ACTIVE MODE-LOCKING AND Q-SWITCHING OF A 1.54 μm Er:GLASS LASER PUMPED BY A 1.064 μm Nd:YAG LASER

D.C. HANNA, A. KAZER and D.P. SHEPHERD
Department of Physics, University of Southampton, Highfield, Southampton S09 5NH, UK

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A Nd:YAG pumped Yb:Er:Phosphate glass laser oscillator has been actively mode-locked and Q-switched, producing stable ~70 ps fwhm mode-locked pulses at 1.54 μm. Peak powers of ~20 kW are achieved when Q-switched and mode-locked and ~20 W when quasi-cw mode-locked, thus providing a convenient source suitable for investigation of nonlinear propagation behaviour in the negative dispersion region of silica optical fibres.

1. Introduction

In a previous paper [1] we have reported operation of a 1.54 μm Er glass laser pumped by a 1.064 μm Nd:YAG laser, via absorption by Yb sensitisers. Here we report mode-locked and Q-switched operation of this laser, at power levels which are suitable for studies of nonlinear propagation and pulse compression in the negative velocity dispersion region of silica fibre [2,3]. Mode-locked pulse durations of 70 ps have been measured, having a time-bandwidth product of 0.6, and a peak power of 20 W. When Q-switched and mode-locked, a peak power of ~20 kW has been achieved.

2. Experimental arrangement

The laser medium is the same as reported in ref. [1], consisting of a 7.5 cm long rod of Kigre QE-7 glass, with end faces anti-reflection coated for 1.5 μm and wedged by 1/2° relative to the axis of the rod. The pump laser is a pulsed Nd:YAG, providing pulses of 5 ms duration, of up to 90 W, in a linearly polarised TEM_{00} mode, at a repetition rate of 5 Hz [1]. As in ref. [1], the Er laser was isolated from the pump laser by means of a quarter wave plate and polariser. Through all of the measurements reported here the pump beam was focussed to a spot-size (radius, w) of 170 μm. The various resonators used for the Er laser have been designed to provide a comparable spot size in the laser rod for the laser wavelength of 1.54 μm, so as to achieve good beam overlap. To enhance absorption of the 1.064 μm radiation in the Er glass we have operated with the glass rod maintained at a temperature of ~90°C.

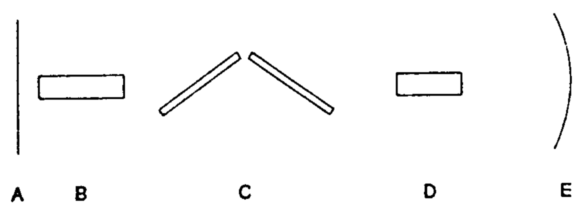

Fig. 1. Resonator for Q-switched operation. (A) plane pump input mirror, (B) Er rod, (C) Brewster plates, (D) $LiNbO_3$ crystal, (E) concave output mirror.

Q-switching has been achieved using a $LiNbO_3$ Pockels cell, with field applied transversely, in the x_1 direction, and propagation in the x_3 direction. The crystal, of dimensions 9×9×25 (x_3) mm, had anti-reflection coatings for 1.5 μm on the end faces. Applying a quarter wave voltage (~2.5 kV) was sufficient, in conjunction with a polariser consisting of two Brewster-angled silica plates, to suppress laser action during the entire pumping pulse. The Pockels cell voltage was removed at the end of the pumping pulse to produce a Q-switched output. Using the resonator of fig. 1, with a concave (50 cm) output mirror of ~10% transmission, and a resonator length of ~50 cm (i.e. a near hemi-spherical resonator), gave

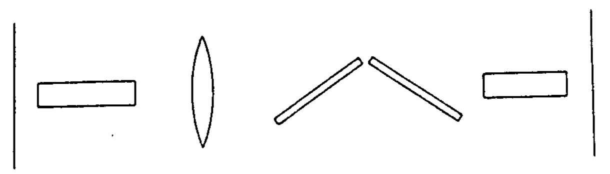

Fig. 2. Resonator for mode-locked operation. (A) plane pump input mirror, (B) Er rod, (C) 40 m lens, (D) Brewster plates, (E) modelocker, (F) plane output mirror.

a TEM_{00} output pulse of ~0.7 mJ in a ~60 ns (fwhm) pulse, hence a peak power of ~10 kW. This corresponds to ~20% of the energy obtained in long pulse operation (~4 ms) being available as Q-switched output. Amplitude stability was good, with <5% fluctuation in output.

Active mode-locked operation has been tested both under long-pulse, i.e. quasi-cw conditions, and under Q-switched operation. First we consider quasi-cw operation. The resonator for quasi-cw operation is shown in fig. 2. The resonator design was constrained by three considerations. First there was the need for a resonator length of 115 cm, to match the modulation frequency (ω_m~67 MHz) of the acousto-optic modulator available to us. Also there was the need for an appropriate spot size (~170 μm) in the glass rod, and a sufficiently collimated beam in the acousto-optic modulator. A 40 cm lens, anti-reflection coated for 1.5 μm achieved the desired resonator, with a ~0.8 mm waist spot-size at the plane output mirror. This output mirror was wedged, effectively suppressing etalon effects. The input mirror was not wedged, or anti-reflection coated, and despite its high reflectivity (~99%) at 1.5 μm, it produced readily detectable etalon effects which may have degraded the mode-locking performance. In arriving at the resonator design, allowance was made for the effect of thermally induced lensing in the laser rod, following the analysis of Gordon et al. [4].

The acousto-optic modulator consisted of a 7 cm long fused silica slab originally intended for use at 1.06 μm and therefore having wedged end faces anti-reflection coated for 1.06 μm operation [Intra Action ML-67J]. It was found that these AR coatings gave sufficiently low loss to permit satisfactory operation at 1.5 μm. Using a pulsed rf drive power of 7 W, it was found by measurement that the depth of modulation for 1.5 μm radiation corresponded to a value of $\theta_m \simeq 1.2$ (using the notation of Kuizenga [5] who defines the single-pass amplitude transmission $m(t)$ as $m(t)=\cos(\theta_m \sin \omega_m t)$). The Brewster plate polariser was retained in this resonator to constrain the laser polarisation to that for which the modulator produced strongest modulation.

To obtain mode-locked operation the resonator length was adjusted to match the modulation frequency. Two resonator length positions were found where driven relaxation oscillations occurred for the entire duration of the laser output as described by Kuizenga [5], the correct resonator length corresponded to a position midway between. Fig. 3 shows a typical pulse train obtained under these conditions, with an overall duration of ~3 ms, and with initial relaxation oscillation decaying away in ~2 ms. Measurements of mode-locked pulse duration were made using background-free second-harmonic autocorrelation, in a $LiIO_3$ crystal. The entire pulse train was used in this measurement and fig. 4 shows a typical result with the curve corresponding to a best fit assuming a gaussian pulse shape. The pulse duration deduced from fig. 4 is 70 ps. By using a Pockels cell shutter external to the laser, the initial part of the pulse envelope, containing the relaxation oscillations, could be suppressed in the autoorrelation measurement, however it was found that the measured pulse duration was still 70 ps. The bandwidth of the output, measured using a scanning Fabry-Perot interferometer, was 8 GHz, corresponding to a time bandwidth product of ~0.6. From measurement of output energy in the pulse train, and the measured mode-locked pulse duration, a peak power of ~20 W is deduced.

For combined Q-switching and mode-locking the resonator is as shown in fig. 2 but with the $LiNbO_3$ Pockels cell placed between the Brewster plates and the intracavity lens. The Pockels cell voltage was adjusted to allow 'prelasing' to occur [5]. The prelase lasted for ~2 ms, thus providing sufficient time for the mode-locker to establish a steady state pulse duration. The voltage was then removed from the Pockels cell near the end of the pumping pulse, resulting in a Q-switched envelope of ~300 ns duration (fwhm) and pulse energy of ~70 μJ. Autocorrelation measurement of pulse duration yield ~85 ps, hence indicating peak power of ~20 kW.

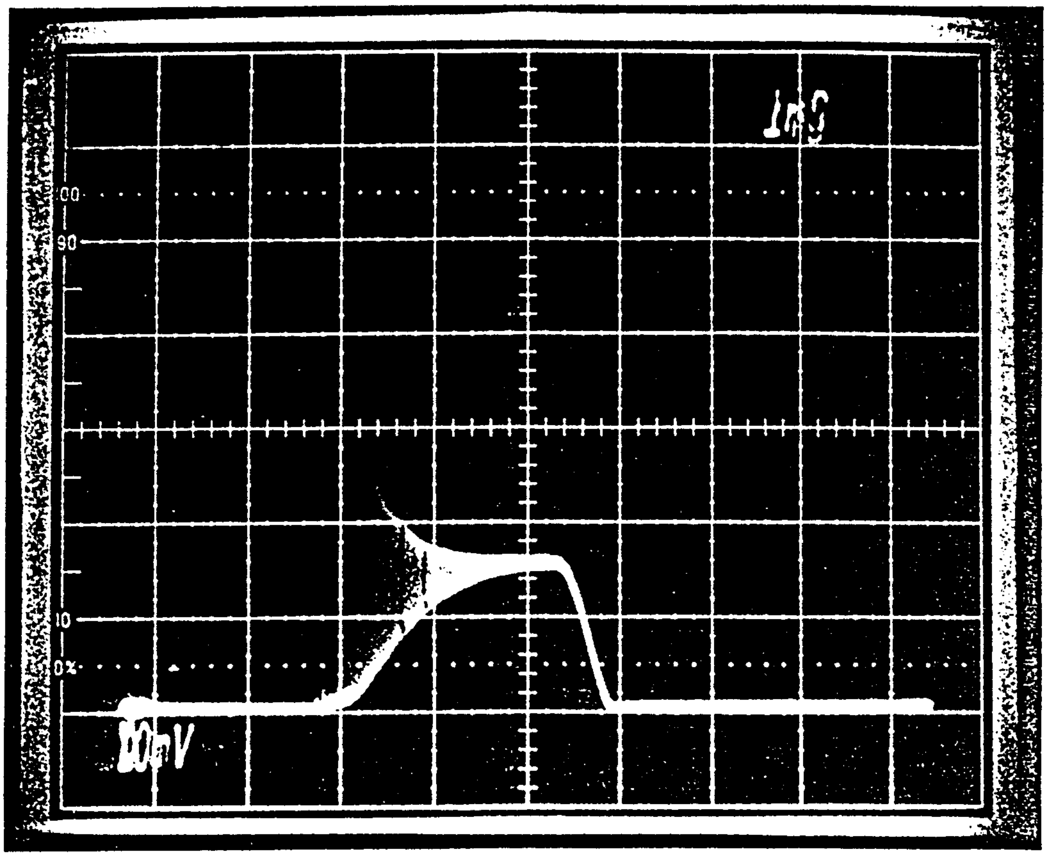

Fig. 3. Envelope of mode-locked pulse train, showing initial relaxation oscillations decaying after ~2 ms.

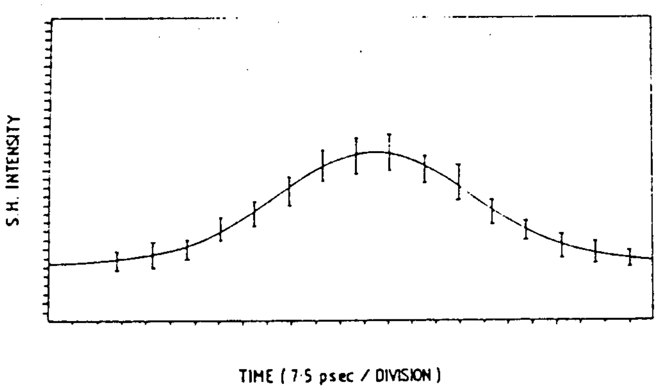

Fig. 4. Second harmonic autocorrelation measurement of pulse duration, fwhm = 70 ± 1 ps. The background level observable on this trace is due to ambient room light.

3. Conclusion

The results reported here give further confirmation that the Nd:YAG-pulsed Er glass laser is a versatile and convenient source of 1.54 μm radiation. Significant improvements on our results should be possible as a number of the components we have used were not optimally designed for operation at 1.54 μm. The power levels and pulse durations suggest that this source should be useful for investigations of nonlinear propagation in silica fibre, and, in particular the mode-locked laser could form the basis of a soliton laser, as described by Mollenauer and Stolen [6].

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