Passive harmonic mode-locked soliton fiber laser stabilized by an optically pumped saturable Bragg reflector

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Stabilization of passive harmonic mode locking is achieved for what is believed to be the first time in an Er–Yb soliton fiber laser by optical pumping of the semiconductor saturable absorber above the bandgap. The results show 35-dB mode suppression of undesired harmonics. © 2000 Optical Society of America

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The development of ultrashort optical pulse sources in the 1.5-μm spectral region is a key element in the future of high-speed time-division multiplexing and wavelength-division multiplexing networks.[1] Short pulses can be time multiplexed to hundreds of gigahertz,[2] and their large bandwidth can be sliced into a thousand channels for wavelength multiplexing.[3]

Of particular interest are ultrashort-pulse sources that generate repetition rates in the gigahertz range. Much attention has been given to actively mode-locked fiber lasers that are capable of producing picosecond pulses at high repetition rates. The introduction of modulators inside the cavity produces large losses, requiring the use of long gain fiber length and considerably lowering the fundamental repetition rate.[1,4] These lasers tend to have complex cavities and operate with thousands of pulses per round trip.

Passively mode-locked lasers, in contrast, have simple and compact cavities capable of generating subpicosecond pulses at very high fundamental rates. In particular, Er–Yb fiber lasers mode locked with saturable Bragg reflectors (SBR's) have high fundamental rates (~100–350 MHz), generate ultrashort pulses (~270 fs), and when operated in the soliton regime can run with as many as 24 pulses per round trip, producing multigigahertz pulse trains.[5] Unfortunately, the mechanism for self-stabilization of the pulse spacing, gain depletion, and recovery in Er is very weak,[6] resulting in soliton trains that are not equally spaced.[5]

In this Letter we present a new method of generating an equally spaced soliton pulse train from a harmonic passively mode-locked Er–Yb fiber laser. The method consists of modulating the saturable loss of the SBR's InGaAs–InP quantum wells by optically pumping it above the bandgap with an external laser that is amplitude modulated at a high harmonic of the fundamental repetition rate. This method results in 35-dB suppression of the undesired harmonic modes and a great reduction of timing jitter and pattern fluctuations. This technique should be applicable to many other types of laser, including semiconductor integrated lasers and solid-state lasers.

Gain depletion and recovery of the Er leads to gain modulation of the order of 10^{-7},[6] which is enough to keep pulses from bunching together, thus forming a quasi-equally spaced pulse train. The time ordering and jitter can be improved by larger modulation in the cavity losses, which is achieved by optical pumping of the InGaAs–InP quantum wells that are present in the SBR structures. These quantum wells have excitonic absorption near 1550 nm and a continuum of carrier absorption at shorter wavelengths.[5] Pump–probe measurements show that the normalized reflectivity ($\Delta R/R$) of the SBR can be changed by 10^{-4}–10^{-5} by bleaching of the absorption of the quantum wells. Therefore it is possible to produce modulation in the loss of the cavity that is more than 2 orders of magnitude larger than that caused by the self-stabilization mechanism.

Figure 1(a) shows the change in reflectivity of the pulses centered at 1550 nm as a result of the generation of carriers at 1480 nm for various pump-power densities. The saturation of the quantum wells is almost complete at power densities of the order of 1 W/cm^2, corresponding to a change in reflectivity of $\Delta R/R \sim 6 \times 10^{-5}$. This is only a half percent of the total cavity loss ($\sim 2 \times 10^{-2}$). Figure 1(b) shows the change in the reflectivity as a function of delay for a pump beam that is modulated at 2.488 GHz. The changes in the reflectivity follow the pump

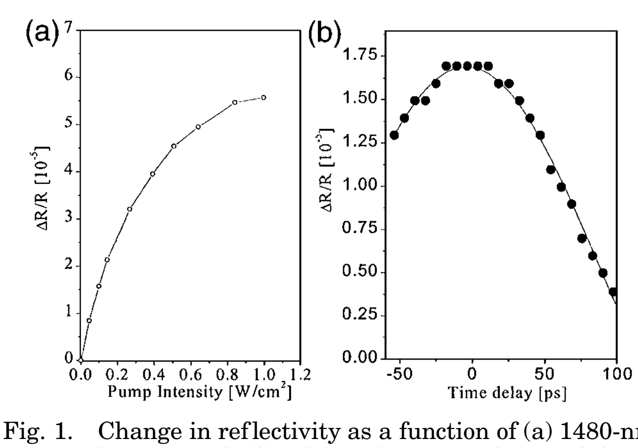

Fig. 1. Change in reflectivity as a function of (a) 1480-nm power density and (b) delay between the modulated 1480-nm pump and the 1550-nm pulses.

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modulation, as expected from earlier ultrafast resonant measurements of the carrier dynamics in these quantum wells.[5]

We implement our approach in a 103.6-MHz repetition-rate fiber laser running in the 12th harmonic (1.244 GHz). This laser produces ~430-fs soliton pulses with a time–bandwidth product of ~0.330 (see the curves in Fig. 2). At one end the linear cavity has a 99% reflectivity broadband dielectric output coupler on Franck–Condon connector. The other end is butt coupled to the SBR structure. The SBR consists of a >99% reflectivity broadband GaAs–AlAs Bragg reflector centered at 1550 nm and two InGaAs–InP quantum wells grown on top of a strain-relief InP layer deposit on top of the mirror.[5] The quantum wells act as fast saturable absorbers, providing a reliable passive mode-locking mechanism for the laser. The pump is composed of two 980-nm diode lasers that have been polarization combined to provide as much as 200 mW of power.

The pulse train is measured by a fast photodiode generating an electrical signal that is amplified and then filtered by a narrow-bandpass filter (BPF) tuned to 2.488 GHz (24th harmonic). The electrical signal externally modulates the intensity of a 1480-nm laser. A variable electronic delay aligns the phase of the optical feedback to the pulse train inside the laser cavity. The modulated 1480-nm laser light is then focused on the polished back side of the SBR structure. Figure 2 shows a diagram of the laser and feedback loop.

Figure 3 shows the rf spectrum of the laser output with the optical feedback on and off. Suppression of the unwanted harmonics is ~35 dB in the optical power (see the inset of Fig. 3). We obtain this suppression without compromising the spectral or temporal characteristics of the soliton pulses created by this laser (see the curves in Fig. 2) and by use of only standard telecommunications components. The phase of the electronic delay is set so that the pulses are aligned with the maximum saturation of the SBR. Even though there is some flexibility in the phase setting, a change of >60° results in complete destruction of the equally spaced pattern. We also note that the equally spaced pattern does not occur immediately after the feedback laser is turned on but takes a couple seconds to lock the pulses, as predicted for perturbations of the order of 10^{-5}.[6] Lowering the pump power results in longer stabilization time; however, for power-density values below 100 mW/cm^2 the stabilization time becomes long enough that the environmental perturbations override any possible stabilization. Using densities higher than 1 W/cm^2 does not lead to any improvement, since, as shown in Fig. 1(a), it is clear that the differential reflection saturates. Experiments in which the pump modulation frequency was changed to the 48th (4.976-GHz) and 96th (9.952-GHz) harmonics of the fundamental laser rate did not yield a significant improvement in the harmonic suppression or equalization of the time spacing. This result points to the limited saturation amplitude provided by the SBR structure as the main limiting factor.

The dramatic effect of the optical feedback on the interpulse timing can be observed clearly in the time domain. Figure 4 shows that without optical feedback the interpulse spacing can vary by more than 30 ps from pulse to pulse; however, the pulse train becomes equally spaced when the optical feedback is turned on. The deviations from the equally spaced pattern were reduced below the resolution of the scope (<10 ps).

To observe these deviations it is necessary to perform a cross correlation of the pulses. We set up a

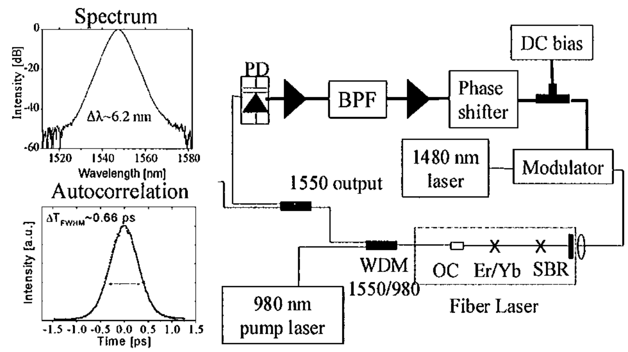

Fig. 2. Diagram of the fiber laser and the optical feedback loop. Top inset, laser spectrum; bottom inset, laser pulse autocorrelation. PD, photodiode; WDM, wavelength-division multiplexer; OC, output coupler.

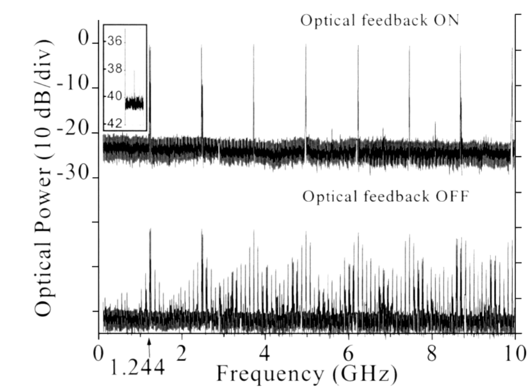

Fig. 3. rf spectra of the laser output with the optical feedback on and off. The fundamental mode of the cavity is suppressed by ~37 dB (see inset).

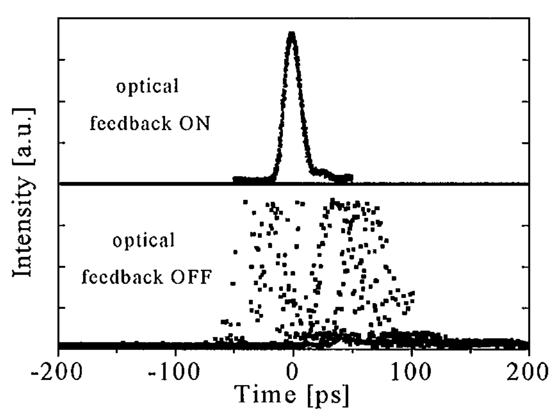

Fig. 4. Fast digital scope traces of the laser output with the optical feedback on and off.

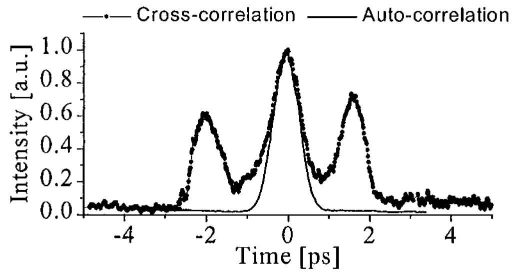

Fig. 5. Autocorrelation and cross correlation between adjacent pulses.

cross correlator by using a Michelson interferometer and a high-sensitivity InGaP laser diode as a photodetector. The high two-photon response of these diodes allows for measurements without amplification of the laser pulses, avoiding complications owing to pulse distortions in the amplifier.

Figure 5 shows a comparison of the pulse autocorrelation and cross correlation. We obtain the cross-correlation trace by delaying one arm by ~400 ps (i.e., one time slot). The cross correlation shows a feature at the center and a smaller peak at each side. The center peak arises from pulses that are equally spaced. A comparison between the widths of the autocorrelation and the cross correlation yields an estimated timing jitter of 0.4 ps.

The smaller peaks are deviations from a perfectly equally spaced pattern and represent pulse timing offsets of the order of 2 ps. This result indicates that the modulation may not be enough to keep all the pulses in the middle of the slots, and some fluctuations from that position can be observed. Nevertheless, the data suggest that, if pattern fluctuations in the pulse train can be reduced, the inherent timing jitter of such a laser will be of the order of 0.4 ps.

We expect that the use of SBR structures engineered to provide optimal modulation of the absorption by optical pumping will improve the stability and performance of the laser. A simple threefold increase in the number of quantum wells in the SBR may be enough to perfectly lock the equally spaced pattern.[6]

In conclusion, we have reported on a method of stabilizing passive harmonically mode-locked fiber lasers by optical modulation of saturable absorption. We obtained a significant reduction of the unwanted harmonics as well as a decrease in the deviations of an equally spaced pulse train. The data show that is possible to obtain a sech-pulse train of 430 fs at 1.244 GHz with time fluctuations of the order 2 ps. We believe that our approach has the potential to generate a nearly jitter-free pulse train at even higher rates and shorter pulses for the use in future time-division multiplexing experiments. This would be a great improvement over current sources in terms of stability and complexity.

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