Mode-locked fiber laser frequency-controlled with an intracavity electro-optic modulator

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We demonstrate a mode-locked, erbium-doped fiber laser with its repetition frequency synchronized to a second fiber laser via an intracavity electro-optic modulator (EOM). With servo control from the EOM (bandwidth ~230 kHz) and a slower speed intracavity piezoelectric transducer (resonance at ~20 kHz), we demonstrate stabilization of the repetition frequency with an in-loop rms timing jitter of 10 fs, integrated over a bandwidth from 1 Hz to 100 kHz. This represents what is to our knowledge the first time an EOM has been introduced inside a mode-locked laser cavity for fast servo action and the lowest timing jitter reported for a mode-locked fiber laser. © 2005 Optical Society of America

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Mode-locked lasers have become increasingly prevalent tools in frequency metrology over the past several years.[1] The current laser workhorse of the field is the Ti:sapphire femtosecond (fs) laser. However, mode-locked fiber lasers offer a compelling alternative in terms of cost, deployability, and ease of use among other reasons.[2–5] Prior work with frequency combs generated from fiber lasers[6] has found a large amount of high-frequency noise on both the pulse repetition rate and the offset frequency. These fluctuations of the repetition frequency are likely due to the high-gain–high-loss condition in the fiber laser cavity, which means the pulses receive a strong spontaneous-emission kick on every pass through the erbium-doped fiber.[7] Therefore, applications to timing synchronization require a broad bandwidth feedback loop to stabilize the repetition rate. Moreover, in frequency metrology it is often necessary to minimize the linewidth of the individual comb components.[8] Accordingly, a high-bandwidth actuator (>100 kHz) capable of correcting these fluctuations is a key component for fs frequency combs produced by fiber lasers to become viable alternatives to solid-state lasers. In this Letter we report for the first time to our knowledge the use of an electro-optic modulator (EOM) inside a mode-locked laser cavity as a large bandwidth frequency/phase servo transducer.

Due to the long upper-state lifetime (~10 ms) of erbium-doped fiber, direct amplitude modulation of the 980 nm pump diodes is limited in speed. An alternative, nonmechanical actuator is an intracavity EOM. One can think of an index change of the intracavity EOM as a small change in the cavity length, thus producing a small change in the repetition frequency. While the EOM does introduce some dispersion in the fiber laser cavity, the relative change in dispersion is small and can be easily compensated for in a fiber laser system. The combination of a high-bandwidth actuator consisting of an intracavity EOM and a low-bandwidth actuator consisting of an intracavity piezoelectric- (PZT-) actuated mirror allow for tight stabilization of the fiber laser repetition frequency to a reference over a large dynamic range. There also exists the possibility of controlling not only the repetition frequency but also the offset frequency via an intracavity EOM. In this scenario, the phase index would be set by a DC voltage across the EOM and the group index could be tuned via an AC voltage modulation, at a harmonic of the repetition frequency, on the EOM crystal.[9] The EOM modulation would impart a positive, negative, or zero frequency shift to the pulse, depending on which part of the modulation waveform the pulse encountered. This frequency shift coupled with the dispersive fiber in the cavity would allow for group index control.

Our fiber laser is a standard ring cavity design[10] with a polarizing beam splitter as the output coupler (Fig. 1). A low-bandwidth actuator consisting of a mirror mounted on a PZT is positioned at the fold of the cavity. The EOM (a 2 cm long, 5 mm thick piece of $LiNbO_3$ with dispersion at 1.55 μm of +0.002 ps^2) is inserted into the free-space section of the cavity

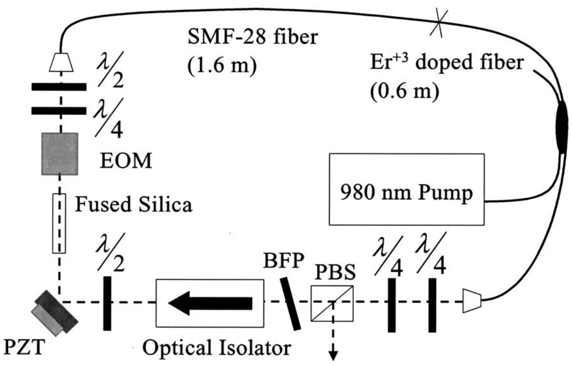

Fig. 1. Schematic of the fiber laser with intracavity EOM and intracavity PZT. The output coupler is the polarizing beam splitter (PBS). A half-wave plate after the optical isolator allows for polarization adjustment into the e-wave axis of the EOM. BFP, birefringent tuning plate; SMF, single-mode fiber.

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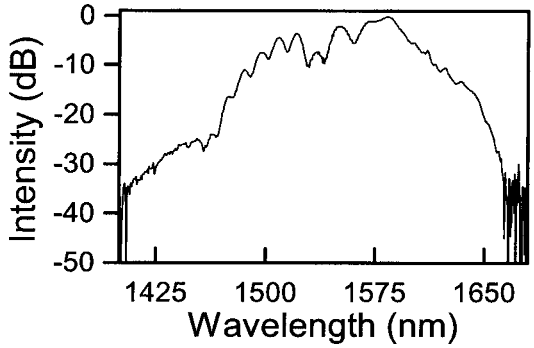

Fig. 2. Optical spectrum of the fiber laser pulses.

and presents a 2% insertion loss. The EOM dispersion is compensated for by adding a 9 cm long fused silica rod inside the fiber laser cavity. Overall, the laser cavity has a net anomalous dispersion ($-0.008\ ps^2$), thus operating in the soliton regime. An autocorrelation reveals 170 fs pulses, assuming a hyperbolic secant pulse shape, with the pulse spectrum as shown in Fig. 2.

We performed various tests on the EOM to understand its action on the fs comb. In terms of a servo actuator, two key tests are the dynamic range of the EOM action and its servo bandwidth. To measure the dynamic range, we applied various voltage steps across the two EOM electrodes and measured the responses of the repetition frequency. To precisely monitor these changes, we stabilized the laser to an RF reference using a low-bandwidth (<150 Hz), low-gain PZT lock. This allows the DC value of the repetition frequency to be stable while the fast changes in the repetition frequency induced by the EOM can be monitored through the in-loop servo error signal, which is not affected by the slow PZT servo [Fig. 3(a)]. Measuring the change in the phase of the repetition frequency signal with time after applying the voltage step allowed us to calculate the shift of the repetition frequency. The EOM driver can provide a maximum voltage step of 500 V to the EOM. As seen in the inset of Fig. 3(a), within this voltage range the frequency change is linear and the maximum frequency change is ~1 kHz out of the 80th harmonic of the fundamental repetition rate of 93 MHz. This maximum variation is equivalent to a refractive index change of 2.0×10^{-6}. The theoretical index change is given by $\Delta n = r_{22}Vn^3/2d$, where r_{22} is the only nonzero component of the electro-optic tensor for $LiNbO_2$, V is the voltage applied across the EOM, n is the index of refraction of $LiNbO_2$, and d is the distance between the electrodes on the EOM. With a 500 V applied voltage this equation gives an index change of 2.5×10^{-6}, in reasonable agreement with that extrapolated from the step response measurement.

The EOM bandwidth is determined via the measurement of its transfer function as shown in Fig. 3(b). Again, the laser was weakly stabilized to a reference via a low-bandwidth (<150 Hz), low-gain PZT lock. We monitored the error signal from the phase-locked loop in the Fourier frequency domain. For the input signal frequency below 150 Hz, the transfer function is suppressed artificially due to the low-bandwidth PZT lock that was being applied. From the plot we see that the −3 dB roll-off point of the EOM response is around 230 kHz, while the phase lag reaches 90° at 200 kHz.

To investigate the practical application of the intracavity EOM we used it to lock the repetition frequency of the fiber laser to a second, independent mode-locked fiber laser with a fundamental repetition frequency of around 31 MHz. Separate photodetectors were used to detect the 80th repetition frequency harmonic of the 93 MHz laser and the 240th harmonic of the 31 MHz laser, which were then phase-sensitively compared. The error signal, which is proportional to the phase difference in the repetition frequencies of the two lasers, was then filtered and fed back to the actuators in the slave laser cavity. Spectral analysis of the locking was accomplished by use of a fast Fourier-transform spectrum analyzer. The in-loop jitter spectral densities for the free-running case and locking with the PZT and the EOM are shown in Fig. 4(a). The EOM and PZT together reduce the integrated jitter (over a bandwidth from 1 Hz to 100 kHz) from approximately 1800 to 10 fs [Fig. 4(b)]. The measurement noise floor was determined by feeding an identical signal into both arms of the mixer, with appropriate phase shift and amplitude adjustment. The integrated jitter of the noise floor from 1 Hz to 100 kHz is less than 5 fs. Figure 4(a) shows that the locking is limited by the noise

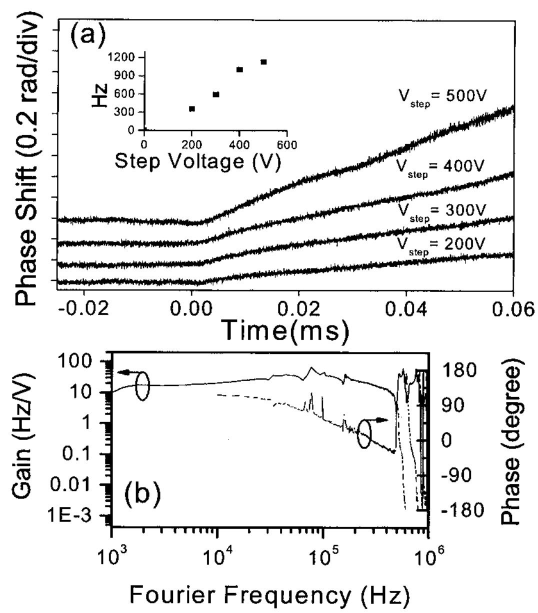

Fig. 3. (a) Step response of the EOM measured at increasing input voltages. The ordinate axis shows the phase change of the 80th harmonic of the repetition frequency signal. The voltage step turns on at 0 ms on the plot and stays on for 10 ms. The repetition frequency change of the laser reaches a limit of around 1 kHz (at the 80th harmonic) at a maximum of 500 V across the EOM. The inset shows the change of the 80th harmonic of the repetition frequency of the laser with increasing voltage across the EOM. (b) Transfer function of the EOM. The −3 dB roll-off frequency is approximately 230 kHz, while the phase lag reaches 90° at approximately 200 kHz.

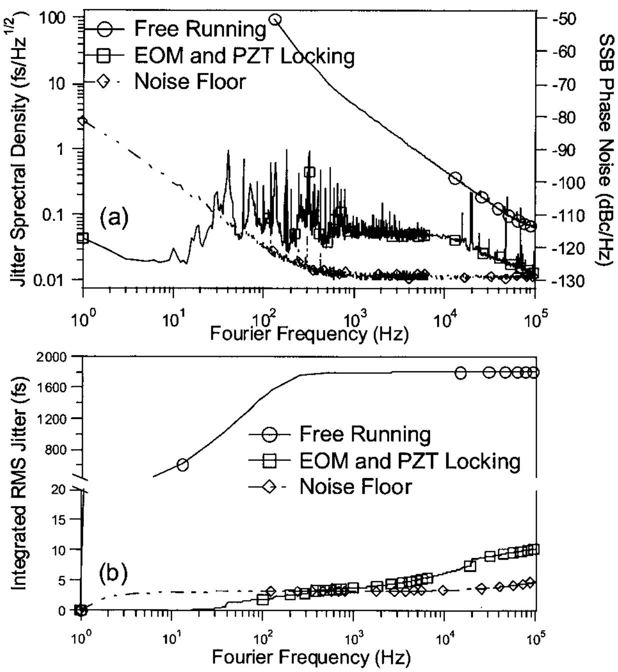

Fig. 4. (a) Jitter spectral density (left axis) and single-sideband phase noise (right axis) for locking the 80th harmonic of the repetition frequency (7.5 GHz) of the laser to the second fiber laser. (b) The free-running rms jitter is around 1800 fs. With the intracavity EOM used in conjunction with the PZT, the integrated rms jitter is reduced to 10 fs. The noise floor of the measurement is limited by the thermal noise, which has an integrated rms jitter over 1 Hz to 100 kHz of less than 5 fs.

floor, which is dominated by the RF amplifiers, below 60 Hz. At frequencies above 100 kHz the noise spectrum is also limited by the RF amplifiers. A realistic estimate of the jitter at a larger bandwidth can be performed by rolling off the noise floor to match the extrapolated free-running roll-off at high frequencies, due to the lack of servo actions there. This method yields 20 fs of integrated jitter for a 10 MHz upper limit and 21 fs of jitter for a 46.5 MHz (Nyquist frequency) upper limit.

The EOM loop bandwidth is ultimately limited by resonances above 500 kHz. These resonances are most likely due to piezolike electromechanical resonances in the EOM crystal. The EOM is mounted in a Teflon casing with vibration-absorbing material surrounding the crystal. However, at high driving frequencies the mechanical resonances are not completely suppressed. These issues could perhaps be resolved by replacing the free-space EOM with an inline fiber EOM.

In summary, synchronization of a mode-locked fiber laser to a reference via an intracavity EOM has been achieved at a record-low level of 10 fs of integrated jitter over a bandwidth of 1 Hz to 100 kHz. In future experiments, we plan to synchronize this fiber laser to another, remotely located, fiber laser. This will be possible given the recent advances in frequency standard transfer using mode-locked fiber lasers[11–14] and the broad bandwidth control provided by the EOM.

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