Carrier-envelope frequency stabilization of a Ti:sapphire oscillator using different pump lasers: part II

Andreas Vernaleken · Bernhard Schmidt · Theodor W. Hänisch · Ronald Holzwarth · Peter Hommelhoff

Received: 11 July 2013 / Accepted: 4 February 2014 / Published online: 23 March 2014 © Springer-Verlag Berlin Heidelberg 2014

Abstract Complementing an earlier report (Vernaleken et al. in Opt Exp 20:18387, 2012), we investigate the residual phase jitter of a carrier-envelope frequency stabilized Ti:sapphire oscillator when pumped by additional commercially available pump lasers that were not part of the first study. We find that all tested pump lasers allow stabilization of the oscillator with a residual rms phase noise (integrated between 2 Hz and 5 MHz) of less than 150 mrad despite their different design and properties. Possible sources of technical noise and their elimination for specific models are discussed.

1 Introduction

Among the various femtosecond laser oscillators that are commonly used as optical frequency combs [1, 2] in a wide range of fields, Ti:sapphire lasers support the shortest pulses directly from the oscillator, operate at the highest repetition rates, and exhibit favorable residual frequency noise characteristics due to the high quality factor of their resonators. However, the high saturation intensity of Ti:sapphire necessitates a pump laser source with high brightness emitting near the peak absorption of the gain material around 500 nm. Thus, the pump lasers of choice in the past have mostly been the comparably expensive frequency-doubled single-longitudinal-mode (SLM) diode-pumped solid-state (DPSS) lasers emitting at 532 nm. While the recently demonstrated direct diode pumping of a Kerr-lens mode-locked Ti:sapphire oscillator [3] might mature into an interesting alternative at significantly reduced costs with the ongoing advances in laser diode technology, several cost-efficient single- and multi-longitudinal-mode (MLM) DPSS lasers and optically pumped semiconductor lasers (OPSL) emitting at 532 nm are now commercially available as alternative pump sources.

In a recently reported set of measurements [4], we characterized and compared the performance of a carrier-envelope frequency stabilized femtosecond Ti:sapphire oscillator when pumped by four different pump lasers: a frequency-doubled MLM DPSS laser with active noise cancelation (Lighthouse Photonics Sprout G-10W NET), a frequency-doubled MLM OPSL (Coherent Verdi G5), and two frequency-doubled SLM DPSS lasers (Coherent Verdi V10, Coherent Verdi V5). While both SLM lasers under test were expected to be suitable for the purpose from their extensive use in many laboratories including ours, we found both tested, relatively new MLM pump lasers to be equally applicable. The relative intensity noise (RIN) of the pump lasers was also measured and proved to be low enough to enable carrier-envelope frequency stabilization in all cases although certain noise signatures could be detected in the performance of the oscillator.

In this paper, we complement our earlier work [4] by applying the same methods to three additional commercial pump lasers that could not be made available to us at the time of the first study. After a brief review of the underlying basics, a short survey of the tested pump lasers, and a
summary of the experimental setup and methods, the results of these additional measurements are presented and discussed in the context of our earlier report. We find that all tested pump lasers are suitable choices for operation with a carrier-envelope frequency stabilized Ti:sapphire oscillator.

2 Basics

A mode-locked laser emits an infinite train of short pulses. Its corresponding spectrum consists of a series of equidistant spectral lines at frequencies \( f_n = nf_r + f_0 \) with integer mode number \( n \), pulse repetition frequency \( f_r \), and carrier-envelope frequency \( f_0 \). Once the radio frequencies \( f_r \) and \( f_0 \) are measured and controlled, the mode-locked laser forms a frequency comb that can be used as an optical reference. While it is straightforward to experimentally access \( f_r \), a more sophisticated scheme is required in the case of \( f_0 \), which quantifies the time evolution of the phase advance \( \phi_0 \) of the electric carrier field with respect to the pulse envelope according to

\[
f_0 = \frac{1}{2\pi} \frac{d\phi_0}{dr} = \frac{\Delta\phi_0}{2\pi} f_r.
\]

Here, \( \Delta\phi_0 \) denotes the slippage of the carrier-envelope phase (CEP) \( \phi_0 \) from pulse to pulse. The most commonly used scheme to measure \( f_0 \) is the so-called \( f \)-to-\( 2f \) interferometer [5, 6], which allows to extract \( f_0 \) from heterodyning light at frequency \( f \) with light at frequency \( 2f \) if the laser spectrum spans a full octave. Since this is generally not the case even for Ti:sapphire oscillators, nonlinear spectral broadening techniques such as self-phase modulation in a photonic crystal fiber (PCF) [7] are typically employed. The carrier-envelope frequency \( f_0 \) can be controlled either using a feed-forward scheme [8] or by means of active feedback to the oscillator. The widely used latter approach of stabilizing \( f_0 \) to a stable rf reference using a phase-locked loop can be impaired by various sources of noise and has thus been the subject of numerous theoretical and experimental studies (compare [4] and the references therein). Among others, beam pointing instabilities and intensity fluctuations of the pump laser were identified as sources of residual noise [9, 10] because they directly translate into intensity variations of the oscillator where they cause phase variations due to amplitude-to-phase coupling via the nonlinear Kerr effect. Although this coupling is actively exploited in standard feedback loops to control \( f_0 \), it can also hamper the stabilization of \( f_0 \) due to the intrinsic intensity noise of the pump laser. While the use of MLM pump lasers resulted in a systematically higher phase noise than the use of a SLM pump laser in previous investigations [9, 10], we did not find a significant difference in performance for the MLM pump lasers in our tests [4], in agreement with the recent work of Sutyrin et al. [11].

3 Tested pump lasers

When we contacted, to the best of our knowledge, all manufacturers of pump lasers emitting at 532 nm with supposedly suitable specifications for CEP-critical applications prior to our initial set of measurements described in [4], not all of them could provide a laser for our tests at that time. We have since been in contact with these manufacturers to schedule further measurements to complement our earlier studies. Unfortunately, our efforts to include two potentially suitable SLM and MLM pump lasers (Spectra-Physics Millennia Edge and Spectra-Physics Millennia Prime) remained unsuccessful because the manufacturer could not provide either of the two lasers at the time of neither of our measurements. Thus, the group of devices under test comprised a frequency-doubled MLM DPSS laser with a maximum output power of \( P_{\text{max}} = 8 \) W (Laser Quantum Finesse Pure 8) and two special versions of the frequency-doubled OPSL whose standard model was part of the first study: One is a designated low-noise MLM laser (Coherent Verdi G5 CEP, \( P_{\text{max}} = 5 \) W), which is selected for CEP-sensitive applications by the company upon request from the otherwise identical standard G5 series after internal performance tests, and one is an SLM laser (Coherent Verdi G5 SLM, \( P_{\text{max}} = 5 \) W). In order to compare the new measurements to our initial ones, the same SLM DPSS (Coherent Verdi V10, \( P_{\text{max}} = 10 \) W) used in the first study was tested along with the other lasers again. Comparing the specified relative intensity noise at full output power of the Finesse Pure 8 and both Verdi G5 (<0.03 % root-mean-square (rms) from 10 Hz to 100 MHz for all three) with the Verdi V10 (<0.02 % rms from 10 Hz to 1 GHz) and considering the results of our previous report, both the Finesse Pure 8 and the two different Verdi G5 are expected to be suitable for pumping an \( f_0 \)-stabilized Ti:sapphire oscillator.

4 Experimental setup and methods

Both experimental setup and methods are identical to those described in detail in [4] to ensure a maximum level of comparability between the two studies. A schematic of the setup is shown in Fig. 1. In brief, a free-running commercial Kerr-lens mode-locked Ti:sapphire oscillator (Femtolasers Femtosource 20, \( f_r = 102 \) MHz, pulse duration \( \sim 20 \) fs) is pumped by the respective pump laser at \( \sim 3.6 \) W. The measurement and stabilization of \( f_0 \) is
achieved by the $f$-to-$2f$ self-referencing technique \cite{5,6} using an acoustically shielded $f$-to-$2f$ interferometer, in which spectral broadening in a nonlinear photonic crystal fiber (PCF) is employed to generate an octave-spanning spectrum from the oscillator output ($\sim 40$ nm FWHM). A commercially available loop filter processes the resulting $f_0$ beat signal and compares it to a reference signal at 22.5 MHz from an rf function generator. The same electronics is used to apply the generated feedback signal to an acousto-optic modulator in the pump beam path, which enables locking of $f_0$ via modulating the pump laser power sent to the Ti:sapphire oscillator.

We employed a second $f$-to-$2f$ interferometer to measure the residual phase noise of the $f_0$-stabilized oscillator independently from the feedback loop. The signal acquisition is performed in the frequency domain with an rf spectrum analyzer. As described in \cite{4}, the spectra of the $f_0$ beat signals recorded with the avalanche photodiode (APD) for different frequency spans and resolution bandwidths are processed into the respective residual phase noise spectra using commercial software (MenloSystems PhaseNoise).

Just as in our previous measurements \cite{4}, we also recorded the relative intensity noise (RIN) of all pump lasers in the range between 2 Hz and 625 kHz at different power levels to check whether the intensity fluctuations of the pump lasers affected the stabilization of $f_0$. To this end, the signal obtained from focusing a small part of the pump laser output onto a 9 V-biased PIN diode (Hamamatsu S5973) was acquired on a personal computer using a data acquisition card (National Instruments USB-6251) and the above-mentioned commercial software.

5 Results and discussion

In this section, we first summarize the results of the relative intensity noise measurements in Sect. 5.1 so that the results of our phase noise measurements can be discussed in a more coherent way in Sect. 5.2.

5.1 Relative intensity noise of tested pump lasers

The integrated RIN of the four tested pump lasers in the frequency range between 2 Hz and 625 kHz is shown in Fig. 2. The depicted data were taken at 3.6 W for the V10 and the G5 SLM, at 4 W for the Finesse Pure 8, and at 3.3 W for the G5 CEP, i.e., at or close to the power levels used in the phase noise measurements. We confirmed that the noise floor of our RIN measurements, which is exemplified by the dashed black line in Fig. 2a, lies well below the
acquired data. While operation at the specified maximum output power is expected and confirmed to yield the lowest RIN, we found all pump lasers to meet their specifications even at the lower output powers used in the experiments. Note that the frequency ranges for which the RIN of the pump lasers is specified by the manufacturers are different from the range covered by our measurements.

The measured intensity noise of the V10 (Fig. 2a) agrees very well with the results of our earlier investigation [4], in which we argued that the continuous increase in RIN below 1 kHz could at least partly be due to aging of the laser itself. The Finesse Pure 8 (Fig. 2b) exhibits a distinct step in its integrated RIN at about 30 kHz and accumulates the majority of its additional RIN above 50 kHz while being mostly quiet below 10 kHz. Further experiments at higher pump powers showed that both the high-frequency increase and the noise feature become less prominent when approaching the maximum power (8 W) at which the integrated RIN of the Finesse Pure 8 amounts to about 0.014 %. Both the G5 SLM (Fig. 2c) and the G5 CEP (Fig. 2d) exhibit a similarly flat integrated RIN for frequencies below 10 kHz. Between 50 and 500 kHz, the increase in noise is slightly more pronounced for the G5 SLM than for the G5 CEP. However, both G5 lasers share two prominent noise contributions around 55 kHz and at ~260 kHz. While these intensity fluctuations are generally less distinctive for the G5 SLM than for the G5 CEP, the high-frequency one contributes about one-third of the overall integrated RIN for either laser. Similarly to the Finesse Pure 8, when operated at full specified output power (5 W), the integrated RIN decreases to about 0.014 and 0.015 % for the G5 SLM and the G5 CEP, respectively.

As underlined by the data presented in Fig. 2, the relative intensity noise of the tested pump lasers does not differ fundamentally for SLM and MLM lasers (first and second column of Fig. 2, respectively), but rather exhibits signatures that seem to be a consequence of differences in design and thus dependent on the manufacturer and the model. However, even when comparing the integrated RIN of the G5 CEP (Fig. 2d) to that of the identically constructed Verdi G5 that we characterized for our earlier report (Fig. 5c in [4]), there are several obvious differences: While the former shows two significant steps above and only negligible noise contributions below 10 kHz, the noise feature at ~260 kHz is much weaker for the latter and the RIN above 10 kHz is accumulated in a more continuous way. It is interesting to note that the intensity fluctuations that we observed below 10 Hz for the G5 (Fig. 5c in [4]) could also be reproduced for the G5 CEP and the G5 SLM. We found that the integrated RIN might rise by

---

Fig. 2 Comparison of integrated relative intensity noise of a V10, b Finesse Pure, c G5 SLM, and d G5 CEP in the frequency range between 2 Hz and 625 kHz. For each laser, several measurements taken at the same day are shown. Note that the RIN was measured about the power level of operation during the phase noise measurements and not at the respective full output power of the different pump lasers. The noise floor of the measurements is indicated in a by a dashed black line.

---

36 A. Vernaleken et al.

 Springer
more than a factor of 2 below \( \sim 30 \) Hz when the water flow from the chiller to their (identical) base plate is not carefully controlled. Despite using the same chiller and tubing, the same effect was not observed for the Finesse Pure 8 (Fig. 2b) and to a much smaller extent for the V10 (Fig. 2a). Therefore, we assume that a modification of the inner construction of the base plate of the G5 should also resolve the issue. In our case, the practical and easy-to-implement approach of inserting several additional meters of flexible tube in the water supply of the base plate removed the low-frequency RIN contribution of both G5 lasers (Fig. 2c,d).

5.2 Phase noise of stabilized carrier-envelope frequency

In Fig. 3, we present the residual rms integrated phase jitter \( \Delta \phi_0 \) of the \( f_0 \)-stabilized Ti:sapphire oscillator in the frequency range from 2 Hz to 5 MHz when pumped by the four different pump lasers under test. For each laser, the minimum achievable integrated phase noise in our measurements is shown along with a series of three typical datasets that illustrate the repeatability of the oscillator performance. While the typical data originate from randomly combining the acquired rf spectra of \( f_0 \) for each frequency span, the best curve is obtained by selectively combining the underlying data with lowest noise. Note that this minimum value does not represent an absolute lower limit since it also contains the individual noise contributions of both \( f_\text{to-2f} \)-interferometers and both loop filters. Moreover, the overall oscillator performance depends both on the alignment of the oscillator and the resulting mode-locked state which are not guaranteed to be absolutely identical throughout our measurements despite our best efforts. As can be seen in Fig. 3, the contributions to the residual phase jitter of the Ti:sapphire oscillator originate primarily from the frequency range between 10 and 100 kHz for all pump lasers. This is the expected behavior since the lifetime of the upper laser level in Ti:sapphire and the resulting relaxation oscillations effectively form a low-pass filter at several 100 kHz \[12\] while the employed feedback loops are able to suppress residual phase noise up to bandwidths of typically several 10 kHz. Note that the bandwidth limitation of the feedback system used here does not originate from the nominal bandwidth of the loop filter but from the speed of sound in the AOM crystal.

In accordance with our previous investigation \[4\], we find that all tested pump lasers enable \( f_0 \)-stabilized operation of the Ti:sapphire oscillator with residual phase jitters below 150 mrad, i.e., \( f_0 \) is stabilized to less than \( 1/40 \) of an optical cycle, corresponding to a residual timing jitter of below 65 as. Although we cannot identify fundamental differences in the performance of the oscillator depending on SLM or MLM operation of the tested pump lasers,

---

**Fig. 3** Comparison of integrated carrier-envelope phase jitter datasets of a V10, b Finesse Pure 8, c G5 SLM, and d G5 CEP. Three typical datasets and the respective best curve resulting from these are depicted for each laser.
Fig. 3 illustrates that using different models results in minor differences in the phase noise behavior of the oscillator that we will discuss in the following.

When pumped by the V10 (Fig. 3a), the oscillator accumulates about half of the integrated residual phase noise at the bandwidth limit of our feedback loop at \( \sim 70 \) kHz, whereas the contributions below 30 kHz amount to less than 10 mrad. In our earlier measurements, the same pump laser led to a less prominent increase in phase noise in the kHz range at around 20 kHz and a slightly larger one between 80 and 800 Hz. Since the V10 showed intensity fluctuations in the lower-frequency range both in the previous and the current measurements (compare Fig. 2a), we assume that the observed differences in oscillator performance can be attributed to the different parameter settings of the loop filter.

Figure 3b illustrates that using the Finesse Pure 8 as a pump laser results in a similar increase in the integrated residual phase jitter of \( f_0 \) at about 70 kHz. In addition, the comparison with Fig. 2b shows that the intensity noise of the pump laser around 30 kHz is directly translated into strong phase fluctuations of the oscillator at the same frequency. Below 20 kHz, the integrated phase noise rises by about 10 mrad, mainly between 100 Hz and 10 kHz. We verified that the performance of the stabilized oscillator is similar when the internal modulation input of the Finesse Pure 8 is used for feedback instead of the AOM in the pump laser beam path. Again, in this case, the RIN feature at \( \sim 30 \) kHz can be seen in the integrated phase jitter as well.

Operation of the oscillator with the G5 SLM (Fig. 3c) and the G5 CEP (Fig. 3d) leads to similar results once the water flow to the base plate is controlled to reduce the intensity fluctuations of the pump lasers. In that case, similar to the other lasers, the integrated phase jitter does not increase but on the order of 10 mrad below 10 kHz (mostly in the 50–500 Hz range and including some 50 Hz pickup) while its main contribution originates from frequencies above \( \sim 70 \) kHz. The intensity fluctuations of both G5 SLM and G5 CEP at 55 kHz (Fig. 2c,d) cannot be unambiguously identified to influence the stabilization of \( f_0 \) but the intensity noise around 260 kHz coincides with phase fluctuations at the same frequency that are much more pronounced for the G5 SLM than for the G5 CEP. These noise features are small enough to allow for slightly better \( f_0 \)-stabilized performance of the oscillator with both pump lasers compared with the G5 used in the previous test [4]. In general, noise in this spectral range can severely affect the stabilization, as it is outside the bandwidth of typical feedback loops and not entirely low-pass filtered by the gain medium. It has been brought to the authors’ attention by one of the reviewers that a possible source of such noise may be the switching power supply of the pump laser. If the water flow to the base plate is not controlled, the phase noise of the oscillator can rise by more than a factor of 2 below \( \sim 30 \) Hz, thus indicating that the amplitude of the fluctuations is too large to be fully compensated for by our feedback loop. Therefore, it seems generally recommendable to check for a possible detrimental influence on the stabilization when both the oscillator crystal and the base plate of the pump laser are water-cooled.

6 Summary

Complementing our earlier report [4], we have investigated the suitability of additional commercially available single- and MLM lasers emitting at 532 nm for pumping a Ti:sapphire femtosecond oscillator whose carrier-envelope frequency \( f_0 \) is stabilized using the \( f \)-to-\( 2f \) self-referencing technique. By means of a second identical \( f \)-to-\( 2f \) interferometer outside the feedback loop, we characterized and compared the dependence of the residual phase jitter of the stabilized oscillator on the different pump sources. The relative intensity noise of the pump lasers was also recorded and checked for a potential influence on the stabilization.

As in our previous work, we find all tested pump lasers suitable for \( f_0 \)-stabilized operation of a Ti:sapphire oscillator, independent of their single- or MLM operation. The integrated rms residual phase noise of the stabilized oscillator amounted to less than 150 mrad for all pump lasers, which corresponds to less than 1/40 of an optical cycle and an rms timing jitter of less than 65 as. While the measured intensity fluctuations of none of the tested pump lasers are large enough to prevent stabilization of \( f_0 \), certain individual noise characteristics of the pump sources directly translate into phase jitter of the oscillator. In particular, the flow of the cooling water to the base plate turns out to affect the stabilization of the oscillator for specific pump lasers and should therefore be controlled.

Conflict of interest Neither of the authors nor their respective institution hold any privileged relations to any of the companies mentioned in this article. In particular, Menlo Systems GmbH is not exclusively engaged with any of the forecited companies.

References

1. T. Udem, R. Holzwarth, T.W. Hänsch, Femtosecond optical frequency combs. Eur. Phys. J. Spec. Top. 172, 69–79 (2009)
2. S.A. Diddams, The evolving optical frequency comb. J. Opt. Soc. Am. B 27, B51–B62 (2010)
3. C.G. Durfee, T. Storz, J. Garlick, S. Hill, J.A. Squier, M. Kirchner, G. Taft, K. Shea, H. Kapteyn, M. Murnane, S. Backus, Direct diode-pumped Kerr-lens mode-locked Ti:sapphire laser. Opt. Express 20, 13677–13683 (2012)
4. A. Vernaleken, B. Schmidt, M. Wolfersetter, T.W. Hänsch, R. Holzwarth, P. Hommelhoff, Carrier-envelope frequency
stabilization of a Ti:sapphire oscillator using different pump lasers. Opt. Express 20, 18387–18396 (2012)
5. J. Reichert, R. Holzwarth, T. Udem, T.W. Hänsch, Measuring the frequency of light with mode-locked lasers. Opt. Commun. 172, 59–68 (1999)
6. S.A. Diddams, D.J. Jones, J. Ye, S.T. Cundiff, J.L. Hall, J.K. Ranka, R.S. Windeler, R. Holzwarth, T. Udem, T.W. Hänsch, Direct link between microwave and optical frequencies with a 300 THz femtosecond laser comb. Phys. Rev. Lett. 84, 5102–5105 (2000)
7. D.J. Jones, S.A. Diddams, J.K. Ranka, A. Stentz, R.S. Windeler, J.L. Hall, S.T. Cundiff, Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis. Science 288, 635–639 (2000)
8. S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion, G. Steinmeyer, Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise. Nat. Photon. 4, 462–465 (2010)
9. S. Witte, R. Zinkstok, W. Hogervorst, K. Eikema, Control and precise measurement of carrier-envelope phase dynamics. Appl. Phys. B 78, 5–12 (2004)
10. L. Matos, O.D. Mücke, J. Chen, F.X. Kärtner, Carrier-envelope phase dynamics and noise analysis in octave-spanning Ti:sapphire lasers. Opt. Express 14, 2497–2511 (2006)
11. D. Sutyrin, N. Poli, N. Beverini, S. Chepurov, M. Prevedelli, M. Schioppo, F. Sorrentino, M. Tarallo, G. Tino, Frequency noise performances of a Ti:sapphire optical frequency comb stabilized to an optical reference. Opt. Commun. 291, 291–298 (2013)
12. R.P. Scott, T.D. Mulder, K.A. Baker, B.H. Kolner, Amplitude and phase noise sensitivity of modelocked Ti:sapphire lasers in terms of a complex noise transfer function. Opt. Express 15, 9090–9095 (2007)