Stable multigigahertz pulse-train formation in a short-cavity passively harmonic mode-locked erbium/ytterbium fiber laser

B. C. Collings and K. Bergman

Department of Electrical Engineering, Engineering Quadrangle, Princeton University, Princeton, New Jersey 08544

W. H. Knox

Lucent Technologies, Bell Laboratories, 101 Crawfords Corner Road, Holmdel, New Jersey 07733

Received August 20, 1997

We demonstrate a short-cavity erbium–ytterbium fiber laser that is passively mode locked by a saturable Bragg reflector with a fundamental repetition rate of 235 MHz. The laser operates in the soliton regime and under passive harmonic mode locking with 11 pulses in the cavity and produces output pulse trains at 2.6 GHz with transform-limited 270-fs pulses and 1.6 mW of average power. Within the cavity the multiple pulses form a stable pattern with fixed, nearly equal pulse-to-pulse temporal spacings, causing the output pulse train to have timing offsets of less than 15 ps. A slow gain-recovery model is proposed to explain the pulse-train self-organization. © 1998 Optical Society of America

OCIS codes: 060.2320, 140.3510, 320.0320, 190.5530, 060.2410, 060.5530.

Future high-speed and high-capacity optical networks will require sources of ultrashort pulses at ever-increasing repetition rates and output powers. Currently, many research efforts are concentrating on high-repetition-rate mode-locked erbium-doped fiber (EDF) lasers as reliable and compact sources for network transmitters in the 1550-nm spectral region. The wide optical bandwidth generated in a single mode-locked laser pulse can be partitioned into a large number of channels for wavelength-division-multiplexed applications, an approach that may be economically advantageous over employing a large bank of individually selected cw sources.[1]

In construction of a high-repetition-rate, short pulse source, selection of the mode-locking mechanism becomes crucial. Active harmonic mode locking through amplitude modulation of an EDF laser has produced picosecond pulses at a 10-GHz repetition rate.[2] Several passive mode-locking techniques have produced subpicosecond pulses[3]; these techniques include additive-pulse mode locking by use of either an external cavity or nonlinear polarization rotation,[4] saturable-absorber mode locking[5] and a combination of additive-pulse mode locking and saturable absorption.[6] Typically, these mode-locking techniques introduce a large amount of cavity loss and (or) need large intracavity powers to achieve sufficient nonlinearities for stable operation. Thus significant lengths of gain fiber are required, resulting in long cavities and low fundamental repetition rates. The semiconductor saturable Bragg reflector (SBR) has been shown to be an efficient mode-locking mechanism for extremely low-gain lasers, owing to its low saturation intensity and introduction of minimal cavity loss.[7] With a SBR, short-cavity mode-locked EDF lasers have produced 250-fs pulses at relatively high fundamental repetition rates (200 MHz).[8]

In this Letter we present a short-cavity erbium/ytterbium (Er/Yb) fiber laser that is passively mode locked with a SBR, producing 270-fs pulses at a fundamental repetition rate of 235 MHz.[9] Utilizing the soliton quantization of the total cavity energy for passive harmonic mode locking allows us to reach a repetition rate of 2.6 GHz with only 11 pulses in the cavity, a small number of pulses compared with the hundreds required by a <20-MHz fundamental-repetition-rate EDF laser.[2,6] Harmonic operation with a low number of pulses has significant advantages. Since the energy of each pulse constitutes a significant fraction of the total cavity energy and is much larger than the noise fluctuations in the total cavity energy, repetition-rate frequency hopping caused by pulse drop in–out does not occur. With no active modulation in this laser, the pulses are observed to self-organize into nearly uniformly spaced patterns with small static offsets. A model based on the slow recovery of the gain is proposed as a possible explanation for this behavior.

The linear fiber cavity consists of a 15-cm length of codoped Er/Yb single-mode fiber (SMF) fusion spliced to a 29-cm length of standard single-mode fiber as shown in Fig. 1.[8] The unspliced end of the single-mode fiber is FC connectorized, and a 99% broadband dielectric output coupler centered at 1550 nm is deposited upon the end face of the fiber and the connector ferrule. A second uncoated connector is coupled to the coated connector, allowing both output coupling and pumping of the Er/Yb fiber. A standard 1550/980-nm wavelength-division multiplexer (WDM) separates the output-coupled light from the incident light from an isolated, grating-stabilized, fiber-coupled 90-mW pump diode operating at 980 nm. The coating has >90% transmission at 980 nm. The unspliced end of the Er/Yb fiber is cleaved and butt coupled to the SBR. The structure of the SBR

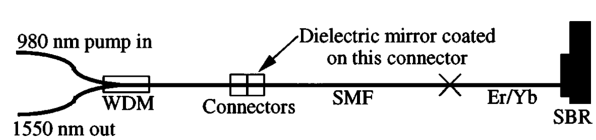

Fig. 1. Schematic of the fiber laser cavity.

0146-9592/98/020123-03$10.00/0

consists of a broadband ≥99.5% Bragg reflector centered at 1550 nm that is constructed from GaAs and AlAs quarter-wave layers and two InGaAs/InP quantum wells grown near the surface of an InP half-wave strain relief layer.[7,8,10] The Er/Yb fiber has a measured (normal) group-velocity dispersion (GVD) of −9 (ps/nm)/km, such that the cavity has an average GVD of +7.8 (ps/nm)/km in the anomalous, or soliton, regime.

Careful coupling of the SBR to the cleaved end of the Er/Yb fiber results in self-starting harmonic mode locking of the laser that is initiated and stabilized by the saturation dynamics of the SBR.[7,11] Figure 2 shows a typical background-free autocorrelation and optical spectrum of the laser output. The pulses are approximately 270 fs long (FWHM, assuming a sech^2 pulse shape), with a calculated time–bandwidth product of 0.325, indicating that the pulses are nearly transform limited, as is characteristic of a fundamental soliton pulse. For pulse-width measurements, the chirp introduced by the fiber pigtails (external to the cavity) is minimized by use of ~25 cm of dispersion-compensating fiber [GVD, −51 (ps/nm)/km]. Operating the pump diode at its maximum rated power couples approximately 60 mW of pump light into the cavity (losses are due primarily to the isolator and the dielectric coating) and produces harmonic operation with 11 pulses in the cavity and a stable 2.6-GHz output pulse train with 1.6 mW of average power. The intracavity pulses are calculated to be nearly fundamental solitons of the averaged cavity GVD and nonlinearity. Decreasing the pump power causes periodic reduction of the number of pulses in the cavity [see the inset of Fig. 3(b)], as expected for operation in the soliton regime. Because of the gain–loss and GVD considerations of this current cavity configuration, we found a practical upper limit on the fundamental repetition rate of approximately 350 MHz. For this cavity less than 1 mW of pump light reaches the SBR, and we found no evidence that this light significantly affects the dynamics of the SBR.

Since the temporal locations of the multiple pulses determine the periodicity and quality of the output pulse train, data errors will be present in systems applications if the pulses are not periodically spaced within the cavity. Furthermore, with no active modulation in the cavity to control the relative locations of the pulses, the pulses are not rigorously constrained to periodic locations. A schematic example of a pulse train with small temporal offsets is given in Fig. 3(a). For this laser the cavity harmonics in the rf spectrum of the laser's output [shown in Fig. 3(b)] at frequencies lower than the operating cavity harmonic are suppressed by only 20–50 dB, indicating that the output pulse train is not completely periodic. The temporal periods between adjacent pulses can be directly measured by cross correlation of adjacent pulses from the output pulse train (with the same frequency-doubling technique as that used for standard autocorrelation), and the magnitude of the offsets of the pulses from an ideally periodic pulse train can be determined. Typical results [shown in Fig. 3(c)] demonstrate that the offsets of the pulses can be as large as 15 ps. The unequal amplitudes in Fig. 3(c) are caused by the temporal evolution of the laser's output polarization (discussed in Ref. 12) in conjunction with the polarization sensitivity of the frequency-doubling process. For various amounts of cavity birefringence the polarization evolution ceases and the output polarization is constant.[12] Evaluation of higher rf harmonics (of 2.6 GHz) indicates a timing jitter of 10 ps, in relative agreement with the correlation measurement.[13]

Since the traces displayed in Figs. 3(b) and 3(c) are stable of the order of tens of minutes, the average temporal locations of the pulses do not fluctuate with time. However, jitter in the temporal separations between adjacent pulses in the output train can be measured with the cross-correlation technique discussed above. The magnitude of this jitter ($\Delta\tau_j$) is related to the widths of the cross-correlation and the autocorrelation peaks ($\Delta\tau_{cc}$ and $\Delta\tau_{ac}$, respectively) according to

$$\Delta\tau_{cc}^2 = \Delta\tau_j^2 + \Delta\tau_{ac}^2 .$$

The measurement shown in Fig. 3(c) required optical amplification with an EDF amplifier, resulting in the correlation of slightly chirped pulses and $\Delta\tau_{ac} = 700$ fs and $\Delta\tau_{cc} = 900$ fs. This result indicates a jitter of less than 600 fs over frequencies greater than 10 Hz (the delay-arm sweep rate). Since the gain of the cavity is small and approximately 14 dB into compression, the amount of spontaneous emission causing random optical frequency shifts and jitter is expected to be low.[14] Since no active cavity-length stabilization was implemented, this measured jitter is believed to arise from environmental fluctuations of the cavity length.

When the pump power is decreased such that the number of pulses decreases by one, the remaining pulses self-organize into a new, nearly periodic pattern with spacings that are proper for the new number of pulses. This behavior indicates the presence of a mechanism causing the pulses to become organized in this nearly periodic manner rather than in bunches or random distributions. As a possible explanation for

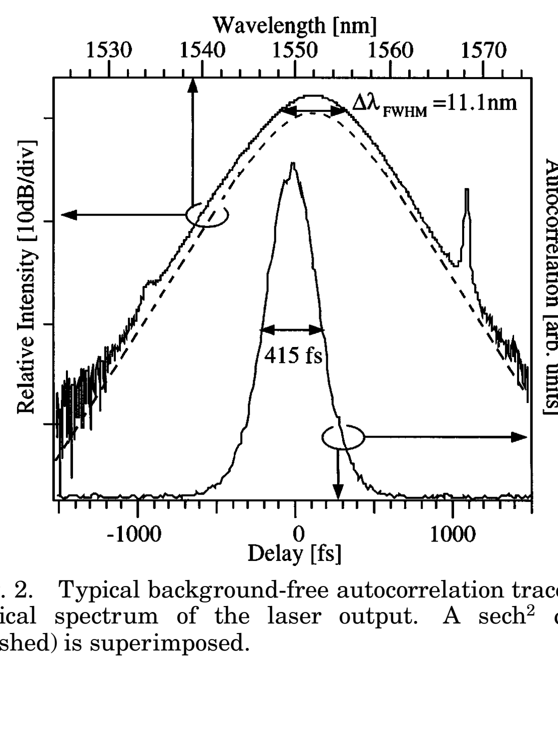

Fig. 2. Typical background-free autocorrelation trace and optical spectrum of the laser output. A sech^2 curve (dashed) is superimposed.

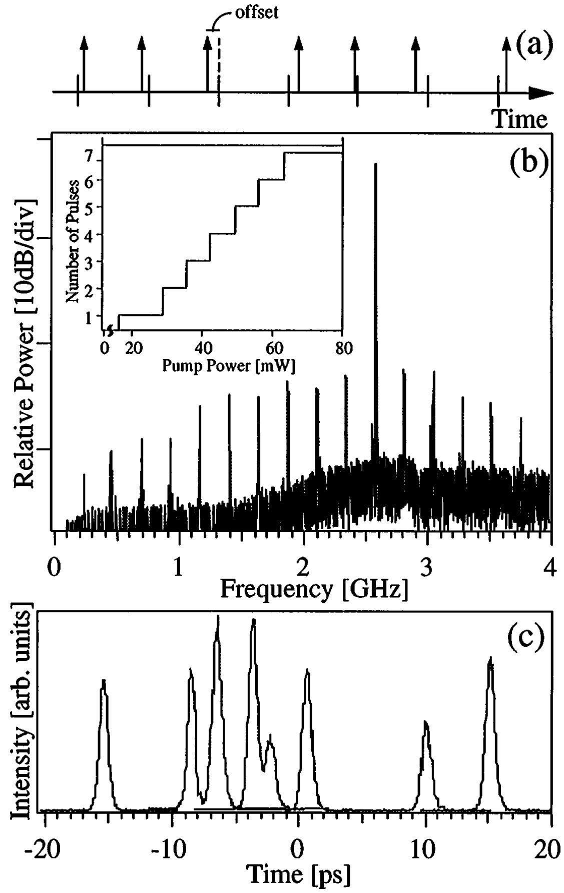

Fig. 3. (a) Example of a pulse train containing temporal offsets between the pulses and their respective locations for an ideally periodic train. (b) rf spectrum of the output with 11 pulses in the cavity. An example of the dependence of the number of circulating pulses on pump power is shown in the inset. (c) Typical cross-correlation trace of adjacent pulses, used to measure directly the periods between adjacent pulses.

this type of behavior, a model based on the recovery dynamics of a saturated gain medium has been proposed. An overview of this model is discussed here, and a complete version will be presented in the future. In general, the slight asymmetric gain experienced across a pulse imparts a small group-velocity drift to that pulse. The magnitude of this drift depends on the separation between pulses and the recovery time scale of the gain. The result is an effective repulsion force between adjacent pulses and a steady-state condition consisting of a set of equally spaced pulses. For this subtle effect to be of significance in a laser, we believe that perturbations to the pulses by the GVD, nonlinearities, gain, and losses must be low. Phase modulation effects owing to the free-carrier relaxation of the SBR are expected to be small because of the relatively short-free carrier lifetime of the SBR quantum wells (14 ps).[6]

In conclusion, we have demonstrated a short-cavity Er/Yb fiber laser that is passively harmonically mode locked, producing 270-fs transform-limited pulses at a 2.6-GHz repetition rate. The repetition rate is stable against fluctuations in cavity energy because each pulse constitutes a relatively large fraction of the total cavity energy. The multiple pulses are observed to form highly stable, nearly equally spaced patterns with measured timing offsets of less than 15 ps.

B. C. Collings and K. Bergman acknowledge support from the National Science Foundation (ECS-9502491) and the U.S. Office of Naval Research (N00014-96-0773).

References

1. L. Boivin, M. C. Nuss, W. H. Knox, and J. B. Stark, Electron. Lett. **33,** 827 (1997); T. Morioka, H. Takara, S. Kawanishi, O. Katamatani, K. Takiguchi, K. Uchiyama, M. Saruwatari, H. Takahashi, M. Yamada, T. Kanamori, and H. Ono, in *Optical Fiber Communication*, Vol. 2 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), postdeadline paper PD21.
2. T. F. Carruthers and I. N. Duling III, Opt. Lett. **21,** 1927 (1996).
3. I. N. Duling III and M. L. Dennis, *Compact Sources Of Ultrafast Pulses* (Cambridge U. Press, Cambridge, 1995).
4. H. A. Haus, E. P. Ippen, and K. Tamura, IEEE J. Quantum Electron. **30,** 200 (1994); M. E. Fermann, M. J. Andrjco, Y. Silberberg, and M. L. Stock, Opt. Lett. **18,** 894 (1993).
5. E. A. De Souza, C. E. Soccolich, W. Pleibel, R. H. Stolen, J. R. Simpson, and D. J. DiGiovanni, Electron. Lett. **29,** 447 (1993); M. Zirngibil, L. W. Stulz, J. Stone, J. Hugi, D. DiGiovanni, and P. B. Hensen, Electron Lett. **27,** 1734 (1991).
6. A. B. Grundinn and S. Gray, J. Opt. Soc. Am. B **14,** 144 (1997).
7. S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, IEEE J. Sel. Topics Quantum Electron. **2,** 454 (1996).
8. S. Tsuda, W. H. Knox, J. L. Zyskind, J. E. Cunningham, W. Y. Jan, and R. Pathak, in *Conference on Lasers and Electro-Optics*, Vol. 9 of 1996 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1996), paper CFD2; B. C. Collings, K. Bergman, S. T. Cundiff, S. Tsuda, J. N. Kutz, J. E. Cunningham, W. Y. Jan, M. Koch, and W. H. Knox, "Short cavity erbium/ytterbium fiber lasers modelocked with a saturable Bragg reflector," IEEE J. Sel. Topics Quantum Electron. (to be published).
9. B. C. Collings, S. Tsuda, W. H. Knox, and K. Bergman, in *Conference on Lasers and Electro-Optics*, Vol. 11 of 1997 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1997), paper CThH2.
10. B. C. Collings, J. B. Stark, S. Tsuda, W. H. Knox, J. E. Cunningham, W. Y. Jan, R. Pathak, and K. Bergman, Opt. Lett. **21,** 1171 (1996).
11. J. N. Kutz, B. C. Collings, K. Bergman, S. Tsuda, S. T. Cundiff, W. H. Knox, P. Holmes, and M. Weinstein, J. Opt. Soc. Am. B **14,** 2681 (1997).
12. S. T. Cundiff, B. C. Collings, and W. H. Knox, Opt. Express **1,** 12 (1997).
13. D. von de Linde, Appl. Phys. B **39,** 201 (1985).
14. S. Namiki, C. X. Yu, and H. A. Haus, J. Opt. Soc. Am. B **13,** 2817 (1996).