Passively mode-locked glass waveguide laser with 14-fs timing jitter

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Ultralow jitter pulse trains are produced from a passively mode-locked, erbium/ytterbium co-doped, planar waveguide laser by use of high-bandwidth feedback control acting on the physical cavity length and optical pump power. Synchronization of a 750-MHz, fundamentally mode-locked laser to an external clock signal yields an ultralow, root-mean-square relative timing jitter of 14.4 fs integrated from 10 Hz to the Nyquist frequency of 375 MHz. © 2003 Optical Society of America

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Passively mode-locked planar waveguide lasers (MLWLs) based on Er/Yb co-doped phosphate glass provide a potentially compact source of ultralow-jitter, 3-ps optical pulses with average powers as high as 20 mW.[1] Such sources are attractive for high-data-rate communication systems and optical sampling systems used for high-speed, photonic, analog-to-digital (A/D) conversion.[2] They can also find use in long-distance distribution of optical atomic-clock signals over optical fiber. Actively referencing the pulse round-trip frequency of such a laser to an external clock by controlling the physical length of the laser cavity is successful in reducing relative timing jitter.[1] However, to meet the stringent jitter requirements for the above applications, a feedback loop with significantly higher bandwidth is required.[3–5] In this Letter we show that, by combining a high-speed servo loop acting on the current of the semiconductor pump laser along with an improved low-frequency servo acting on the length of the extended laser cavity, we obtained ultralow-jitter performance when we integrated the in-loop error signal from 10 Hz to the Nyquist Fourier frequency of 375 MHz, demonstrating the attractive potential of this laser for a wide range of applications.

The laser and the associated stabilization circuitry are shown schematically in Fig. 1. Through coupling optics and an optical isolator, an optically pumped semiconductor laser[6] (OPSL) emitting 500 mW at a wavelength of 975 nm, pumped a 2-cm-long waveguide positioned at one end of the laser cavity. A partially reflecting mirror, serving as the output coupler, was optically gated to one polished facet of the waveguide and held in place by a small spring. The other facet was cut and polished at Brewster's angle to minimize intracavity reflections in the extended-cavity setup. A microscope objective collimated the light from the waveguide, and this beam was focused onto a semiconductor saturable absorbing mirror (SESAM) with a second lens. The SESAM had a multiple-quantum-well layer made of three low-temperature-grown InGaAs/GaAs quantum wells in an antiresonant configuration on top of a 22.5-period distributed Bragg reflector consisting of alternating AlAs/GaAs quarter-wave layers. The absorber had a saturable loss of 9.5 ± 0.5% and a nonsaturable loss of less than 3%. Its saturation fluence was 25 μJ/cm^2. Details of the waveguide and (Be-free) SESAM fabrication and characterization are given elsewhere.[1,7] The SESAM was mounted on a cylindrical piezoelectric transducer (PZT) for active length control of the extended cavity. A dichroic beam splitter passed the 975-nm pump light and coupled the 1534-nm laser output into a single-mode optical fiber. Average output power exceeded 7 mW with 500 mW of pump power. Pulse durations were 6 ps full width at half-maximum. A fiber coupler sent a portion of the laser output to a high-speed photodetector. Signals from the photodetector and the reference clock were compared in a phase-sensitive manner by a double-balanced mixer to produce a phase-error signal suitable for synchronization. To enhance the phase-detection sensitivity, we chose to compare the 8th harmonic of the laser repetition frequency with the external clock

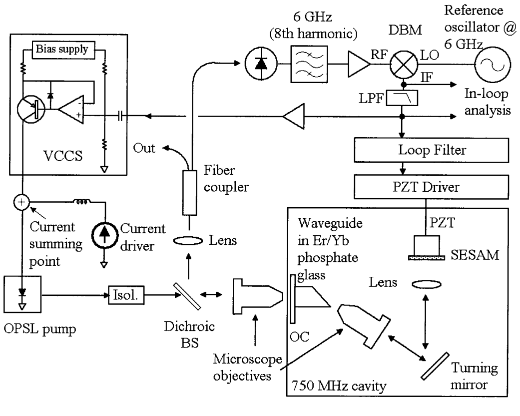

Fig. 1. Experimental configuration for a passively MLWL and stabilization electronics. RF, radio frequency; IF, intermediate frequency; LO, local oscillator; LPF, low-pass filter; OC, output coupler; BS, beam splitter.

signal at 6 GHz. A slow servo loop, employing a double-integrator loop filter, stabilized the length of the extended cavity by moving the PZT-mounted SESAM for Fourier frequencies below ~12 kHz. The error signal in the high-frequency range beyond 12 kHz was processed by a high-speed servo loop acting on the current supplied to the OPSL pump. Modulation of the pump laser current changes pump power, which in turn is observed to change the optical path length of the Er/Yb-doped gain medium. This effect is probably due to a pump-induced change in atomic dispersion.[8] The pump feedback was accomplished with a voltage-controlled current source (VCCS) that added current to the original dc bias of ~2100 mA provided by a commercial current driver.[9] The unity-gain frequency of the VCCS circuit was ~1 MHz. Special care was used to provide a smooth transition between the response of the low-frequency and high-frequency loops, providing an overall smooth feedback function optimized throughout the frequency range within the unity-gain bandwidth. We achieved this optimization by changing the gain and frequency response of our variable loop filter (a proportional-integral circuit with a secondary integrator and adjustable corners) and by adjusting the turn-on frequency of the high-pass filter at the input to the VCCS.

Figure 2 shows the in-loop jitter spectral density (JSD) or the single-sideband phase noise *L* (in decibels down from carrier per hertz bandwidth, dBc/Hz) with and without the high-speed servo control of the pump current. The PZT control loop is active for both traces. When the PZT is the sole servo transducer for the feedback, its mechanical resonance limits the attainable servo bandwidth at ~12 kHz. Addition of the high-speed loop reduces overall JSD and suppresses the prominent servo bump around 12 kHz. Integration per Eq. (1),

$$\tau_{j\mathrm{rms}} = \left(\int_{f_{\min}}^{f_{\max}} \mathrm{JSD}^2 \mathrm{d}f\right)^{1/2}, \qquad (1)$$

over the Fourier frequency range 1–100 kHz reveals a dramatic drop in rms timing jitter $\tau_{j\mathrm{rms}}$ from 230 to 37 fs. The improved rms timing jitter over this frequency range is 11.8 fs if the high-*Q* spur at ~51 kHz, which is not resolved by the analyzer resolution bandwidth, is excluded from integration. We expect the high-*Q* spur that is due to a PZT resonance effect to be removed with an improved feedback loop.

Figure 3 shows the JSD or the single-sideband phase noise and integrated residual jitter from 10 Hz to 375 MHz for the 750-MHz MLWL. The total residual rms jitter out to the Nyquist frequency is 14.4 fs after removal of the spur that occurs at 51 kHz. With the 51-kHz spur included the residual rms jitter is 38.2 fs (a conservative estimate since the spur linewidth is unresolved). The JSD level beyond 10 MHz (0.0004 fs/$\sqrt{\mathrm{Hz}}$ or -160 dBc/Hz) is attributed to the intrinsic phase noise floor of the mixer and thus merely gives an upper bound for the actual laser noise. Although an out-of-loop analysis is required for assessment of true noise performance independent of the feedback loop, we do not expect such an analysis to give a jitter performance significantly different from that reported here, especially for Fourier frequencies above 1 MHz.[5]

It is instructive to compare the JSD for the MLWL reported here with that of a hybrid mode-locked laser diode (MLLD) that was recently measured. In Ref. 5, Jones *et al.* achieved the lowest reported timing jitter for a MLLD (20 fs integrated from 1 Hz to 10 MHz). Figure 4 shows the in-loop JSD for both the MLWL and the fundamentally MLLD. For Fourier frequencies below 100 kHz, the MLLD exhibits less than 2 fs of rms jitter, whereas the MLWL has 12.4 fs (37.5 fs including the spur at 51 kHz). However, beyond 100 kHz, the MLWL accumulates little additional jitter whereas the jitter for the MLLD increases to 20 fs at a Fourier frequency of 10 MHz. Furthermore, more high-frequency jitter is expected beyond 10 MHz for the MLLD because of its fast gain dynamics[10] and overall lower cavity *Q* (the latter, because of higher gain requirements, leads to more spontaneous noise photons on the pulse as it circulates in the cavity). On the other hand, the higher-frequency

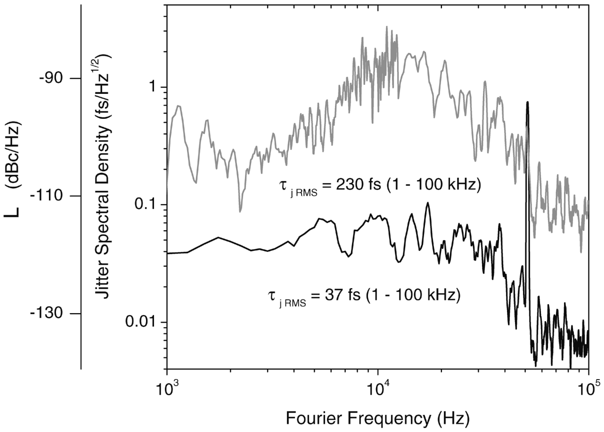

Fig. 2. JSD or single-sideband phase noise and integrated rms timing jitter from 1 kHz to 100 kHz for a passively MLWL with (black) and without (gray) high-bandwidth feedback acting on pump current.

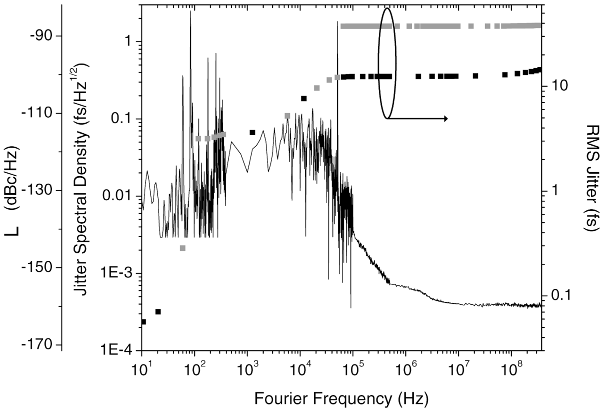

Fig. 3. JSD or single-sideband phase noise (line) and rms jitter with high-*Q* spur (gray boxes) and without spur (black boxes) at ~51 kHz for a passively MLWL from 10 Hz to 375 MHz, the Nyquist frequency.

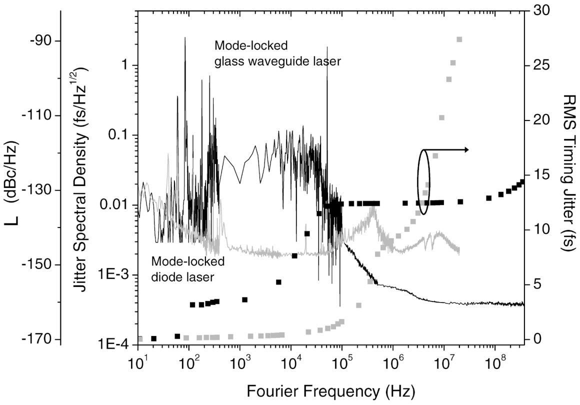

Fig. 4. JSD or single-sideband phase noise (10 Hz to 10 MHz) and rms timing jitter for a passively MLWL (black) and a hybrid MLLD (gray).

(beyond 10 MHz) contribution to the overall timing jitter for the solid-state MLWL is only 7.1 fs, allowing the total jitter measured over the entire Nyquist frequency range (out to 375 MHz) to remain below 14.4 fs (38.2 fs including the spur at 51 kHz). Again, in the frequency range of 10–375 MHz, our jitter measurements are limited by the mixer noise floor rather than by dynamics in the MLWL. Thus 14.4 fs represents a conservative upper bound for the reported total jitter. Such jitter performance shows great promise for applications such as photonic A/D conversion, where the jitter performance over the entire Fourier frequency spectrum is important.

In conclusion, a high-bandwidth servo loop acting on the optical pump of a passively mode-locked, Er/Yb co-doped, glass waveguide laser successfully complemented a PZT servo to reduce timing jitter to ultralow levels. In contrast with a MLLD, most phase noise is confined to Fourier frequencies below 100 kHz. From 100 kHz to the Nyquist frequency of the laser, contributions to jitter are minimal. These results indicate that the performance of the MLWL can be further enhanced with improved gain in the feedback design. The MLWL should be well suited for high-speed optical sampling in photonic A/D converters and other applications for which low jitter over the entire Fourier frequency range is critical. Future research planned for packaging and making shorter monolithic lasers (up to ~10 GHz fundamentally mode-locked repetition rates) will also make these sources particularly well suited for integration into both mobile and fixed optical-fiber-based systems.

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