Nearly quantum-noise-limited timing jitter from miniature Er:Yb:glass lasers

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We report on nearly quantum-limited timing-jitter performance of two passively mode-locked Er:Yb:glass lasers with a repetition rate of 10 GHz. The relative timing jitter of both lasers was measured to be 190 fs (100 Hz−1.56 MHz) root mean square. The remaining cavity-length fluctuations are below 7.5 pm in the 6 Hz−8 kHz frequency range, indicating the stability of a rugged miniature cavity setup. By actively controlling the cavity length we reduced the timing jitter to 26 fs (6 Hz−1.56 MHz). We also discuss the influence of cavity length on the practically achievable timing jitter. © 2005 Optical Society of America

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Mode-locked laser sources with low timing jitter are needed for high-speed optical data transmission systems. As the bit rates increase, the requirements on the timing jitter to prevent bit errors become increasingly more stringent. Other important applications of such sources are in the field of optically sampled analog-to-digital conversion to permit precise measurements at high sampling rates.[1] Timing jitter of mode-locked lasers with non-quantum-noise-limited performance has been measured many times.[2–7] Quantum-noise-limited timing jitter has been demonstrated with passively mode-locked fiber lasers,[8] active harmonically mode-locked fiber lasers,[9] and hybrid mode-locked laser diodes.[10] A passively mode-locked bulk laser has been described[11] that has a measured timing-noise power density some 30 dB above the quantum limit in free-running operation. In a synchronized configuration the laser came closer to its quantum-noise limit but was still significantly more than 10 dB above it, corresponding to a root-mean-square (rms) timing jitter of 170 fs (100 Hz−5 kHz).

In this Letter we present nearly quantum-noise-limited timing-jitter measurements for two passively mode-locked Er:Yb:glass bulk lasers with repetition rates of 10 GHz. The cavities are similar to the cavity described in Ref. 12 but are built with great care for mechanical stability and are additionally enclosed in a metal case. The lasers are commercially available from Time-Bandwidth Products (Model ERGO PGL 10G) and produce ≈15 mW of average output power (fiber coupled) in 1.5-ps Gaussian pulses. The timing of the pulses relative to that of an external reference oscillator can be stabilized with a phase-locked loop similar to the loop described in Ref. 4. It uses a small fraction (≈0.5 mW) of the output beam as feedback and controls the cavity length by moving an end mirror mounted upon a piezo actuator.

For measuring the relative timing noise of the two lasers we use an indirect phase comparison method[13] that allows precise jitter measurements for free-running or timing-stabilized mode-locked lasers. We used this method instead of, e.g., the method described by von der Linde[14] because it does not depend on a reference oscillator with lower timing noise than the device under test. The setup (Fig. 1) consists of two fast photodiodes, each detecting the output power of one laser. The electrical signals are downconverted to ≈2 MHz by two mixers and a common local oscillator. After antialias filtering, the signals are recorded by a two-channel digitizer. We then numerically process the traces obtained and calculate the relative timing fluctuations between the two lasers. For an in-depth description of the measurement method we refer the reader to Ref. 13.

Figure 2 shows measured two-sided timing phase noise power spectra of the free-running and the timing-stabilized lasers. Each curve represents the

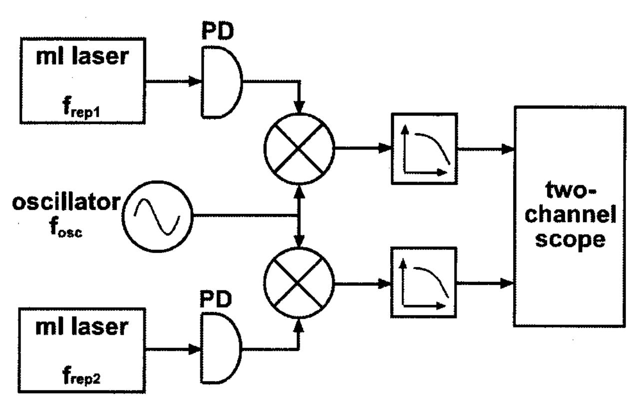

Fig. 1. Experimental setup for our jitter measurements: ml, mode locked; PDs, fast photodiodes. The photodiode signals are downconverted to low frequencies, low-pass filtered, and digitally recorded.

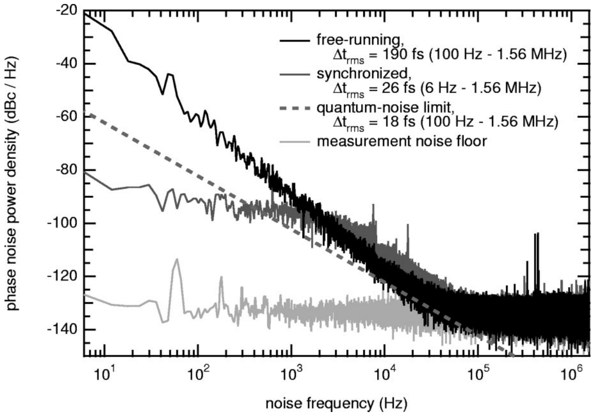

Fig. 2. Power spectral densities of the measured timing phase noise of the free-running and the timing-stabilized lasers. Each curve shows the average of four measurements with a measurement time of 0.17 s each. The dashed line is the quantum limit for relative timing fluctuations [$=2S_{\varphi t}^{\mathrm{qn}}(f)$]. The vertical axis shows $10\log_{10}[S_{\varphi t}(f)\times 1\ \mathrm{Hz}]$ in units of decibels relative to carrier per hertz.

average of four single measurements with a measurement time of 0.17 s. The dashed line shows the limit given by quantum-noise sources in the cavities,[15] which is equal to the sum of the noise power densities of the individual lasers. The quantum noise of a single laser $S_{\varphi t}^{\mathrm{qn}}(f)$ was previously derived for soliton-like pulses[16] based on soliton perturbation theory (which is not applicable here) and more recently for arbitrary pulse shaping mechanisms.[15] For Gaussian pulses, $S_{\varphi t}^{\mathrm{qn}}(f)$ was found to be[15]

$$S_{\varphi t}^{\mathrm{qn}}(f) \cong 0.3607\frac{h\nu}{E_p}\frac{\theta g}{T_{\mathrm{rt}}}{\tau_p}^2\left(\frac{f_{\mathrm{rep}}}{f}\right)^2. \quad (1)$$

We have omitted the term that describes the coupling of center frequency fluctuations to the timing phase jitter by means of group-delay dispersion because it is negligible in our case. The laser parameters are the following: optical center frequency, $\nu=195.6$ THz; intracavity pulse energy, $E_p=0.2$ nJ; intensity gain coefficient per round trip, $g=2\%$; round-trip time, $T_{\mathrm{rt}}=100$ ps; pulse repetition rate, $f_{\mathrm{rep}}=10$ GHz; full width at half-maximum pulse length, $\tau_p=1.5$ ps. The factor θ describes the spontaneous-emission noise caused by the gain medium relative to the noise of an ideal four-level system. Assuming that $\approx 65\%$ inversion is needed to overcome the reabsorption losses and to provide 2% gain, θ is ≈ 3 in our lasers. Because timing error Δt is equal to $\Delta\varphi/(2\pi f_{\mathrm{rep}})$, timing-noise power density $S_{\Delta t}(f)$ is related to the timing phase noise by

$$S_{\Delta t}(f) = (2\pi f_{\mathrm{rep}})^{-2} S_{\varphi t}(f). \quad (2)$$

The rms value Δt_{rms} in the frequency range f_1–f_2 is given by

$$\Delta {t_{\mathrm{rms}}}^2 = 2\int_{f_1}^{f_2} S_{\Delta t}(f)\mathrm{d}f; \quad (3)$$

the factor of 2 is included because of the two-sided power density.

For the free-running lasers, the timing phase noise at noise frequencies above 40 kHz is below the noise floor of the measurement, which is dominated by the sampling card. From ≈ 8 to ≈ 40 kHz, the measured phase-noise power density is at the quantum limit within ≈ 5 dB. Toward lower frequencies, the phase-noise power density increases by 30 dB per decade ($\propto 1/f^3$) and departs from the quantum limit that grows only by 20 dB per decade ($\propto 1/f^2$), corresponding to white frequency noise. The rms relative timing jitter is 190 fs (100 Hz–1.56 MHz), i.e., only ~ 10 times the quantum limit of 18 fs. More than 99% of the 190 fs rms jitter originates from the decade from 100 Hz to 1 kHz, where the phase-noise power density is significantly above the quantum limit. The instantaneous repetition rate $f_{\mathrm{rep,inst}}$ is defined by $2\pi f_{\mathrm{rep,inst}}=\partial\varphi_t/\partial t$, and we find the power density of instantaneous frequency fluctuations $S_{\Delta f\mathrm{rep,inst}}(f)$ $=f^2 S_{\varphi t}(f)$. Therefore the $1/f^3$ phase noise means that the spectral power density of the instantaneous repetition rate is proportional to $1/f$, which is commonly referred to as flicker of frequency. It has a rms value of 1.7 Hz in the range 100 Hz–1 kHz for each laser. Fluctuations of the cavity length Δl lead to a change in repetition rate $\Delta f_{\mathrm{rep,inst}}$ of

$$\Delta f_{\mathrm{rep,inst}} = -c/(2l^2)\Delta l = -f_{\mathrm{rep}}\Delta l/l \quad (4)$$

(l is the average cavity length and c is the speed of light). From Eq. (4) we derive that rms fluctuations of the (optical) cavity length of each laser as small as 2.6 pm (100 Hz–1 kHz) are already enough to explain the observed timing noise (in the range 6 Hz–8 kHz this value increases to 7.5 pm). This magnitude of jitter might result, e.g., from thermal fluctuations in the gain medium or from air currents. We do not observe the peaks that are typically associated with mechanical vibrations.

Note that the coupling of intensity noise to timing noise within the laser by means of the Kerr nonlinearity, a Kramers–Krönig-related effect, or the saturable absorber[15] is expected to be weak. For the low level of intensity noise of these lasers,[13] it cannot influence the timing jitter.

In what follows, we discuss measurements for which both lasers are timing stabilized to the same electronic reference oscillator (Agilent E8241A). In this case the phase-noise spectrum at low frequencies up to the feedback loop bandwidth of ~ 2 kHz is approximately flat. As expected, the external timing reference limits the timing error over arbitrary times and therefore removes the divergence of the phase-noise power density at zero frequency. The relative rms timing jitter is reduced to 26 fs (6 Hz–1.56 MHz), and frequencies below 6 Hz should have a negligible influence. Above 2 kHz, where the feedback loop has no influence, the behavior of the free-running and the timing-stabilized lasers is quite similar. There are two peaks in the power spectrum of the synchronized lasers (at 8 and 20 kHz) that have not been observed in the free-running case. Additionally, the synchronized power spectrum is slightly higher near these peaks. We attribute this effect to mechanical resonances of the piezo mounts that are excited by noise on the piezo control voltage. Looking at the fluctuations of the instantaneous repetition rate in the 6 Hz–2 kHz range, we find a remaining rms deviation of 1.1 Hz between the two lasers. This means that the timing stabilization is able to control the relative cavity length to an accuracy of 1.6 pm within the feedback loop's bandwidth; in terms of voltage applied to the piezo actuators, this corresponds to ≈ 0.1 mV. One could decrease the timing jitter even further by increasing the bandwidth of the feedback loops, which is limited by a mechanical resonance of the piezo mounts. We believe that mechanically redesigning the piezo mounts should make feasible a bandwidth of ~ 10 kHz, limited by a resonance of the piezo itself with a semiconductor saturable absorber mirror attached to it. This would reduce the rms timing error (6 Hz–1.56 MHz) by an estimated factor of 2.

We have seen that 10-GHz miniature bulk lasers with a stable cavity setup can have low timing jitter not far from the quantum limit. This means that lasers with still shorter cavities will have a higher free-running timing jitter, assuming the same average output power, because the quantum limit will then be higher [Eq. (1)]. A lower free-running timing jitter might be possible for longer cavities, however. Equation (1) shows that, for fundamentally (i.e., not harmonically) mode-locked lasers, the quantum-noise power density of the pulse timing is proportional to $1/T_{rt}^2$. Note that for constant average output power the pulse energy is proportional to the round-trip time. (For harmonically mode-locked lasers with a fixed pulse repetition rate, the power density would be proportional to $1/T_{rt}$.) Therefore, lower timing jitter would appear to be possible in longer cavities. However, it typically becomes mechanically more challenging to make longer cavities highly stable. Assuming that the relative cavity-length fluctuations can be kept constant (as would be the case, e.g., for drifts from thermal expansion), the timing jitter that is due to such technical noise sources would stay constant, whereas the influence of quantum noise would decrease for longer cavities. For low noise frequencies, for which technical noise is dominating, an improvement would not be achieved, but some improvement might be possible at high frequencies, which, however, are not dominating for the rms jitter. In summary, for shorter cavities the free-running timing jitter will increase because the quantum limit does so. In principle, longer cavities allow for decreased timing jitter, but we expect that it will then be more difficult to suppress technical noise.

Note that in principle one may suppress the timing jitter of a 10-GHz miniature laser even more by inserting an amplitude modulator driven by a stable 10-GHz timing signal, i.e., by using hybrid mode locking. (Active mode locking alone would not provide sufficiently short pulses.) This is so because the effective restoring force for the timing would be particularly strong for a fundamentally mode-locked laser with a multigigahertz repetition rate: The time constant associated with the restoring force[17] would be of the order of 20 ns, equivalent to a feedback bandwidth of several megahertz. However, space constraints would make the integration of a modulator difficult in our laser, and cavity-length stabilization would also be required.

In conclusion, we have described nearly quantum-noise-limited timing jitter from passively mode-locked Er:Yb:glass lasers with a pulse repetition rate of 10 GHz. In the frequency range from 100 Hz to 1.56 MHz we have measured 190-fs relative rms timing fluctuations between the two free-running lasers. The remaining technical noise at frequencies below 8 kHz can be explained as being due to minute cavity-length fluctuations, of the order of only a few picometers within a measurement time of 0.17 s. We have been able to greatly reduce the timing jitter to 26 fs (6 Hz–1.56 MHz) with an active stabilization that controls the cavity length and have clarified the potential of lasers with different cavity lengths for low timing jitter.

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