CHAPTER 4

Coherence Measurements of the Light of the Firefly

4.1 Introduction

The emission of light from lasers is characterized by a high degree of ordering of the light field. The term ‘coherence’ is originated from the Latin verb ‘cohaerere’, which means ‘to join together’ [1], and is highly regarded as one of the most fundamental and unique characteristics of lasers. It is important from the point of view of its tremendous applications in holography, spectroscopy and to a large extent in communications [2], and in recent times, it is extensively used in the non-linear generation of new frequencies [3]. It is that property by which waves of light remain in phase with one another. For a random laser, as the multiple scattering process is elastic, it is possible only with incoherent feedback [4].

For any electromagnetic wave, two types of coherence can be distinguished viz. temporal and spatial. Radiation field at a given point $P$ is temporally coherent if nearly the same phase difference,
\[ \varphi_n = \varphi_n(P, t_1) - \varphi_n(P, t_2) \]  

exists between two different times \( t_1 \) and \( t_2 \) for all the partial waves, coming out of an extended source [5]. Thus, it represents the ability of a wave to interfere with a time shifted copy of itself over a propagation length known as coherence length during the time in which the phase of the wave changes by a significant amount and reduce the interference [1]. As the formation of fringes is a manifestation of temporal coherence, arising from correlations that exist between two interfering beams after introduction of a time delay \( \Delta t \) [6], it is widely useful in interferometry.

It is well known that temporal properties of light beams can be accessed by using either a Michelson interferometer [5-7], or a Fabry-Perot interferometer [8]. In the Michelson interferometer, a beam is divided into two and again re-united after introducing a path difference,

\[ \Delta l = c \Delta t \]  

where \( c \) is the speed of light in vacuum and \( \Delta t \) is the time delay [6]. Therefore, the primary advantages of finding coherence length in the Michelson interferometer are (1) one has the ability to arrange both arms of the interferometer equal in optical length up to a fraction of a wavelength, and (2) to measure the changes of position of one of the mirrors from a scale in terms of wavelength simply by counting the number of fringes [9]. Movement of one of the arm of the interferometer involves measurement of fringe visibility as a function of interference order using Fourier transform spectroscopy [9], or as a function of optical path difference [8, 10].

The spatial or transverse coherence, on the other hand, describes how far apart two sources or two points of the same source can be located in a direction transverse to its
propagation and still exhibit interfering properties over a range of observation points [11], thereby, denoting the transverse distance between two points of the wave over which they exhibit interference [1]. Thus, if a constant time-independent phase difference, 

$$\Delta \varphi = \varphi(P_1) - \varphi(P_2)$$  \hspace{1cm} (3)

exists for a total field amplitude at two difference points \( P_1 \) and \( P_2 \), the radiation field is called spatially coherent [5]. Till date, Reversible shear interferometer [12, 13] and Young’s double hole method [5-8] have been considered as the standard ones to measure the spatial coherence length. Measurement of fringe visibility or the contrast of the fringes as a function of coherence length is defined as

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$  \hspace{1cm} (4)

where \( I_{\text{max}} \) is the maximum intensity at the center of a bright fringe and \( I_{\text{min}} \) is the minimum intensity at the center of adjoining dark fringe [9].

In a diffraction grating, though the diffractive and mutual interference effects focus the reflected or the transmitted electromagnetic energy of a source in several spectral orders [14], predominance of a colour in the central principal maximum indicates towards the coherence of that particular colour. In the present chapter, the diffraction pattern of the light of the firefly \( L. \) praeusta recorded in a diffraction grating, and the interference patterns obtained in the Michelson interferometer and Young two pin hole set up are presented.

4.2  Materials and methods

4.2.1  Recording diffraction pattern

Prior to this, one of the strongest specimens of this firefly was made to inhale vapours of ethyl-acetate. The experimental arrangement used to record the diffraction pattern is shown in figure
in which the firefly with continuous glow was kept in front of a Hilger Analytical grating of 15,000 LPI. The distance of the source (firefly lantern) from grating was approximately 1 cm. A Sony Cyber-shot DSC-H7S camera acting as a screen was used to photograph the pattern from a distance of approximately 2 cm. A total of 10 specimens were used for this control experiment, and the experiment was conducted from about 19:00 to 23:00 hours IST at laboratory temperature of 25 °C. The intensity distribution of the diffraction pattern was carried out with the help of open software ImageJ.

![Experimental set up for recording diffraction pattern.](image)

**Figure 4.1** Experimental set up for recording diffraction pattern.

### 4.2.2 Recording interference patterns

#### 4.2.2.1 In Michelson interferometer

The experimental set up to record the interference pattern in Michelson interferometer is shown in figure 2. Before recording, both the mirrors M1 (moving) and M2 (fixed) in the two arms of the interferometer were adjusted to increase the sharpness and visibility of the fringes for zero optical path difference of the two beams.
Figure 4.2 Experimental set up of the Michelson interferometer. The movable mirror M1 can be moved a maximum of 8.5 cm from initial position (M1) towards the beam splitter (B.S.) to M1'; the other mirror M2 can be moved away from the compensating glass plate (C.P.) up to a maximum distance of 3.5 cm to M2'.

By varying the interferometer arms the interferometer was tested for sodium source, and the fringes were found to exist up to a path difference of 3.2 mm, which is the standard value. An intense specimen of the firefly was now kept fitted with a beam expander so that the light waves after passing through diffuser arrived at beam splitter. For recording interference pattern for zero path difference, both the mirrors M1 and M2 were placed at a minimum equidistant optical distance of 12 cm from beam splitter, which is marked at the place 8.5 cm in the interferometer scale, as shown in figure 2. Now, keeping mirror M2 fixed and by turning the screw in assembly of the optical bench on which M1 is mounted, the path difference in the interferometer was introduced gradually in steps of 1 mm towards the beam splitter.
The interference patterns were recorded in each step with a NIKKON D7000 camera, fitted with an AF-S 50 mm NIKKOR f/1.4 G lens. By moving mirror M1 up to a position M1' towards beam splitter, fringes were recorded for a maximum path of 8.5 cm. As the mirror M1 reaches the zero of the scale, which is at a distance of 3.5 cm from beam splitter, it was kept fixed there and the mirror M2 in the other arms of the interferometer was gradually moved away from beam splitter/compensating glass plate again in steps of 1 mm up to a distance of 3.5 cm (position M2', figure 2), which is marked as 12 cm in the interferometer. Thus, interference patterns were recorded for a total path difference of 8.5 plus 3.5 cms. In order to verify the results the interference fringes were also recorded without using diffuser.

4.2.2.2 In Young two pin hole

For the study of transverse coherence, two pin holes of different diameters from 150 µm up to 200 µm were made in different positions in a black paper board of width 0.5 mm with a micro pin. In this control experiment, the firefly with the brightest glow was placed in a groove made in a black coloured thick sponge, and fixed with cotton and Sello tape with its light organ facing the two pin holes. The experimental arrangement is shown in figure 3. To obtain the best possible interference fringes the distance between the lantern and the plane of the holes was varied from 1 mm to 5 mm and the separation between holes was varied from 150 to 200 µm.
However, interference fringes presented here were produced with a constant hole diameter of 160 µm and a gap of 3 mm in between the firefly lantern and the plane containing two pin holes. The fringes were recorded with the same camera, which was used in the Michelson interferometer experiment. The distance of the camera from the plane of the holes was 30 cm. A closer view of the central fringe pattern was also obtained from a distance of 15 cm, and the intensity plots of the interference fringes were carried out by ImageJ.

### 4.3 Results and discussion

#### 4.3.1 Diffraction pattern

The diffraction pattern of the light of the firefly *L. praeusta* along with its intensity distribution is shown in figure 4. The central principal maximum is found to be predominantly yellow. In the other orders of maxima different colours, green and red appear exactly as per the grating equation,

$$(e + b)\sin \theta = \pm n\lambda$$

where $(e + b)$ is the grating element and $\theta$ is the diffraction angle, $n = 0,1,2, \ldots$ and, $\lambda$ being the wavelength of light [15]. That is, green appears first followed by yellow and red. From the pattern, it is evident that in the higher order maxima, green and red bands become broader, while the yellow one narrower. This implies that with increasing orders the wavelength spread $d\lambda$ of red and green sectors become considerable as compared to that of the yellow. It is clearly observable that in the first order maxima the yellow band is noticeably less intense and almost non-existence in the second order.

As the pattern presented here is produced without using any collimating or telescopic lens, this represents an impure spectrum. It is worth mentioning here that for the central image $(n= 0)$, the path difference is zero for each wavelength of a polychromatic source, therefore the
central maxima of different wavelengths coincide forming the central image obviously of the same colour as that of the primary source of light [15]. As three colours overlap in the diffraction pattern, being deviated by different amounts, the colour with greater intensity dominates one particular order. Hence, it gives a good representation of the relative intensity spreads of the most intense yellow portion in the wavelength sectors.

As the central principal maximum is predominantly yellow in the diffraction pattern, and the narrow yellow sector is suppressed considerably in the higher order maxima, we propose that the photons in the yellow sector exhibit coherence properties. The detection of a sharp and intense line at 591 nm in the emission spectra of this firefly [16] appears to have supported this proposition. Another noticeable aspect of the pattern (figure 4) is that in the first order maximum, especially on the right hand side of the principal maximum, the yellow boundary is quite marked. It is inferred that the firefly light has a tendency for spectral narrowing in the narrow yellow sector of emission [17], which is firmly substantiated by the diffraction pattern, presented here.
Figure 4.4 (a) Diffraction pattern of the light of the firefly. The central principal maximum is yellow. The other colours green and red appear from the first order maxima. In the higher order maxima, the yellow sector shrinks considerably, and the boundary separating the yellow portion from green and red sectors is quite marked (b) Intensity distribution of the diffraction pattern.
4.3.2  Interference patterns

4.3.2.1  Temporal coherence

The interference pattern of the light of the firefly *L. praeusta* at zero optical path difference of the two beams recorded in the Michelson interferometer, and the corresponding oscillating intensity plot is shown in figure 5. The pattern strikingly reveals thin concentric circular yellow rings. For an equal optical path length of the two interfering beams, the contrast of the interference fringes produced is always good as they traversed the distance in between the interferometer in equal times [7], and this particular pattern represents that. A close observation on green and red colours indicates that those are diffused and scattered in between bright yellow concentric rings. The dark regions are not exactly dark; those are occupied by green and red. We can consider the emissions in the narrow yellow sector as *signal*, and that in green and red regions as *noise*. In spite of the effect of this *noise*, the yellow bright rings are quite distinct.

It is considered significant that formation of fringes in the observation plane as arising from addition of spatially periodic distributions, each of which being formed by a frequency component of the light spectrum, and with an increasing time delay in between the two beams their addition produce a less and less well-defined fringe pattern, because of the maxima of various monochromatic components get more and more out of step [6], or slightly displaced with respect to one another [7], and that appear with poorer and poorer contrast in between the dark and bright fringes. It is clearly evident in figure 6 for path differences of 2 and 4 cms of the two mirrors.

On moving mirror M1, the movable one, approximately 6 cm towards the beam splitter, fringes begin to appear in two individual images, as shown in figure 7. It is important to mention that the light emitting organ of firefly has two segments of width approximately 1 mm
**Figure 4.5** (a) Interference pattern of the light of the firefly *Luciola praeusta* in the Michelson interferometer at zero optical path difference of the two mirrors. Rings are bright yellow in colour, while the dark spaces appear to be filled by green and red. As expected, this pattern represents fringes of best contrast. (b) Oscillating intensity plot of the pattern. Although the dark regions are occupied by green and red colours, the interference maxima are quite distinct, especially in the rising and falling halves, away from the center. A total of eight maxima in each halves could be observed in this plot.
separated by a fraction of a millimeter due to which the interference fringes appear in two individual images. It is quite clear that light from two segments appear to arise from two different sources, and hence we have to consider the external envelope of the two images for quantifying the temporal coherence length to an approximation. With increasing path difference, as presented in figures 7 and 8, the contrast of interference patterns appear to be more diminished. In the present experiment, as the noisy green and red emissions fill up the dark spaces in a random fashion, the measurement of visibility of fringes as a function of coherence length is considered to be pointless. Still, to have a general idea on the distribution of intensity, intensity plots of the interference fringes for various path differences are presented in figures 6-8. It could be mentioned here that as the contrast of the fringes decreases gradually, a 2-point smoothening work for figure 7, a 3-point smoothening for figure 8 (a) and an 8-point smoothening for figure 8 (b), are done in origin 6.0 to reduce the noises. In the present experiment, with a considerable decrease in the contrast for a path difference of 11.5 cm, as presented in figure 8 (b), we can consider this to be a limiting case. The intensity plot of the fringe pattern also substantiates that. As the coherence length \( l_c = 2 \times \text{optical path difference} \) [18], hence the coherence length \( (l_c) \), of this light more specifically of the yellow coloured firefly light should be at least \( 2 \times 11.5 \text{ cm} = 23 \text{ cm} \).
Figure 4.6 (a) Interference pattern for a path difference of 2 cm of the two mirrors, and its intensity plot. Similar bright yellow rings to those of zero optical path difference appear with dark spaces covered by green and red colours of slightly diminished contrast than that obtained for zero path difference. The maxima in each of the rising and falling halves are clearly noticeable in this plot. (b) Interference fringes for difference in the arm length of 4 cm in the interferometer and the corresponding intensity distribution. The contrast in between bright and dark gets more diminished, which could also be prominent in the intensity plot.
Figure 4.7 Interference patterns alongwith the intensity plots obtained in the Michelson interferometer for the Indian firefly *L. praeusta* for the difference in the arm length of (a) 6 cm (b) 8 cm. Fringes appear individually in the two images on moving one of the mirror towards the beam splitter, while the envelope of the combined fringe patterns produced by the two light emitting segments show a much lower contrast. Here, a 2-point smoothening work is done to ‘clean’ the intensity plots in both the cases, and to avoid the individual interference patterns formed by the two images, the region selected for the intensity profiles are in between these two. Six and three interference maxima, respectively, are clearly prominent in both the rising and falling halves of the plots.
Figure 4.8 (a) Interference pattern for a path difference of 10 cm, and its intensity profile after a 3-point smoothing. Although the fringes appear with much poorer contrast, still two prominent maxima in each halves are clear. (b) Interference pattern for a path difference of 11.5 cm of the two mirrors, and its intensity plot after 8-point smoothing work in origin 6.0 to reduce the fluctuations. Fringes just disappear, but the individual fringes still remain in the pattern, and the fluctuations appearing in the constant intensity regions are the usual ones that present in the firefly light beam, and consequently this length may be considered as the limiting one for the present experiment.
Random laser normally exhibits low temporal coherence length in between 10 to 20 μm [19, 20]. For a typical 1.064 μm Nd: YAG laser (FWHM = 0.45 nm) the coherence length is just over 2 mm [21], and that for a pulsed one, it is normally on the order of a few centimeters [22]. An 800 nm diode laser have a coherence length of about 0.64 mm [23]. Compared to these values, the 23 cm long coherence length for firefly light can be considered to be a striking one. Very recently, the coherence length of a multimode narrow bandwidth tunable dye laser is reported as 10 cm, and for a multimode 632.8 nm helium-neon laser as 19.20 cm, and for a copper vapor laser of wavelengths 510.6 and 578.2 nm as 4.3 and 2.7 cm, respectively [21]. This value also varies from a few millimeters to 7 cm for a copper vapor pumped dye laser [24]. The red cadmium line at 643.8 nm exhibits coherence length of about 30 cm [7]. These values, as a matter of fact, are compared favourably well to that of the firefly yellow light.

From \( l_c = c \tau_c \), and considering \( c = 3 \times 10^{10} \) cm and \( l_c = 23 \) cm, we have the coherence time, \( \tau_c = 7.66 \times 10^3 \) s. Thus for the firefly yellow light at 591 nm [16], we have,

\[
\tau_c = \frac{\lambda^2}{c \delta \lambda}
\]

or \( \delta \lambda = \frac{\lambda^2}{c \tau_c} = 1.5 \times 10^{-3} \) nm.

Therefore, the FWHM of the sharp yellow line of the firefly bioluminescence emission is considered to be of the order of \( \sim 10^{-3} \) nm. It is reported that random laser normally exhibits broad emission spectra of bandwidth of approximately 10 nm [20]. The typical linewidth for an 800 nm diode laser, as well as for a multimode free-running diode laser is 1 nm [23, 25].

**4.3.2.2 Spatial coherence**

In the Young two pin hole experiment, interference fringes recorded for a constant hole diameter of 160 μm at pinhole separations of 160, 170 and 180 μm along with their intensity
Figure 4.9 Interference patterns of the light of the firefly recorded in the Young two pin hole experiment for a constant hole diameter of 160 µm (a) for a hole separation of 160 µm: central as well as first order fringes come out with a good visibility of 0.65 in between the bright and dark fringes (b) for a hole separation of 170 µm, showing a lower visibility of 0.56 (c) for a hole separation of 180 µm: the contrast in between the bright and dark fringes is reduced by a significant amount. The central fringe visibility is 0.39 (d) a close view of the central fringe pattern recorded from 15 cm distance, showing the effect of green and red noises on the bright yellow.
profiles are shown in figure 9. Using the equation 4, the best central fringe visibilities for these three cases are measured as 0.65, 0.56, and 0.39, respectively. The interference pattern presented here is quite similar to the one, obtained in a double slit interference experiment, and the inference is that the firefly emission has a tendency for spectral narrowing in the narrow yellow sector [17]. In the present experiment, due to the faintness in the intensity of firefly emissions, the hole diameter had to be increased to a large value, due to which overlapped fringe patterns appear from hole separation of 170 µm. Large pin holes along with the noisy green and red emissions definitely affect the visibility of the fringes. In spite of this, the interference fringes are reasonably good in appearance. In order to observe the effect of green and red sectors on yellow fringes, a close up view of the central fringe is also shown in figure 9 (d).

The measured fringe visibilities compare favourably well to the spatial coherence fringes for a random laser containing Rh6G and Al₂O₃ nanoparticles, excited above the lasing threshold, exhibiting a maximum visibility of 0.34, and as well as to a narrow bandwidth dye laser at a slit separation of 100 µm, showing a central fringe visibility of 0.85 [9]. It is reported that the random lasers have a spatial coherence much lower than that of the conventional lasers [26-29], and they can be engineered to provide low spatial coherence [30].

4.3.2.3 Validation Works

To validate the above experiments, interference patterns have been recorded in the Michelson as well as in the Young’s double hole set up for a 632.8 nm He-Ne laser, 405 nm diode laser and sodium light sources. For He-Ne laser interference patterns have been found to exist up to path difference of 9.5 cm of the two mirrors, which is the standard value. The interference fringes of He-Ne laser recorded for zero, 4.6, and 9.5 cm path difference are shown in figure 10. Similarly, for diode laser the interference patterns have been recorded for zero, 160 and 280
\( \mu \text{m} \) differences of the interferometer arms, and are shown in figure 11. Fringes for a sodium light source for zero and 3.2 mm path difference are shown in figure 12. As the appearance of contrast of the interference fringes decreases gradually with an increase in path difference in the two arms of the interferometer, the temporal coherence length for He-Ne, diode lasers and sodium source are measured to be approximately 19.2 cm, 570 \( \mu \text{m} \) and 6.6 mm, respectively. These values, as a matter of fact, are well known as the standard ones. In the Young’s double pin hole experiment, interference fringes obtained for He-Ne laser, diode laser and sodium light sources are shown in fig.13-15.
Figure 4.10 Interference patterns obtained in the Michelson interferometer for a commercial 632.8 nm He-Ne laser (a) for zero path difference of the two mirrors, showing fringes of best contrast (b) for a path difference of 4.6 cm, fringes come out with diminishing contrast (c) for a path difference of 9.5 cm, showing much poorer contrast, which is considered to be the limiting case.

Figure 4.11 Interference patterns obtained with a 405 nm diode laser (Pegasus Shanghai) for the difference in the Michelson interferometer arm of (a) zero (b) 160 and (c) 280 µm, which is the limiting case as the contrast of the fringes become very poor.
Figure 4.12 Interference fringes of sodium light recorded in the Michelson interferometer for arm differences of (a) zero (b) 3.2 mm, fringes become so poor that this may be considered as the limiting case.

Figure 4.13 Interference fringes in the Young double hole set up for a He-Ne laser for hole separations of (a) 160 µm, showing a contrast of 0.80 in between bright and dark fringes (b) 180 µm, where an average fringe visibility of 0.71 shows that the He-Ne laser light has better spatial coherence than that of the firefly light.
Figure 4.14 Interference fringes obtained in the Young double hole experiment for a 405 nm diode laser for hole separations of (a) 160 µm, (b) 180, and (c) 240 µm. The fringe visibility decreases with increasing hole separations. The divergence is roughly equal to firefly light but worse than He-Ne laser source.

Figure 4.15 Sodium light source in the Young two pin hole experiment for hole separation of 160 µm, no fringes are noticed. We conclude that the divergence of this source is very high as compared to firefly light.
4.4 Conclusions

In this work, we investigate coherence properties of the bioluminescence emissions of the firefly *L. praeusta*. The observed temporal coherence length of a couple of tens of centimeters for this firefly is quite surprising. From the coherence length, the linewidth of the sharp yellow line has also been determined. This value is found to be considerably narrower than many a multimode solid state lasers. We conclude that the firefly yellow emission exhibits excellent temporal coherence. The measured central fringe visibilities in the Young two pin hole experiment also points towards a reasonably good spatial coherence of the light of this firefly.
References


