Abstract. This report concerns the optimization and mode locking of a continuous wave titanium-doped sapphire laser. Pulses as short as 10 ps duration were obtained through active mode locking by loss modulation. Upon adding a nonlinear external cavity, subpicosecond pulses were directly generated from a titanium-doped sapphire laser for the first time. Passive mode locking using nonlinear external cavity feedback, and mode locking with a linear external cavity have also been investigated.

The recent demonstration of cw laser operation of titanium-doped sapphire (Ti:Al₂O₃), tunable over -400 nm, is important for many areas of laser physics [1]. As a cw mode-locked laser, it is a convenient spectroscopic tool for time-resolved studies of semi-conductors with a potential femtosecond time resolution. Owing to the relatively long upper-state lifetime (\(\tau_0\)) and low gain cross-section (\(\sim 10^{-19} \text{ cm}^2\)), the techniques of synchronous pumping and passive mode locking with a slow saturable absorber, which have been successfully employed for mode locking cw dye lasers, are not appropriate for Ti:Al₂O₃. Active mode locking through loss modulation, however, has generated pulses as short as 6 ps [2] though pulse durations of several tens of picoseconds are more typical.

The performance of Ti:Al₂O₃ lasers is very sensitive to the quality of the laser crystal. The work reported here, commercially available crystals (from Union Carbide) of nominal 0.1% concentration of Ti³⁺ were used. Initially the simple astigmatically-compensated cavity of Figure 1 was constructed. The folding mirrors (M₁, M₂) were of 15 cm radius of curvature and lens L₃ was of 10 cm focal length. The Ti:Al₂O₃ rod was 16 cm long with Brewster-angled end faces and was mounted on a copper block, water cooled to 17°C. Pumping with the "all-lines" visible output of an argon ion laser, the laser threshold was 0.92 absorbed pump power and the laser exhibited a 1% slope efficiency for up to 6 W pump power. For higher powers the laser efficiency dropped rapidly due to thermal lensing. In a later configuration employing folding mirrors of 10 cm radius, a 27 cm length rod which was cooled to 5°C maintained a 1% slope efficiency for up to 15 W pump power. Figure 2 shows the tuning curve obtained...
for 150 pump power. The limited tuning range and the gap around 820nm is believed to be due to excited state absorption.

The laser was actively mode locked in the cavity shown in Figure 3. A standard Spectra Physics acousto-optic prism modulator driven with -1W RF power yielded pulses as short as 75ps in duration at a repetition rate of 128MHz. With a 98% output coupler the laser tuned from ~720nm to 840nm (though not between 800nm and 850nm) and with a 20% output coupler the laser yielded a maximum average output power of 920mW. Pulse durations were routinely maintained below 100ps.

In order to generate subpicosecond pulses, the technique of nonlinear external cavity feedback was used, based on the theoretical and experimental work of Blow et al. [3,4]. An optimised 65cm length of single-mode polarization-preserving fibre (from York Technology) provided the nonlinearity in the resonant external cavity which was twice the length of the main cavity. Figure 4 shows the experimental configuration. A stabilization scheme based on the design by Mitschke and Mollenauer [5] was incorporated to interferometrically match the main and external cavity lengths. For an average power of 200mW in the fibre, subpicosecond pulses as short as 710fs were obtained for the first
Figure 5. Cavity for the actively mode locked Ti:Al$_2$O$_3$ laser.

Figure 6. Experimental configuration for the actively mode locked Ti:Al$_2$O$_3$ laser with nonlinear external cavity feedback.

time [fl]. Figure 5 shows the autocorrelation trace obtained at 788nm. The output was highly sensitive to the interferometric mismatch between the cavity lengths (i.e. less than 0.5nm) but the external cavity length could be coarsely adjusted over several mm without broadening the autocorrelation trace. It should be understood that at 788nm the fibre displayed positive group velocity dispersion and so this laser is certainly not a "soliton laser". The pulse compression mechanism has yet to be elucidated but possibly involves (a) spectral broadening in the external cavity; (b) the intensity-dependent refractive index of the fibre resulting in more constructive interference between the peaks of the pulses in the main and external cavities than between the wings of the pulses (described as Additive Mode Locking in [7]); (c) a beating between the (different) frequency modes of the main and external cavities, inducing a stronger coupling between the modes of the laser system.
We have recently demonstrated that the laser system of Figure 4 yields mode locked pulses even when there is no active mode locking. This was first demonstrated by Goodberlet et al. [8] who measured chirped pulses of 2ps duration from the "passively mode locked" laser which were linearly compressed to 560fs. We have also shown that a linear (i.e. empty) external cavity coupled to a cw Ti:Al_2O_3 laser can result in mode locked pulse trains. This is observed as the external (or main) cavity length is slowly adjusted - either manually or by a mirror mounted on a shaker which moves it through ~20nm at a frequency of ~200Hz. Figure 6(a) shows the mode locked pulse train and Figure 6(b) shows the trace obtained from a sampling oscilloscope with a response of ~70ps. Synchroscan streak camera measurements have been made of pulses as short as 40ps. The physical mechanisms behind this very recent experimental observation are not yet understood. Kelly [9] has, however, numerically studied the influence of a linear external cavity on a synchronously mode locked colour centre laser, where he speculates that some pulse compression can arise as a consequence of the radiation in the linear and external cavities beating together.
References