Physics and technology of tunable pulsed single longitudinal mode dye laser

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Abstract. Design and technology demonstration of compact, narrow bandwidth, high repetition rate, tunable SLM dye lasers in two different configurations, namely Littrow and grazing incidence grating (GIG), were carried out in our lab at BARC, India. The single longitudinal mode (SLM) dye laser generates single-mode laser beams of ∼400 MHz (GIG configuration) and ∼600 MHz (Littrow configuration) bandwidth. Detailed performance studies of the Littrow and GIG dye laser resonators showed that GIG dye laser results in narrower linewidth and broad mode hop free wavelength scanning over 70 GHz. In this paper we present experimental studies carried out on the high repetition rate SLM dye laser system.

Keywords. Dye laser; single longitudinal mode.

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1. Introduction

Narrow band broadly tunable pulsed dye lasers have a profound impact in the areas of scientific research, medicine, remote sensing and laser-based purification of precious materials. In particular, single-longitudinal mode dye lasers are useful laser sources for high-resolution nonlinear spectroscopy and coherent spectroscopy with high peak power requirement. Higher repetition rate single-mode dye laser expands the field of application into high-resolution laser spectroscopy of short-lived radionuclides and laser isotope separation of species with narrower isotopic shifts. Various configurations are reported in literature to obtain single longitudinal mode operation in pulsed dye lasers [1–5] such as direct pulsed amplification of CW dye laser, Hänsch-type cavity with intracavity etalons and short Littman-type grazing incidence grating cavity. Though spectral widths obtained from the modified Hänsch configurations are closer to Fourier-limited spectral widths, spectral control and tuning of these laser systems are relatively complex. Among these cavities, Littman-type GIG compact cavity is a simple one which utilizes grating as the only
frequency selecting component for single-mode operation without any additional beam expander and etalons. A shorter cavity of 5–7 cm can be formed with grazing incidence grating configurations. In this paper, experimental studies carried out on high repetition rate (6 kHz) computer-controlled tunable single longitudinal mode dye lasers developed in our lab is presented.

2. SLM oscillator

Single longitudinal mode in a pulsed dye laser cavity can be achieved by designing a compact cavity with sufficient dispersive mode discrimination for nearby modes. Shorter cavity lengths increase free spectral range of longitudinal modes and facilitate single-mode operation. Various dispersive elements used for the selection of single mode in pulsed cavity are etalon, grating, solid Fiezo interferometer and other variations of resonant reflectors. For long pulse and CW dye laser cavity, moderate wavelength dispersion will generate single-mode operation because of a large number of round trips. Spectral linewidth of the dye laser is progressively narrowed [6]. For short-pulsed dye laser, dispersive single-pass bandwidth has to be of the order of longitudinal mode spacing to select single-mode operation with a few round trips.

Two narrow band dye lasers which utilize minimum optical components for single-mode selection were built and studied in our lab. One of the cavities for SLM dye laser was a compact Littrow cavity formed by only two cavity optics of a grating and an output coupler (4%) built around a dye cell. This could be one of the simplest cavities for single-mode selection. Schematic of the cavity is shown in figure 1. Gain medium was formed by rhodamine 6G (1 mM) dye dissolved in a binary solvent of glycerol and ethylene glycol. Cavity distance was kept around 15 mm corresponding to the longitudinal mode spacing of 10 GHz. Grating of 3300 lines per mm was used [7]. Dye cell was longitudinally pumped by green part (λ = 510.6 nm) of copper vapour laser operating at a repetition rate of 6 kHz with the help of a lens (f = 200 mm). Pump beam pulse energy stability of the pump beam was measured to be 1%.
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Figure 2. FP spectrum of SLM Littrow dye laser.

The divergence of CVL laser was measured to be 1 mrad. Single-pass linewidth for Littrow cavity can be written as

$$\Delta \lambda_{\text{Littrow}} = \frac{\lambda^2}{2\pi w \tan \theta}.$$  

Spot size ($w$) of 100 $\mu$m at the gain medium and the corresponding Littrow angle of 67.5° for 560 nm wavelength results in a single-pass linewidth of 200 GHz. Due to shorter cavity and smaller round trip time (0.1 ns), multiple round trips are possible with 30 ns pump pulse. Even though longitudinal mode spacing of our Littrow cavity is an order less than the single-pass linewidth of the grating, line narrowing and single-mode operation was achieved thanks to the larger number of round trips and progressively narrowed spectral widths [6]. Single-mode spectrum of short Littrow cavity is shown in figure 2. The spectrum was obtained with Fabry Perot etalon with 7.5 GHz free spectral range. Spectral linewidth of 600 MHz–1.5 GHz was obtained with Littrow cavity. Tuning range of 15 nm was obtained with a peak wavelength of 570 nm.

Though single longitudinal mode was obtained in short Littrow cavity, this cavity has the limitation of operating beyond 606 nm, which is the upper cut-off wavelength of Littrow mode of operation with 3300 lines/mm cavity and minimum linewidth is limited to 600 MHz. Upper cut-off wavelength can be extended up to 666 nm with 3000 lines per mm grating. This resonator can be used for applications that require single-mode laser with relatively larger linewidths. As the grating is used in Littrow mode of operation and cavity distances are minimum, the cavity is a low-loss cavity with an output of 40 mW with 5% efficiency at an operating repetition rate of 6 kHz.

3. Grazing incidence grating cavity SLM dye laser

To achieve narrower linewidths, grazing incidence grating (GIG) cavity was built with a grating of 2400 lines per mm. Littman-type GIG cavity was successfully applied to high repetition rate single-mode dye laser [8]. A typical schematic of GIG SLM dye laser developed in our lab is given in figure 3. In this configuration grating is kept at an angle close to 89° and tuning mirror was used for feedback.
and as wavelength tuning element. Cavity length as short as 5 cm is possible with this configuration. Pump beam was focused from the grating mirror side into the dye cell using a planoconvex lens of 200 mm focal length. To operate with high repetition rate dye laser, dye cell should be operated with a flow velocity sufficient to clear the heated dye molecules from the pumped zone before the arrival of next pump pulse.

Dye cell is a critical element to provide optical-quality gain medium. The regions of concern are those with higher shear near the liquid–solid interface where the average velocity varies from zero at the wall to the free stream velocity at some distance. Detailed computational fluid dynamics simulation was carried out [9] to design and fabricate flow through cells for the SLM dye laser resulting in higher flow velocities without vortices and low pressure drop. Indigenous demountable dye cell with $5 \times 1$ mm cross-section with optimized entry of fluid to dye cell was developed and used for narrow-band dye laser experiments. With this dye cell we were able to obtain optical quality gain medium with a higher flow rate of 3 m/s. This flow rate corresponds to the clearance ratio of 2.5.

Cavity length 6 cm of the SLM cavity corresponds to the longitudinal mode spacing of 2.5 GHz. Single-pass linewidth for the grating mirror pair can be estimated using the equation
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\[ \Delta \lambda = \frac{\sqrt{2} \lambda^2}{\pi l (\sin \theta_i + \sin \theta_d)}. \]

For a grating illumination length of 62.5 mm, single-pass linewidth was estimated to be 1.5 GHz. As the single-pass linewidth is less than the longitudinal mode spacing, single mode is selected in one round trip with full grating illumination. Further filtering of higher transverse modes other than fundamental is achieved by focal spot of the pump beam at the dye cell which acts like a gain aperture.

4. Computer-controlled GIG SLM dye laser

All the optical components are placed on the engineered precision rotation table with a rotation accuracy of 4 milliarcsecond (19 nanoradians). End mirror and tuning mirrors are fixed on piezotransducers for close loop wavelength control. Optical components of the cavity, namely grating, dye cell and end mirrors, are fixed on the fixed part of the rotation table. Tuning mirror can be rotated by two types of rotations, namely coarse and fine rotation, to change the wavelength. Coarse wavelength tuning was done through 50,000 steps per revolution microstepper motor attached to the centre of the rotation table. Fine tuning was done through the rotation of the tuning mirror using an arm length of 100 mm and piezotransducer of 20 \( \mu \) travel length. Minimum frequency change designed for coarse and fine tuning was 39 GHz and 3 MHz, respectively, which was experimentally validated. Change in wavelength due to angle tuning of the tuning mirror is given as

\[ \text{Angle tuning} = \Delta \nu = \frac{c \cos \theta_d \Delta \theta}{d (\sin \theta_i + \sin \theta_d)^2}, \]

where \( c \) is the velocity of light, \( \Delta \theta \) is the change in the angle of tuning mirror produced by various actuators.

5. Performance characteristics of SLM GIG dye laser

SLM dye laser was mounted on a specially designed vibration isolated vertical wall. The performance characteristics of the SLM dye laser was studied in detail [10]. Figure 4 shows the typical Fabry Perrot spectrum of the SLM GIG dye laser using FP etalon with an FSR of 7.5 GHz. Tuning range of the SLM laser was observed to be 556.4–568.5 nm. The smaller tuning range of 12 nm for the SLM dye laser results from high loss in the GIG cavity. The dye laser beam divergence was measured to be 0.5 mrad. The CVL beam size was telescopically reduced from 40 to 10 mm and spatially filtered using a pinhole of 700 \( \mu \)m diameter. Dye concentration for rhodamine 6G dye solution was 0.1 mM. The SLM dye laser efficiency was 2.3% with an output power of 95 mW at 3.8 W CVL green beam. Beyond this pump power, a second mode started appearing on and off as expected from spatial-hole burning effect. It was observed that the maximum pump power input for the single-mode operation inversely depends on the concentration of the dye. As the concentration increases, the threshold for two-mode operation and the SLM
output power is observed to be decreased. Figure 5 shows the spectral output of the SLM dye laser using commercial wavemeter of WS-7L from M/s Angstrom. The linewidth is shown in figure 5 as 0.1 pm.

Mode hop free scanning of the single-mode dye laser was carried out by rotating the tuning mirror around the geometrical pivot point [11], where the optical planes of grating, tuning mirror and end mirror meet. We were able to achieve mode hop
free scanning of 70 GHz using 20 µm PZT connected to tuning arm. While tuning the SLM laser, the sudden jump of 3 GHz (cavity FSR) in the wavelength was not detected and no two-mode operation was observed in the scan range. Single-pulse spectrum of the laser was measured to be 315 MHz using the fast CCD camera and 7.5 GHz FSR FP etalon and shown in figure 6.

6. Temperature effects on spectral dynamics of the SLM dye laser

It was observed that single-mode operation of the SLM dye laser was evolving towards two-mode operation with time. Figure 7 shows the record of wavelength meter measurement of the dye laser wavelength. Twin-mode operation is shown as the band of wavelength covering 3 pm and SLM operation was shown in the band of 0.5 pm. The single to twin-mode transition is periodic in nature. Dye solution temperature was maintained at ±0.1°C using constant temperature bath. The time interval between the single- and twin-mode operation depends on the settling time of the dye temperature. We have observed that the time interval between the single-mode and the twin-mode operation is increased as the dye temperature is led to its stabilized value (wavelength drift rate varies from 0.3 GHz/min to 0.08 GHz/min corresponding to the temperature change of 0.05°C/min to 0.013°C/min respectively). Laser remains in single-mode or twin-mode operation for longer time if the dye temperature reaches its set value.

$$\frac{dn}{dt}$$ of ethanol is $$-4 \times 10^{-4} / \text{K}$$.

For 560 nm drift in the laser frequency, the temperature of dye solution can be calculated using the relation

$$\Delta \nu / \nu = (\frac{dn}{dt} \times dT) \times l / L = 3.733 \text{ GHz/°C}.$$
Experimentally observed wavelength change is \(2.5 \text{ pm/}^\circ\text{C} = 2.39 \text{ GHz/}^\circ\text{C}\) at 560 nm.

It was observed that if the dye temperature was stabilized there was no transition from single-mode to twin-mode over an hour operation.

Change in temperature results in change in refractive index, which results in cavity mode tuning. Grating passband at the grazing angle of incidence is nearly 2 GHz FWHM. Cavity mode scanning will not be extended beyond grating passband. Cavity FSR of the laser cavity is 2.5 GHz for 6 cm cavity length. As the cavity mode matches with the peak of grating passband, single-mode operation is achieved. As the cavity mode detunes away from the peak of the grating passband peak, nearby mode starts oscillating along with brighter mode as shown in figure 8. For stable single-mode operation, dye solution needs to be maintained within the error band less than 0.1\(^\circ\text{C}\) which corresponds to 373 MHz change.
7. Wavelength stabilization

A compact wavelength error sensor based on FP etalon was designed. The input to the sensor is a 0.22 NA (numerical aperture) multimode fibre. The output of the fibre is collimated by specially designed fibre collimator (<0.1 mrad) and further focussed by cylindrical objective lens to form the line image of Fabry Perot fringes on the sensor of CMOS-based one-dimensional detector array. Change in the peak position of the FP fringe generated an error signal of change in wavelength which was fed back to the PZT of the end mirror to correct the wavelength change. From the experimental studies of temporal effect on the spectral dynamics of SLM, an algorithm was developed to detect two-mode operation and correct two mode and wavelength back to locking point was developed. Two-mode operations were detected by commercial wave metre. With this algorithm the wavelength stabilization was obtained for 2 h within the error band ±200 MHz.

8. Pre-amplifier

Low-power single-mode dye laser was amplified in transversely pumped dye amplifier [12]. Indigenously designed demountable flow-through dye cell of $16 \times 0.5 \text{ mm}^2$ cross-section was used. The dye gain medium used was the ethanolic solution of rhodamine 6G of 0.5 mM concentration. Parametric studies of the amplifier output with pump power, input signal and wavelength were carried out. Figure 9 shows the plot of the input SLM signal and amplifier efficiency as a function of wavelength. SLM oscillator output peaks at 563 nm wavelength. The amplifier output of the single-mode signal shows maximum output at 568 nm, whereas the input signal is 6 mW. The SLM dye oscillator peak wavelength blue shifts away from the peak of fluorescence spectrum of rhodamine 6G, because the losses of the narrow-band
oscillator is high. SLM signal was varied from 1 mW to 9 mW and the pump power was kept constant at 8.6 W. The efficiency was plotted as a function of input SLM dye signal in figure 10.

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References