10-GHz straight-cavity SESAM-modelocked Yb:CALGO laser enabled by cascading of second-order nonlinearities


Department of Physics, Institute of Quantum Electronics, ETH Zurich, 8093 Zurich, Switzerland
mayeral@phys.ethz.ch

Abstract: We demonstrate a 10-GHz SESAM-modelocked Yb:CALGO laser achieving 166 fs at 1.2 W from a straight cavity containing a low-loss fanout-apodized-PPLN device that enables soliton modelocking via cascaded second-order nonlinearities and suppresses Q-switching-damage via a self-defocussing lens.

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1. Introduction

The advancement of passively modelocked solid-state lasers has provided the basis for the development of reliable low-noise frequency combs, which have nowadays become important tools within the fields of metrology and spectroscopy. Certain applications, such as the calibration of astronomical spectographs or line-by-line waveform generation, rely on combs with large comb line spacings, typically above 10 GHz, i.e. where the spacing is sufficient to individually resolve the optical lines. However, the design of femtosecond multi-gigahertz solid-state oscillators poses several challenges: the small cavity size restricts the number and choice of optical components and the intracavity pulse energy is intrinsically low, which makes femtosecond soliton modelocking challenging and increases the susceptibility to damage due to Q-switching instabilities.

Here we demonstrate a new approach to high-repetition-rate modelocked lasers that addresses these issues simultaneously. We excite a cascaded quadratic nonlinearity in a low-loss quasi-phase-matching (QPM) device, which enables soliton formation with a large negative nonlinear phase in the positive dispersion regime and furthermore provides a strong dynamic self-defocussing Kerr lens against Q-switching-induced damage. By inserting this device in a compact straight cavity containing an Yb:CALGO crystal for broadband gain and a semiconductor saturable absorber mirror (SESAM), we achieve for the first time femtosecond Watt-level fundamental modelocking of a diode-pumped solid-state laser with a repetition rate above 10 GHz.

In conventional high repetition rate lasers utilizing the Kerr effect in the gain medium, an excellent pump beam quality (i.e. M^2 ≈1) is typically required, which either implies a power limitation or high costs. In [1], the authors used a green single-mode pump and modelocking initiation at the cavity stability limit, demonstrating 0.65 W of average output power with 42-fs pulses in a 10 GHz Ti:Sapphire ring cavity using Kerr lens modelocking. Using a similar ring cavity design, 152 fs were reported at 15 GHz in Yb:Y_2O_3 with an output power of 60 mW [2]. While the latter oscillator was directly diode pumped at 976 nm, the available pump power is limited to about 1 W for single mode beam quality. SESAMs provide a way to modelock an oscillator without the need to operate at the edge of the cavity stability range and allow for high-power pumping with low-cost spatially multimode diodes. Recently, a 5-GHz Yb:CALGO laser with 96 fs and 4 W was achieved in a V-shaped cavity modelocked with a SESAM [3]. Nonetheless, for SESAM modelocking at multi-gigahertz repetition rates, Q-switching instabilities are a principal concern [4]: without careful design, the intracavity components are damaged before the onset of continuous wave mode locking (cw ML).

To overcome these issues, the new approach we demonstrate here combines the advantages of SESAM modelocking with the benefits of cascading of quadratic nonlinearities (CQN) [5], adiabatically excited in a QPM device [6]. The CQN technique consists of using phase-mismatched second harmonic generation (SHG) to generate a Kerr-like (i.e. third-order) response. The result is an effective nonlinear index n_{2,eff} which can be tuned in amplitude and sign by varying the phase mismatch Δk. Modeling has been obtained using CQNs in a variety of laser configurations [7-13], but to the best of our knowledge, repetition rates above 600 MHz have not been demonstrated using CQNs until now.

2. Experimental Setup

The laser cavity is depicted in Fig. 1a. The 1.5-mm-long Yb:CALGO gain crystal is pumped by an internally wavelength-stabilized, spatially multimode diode (Lissotschenko Mikrooptik GmbH, M^2=36) capable of providing up to 60 W at 980 nm. In order to minimize the thermal load inside the laser cavity, the horizontally polarized pump light, which would only be weakly absorbed in the gain crystal, is removed using a polarizing beam splitter. The beam splitter at the same time allows the vertically polarized laser beam to exit. The pump beam is focused through a 12 mm radius pump-transparent mirror that acts as a 2.8 % output coupler for the 1050 nm laser center wavelength. The AIAs-embedded single-InGaAs quantum well SESAM has a saturation fluence of F_s≈8 μJ/cm^2, a modulation depth ΔR≈1 %, non-saturable losses ≈0.12 % and an inverse saturable absorption coefficient F_2≈500 mJ/cm^2.
The 2-mm-long PPLN crystal serves two key purposes:

1. It provides an effective nonlinear refractive index ($n_{2,\text{eff}}$) that is large and negative in sign. This enables soliton modelocking with net positive material dispersion and thus eliminates the need for dispersion-compensating mirrors.

2. It acts as a dynamic self-defocussing lens, i.e. negative Kerr lens. As depicted in Fig. 1b, this self-defocussing lens effect suppresses damage induced by Q-switching instabilities. Without the PPLN, the high intracavity pulse energies that can occur during Q-switching instabilities would lead to a tight focus on the SESAM due to the positive Kerr lens in the Yb:CALGO crystal, ultimately inducing damage. With the PPLN self-defocussing lens however, the laser mode size increases on all the cavity elements as a function of the intracavity elements, thus clamping the fluence and preventing damage.

![Diagram of laser setup](image)

**Fig. 1** (a) Laser setup: The cavity consists of a pump-transparent curved mirror, a 1.5-mm-long Yb:CALGO gain crystal, a 2-mm-long fanout and apodized PPLN device and a SESAM. A spatially multimode diode emitting at 980 nm is used as a pump. (b) Sketch of the self-defocussing lens effect: without the PPLN, the high pulse energies occurring during Q-switching instabilities would lead to beam focussing on the SESAM and induce damage. The PPLN device acts as a defocussing element preventing this damage by increasing the mode size on all cavity elements. (c) Schematic of the fanout and apodized PPLN device. The phase mismatch and thus the value of the nonlinear index $n_{2,\text{eff}}$ can be tuned by moving the device transversely with respect to the laser beam. To minimize the nonlinear losses, the device has an apodized structure, in which the second harmonic (SH) is adiabatically excited at the input and de-excited again at the output. (d) Fluence on the SESAM as a function of intracavity pulse energy. By choosing the right operating position in the PPLN device (i.e. creating a negative lens that is strong enough), the fluence on the SESAM can be clamped below the damage threshold.

### 3. Modelocking Results

The best modelocking results (presented in Fig. 2) were obtained with the PPLN device in position 2 (Fig. 1c/d), i.e. with a PPLN grating vector $K_g=889$ mm$^{-1}$, corresponding to a phase mismatch of 44.9 mm$^{-1}$ and an effective nonlinear index $n_{2,\text{eff}}\approx2.07\times10^{-18}$ m$^2$/W at 1052 nm. For comparison, the intrinsic material nonlinear index of the Yb:CALGO crystal is $n_{2,\text{intrinsic}}^{\text{CALGO}}\approx+8\times10^{-20}$ m$^2$/W, which is 25x smaller and thus has a negligible effect. When operating closer to pos. 1, the defocusing lens effect becomes too weak and Q-switching damage can be observed (see Fig. 1d). When moving towards a smaller phase mismatch (pos. 3), the rapidly increasing nonlinear losses are accompanied by a corresponding self-frequency shift towards shorter center wavelengths. While this shift reduces the nonlinear losses, it also moves the pulse away from the spectral region with highest gain in the Yb:CALGO crystal. We have a net total intracavity group delay dispersion (GDD) of $\approx+1'280$ fs$^2$ per roundtrip arising from the PPLN and the Yb:CALGO crystal.

The lasing operation can be divided into two regions: at low pump power, mode-beating and Q-switching instabilities are observed. When increasing the pump power further, the laser reliably jumps into a stable continuous wave modelocking state (no tweaking/shaking of any cavity component is necessary) at around 3.3 W of pump power/734 mW of average output power (Fig. 2a). This low Q-switching threshold is in good agreement with the value predicted by adapting the formalism described in [14], taking into account the effect of gain saturation in the...
Yb:CALGO gain medium, the roll-over of the SESAM and the fact that the PPLN provides an additional inverse saturable absorber mechanism via the nonlinear SHG losses. Clean cw modelocking with a TEM\textsubscript{00} beam profile is maintained up to an average power of 1.2 W. Over this range, the duration of the transform-limited pulses decreases from 227 fs to 166 fs, consistent with the prediction of soliton modelocking, and the center wavelength shifts from 1052 nm to 1050 nm. If the pump power is further increased, higher order spatial modes start to lase, which become visible in the laser beam profile and as sidepeaks in the radio-frequency (RF) trace. The onset of higher order modes can be explained by the strong beam divergence of the multi-mode pump within the length of the gain medium, which allows for non-TEM\textsubscript{00}-modes to experience sufficient gain above a certain pump power. Using a pump with a lower M\textsuperscript{2}-value and/or a shorter gain crystal would mitigate this effect. The amplitude noise during clean cw ML shown in Fig. 2b is very similar to the noise measured in our SESAM modelocked 1-GHz Yb:CALGO laser [15] which operates in the conventional negative-dispersion soliton-regime and does not contain a PPLN crystal. Hence, the CQN modelocking regime does seem to alter the amplitude noise in any significant way. Both lasers are pumped with the same multimode pump diode, which is the limiting factor for the noise of both lasers (Fig. 2b).

Fig. 2 (a) Pump power versus output power and pulse duration. (b) Amplitude noise comparison between the 10 GHz Yb:CALGO laser and a 1 GHz Yb:CALGO laser operating in the conventional modelocking regime without a PPLN device. The amplitude noise performance is limited in both cases by the multimode pump diode. (c) Autocorrelation trace. (b) Optical spectrum. (e) Radio-frequency (RF) signal corresponding to the pulse repetition rate at 10.6 GHz recorded with a microwave spectrum analyzer (MSA). (f) MSA trace of the first 3 harmonics of the repetition rate signal recorded with a 45-GHz-bandwidth photodiode.

4. Conclusion

In conclusion, we have presented a straight-cavity 10 GHz SESAM-modelocked laser that operates in the positive GDD regime. The intracavity PPLN crystal provides negative SPM for soliton modelocking, helps to lower the overall Q-switching threshold and acts as a dynamic defocusing lens, which protects the cavity elements from Q-switching related damage. Combining those effects allowed us to achieve for the first time femtosecond Watt-level fundamental modelocking of a diode-pumped solid-state laser with a repetition rate above 10 GHz.

5. References