T2: High repetition rate, narrow line-width, tunable dye laser activity at RRCAT

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1. Introduction

The Laser System Engineering Division (LSED) at RRCAT aims at establishing a high repetition rate, narrow line-width, tunable dye laser umbrella facility with parameters such as pulse repetition rate from 5 to 20 kHz, tuned wavelength from 550 to 700 nm and from 275 to 350 nm from second harmonic, line-width from 100s of MHz (single mode) to few GHz (multimode), pulse width from 20 to 50 ns and high average output power up to 10 W. The whole facility aims at indigenous laser technology development, basic research in optics and lasers and pursuing tunable laser based spectroscopic application programs.

This article presents the research and development work carried out, mainly in last two years, in the field of high repetition rate tunable dye laser at LSED. Each and every part of dye laser namely dye cells, dye laser mechanical assembly, dye laser optical resonator, dye flow system, precision dye solution temperature control system, computer controlled dye laser wavelength tuning and high repetition rate laser pump sources are indigenously developed. These developments are outlined. Results on pulsed dye laser oscillator performance both in single and multimode operation as well as dye laser master oscillator power amplifier (MOPA) systems are presented. Studies on pulsed amplification characteristics of single mode continuous wave (CW) dye laser, in a pulsed dye laser amplifier pumped by high repetition rate pump laser, is presented. The advanced high power pump laser namely Copper HyBRID laser operating at around 20 kHz repetition rate is briefly described. Though in most of the studies on dye laser, the pump source was conventional 5-6 kHz repetition rate copper vapour laser (CVL), some dye laser results with 5-6 kHz repetition rate 2nd harmonic Nd:YAG laser and higher repetition rate (20 kHz) Copper HyBRID pump lasers are also presented. Initial results on tunable UV generation through second harmonic of dye laser are also presented.

2. Development of high repetition rate, single axial mode dye laser

Fig.T.2.1 shows the experimental set up of the indigenously developed [1,2] single mode dye laser oscillator. It is based on a modified version [3] of a curved SS dye flow cell developed earlier [4]. The optical resonator consisted of double prism beam expander (M ~ 22 at angle of incidence 80^0), an intra-cavity etalon (FSR = 10 GHz, Reflective finesse ~12), and a 2400 lines/mm grazing incidence ($\approx 84^0$) grating. The double prism beam expander folded the incident dye beam about 90^0 with respect to dye cell to fall on the grating. The optical resonator length was about 17 cm. The dye laser output was taken through an output coupler of reflectivity 40 %. All optical components were mounted on a heavy single piece SS plate to reduce the effect of mechanical vibration.

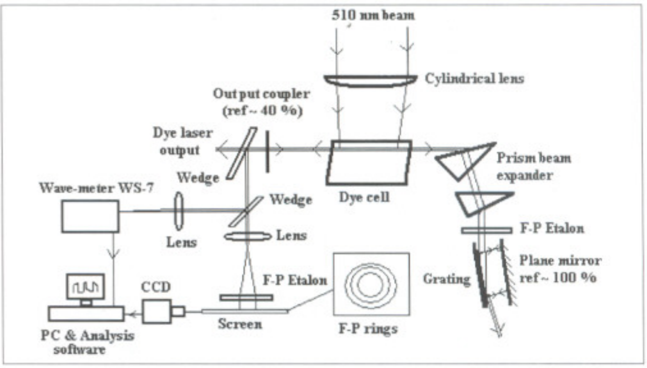

Fig.T.2.1: Experimental set-up of single axial mode CVL pumped dye laser

The dye solution of 2 mM concentration of laser grade Rhodamine-6G dye in the ethanol was circulated through the dye cell. A CVL beam (510 nm) of average power of 3.0 W at the 5.5 kHz transversely pumped the dye laser with the help of a cylindrical lens of focal length 50 mm. The dye gain medium dimension was about 0.2 mm x 0.5 mm x 15 mm. The dye solution flow rate was measured by a flow meter (turbine type, Electronet Equipment, FL-100). The flow rate of the dye solution was controlled by a variable frequency drive to the pump. The temperature of dye laser solution was controlled to 23 ± 0.1^0C by PID controlled thermo electric cooling (TEC) system - a system described in section 3.2. The dye laser line-width was measured by capturing the rings from an external high resolution analyzing Fabry-Perot (F-P) etalon (FSR = 5 GHz, Reflective finesse = 50), onto a time gated CCD (Pixelfly qe, PCO AG). The long term line width evolution was studied by generating time stacked picture of F-P rings by a software facility developed in house [5].

Fig. T.2.2a shows F-P ring pattern of the dye laser oscillator. It clearly demonstrated that single axial mode nature of the dye laser. The laser line-width was estimated from this ring pattern, as ratio of the width at FWHM of peak intensity of second ring to the separation between the 1st and 2nd ring and multiplied the FSR of the analyzing etalon. The measured single mode dye laser line width was about 200 MHz. Evolution of F-P rings with time (Fig. T.2.2b) clearly suggested that the stability of single mode operation of dye laser during the investigated period.

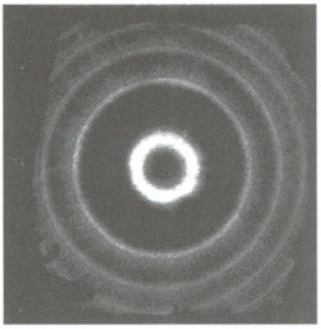

Fig.T.2.2a :Fabry-Perot (FSR 5.0 GHz, Finesse~ 50) rings of dye laser demonstrating single axial mode operation

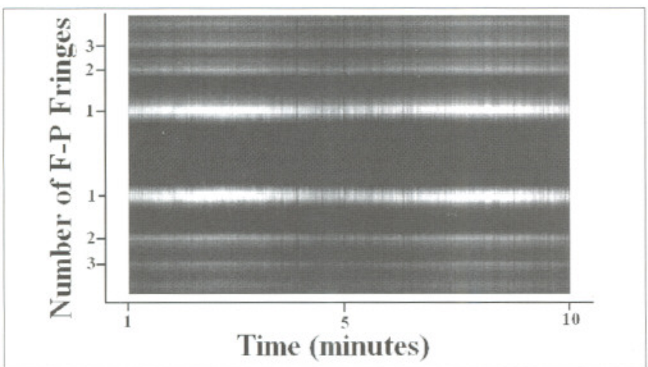

Fig. T.2.2b :Variation of F-P fringes with time, demonstrating stability of single mode dye laser

2.1 Mode hop free tuning of single mode dye laser

The utilization of singe mode dye laser requires the matching of dye laser wavelength with the selected atomic transitions. This, in turn, requires tuning of dye laser wavelength around the transition. Fig. T.2.3 a, b shows the single mode dye laser tuning by separately tilting the tuning mirror and intra-cavity etalon (Fig. T.2.1), respectively. This study was made by a wave-meter (WS-7, Angstrom, High Finesse). A part of the dye laser beam was taken by wedge and guided into wave-meter through the optical fiber. For dye laser tuning, the tuning mirror and the etalon were mounted on separate precision pico-meter drives, controlled by a computer. In both the cases (Fig. T.2.3a,b), dye laser wavelength tuning is accompanied by axial mode hoping. This mode hoping is a clear signature of robust singe mode operation. These mode hops are due to the discrete nature of axial modes as well as a limited value of grating/etalon pass band. For stationary etalon and moving tuning mirror (Fig. T.2.3a), the mode hoping appears due to crossing of successive etalon pass band. The mode hop free tuning of about 2.5 GHz is observed for scanning within a single etalon pass band. The frequency jump of 8 GHz was close to FSR of intra-cavity etalon.

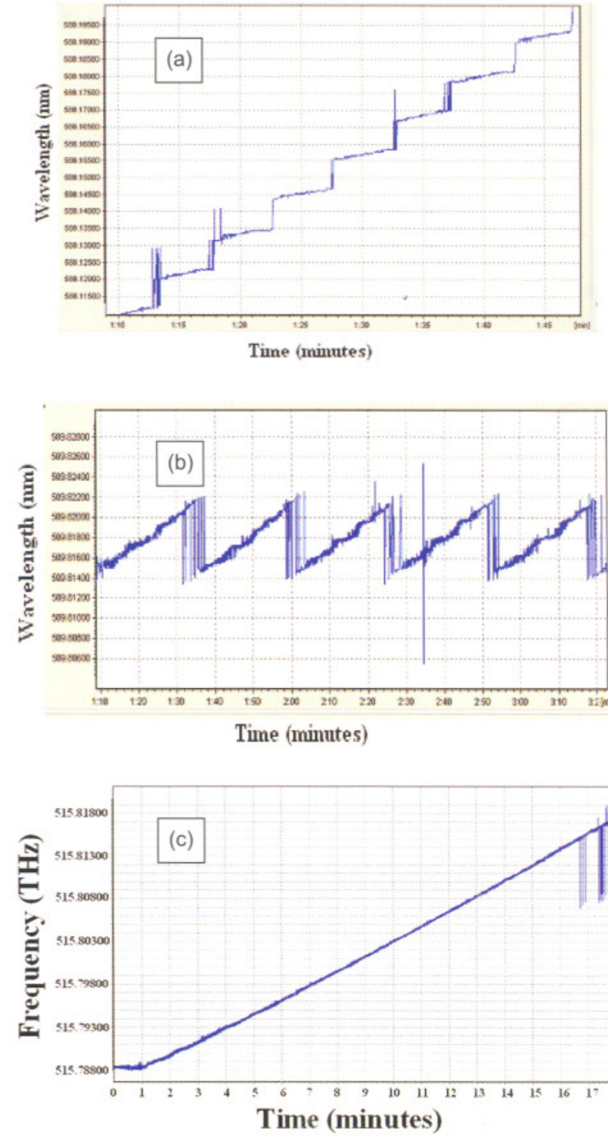

Fig. T.2.3 : Scanning of dye laser wavelength (a) grating tuning with stationary etalon, (b) etalon tuning with stationary grating, and (c) Synchronized tuning of both grating and etalon- Extended Mode hop free tuning

On the other hand with stationary grating and scanning etalon (Fig. T.2.3b) , the wavelength range is periodically scanned by successive pass band of etalon. In this situation, the etalon is scanning the grating pass band. The mode hop free tuning of 8 GHz was obtained.

For many high resolution spectroscopic applications of dye laser, such limited continuous dye laser tuning is not acceptable. For the extended mode hop free wavelength tuning, the tilt of etalon, angle of tuning mirror and the cavity length are to be changed simultaneously in a prescribed manner. In the first phase, the computer controlled simultaneously tilting of the tuning mirror and etalon was implemented in the present single mode dye laser set up (Fig. T.2.1). More than 25 GHz mode hop free scanning was obtained (Fig. T.2.3c). In the second phase, the cavity length control is also being implemented to further enhance the mode hop free scan limits.

2.2 Wavelength and line-width stability of single mode dye laser

The long term stability of dye laser wavelength and line-width is very crucial for dye laser to remain locked to the investigated atomic transition. These dye laser parameters are crucially linked dye solution flow rate and its temperature control. In order to exclusively bring out the role of flow of dye gain medium on wavelength stability of a single axial mode kilo-hertz repetition rate dye laser, other wavelength destabilization effects such as mechanical vibrations and dye solution temperature variation are minimized by using a metal dye cell with circular flow loop, integrating all optical components in one structure and controlling the dye solution temperature to within $\pm 0.1^{\circ}$C as employed in set up of Fig. T.2.1. The flow rate of the dye solution was again controlled by variable frequency drive (VFD) controlling the dye circulation pump. The dye solution flow rate was measured by a flow meter. The real time dye laser wavelength stability was studied with the wave-meter.

Figure T.2.4 (a-d) shows the typical variation of single mode dye laser wavelength with time for about 10 minutes at flow rates 1.4 lpm (flow velocity~3.1 m/sec, Reynold number ~1946), 1.7 lpm (flow velocity~3.9 m/sec, Reynold number~2468), 2.0 lpm (flow velocity~ 4.4 m/sec, Reynold number~2820), and 2.8 lpm (flow velocity~6.1 m/sec, Reynold number~3877), respectively. At flow rate of 1.4 lpm, the central wavelength varied (drift) about 0.5 pm from 587.16120 nm to 587. 16070 nm. The drift rate was about 1.0 MHz/sec. It was observed that the wavelength drift rate reduced to 0.5 MHz/sec (from 587.11860 nm to 587.11825 nm), 0.4 MHz/sec (from 587.11080 nm to 587.11055 nm) and 0. 2 MHz/sec (from 587.10815 nm to 587.10805 nm) at flow rates of 1.7 lpm, 2.0 lpm and 2.8 lpm, respectively. The wavelength jitter was estimated from the graphs (Fig. T.2.4 a-d) in first 30 second around central wavelength. The wavelength jitter was ±0.15 pm (±130 MHz), ±0.10 pm (±87 MHz), ±0.10 pm (±87 MHz) and ±0.08 pm (±70 MHz) at dye flow rate of 1.4 lpm, 1.7 lpm, 2.0 lpm and 2.8 lpm respectively. For the flow rate 1.7 lpm, the wavelength variation was smooth, free from any sudden jump in the wavelength. However at flow rate of 2.0 lpm, some random jump in wavelength was noticed. The number of wavelength jumps further increased at higher flow rate of 2.8 lpm. The observed wavelength jitter/drift and random fluctuation behaviour was linked to the flow related different values/variation of angular spread and angular drift of the dye laser beam circulating in the cavity.

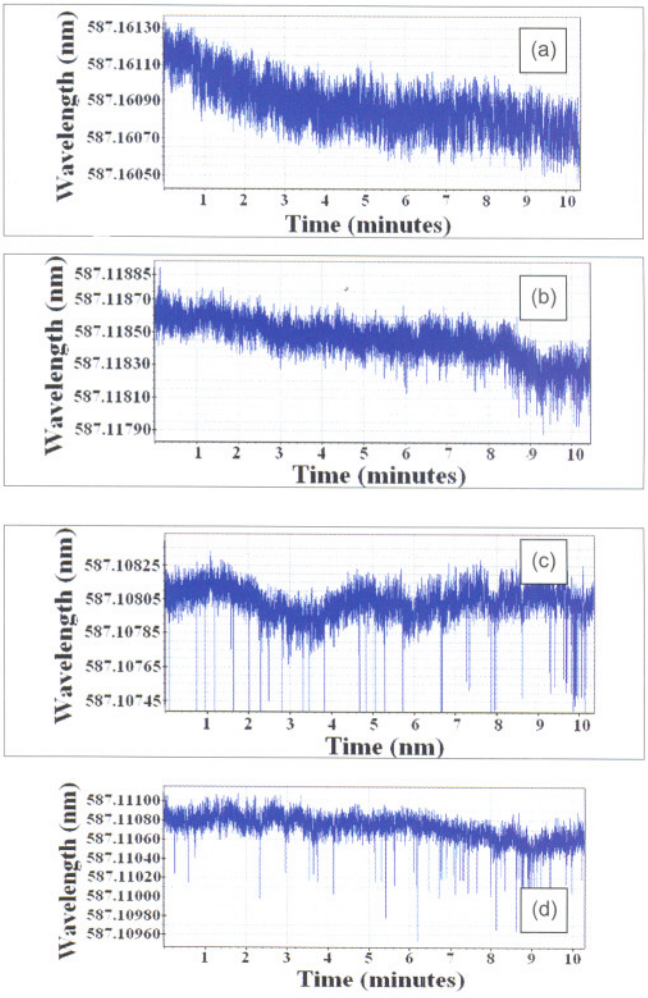

Fig. T.2.4 : Variation of wavelength of single axial mode dye laser with time at the dye solution flow rates of (a) 1.4 lpm (b) 1.7 lpm (c) 2.0 lpm (d) 2.8 lpm

The dye laser spectral stability performance was also studied at a fixed optimized dye flow rate but with coarse control of temperature $23\pm2^{\circ}$C of dye solution using a refrigeration based water chiller system. This was in contrast to precision temperature control ($23\pm 0.1^{\circ}$C) employed in Fig. T.2.1. The whole aim was to bring out exclusively the role of dye temperature control on single mode dye laser performance. The real time line width variation was monitored with a line-width module of the wave-meter. Fig. T.2.5a, b shows the variation of dye laser line-width with time with fine ($\pm 0.1^{\circ}$C) and coarse control ($\pm 2^{\circ}$ C) of dye solution temperature, respectively

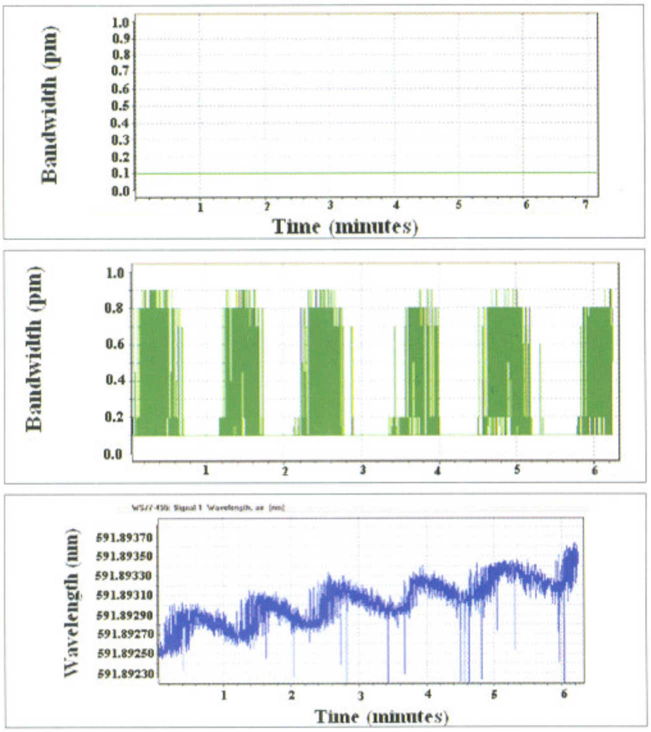

Fig. T.2.5 : Variation of line-width single axial mode dye laser with time (a) With temperature of dye gain medium controlled to 23 ± 0.1 °C, (b) With temperature of dye gain medium coarsely controlled to 23 ± 2 °C, and (c) Variation of wavelength of single axial mode dye laser with time for coarse temperature control of 23 ± 2 °C

The flow rate of the dye cell was set at 1.7 lpm. In case of coarse dye solution temperature control, a periodic variation in the dye laser line-width was observed (Fig. T.2.5b). The line-width remained constant at about 100 MHz for about 35 second and then for next 25 seconds (after every 35 seconds), it fluctuates rapidly between 100 to 770 MHz. It is obvious that the dye lasing is periodically switching from single axial mode to double mode and so on. Similarly periodic variations in dye laser wavelength were also noticed (Fig. T.2.5c). However when dye solution temperature is controlled within 23± 0.1°C, the fluctuations in dye laser line width was removed completely (Fig. T.2.5a) and the line width was always 100 MHz for the investigated period of 7 minutes. It is clear that the control of dye solution temperature has brought about significant improvement in dye laser performance. It is obvious that these periodic variations are due to some effects induced in periodic fashion during long-term dye laser operation, which is also intimately connected to variation in dye solution temperature. In a high repetition rate dye laser pumping such in present case (CVL pump dye laser), the pump beam absorption will have a tendency to heat the dye solution while the refrigeration based chiller system will tend to cool the dye solution. It is well known that change in temperature of dye solvent (ethanol) leads to change in its refractive index and hence change in dye laser frequency [1]. For the present case, dye laser frequency shift with change in dye solvent (ethanol) temperature is estimated to be in range of 8 GHz/ K [1]. Also in the present dye laser set up (Fig T.2.1), separation of dye laser cavity modes (≈ 890 MHz) corresponding to cavity length of 17 cm and width of etalon pass band at $1/e^2$ point of the maximum intensity (≈ 830 MHz) are comparable. At a particular dye solution temperature, a particular dye laser cavity mode exactly coincide with the peak of etalon pass band. This gives rise single mode lasing. However since the dye solution temperature is continually changing, it leads to a situation that two dye laser mode, located on either side of peak of etalon transmission band, crosses the cavity loss line. Thus giving rise to two mode lasing. Hence a periodic switching in dye laser lasing from single to double mode will occur irrespective of whether dye solution temperature is increasing or decreasing, as observed. From this logic, the mode switching can be avoided if the dye solution is controlled within such a value that the maximum frequency shift due to dye solution temperature change is less that the etalon pass-band width of about 1.0 GHz. This guides the dye solution temperature to be controlled in the range of ±0.1°C. This turns out to be indeed the case. Dye solution temperature controlled within ±0.1°C led to single mode dye laser performance without switching to double mode.

3. Development of high repetition rate, narrow line-width (2-3 GHz), multimode dye laser

3.1 Development of dye laser set up

A complete dye laser oscillator mechanical setup was developed and fabricated in house. Fig. T.2.6a shows the set up. It consisted of a home designed, cemented rectangular glass dye cell with constricted flow region to attain the required flow velocity of dye solution through the active region. The dye cell was contained in a leak proof SS housing with a provision of dye circulation through it. In front of the dye cell, a cylindrical lens holder is mounted. This holder has a feature to rotate the cylindrical lens which helps in aligning

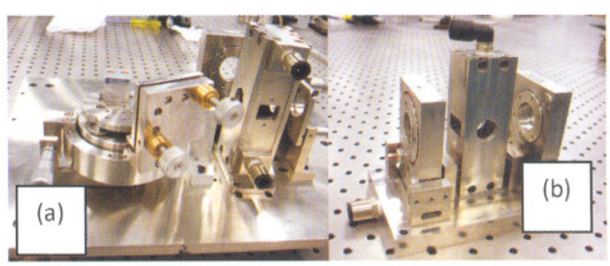

Fig.T.2.6 : (a) A dye laser oscillator mechanical assembly with dye cell in place, (b) A double sided pumped dye amplifier cell mechanical assembly the pump beam with the dye laser axis.

The cylindrical lens holder was mounted on a linear translation stage which aids in focus the pump beam on the dye cell. On one side of the dye cell, an output coupler holder was placed. The output coupler can align the optics with two micrometers. On the other side of dye cell, a post to hold a prism beam expander and circular geometry rotating assembly was positioned. This assemble has, in the center, a non rotating plate-form with fine tilts adjustments. On this plate-form, the grating is placed. The outer ring of the circular assembly, mounted on balls, gives the rotational movement to the tuning mirror fitted on a mirror mount. This mirror is used to tune the dye laser wavelength. These all units were assembled on a rectangular base plate which can be leveled by screw thread.

Another dye laser assembly, suitable for dye cell to be employed as double sided pumped dye laser amplifiers, was also developed in house (Fig. T.2.6b). Double side pumping improves the power as well as beam quality of dye amplifier output in dye laser MOPA system. This dye amplifier assembly consisted of housing for glass dye cell and provision for two cylindrical lens holders for optical pumping from both the sides. The cylindrical lens holders have option for linear motion as well as rotation for cylindrical lens for optimizing the pump CVL beam focusing. The dye solution inlet and outlet port as so designed to have unobstructed double side optical pumping of the dye active medium.

3.2 Development of temperature controlled dye flow system

For long term frequency and line - width stability of dye laser oscillator beam, temperature control of circulating dye solution is essential [1]. A dye circulation cooling system with temperature controlled to ±0.1°C was developed in house. This is based on long term dye solution temperature by thermo electric cooling (TEC) modules. Fig. T.2.7a shows the block diagram of the dye circulation system along-with TEC set-up. The dye reservoir is a thin walled cuboidal shape SS container of volume approximately 2.2 liters. Four number of TEC assemblies are attached to the outer walls of the SS reservoir, with a total heat removal capacity of approximately 480 Watts. Each TEC assembly consisted of a TEC, a heat sink and a cooling fan attached to the heat sink. These TECs are driven by a programmable DC power drive designed to regulate the DC voltage of 0-12 V with 0.1% accuracy up to a current of 0-5 Amps. Set point of 0-5V, to this DC drive is given through a PID controller. The dye solution temperature was monitored with a sensor (PT 100) in a range of 0-50°C with ±0.1°C accuracy. The chilled dye was circulated in the dye cell by magnetic drive gear pump from the dye container. The container, power supply and dye circulation pump were housed in a cabinet as shown in Fig. T.2.7b. This dye circulation unit has been very successfully used in development of single mode dye laser (Section 2). This

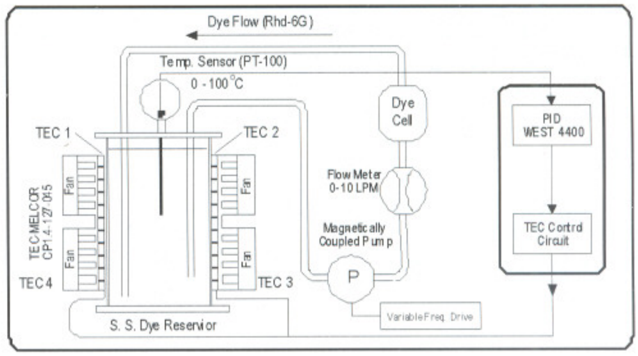

Fig.T.2.7 : The temperature controlled dye circulation system along-with TEC, (a) Block diagram, (b) Assembled system

system is now being upgraded employing higher cooling capacity TECs.

3.3 Development of high repetition rate advanced pump lasers - Copper HyBrID Lasers

High repetition rate, high power and narrow line- width tunable dye lasers have applications in laser based isotopes separation (LIS). Requirement of high repetition rate of laser pulses, in LIS, is guided by maximum interaction of evaporated atoms with laser radiation. This requires that the time taken by the evaporated atoms in traversing the irradiated zone should match the inter-pulse duration of the repetitive laser pulses. For many actinides and lanthanides of interest e.g. Uranium and Ytterbium, the thermal velocity of atoms is in range of several hundred meters per second. For the AVLIS experiments, for the normally used transverse size of dye laser beam of 15 to 20 mm, the required pulse repetition rate (PRR) should be in 15 to 30 kHz. For achieving kHz range repetition rate dye laser, copper vapour laser (CVL) pump have been widely used. However, CVL normally operates at 5 to 6 kHz PRR. In order to achieve the required repetition rate of 15-30

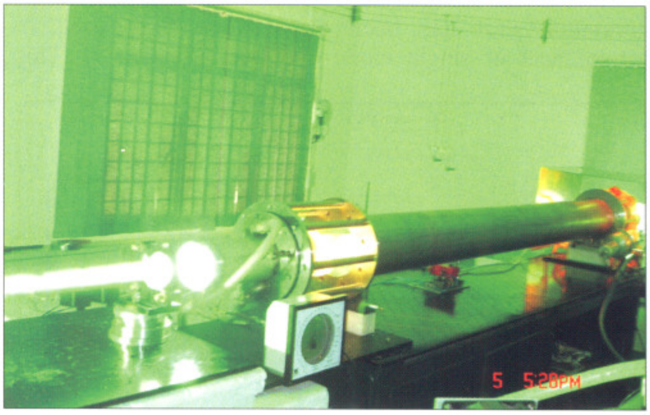

Fig. T.2.8: A 110 W, 18 kHz repetition rate Copper HyBrID laser developed at LSED, RRCAT

kHz, electronically and optically multiplexing of several beams can be carried out . This required a complicated scheme of optical and electronic arrangements.

The new, low temperature variant of CVL namely, copper HyBrID laser, has capability of operating at variable pulse repetition rate (PRR) from 10 to 30 kHz from a single unit. Also copper HyBrID lasers have advantage of much higher output power (factor of 2 to 3) from equivalent active medium volume of conventional high temperature CVL.

In LSED, a program was taken up to develop copper HyBrID lasers upto average power of 100 W [6,7]. This target was successfully achieved and summarized in the table 1. Fig. T.2.8 shows a 110 W, 18 kHz repetition rate, indigenously designed and developed copper HyBrID laser

Sl. No	Laser tube dimensions (ID x Length)	Average output power achieved
1.	50 mm x 1300 mm	40 W @ PRR=18 kHz
2.	47 mm x 1500 mm	70 W @ PRR=18 kHz
3.	58 mm x 1500 mm	80 W @ PRR =18 kHz
4.	60 mm x 2000 mm	110 W @ PRR =18 kHz

Table 1: Various models of Copper HyBrID lasers developed at LSED, RRCAT

3.4 Studies on narrow line-width (2-3 GHz), multimode dye laser

Tens of kilohertz, 2-3 GHz line-width tunable dye laser in orange-red region of spectrum is very optimum for separation of isotopes of many important actinides including that of uranium. The home made tunable dye laser performance has been exhaustively studied for narrow line-width operation (2-3 GHz) using a variety of pump sources such as 5-6 kHz repetition rate copper vapour laser (CVL, λ = 510 nm), 18-20 kHz repetition rate Copper HyBRID laser (λ = 510 nm) and 5-6 kHz repetition rate 2nd harmonic Nd:YAG laser (λ = 532 nm) for average pump laser power upto 10W. Two laser dyes namely Rhodamine 6G (Rh6G) and Rhodamine 110 (Rh110) were studied.

Fig. T.2.9 shows that actual experimental set up used in most of the studies. This is based on the developed dye laser oscillator set up (Fig. T.2.6a). The dye laser resonator consisted of double prism pre-expander (magnification ≈ 20), grazing-incidence grating (2400 lines/mm) and tuning mirror (Reflectivity ≈ 100%).

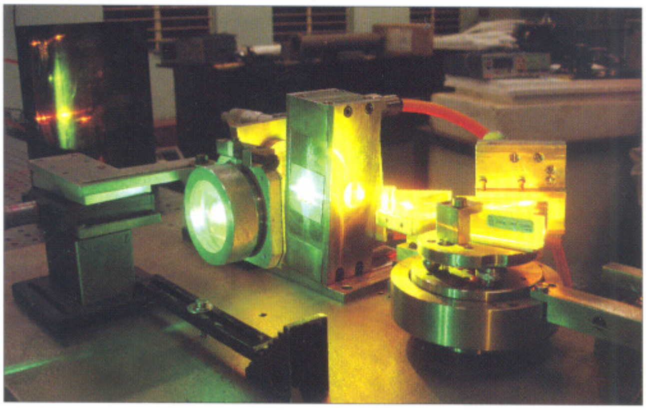

Fig.T.2.9 : A multimode dye laser (Line-width: 2-3 GHz) developed at LSED, RRCAT

The dye laser output power was taken through a 4% reflecting output coupler. The overall cavity length was 18 cm. The dye laser wavelength was changed by rotating the

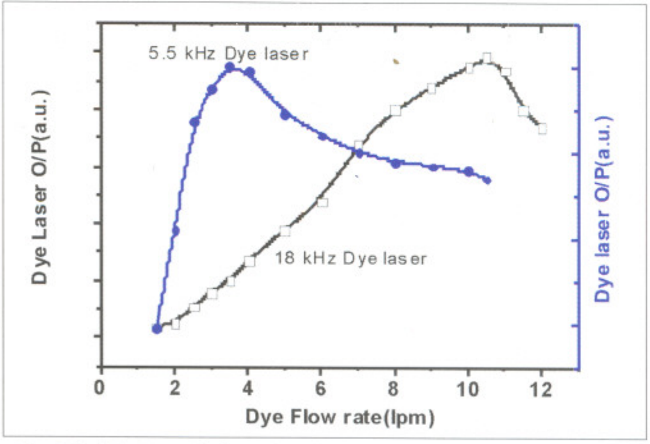

Fig.T.2.10 : Trends for 5 kHz/18kHz repetition rate dye laser power vs dye solution flow rate tuning mirror. A 2.0 mM dye solution of Rh6G/Rh110 dye in ethanol flowed through the dye cell. The dye cell was set at 5 degrees with respect to the optical axis to avoid multiple-reflection of the laser beam between the inner surfaces of the dye cell. First of all, for both 5.5 kHz (CVL) and 18 kHz (Cu: HyBRID laser) pump lasers, the effect of dye solution flow rate on the dye laser performance was studied. This was carried out by measuring the output power of dye laser with a plane-plane resonator (broad-band operation) for different dye solution flow rates. Fig. T.2.10 shows the variation of broad-band (BB) dye laser output power with different flow rates from 1.5 to 12 lpm for both the pump beams. It is seen that the dye laser output power is maximum at flow rate of about 3 lpm (Litre per minute) for 5.5 kHz operation as compared to about 10 lpm for 18 kHz operation. On both the sides of this optimum flow, there is a fall in the dye laser power.

The optimum dye laser power at a particular flow rate was due to two contrasting processes. As the dye solution flow rate increases from a very low value, there is reduction in thermal effect due to increased clearing ratio (CR) of irradiated dye volume between the inter pulse period. This effect has tendency to increase the dye laser gain and hence laser power. However the high flow rate also leads to turbulence in the dye gain medium. This, in turn, leads to scattering of the circulating radiation and hence decrease in laser power. Hence there is an optimum dye solution flow rate to obtain the maximum dye laser power. As expected this optimum flow value is different for different inter-pulse period of the pump laser (181 μs for CVL as against 55 μs for Cu:HyBRID laser). It was also found that in narrow line-width dye laser configuration also, the optimum flow rate remains same as in broadband operation.

Fig. T.2.11 shows the variation of narrow line-width dye laser output power (Fig.T.2.9) as a function of dye laser wavelength for two different laser dyes i.e. Rh110 and Rh6G dissolved in ethanol with same concentration of 2 mM, at optimum flow rate. The pump beam was from CVL, fitted with high beam quality Unstable resonator of high magnification (M=100). The CVL power of about 5.5 W (at

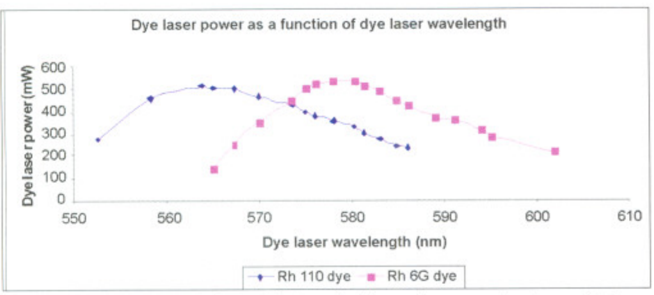

Fig. T.2.11: Wavelength tunability characteristics of dye laser with Rh110 and Rh6G laser dyes

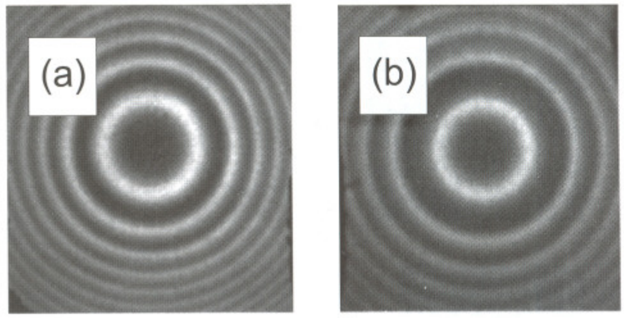

Fig.T.2.12 : Line-width characteristics of 5.5 kHz repetition rate multimode dye laser with (a) CVL pump, (b) 2nd harmonic of Nd:YAG pump

5.5 kHz). The dye laser power was measured, a power meter (Gentec, PS- 310 WB) placed in front of output coupler. Dye laser wavelength tuning from 553 nm to 585 nm in case of Rh110 dye laser and from 565 to 604 nm for Rh6G dye laser was observed. The peak conversion efficiency at 564 nm for Rh10 dye and at 580 nm for Rh6G dye was about 9%. As the diffraction limited beam quality pump CVL power is increased from 5.5 W to 10 W (through CVL MOPA), the dye laser average power has increase to about 900 mW. As the pump beam is changed from CVL (λ = 510 nm) to second harmonic of diode pumped Nd:YAG laser (λ = 532 nm) otherwise with same repetition rate (5.5 kHz) and same average power of 10 W, the Rh6G dye laser power was about 700 mW. The reduced dye laser power at pump wavelength of 532nm is most likely due to much reduced absorption of 532 nm beam in Rh6G laser dye solution as compare to pump wavelength at 510 nm.

The dye laser line-width was studied with all the three pump beams under identical experimental conditions as in set up (Fig. T.2.9). The dye laser line-width was measured by capturing the rings from an external high resolution analyzing Fabry-Perot (F-P) etalon (FSR = 10 GHz, Reflective finesse = 50), onto a time gated CCD (Pixelfly qe, PCO AG). Fig. T.2.12 shows F-P ring pattern of dye laser oscillator pumped by CVL (Fig. T.2.12a) and second harmonic Nd:YAG (Fig. T.2.12b), both with same pump power of 10 W at same repetition rate of 5.5 kHz.. The measured line-width in both the cases were very close in range 2 to 2.5 GHz. However for 18 kHz dye laser measured dye laser line width was in range 2.5 to 3.0 GHz depending on the flow rate of dye solution. In an another experiment for CVL pump dye laser, the line width was reduced to about 750 MHz by replacing the tuning mirror in dye laser oscillator (Fig. T.2.9) by another grating in Littrow mode.

The narrow line-width multimode dye laser was also characterized by its beam quality namely near and far-field beam profiles and laser temporal pulse. Fig.T.2.13 a, b show the near and far field profiles respectively along with intensity

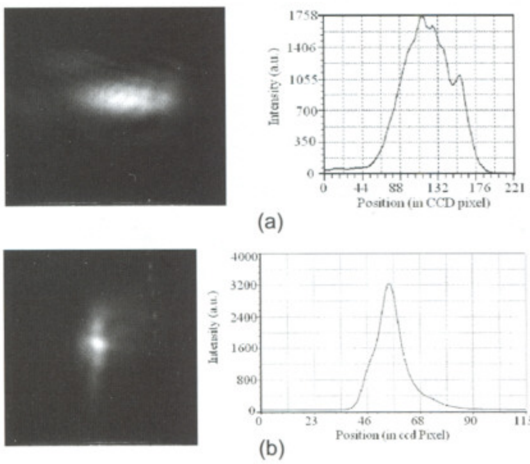

Fig.T.2.13 : Near and far field dye laser spot along with intensity profile along horizontal line

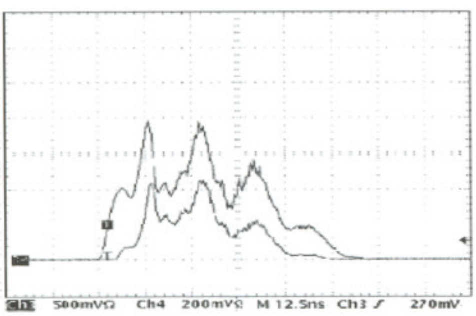

Fig.T.2.14 : Temporal profile of the dye laser (lower trace) and the pump CVL (upper trace)

plot. These profiles indicated good spatial beam characteristic of dye laser. Fig. T.2.14 shows the pulse shape of CVL (upper trace) and dye laser (lower trace). The dye laser pulse of pulse width 20 ns (FWHM) was delayed about 5 ns with respect to CVL pulse. The peak of dye laser follows the peak of CVL pulse.

4. Setting up and studies on dye laser MOPA system

To further enhance the laser power from dye single/multimode dye laser oscillator, the dye laser MOPA systems were studied. Fig. T.2.15 shows the schematic (Fig. T.2.15a) and the actual CVL pumped single mode dye laser (Fig. T.2.15 b). The dye laser MOPA system consisted of an oscillator, a pre-amplifier and an amplifier. The dye laser master oscillator was single mode as described in section 2. Dye laser oscillator and pre-amplifier/amplifier were transversely pumped by line focused (f=50mm) CVL-MOPA beam (510 nm, 5.5 kHz) of total average power of 19 Watt. The CVL power was suitably distributed to pump dye oscillator/amplifiers using mirrors M1 (R = 30%), M2 (R= 50%) and M3 (R= 100%). Dye solutions of 2 mM and 1 mM

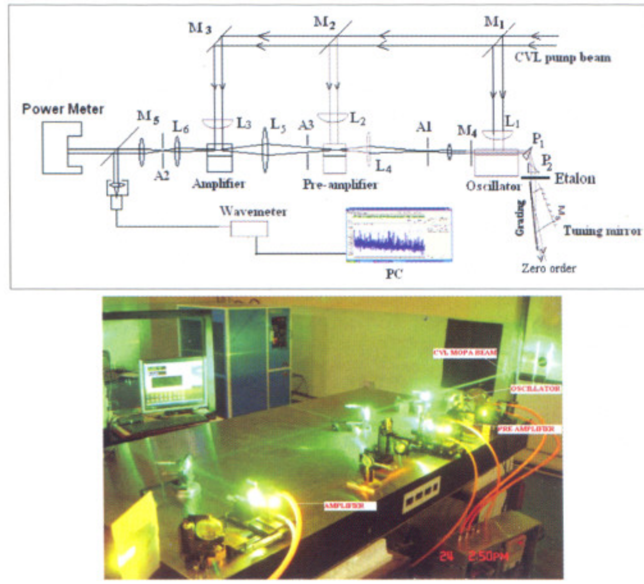

Fig.T.2.15: CVL pumped dye laser MOPA configuration, (a) Schematic, (b) Actual set up

laser grade Rhodamine-6G in ethanol were flowing at about 2 lpm through the oscillator and amplifier respectively. The dye oscillator beam was injected into a pre- amplifier with the help of a convex lens (L4) of focal length 25 cm. The dye laser beam from pre-amplifier is again injected to the amplifier by the lens (L5).

With dye oscillator beam injected into pre-amplifier, the amplified output power was about 55 mW at λ =580 nm. With dye laser pre-amplifier beam injected into dye amplifier, the total dye laser output power of amplified beam was about is 1.1 Watt at 580 nm. About 20% extraction efficiency was obtained at final dye amplifier stage. The wavelength variation of amplified beam follows the oscillator beam wavelength variation. The line-width of the amplified beam was about 250 MHz. This dye laser MOPA experiment was further extended by employing a multimode dye laser oscillator of line width 2.0 GHz. In the similar set up (Fig. T.2.15), the final dye laser average power was 3.0 W. This dye laser power was limited by the available CVL pump power.

In an another dye MOPA experiment, the pulsed amplification characteristics of single mode continuous wave (CW) dye laser was studied in a dye laser amplifier pumped by high repetition rate copper vapour laser (CVL). Pulsed amplification of a CW laser combines the advantages of ultra narrow line-width, high frequency stability, good beam quality of cw laser and high energy of a pulsed laser. The whole laser system consisted of a commercial single mode CW ring dye laser oscillator and indigenously developed pulsed dye laser amplifier. The gain of the pulsed dye laser amplifier was studied at different CVL pump powers, CW dye laser input powers and input dye laser wavelengths. Figure T.2.16 shows the experimental set-up for pulsed dye laser amplification studies with CW dye laser input. A commercial CW ring dye laser, based on a high flow dye jet of Rh6G dye dissolved in ethylene glycol which is optically pumped by 2nd harmonic of CW Nd:YAG, was used as an oscillator. At the CW pump power of 5 W (532 nm), ring dye laser oscillator produced power more than 100 mW in wavelength range tunable from 570 nm to 590 nm. This CW dye laser output beam was focused in dye amplifier cell with a spherical lens L1 of focal length 40 cm. The dye amplifier cell was pumped by a CVL master oscillator power amplifier (MOPA) beam using a cylindrical lens (CL) of focal length 10 cm. The CVL power was varied from 1 W to 10 W at a repetition rate of 6.3

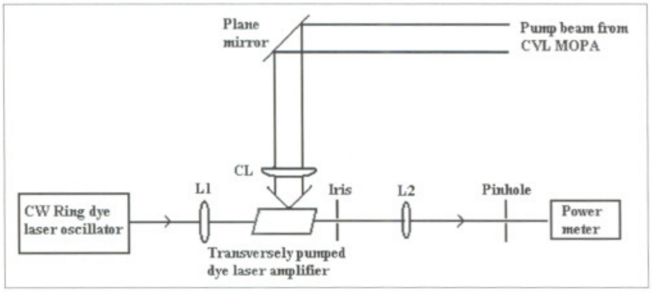

Fig.T.2.16: Schematic of the experimental setup for CW dye laser amplification in pulsed amplifiers

kHz. The CVL pulse width at FWHM was 30 ns. The dimensions of dye laser amplifier active medium were about 0.2 mm x 0.2 mm x 10 mm. A dye solution of concentration 1mM Rhodamine 6G in ethanol was flowing in the dye amplifier. The dye cell was slightly tilted in order to prevent the laser action due to reflection from the windows of the dye cell.

Fig. T.2.17 shows the dye amplifier gain Vs CVL pump power for fixed CW dye oscillator wavelength at 578 nm and input power of 120 mW. Wavelength and power measurements were carried out by a fiber optic spectrometer (Avaspec-3648-USB2) and power meter (Gentec: TPM-300), respectively. The gain was estimated as the ratio of the peak power of amplified output beam and the CW input power. This

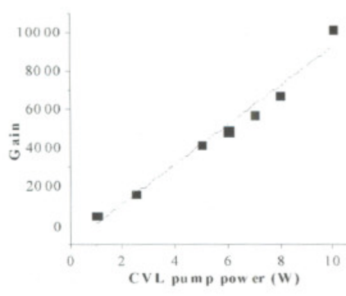

Fig.T.2.17: Variation of dye amplifier gain with the CVL pump power at fixed CW dye input power

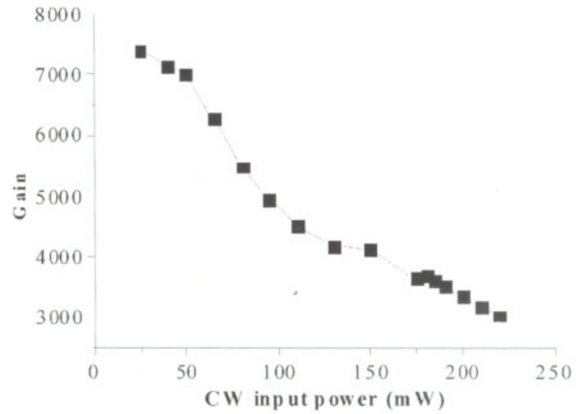

Fig. T.2.18 : Variation of dye amplifier gain with the CW dye laser oscillator input power at fixed CVL pump power

estimation was based on measuring the average amplified dye laser output power after subtracting the ASE content, through a pinhole placed at focal plane of a converging lens (Fig. T.2.16).

It is seen that as the CVL pump power increases from 1 to 10 W, the dye amplifier gain increases linearly from about 500 to 10000. No saturation behavior was observed. The maximum (ASE filtered) average amplified dye laser output power was 230 mW at 10 W of CVL pump power and with CW dye input of 120 mW.

Fig. T.2.18 shows the dye amplifier gain with the variation of CW seed oscillator power. In this set up, the CW dye oscillator wavelength and CVL pump power were fixed at 580 nm and 5 W, respectively. The gain of 7500 was observed at oscillator input power of 25 mW. The gain reduces from 7500 to 3000 as the oscillator power increased from 25 mW to 220 mW.

5. Studied on second harmonic of dye laser - High

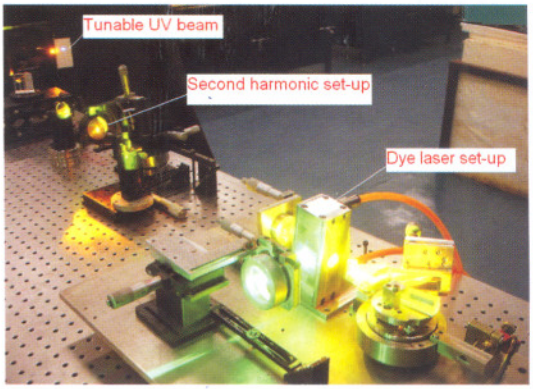

Fig.T.2.19 : Set up for second harmonic generation of tunable dye laser

repetition rate tunable UV generation

Coherent, high repetition rate tunable UV radiation is very useful for many spectroscopic applications. A new program is initiated at LSED to generate tunable UV sources based on non linear frequency conversion of indigenously developed high repetition rate dye laser radiation. Fig. T.2.19 shows such an experimental set up developed in house. It consisted on a multimode (2.5 GHz line- width) dye oscillator pumped with CVL, second harmonic type -I phase matched BBO and other optical arrangements. The BBO (cut angle = 50^0) crystal is optimized for SHG of CVL wavelength (510 nm), however has been utilized in the present set up (Fig. T.2.19) with suitable tilt angle. The dye laser beam was focused on the crystal with a spherical lens of focal length 10 cm. After the crystal, the fundamental and UV beams were separated by a UV grade dispersing prism. The average UV power was measured with a power meter. Typical average UV (290-300 nm) power of 50 mW was measured from the fundamental dye laser power of 400 mW (580-600 nm). The UV power rose to 125mW at 1.2 W input from Dye MOPA. Further study is in progress for better optimization of the UV system.

6. Conclusion

This article presented the R&D activity being carried out in the field of high repetition rate dye laser at LSED, RRCAT. The development carried out so far in the field of single/multimode dye laser systems are detailed. Efforts are on to further improve the performance of dye laser MOPA system and second harmonic of dye laser. A program is also initiated to develop a continuous wave dye laser. A plan for exhaustive study of dye laser pumped by second harmonic of high repetition rate diode pumped Nd:YAG is being worked out. This will be a collaborative activity between LSED and Solid state laser division (SSLD).

Most of the works presented in this article are published/being published [1-20] in various forums. The contributing author of this theme article acknowledges with sincere gratitude the scientific contributions of all the co-authors. The contributing author also wish to acknowledge power supply maintenance team of LSED, Dr C. Mukharjee and his team for the AR coating of the double prism beam expander and Dr. Sanjib Chatterjee and his team for fabrication of glass dye cells.

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