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Diffraction of the light of the firefly by a grating

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A *control* experiment is performed to study diffraction of the light from three species of fireflies: one Indian species *Luciola praeusta* and two Japanese species *Luciola cruciata* and *Luciola lateralis*. The firefly emits stable, continuous light a few minutes after it is made to inhale vapors of ethyl acetate. The diffraction pattern produced by a plane diffraction grating of this light shows that the central principal maximum is predominantly yellow. From the first order principal maximum onwards, green and red colored bands appear. With increasing orders, these bands become broader which appear to suppress the yellow band. This result suggests that the intense yellow region, as a matter of fact, is very narrow, and the firefly most probably emits coherent yellow-colored light.

1 Introduction

The process by which living organisms, such as fireflies, convert chemical energy to light is called bioluminescence. The enzyme luciferase catalyzes the reaction, which uses luciferin, O_2, ATP and Mg^{2+} to yield an electronically excited oxyluciferin species. Visible light is emitted as the oxyluciferin decays to the ground state. This reaction taking place in the lantern of the firefly is called chemiluminescence reaction. While most of the light-producing chemical reactions are only about 1% efficient, this particular one is well-known for its extremely high quantum yield value [1-3]. That is where the importance of bioluminescence lies.

Fireflies belong to the glow-worm family Lampyridae of which there are more than two thousand species throughout the world, especially in the tropics. It is hypothesized that different species of fireflies emit in different wavelength regions because of slight differences in their enzyme structures. Specimens used for our investigation belong to Indian species *Luciola praeusta* (Fig 1(A)), and Japanese ones *Luciola cruciata* and *Luciola lateralis* (Figs 2(A) and 2(B), respectively). Flashing patterns of these three species of fireflies in control and under a strong static magnetic field are documented recently [4]. It is reported that fireflies of the Indian species *Luciola praeusta* Kiesenwetter 1874 (Coleoptera : Lampyridae: Luciolinae) emit in the peak wavelength 562 nm (greenish yellow) and FWHM (full width at half maximum) 55 nm, extending from 537 nm to 592 nm (green and yellow) [5]. In the same report, it is shown that fireflies of this species emit pulses, displaying resemblance to the output of a multimode laser, of duration approximately 2 microseconds, and about 30,000 pulses constitute a flash of duration approximately 100 milliseconds. For various species of fireflies, measurements on durations of a single flash yield values varying from about 70 milliseconds to a few hundred milliseconds [6-10]. It is shown that the pulses produced by the firefly are manifestations of an oscillating chemical reaction, like the B-Z reaction, and that the continuous train of triangular pulses exhibits both pulse amplitude modulation (PAM) as well as pulse width modulation (PWM) [11-12]. Emission spectra recorded on color films reveal three colors: green, yellow and red, of which the red is not observable to the naked eye under usual conditions [13]. Some of the aspects of firefly flashing studied in recent times are: influences by calcium, nitric oxide vapors, gating of oxygen to light-emitting cells, geographic locations, temperature variations, and static and pulsed magnetic fields [14-19]. Very recently, a narrow strong laser-like line is found in the emission spectrum of the species *Luciola praeusta*, whose similarity with the random laser is hypothesized [20].

In this work, diffraction patterns of three different species of fireflies are obtained by using a diffraction grating. The predominantly yellow-colored region in the central principal diffraction maximum shrinks down considerably in first and second orders, which raises curiosity. This observation points towards coherence in the yellow sector of the light of fireflies.

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2 Experimental procedure

Adult male specimens of the firefly species *Luciola praeusta* were caught during early evening hours in the campus of Gauhati University. One of them was placed in a test tube, the mouth of which was filled with cotton dipped in ethyl acetate. The tube was held upside down and lightly stirred to bring the firefly in contact with the wet cotton. It was observed that the flashing rate of the firefly rapidly decreased. After about a minute, a constant glow appeared from the last segment in the abdomen of the firefly which spread to the other light emitting segment in about 3 minutes. A black patch in the middle of the upper segment of the lantern finally gave way to the glow in 5 to 6 minutes. Adult male specimens of the two Japanese species, *Luciola cruciata* and *Luciola lateralis,* were delivered by an experimental animal provider, Saitama Experimental Animal Co. Ltd., and the experimental protocol was authorised by the ethics committee for biological study in Chiba University prior to the work. Following the same procedure for the Indian species, specimens of these two Japanese species were influenced by ethyl acetate. Specimens of the three species of fireflies are shown in Fig 1(A), Fig 2(A) and Fig 2(B). Specimens of *Luciola praeusta* were of average body length 8 mm and body weight 9 mg, while those of *Luciola cruciata* and *Luciola lateralis* were of average body lengths 15 and 9 mm, respectively, and average body weights 11 and 20 mg, respectively.

A Hilger Analytical grating of lines per inch of 15000 was used for recording the diffraction pattern of this continuous glow. Distance of the grating from the source (lantern) was approximately 1 cm. A Sony Cyber-shot DSC-H7S camera was used to photograph the patterns produced by the light of the fireflies. Distance of the lens of the camera from the grating was approximately 2 cms. A total of 30 specimens of the species *Luciola praeusta* and 3 each of the species *Luciola cruciata* and *Luciola lateralis* were used to perform these *control* experiments.The experiments were conducted from 1900 to 2300 hours IST at Gauhati University, India, and in the early evening hours at Chiba University, Japan. The average temperature in the laboratories during that period was 25 °C. Intensity profiles of the diffractions patterns were plotted with the help of the software Image J.

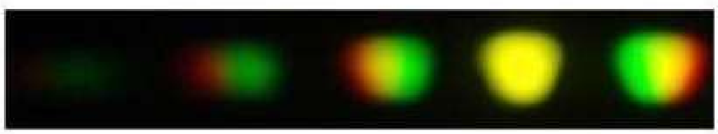
3 Results and discussion

The diffraction pattern of the light from a specimen of the Indian species *Luciola praeusta* produced by the grating is shown in Fig 1(A1) along with the intensity profile in Fig 1(A2). Diffraction patterns produced by specimens of the two Japanese species *Luciola cruciata* and *Luciola lateralis* are shown in Fig 2 with their intensity profiles. The patterns are similar and quite striking. The central principal maxima are yellow. It is worth mentioning here that for a polychromatic source the coloor of the central maximum is the predominant one of the source. In other orders of maxima, different colors appear approximately as per the grating equation $(a+b)sin\theta - n\lambda$, where $(a+b)$ is the grating element, θ is the angle of diffraction, $n = 0, 1, 2, ...$ and λ is the wavelength of light. That is, the green color appears first, followed by yellow and red ones. It is clear that with increasing orders green and red bands become broader – which implies that their wavelength spreads $d\lambda$ are considerable – while the yellow one becomes narrower, implying that its wavelength spread, in fact, is very narrow. The yellow band is noticeably less intense in the first order, and almost non-existent in the second order. The red does not spread as much as the green, and one significant feature is that its boundary is somewhat marked.

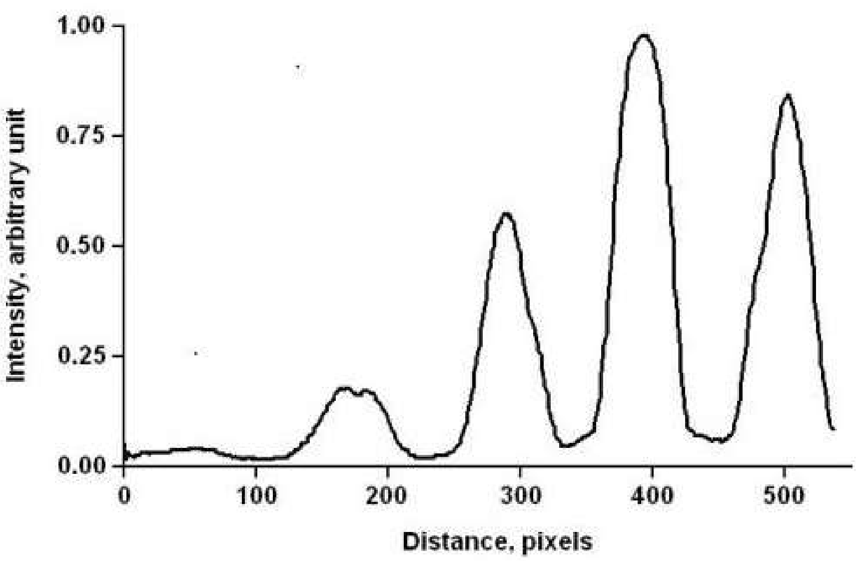
As the central principal maximum, in general, becomes intense yellow in the diffraction pattern produced by the grating, we propose that the yellow photons exhibit temporal coherence property. A sharp intense line, which is a signal-enhanced noise, shown explicitly at the yellow wavelength of 591 nm in the emission spectrum of the Indian species, appears to have supported this proposition [20]. Similar spectra of the other two (Japanese) species would make this proposition conclusive. It is to be noted here that in the present experiment, neither the light falling on the grating was collimated nor the diffracted light going in various orders was collected by a telescopic lens. Hence the spectrum formed was an impure one. As three colors overlap in this diffraction pattern, being deviated by different amounts, the dominant color at a particular location will be the one with the greatest intensity. Hence it gives a good representation of the relative intensity spreads in the wavelength sectors, especially that of the most intense yellow portion.

In the present diffraction pattern, though green and red are completely dominated by the yellow in the central principal maximum, with increasing orders of maxima, green and red bands become broader, which shrinks the yellow band. A significant feature is that in the first order on the right hand side of the principal diffraction maximum for each of the three species (Figs 1(A1), Fig 2 (A1) and Fig 2 (B1)), the yellow boundary is quite marked. It is proposed that the firefly has a tendency for spectral narrowing around the peak wavelength region [13]. The work presented here seems to substantiate that proposition.

(A)



(A1)



(A2)

Fig 1.(A) Indian firefly species *Luciola praeusta*. (A1) Diffraction pattern of the light from a specimen of this species produced by a grating.(A2) Intensity profile of the diffraction pattern. It is plotted with the help of the software Image J.

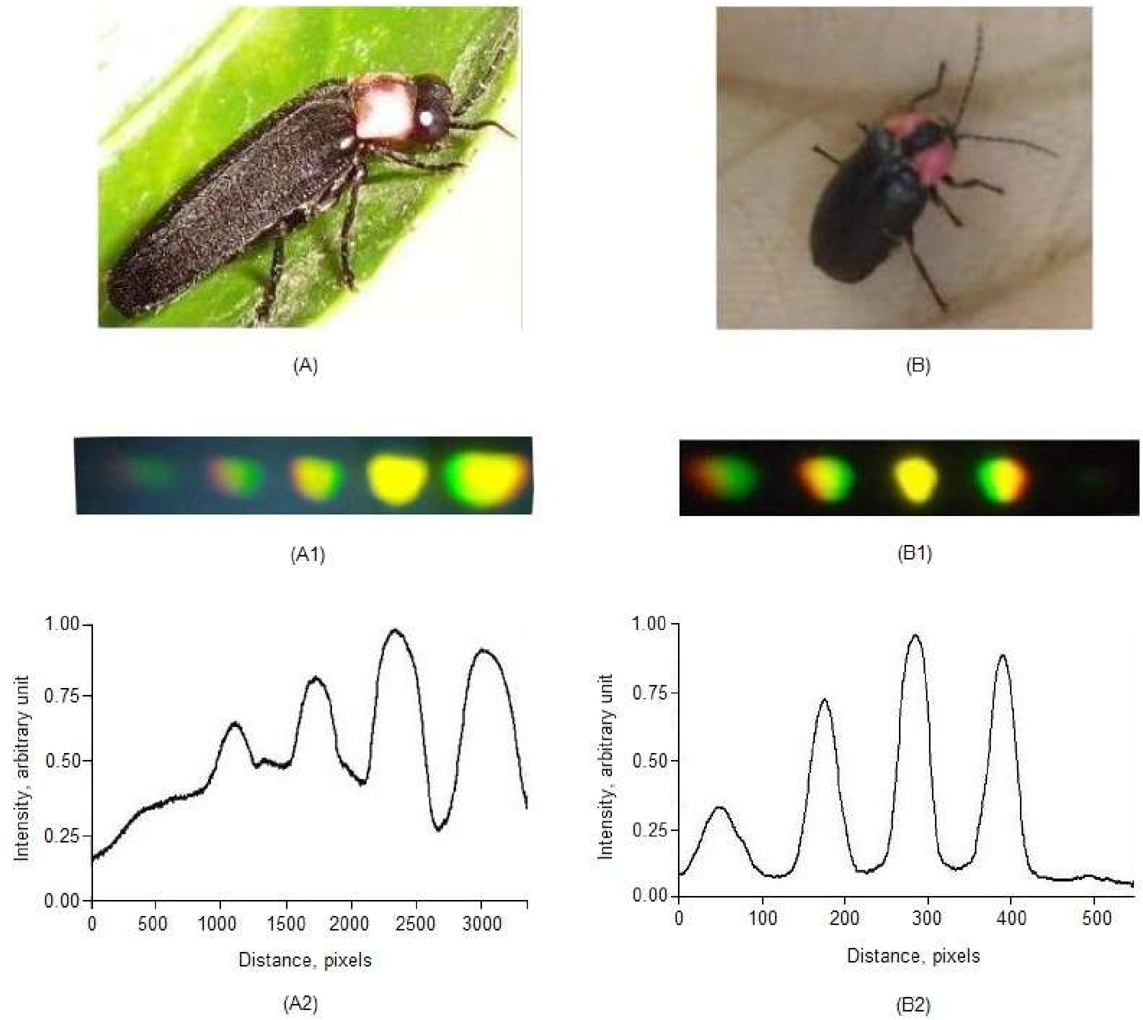


Fig. 2(A) Japanese firefly species *Luciola cruciata*. (A1) Diffraction pattern of the light from a specimen of this species produced by a grating. (A2) Intensity profile of the diffraction pattern, plotted with the software ImageJ. (B) Japanese firefly species *Luciola lateralis*. (B1) Diffraction pattern of the light from a specimen of this species produced by a grating. (B2) Intensity profile of the diffraction pattern, plotted with Image J.

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