Pulse shortening and power scaling of passively mode-locked feedback-stabilised Nd:KGW laser

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Abstract: We show that by incorporating negative feedback stabilisation to allow on increasing the modulation depth of the saturable absorber in a diode-pumped mode-locked Nd:KGd$(WO_4)_2$ laser leads to significant pulse shortening.

1. Introduction

Diode-pumped mode-locked solid-state lasers have developed into a mature technology over the last two decades, and are currently finding applications in many areas such as micro-machining, displays, neurosurgery, eye surgery, confocal microscopy, and others. Many techniques have been applied to achieve mode-locked operation of solid-state lasers, however passive saturable absorbers have been especially notable. With the advent of high-power diode-pumped solid-state lasers, semiconductor saturable Bragg reflector structures (SBR) have been demonstrated to be very reliable for passive mode-locking in the 800 nm to 1.5 μm spectral region. The operating parameter range of lasers mode-locked by SBRs has been traditionally limited by the condition for continuous-wave mode-locking (CWML) [1], which places a restriction on the range of intracavity pulse energies and on the modulation depth of the saturable absorber. It has recently been shown that negative feedback stabilisation can be used to suppress Q-switching instabilities and so increase the parameter range of CWML operation of SBR mode-locked lasers [2, 3] but up to now no details on the performance of feedback-stabilised mode-locked lasers have been reported.

Nd-doped potassium gadolinium tungstate (Nd:KGW) [4] is an efficient laser material having a 10-nm wide absorption band with a peak at 810 nm. The high stimulated emission cross section (3.5×10^{-19} cm^2) and short upper-state life time of Nd:KGW act to reduce the tendency of self-Q-switching when mode-locked by semiconductor saturable absorbers. A Nd:KGW laser mode-locked by an SBR has been previously demonstrated to produce 6.3-ps pulses at an average power of 1 W [5], however the $\Delta\nu\Delta\tau$ was over 3 times that for Fourier transform limited pulses. The Nd:KGW emission line is ~720 GHz wide and therefore transform-limited pulses with around 1 ps duration should be obtainable.

The goal of this work was to further investigate SBR mode-locking of the Nd:KGW laser such that the limitations to the pulse duration could be studied. We have utilised the negative feedback stabilisation technique to allow an investigation of the influence of intracavity saturable modulation depth on the output pulse duration of an SBR-mode-locked laser. To control the modulation depth, the temperature of the SBR was changed to shift the quantum wells' exciton peak relative to the laser wavelength. The saturable absorption was also increased by exploiting two SBRs in the cavity. Negative feedback stabilisation was also used in a quasi-continuous pumping configuration, to assess power scaling of the on-time output by damping the relaxation oscillations that occur after rapid pump power turn-on.

2. Continuous wave operation

The Nd:KGW crystal sample (Alphalas GmbH) cut along [010] axis, 4% doped with Nd, was 8 mm long and 3 mm in diameter. The crystal was wrapped in indium foil and mounted in a water-cooled copper block while the circulating water temperature was maintained at 16 degrees Celsius. The parallel crystal facets were AR coated at 810 nm and 1067 nm. The crystal was end-pumped by a fibre-coupled laser diode (Jenoptik JOLD-20-CPXF1L)

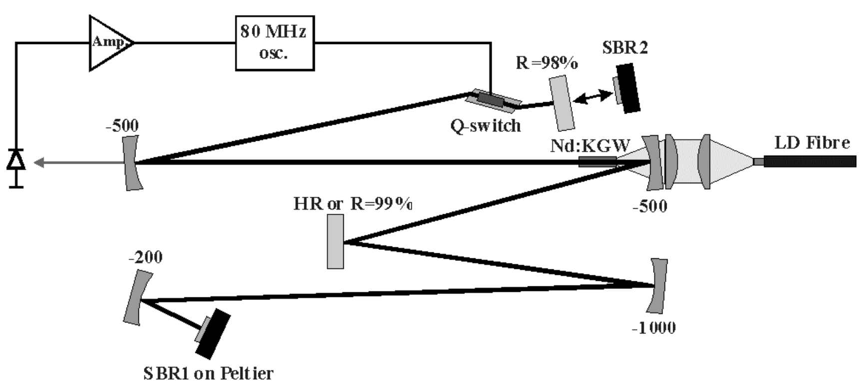

Fig. 1. SBR mode-locked feedback-stabilised Nd:KGW laser. Amp., proportional amplifier; LD, laser diode; HR, high reflector at laser wavelength; R, reflectivity; osc., oscillator; radius of curvature noted for concave mirrors.

with 20 W maximum output power and a 600-µm fibre of 0.22 numerical aperture.

To investigate the quality of the available crystal sample, cw operation in a 5 cm-long cavity with a rear mirror of 100 radius of curvature (ROC) and flat output coupler was initially investigated. The pump fibre was 1:1 imaged into the laser crystal using two 35 mm plano-convex lenses. To reduce stress in the crystal the diode wavelength was tuned away from the absorption peak at 810 nm and thus about 70% of pump radiation was absorbed in the medium. The absorbed pump power was limited to 4.2 W to prevent thermal damage in the crystal [6]. A slope efficiency of 48% and output power of 1.7 W was obtained with an output coupler of 95% reflectivity, which is an improvement compared to previously published results with this material in similar pump and resonator configurations [6, 7]. This can be attributed to mature growth technology achieved by manufacturers in recent years.

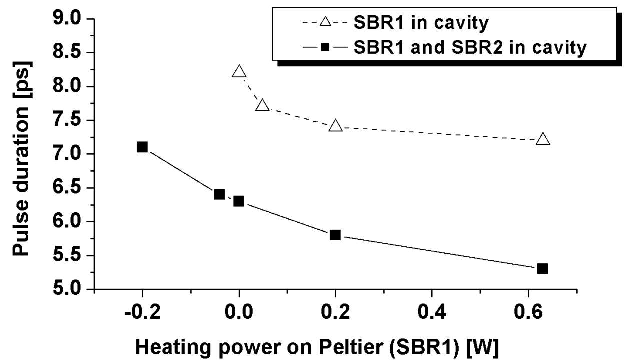

Fig. 2. Pulse duration as a function of heating power applied to Peltier module with mounted SBR1. Cooling of the SBR1 is indicated by negative heating power.

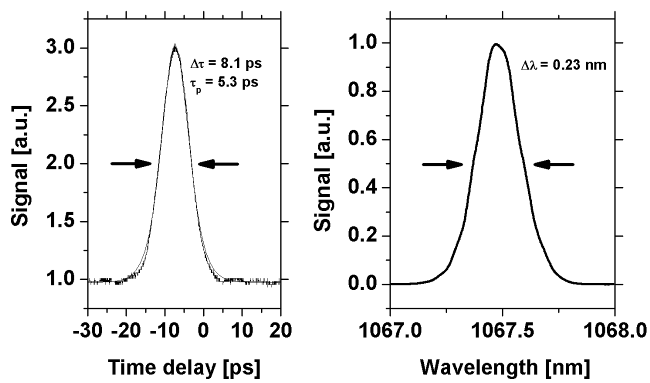

Fig. 3. Autocorrelation curve and spectral line profile of 5.3-ps pulses.

Mode-locking of a Nd:KGW laser was studied with the laser cavity drawn in Fig. 1. A Strain-balanced double-quantum-well InGaAs/GaAsP saturable Bragg reflector [8] was used as the passive mode-locking element. The gain medium was placed away from the end of the cavity to avoid effects associated with spatial hole burning [9]. Negative feedback stabilisation employing a 3-cm long Brewster–cut Q-switch crystal was used to prevent Q-switch instabilities [3]. An InGaAs photodiode with 1 GHz bandwidth was used for detection of laser radiation leaked through one of the cavity folding mirrors. The detected signal was used for driving the acousto-optics Q-switch via a proportional amplifier. Self-starting mode-locked operation was obtained at a pulse repetition rate of 77 MHz. With feedback stabilisation switched off only Q-switched mode-locked operation could be obtained in this cavity configuration The mode size on the SBR (SBR1 in Fig. 1) was calculated to be ~100 µm in diameter. The modulation depth present in the cavity was varied by changing the temperature of the SBR, which was mounted on a 5x5 mm 4-W Peltier cooler. The output pulse duration for 4.2 W of absorbed power for different Peltier cooling/heating powers was measured by an intensity autocorrelator. The measurement results are shown in Fig. 2. The pulse duration decreased from 8.2 ps with an SBR at room temperature to 7.2 ps with an SBR heated with 0.63 W. The pulse duration did not decrease by additional heating of SBR1 indicating that the maximum modulation depth available in this cavity configuration was reached. The overall modulation depth inside the cavity was increased further by replacing the second end mirror by a second SBR (SBR2 in Fig. 1). At the same time a flat folding mirror was replaced by an output coupler (see Fig. 1). At room temperature the pulse duration decreased to 6.3 ps and when 0.63-W heating was applied to SBR1, the pulse duration was reduced down to 5.3 ps. The total output coupling used in the measurements was 98% and an output power of 0.5 W was constantly measured for all configurations. The output radiation spectrum was measured using an optical spectrum analyser (HP 86142A). The output pulses were measured to be transform-limited with the time-bandwidth product close to 0.315 for the assumed sech^2 pulses. The autocorrelation curve and spectral profile of 5.3-ps pulses are shown in Fig. 3.

3. Quasi-continuous wave operation

A quasi-cw pump regime effectively reduces the heat load in the laser crystal and therefore much higher on-time pump powers are possible before thermal damage in the laser medium occurs. Many applications require high-energy pulsed radiation and this method allows for considerable power scaling.

The previously described laser diode was operated in a pulsed regime. The driving pulses were of 240 μs duration and 30 Hz repetition rate. Higher repetition rate was not achievable due to the available diode driver. The maximum available on-time pump power was 20 W, which corresponded to 5.5 mJ pump pulse energy. In a short cavity arrangement identical to the one used in the cw-pump mode and with an output coupler reflectivity of 85%, slope efficiencies as high as 66% and on-time output power of 8 W were measured for 14 W of absorbed pump. Nd:KGW thus exhibits very good efficiency when thermal problems are eliminated.

Quasi-cw pumping is commonly associated with relaxation oscillations and Q-switching instabilities at the front part of the mode-locked laser pulses train. This behaviour was suppressed by applying negative feedback stabilisation in a similar laser configuration as for cw pumped operation. Using the stabilisation, relaxation oscillations were damped after ~ 10 μs while the first turn-on spike was strongly reduced and the subsequent spikes completely diminished (see Fig. 4). A stable train of mode-locked pulses at a repetition rate of 83 MHz was produced (see insert (a) in Fig. 4). With an output coupler reflectivity of 90%, a slope efficiency of 44% and 5.3 W on-time output power was measured for 14 W power absorbed. The pulse duration was measured to be 12 ps using a slow scanning intensity autocorrelator when $sech^2$ output pulses were assumed (see insert (b) in Fig. 4). The output power was limited by the available pump power in this configuration.

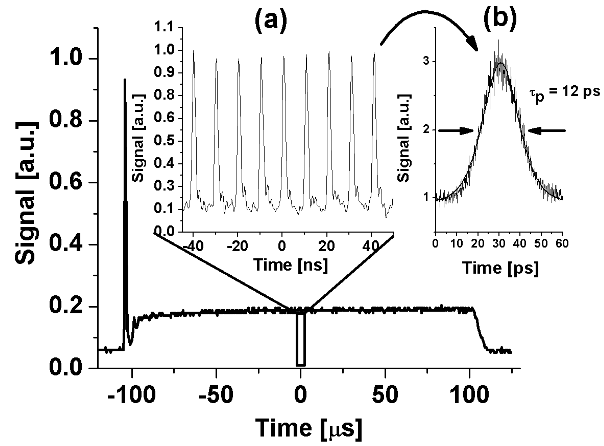

Fig. 4. Quasi-continuous-wave pulse train emitted during the on time of the pump with active stabilization (individual pulses are not resolved); (a) detail of the individual pulses; (b) the measured intensity autocorrelation.

3. Conclusion

Adopting a previously developed negative feedback stabilisation technique we have shown that by regulating the modulation depth present in the cavity of an SBR-mode-locked Nd:KGW laser, the pulse duration can be shortened substantially. This method could be pursued further by placing multiple saturable absorbing mirrors inside the resonator. The next step would be to tailor the modulation depth of a strain-balanced SBR during the growth process by incorporating multiple quantum wells. We believe that this technique can lead to extensive output pulse shortening of SBR mode-locked lasers to durations comparable to those achieved with other mode-locking methods e.g. additive pulse mode-locking.

Negative feedback stabilisation was also utilised in quasi-CW operation of an Nd:KGW laser. The output pulse power was scaled-up to 5.3 W on-time with a mode-locked pulse duration of 12 ps. The output power was limited by the available pump power and further scaling of up to 10x should be achievable with commercially available pump diodes.

In conclusion, negative feedback stabilisation considerably increases the operational range of SBR mode-locked solid-state lasers. We believe that by further development of the methods exploited in this work, power-scaled lasers with pulse durations close to the limit imposed by the gain material can be foreseen.

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