably delayed (Figure 3.1). This return can, however, occur in the event of a collision between an electron and a photon. The average life of a normally excited electron is $10^{-8} s$; in the metastable state it is around 10^{-2} s.

b. Optical Pumping: It is possible to raise electrons to metastable states by light absorption. This is called optical pumping.

c. Fluorescence: Emission of light when an electron jumps from a metastable state to the ground state is called fluorescence. In light sources, the gas pressure is kept very low to minimize the possibility of collision between particles, increase the particle life in the metastable state and minimize the production of thermal energy. Hence the resulting electronic transitions mainly classify as fluorescence.

d. Population Inversion: When the number of electrons in the metastable state exceeds that in the ground state it is called as population inversion.

e. Resonance: In the absence of collisions the electrons undergoing transition from the metastable state will emit radiation at the frequency that is equal to the absorption frequency. This is called as resonance.

f. Stimulated Emission: A photon released during emission from an electron in the metastable state can stimulate another high energy electron to release a photon of identical frequency, direction, polarization, phase and speed. The two photons are now completely identical and radiation is both temporally and spatially coherent. Stimulated emission and stimulated absorption in the ground state are equally probable. For a net emission, i.e., to construct a light source it is important to have a population inversion.

g. Cavity Oscillation: Starting with a gas with metastable states and population inversion, a light source can be constructed. However, the effectiveness of stimulation is increased by confining the gas between parallel mirrors. Here, reflections lead to increased stimulation and a large number of photons will surge back and forth in the cavity formed by the mirrors. Further the wavelength λ_L for which the cavity length $L = n\lambda_L$ with n being an integer will produce a standing wave pattern whose wavelength is λ_L. Others wavelengths will be dissipated as thermal energy. A small opening in one of the mirrors will then generate a net monochromatic radiation of wavelength λ_L that can be used in measurements.

h. Helium-Neon Laser: A He $-Ne$ laser is a popular light source in optical instrumentation. It has a continuous wave output typically in the range of 0.5 to $75mW$ and a wavelength of 632.8 nm. It is sturdy in construction, economical and stable in operation. A sketch of this laser is given in Figure 3.2.

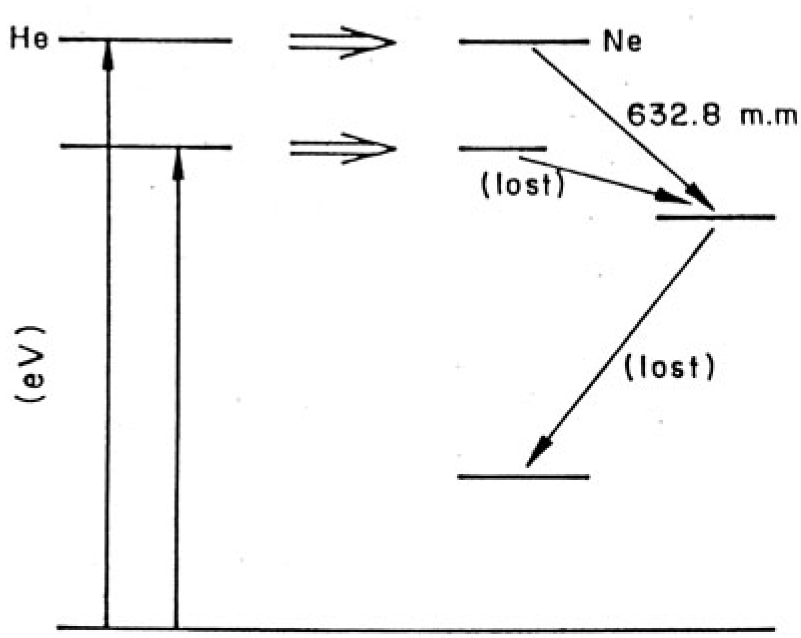

Figure 3.1: Atomic Transitions in a He-Ne Laser.

In Figure 3.2, 1 and 2 are fully and partly silvered mirrors respectively which form a cavity. V is a high DC voltage used to excite the He atoms. Gas in the cavity is at a low pressure; the partial pressures of He and Ne are 1 and $0.1mm$ of mercury (1/300 and 1/3000 of the standard atmospheric pressure). The lasing action is related to stimulated emission of the Neon atoms. Helium atoms are excited to metastable states by the external applied voltage. These can return to the ground state only by collision with unexcited Neon atoms. In the process, the upper most energy levels of Neon get populated. As the Neon atoms in turn return to lower energy levels the photons released stimulate additional radiation from excited Neon atoms and the entire process is intensified by the reflecting cavity walls. The wavelength of $632.8nm$,(an orange-red-color) is chosen over other wavelengths by proper choice of the cavity length. The atomic processes taking place in the laser cavity is sketched in Figure 3.1.

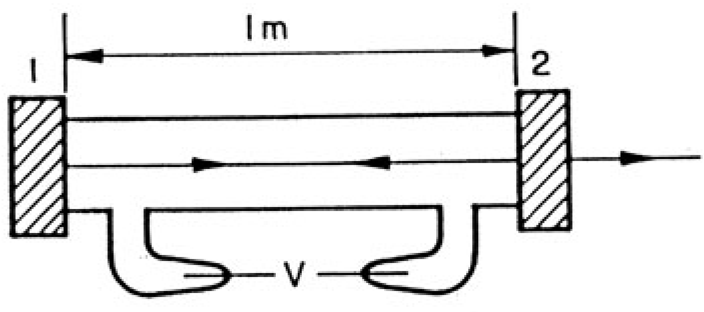

Figure 3.2: Construction of Helium-Neon Laser.

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Laser Doppler Velocimetry

An optical method of measuring instantaneous point velocity in a flow region is described as below.: Laser Doppler Velocimetry (LDV) is a non-intrusive technique for velocity measurement though it requires seeding of flow with small non-buoyant particles. Liquids naturally contain a large number of suspensions that can scatter light; in gaseous flows a seed generator that atomizes non-volatile oil, e.g. glycerine is required. LDV is based on the Doppler effect. It measures velocity in both isothermal and non-isothermal flows and is not affected by temperature variations in the fluid. This is a major advantage over thermal transducers, e.g. a hot-wire. Fluid temperature can be measured using interferometry or by Rayleigh scattering. LDV is a linear device and is hence uniformly sensitive to low as well as high velocities. It can measure three components of velocity as well as turbulence. Monochromatic light is adequate for mean velocity measurement; however, coherence of light is required for turbulence measurement. LDV tends to be expensive and requires an exceptionally clean and stable environment for its operation.

Let s be the direction of propagation of light from a monochromatic source (Figure 3.3). The point at which the velocity is being measured is denoted as P. Let r be the unit vector that represents the position of the observer O relative to P and let u be the velocity vector. The Doppler effect is stated as: The frequency of radiation from a source that is scattered by a particle moving relative to it is changed by an amount that depends on the relative velocity and the positions of the source and the observer. Let f_i be the frequency, λ_i the wavelength of the incident light, f_0 the frequency of scattered light from a particle moving with a velocity u assuming that the observer is stationary. Scattering will be more or less uniform in all directions. The Doppler shift in the frequency of the scattered light is given by

$$\Delta f = f_0 - f_i = u \,.\, \frac{(r - s)}{\lambda_i}$$

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provided that the distance $\overline{OP}$ is much larger than the particle diameter, i.e. the observer is located in the far-field relative to the particle. In the above expression, Δf is a maximum when u is parallel to $(r - s)$. For a He-Ne laser $\Delta f(\max) = 4$MHz /(m/s). In applications, the scattering configuration used is based on convenience and a typical value of Δf is 0.4 MHz/(m/s). The forward and backward scatter configurations are marked (a) and (b) in Figure 3.4 . The latter has the disadvantage of low scattered light intensity but is easily compensated because of the compactness achieved by integrating the source and the receiver optics.

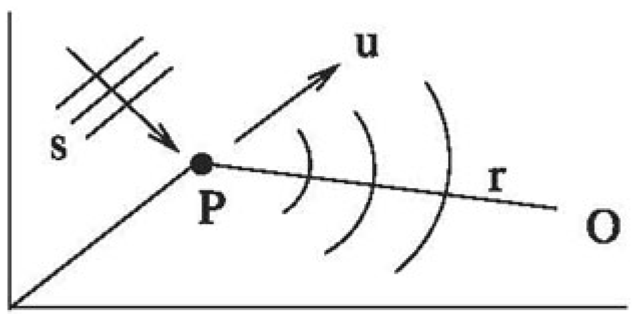

Figure 3.3: Schematic Drawing of Doppler Effect.

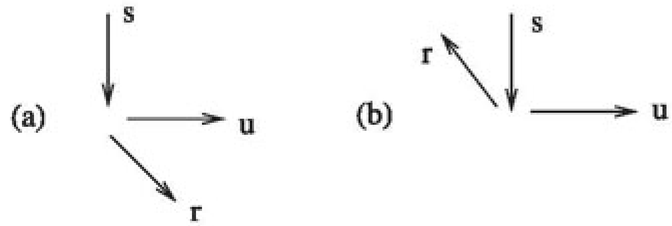

Figure 3.4: (a) Forward and (b) Backward Scattering Configurations.

The heterodyne configuration of a one-dimensional LDV is commonly used in practice (Figure 3.5). In principle one light source and two beams (1 and 2) are required per dimension; in three dimensions three sources preferably of different wavelengths are required. The receiver R is a photodetector such as a photodiode or a photomultiplier tube that converts the optical signal to an electrical signal. It is useful in determining the Doppler shift frequency. Both original and the scattered light, are combined on the surface of the photodetector. These signals are of the form $\sin f_i t$ and $\sin f_0 t$. Since the photodetector is a square law device its output oscillates as

$$(\sin f_i t + \sin f_0 t)^2$$

$$i.e. \qquad 4\sin^2\left(\frac{f_i + f_0}{2}\right) t \ \cos^2\left(\frac{f_0 - f_i}{2}\right) t$$

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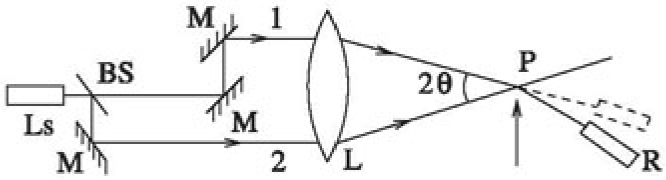

Figure 3.5: Heterodyne Configuration of LDV.

For visible light $f_i = 10^8$ MHz and the photo-optics will not respond to such high frequencies. Hence the electrical output will oscillate as the $cos^2\ term$ at a frequency $(f_0 - f_i)$. These frequencies can be measured using one of the following methods:

1. Spectroscopy (in which case an electrical signal is not generated).

2. Counting the number of zero crossings.

3. Digitizing the electrical signal and applying FFT algorithm to obtain the frequency spectrum.

In (3) the dominant frequency in the spectrum corresponds to the Doppler shift. Convenient instruments such as a apectrum analyzer are available for making such measurements.

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The following practical considerations must be borne in mind while using an LDV: The signal generated at the receiver should have a high signal-to-noise ratio. Hence particles used as seeds in flow must be small, large in number and nearly of uniform size. The seeds must also be non-buoyant. As mentioned earlier, gas flows require seeding and atomized non-volatile oils such as glycerine are used for this purpose. The receiver optics must be of suitably high quality so that they can respond to optical signals of low intensity. These are usually protected by interference filters to prevent contamination of scattered light by the room illumination. When photodetectors are used with frequency counters, phase information in the signal is lost due to the squaring of the signal and the LDV setup can be used to measure mean velocity but not turbulence. Note that a change in velocity u to $-u$ produces a Doppler shift in frequency of identical magnitude. This problem is circumvented by the use of a Bragg cell that is described later. With reference to the LDV configuration considered in Figure 3.5, the following analysis is applicable. Writing the Doppler shift equation for each ray 1 and 2, we get

$$f_2 = f_i + u.\frac{(r - s_2)}{\lambda_i}\ 2f_1 = f_i + u \cdot \frac{(r - s_1)}{\lambda_i}$$

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Hence

$$f_2 - f_1 = u \cdot \frac{(s_1 - s_2)}{\lambda_i}$$

As discussed above, the output of the photodetector oscillates at a frequency $(f_2 - f_1)$. Hence the measurement of the frequency shift enables one to measure velocity. Note that the Doppler shift is independent of r, the receiver position. Instead the sensitivity of LDV is adjusted by changing θ and hence $(s_2 - s_1)$. The angle θ is accurately measured from the fringe pattern that forms at the measurement volume owing to interference of the beams 1 and 2 (Figure 3.6). The fringe spacing can be shown to be given by $\varepsilon = \lambda_i/(2\sin\theta)$ from which θ can be determined.

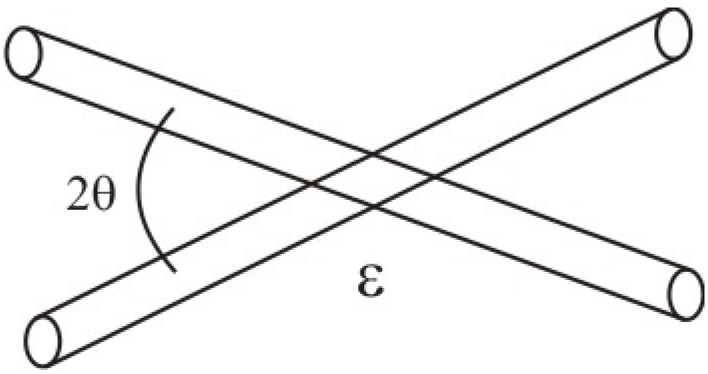

Figure 3.6: Fringe Pattern at Measurement Location.

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If u becomes small Δf is also small; further Δf is insensitive to the sign of the velocity. To circumvent this problem a frequency shifter such as Bragg cell (BC), an electro-optic device capable of increasing the frequency of light, is put in the path of one of the beams. A typical value of this increase is about 40 MHz. The modified LDV arrangement is shown in Figure 3.7.

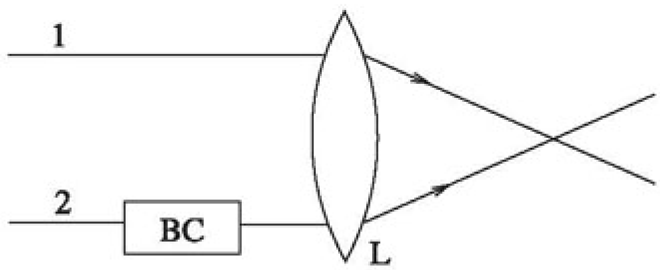

Figure 3.7: Use of a Bragg Cell.

The Doppler shift equations for rays 1 and 2 now become

$$f_1 = f_i + u \cdot \frac{(r - s_1)}{\lambda_i}$$

$$f_2 = f_i + f_B + u \cdot \frac{(r - s_2)}{\lambda_i}$$

where f_B is the shift frequency introduced by the Bragg cell. Hence

$$f_2 - f_1 = f_B + u \cdot \frac{(s_1 - s_2)}{\lambda_i}$$

Note that as $u \to 0$, $f_1 - f_2$ remains finite and can be conveniently determined since its value is around f_B. Values of $(f_2 - f_1) < f_B$ are interpreted as referring to velocities in the negative direction.

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