Additive-pulse limiting

C. R. Doerr, H. A. Haus, E. P. Ippen, M. Shirasaki, and K. Tamura

Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received June 25, 1993

When lasers with a long gain-relaxation time are actively mode locked at a harmonic of the round-trip frequency, the energy fluctuates from pulse to pulse unless stabilized. We report a new principle for pulse energy stabilization in harmonically mode-locked lasers.

Actively mode-locked lasers are important sources of pulses because the pulses can be synchronized to a master clock at high repetition rates ($\geq$1 GHz) with a high pulse quality, which is important in optical communications. A convenient source for fiber systems is the erbium-doped fiber laser, which generally has a cavity length of 1 m or greater. To obtain a high pulse repetition rate directly from such a long-cavity laser, one must mode lock the laser at a harmonic of the laser round-trip frequency with multiple pulses in the cavity.[1–5] It has been found in such cases that the pulse energies may fluctuate from pulse to pulse.[5,6] This is because the relaxation time of the erbium gain medium is much longer than the pulse spacing, and so the saturation of the gain medium cannot stabilize against such fluctuations.

The fluctuations have been stabilized by introduction of a Fabry–Perot interferometer into the laser[5] or by addition of a recirculation loop.[7] These methods reinject a fraction of each pulse to seed the next pulse and, in this way, eliminate the fluctuations. A disadvantage of both schemes is that they must be interferometrically stabilized. The fluctuations have also been suppressed by slowly varying the cavity length.[8]

In this Letter we report a new means of pulse energy stabilization that is completely passive. The scheme utilizes the principle of additive-pulse mode locking[9] (APM) but with a different function. APM uses the interference of two pulses to create, with a reactive nonlinearity, the effect of a fast saturable absorber. It has been used recently to produce short pulses with fiber lasers.[10–13] By a change in the phase of the interference, it is equally possible to produce the opposite effect: intensity limiting. This latter process invites the name additive-pulse limiting (APL). Although other nonlinear techniques have been considered previously for power limiting,[14–16] they have not been applied to the stabilization of pulse-to-pulse fluctuations in a mode-locked laser.

We demonstrate this application of APL by using nonlinear polarization rotation in a fiber laser. Figure 1 illustrates the principle. An elliptical polarization (which is the sum of two orthogonal polarization modes) will rotate in a fiber as a function of intensity. By appropriately adjusting either the birefringent elements or the polarizer, we can bias the system for increased transmission through the polarizer with increasing intensity (APM) or for decreased transmission with increasing intensity (APL).

When active mode locking at a cavity harmonic is applied to a laser with an intensity-dependent loss, there will be two distinct regimes of operation (APM and APL). Essentially, for a given amount of energy in the laser cavity, the pulse solution will be the one that experiences the least loss per round trip. When the laser is biased in the APM regime, higher-intensity pulses experience less loss, so the energy will be concentrated into only a few pulses in the cavity rather than filling all the windows of transmission created by the modulator. However, when the laser is biased in the APL regime, higher-intensity pulses experience greater loss, so the laser will minimize its pulse intensity fluctuations. As a result, the laser will oscillate with pulses of equal energy in every modulator transmission window.

A schematic of the experimental setup is shown in Fig. 2. The fiber ring of a 6.6-m length with an isolator/polarizer is mode locked by a Ti:$LiNbO_3$ Mach–Zehnder waveguide modulator. The isolator/polarizer has appropriately aligned polarization-maintaining (PM) fiber coupled to its output. The PM fiber ensures that the light enters the modulator with the proper polarization. The rest of the laser

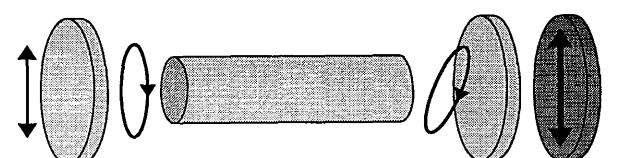

Fig. 1. Intensity-dependent transmission produced by nonlinear polarization rotation.

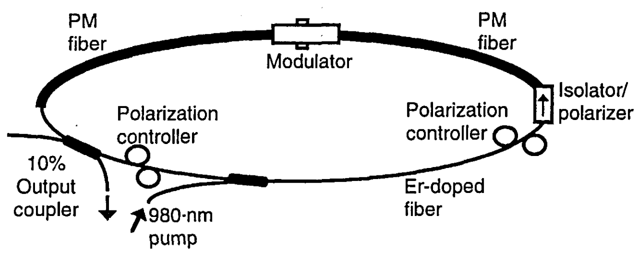

Fig. 2. Fiber laser used in the experiment.

0146-9592/94/010031-03$6.00/0

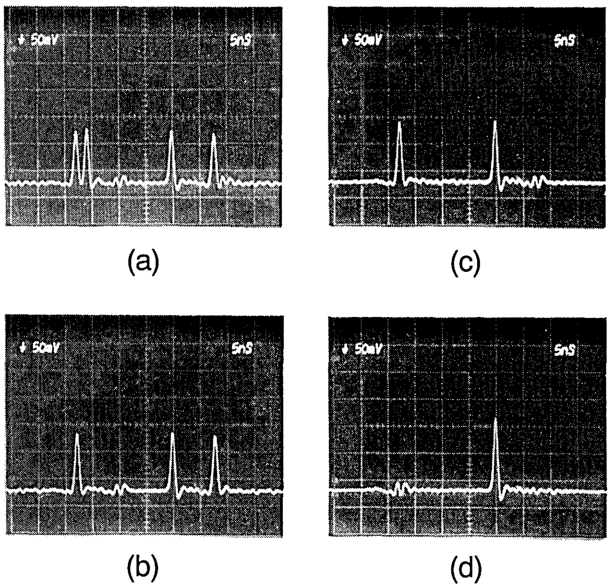

Fig. 3. APM pulse trains as the pump power was successively decreased from (a) to (d). The modulator frequency was 510 MHz (17 times the round-trip frequency). The horizontal scale is 5 ns/division.

consists of non-PM fiber, within which nonlinear polarization rotation can occur. The net dispersion of the entire ring was calculated to be 0.0 ± 0.008 ps^2. The pumping was provided by a Ti:sapphire laser operating at a wavelength of 980 nm.

When no radio-frequency power is applied to the modulator, the laser output power can be nearly extinguished by appropriate adjustment of the polarization controllers so that nearly all the light is absorbed by the isolator/polarizer. Also, the laser can be made to self-*Q* switch by appropriate adjustment of the polarization controllers. These behaviors indicate that the laser is capable of polarization APM and is near conditions of passive mode locking. The laser did not self-start, though, probably because of the high loss in the cavity. The modulator and the isolator together inflict approximately 4 dB of loss.

When a radio frequency is applied to the modulator with a frequency equal to an integer multiple of the laser round-trip frequency, the laser produces a pulse train. With the polarization controllers adjusted for APM, the laser tends to oscillate with fewer pulses than dictated by the modulator. Figure 3(a) shows an example of an APM pulse train obtained with the modulator running at 510 MHz (17 time slots in the ring). Figures 3(b)–3(d) show the same APM pulse train as the pump power is successively decreased. As one can see, the energy has gone into only a few pulses in the cavity, the number of pulses determined by the APM bias point and the pump power.

Figure 4 shows the same case as in Fig. 3 but with the polarization controllers adjusted for APL. Although the waveform resolution is limited by the bandwidth of the oscilloscope, the presence of one pulse per modulation period is apparent. Figure 5 shows an APL pulse train viewed with better resolution on a sampling scope with the modulator running at 1.05 GHz (35 pulses in the ring). The spectrum measured from the current of a fast detector of this pulse train is shown in Fig. 6. If there were large pulse-to-pulse amplitude fluctuations or missing pulses, significant subharmonic sidebands would be apparent between the 1.05-GHz harmonics. In our case, measurement of these sidebands reveals the pulse-to-pulse intensity noise to be less than 0.05%. When the pump power was reduced below the point at which APL is effective (a launched pump power of

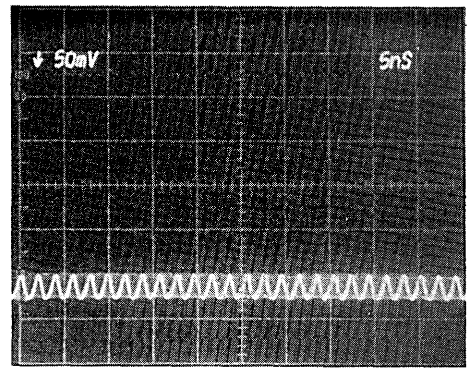

Fig. 4. APL pulse train for the same situation as in Fig. 3.

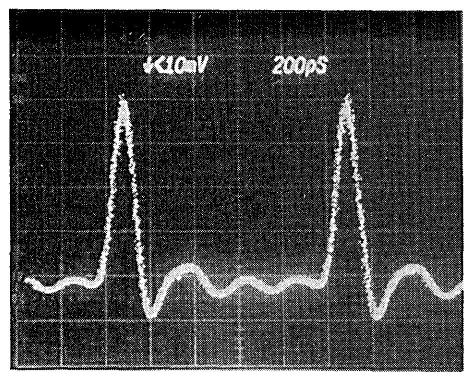

Fig. 5. 1.05-GHz APL pulse train shown on a sampling scope. The horizontal scale is 200 ps/division.

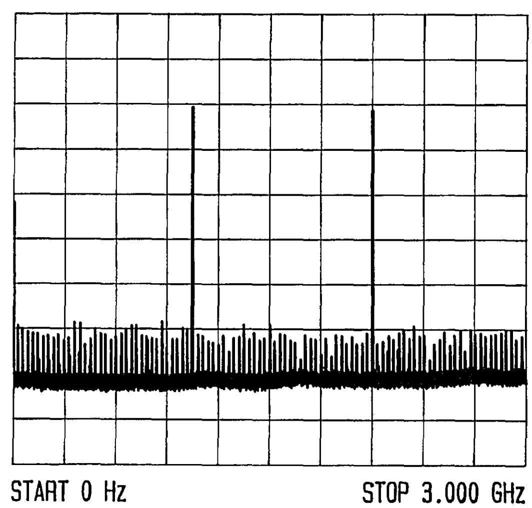

Fig. 6. Spectrum of the 1.05-GHz APL pulse train measured from the current of a fast detector. The vertical scale is 10 dB/division, and the resolution bandwidth is 300 kHz.

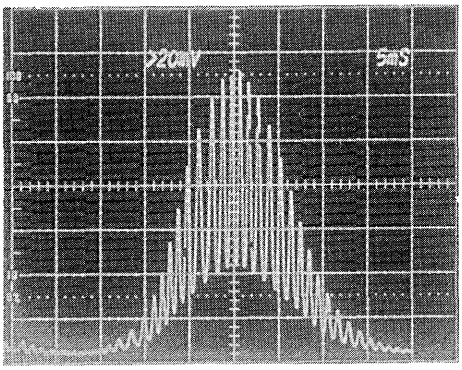

Fig. 7. 1.05-GHz APL pulse train optical spectrum measured with a scanning Fabry–Perot interferometer. The horizontal scale is 4.5 GHz/division.

220 mW with a fiber laser output of 180 μW), fluctuations increased. We achieved long-term stability of APL by placing the laser in a thermally insulated box.

In the APL case at 1.05 GHz, the pulses typically had an optical spectrum FWHM of approximately 12 GHz (see Fig. 7), although it varied from approximately 10 to 14 GHz, depending on the laser operating point. Assuming Gaussian, transform-limited pulses, the 12-GHz spectral width corresponds to pulses with an intensity FWHM of 37 ps. The peak intensities of the APL pulses were too low for effective pulse autocorrelation, but direct time-resolved measurement showed the pulses to be shorter than our detector apparatus response time of 80 ps. The APM pulses had spectra roughly twice as broad as those for the APL pulses.

The APL property of pulse-to-pulse fluctuation reduction was confirmed with a computer simulation that used the same parameters as the laser used in the experiment with the modulator running at 1 GHz. APL could be used to equalize the pulses in an initially uneven pulse train in fewer than 200 round trips, with the exact round-trip number depending on the APL bias point.

In conclusion, APL suppresses pulse-to-pulse amplitude fluctuations in harmonically mode-locked lasers with gain-relaxation times that are long compared with the pulse spacing. We have confirmed this principle experimentally with an erbium-doped fiber laser that uses nonlinear polarization rotation. Finally, we note that APL should be achievable with any fast (compared with the pulse spacing) intracavity nonlinear effect adjusted for higher loss for higher pulse energy.

This research was supported in part by the Charles Stark Draper Laboratory, Fujitsu Laboratories Ltd., Japan, the Joint Services Electronics Program under contract DAAL03-92-C-0001, and the U.S. Air Force Office of Scientific Research under contract F49620-91-C-0091. The authors are grateful to AT&T Bell Laboratories for donating the erbium-doped fiber. The authors thank L. F. Mollenauer and G. T. Harvey of Bell Laboratories and L. E. Nelson of the Massachusetts Institute of Technology for helpful discussions, K. Champagne of the Charles Stark Draper Laboratory for the fiber splicing, and P. Gavrilovic and L. Heath of Polaroid for donating 980-nm pump laser diodes.

M. Shirasaki is also with Fujitsu Laboratories Ltd., Kawasaki, Japan.

References

1. J. D. Kafka and T. Baer, Opt. Lett. **14,** 1269 (1989).
2. A. Takada and H. Miyazawa, Electron. Lett. **26,** 216 (1990).
3. X. Shan, D. Cleland, and A. Ellis, Electron. Lett. **28,** 182 (1992).
4. F. Fontana, G. Grasso, N. Manfredini, M. Romagnoli, and B. Daino, Electron. Lett. **28,** 1291 (1992).
5. G. T. Harvey and L. F. Mollenauer, Opt. Lett. **18,** 107 (1993).
6. A. E. Siegman, *Lasers* (University Science, Mill Valley, Calif., 1986), p. 1073.
7. E. Yoshida, Y. Kimura, and M. Nakazawa, Appl. Phys. Lett. **60,** 932 (1992).
8. X. Shan and D. M. Spirit, Electron. Lett. **29,** 979 (1993).
9. E. P. Ippen, H. A. Haus, and L. Y. Liu, J. Opt. Soc. Am. B **6,** 1736 (1989).
10. I. N. Duling III, Electron. Lett. **27,** 544 (1991).
11. M. Hofer, M. E. Fermann, F. Haberl, M. H. Ober, and A. J. Schmidt, Opt. Lett. **16,** 502 (1991).
12. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. N. Payne, Electron. Lett. **28,** 1391 (1992).
13. K. Tamura, H. A. Haus, and E. P. Ippen, Electron. Lett. **28,** 2226 (1992).
14. A. Hordvik, IEEE J. Quantum Electron. **QE-6,** 199 (1970).
15. D. J. Harter, M. L. Shand, and Y. B. Band, J. Appl. Phys. **56,** 865 (1984).
16. E. W. Van Stryland, Y. Y. Wu, D. J. Hagan, M. J. Soileau, and K. Mansour, J. Opt. Soc. Am. B **5,** 1980 (1988).