On the coherence measurement of a narrow bandwidth dye laser

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Abstract In this paper, we report a new technique for spatial and temporal coherence measurement of narrow bandwidth sources. In particular, coherence measurement of a narrow bandwidth dye laser using Young's double slit method and the Fabry–Perot interferometer has been carried out. In the spatial coherence measurement, a central fringe visibility of 0.85 was observed, and from this measurement, the dye gain medium source size was estimated. The variation in the visibility with slit separation (0.1–3.0 mm) for different source sizes (0.1–0.2 mm) was also analyzed. The temporal coherence length of the tunable dye laser was measured to be 10 and 60 cm for multimode and single-mode operations, respectively. The technique, in general, can also be used for spatial and temporal measurement of broadband spectrum source.

1 Introduction

Coherence is one of the fundamental characteristics of laser, which discriminates between laser radiation and other types of radiation (e.g., radiation of thermal origin). The light from an ordinary spectral lamp or even lasers consists of wave trains of finite length. The length of the wave train is related to the coherence length of light. The spatial coherence is associated with the location of the two waves, whereas temporal coherence is associated with the difference in frequencies of the two waves. The coherence properties of lasers are crucial in many applications such as efficient coupling to optical fibers or non-linear generation of new frequencies [1]. As an example, crystals for second harmonic generation (SHG) or optical parametric oscillations (OPOs), require a pump laser with high spatial and temporal coherence [1]. In the SHG, the maximum conversion efficiency depends on the spatial coherence of the pump source [2].

Tunable pulsed dye lasers have found a wide range of applications [3] in fields like spectroscopy, chemistry, isotopes separation, trace analysis, environment pollution monitoring, etc. The physics and technology of dye lasers have been important research areas in last four decades. Tunability and narrow bandwidth operation are two key areas of investigations related to dye lasers [4]. Very few studies were reported on the measurement of beam qualities of tunable dye lasers. Singh et al. [5] 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 arises because of the difference in the dimensions of the gain region in the horizontal and vertical directions. The study of coherence properties of tunable dye laser is also extremely essential to get tunable ultra-violet laser by frequency doubling using an intra-cavity non-linear crystal. This has many applications in laser photo-chemistry and high-resolution spectroscopy. To the best of our

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knowledge, no report is available on the coherence measurement of a narrow bandwidth tunable dye laser. In this paper, we report the measurement of spatial coherence of narrow bandwidth tunable dye laser using a Young's double slit and the temporal coherence by a Fabry–Perot interferometer. The technique, though used for a narrow width source, can be used for any broadband spectrum.

2 Theory of coherence measurement

2.1 Spatial coherence

Reversible shear interferometer [2, 6] and Young's double slit [1, 7] have been reported in the literature to measure the spatial coherence of a laser. The reversible shear interferometer requires collimated beam and also a reasonable beam size for overlapping of two beams in order to get a number of fringes. For the study of spatial coherence of a laser, which has different horizontal and vertical divergences and a small beam size, a reversible shear interferometer is not appropriate. Young's double slit is a standard technique [1, 7] used to measure the spatial coherence of light. The degree of contrast of the fringes produced by interference of two waves is equal to the degree of spatial coherence between these two waves.

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_{max}, at the center of a bright interference fringe and minimum intensities, I_{min}, at the center of the adjoining dark fringe as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{1}$$

Furthermore, the intensity at any point can be written [8] as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} R_e \gamma_{12}(x) \tag{2}$$

or

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \frac{\sin(\pi ds/R\lambda)}{\pi ds/R\lambda} \cos(kdx/D) \tag{3}$$

where I is the intensity at the slit location, s is the 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 the slit separation, and λ is the wavelength of light. From the above equation, the fringe visibility can be written as

$$V = \left| \frac{\sin(\pi ds/R\lambda)}{\pi ds/R\lambda} \right|. \tag{4}$$

2.2 Temporal coherence

It is known that an ideal source is one which is perfectly monochromatic. It can be assumed that wave trains from

any source contain a number of frequencies, rather than being monochromatic. The intensity, therefore, involves a summation over frequency. The total intensity I_T will then be

$$I_T = \sum_m I(v_m) \tag{5}$$

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

$$I_T = \int_{-\infty}^{\infty} I(v')dv' \tag{6}$$

If v_0 is the value at the center of the spectrum produced by the source, then we write $v' = v_0 + v$, hence

$$I_T = \int_{-\infty}^{\infty} I(v)[1 + \cos\{2\pi\Delta(v_0 + v)\}]dv \tag{7}$$

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

$$\cos[2\pi\Delta(v_0 + v)] = \cos(2\pi v_0)\cos(2\pi\Delta v) \\ - \sin(2\pi\Delta v_0)\sin(2\pi\Delta v)$$

With the substitution of

$$\theta = 2\pi\Delta v_0 \tag{8}$$

$$P = \int I(v)dv \tag{9}$$

$$C = \int I(v)\cos(2\pi\Delta v)dv \tag{10}$$

$$S = \int I(v)\sin(2\pi\Delta v)dv \tag{11}$$

the intensity equation becomes

$$I_T = P + C\cos\theta - S\sin\theta \tag{12}$$

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

$$V = \frac{\left| (C^2 + S^2)^{1/2} \right|}{P} \tag{13}$$

Lasers of cavity length l are operating in a number of longitudinal modes corresponding to distance, $\frac{c}{2l}$, within the gain profile. For example, for a laser operating in three frequencies $v, v + \delta$, and $v - \delta$ with relative intensity coefficients of the components of A, B, and C, respectively, the expression for the intensity profile of the laser can be written as

$$I(v) = \left[A \exp\left\{ -\left(\frac{v}{\alpha}\right)^2 \right\} + B \exp\left\{ -\left(\frac{v+\delta}{\alpha}\right)^2 \right\} \right.$$
$$\left. + C \exp\left\{ -\left(\frac{v-\delta}{\alpha}\right)^2 \right\} \right], \tag{14}$$

where δ is the peak separation between modes and α 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 solving the above equations.

Michelson interferometer is used to measure the temporal coherence of light [7]. In the Michelson 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 (1) the ability to make both arms equal in optical length to a fraction of a wavelength and (2) 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. Movable arms of the Michelson's interferometer have been used to find the shape and structure of a spectral emission and hence measure the temporal coherence of light sources [2]. 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 a narrow bandwidth source, where the coherence length is of the order of tens of centimeters, it becomes very difficult to align and use the interferometer because of impractical arm length. The Fabry–Perot interferometer [9], used for high-resolution spectrum analysis, is very compact and free from alignment problems encountered in the Michelson's interferometer. In the 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 width, the coherence length, and time of a light wave is provided by damped simple harmonic motion. The spectral linewidth Δv 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 [10], i.e.,

$$l_c = \frac{c}{\Delta v}, \tag{15}$$

where c is the speed of light and Δv is the spread in frequency (i.e., bandwidth).

The bandwidth is calculated from the intensity distribution, expressed in terms of the diameters of different orders of the fringes, using the following relation [7, 11]

$$\Delta v = \text{FSR} \left[\frac{(D_{1b}^2 - D_{1a}^2)}{(D_{2a}^2 - D_{1a}^2)} \right] \tag{16}$$

where FSR is the free spectral range of the FP interferometer, D is the diameter, 1 and 2 are the two adjacent FPI orders, and a and b are the two points between which Δv is measured. Recording the FP fringes of the laser and measuring the diameters of different orders of the fringes have been used to measure the bandwidth of the laser. The same has been programed in such a way that the software locates the peaks automatically by finding the slope of the intensity pattern and hence calculates the ring diameter of the fringe from the record. Therefore, from (15) and (16), the temporal coherence length can be written as

$$l_c = \frac{c}{\text{FSR} \left[\frac{(D_{1b}^2 - D_{1a}^2)}{D_{2a}^2 - D_{1a}^2} \right]} \tag{17}$$

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

3 Experimental details

The dye laser used in the present experiment is similar to Ref. [12], which consists of an output coupler mirror (20 %, reflectivity), a dye cell, prisms' beam expander (BE), and a grating in grazing incidence with a tuning mirror. The Rhodamine 6G dye laser was tuned to a peak emission wavelength of 576 nm. The Young's double slit arrangement, used in the experiment for spatial coherence studies, is shown in Fig. 1. Double slits with a separation of 100 μm and 1 mm are placed at a distance of 500 mm from the laser sources. The double slit interference fringes' pattern was imaged onto the 12 bits high-resolution (6.45 × 6.45 μm) digital CCD camera (PCO PixelFly). The temporal coherence lengths of the dye laser were

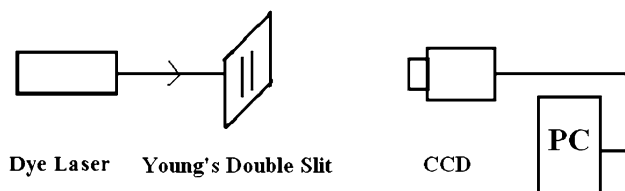analyzed using a Fabry–Perot interferometer. The Fabry–Perot interferometer setup used for temporal coherence measurement is shown in Fig. 2. It consists of a BE, aperture, Fabry–Perot etalon, lens, and a high-resolution CCD camera connected to the personal computer (PC).

4 Results and discussion

The various slit separation values have been tried to see the maximum visibility of the Young's slit fringe pattern. Figure 3 shows (a) the typical double slit fringe and (b) intensity modulation along a line at 100 μm slit separation of the dye laser. The typical dye laser fringe visibility of 0.85 has been observed. The visibility of Young double slit fringe has been evaluated as a function of slit separation for different source size of 0.1, 0.12, and 0.2 mm at the peak dye laser wavelength of 576 nm. Figure 4 shows the variation of the visibility of the fringe as a function of slits' separation at different source sizes. The solid curve is for a source size of 0.1 mm, the dotted curve is for a source size of 0.12 mm, and the dashed curve is for a source size of 0.2 mm diameter.

The visibility or degree of coherence is the property of the source. Attempts were made to estimate the dye laser gain medium source size from the observed visibility. The dye laser source size, which is the penetration depth of the pump beam in the dye medium, has been estimated using Beer's law given by Duarte and Hillman [3] $I/(\sigma_{01}N)$, where $\sigma_{01} = 1.66 \times 10^{-16}$ cm^2 is the absorption cross section for Rhodamine 6G at $\lambda = 510.6$ nm, and N is the dye concentration. The value of the penetration depth of the pump beam in the medium for Rhodamine 6G dye laser in the present experiment is ~102 μm at a given pump power. In practice, the penetration depth of the pump beam is higher than that estimated from above considerations. A visibility of 0.85 and higher is possible with the source size of 120 μm at the slit separation of 1 mm. Thus, the dye laser average transverse source diameter of the order of 120 μm can be deduced. This is consistent with the observed variation in gain medium size from 120 to 210 μm in a similar system [13]. The estimated value of dye laser source size from the fringe visibility curve is almost in close agreement with the experimental one.
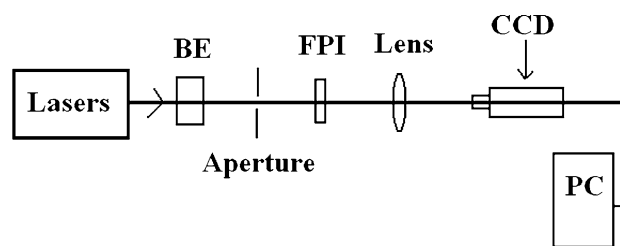
The order of coherence length, associated with the difference in frequencies of the dye laser output, has been measured by the FPI technique. Figure 5 shows the typical Fabry–Perot fringe of a multimode dye laser. The typically measured coherence length of the multimode dye laser is 10 cm. The coherence 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. Figure 6 shows the typical Fabry–Perot fringe of a single-mode dye laser. The typically measured coherence length of a single-mode dye laser is 60 cm. The temporal coherence length is related to the bandwidth of the source. The narrower the bandwidth of
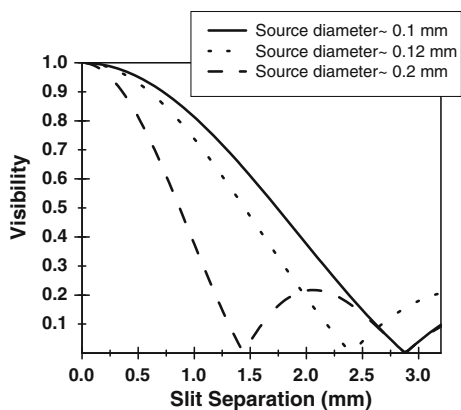
Fig. 4 The variation of the visibility of the fringe as a function of slits' separation at different source sizes

Fig. 6 The typical record of Fabry–Perot interference fringe of a single-mode dye laser
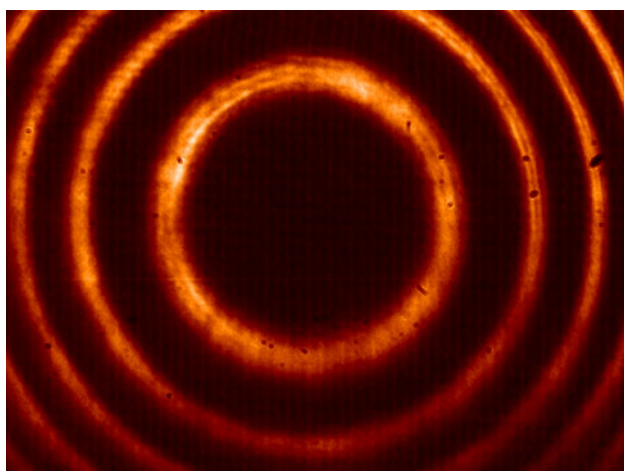

Fig. 5 The typical record of Fabry–Perot interference fringe of a multimode dye laser

the source, the longer the coherence length. The copper vapor laser (CVL) pumped dye lasers have coherence lengths generally from a few millimeters to 7 cm [14]. Thus, the tunable dye laser is coherent. It is because of this fact that the dye laser coherence is primarily established by its resonator components.

Additionally, in order to see the dye laser pump source coherence, in-house developed CVL has been analyzed. CVL is a high repetition rate pulsed laser source in the visible range (510.6 and 578.2 nm) [15, 16]. A dichroic mirror reflecting 510.6 nm at 45° and transmitting 578.2 nm has been used to separate the two wavelengths. The resonator of CVL, used in the present study, consists of one highly reflecting mirror (reflectivity >99.5 %) and the other output coupler (reflectivity 8 %). Figure 7 shows (a) the typical double slit fringe and (b) intensity modulation of the fringe along a line of CVL at 100 μm slit separation. A typical CVL central fringe visibility of 0.23 has been observed. The FPI fringe of CVL wavelengths 510.6
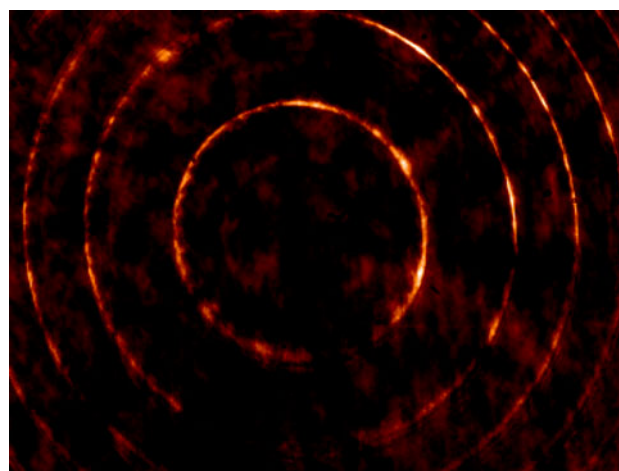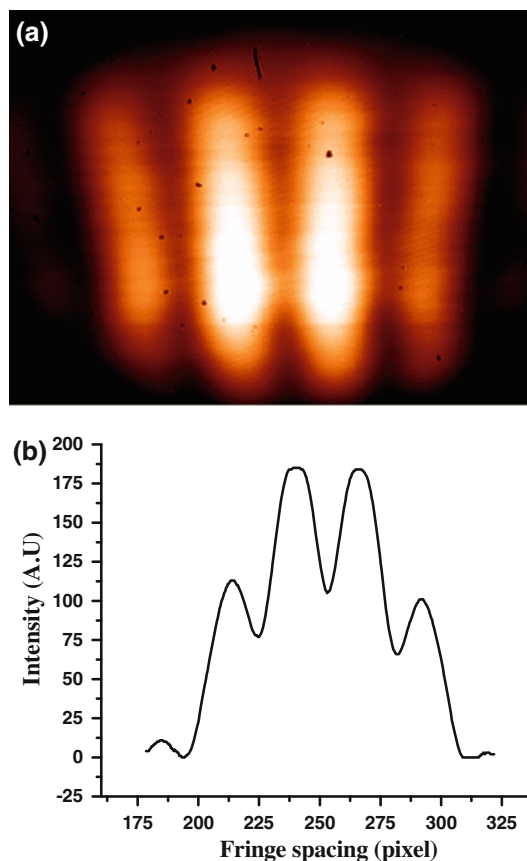

Fig. 7 a The typical record of the double slit fringe pattern of CVL, **b** intensity modulation of the double slit fringe along a line of CVL at 100 μm slit separation

and 578.2 nm is shown in Figs. 8 and 9, respectively. Each has three frequency components. The estimated coherence lengths are ~43 and ~27 mm for the frequency components 510.6 and 578.2 nm, respectively.
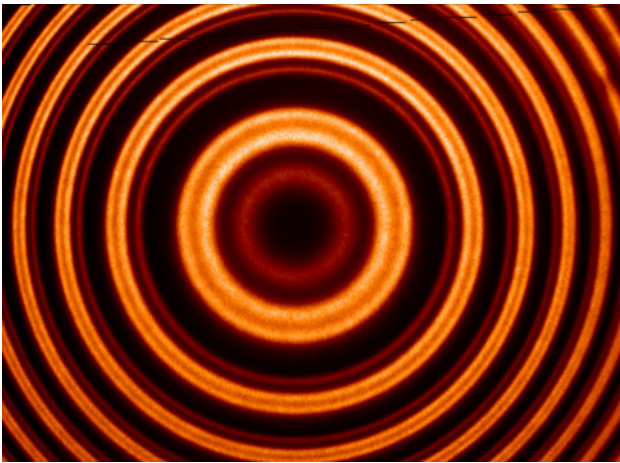
Fig. 8 The typical record of Fabry–Perot interference fringe of wavelength (510.6 nm) of CVL
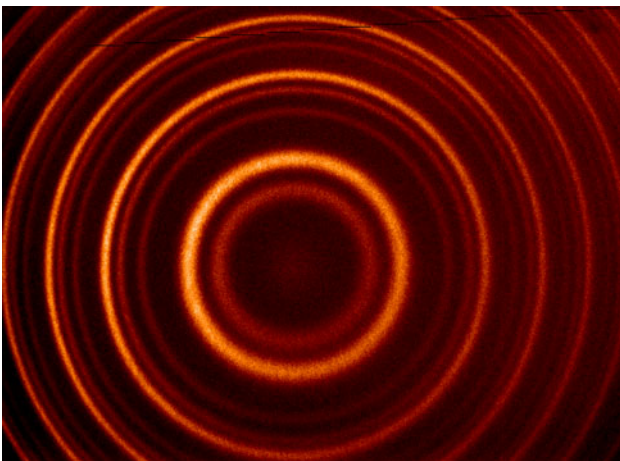

Fig. 9 The typical record of Fabry–Perot interference fringe of wavelength (578.2 nm) of CVL
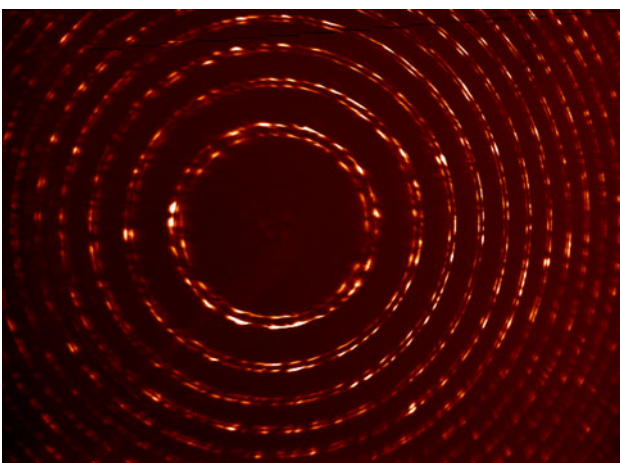

Fig. 10 The typical record of Fabry–Perot interference fringe of He–Ne laser

In order to validate the alignment and performance of the FPI setup, the temporal coherence length measurement of a commercially available He–Ne (632.8 nm) laser was also carried out. Figure 10 shows the typical Fabry–Perot fringe of the He–Ne laser. The observed coherence length of the 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 10–30 cm [17]. The typical coherence length of the He–Ne laser is reported to be about 20 cm [18].

5 Conclusions

In conclusion, the maximum spatial fringe visibility of 0.85 has been observed using the double slit experiment. Visibility of the Young's fringes' pattern has been used to measure the extent of the spatial coherence, and the source size of the gain medium of tunable dye laser was estimated. The Fabry–Perot interferometer-based setup was formulated to measure the coherence length of narrow bandwidth tunable dye laser source. The dye laser coherence length varies from 10 to 60 cm, depending upon the spectral purity (multi/single-mode). The dye laser is highly spatially and temporally coherent. Though the technique is used for dye laser coherence measurement, in general, it can be applied to any broadband spectrum source.

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