Spectral amplitude and phase noise characterization of titanium-sapphire lasers

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Abstract: There are few methods capable of characterizing pulse-to-pulse noise in high repetition rate ultrafast lasers. Here we use a recently developed method, termed fidelity, to determine the spectral amplitude and phase noise that leads to lack of pulse repeatability and degrades the performance of laser sources. We present results for a titanium sapphire oscillator and a regenerative amplifier system under different noise conditions. Our experimental results are backed by numerical calculations.

OCIS codes: (320.7100) Ultrafast measurements; (140.3425) Laser stabilization.

References and links

1. V. V. Lozovoy, G. Rasskazov, D. Pestov, and M. Dantus, "Quantifying noise in ultrafast laser sources and its effect on nonlinear applications," Opt. Express **23**(9), 12037–12044 (2015).
2. H. P. Weber, "Method for pulsewidth measurement of ultrashort light pulses generated by phase-locked lasers using nonlinear optics," J. Appl. Phys. **38**(5), 2231 (1967).
3. J. Ratner, G. Steinmeyer, T. C. Wong, R. Bartels, and R. Trebino, "Coherent artifact in modern pulse measurements," Opt. Lett. **37**(14), 2874–2876 (2012).
4. Y. Li, L. F. Lester, D. Chang, C. Langrock, M. M. Fejer, and D. J. Kane, "Characteristics and instabilities of mode-locked quantum-dot diode lasers," Opt. Express **21**(7), 8007–8017 (2013).
5. M. Rhodes, G. Steinmeyer, J. Ratner, and R. Trebino, "Pulse-shape instabilities and their measurement," Laser Photonics Rev. **7**(4), 557–565 (2013).
6. D. von der Linde, "Characterization of the noise in continuously operating mode-locked lasers," Appl. Phys. B **39**(4), 201–217 (1986).
7. W. A. Gardner, A. Napolitano, and L. Paura, "Cyclostationarity: half a century of research," Signal Process. **86**(4), 639–697 (2006).
8. V. Torres-Company, H. Lajunen, and A. T. Friberg, "Coherence theory of noise in ultrashort-pulse trains," J. Opt. Soc. Am. B **24**(7), 1441 (2007).
9. B. Lacaze and M. Chabert, "Theoretical spectrum of noisy optical pulse trains," Appl. Opt. **47**(18), 3231–3240 (2008).
10. R. W. Schoonover, B. J. Davis, R. A. Bartels, and P. S. Carney, "Optical interferometry with pulsed fields," J. Mod. Opt. **55**(10), 1541–1556 (2008).
11. B. J. Davis, "Observable coherence theory for statistically periodic fields," Phys. Rev. A **76**(4), 043843 (2007).
12. D. E. McCumber, "Intensity fluctuations in the output of cw laser oscillators. I," Phys. Rev. **141**(1), 306–322 (1966).
13. C. M. Miller, "Intensity modulation and noise characterization of high-speed semiconductor lasers," IEEE LTS **2**(2), 44–50 (1991).
14. M. C. Cox, N. J. Copner, and B. Williams, "High sensitivity precision relative intensity noise calibration standard using low noise reference laser source," Sci. Meas. Tech. **145**(4), 163–165 (1998).
15. M. Mangold, S. M. Link, A. Klenner, C. A. Zaugg, M. Golling, B. W. Tilma, and U. Keller, "Amplitude noise and timing jitter characterization of a high-power mode-locked integrated external-cavity surface emitting laser," IEEE Photonics J. **6**, 1500309 (2013).
16. S. A. Diddams, M. Kirchner, T. Fortier, D. Braje, A. M. Weiner, and L. Hollberg, "Improved signal-to-noise ratio of 10 GHz microwave signals generated with a mode-filtered femtosecond laser frequency comb," Opt. Express **17**(5), 3331–3340 (2009).
17. A. F. J. Runge, C. Aguergaray, N. G. R. Broderick, and M. Erkintalo, "Coherence and shot-to-shot spectral fluctuations in noise-like ultrafast fiber lasers," Opt. Lett. **38**(21), 4327–4330 (2013).
18. V. J. Hernandez, C. V. Bennett, B. D. Moran, A. D. Drobshoff, D. Chang, C. Langrock, M. M. Fejer, and M. Ibsen, "104 MHz rate single-shot recording with subpicosecond resolution using temporal imaging," Opt. Express **21**(1), 196–203 (2013).

#242281 Received 5 Jun 2015; revised 4 Aug 2015; accepted 25 Aug 2015; published 31 Aug 2015

19. Y. Coello, V. V. Lozovoy, T. C. Gunaratne, B. Xu, I. Borukhovich, C. Tseng, T. Weinacht, and M. Dantus, "Interference without an interferometer: a different approach to measuring, compressing, and shaping ultrashort laser pulses," J. Opt. Soc. Am. B **25**(6), A140–A150 (2008).
20. V. V. Lozovoy, B. Xu, Y. Coello, and M. Dantus, "Direct measurement of spectral phase for ultrashort laser pulses," Opt. Express **16**(2), 592–597 (2008).

1. Introduction

Pulse-to-pulse instabilities can be expressed in terms of intra or inter pulse property fluctuations such as spectrum, phase, intensity, and timing jitter. Given that characterization of high repetition rate lasers depends on quantities averaged over multiple pulses, it is difficult to determine pulse-to-pulse variations and to quantify their effect on pulse duration i.e. for time-resolved measurements; or nonlinear optical process efficiency i.e. for multiphoton microscopy. Here we explore the noise characteristics of titanium sapphire lasers, which are known to be quite stable. We measure the fidelity of the lasers, as defined in a recent publication from our group [1], to quantify how the spectrum of each pulse in the train is somewhat different and how the spectral phase of each pulse in the train is somewhat different, and even to detect the presence of pre- or post-pulses.

Traditional methods for ultrashort pulse characterization involving some form of autocorrelation and are known to have difficulties in characterizing lasers with random pulse-to- pulse instabilities, although some signatures from partial coherence are present [2–5]. Analysis of noise in pulse trains from mode-locked laser pulses is best illustrated by the work of von der Linde where the power spectrum of the pulse train is shown to contain important information about the noise characteristics [6]. Periodic signals, as well as laser pulses, can be analyzed in terms of cyclostationary theory [7]. Aspects such as jitter, amplitude and duration fluctuations can be detected in the frequency comb spectrum [8, 9], as well as by interferometry [10]. Cyclostationary coherence theory has been applied to the numerical analysis of pulse laser sources with very fast repetition periods (~100fs periods) taking advantage of spectral shearing interferometry and frequency-resolved optical gating [11].

Measurements of amplitude noise of continuous wave lasers [12–15], have evolved to measure the noise and jitter of metrology sources [16]. Shot-to-shot coherence and spectral fluctuations of noise-like ultrafast fiber lasers are now possible using Young's-type interference and single shot spectrometry at megahertz rates [17, 18]. While amplitude and jitter fluctuation measurements are important we focus on measuring spectral phase and amplitude noise in femtosecond lasers, which affects applications such as multiphoton microscopy or the determination of the average pulse duration. We focus on the popular titanium sapphire lasers, in particular an oscillator and a regenerative amplifier under different conditions of noise.

Conceptually, a noisy laser is less sensitive to applied chirp; therefore it produces less SHG in the absence of additional chirp, ϕ'', and more second harmonic generation (SHG) when additional chirp is introduced. We calculate the intensity of the normalized as a function of linear chirp and compare it with experimental measurements in order to obtain the fidelity of the laser source [1]. The expression for measuring fidelity as a function of chirp ϕ'' is given by

$$\left\langle F(\phi'')\right\rangle = \frac{I_{\phi''}^{SHG} \Big/ I_{\phi''=0}^{SHG}}{\left\langle I_{\phi''}^{SHG}\right\rangle \Big/ \left\langle I_{\phi''=0}^{SHG}\right\rangle} = \frac{I_{Theory}^{SHG}(\phi'')}{\left\langle I_{Experiment}^{SHG}(\phi'')\right\rangle}, \tag{1}$$

where $I_{\phi''}^{SHG}$ and $I_{\phi''=0}^{SHG}$ are the SHG intensities for chirped and non chirped, i.e. transform-limited (TL) pulses respectively, calculated based on the averaged laser spectrum assuming coherent noiseless pulses. $\left\langle I_{\phi''}^{SHG}\right\rangle$ and $\left\langle I_{\phi''=0}^{SHG}\right\rangle$ are the ensemble averaged SHG intensities of

#242281 Received 5 Jun 2015; revised 4 Aug 2015; accepted 25 Aug 2015; published 31 Aug 2015

the laser source with added chirp and for chirpless pulses respectively. $I_{Theory}^{SHG}(\phi'')$ and $\left\langle I_{Experiment}^{SHG}(\phi'')\right\rangle$ are, respectively, the calculated and experimental normalized SHG intensity measurements as a function of chirp. The theoretical values are calculated by first measuring the averaged spectrum of the laser and performing an inverse Fourier transformation to the time domain, $E(t) \propto \int \sqrt{\langle I(\omega)\rangle} e^{i\varphi(\omega)} e^{-i\omega t} d\omega$, where $\varphi(\omega) = ½(\omega - \omega_0)^2$ is the spectral phase and ω_0 is a carrier frequency. Once the field in the time domain is calculated, it is used to calculate the theoretical SHG intensity:

$$I_{Theory}^{SHG}(\phi'') \propto \int \left| E^2(t) \right|^2 dt. \tag{2}$$

We find that the fidelity curve as a function of chirp reveals a signature which allows one to determine if the noise is caused by spectral amplitude or phase instabilities [1]. Note that from Eq. (1) it follows that fidelity cannot exceed unity because the averaged pulse duration of a noisy ensemble of pulses is longer than the coherence time τ_c. As a consequence, the noisy ensemble of pulses produces more SHG than a noiseless ensemble with the same averaged spectrum in the presence of a large chirp.

2. Laser noise models and their fidelity

For simulation we used a train of 10,000 pulses with 40fs duration at the full width half maximum (FWHM). Three cases were explored: (a) spectral phase fluctuations involving random individual pulses with random positive and negative chirp values, such that the train of pulses had no net chirp, (b) spectral amplitude fluctuations were simulated as spectral breathing so that the spectral bandwidth changes for each pulse in the train, and (c) random phase and spectral fluctuations that combined both of the previously mentioned models. The SHG intensity and fidelity was calculated for each pulse and chirp value from −10,000 fs^2 to + 10,000 fs^2, using Eqs. (1) and (2).

The noise models were chosen to simulate fluctuations that occur in real lasers. For example, in mode-locked oscillators, random processes such as spontaneous emission cause fluctuations, cavity-length fluctuations, and active beam alignment by piezoelectric-actuated mirror (in some systems). In regenerative Ti:sapphire amplifiers, the shot-to-shot variations may occur because of spontaneous emission and gain fluctuations from spectral turbulence inside the stretcher and compressor compartment or timing jitter associating with firing the Pockels cells. Figure 1 shows results from our simulations for two cases: high and low noise, when the asymptotic fidelity value equals 0.5 or 0.9 respectively. The simulation parameters are specified in the caption; in general we used Gaussian distributions of values. Phase noise affects pulse duration and nonlinear optical processes linearly with the asymptotic fidelity value. Amplitude, because it acts on the intensity and not on the electric field, has a smaller (square root) effect. For example, fidelity of 0.9 caused by phase noise attenuates two-photon excitation by 10% but amplitude noise would affect it by the square root of 10% or ~3.2%.

From Fig. 1 we can see that the fidelity curve for spectral phase noise differs from the one with spectral amplitude noise by having characteristic dips at low chirp values. When both spectral amplitude and phase noise are present, the proportion between the two sources of noise affects the magnitude of the observed dips.

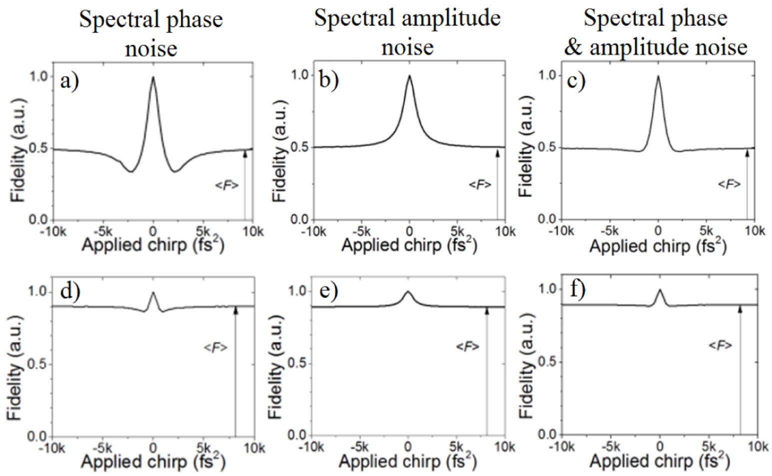

Fig. 1. Calculated fidelity measurements for two cases <*F*> = 0.5, (a)-(c), and <*F*> = 0.9, (d)-(f). The parameters for the simulations: (a) random spectral chirp fluctuations within (–2500 to + 2500) fs^2, (b) random spectral amplitude bandwidth fluctuations within (12 to 24) nm, (c) fluctuations of spectral phase and amplitude bandwidth within (–1450 to + 1450) fs^2 and (16 to 24) nm respectively; (d) random spectral chirp fluctuations within (–510 to + 510) fs^2, (e) random spectral amplitude bandwidth fluctuations at FWHM within (21 to 24) nm, (f) fluctuations of phase and amplitude within (–400 to + 400) fs^2 and (22 to 24) nm respectively.

3. Experimental results

The experimental setup includes a Ti:Sapphire oscillator (Micra, Coherent, Inc.), a pulse shaper (FemtoFit, BioPhotonic Solutions Inc.) placed between the oscillator and amplifier, a Ti:Sapphire regenerative amplifier (Legend, Coherent, Inc.), home-built autocorrelator, focusing lens, nonlinear crystal (KDP crystal), blue filter (BG39) and spectrometer (Ocean Optics, USB 4000). The pulse shaper was used to measure and compensate the averaged dispersion of the laser pulses using MIIPS [19,20], and to scan the linear chirp on the pulses.

In Fig. 2, we present experimental autocorrelation measurements for regeneratively amplified pulses under three different conditions: (a) high fidelity, (b) spectral phase noise, and (c) presence of post pulses. For these measurements the two arms of the interferometer were crossed at the nonlinear crystal and the SHG was detected. As we can see from Figs. 2(a)-2(c), the intensity autocorrelations are comparable; autocorrelation measurements are insensitive to phase noise and to pre/post pulses.

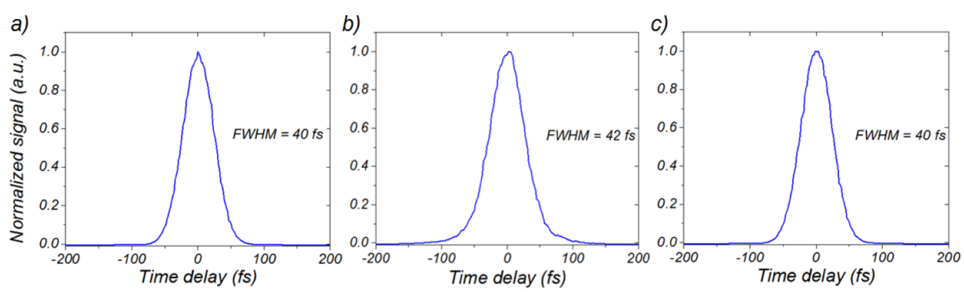

Fig. 2. Non-collinear SHG autocorrelations for amplifier (a) without any distortions, (b) with airflow averaged 100 times, (c) with post-pulse. Note that autocorrelation is not sensitive to changes in pulse duration caused by spectral amplitude or phase noise.

In Fig. 3 we show fidelity measurements after pulse compression using MIIPS [19]. The values for <*F*-> and <*F* + >, were measured at the 10% normalized intensity level, see green dots, where the asymptotic value is reached and the signal to noise ratio is still good [1]. From

#242281 Received 5 Jun 2015; revised 4 Aug 2015; accepted 25 Aug 2015; published 31 Aug 2015

the plots we can conclude that laser pulses were compressed to TL duration and that the oscillator has a very good pulse-to-pulse reproducibility. The fidelity parameters, which are marked as green points, equal to 0.98 and 0.99 respectively. The pulse-to-pulse stability was measured analyzing 22,000 waveforms with the oscilloscope. After statistical analysis of the peak signal values, the relative standard error was calculated and found to be ~0.3% for the fundamental signal and ~1% for the SHG signal. Based on the fidelity curve and its similarity with Fig. 1(d), we conclude the major source of pulse-to-pulse instability in the oscillator is spectral phase fluctuations.

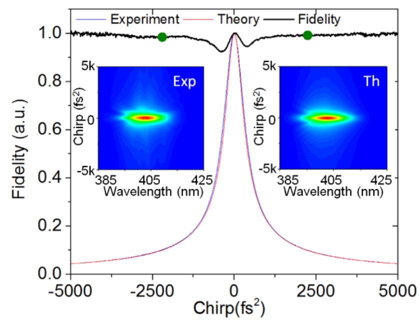

Fig. 3. Fidelity measurements for a Ti:sapphire oscillator (28 fs) when the pulses are fully compressed. The insets show the experimental and theoretical 2D SHG chirp scans. The fidelity asymptotic values, green dots, are 0.98 and 0.99.

Fidelity measurements for amplified TL pulses after pulse compression are shown in Fig. 4(a). We find that fidelity drops from >0.98 to ~0.95 after amplification due to fluctuations of spectral phase introduced by the amplifier. Note that these are some of the best values measured in our lab from our best amplified system. The most pronounced source of noise in the amplifier is the stretcher where the spectrum is dispersed and vulnerable to spectral phase noise. In order to amplify such noise we removed the cover for the stretcher and compressor. For these measurements, 100 chirp scans were averaged in order to smooth the instantaneous SHG intensity fluctuations. The results from this measurement are shown in Fig. 4(b) where we see that fidelity has dropped to 0.88. The pulse-to-pulse intensity fluctuations, measured with an oscilloscope, for these cases are ~1% for the fundamental and ~2% for the SHG signal. When the compressor and stretcher compartments are open the fluctuations increase to ~11% for the SHG signal only. The large difference between the fundamental and SHG signal confirms that the major source of noise is spectral phase fluctuations.

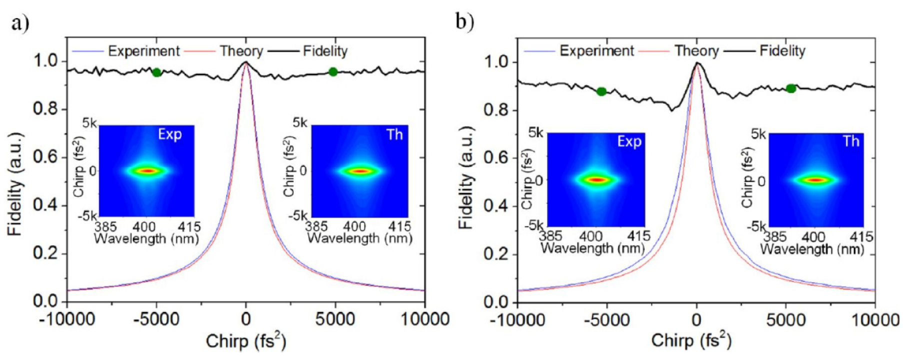

Fig. 4. Fidelity measurements for compressed laser pulses after the regenerative amplifier (a) in the absence of distortions. Both positive and negative fidelity parameters equal to 0.95. (b) When the pulses are distorted by airflow in the stretcher and compressor. The fidelity parameters equal to 0.88 and 0.89 respectively. The pair of insets shows the experimental and theoretical 2D SHG chirp MIIPS scans respectively.

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Beyond noise, it is important to determine if an amplifier generates pre- or post-pulses. We created a post-pulse by misadjusting the timing of the second Pockels cell in the amplifier. The noise statistics for the amplifier output were 1% for fundamental and 2% for SHG signals, which implies pre- and post-pulses cannot be detected by intensity fluctuations. Fidelity measurements for fully compressed amplified pulses that have a post-pulse are shown in Fig. 5(a). Pre- or post-pulses show marked differences for positive and negative chirp and therefore a large difference in the fidelity values for positive or negative chirps. We compare the sensitivity for detecting pre- and post-pulses in an amplifier between fidelity measurements, a fast photodiode, and an oscilloscope in Fig. 5(b). We find approximately similar sensitivity for both types of measurements. The inset shows how the oscilloscope waveform of the signal looks when the second Pockels cell delay time is set to 211.5 ns. The post-pulse can be seen at ~10ns. Most commercial lasers have the same amount of dispersion in the regenerative amplifier per round trip, and therefore the appearance of pre- or-post pulses occurs near positive or negative 8,000 fs^2, respectively.

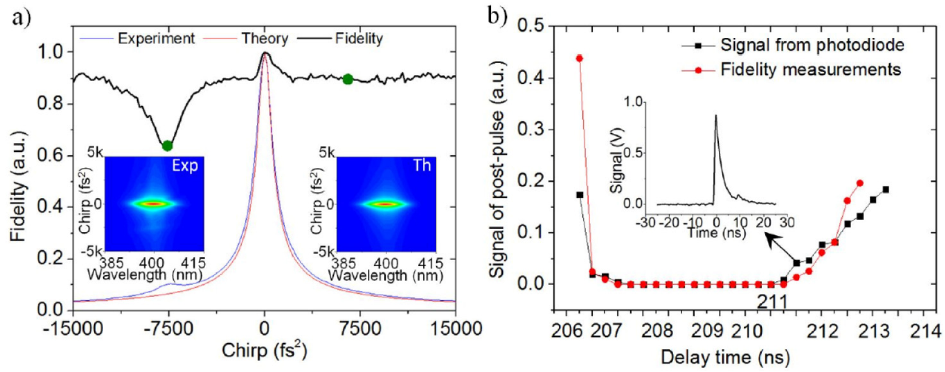

Fig. 5. Fidelity measurements of a Ti:sapphire amplifier with a post-pulse. The pair of insets in (a) shows experimental and theoretical 2D SHG chirp MIIPS scans. The fidelity parameters equal to 0.63 and 0.90 respectively (at the green dots). (b) Pre- and post-pulse detection using fidelity measurements and using a fast photodiode. The inset shows the oscilloscope waveform with post-pulse ~10ns after the main pulse.

4. Conclusion

We have performed fidelity measurements to characterize the random noise present in high-repetition rate titanium sapphire femtosecond laser systems and have found that oscillators can be very quiet, with fidelity values approaching unity. On the other hand, we find that regenerative amplifiers introduce spectral phase and amplitude bandwidth noise that reduces fidelity to ~0.95. By exploring situations that decrease the fidelity of the amplified output, such as opening the stretcher to air and improper adjustment of Pockels cells, we showed that autocorrelation measurements for these situations fail to detect problems in the output. We demonstrate that fidelity measurements provide a robust approach to further characterize the output of ultrafast laser sources, especially for detecting spectral amplitude and phase noise, and for amplified systems to detect pre- or- post- pulses. We note that fidelity measurements are sensitive to high-order dispersion such as third order dispersion in the laser pulses. We have shown that one is able to numerically correct the MIIPS trace in order to obtain an accurate value of fidelity, even without measurement and compression of high-order dispersion [1]. While titanium sapphire lasers are very well behaved, laser sources that derive a large portion of their spectrum from self-phase modulation are more prone to spectral amplitude and phase fluctuations. We are in the process of characterizing the fidelity of such laser sources; however, our goal in this paper is to establish a benchmark based on well-understood laser systems.

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