Chapter 2

Diagnostic techniques for high repetition rate dye laser

2.1 Introduction

Knowledge of dye laser output characteristics in short/long period of time is extremely important because of its practical relevance. There are many applications of dye lasers in which optical stability is of prime importance. Therefore, the acquisition, presentation and quantification of dye laser parameters such as optical average power, temporal and spectral characteristics, etc. are essential issues. The spectral structure of a dye laser is characterized by its wavelength and spectral width, also known as bandwidth or linewidth. Diagnostics of spectral characteristic, over the period of time, needs user friendly programmable software for acquisition of large number of sequential data and software for its presentation and analysis. There are no techniques available, either commercially or in the literature, to present dye laser output data over the specified period of time. Also, literatures lacks in diagnostic methods for computing the number of sequential data. In this thesis, a novel indigenous technique for data acquisition, storage and diagnostic of the dye laser output has been proposed and very effectively utilized for precise measurements of the output characteristics over a long period of time.

2.2 Review of dye laser data presentations

Pulsed dye lasers usually have mode structures [2.1-2.2], which show inherent pulse to pulse fluctuation/instability in the spectral structures. Kajava et al. [2.3], in a study on dye laser, have observed that the spectral structure and intensity fluctuate from pulse to pulse. They presented dye laser spectra of 8, 32 and 100 pulses, in which subsequent laser pulses were superimposed on each other. However, its visual inspection does not provide
any additional information from the representation of time averaged pulses. Pease and Pearson [2.4] have observed the mode structure fluctuations and pulse to pulse dye laser spectral instability, in high repetition rate dye laser. They presented random individual pulse to pulse fluctuations as a set of spots in a graph.

To investigate the dye laser with excellent statistics, acquisition of large number of profiles are needed for better understanding of the output characteristics. Using computer graphics facilities, information can be inferred by drawing superimposed line plots of the signal acquired through 1-D array of photodiodes or CCD camera. For the ideal signal, all line plots should lie on the top of one another within the noise (random) band. This technique is adequate for small variations in parameters, but provides visually confused information for line plots having large variations in it. Situations aggravated when signal contains multiple peaks. Furthermore, in these superimposed line plots, time information is completely missing or lost. However, the time information can be represented by drawing a plot in a specific color or shades but it is difficult to remember color for each line plots. The problem of handling large numbers of line plots (spectrums or traces) having large variation requires a new representation. There are no such techniques available in the literatures to present large number of spectral profile of the tunable dye lasers. Therefore, a novel indigenous technique for spectral data representation has been proposed and implemented to investigate the spectral stability over short/long period of time [2.5]. In fact, this technique is universal and can be used to acquire and analyze many laser parameters; however, in the present thesis, this unique technique is extensively used only for spectral investigations of the dye laser.
2.3 Description of hardware and software

Modern scientific image acquisition system typically consists of tailored optical and electronic components. In the present work, to acquire an image a high resolution temperature compensated 12 bit digital CCD camera (PixelFly, PCO) [2.6] interfaced with the personal computer is used for the dye laser data acquisition. The CCD has spatial resolution of 6.4 μm x 6.4 μm without binning. This camera has also facility of programmable binning, which can be used to enhance S/N ratio of the image. The short exposure time of the camera enables to capture profile of a very fast phenomenon with minimum dark current noise.

PROMISE (PROfile Measurement of Image Size & Enhancement), a graphical user interface (GUI) based software, devised by Vora [2.7], has been comprehensively used for the dye laser investigations. This software handles image up to 16 bits of resolution. To achieve high precision measurements, numbers of special modules has been incorporated in the PROMISE. This software has many unique features like generation of master dark frame and subtraction of self-generated dark current from the signal. This improves the S/N ratio of the CCD and hence the measurement accuracy. Each pixel’s dark current was captured by taking an exposure (with the same chip temperature and integration time) without the incoming light (camera shutter closed). The dark current was subtracted from the actual image, pixel by pixel, to yield the true signal.

Noise (random, hot pixels etc.) is an integral part of the digital imaging system and provides ambiguity in the measurements. Popular programmable spatial image filters [2.8-2.9] were also incorporated for noise removal and smoothing the image. A special type of low pass Median filter was incorporated in the software, which removes isolated noise
effectively but does not blur the image and at the same time retains maximum information. This also diminishes the peculiar electromagnetic interference (EMI) pickup during recording of image caused by associated high voltage power supply system used in the experimental laboratory. The fast switching (~100 ns rise time) of pulse forming network associated with electrical power supply, for high repetition rate excitation source (copper vapour laser), generates the peculiar noise which were picked up by the signal cable linked with diagnostics instruments. These kinds of noises have been effectively and routinely removed using single pass median filter available in the software.

2.4 Methodology adopted for spectral investigation

While investigating tunable laser characteristics, it is essential to know precisely the spectral profile (wavelength and bandwidth). A number of methods for spectral measurement have been reported in the literature [2.10-2.16]. For absolute accuracy and high precision measurements, interferometer based techniques are normally used. The spectrum can be measured accurately by various devices such as a very high-resolution spectrometer [2.17], Michelson & Michelson-type interferometers [2.16, 2.18-2.21], Fourier-transform spectrometer [2.22] based on the Michelson interferometer, polarization-sensitive interferometer [2.10], Fizeau interferometer [2.11] and Fabry-Perot (FP) interferometer [2.12]. The Fabry-Perot interferometer (FPI), designed by C. Fabry and A. Perot, represents a tool essentially to study spectral profile, and can be used with detector to resolve fine spectral details [2.23]. The fringe governing equation represents the equation of a circle, hence fringes appear circular to the observer /detector. Therefore, diameter of fringe takes account of spectral information and has been used for spectral characterizations such as wavelengths and bandwidth [2.24]. It determines wavelength to
any adjusted accuracy by choosing the single or combination of several FP etalon with different free spectral ranges (FSR). Byer et al [2.12] have presented the successive method of wavelength determination through a set of etalons, such that an approximate wavelength value available from the lower resolution etalon was used to determine the order number integer for the next high-resolution etalon with which the closer value of wavelength can be obtained. These methods require the thermal stabilization and precise calibration of etalon constants. To avoid this cumbersome process, an alternative method has been used in which a frequency stabilized He-Ne laser was employed as a reference, along with single FP etalon for the precise measurements [2.14, 2.23].

2.4.1 Theoretical formulation of the spectral measurement

Through FP etalon of spacing \(d\), diameter \(D_p\) of the \(p^{th}\) interference ring, when imaged onto the CCD camera using a lens of focal length \(f\), is given by [2.24],

\[
D_p^2 = \frac{4f^2\lambda (p-1+\varepsilon)}{\mu d}, \quad p = 1, 2, \ldots
\]  

(2.1)

where \(\mu\) is refractive index of medium at wavelength \(\lambda\) and \(\varepsilon\) (0 \(\leq\) \(\varepsilon\) \(\leq\) 1) is the fractional order number at the centre of the fringe.

Again using interference condition for etalon [2.24], we have

\[
2\mu_r d = \lambda_r (m_r + \varepsilon_r), \quad 2\mu d = \lambda (m + \varepsilon)
\]  

(2.2)

where \(\mu_r\) is the refractive index of air at the wavelength \(\lambda_r\), \(\varepsilon_r\) (0 \(\leq\) \(\varepsilon_r\) \(\leq\) 1) is the fractional order number at the centre of the fringe for the reference laser, \(m_r\) and \(m\) are the order numbers of the first (inner most) fully formed FP fringe of the reference laser and the dye laser, respectively.
If $D_{i_d}$ is the diameter of the first FP fringe of the dye laser, $D_{i_r}$ and $D_{2_r}$ be first and second diameter of reference laser at wavelength $\lambda_r$, then from equations (2.1) and (2.2), explicit expression for the dye laser wavelength $\lambda$, in terms of rings diameters, can be written as [2.25]

$$\lambda = \frac{m_r - \frac{D_{i_d}^2 - D_{i_r}^2}{D_{2_r}^2 - D_{i_r}^2}}{\mu_r} \frac{\lambda_r}{m}$$  \hspace{1cm} (2.3)

The equation (2.3) indicates that the wavelength of dye laser increases as the diameter of the FP fringes decreases and vice versa. The initial wavelength was measured using monochromator, which was used for the calculation of order $m$ at the centre of the fringe. The fractional order at the centre of the fringe can be obtained from the plot of square of the rings diameters against the corresponding ring numbers. The intercept on the ring number axis is $(1 - \varepsilon)$. The fraction $\varepsilon$ and hence the values $m_r$ and $m$, using equation (2.2) for known value of FP spacing, can be easily calculated. Therefore, wavelength $\lambda$ of dye laser can be easily computed by directly measuring the rings diameters of the FP fringe, using equation (2.3).

The bandwidth can be calculated from the intensity profile, expressed in terms of the diameters of different orders of the fringes, using the following relation [2.26]

$$\Delta \nu = FSR \ast \left[ \frac{(D_{i_b}^2 - D_{i_a}^2)}{(D_{2_a}^2 - D_{1_a}^2)} \right]$$  \hspace{1cm} (2.4)

where FSR is the free spectral range of the FP etalon, $D$ is the ring diameter; $1, 2$ – two adjacent orders; $a, b$ - the two points between which $\Delta \nu$ was measured. Thus, the bandwidth of the dye laser can be measured by directly recording the FP fringe and
measuring the diameters of different orders of the fringe. The bandwidth of axial modes can be measured easily using equation (2.4)

The FP etalon fringe have different ring diameter for different modes and orders. If $D_p$, $D_{p+1}$ be the diameter of the $p^{th}$ and $(p+1)^{th}$ order ring of one mode, $d_{p+1}$ be the diameter of $(p+1)^{th}$ order ring of next mode, and if there is no overlap occurs between the order of modes then from equation (2.1), the wave number separation between modes, by knowing the ring diameters, can be expressed as follow

$$\Delta \nu = \text{FSR} * \left[ \frac{D_{p+1}^2 - d_{p+1}^2}{D_{p+1}^2 - D_p^2} \right]$$  \hspace{1cm} (2.5)

Thus, by measuring the diameter of the rings, it is possible to evaluate the wave number difference between the modes.

2.4.2 Experimental technique for the data acquisition and analysis of spectral structure

The dye laser spectral structure was analyzed through high resolution FP etalon. Optical arrangement for obtaining the FP fringe of the dye laser and of a frequency stabilized He-Ne laser is shown in Fig.2.1. The He-Ne laser ($\lambda = 632.816$ nm, 5 mW power, 1 mm beam size), which is used as a reference wavelength, is passed through the same optical path as the dye laser beam. An aperture was used to enhance the contrast ratios of the fringe. An imaging lens of suitable focal length was used to image the fringe pattern onto a CCD camera connected to a personal computer (PC). To improve measurement accuracy, the setup was adjusted in such a way that only few number of FPI rings were covered in the entire CCD sensor area. Fig.2.2 shows the typical dye laser (a) fringe, (b) intensity modulation along a line scan across the diameter of the fringe.
Figure 2.1: Optical arrangements for obtaining FP fringe of the dye laser and of the He-Ne laser

Figure 2.2: Typical dye laser (a) fringe, (b) intensity modulation along a line scan across diameter of the fringe

2.4.3 Identification of peaks and rings diameter

Algorithm has been added in the PROMISE software to identify the number of peaks needed for the spectral structure investigation. To find the ring diameters, derivative of line data was obtained by taking the difference between successive pixels. The
peaks were located by finding the slope of the fringe. The line plot of data and its slope were overlaid and the searched peak positions were highlighted while analyzing the data.

Figure 2.3: Typical identification of peaks position and width of line intensity profile (a) first inner most ring, (b) second inner most ring, (c) third inner most ring
Fig. 2.3 shows typical identification of peaks position and widths of line intensity profile (a) the first inner most, (b) second ring, (c) third ring. From the measured ring diameters and peak separations, estimation of $\lambda$, and $\Delta\lambda$ can easily be obtained in the desired units of cm$^{-1}$, MHz or GHz. For stability or drift measurements, the horizontal axis can be programmed either in pixel or in the time domain i.e. time delay in acquiring the successive number of fringes.

The error in the estimation arises from error in determination of the peak position, fringe diameter and its width. The error on the fringe may arise due to random noise of the CCD or due to speckle associated with laser beam which give false peak position or height, thus introducing error in determination of the diameter and the width. The noise present in the fringe can be reduced by FFT filtering which eliminates the selected high frequency components, median filtering for removing typical EMI, averaging and binning of the lines.

2.4.4 Technique for spectral data representation: composite image generation

In order to present large number of vital scientific data simultaneously in the graphical format, a novel technique was conceptualized [2.5]. The fringe generated through FP etalon can be captured through high resolution scientific grade CCD camera and PROMISE software. After capturing the fringe, a cursor was placed on the image, across the diameter of the rings. This cursor provides the reference position to save subsequent line data in a dynamically allocated memory. During this process, two progressively growing images (corresponds to horizontal and vertical cursors), along with current acquired image, were also displayed in the dedicated window. At the end of acquiring preset number of fringe, the data acquisition process stops and software automatically displays the individual line profiles stored in the allocated memory as an image, which is
named as **composite image**. In this composite image, line profiles were stored as an image line so each pixel location of line provides position (or any relevant value depending on the signal information) and its color represents signal amplitude. The number of lines to be stacked or size of generated composite image depends on the RAM available. The height of the composite image depends on the number of fringes acquired and number of lines saved from each fringe. The sideways deviation in the composite image provides the first sight tentative information about fluctuations in spectral structure of the dye laser output. The composite image generation method is independent of the hardware, hence can be used with CCD camera, spectrograph and oscilloscope too.

In the composite image only the part of the fringe has been saved so very less disk space is required compared to saving individually acquired full fringe image. The composite image concept is very general in nature and can be used to present data of any characteristics. To improve the S/N ratio of the composite image, instead of storing a single line from the acquired fringe image, a preset number of lines can be binned (added), normalized and then stored as a line. It further reduces the random noise by a factor equal to the square root of the number of lines used for binning.

Fig.2.4 (a) shows typical window of composite image data of dye laser from the present thesis (chapter). It consists of 1000 lines of FP fringe scanned across the diameter, having three longitudinal modes. To visualize it more, composite image of the line scan across the diameter of fringe of He-Ne laser was generated. Fig.2.4 (b) shows composite image of line scan of FP fringe of He-Ne laser. The composite image appears as a straight line from top to bottom, which manifests the fact of high degree of spectral stability.
Another composite image was generated from dye laser in which spectral instability was created by some means. Fig.2.4 (c) shows composite image of dye laser fringe in presence of spectral fluctuations. The zigzag lines from top to bottom in the composite image manifest the fringe to fringe spectral instability present in the dye laser. In this way, composite image gives visual qualitative information about stability.

![Figure 2.4](image)

**Figure 2.4**: Typically generated composite image from fringe of (a) dye laser, (b) He-Ne laser, and (c) dye laser

### 2.4.5 Spectral measurement from the composite image

For measuring the peak positions and diameters, the software draws the intensity profiles (multi curves) of the line scans from the composite image lines in a dedicated window, as shown in Fig.2.5. From the composite image generated, measurement of wavelength and bandwidth can be performed using special algorithms inbuilt in the PROMISE software. Spectral analysis can be executed using one or two full ring, or three half ring of the FP fringes. The number of rings can be selected using an appropriate command from the Menu displayed in the window, as shown in Fig.2.5. The software plots
multi peaks intensity profiles of each line of composite image, which indicate intensity variation, change in the ring diameters and base line (background) level of the fringes. The diagnostic software offers three different techniques to measure bandwidth, namely, using (a) three half rings with 3, 6 or 9 peaks, (b) one full ring with 4 or 6 peaks, and (c) two full rings with 4, 8 or 12 peaks. Depending on the number of axial modes present, number of peaks can be identified appropriately by the software. Fig.2.5 (b) shows dialog for setting parameters for measurements using 2 full rings. The peaks can be located automatically or their tentative positions can be assigned to eliminate undesired peaks. In the second case, mouse click is used to mark the tentative peaks manually, along with margins (i.e. deviation of peak position). Mouse click on multi curves over a peak location records the tentative peak coordinates in a look up table. Fig.2.6 (a) shows the dialog window to mark tentative peaks position.

(a) (b)

Figure 2.5: Typical (a) window of intensity profiles (multi curves) of the composite image data of Fig.2.4 (a), (b) window menu for setting parameters
In this dialog window, the button has to be pressed according to peak positions i.e. if it is first peak then press first button or if it is 4\textsuperscript{th} peak press 4\textsuperscript{th} button. It saves all peak positions and peak margin information, which helps a lot in the subsequent analysis. The undesired peaks can be ignored by setting a minimum peak separation (in pixels). Any peak that lies within the set separation is ignored.

Small peaks in the base line can be bypassed by setting minimum amplitude of the peak in percentile. The FP etalon details, involved in the calculations, have to be incorporated in the software before measurement start. Fig.2.6 (b) shows dialog window menu for setting parameters for the etalon and widths position. In this way, bandwidth of one, two or any number of axial modes can be accurately measured by this technique.

![Figure 2.6: Dialog window (a) to mark tentative peaks position, (b) for setting parameters of the etalon and widths at peaks percentage height](image)
2.5 Instruments detail used for the investigation of dye laser

The dye laser is characterized, like other laser, in terms of output parameters such as spectral contents (wavelength and bandwidth), optical power, pulse shape, tuning range and laser beam qualities (divergence and coherence). In this section, brief description of the instruments involved in the measurements of dye laser average optical power, pulse profile, tuning range and beam qualities is presented.

2.5.1 Tuning range

For the tunable dye laser, knowledge of complete spectral coverage might be required along with spectral purity. Thus, the dye laser spectral coverage (i.e. tuning range) was measured with the help of spectrometer and software. Spectrograph (USB2000, Ocean Optics) [2.27] interfaced to the PC through USB port was used for the investigation of the dye laser tuning range. A fractional part of the dye laser beam was directed through optical fiber onto the entrance slit of the instrument to the diffraction grating of the spectrometer. The USB2000 spectrograph uses internally a line CCD to collect the photons. The complete spectrum was acquired by using GUI based another software, which was named as Tarang. It has a facility to generate the composite image from the acquired spectrums. To find the tuning range, composite image was generated during the wavelength tuning. By analyzing this composite image the tuning range measurement of the dye laser can be carry out.

2.5.2 Pulse shape

Knowledge of dye laser pulse profile information is very important for applications. For the detection and measurement of optical pulse of the dye laser operating in nanosecond ranges, a very fast phototube/photodiode, along with digital oscilloscope,
are generally used [2.28-2.29]. Fast oscilloscopes are generally used to observe the exact
d wave shape of the signal generated across the detector. A commercially available biplanar
phototube, capable of reproducing ultra-fast pulsed light signals with high accuracy, along
with fast digital oscilloscope was used for acquisition of dye laser temporal behaviour of
the pulses. Biplanar phototube model R1193U-51 (Hamamatsu, Japan) was used for the
laser pulse profile measurements. The phototube system is connected through BNC to
Tektronics 3052 oscilloscope, which is interfaced to PC through USB port by using GPIB
to USB converter.

Dedicated software, named as OsciloGraph, was used for temporal investigation
of the dye pulses. This GUI based software was used for the dye laser pulse data
acquisition and subsequent analysis. The acquired traces are displayed on the PC, moving
mouse over it displays time in the selected unit, amplitude and its percentage with respect
to peak value. A composite image generation technique, similar to described earlier, has
been used to acquire and measure pulse width and its fluctuations, from the acquired
oscilloscope (1-D) traces. The software provides detailed measurements of amplitude,
temporal width, rise & fall time and counts under the trace, etc. The height of the stacked
image depends on the number of traces acquired and its width depends on the number of
elements used in the digitization of the trace.

2.5.3 Optical average power

Average output power of laser beam is generally measured by a pyro-electric
detector, as it covers wide spectral response. In this type of detector, the incident radiation
raises the temperature of the sensor which is measured by thermocouples or temperature
dependent resistors attached to it. Average output power in our experiment was measured
with the help of a commercially available Ophir power meter. It consists of smart head (SH) and USB interface module, to connect the PC through the USB port for recording power. Power meter sensor heads 2A-SH and F300A-SH were used to record dye laser and copper vapour laser optical average power, respectively.

2.5.4 Beam size and divergence

The divergence of laser beam is a measure for how fast the beam expands far from the beam waist, i.e., in the so-called far field. There are four types of beam size measurement techniques, namely, pin hole, slit, knife-edge and camera based system. Each technique has specific advantages and disadvantages. In this work, only CCD camera and imaging system was used to measure the horizontal and vertical divergences. The intensity distribution of the dye laser beam was recorded using PROMISE software by high resolution scientific grade 12 bit PixelFly CCD camera. The measurement from the recorded data directly provides the dye laser beam size and divergence in both horizontal and vertical direction with sub pixel accuracy by using second moment’s algorithm.

2.6 Coherence measurements of pulsed dye laser

Coherence is one of the fundamental characteristics of laser, which discriminate between laser radiation and other types of radiation (e.g., radiation of thermal origin). A very few studies were reported on coherence property of the tunable dye lasers [2.30]. Singh et al [2.30] measured the divergence of dye laser from the spatial intensity profile of the laser spot using a pinhole and photomultiplier tube (PMT). They reported that the output beam from the dye laser was elliptical in shape because of its different divergences in the horizontal and vertical directions. The divergence of the dye laser beam obtained was 10.2 mrad in the horizontal direction and 1.5 mrad in the vertical direction. This
asymmetry in the beam divergence arose because of the difference in the dimensions of the gain region in the horizontal and vertical directions. However, spatial coherence is the true representation of beam quality of a laser. Further, the study of coherence properties of tunable dye laser is also very essential in order to get tunable ultra-violet laser, by frequency doubling using an intra-cavity non-linear crystal, which has many applications in laser photo-chemistry and high-resolution spectroscopy. Measurement of temporal coherence is of almost importance being linked with bandwidth of laser.

2.6.1 Spatial coherence

Since early days of laser invention the reversible shear interferometer [2.31-2.32] and Young’s double slit [2.33-2.34] have been reported in the literature to measure the spatial coherence of laser. Reversible shear interferometer requires collimated beam and also reasonable beam size for overlapping of two beams in order to get number of fringes. For the study of spatial coherence of dye laser, which has different horizontal and vertical divergence and small beam size, reversible shear interferometer is not appropriate. Young’s double slit is standard technique, used to measure the spatial coherence of light.

The visibility or contrast of the fringe due to interference of two beams of light from a source is defined in terms of the maximum intensity, $I_{\text{max}}$, at the center of a bright interference fringe and minimum intensities, $I_{\text{min}}$, at the center of the adjoining dark fringe, as

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \quad (2.6)$$

Furthermore, the intensity at any point can be written [2.35] as
\[ I = I_1 + I_2 + 2 \sqrt{I_1 I_2} R_s \gamma_2(x) \]  
\[ I = I_1 + I_2 + 2 \sqrt{I_1 I_2} \frac{\sin\left(\frac{\pi d s}{R \lambda}\right)}{\pi d s/R \lambda} \cos\left(\frac{k d x}{D}\right) \]

where \( I \) is the intensity at the slit location, \( s \) is source size, \( R \) is the distance of the source from the slit, \( D \) is the distance of the fringe pattern location from the slit and \( d \) is slit separation. From the above equation, the fringe visibility can be written as

\[ V = \left| \frac{\sin\left(\frac{\pi d s}{R \lambda}\right)}{\pi d s/R \lambda} \right| \]

Visibility of the fringe has been evaluated as a function of slits separation, for different source size of 0.1, 0.12 and 0.2 mm at the peak wavelength 576 nm of the dye laser [2.36]. Fig.2.7 shows the typical variation of visibility of dye laser (576.00 nm) with slit separation.

![Figure 2.7: The typical variation of visibility of dye laser (576.00 nm) with slit separation](image-url)
The solid curve is for source size of 0.1 mm, dotted curve is for source size of 0.12 mm and dashed curve is for source size of 0.2 mm diameter. The various slit separation has been tried to maximize the visibility of the fringe of dye laser. Double slit interference fringes were recorded by the CCD camera using PROMISE software.

The interference fringe of copper vapor laser, which is used for dye laser pumping, using Young double slit set-up, was also generated [2.36]. The double slit separated at 100 microns was placed at a distance of 500 mm from the dye laser source. Fig.2.8 shows the typical (a) double slit fringe (b) intensity modulation, of copper vapor laser [2.36]. The central fringe visibility was 0.23. The same setup was used to generate fringe pattern for the dye laser. Fig.2.9 shows the typical double slit (a) fringe pattern, (b) intensity modulation, for the dye laser at 100 microns slit separation [2.36]

![Figure 2.8: Typical record of Young’s double slit (a) fringe, (b) intensity modulation, for CVL, at 100 microns slit separation](image)
The fringe visibility of 0.85 was observed for the dye laser. The dye laser is highly coherent, as compared to its pump source. It is because of the fact that the dye laser spatial coherence is primarily established by its resonator containing a point/shot type source.

2.6.2 Temporal coherence

It is known that perfectly monochromatic source is ideal one. It can be assumed that wave trains from any source contain a number of frequencies, rather than being strictly monochromatic. The intensity, therefore, involves a summation over frequency. The total intensity $I_T$ will be then,

$$I_T = \sum_m I(\nu_m)$$

(2.10)

if the distribution of frequencies involved is continuous rather than discrete, then the sum is replaced by an integral. Thus, the integral becomes

$$I_T = \int I(\nu')d\nu'$$

(2.11)

if $\nu_0$ be the value at the center of the spectrum produced by the source then we write $\nu' = \nu_0 + \nu$, hence
\[ I_T = \int I(\nu) \left[ 1 + \cos(2\pi(\nu_0 + \nu)) \right] d\nu \]  

(2.12)

The cosine term of the above equation can be expanded to give

\[ \cos(2\pi(\nu_0 + \nu)) = \cos(2\pi\nu_0)\cos(2\pi\nu) - \sin(2\pi\nu_0)\sin(2\pi\nu) \]  

(2.13)

With the substitution of

\[ \theta = 2\pi\nu_0 \]  

(2.14)

\[ P = \int I(\nu) d\nu \]  

(2.15)

\[ C = \int I(\nu)\cos(2\pi\nu) d\nu \]  

(2.16)

\[ S = \int I(\nu)\sin(2\pi\nu) d\nu \]  

(2.17)

The intensity equation become

\[ I_T = P + C \cos \theta - S \sin \theta \]  

(2.18)

Using the value of intensities, the visibility \( V \) of the fringe due to interference of two beams of light from a source can be written as

\[ V = \left( \frac{C^2 + S^2}{P} \right)^{1/2} \]  

(2.19)

Lasers of cavity length \( l \) operate in a number of longitudinal modes corresponding to distance \( \frac{c}{2l} \), within the gain profile. For example, a laser operating in three frequencies component with relative intensity coefficients of A, B and C, then the expression for the intensity profile of the laser can be written as

\[ I(\nu) = A \exp\left\{ -\left( \frac{\nu}{\alpha} \right)^2 \right\} + B \exp\left\{ -\left( \frac{\nu + \delta}{\alpha} \right)^2 \right\} + C \exp\left\{ -\left( \frac{\nu - \delta}{\alpha} \right)^2 \right\}, \]  

(2.20)
where, $\delta$ is the peak separation between modes and $\alpha$ is the FWHM of the Gaussian beam. Therefore, the visibility function $V$ for the spectral distribution of laser can be analyzed by measuring the relative intensities and spectral width of the components.

Michelson interferometer is generally used to measure the temporal coherence of the light [2.34]. In Michelson spectral interferometer the two light beams are derived from the same source, and they are brought together after traveling different path lengths. The basic properties of the Michelson interferometer are (a) the ability to make both arms equal in optical length to a fraction of a wavelength, (b) to measure changes of position as measured on a scale (the position of one of the mirror) in terms of wavelength by counting the fringes. The movable arm of Michelson’s interferometer has been used to find the shape and structure of a spectral line and hence measure the temporal coherence of light sources [2.31]. This involves the measurement of fringe visibility as a function of interference order; a subsequent Fourier transformation of the visibility curve gives the profile of the line. The resolving power is equal to the order of interference reached, which is naturally limited to the order necessary to reduce the visibility practically to zero and thus resolve the line. It is suitable and convenient where the coherence length is very small. However, for narrow bandwidth source where the coherence length is of order of tens of centimeters it become very difficult to align and use the interferometer because of impractical arm length. Fabry-Perot interferometer [2.37], used for high–resolution spectrum analysis, is very compact and free from alignment problem encountered in Michelson’s interferometer. In visible region it has largely superseded the Michelson interferometer (and Fourier transform spectroscopy) as a means of spectrum analysis because the spectrum can be read directly from a photographic record of the Fabry–Perot
interference (FPI) pattern. FPI has been used more frequently for high-resolution spectrum analysis. The direct computation of the line profile is easier now than it was with Michelson. Additionally, the Fabry–Perot interferometer easily attains a very high resolving power, in excess of $10^6$, with a fairly good instrumental profile. It also has the great advantage of simplicity.

The relation between spectral line width, and the coherence length and time of a light wave, is provided by damped simple harmonic motion. The spectral linewidth $\Delta \nu$ of a light wave made up of a series of wave trains is determined by $Q$ of the oscillator, which also determines the exponential decay time in each wave train. The temporal coherence is the average coherence length $l_c$, during which the wave train exists for interference fringes [2.38] i.e.

$$l_c = \frac{c}{\Delta \nu}, \quad (2.21)$$

Where, $c$ is the speed of light and $\Delta \nu$ is the spread in frequency (i.e. bandwidth).

Therefore, from equation (2.5) and (2.21), the temporal coherence length become

$$l_c = \frac{c}{FSR \left[ \frac{D_{i_b}^2 - D_{i_a}^2}{D_{2a}^2 - D_{2a}^2} \right]} \quad (2.22)$$

Thus, by computing the parameters and measuring the diameter of fringe the temporal coherence length, associated with the dye laser can be measured by this technique. This technique is general in nature and can be used for any broad spectrum too.

The temporal coherence lengths of the CVL pumped dye laser were analyzed using a FPI [2.25]. The FPI setup used for temporal coherence measurement was the same as described for spectral measurement for dye lasers. Fig.2.10 (a) shows typical Fabry-Perot
fringe of (a) multimode dye laser, (b) single mode dye laser, (c) He-Ne laser. The measured coherence length of this multimode dye laser was \( \sim 10 \) cm. The coherence length of laser light is inversely proportional to the bandwidth of the output laser light; therefore, the coherence length can be extended by reduction of the bandwidth. The measured coherence length of single mode dye laser was \( \sim 60 \) cm. The temporal coherence length is related to the bandwidth of the source. The more narrow the bandwidth of the source, the longer the coherence length. The CVL pumped dye lasers have coherence length generally from a few millimeters to 7 cm [2.39].

![Typical Fabry–Perot fringe](image)

**Figure 2.10:** Typical Fabry–Perot fringe of (a) multimode dye laser, (b) single mode dye laser, (c) He-Ne laser

Thus, the present tunable dye laser is highly coherent. It is because of the fact that the dye laser coherence is primarily established by its resonator components.

In order to validate the alignment and performance of the FPI set-up, the temporal coherence length measurement for commercially available He-Ne (632.8 nm) laser was also carried out. Fig.2.10 (c) shows the typical Fabry-Perot fringe of He–Ne laser. The observed coherence length of He-Ne laser, used in the present experiment, was 19.2 cm. Generally, He-Ne (632.8 nm) lasers have a coherence length of around 10 to 30 cm [2.40]. The typical coherence length of the He-Ne laser is reported to be about 20 cm [2.41].
2.7 Summary

In conclusion, a novel scheme for acquiring and presenting through composite image is formulated and implemented for the investigation of the high repetition rate dye laser characteristics. The work was carried out towards the development and evaluation of a multi-parameter spectral profile data representation model for interactive visualization and investigation of very large data of the high repetition rate dye laser. This technique provides a powerful and effective basis for real-time visualization of a large number of data sets, and is used effectively to represent the statistical feature of a large amount of scientific data.

A diagnostic technique is established for the analysis of spectral structure of a high repetition rate dye laser by deriving explicit relationship of the parameters with ring diameter of the FP fringe. The output characteristics of dye laser are demonstrated by directly measuring the ring diameter of the FP ring. Techniques for precise peak identification, diameter estimation, and all other steps involved in the process for the analysis of the spectral distribution in the dye laser are presented through GUI based software.

Major instruments involved for the dye laser diagnostic are briefly described. Techniques for coherence measurement of narrow bandwidth source, particularly, dye laser and CVL are presented. Spatial coherence measurement using standard double slit experiment shows that dye laser have fringe visibility of 0.85 as compared to 0.23 for CVL. Though the technique is used for dye laser measurement, but in general, can be applied to any source too.
Publications based on this chapter

1. On the coherence measurement of a narrow bandwidth dye laser
   
   
   Nageshwar Singh and H. S. Vora

2. A composite (stacked) picture generation technique for spectral profile representation of dye laser
   
   Optics Communication 282, 4259 (2009)
   
   H. S. Vora and Nageshwar Singh

3. The spectral measurement of a high repetition rate tunable dye laser output using Fabry-Perot fringe,
   
   Optics and Laser Technology 39, 733 (2007)
   
   Nageshwar Singh and H. S. Vora
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[2.41] http://cord.org/cm/leot/course01_mod08/mod01-08frame.htm