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On the stability of the output characteristics of a grazing incidence grating dye laser transversely pumped by a copper vapor laser

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ABSTRACT The output characteristics of a high repetition rate pulsed dye laser has both short-term fluctuations and long-term drift. In high power high repetition rate lasers flow induced variations dominate over those due to other factors. In this paper it is shown by dye laser measurements that bandwidth fluctuations can be traced to the effective changes of the resonator dispersion due to fluctuations in the penetration depth of the pump beam in the dye medium. Short-term wavelength fluctuations can be traced to instantaneous deflection of the dye laser axis by the refractive index changes due to absorption of the pump beam. The fluctuations in both the bandwidth and the wavelength decreases with increasing flow rates within a laminar region. A copper vapor laser operating at 5.6 kHz repetition rate pumped the Rhodamine 6G dye laser used. The wavelength fluctuation of ±0.0035, 0.0030, 0.0004 nm and the bandwidth fluctuation of ±710, 132, 45 MHz over approx. 60 minutes were observed at 1.2, 3.7, 5.5 lpm flow rates respectively.

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1 Introduction

Pulsed dye lasers suffer from pulse to pulse variations in wavelength and bandwidth that seriously affect rea1ization of their full potential as narrowband tunable source in many applications. The problem is compounded in high repetition rate, high power dye laser oscillators due to high flow velocities of the medium through the dye laser axis. It is known that the bandwidth of a dye laser depends on the dye flow velocity [1]. The higher the flow velocity, the higher the bandwidth. Since, the dispersion of the grating depends on the divergence of the radiation falling on it, the bandwidth also depends on the dye source size [2]. The source size, in turn, depends on the depth of penetration of the pump laser pulse in the dye medium [2]. Pulse to-pulse and intra pulse variations of pump beam flux, due to evolving intensity and divergence, can therefore cause fluctuations in the bandwidth. Pump beam induced thermal gradients in the dye medium leading to non-uniform refractive index variation of the medium also cause changes in the output wavelength and bandwidth [3]. Changes in the environmental temperature also lead to a drift in the output wavelength due to a change in the angular position of the optical components and the changes in the resonator length [4]. The temperature coefficient of refractive index of various materials like glass, air, dye medium etc. on the dye laser resonator axis generally give dependent frequency changes, per degree rise of temperature, only between 60 MHz/K to 8 GHz/K [4]. An individual contribution from these factors is masked by flow-induced variations.

In this paper we attempt to isolate the effects that are responsible for wavelength and bandwidth fluctuations, and hence stability, in a narrow band tunable Rh6G dye laser transversely pumped by a copper vapor laser operating at a 5.6 kHz repetition rate.

2 Experimental arrangements

The dye laser used for these experiments consists of a specially designed dye flow duct. The design is based on the concept of entry length, provision of which in any flow study allows the turbulence due to the entry of the fluid to subside and transforms the flow into a fully developed laminar flow in the region of study. A dye laser, designed using such a duct, is described in detail elsewhere [5]. However some details of the duct relevant for this study are presented here. The duct is formed, in such a way that its width continuously decreases from 22 mm to 0.5 mm upstream of the pump region and increases again to 22 mm downstream, by two cylinders of radius of curvatures of 46 mm and 35.5 mm with a height of 25 mm. The center of the inner cylinder was shifted by about 10 mm with respect to that of the outer cylinder to constrict the flow path in the region of the dye laser axis. The flow of the fluid through this duct was laminar, details of which are presented elsewhere. The experimental arrangement for the dye laser wavelength and bandwidth measurement set-up along with dye flow duct is shown schematically in Fig. 1 with higher quality, if possible. The dye laser resonator consists of a 20% reflectivity output coupler, 2400 lines grating–mirror combination in grazing incidence configuration and a single prism beam expander (magnification ≈ 8). A 1.0 mM solution of Rhodamine 6G dye in 30% ethanol and 70% ethylene glycol mixture (Viscosity about 7.25 cPs) was pumped by a 5 cm focal length cylindrical lens using a copper vapor laser [$\lambda = 510.6$ nm, 5 W (5.6 kHz), plane-parallel resonator]. The output beam of the dye laser was analyzed using a Fabry–

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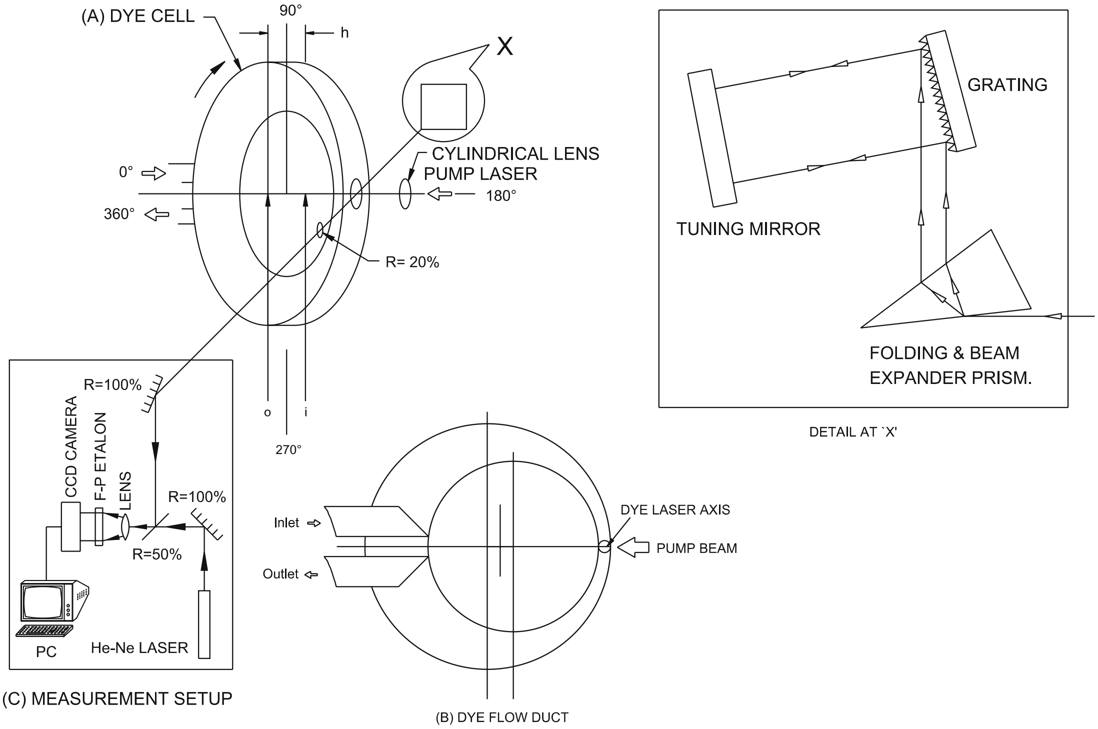

FIGURE 1 The experimental arrangement for the dye laser wavelength and bandwidth measurement set-up along with dye flow duct

Perot etalon (FSR = 5 GHz, finesse = 25), a CCD camera, and a frame grabber card. The software was developed by Vora et al. [6]. A frequency stabilized He-Ne laser ($\lambda = 632.816$ nm) beam, passing through the same optical path as the dye laser beam, was used as the reference laser. The software has the facility of automatically acquiring the intensity profile of the fringes at a preset time interval and composes a picture of the data collected over a long time.

3 Results and discussion

Figure 2a–c shows a record of the fringe pattern taken over approx 60 minutes at the flow rates of 1.2 lpm ($R_e = 221$), 3.7 lpm ($R_e = 681$) and 5.5 lpm ($R_e = 1012$) respectively. It is seen that predominantly three axial modes exist over the period of observation. The fringe spacing varies from record to record and slowly over time. It is also seen that as the flow is increased the fluctuations decrease. The individual modes that appear indistinguishable at low flow rate are clearly distinguishable at higher flow rates. Figure 3a–c shows typical intensity profiles of the F–P fringes, obtained from single trace of Fig. 2a–c for the three flow rates. These profiles, along with F–P fringe profiles for the reference laser, were used for estimating the output wavelength and bandwidth by first roughly measuring the dye laser wavelength using a 0.5 m monochromator and then using this value along with the known wavelength of the He-Ne laser beam, FSR of the Fabry–Perot used, the diameter and width of the fringes using standard formulae [7, 8]. Figure 4a–c shows the scatter of bandwidth and wavelength data for the central mode represented in Fig. 2a–c. It is observed that both the bandwidth and the wavelength vary over the period of observation. The wavelengths vary from 576.2281 nm to 576.2289 nm, 575.9966 nm to 576.003 nm and 575.9861 nm to 575.9928 nm, and bandwidth from 235 MHz to 324 MHz, 282 MHz to 545 MHz, 330 MHz to 1.75 GHz at the flow rates of 5.5, 3.7 and 1.2 lpm respectively. The number of modes oscillating also varies from pulse to pulse. The small peaks superimposed on the broader intensity profile at the same location as the axial modes indicate that the width of the modes increases as the dye flow is decreased. Figure 5a shows the fluctuations in bandwidth and wavelength with Reynolds number and b shows the variation of observed $\Delta\lambda/\lambda$ with Reynolds number.

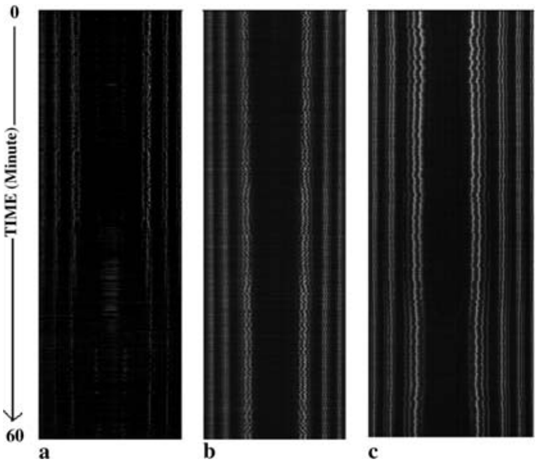

FIGURE 2 Record of the fringe pattern taken over a long time (approx. 60 min) for Reynolds number of (**a**) 221 (**b**) 681 (**c**) 1012

The decrease in fluctuations in bandwidth ($\Delta\lambda$), wavelength (λ) and its ratio with increasing Reynolds number clearly shows that the flow of the dye solution through the

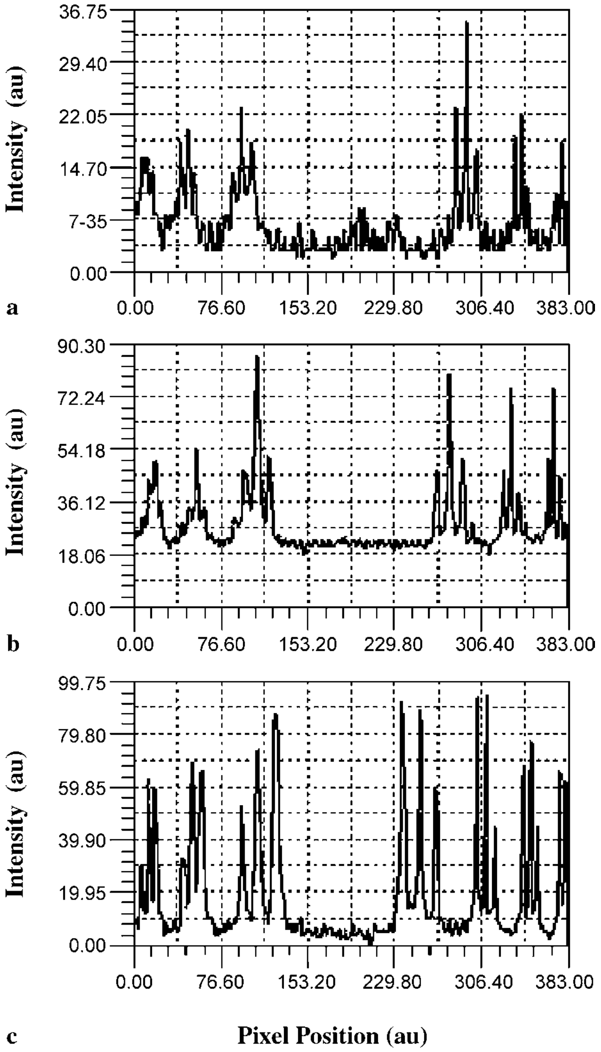

FIGURE 3 Typical FP intensity patterns for the dye laser output at dye flow Reynolds number of (**a**) 221 (**b**) 681 (**c**) 1012

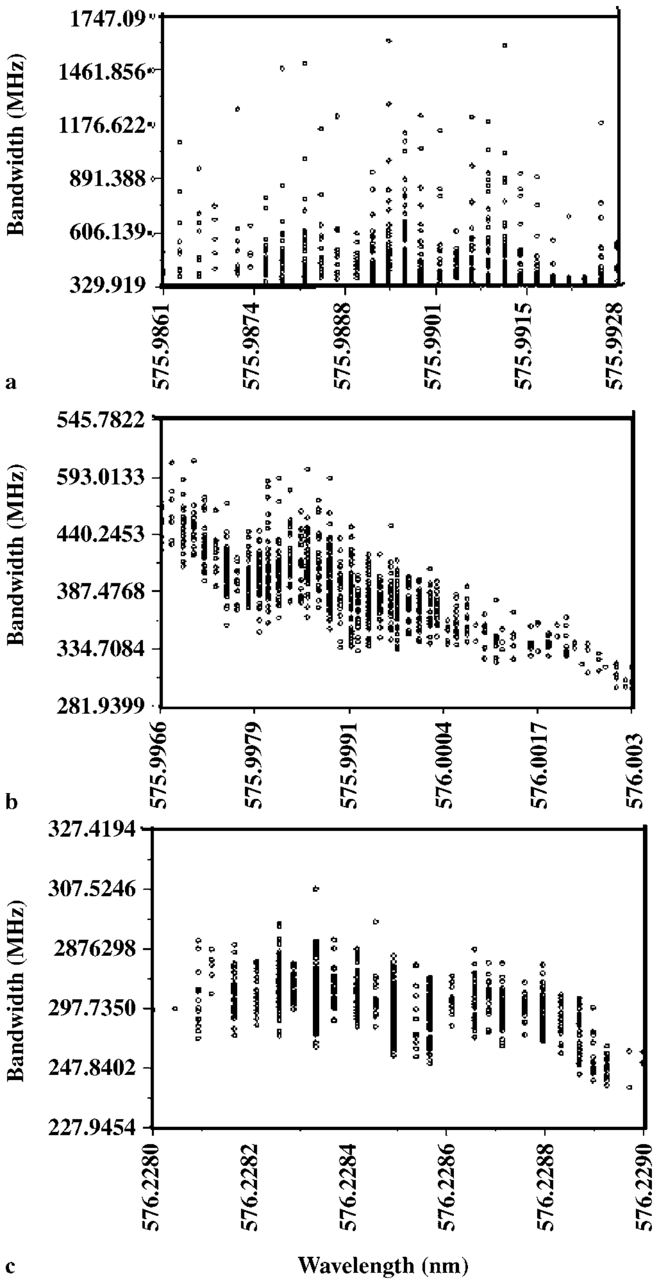

FIGURE 4 Variation of bandwidth and wavelength of central mode for flow Reynolds number of (**a**) 221 (**b**) 681 (**c**) 1012

dye laser axis has a strong influence on the stability of output characteristics of high repetition rate, high power, narrow bandwidth dye laser transversely pumped by copper vapor laser.

Maruyama et al. [1] have observed that the bandwidth varies from 50 to 300 MHz as the flow Reynolds number is increased from 1000 to 20 000. The observed behavior in our case seems to be different. Since the flow Reynolds number remains well within the laminar flow this result of decreasing bandwidth is rather surprising. It suggests however, that within the laminar flow regime the behavior of the dye laser is different. And some other factors may be responsible for increase in bandwidth at lower flow Reynolds number. It is known that the absorption of pump laser pulses causes an acoustic wave in the medium [9]. The disturbance thus affects the dye upstream of the pump region [3]. This may explain our results, as in our experiments it is expected to have an affect more at lower flow rates than at high flow rates, as the disturbed medium will pass through the dye axis earlier than that at higher flow velocities. It was not essential to try and understand what causes bandwidth change and what causes short-term wavelength fluctuations. It is known that the passive bandwidth of a prism beam expander-GIG-tuning mirror configuration dye laser resonator is given [10] by

$$\frac{\Delta\lambda}{\lambda} = \frac{2^{3/2}}{\pi M W}\left[\left(\frac{2^{1/2}(\sin\alpha+\sin\beta)}{\lambda\cos\alpha}\right)_{\mathrm{G}} + \left(\frac{2\sin A}{\cos\theta_1\cos\theta_3}\frac{\mathrm{d}n}{\mathrm{d}\lambda}\right)_{\mathrm{P}}\right]^{-1}, \qquad (1)$$

where the terms in the bracket are the dispersion due to the grating (G) and the prism (P) respectively, λ is the wavelength, α and β are the angles of incidence and diffraction, and A and M are the apex angle and magnification of the prism respectively. θ_1 and θ_3 are the angles of incidence at the first and second surface of the prism respectively. W is the beam size

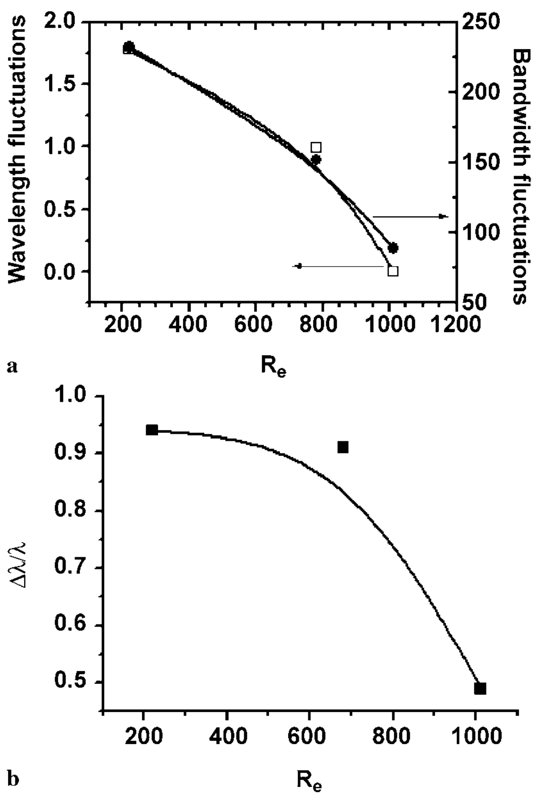

FIGURE 5 (**a**) Fluctuations of the bandwidth and the wavelength with Reynolds numbers (**b**) Variation of observed $\Delta\lambda/\lambda$ with Reynolds number

and $\mathrm{d}n/\mathrm{d}\lambda$ is the variation of refractive index of the prism material with wavelength. Since the dispersion due to the prism is much smaller than that due to the grating [10], by neglecting the second term, the above equation can be written as

$$\frac{\Delta\lambda}{\lambda} = \frac{2\lambda\cos\alpha}{\pi MW[(\sin\alpha+\sin\beta)]}\,. \tag{2}$$

If α is kept constant and the tuning angle does not change,

$$\frac{\Delta\lambda}{\lambda} = Z\left(\frac{\lambda}{W}\right), \tag{3}$$

where $Z = \dfrac{2\cos\alpha}{\pi M(\sin\alpha+\sin\beta)}$.

It is seen that $\frac{\Delta\lambda}{\lambda}$ depends on angle of incidence α, wavelength λ, and the dye beam size W. In general, $\frac{\Delta\lambda}{\lambda}$ is independent of λ if α does not vary. If α is constant then the ratio $\frac{\Delta\lambda}{\lambda}$ is proportional to λ and the slope $\frac{Z}{W}$ will give an estimate of the beam size W. It is therefore possible to check, by measuring the variation of the output wavelength recorded over a long time, whether the change is due to mechanical changes in the alignment of optical components or because of bandwidth changes due to changes in the divergence of radiation falling on the grating due to changes in W.

Hence, it is seen that $\frac{\Delta\lambda}{\lambda}$, depends on both angle of incidence on the grating, α and dye beam size W. Since these changes occur from pulse to pulse with time interval of about 5 seconds it is unlikely to be due to environmental factors. These fluctuations can be attributed to the pump beam induced refractive index gradient in the dye medium, as the dye medium is asymmetrically pumped from one side only. Since the pump beam is absorbed in the dye medium following exponential absorption law, the dye axis predominantly lies close to the pump beam entrance window and hence the dye laser performance is strongly influenced by the flow of the medium. At a particular flow rate the fluctuation in bandwidth may be due to the change in the divergence of radiation falling on the grating due to change in beam size, and in wavelength it may be due to the deflection of the beam because of non-uniform refractive index variation of the medium, causing change in angle of incidence and hence optical path length. When the flow is increased the dye medium across the optical axis becomes more uniform and consequently the fluctuations decreases. An output measurement at higher flow rates has not been performed because of limitations. The estimated value of the penetration depth of the pump beam in the medium for 1 mM solution of Rh6G in ethanol–ethylene glycol (solvent used in the experiments), given by [2], $1/(\sigma_{01}N)$, where $\sigma_{01} = 1.66\times10^{-16}\,\mathrm{cm}^2$ is the absorption cross-section for Rhodamine 6G at $\lambda = 510.6\,\mathrm{nm}$, and N is the dye concentration, is about 102 microns. In practice the penetration depth of the pump beam is higher than that estimated from the above considerations. In similar experiments variation from 120–210 microns [11] were measured.

4 Conclusions

In conclusion it is seen that the flow within a laminar region plays an important role on the stability of the output bandwidth and wavelength of a high repetition rate grazing incidence grating dye laser, transversely pumped by a copper vapor laser operating at 5.6 kHz repetition rate. The wavelength variations from 575.9861 to 575.9928, 575.9966 to 576.003, 576.2281 to 576.2289 nm, and bandwidth variations from 330 to 1750, 282 to 545, 235 to 324 MHz were observed at the flow rates of 1.2, 3.7 and 5.5 lpm respectively. The fluctuation in bandwidth and wavelength decreases with increasing flow rates. The output wavelength is affected by deflection of the beam, causing a change in the angle of incidence and hence optical path length. The bandwidth fluctuations are due to the change in the divergence of radiation falling on the grating due to change in beam size.

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