Self-stabilized passive, harmonically mode-locked stretched-pulse erbium fiber ring laser

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We have studied a passive, harmonically mode-locked stretched-pulse erbium fiber ring laser with net positive dispersion that is self-stabilized by gain depletion and electrostriction. Periodic pulses with supermode suppression of >75 dB and picosecond jitter are achieved. The pulses are compressible to 125 fs by external chirp compensation. The repetition rate is 220 MHz, and the average power is as high as 80 mW. © 2002 Optical Society of America

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High-repetition-rate lasers have important applications in high-speed optical communication and precision optical sampling. High-repetition-rate pulse trains can be produced from harmonically mode-locked lasers, where multiple pulses circulate within the cavity. Multiple pulses can be generated passively in a laser because of the phenomenon of soliton energy quantization. Generally, the generated multiple pulses are randomly spaced. Active techniques, such as regenerative mode locking[1] or synchronization to an external pulse train,[2] can be used to order the pulses.

Many groups have reported passive, harmonically mode-locked solid-state and fiber lasers that self-organize without active control.[3–5] A number of explanations have been proposed for these effects. The acousto-optic effect, in which a pulse generates a transverse acoustic wave by electrostriction that modulates the local refractive index of refraction of the following pulses, has been proposed as the dominant mechanism in a soliton fiber laser.[3,4] It was shown numerically[4,5] that the acousto-optic effect can generate a weak pulse-to-pulse repulsive force that leads to equal pulse spacing. It was also shown that interaction between soliton pulses and the continuum[6] in a soliton laser generates a pulse-to-pulse repulsive force and could also contribute to equal pulse spacing.[7] It was suggested by Kutz *et al.*[8] that dynamic gain depletion can generate the necessary force in a soliton fiber laser.

To the best of our knowledge, there has been little explanation of the mechanism producing self-ordered pulses from passive, harmonically mode-locked stretched-pulse lasers. Stretched-pulse fiber lasers consist of normal and anomalous dispersion fibers with lengths such that the aggregate dispersion is slightly normal. These lasers[9,10] are capable of producing pulses with much higher energy, broader spectral width, and correspondingly shorter pulse widths than those with net anomalous dispersion. In this Letter we present a study of self-stabilized harmonic operation of a stretched-pulse fiber laser in a normal dispersion region. Highly periodic harmonic pulses with repetition rates of 220 MHz and average power as high as 80 mW have been achieved. The pulses have 1-ps jitter and supermode noise suppression of >75 dB and could be compressed to ~125 fs by external chirp compensation.

A schematic diagram of the experimental setup is shown in Fig. 1. Er-doped fiber (EDF) with an unpumped absorption coefficient of 55 dB/m at 1.535 μm and a group-velocity dispersion (GVD) of $+0.075 \pm 0.005$ ps^2/m at 1.55 μm is used as a gain medium. The normal dispersion of the 1.77-m EDF is partially compensated for with 4.35 m of standard single-mode fiber (SMF 28; GVD, -0.022 ps^2/m), producing a total cavity dispersion of 0.036 ps^2. Polarization additive pulse mode locking is initiated by use of wave plates, a polarization beam splitter (PBS), and an isolator, and a quartz birefringent plate ($5T$, $T = 0.512$ mm) placed at the Brewster angle allows wavelength tuning. A master oscillator power amplifier (MOPA) operating at 992 nm was used to pump the EDF through a fused wavelength-division-multiplexing (WDM) coupler made of Corning Flexcore fiber (GVD, -0.007 ps^2/m). The length of the Flexcore fiber was 23 cm and that of the free-space section was 20 cm. The fundamental cavity repetition rate was 31.52 MHz.

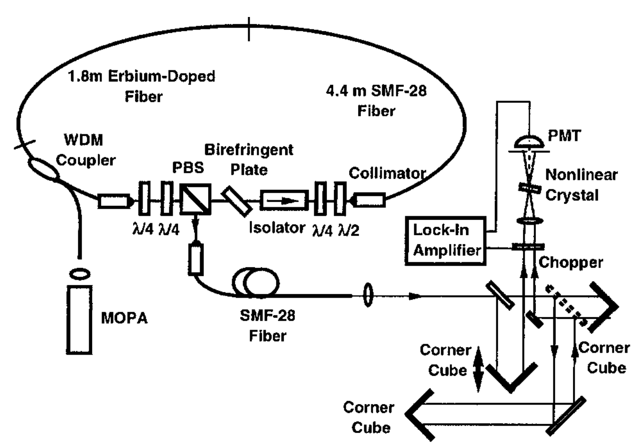

Fig. 1. Experimental setup: PMT, piezomultiplier tube; $\lambda/4$, quarter-wave plates; $\lambda/2$, half-wave plates. Other abbreviations defined in text.

For a launched pump power of 550 mW, average output powers as high as 110 mW could be obtained in cw operation. By adjustment of the wave plates, self-starting single-pulse mode locking of the laser was achieved at the fundamental cavity repetition rate. Gaussian-like pulses with widths varying from 1.7 to 1.9 ps and average output powers as high as ~96 mW were produced. For particular settings of the wave plates, it was possible to produce multiple uniformly spaced pulses. As the wave plates were adjusted initially, the high-energy pulse split into a group consisting of two to seven pulses. Next, the pulses uniformly distributed themselves over the round-trip period on a time scale of 15 s to ~1 min. Stable operation, with lower-order cavity harmonics (or supermodes) suppressed by >75 dB (repetition rates of 157.6 MHz, $N = 5$) and >70 dB (repetition rate of 220.6 MHz, $N = 7$) can be achieved, as shown in Fig. 2. For fifth-harmonic operation, we observed suppression of the fundamental cavity repetition frequency by ~80 dB. These states continued for many hours without further adjustment. For a pump power of 550 mW, average output powers as high as 82 mW [Fig. 2(c)] were demonstrated at seventh-harmonic operation. As the pump power was gradually decreased, the number of pulses in the cavity decreased in steps as a result of energy quantization effects.

Chirped pulses with widths of ~1.7 ps and spectral widths of 50 nm were obtained from the laser at seventh-harmonic operation. The pulses were chirp compensated by transmission through 2.5 to 3.0 m of standard SMF. Figure 3(a) shows the compressed pulse width measured versus fiber length, as well as the optical spectrum [Fig. 3(b)]. The minimum pulse width obtained was 125 fs, with a time–bandwidth product of 0.77. That the time–bandwidth product was much larger than the transform-limited value indicated the presence of nonlinear chirp on the laser output pulses, which occurs when cavity dispersion is rather large (>0.1 ps^2).[10]

To characterize the noise of the harmonically mode-locked laser, we performed cross correlations between successive pulses in the train, delaying one arm by the pulse period T/N (Fig. 1), where T is the round-trip time and N is the harmonic number. Figure 3(c) shows cross-correlation traces (dotted curves) of uncompensated, partially compensated, and optimally compensated pulses. The envelope of the cross-correlation trace was irregular and had a width of ~2 ps. From the scan speed of ~120 fs/s and an average separation of 50 fs between successive peaks, we conclude that the separation between successive pulses can change by ±1 ps on a time scale of 0.5 s. This slow change suggests that it can take a relatively long time for the laser to settle after perturbation, an indication that the repulsive force leading to self-stabilization is rather weak. Such a random walk of the pulse from the optimally periodic position results in the generation of supermodes in the rf spectrum. If we consider a simple picture of a train of N number of pulses where just one pulse is displaced by $\sigma \ll T/N$, the supermode suppression at the fundamental cavity frequency compared with the Nth harmonic can be expressed in decibels as $-10 \log[4 \sin^2(\pi\sigma/T)/N^2]$. For $\sigma = 1$ ps, $T = 32$ ns, and $N = 5$, we obtain a value of ~88 dB, which is reasonably close to that observed in the rf spectrum.

We did further experiments to determine the origin of the force causing self-stabilization in the laser. The force could result from dynamic gain depletion or acousto-optic interactions between pulses. We added 1 m of SMF to the cavity and measured the suppression of the fundamental cavity frequency component at fifth-harmonic operation. The fiber was shortened by 10–15 cm, and the suppression was measured again. This procedure was repeated, leading to a plot (Fig. 4) of suppression of the fundamental cavity frequency versus pulse repetition rate. Additionally, we repeated the same procedure with 1 m of dispersion-shifted fiber placed between the EDF and SMF. Suppression varied considerably as the pulse repetition rate changed. The suppression of ~84 dB near 155 MHz decreased to ~30 dB near 145 MHz. The presence of any subcavity[11] that may affect or enhance the harmonic operation as shown in Fig. 4 was not apparent. We continuously changed the cavity length of the laser (operating near 157 MHz) by

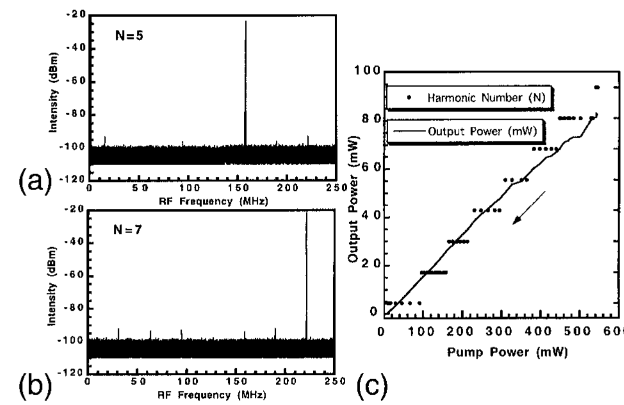

Fig. 2. Laser output: (a) rf spectra of the laser operating at the fifth and seventh harmonics of the fundamental cavity repetition rate. (b) Output power and harmonic number as a function of the pump power.

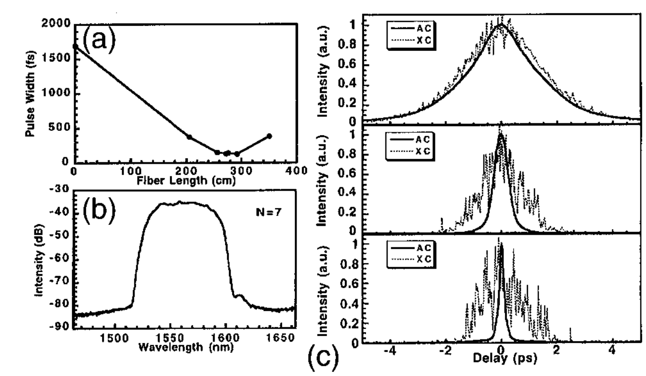

Fig. 3. Pulse characteristics: (a) pulse width as a function of length of the chirp-compensating fiber, (b) optical spectrum, (c) autocorrelation (AC) and cross correlation (XC) of the mode-locked pulses ($N = 5$) with varying degrees of external chirp compensation. Cross correlation is performed with a delay of $T/5$ (T is the fundamental cavity period).

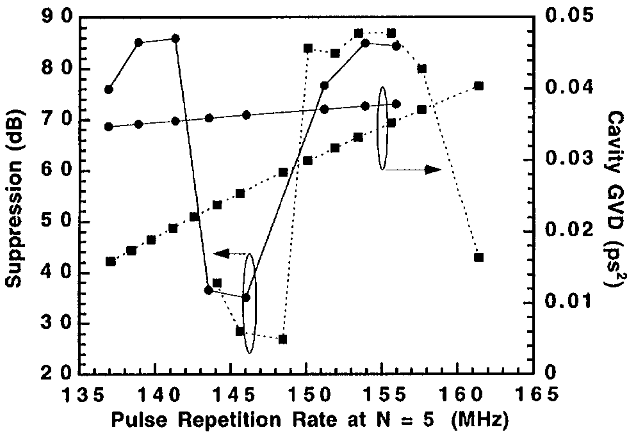

Fig. 4. Suppression of the first harmonic and the cavity GVD as a function of the repetition rate ($N = 5$) when SMFs (squares) and DSFs (circles) are added to the cavity.

moving the right collimator with a translation stage over 3 cm, and we could achieve suppression better than 80 dB within this range.

The high average output power in the laser could cause large dynamic gain depletion, leading to a self-stabilizing repulsive force. The ratio of gain depletion to the saturated gain can be expressed as $\Delta g/g = 1/\alpha = 2(P_c/A_{\text{eff}}\hbar\nu)\sigma_s(T/N)$, where P_c is the average intracavity power, A_{eff} is the optical fiber core area, $\hbar$ is Planck's constant, ν is the optical frequency, and σ_s is the emission cross section. For $P_c = \sim 150$ mW and a 157-MHz repetition rate, we obtain a value of $\sim 10^3$ for α. By adapting the theory of Kutz *et al.*[8] to nonsoliton Gaussian pulses, we derive an expression for the time constant: $2\sqrt{\pi}\,\alpha^2T^2/(\tau_0 gN)$. Using a pulse half-width at the $1/e$-intensity point, τ_0, of 1 ps, $g = 1.75$ (from 7.6-dB round-trip loss), $T = 31.8$ ns, and $N = 5$, we obtain a time constant of 6.8 min.

Our results indicate that gain saturation by itself cannot explain the self-ordering of the pulses, since stability of the ordering depends on the pulse repetition rate but not in a systematic way. Previous work on soliton lasers and lasers with net anomalous GVD[3–5] identified as one of the causes of self-ordering the excitation of acoustic waves through the electrostrictive effect. The acoustic waves excite a time-dependent index profile that changes the carrier frequency of a displaced pulse. The frequency shift translates into a timing shift that restores the pulse to its proper position. Only one sign of the index curvature is stabilizing; the other is destabilizing. If stabilization has been demonstrated for systems with net anomalous dispersion, how can one argue that the same mechanism can stabilize a laser with normal dispersion? Clearly a change in the sign of the index profile is required.

We investigated this problem using the equations developed in Refs. 12 and 13. An analysis of the acoustic waves excited by the pulses shows that the phase of the index profile is determined from the detuning of the pulse repetition rate from the spectral peak of the acoustic-wave excitation. The acoustic eigenfrequencies that correspond to the spectral peaks are identical for the EDF and SMF, which have the same cladding diameter of 125 μm. Stabilization is found in a laser with net normal dispersion at a detuning different from that of the laser with net anomalous dispersion. Recently, frequency dependence in the phase of the acousto-optic index change (with respect to the Kerr self-induced index change) was also observed in a train of periodic nonreturn-to-zero pulses in an optical transmission line.[14]

In summary, we have observed self-stabilization in a harmonic passively mode-locked stretched-pulse fiber laser and studied its characteristics. With no active modulation or optical feedback, a highly stable and periodic train of 125-fs pulses with a maximum repetition rate of 220 MHz and an average output power of ~80 mW was obtained from the laser. Supermode noise could be suppressed by more than ~75 dB, with pulse-to-pulse timing jitter of 1 ps.

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