THE PASSIVELY MODE LOCKED AND DISPERSION COMPENSATED RHODAMINE 110 DYE LASER

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The passive mode locking of a CW Rhodamine 110 dye laser in various dispersion compensated cavities is reported. Using the dye 1, 1, 1, 3, 3, 3-hexamethylindocarboxylic acid (HMIDCA) as the saturable absorber, pulses as short as 80 fs have been obtained from a CPM ring laser operating at a wavelength of 581 nm.

Since its first demonstration in 1972 [1], the passively mode locked cw dye laser has been the source of the temporally shortest pulses and, compared to its synchronously or hybridly mode locked counterparts, generally offers higher amplitude stability and lower inter pulse jitter [2]. Until very recently, however, this system was limited to a single active/passive dye combination (Rhodamine 6G/DDDCI) operating around 620 nm [3–7]. In 1984 Rhodamine 700 was passively mode locked around 540 nm in a krypton ion laser-pumped system [8]. Since then passive mode locking has been demonstrated in the yellow [9,10], red [11] and near infrared [12,13], with pulses of less than 500 fs being generated continuously from ~550 nm to 700 nm in a simple linear cavity with no dispersion compensation — the shortest pulse being of 120 fs duration. We now report on the first investigation (to the authors’ knowledge) of passive mode locking with an active/passive dye combination other than Rhodamine 6G/DDDCI in a cavity which incorporates adjustable group velocity dispersion.

Various different cavity configurations were employed which are shown in Fig. 1. For the cavities used, all the mirrors were coated with a single stack dielectric coating of 100% reflectivity centred at 560 nm apart from an output coupler which had a single stack dielectric coating for 99% reflectivity at 560 nm. These dye lasers were pumped by the all lines output of a Spectra-Physics argon ion laser (Model 2020) which was coupled into the gain medium (1.7 X 10⁻³ M)

Fig. 1. Experimental cavity configurations used.
Rhodamine 110 in ethylene glycol) by a focusing mirror of 25 mm radius of curvature. The dye laser beam was focused into the active and passive vertical jet streams (100 μm thickness) using folded sections with 100 mm and 50 mm radius of curvature mirrors respectively.

The intra cavity group velocity dispersion was adjusted by either using a prism sequence [14,15], or by using the dielectric mirrors away from normal incidence [16,17]. The output of the dye laser was monitored using a fast photodiode (BPW28) and the pulse durations were measured by the standard collinear second harmonic generation autocorrelation technique employing crystals of KD.P or LiIO₃ of less than 150 µm thickness. Our autocorrelator incorporated a scanning "real time" facility which aided the optimisation of the dye laser, though the autocorrelation traces displayed here were taken using a single slow scan. Sech² pulse shapes were assumed throughout this work.

In the first cavity arrangement examined (fig. 1a) where M5 was the 1% output coupler, both 2-(p-dimethylaminomethyl)-benthiazocarboxyamine iodide (DASBBI) and 1, 1, 3, 3', 3'-hexamethyldi.Observablecarboxyamine iodide (HBO) were used as saturable absorbers [10]. There was no restriction on the laser bandwidth for this cavity since all the mirrors were used near normal incidence. For both saturable absorbers the laser wavelength increased steadily with the dye concentration resulting in pulses of the order of 300 fs at around 600 nm. The pulse durations were minimised by adjusting the GVD via the translation of one of the intra cavity prisms [14]. When DASBBI was used, the wavelength of the laser intermittently jumped to the green around 545 nm where it was not mode locked. This was not observed when using HBO.

The insertion of the aperture between the output coupler M₄ and the first prism P₁ (where there is a spatial distribution of the laser spectrum [14]) made it possible to restrict the oscillating wavelength.

For this arrangement, the laser was very unstable with DASBBI as the saturable absorber but was slightly better with HBO where pulses of 190 fs were obtained at M₄ at 564 nm upon adjustment of the intracavity GVD. This instability arose because the wavelength of the laser depended very critically on the exact path of the laser beam. The laser tended to self adjust such that it could lase at a wavelength of minimum loss.

To overcome this the cavity shown in fig. 1b was investigated where the mirror M₂ was the 1% output coupler. Mirror M₃ was used at an angle of 2° which causes its spectral region of high reflectivity to be shifted towards the yellow resulting in a long wavelength cut off, as well as a reduction in reflectivity and a contribution of negative intracavity GVD [16,17]. When optimised this configuration yielded transform limited pulses of ≈120 fs at 579 nm for an HCl concentration of 10⁻² M. The value of α was 76°, the prism separation was 350 mm and the intracavity glass path was 9.5 mm. A typical autocorrelation trace is shown in fig. 2 which was obtained at a pump power of 4.6 W. Two beams of 20 mW average output power were obtained from M₃ and one of 3 mW from M₄. The cavity round trip time was ≈11 ns. For both these linear configurations the frequency spectrum of the output beam was distributed across its spatial profile due to the action of the intracavity prisms. This could be corrected by employing a further pair of prisms extra-cavity, or by reconfiguring the laser cavity such that the output was taken from the opposite end.

A CPM ring cavity was constructed following the design by Valdisserri et al [7] where all the mirrors were used at near normal incidence and a sequence of four prisms was used to adjust the intracavity GVD. Once again, with no restriction on the oscillating wavelength, the laser operated in the orange, this time yielding pulses as long as 800 fs. With an aperture placed between the central two prisms (where again the laser spectrum is spatially distributed) it was possible to obtain pulses of ≈104 fs but the laser output was unstable for the same reason as the linear cavity in fig. 1a.

Fig. 2. Autocorrelation of optimized pulse durations obtained using cavity shown in fig. 1b.)
In order to limit the laser wavelength, the cavity shown in Fig. 1c was designed. Mirror $M_0$ was a single stack coating of 100% reflectivity centred on 632 nm for normal incidence which was used at an angle $\beta/2$ such that its spectral region of high reflectivity was shifted towards the yellow. All the other mirrors were the 100% reflecting coating already described. The prism pairs were each separated by 230 mm and the values of $a$, $b$ and $y$ were $70^\circ$, $89^\circ$ and $27^\circ$ respectively. The folding angles were both approximately $7^\circ$ and the active and passive jets were separated by 675 mm corresponding roughly to one quarter of the total cavity length (round trip time = 9.2 ns). Almost transform limited pulses as short as 100 fs duration were obtained at 583 nm for an HCl concentration of $10^{-3}$ M and an intra-cavity glass path of 9 mm. This configuration required no intra-cavity aperture and the laser output was very stable yielding up to 15 mW average power in each of the two output beams from mirror $M_7$, for 4.2 W pump power. For this concentration of HCl the laser threshold was 3.4 W and the laser output was stable for up to 4.4 W pump power with no significant change in pulse duration. Higher pump powers resulted in the onset of multi-pulsing and poor stability. Fig. 3 shows the autocorrelation trace of the shortest pulses obtained and Fig. 4 shows how the pulse duration varied as the amount of intra-cavity glass path was adjusted. The graph is only slightly asymmetric where the pulse duration increases faster with more glass path than optimum — in contrast to the dramatic asymmetry reported by Martinov et al. [18] for the Rhodamine 6G DODCI CPM ring laser. This implies that there is rather less net positive SPM in this laser and hence less soliton shaping [18] — perhaps explaining why the measured pulse dura-

![Fig. 3. Autocorrelation of minimum pulsewidths at 583 nm obtained using cavity arrangement of Fig. 1b.](image)

![Fig. 4. Output pulsewidth variation with intra-cavity glass path length.](image)

![Fig. 5. Autocorrelation showing structured pulse obtained for specific glass path, the temporal separation of the main and side peaks is ~200 fs.](image)
wavelength to the green. Also, as the pump power was increased, the laser tended to "double pulse" far earlier than when HCl was used.

The shortest pulses obtained were from the cavity shown in fig. 1d. This is similar to the previous CPM laser except that the prism sequence was omitted, permitting the cavity round trip time to be as short as 7.5 ns. The active and passive jets were separated by 540 mm. Angles α, β and γ were approximately 70°, 90° and 27° respectively and the saturable absorber was a 10-4 M solution of HCl which resulted in a lasing threshold of 4.3 W. Two outputs of ~17 mW were obtained from M7 for a pump power of 7.0 W. Fig. 6 shows an autocorrelation trace of the pulses of 80 fs duration obtained at 581 nm which were close to transform limited. For lower pump powers pulse durations were up to ~30% longer though the laser was still highly stable. It was observed that pulses of less than 100 fs duration were obtained as long as 70° < a < 75° and 80° < β < 92° (though particular pairs of values gave the shortest pulses, presumably corresponding to a particular value of group velocity dispersion.

One reason why this cavity produced the shortest pulses may have been that the cavity round trip time was only 7.5 ns i.e. roughly twice the lifetime of Rhodamine 110. According to New's criteria this results in a broader stability range for single pulse evolution [20]. Multipulsing was not observed at any time, even when the laser was pumped several watts above threshold.

For all the systems described here it was noted that

\[ \tau_p = 80 \text{ fs} \]

\[ \tau_{\text{of}} = 1.65 \text{ ps} \]

Fig. 6. Autocorrelation of optimised 80 fs pulses obtained from the cavity configuration of fig. 1 (d).

the shortest pulses were obtained when the saturable absorber jet was at the focus of its folded section which is in contrast to the Rhodamine 6G/DODCI CPM laser described by Valdmanis et al. [7]. As the passive jet was moved away from the focus, the optimum intracavity glass path correspondingly changed. These observations illustrate the dependence of the pulse duration on the balance between intracavity SPM and GVD but suggest that the nature of the dyes used for this work are somewhat different from that of the conventional Rhodamine 6G/DODCI combination. The fact that the lasers all seem to operate best in the spectral regions where the gain and absorption are low is perhaps significant and mode locking may be attributed to the photokomers of HCl and DAS DASRTI as with DODCI. A more complete understanding of the phochemistry of saturable absorbers is clearly desirable and the authors suggest that this may be achieved, in part, by further investigation of new active/passive dye combinations. We are currently quantifying photophysicsical processes in the saturable absorbers used for c.w. dye lasers.

It is also interesting to note that the CPM ring laser configurations yielded significantly shorter pulses than the dispersion compensated linear cavities, again in contrast to the results reported by Valdmanis et al. [7]. In this instance the CPM mechanism appears to play a more important role in the short pulse generation. For this reason it may well be possible to generate yet shorter pulses by employing a thinner saturable absorber jet to maximise the effect of the coherent interaction [21].

In conclusion we have reported the passive mode locking of Rhodamine 110 in a dispersion compensated cavity for the first time. Pulses as short as 80 fs have been obtained from a CPM ring laser. Various properties of these cavities have been described which contrast with those reported of conventional Rhodamine 6G/DODCI laser systems.

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References


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