Noise Characterization of Sub-10-fs Ti:Sapphire Oscillators

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***Abstract*— A complete noise characterization of sub-10-fs Ti:sapphire oscillators in terms of pulse energy fluctuations, timing jitter, and the coupling between these two noise components is presented for the first time. The noise performance of a self-mode-locked mirror-dispersion-controlled (MDC) oscillator pumped by an Ar–ion laser and, alternatively, a diode-pumped laser (Millennia, Spectra Physics Inc.) is compared. The all-solid-state sub-10-fs system exhibits an excellent noise performance far superior to its Ar–ion-pumped counterpart. The root-mean-square (rms) pulse-energy fluctuation of the all-solid-state source is as low as 0.19% over the frequency range of 0.06 Hz–1.5 MHz. A coupling between energy noise and timing jitter has been observed for what is to our knowledge the first time in a passively mode-locked femtosecond Ti:sapphire laser.**

***Index Terms*—Laser noise, laser stability, mode-locked lasers, noise measurement, pulsed lasers, timing jitter.**

I. INTRODUCTION

THE INVENTION of the self-mode-locked (or Kerr-lens mode-locked, KLM) Ti:sapphire laser oscillator [1]–[3] has benefited a wide range of application fields of ultrafast optics. These systems are superior to other ultrashort-pulse oscillators in terms of achievable output power as well as pulse duration and have now become the major workhorse for ultrafast optical studies. Improved broad-band dispersion control by prisms [4], [5] and chirped mirrors [6]–[10] have allowed the routine generation of sub-10-fs pulses directly from these oscillators. Owing to the availability of chirped mirrors capable of providing both high reflectivity and tailored dispersion over unprecedented bandwidths sub-10-fs pulses with megawatt peak powers can now be obtained with extremely compact mirror-dispersion-controlled (MDC) oscillators containing no intracavity components other than the gain medium [11].

Fluctuations of the pulse parameters in the continuous train of pulses may adversely affect a number of applications. Pulse energy variations (henceforth, energy noise) generally set a limit to the signal-to-noise ratio (SNR) achievable in pump-probe experiments. Random changes in the time instant of the arrival of the individual pulses (henceforth timing jitter) becomes a severe limitation if, for instance, different ultrafast sources are employed in time-resolved spectroscopy.

Noise characterization drawing on the theory of von der Linde [12] has been previously performed on prism-dispersion-controlled self-mode-locked Ti:sapphire lasers operating at pulse durations $\geq$50 fs [14]–[16]. More recently, energy noise and timing jitter measurements performed on a 10-fs MDC Ti:sapphire laser over a limited frequency range have also been reported [17]. Drawing on the theory of Haus and Mecozzi [13], in this paper we present a complete noise characterization of a sub-10-fs laser, which includes not only energy noise and timing jitter, but also the coupling between these two quantities. Investigations have been performed over a frequency range extending from 0.06 Hz to 1.5 MHz.[1] The noise performance of the MDC Ti:sapphire oscillator investigated has been found to be far superior to those of femtosecond Ti:sapphire oscillators reported previously in the literature. Furthermore, it has been found that 1) replacement of the Ar–ion laser with a diode-pumped pump source (Millennia, Spectra Physics, Inc.) significantly reduces *both* pulse energy noise *and* timing jitter [17], [18], resulting in an all-solid-state sub-10-fs source with unprecedented noise characteristics and 2) timing jitter is strongly coupled to the energy noise in a sub-10-fs Ti:sapphire oscillator.

II. THEORETICAL BACKGROUND

A continuous-wave (CW) mode-locked laser emits a train of ultrashort pulses, resulting in an (instantaneous) output power

$$P(t) = \overline{P}[1 + E(T)] \sum_{n=-\infty}^{+\infty} h(t - nT_R - J(T)) \qquad (1)$$

where $\overline{P}$ is the average output power, $E(T)$ is the normalized pulse energy fluctuation, T is a "slow" time variable on the scale of many cavity round-trip times [13], $T_R, h(t)$ is the normalized dimensionless power envelope of the pulses, and $J(T)$ accounts for fluctuations in the pulse arrival time, commonly referred to as timing jitter.[2]

The frequency spectrum of $P(t)$ consists of distinct spikes at harmonics of the pulse repetition frequency $f_R = 1/T_R$ surrounded by some pedestal accounting for timing and pulse energy fluctuations. Assuming the harmonic number n of the pulse repetition frequency to be much smaller than the total number axial modes in the laser and a small timing jitter [12],

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[1] Preliminary results of these investigations have recently been presented in [11].

[2] The pulse shape is assumed to be constant here. This model has recently be extended to include pulsewidth fluctuations also by [19].

[19], [20] the power spectrum of $P(t)$ is given by

$$P(\overline{f}) = \overline{P}^2 \cdot \sum[\delta(\overline{f} - n \cdot f_R) + S_n(\overline{f} - n \cdot f_R)] \quad (2)$$

where S_n represents the noise spectral density. These noise side bands $S_n(\overline{f} - n \cdot f_R)$ are a function of the frequency offset $f = \overline{f} - n \cdot f_R$ to their "carrier frequency" $n \cdot f_R$ and can be written as [13], [19]

$$S_n(f) = S_E(f) + (2\pi f_R \cdot n) S_{EJ}(f) + (2\pi f_R \cdot n)^2 S_J(f). \quad (3)$$

Here $S_E(f)$ and $S_J(f)$ can be shown to be equivalent to the power spectral densities of $E(T)$ and $J(T)$ [see (1)], respectively, whereas the term $S_{EJ}(f)$ accounts for a possible coupling between the pulse energy fluctuations and the timing jitter. By neglecting coupling, this decomposition of the noise sidebands into power spectral densities of pulse parameter fluctuations was first derived by von der Linde [12]. The theory of Haus and Mecozzi [13] resulted in the more complete expression given by (3). Whereas $S_E(f)$ and $S_J(f)$ are even functions of $f, S_{EJ}(-f) = -S_{EJ}(f)$, consequently a coupling between energy fluctuations and timing jitter is predicted to give rise to asymmetric noise sidebands.

Measuring the noise sidebands at several harmonics of f_R allows a unique determination of $S_E(f)$ and $S_J(f)$ [12], [14]–[22]. The integration of these spectra over a given frequency range $[f_{\min}, f_{\max}](0 < f_{\min} < f_{\max} < f_R/2)$ yields the root-mean square (rms) of the respective fluctuations (over that given frequency range):

$$\sigma_E(f_{\text{low}}, f_{\text{high}}) = \sqrt{\langle E(T)^2 \rangle} = \sqrt{2 \int_{f_{\text{low}}}^{f_{\text{high}}} S_E(f)\, df} \quad (4)$$

and

$$\sigma_J(f_{\text{low}}, f_{\text{high}}) = \sqrt{\langle J(T)^2 \rangle} = \sqrt{2 \int_{f_{\text{low}}}^{f_{\text{high}}} S_J(f)\, df}. \quad (5)$$

III. EXPERIMENTAL SETUP

The Ti:sapphire oscillator (Fig. 1) is pumped either by the 488–514-nm lines of an Ar–ion laser (Innova 310, Coherent) or by an intracavity frequency-doubled diode-pumped Nd:YVO$_4$ laser (Millennia, Spectra Physics). The resonator is formed by a highly-doped 2.3-mm-long Brewster-angled crystal, four chirped mirrors M1-M4 (FemtoSource/Pro Mirror Set, Femto-Lasers GmbH) and a 16%-transmitting output coupler. Mode locking is accomplished by self-focusing in the Ti:sapphire crystal transformed into self amplitude modulation (synthesizing a fast saturable absorber) by an intracavity aperture near the chirped mirror M3. This oscillator can produce pulses as short as 7.5 fs with average powers up to 900 mW. For more details about these MDC-KLM oscillators and their performance the reader is referred to [11].

The noise measurements reported below have been performed at pulse durations of typically 8 fs and with the laser covered to suppress environmental influences. The pump threshold was found to be at ≈0.5 W and with the absorbed pump power levels of 3 and 5 W the respective output power reached ≈350 mW and ≈550 mW for the Nd:YVO$_4$ and the Ar–ion laser as pump source, respectively. The resonator length was ≈1.86 m, which corresponds to a repetition frequency of f_R ≈80 MHz.

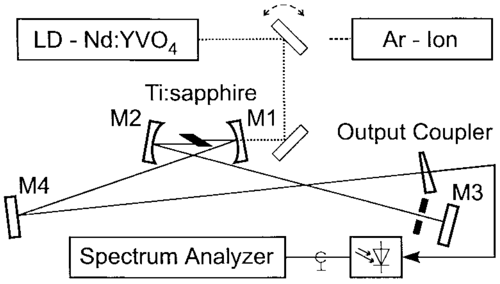

Fig. 1. Schematic of the experimental setup. The MDC Ti:sapphire oscillator can be pumped alternatively by an Ar–ion laser or a frequency-doubled diode-pumped Nd:YVO$_4$ laser.

To measure the radio-frequency (RF) power spectrum of the sub-10-fs MDC Ti:sapphire laser the output beam was directed to a picosecond photodiode (AR-S3, Antel Optronics Inc.) having a bandwidth of 14 GHz. The photodiode signal was fed to a Rohde & Schwarz FSA spectrum analyzer accepting frequency components in the range of 100 kHz–2 GHz with a minimum resolution bandwidth of 6 Hz and a dynamic range of 140 dB. This allowed analyzing the harmonic spectra between the first and the 24th harmonic of the 80-MHz pulse train. The low-frequency ($\leq$100 kHz) components of the power spectrum were acquired with a HP 35665A digital spectrum analyzer (130 dB dynamic range). Optimum SNR was achieved at a photocurrent of 1.7 mA, which was kept constant in all measurements.

IV. NOISE MEASUREMENTS

A. Spectral Characterization

Spectral measurements around different harmonics have been performed for frequency offsets to the respective carrier extending from 20 Hz to 1.5 MHz. In order to be able to keep both the relative resolution nearly constant over this broad-spectral range and the measurement time short, the noise side band spectra have been obtained from up to 9 subsequent scans recorded over increasing frequency spans (300 Hz, 1, 3, 10 kHz, etc.) with correspondingly increasing resolution (6 Hz, 10, 30, 100 Hz, etc.). Normalization of the measured spectra to the carrier power $\overline{P}^2$ [see (2)] and the respective resolution bandwidth yields the noise spectral density $S_n(f)$. Integrated over a 1-Hz bandwidth it can be depicted on a logarithmic scale in units of dBc/Hz. In what follows, all the noise spectra including the constituents of $S_n(f)$ [as given by (3)] will be presented on a logarithmic scale in dBc/Hz, the noise sidebands as 10 ×lg[$S_n(f) \times 1$ Hz] the energy noise spectrum as 10 ×lg[$S_E(f) \times 1$ Hz] the timing jitter spectrum, 10 ×lg[$(2\pi f_R)^2 S_J(f) \times 1$ Hz], and the spectrum of the coupling term as 10×lg[$(2\pi f_R) S_{EJ}(f)$×1 Hz].

Fig. 2 shows the dc-baseband ($n = 0$) noise spectrum and the average of the left-hand and right-hand side noise bands of the Ar-laser-pumped oscillator at harmonics of order of $n =$ 2, 10, 20. The averaging eliminates the coupling term from (3). A comparison of the second-harmonic sideband with the baseband noise reveals that timing jitter dominates the noise spectrum already at the second harmonic at frequencies below 1 kHz. As a consequence of (3), the sideband spectral intensity

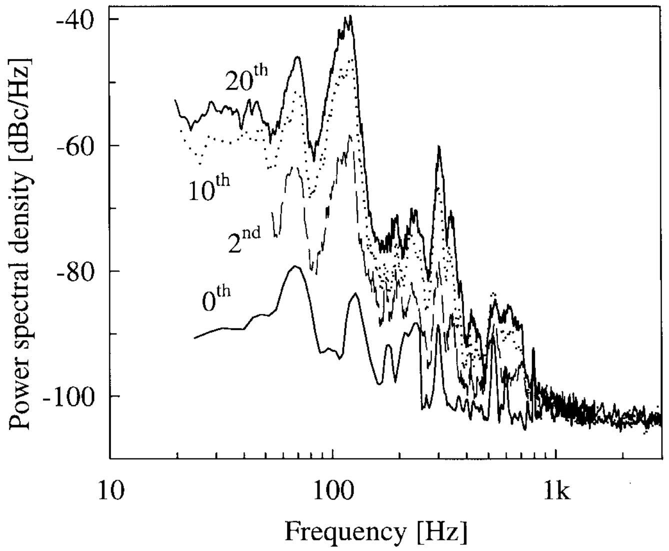

Fig. 2. Noise sidebands of different harmonics of the power spectrum of the sub-10-fs Ti:sapphire laser pumped by the Ar–ion laser. For explanation see the first paragraph of Section IV-A.

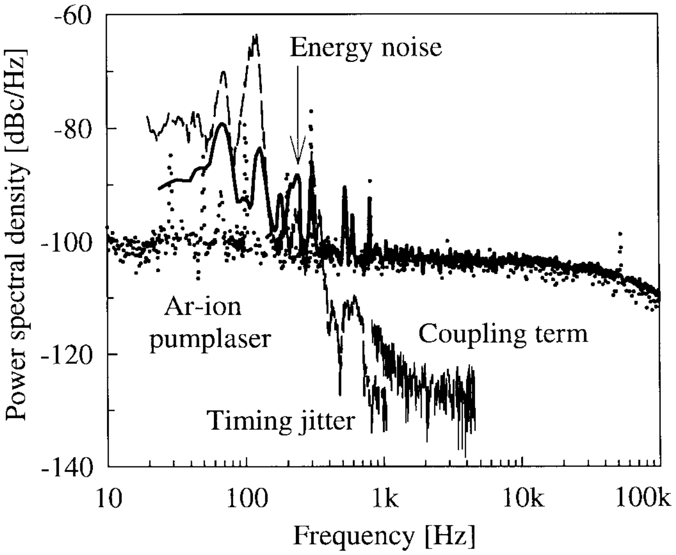

Fig. 3. Energy noise, timing jitter, and coupling-term spectrum of the Ti:sapphire laser and power spectrum of the Ar–ion pump laser. To avoid excessive errors in the evaluation, the energy-timing coupling term is shown only over a limited range, where this coupling provides a dominant contribution to the noise sidebands. For explanation see the first paragraph of Section IV-A.

should, therefore, increase quadratically with harmonic order at $f \leq 1$ kHz. The corresponding 14-dB and 20-dB increase of the 10th and 20th harmonic sidebands with respect to that of the second harmonic is clearly evident in Fig. 2.

The energy noise and timing jitter spectra determined from these measurements are shown in Fig. 3. For frequencies $f > 300$ Hz, the energy noise is limited by pump power fluctuations. Below 1 kHz both the energy noise and the timing jitter is by 1–2 orders of magnitude lower than those previously reported for a prism-controlled KLM Ti:sapphire laser [15] pumped similar Ar–ion laser.[3]

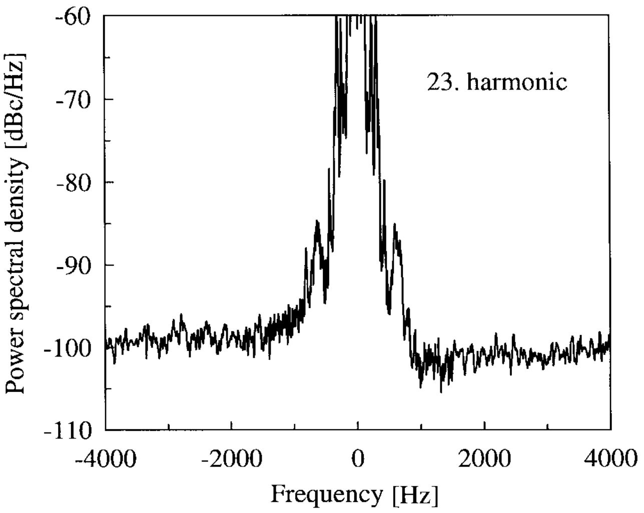

Fig. 4. 23rd harmonic of the pulse repetition frequency in the power spectrum of the Ar–ion pumped sub-10-fs Ti:sapphire oscillator, showing asymmetric noise sidebands.

Fig. 3 also plots the spectrum of the coupling term, which is evaluated from the noise sideband of the 23rd harmonic shown in Fig. 4. The pronounced asymmetry of the noise bands at positive and negative frequency offsets provides a clear evidence for the occurrence of a significant coupling between timing jitter and pulse energy fluctuations. A comparison of the noise spectral density introduced by the coupling with that originating purely from timing jitter (Fig. 3) indicates that disregard of the spectral asymmetry may severely compromise the accuracy of the determination of the timing jitter in a sub-10-fs Ti:sapphire oscillator.

A closer inspection of the noise spectra shown in Figs. 2 and 3 provides further support for the coupling. The big spikes at around 70 and 110 Hz in the base band noise spectrum (Fig. 2) show up at the same position in the side bands of higher-order harmonics, in which timing jitter dominates. This implies that these spikes must also be present in the timing jitter spectrum, as confirmed by Fig. 3. Because of the relatively low noise of the pump source in this frequency regime (as compared to $S_E(f)$ and $S_J(f)$) pump fluctuations can not cause these spikes in $S_E(f)$ and $S_J(f)$ through independent channels, suggesting that a coupling between energy noise and timing jitter is responsible for the observed behavior.

Fig. 5 shows the energy noise and timing jitter spectra for the all-solid-state sub-10-fs Ti:sapphire laser. The pump noise is now significantly lower, resulting in an energy noise of the Ti:sapphire laser that is no longer limited by pump power fluctuations at frequencies <20 kHz.

A comparison of the noise characteristics of the Ar–ion-pumped and all-solid-state Ti:sapphire laser is shown in Fig. 6. Whereas the energy noise spectrum of the Ar–ion-pumped system is pump-source-limited in the frequency range of 0.3–100 kHz at a level of ≈ -100 dB, starting from the same level it rolls off with -10 dB/decade to reach the pump noise of ≈ -120 dB at around 20 kHz in the all-solid-state system. The two spectra approximately coincide beyond 0.5 MHz,

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[3] It remains to be verified by a comparative characterization of a prism-controlled and MDC oscillator under the same experimental conditions, if this improvement is due to the removal of the prisms from the cavity.

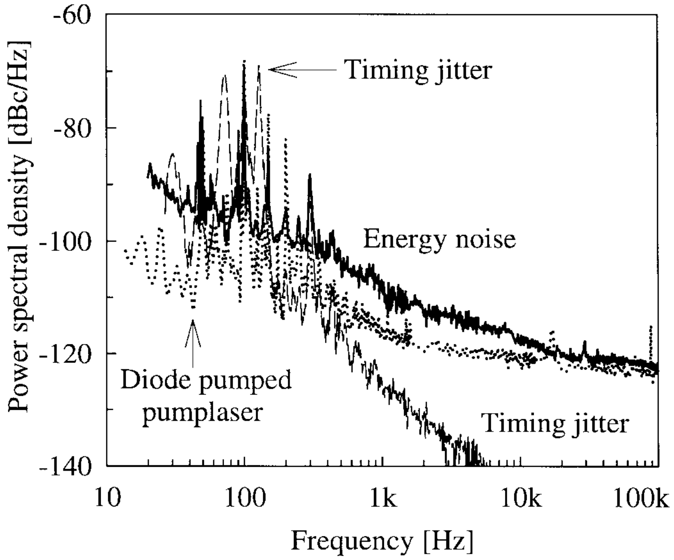

Fig. 5. The same as in Fig. 3 for the all-solid-state sub-10-fs laser without the coupling term.

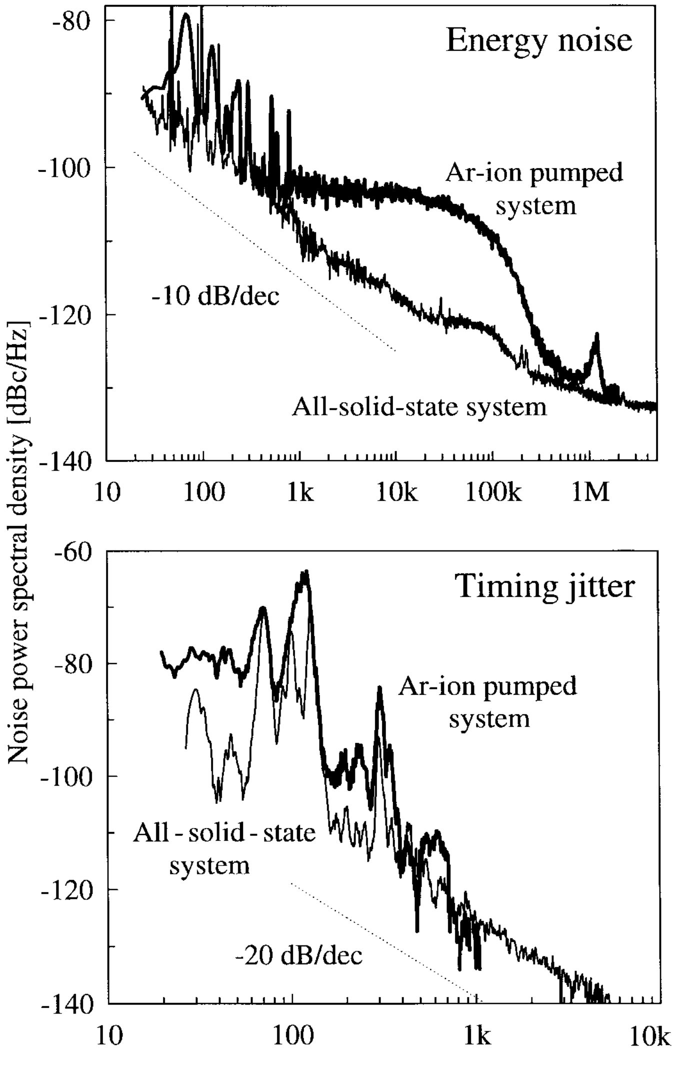

Fig. 6. Comparison of the energy noise and timing jitter spectra for the all-solid-state and Ar–ion-pumped MDC Ti:sapphire laser.

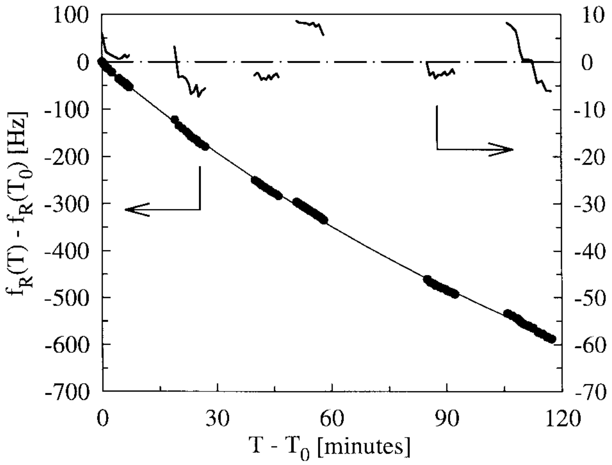

Fig. 7. Time evolution of the pulse repetition rate $f_R(T)$ (thick dashed line) and its random walk defined $\delta f_R(T) = f_R(T_0) - f_R(T) - \Delta f_R(T)$, where the drift component $\Delta f_R(T)$ is given by (6) (thin solid line).

where the gain medium starts efficiently filtering pump fluctuations due to the ≈ 3-μs lifetime of the upper laser level. The timing jitter spectra roll off for frequencies above 100 Hz with ≈ -20 dB/decade. In a laser generating solitonlike pulses, this behavior has been predicted by Haus and Mecozzi for frequencies obeying $f \ll f_R[g/(\Omega_g\tau)^2]$, where g is the saturated gain, Ω_g is the gain bandwidth, and τ is the pulse duration [13]. Since the pulse duration in our oscillator does not substantially exceed the inverse gain bandwidth, the above condition is met below 100 kHz, in accordance with the experimental observation.

Particular care has to be taken when measuring the noise sidebands of higher harmonics at low frequency offsets, because the harmonic spectrum may be subject to some drift and/or random walk in a passively mode-locked laser [13]. This is because a restoring force introduced by a modulator driven by an external frequency synthesizer in an actively mode-locked laser is absent in such a system. A change in the pulse repetition frequency f_R during the spectral scan due to these effects may distort the noise spectral density and falsify the evaluated timing jitter. In order that this can be avoided, the evolution of the pulse repetition frequency $f_R(T)$ has been accurately monitored during the measurements (see Fig. 7) and each scan has been repeated several times for the same experimental conditions. As revealed by Fig. 7, the repetition frequency was indeed continuously drifting over an extended period of time. This monotonic component of the change in f_R was found to follow an exponential evolution as given by

$$\Delta f_R(T) = F \exp(-T/T_d) \tag{6}$$

with $F = 1120$ Hz and $T_d = 160$ min. The deviation $\delta f_R(T)$ from this deterministic motion is also depicted in Fig. 7. Owing to the small value ($< \pm 10$ Hz) of this random walk and the associated long time scale, repeated scans at low frequency offsets to higher harmonics under unchanged experimental conditions allowed an accurate and reliable determination of the timing jitter spectrum down to 20 Hz.

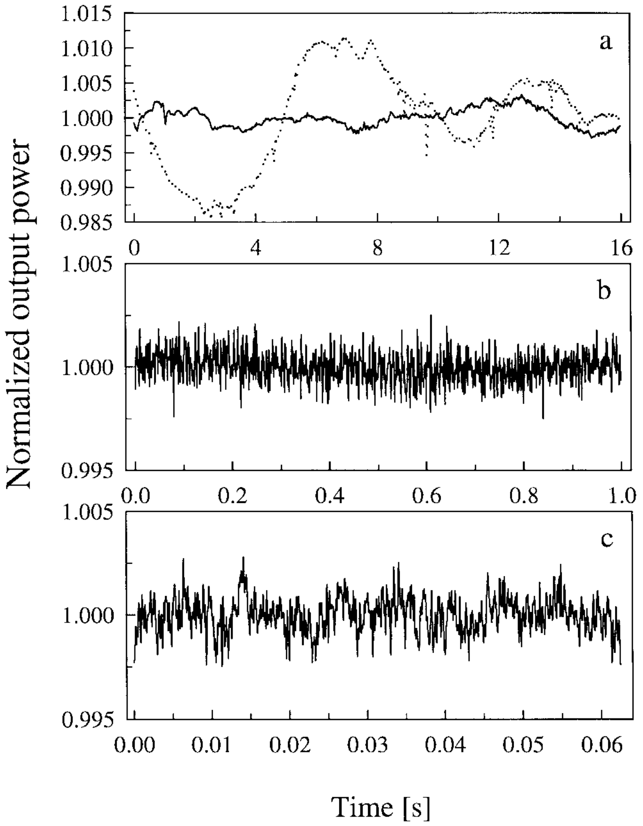

Fig. 8. Normalized (averaged) output power of the all-solid-state sub-10-fs source recorded on various time scales. The dashed line in (a) represents the Ar–ion-pumped source.

B. Energy Noise Measurements in the Time Domain

In contrast with the timing jitter, the low-frequency components of the pulse energy noise can be easily obtained. Measuring the evolution of the average output power, i.e., $E(T)$, directly in the time domain gives access to the low-frequency components of the energy noise spectrum, with a cutoff limited merely by the measurement time T_m. In fact, sampling $E(T)$ at $T_k = T_0 + kT_m/N$ over a period of T_m $(k = 1, \cdots, N)$ allows to calculate the rms energy noise over the frequency interval of $[f_{\text{low}} = 1/T_m, f_{\text{high}} = (1/2)N/T_m]$ as

$$\sigma_E(f_{\text{low}}, f_{\text{high}}) = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N} E(T_k)^2}. \tag{7}$$

Fig. 8(a)–(c) shows the normalized output power $1 + E(T)$ of the all-solid-state system recorded over a time interval of T_m = 16, 1, and 1/16 s, respectively. Fig. 8(a) also depicts the output of the Ar–ion-pumped system (dotted line) for comparison. This superior noise performance of the all-solid-state source is evident. Each graph consists of 1024 data points, which allow to determine the rms energy noise in the frequency range of $[f_{\min} = 1/T_m, f_{\max} = 512/T_m]$ (see Section IV-C).

C. RMS Energy Noise and Timing Jitter

The noise spectral densities plotted in Fig. 6 and the time-domain data shown in Fig. 8 can now be used to determine the corresponding rms quantities according to (4), (5), (7). Tables I and II show the rms pulse energy noise and the timing jitter, respectively, evaluated for different frequency ranges. It is noteworthy that σ_E obtained from spectral as well as time-domain investigations compare excellently (in the overlapping frequency range). The all-solid-state system performs significantly better than its Ar–ion-pumped counterpart in terms of both energy noise and timing jitter throughout the investigated frequency range. Particularly striking is the superiority of the all-solid-state source in terms of energy noise in the subhertz regime.

TABLE I
THE rms PULSE ENERGY FLUCTUATIONS σ_E EVALUATED FOR DIFFERENT FREQUENCY RANGES

Frequency domain measurements				
Frequency Range [Hz]	Ar pumped Ti:S		All-solid-state Ti:S	
	Ar-ion	Ti:S	Millennia	Ti:S
20 - 200	0.031	0.086	0.035	0.095
200 - 2k	0.062	0.063	0.019	0.035
2k - 20k	0.112	0.126	0.019	0.028
20k - 100k	0.169	0.187	0.030	0.035
100k - 1.5M	-	0.138	-	0.070
Time domain measurements				
0.0625 - 16	-	0.523	-	0.136
1 - 512	-	0.111	-	0.076
16 - 8.2k	-	0.120	-	0.108
0.06 Hz - 1.5 MHz	-	**0.595**	-	**0.189**

TABLE II
THE rms TIMING JITTER FLUCTUATIONS, σ_J, EVALUATED FOR DIFFERENT FREQUENCY RANGES

	σ_J [ps]	
Range [Hz]	Ar pumped Ti:S	All-Solid-State Ti:S
20 - 200	6.53	3.08
200 - 2000	<0.66	<0.28
20 - 2000	**6.56**	**3.09**

The improved timing jitter is, however, somewhat surprising. Unless some thermal fluctuations induced in the gain medium by pump power fluctuations can be made responsible, this may indicate that a substantial component of the timing jitter originates from energy fluctuations in the sub-10-fs MDC oscillator. This coupling can be understood in terms of a shift of the mode-locked spectrum induced by a change in the pulse energy, which is due to some residual high-order dispersion in the resonator and to the finite-response time of the Kerr nonlinearity in the gain medium [23]. The nonzero net cavity dispersion (i.e., frequency-dependent round-trip time) translates this frequency shift into a change in the round-trip time, giving rise to a coupling between pulse energy and timing.

V. CONCLUSION

We have performed a comprehensive noise characterization of a mode-locked laser operating in the sub-10-fs regime for the first time. The pulse energy fluctuations have been characterized over a frequency range from 0.06 Hz to 1.5 MHz. Careful characterization of the drift and random walk of the pulse repetition rate allowed accurate measurement of the timing jitter spectra down to 20 Hz. A comparison with data previously reported on the literature [15] suggests that the noise performance of compact mirror-dispersion-controlled Ti:sapphire lasers is superior to their prism-dispersion-controlled predecessors. When pumped with a diode-pumped laser this all-solid-state source delivers sub-10-fs pulses with rms pulse energy fluctuations as small as 0.19% over the frequency range of 0.06 Hz–1.5 MHz.

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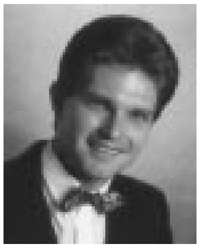

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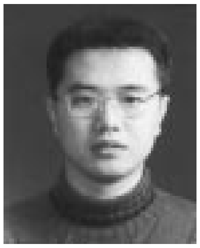

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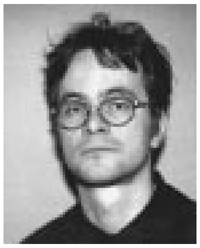

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