

Cladding-pumped passive harmonically mode-locked fiber laser

M. E. Fermann

IMRA America, Inc., 1044 Woodridge Avenue, Ann Arbor, Michigan 48105

J. D. Minelly

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

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A passive harmonically mode-locked fiber laser cladding pumped by a broad-area diode-laser array is described. Harmonic mode locking is obtained in a frequency range from 33.3 to 128.6 MHz, where the higher frequency limit is imposed because of insufficient available pump power. The maximum pulse jitter in one cavity round-trip time is between 300 and 50 ps in the whole frequency range, and the sidebands in the frequency domain are suppressed by as much as 50 dB. 600-fs bandwidth-limited pulses with pulse energies of as much as 20 pJ are obtained, giving rise to an average output power as great as 2.5 mW. © 1996 Optical Society of America

Applications of passively mode-locked fiber lasers^{1,2} in instrumentation and sensing would greatly benefit from the availability of high-average powers or high repetition rates. Unfortunately, particularly erbium fiber lasers typically suffer from strict limitations in both of these areas because of the long erbium fiber lengths that have to be used in the fiber cavities. Although the incorporation of chirped fiber gratings into fiber oscillators can overcome the power limitations³ (at the cost of an increase in pulse width), the limitations in repetition rate still prevail. The same holds for fiber systems based on chirped-pulse amplification,⁴ which also add a lot of complexity to the laser system.

A partial solution to these problems was recently suggested by Grudinin *et al.*,⁵ who discovered that soliton interactions can make possible stable passive harmonic mode locking in fiber lasers. As Grudinin postulated originally, it is now generally believed^{6,7} that long-lived acousto-optic interactions can lead to soliton repulsion between the pulses in a fiber laser; in turn this leads to the buildup of a stable harmonically mode-locked pulse train within a time period of a few tens of milliseconds to a few seconds. Recently Gray and Grudinin suggested⁸ that a similar effect can also be obtained from phase effects in saturable absorbers, i.e., the decay of the free carriers in the absorber excited by an optical pulse leads to a phase modulation, which leads to pulse repulsion in negative dispersion fiber.

As harmonically mode-locked lasers require large pump powers for their operation, the early research in this area relied on bulk high-power solid-state pump lasers. We show here that one can eliminate the need for solid-state pump lasers by incorporating double-clad fibers⁹ into the oscillator. As a result the whole system can be cladding pumped with low-cost diode-array lasers. An optimized laser system should eventually permit the generation of average output powers of several tens of milliwatts at repetition rates in excess of 1 GHz.

The experimental setup for a cladding-pumped passive harmonically mode-locked fiber oscillator is shown in Fig. 1. For the gain medium we used a single 4-m length of Er³⁺-doped fiber sensitized by Yb³⁺ (Ref. 10) to permit pumping of the Er³⁺ through energy transfer from Yb³⁺; the details of the fiber design were described in Ref. 11. As in Ref. 7 we found empirically that it is advantageous to operate harmonically mode-locked fiber lasers at fundamental cavity round-trip times of ~100 ns. We therefore added a length of 6.6 m of undoped Corning SMF-28 fiber to the cavity. As a 0.6-m length of undoped Corning DC-fiber (positive dispersion fiber) was also part of the cavity, the total cavity round-trip time was 120 ns, giving a fundamental pulse-repetition rate of 8.33 MHz. The round-trip dispersion of the cavity was estimated to be $D_2 = -0.26 \text{ ps}^2$.

The active fiber was pumped through a dichroic mirror with a standard 1-W, 100 μm × 1 μm broad-area diode array operating at 973 nm. Using an imaging system with a magnification of 1×, we ob-

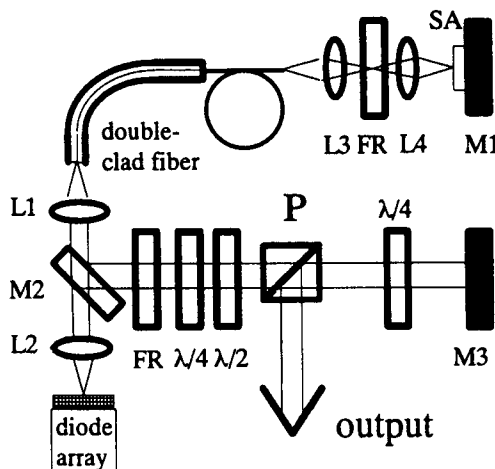


Fig. 1. Setup of a harmonically mode-locked cladding-pumped fiber laser: SA, saturable absorber; L1–L3, lenses; M1–M3, mirrors; P, polarizer; FR, Faraday rotator.

tained a coupling efficiency of as much as 60% into the inner cladding of the active fiber. As in Ref. 11, we used nonlinear polarization evolution as the steady-state mode-locking mechanism,¹² and we used a cavity design with two Faraday rotators¹³ to ensure the environmental stability of the system. For pulse start-up and to make possible soliton repulsion in the cavity, we used a saturable absorber with a measured carrier lifetime of 15 ns and a saturation energy density of $\approx 20 \text{ J/m}^2$. The focal-spot diameter on the saturable absorber was $5 \mu\text{m}$. For experimental convenience the absorber was located at the end opposite the pump. Because of the large number of intracavity elements and the relatively inefficient fiber, we obtained a maximum cw output power of only 7.5 mW from the laser. Under mode-locked operation, the maximum output power was 2.5 mW. At a maximum pulse-repetition rate of 128.6 MHz this corresponds to a pulse energy of 20 pJ.

The number of pulses in the cavity (#pc) measured when the pump current is upramped and downramped is shown in Fig. 2. In this figure a pump current of 1400 mA corresponds to a launched pump power of $\approx 500 \text{ mW}$. Note that in this experiment the pump power was upramped and downramped by hand, and care was taken not to miss a stability regime for a certain #pc. A significant amount of hysteresis is observed between upramping and downramping of the pump power. Whereas in upramping the laser occasionally adds more than one pulse to the cavity from the previous #pc, in downramping the #pc drops reliably one by one (at least for these relatively low #pc). This indicates that the lower stability limit for a certain #pc is better defined.

Furthermore, when we ramped the pump power quickly (by switching on the laser diode), a higher #pc was typically obtained compared with the #pc obtained with a slow ramp speed. At least for these relatively low #pc, the #pc was a very reproducible function of both pump power and ramp speed. Some long-term drift may not be excluded, however, because of the presence of the relatively long length of low-birefringence fiber.

Typically the lower pulse jitter was obtained in the middle of each stability plateau, and a pulse jitter of less than 300 ps was obtained for all frequencies $\geq 33 \text{ MHz}$. A decrease in pulse jitter was observed with an increase in repetition rate, and a pulse jitter as low as 50–100 ps (as observed on a gigahertz oscilloscope) was obtained at a pulse rate of $\sim 100 \text{ MHz}$. As the dominant pulse jitter in a passive harmonically mode-locked laser is in fact the uncertainty in the positioning of the pulses within one cavity round-trip time, the pulse jitter shows up as sidebands in the rf spectrum at the fundamental cavity frequency. For a pulse jitter of less than 100 ps, we indeed obtained a sideband suppression of $\geq 50 \text{ dB}$, as shown in Fig. 3. Typically, the pulse jitter decreased with a decrease in intracavity loss, and indeed we recently observed a sideband suppression of $> 70 \text{ dB}$ for fiber cavities with minimized intracavity loss.

A typical pulse spectrum is shown in Fig. 4. The sideband instability is characteristic of soliton lasers,¹⁴ as is the case here. From the spectral width

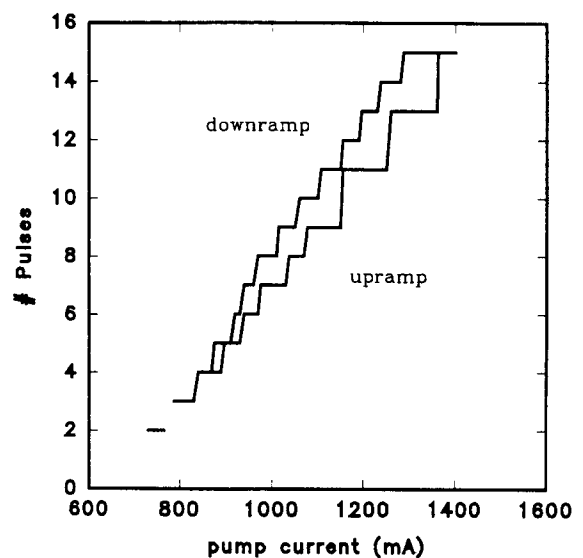


Fig. 2. Number of pulses in the cavity as a function of slow upramping and downramping of pump current.

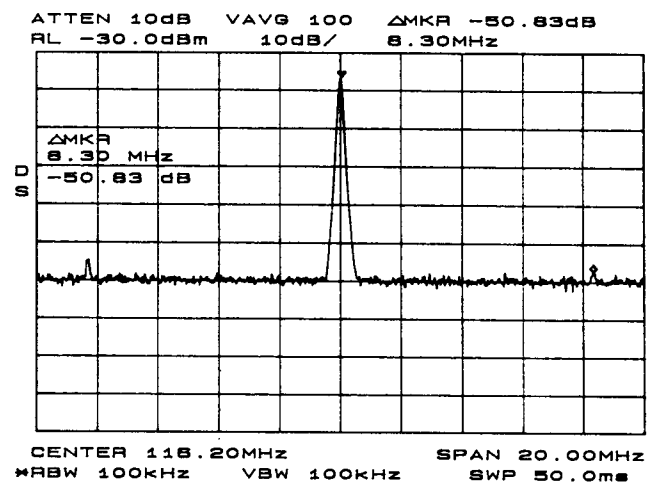


Fig. 3. Rf spectrum for a harmonically mode-locked laser operating with 14 pulses in the cavity. The rf sidebands are suppressed by more than 50 dB.

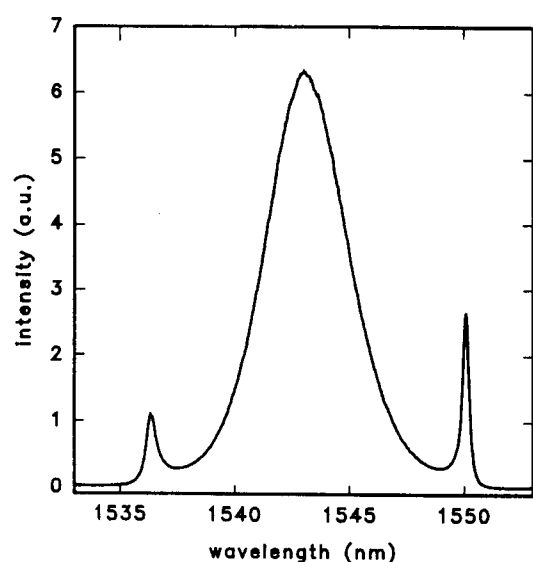


Fig. 4. Pulse spectrum for a harmonically mode-locked fiber laser.

of the pulses we can estimate the FWHM pulse width as ≈ 600 fs. Pulses with widths between 200 and 300 fs could be easily obtained with an increase in the length of the positive dispersion fiber in the cavity.

By using identical, albeit radiation-treated, absorbers with lifetimes of 500 ps and also 5 ns, we verified that indeed the saturable absorber is dominantly responsible for self-organization. Whereas self-organization of the pulses could be observed for the absorber with a carrier lifetime of 5 ns, the pulse jitter never decreased to less than 1 ns. On the other hand no uniform pulse distribution was ever observed for the sample with a carrier lifetime of 500 ps; rather, the pulses were distributed in random bunches.⁶ Part of the reason for this behavior is, of course, also the presence of intracavity reflections (and intramode scattering) in (double-clad) Fabry-Perot cavities,¹¹ which tend to inhibit self-organization.

The repulsive forces between the pulses are very sensitive to amplitude fluctuations in the cavity, and our experiments indicate that the presence of repulsive forces alone is not sufficient to explain the low values of pulse jitter that are obtainable. Indeed we have found that the buildup of a stable amplitude train is ensured by the presence of optical limiting in the cavity.¹⁵ Here we varied the pump power to the laser and measured the pulse energy transmitted and rejected at the intracavity polarizer. Whereas a variation of the applied pump power led to corresponding variations in the rejected pulse energy at the polarizer, the transmitted pulse energy stayed nearly constant; i.e., a variation of the rejected pulse energy by $\pm 50\%$ was accompanied by a variation in the transmitted pulse energy by less than $\pm 5\%$. Hence, to obtain low-jitter passive harmonic mode locking, the exploitation of Kerr-effect-induced amplitude shaping seems to be highly desirable.

Finally, let us discuss the prospect of cladding-pumped fiber lasers operating at higher repetition rates with higher average powers. Apart from a reduction of the intracavity losses, it should be possible to increase the output power by use of double-clad fibers with larger primary claddings, which would permit the use of broader, higher-power pump diodes. Note that the use of larger primary claddings should also reduce intramodal scattering at any fiber discontinuities, which tend to inhibit strongly the mode-locked operation of double-clad fibers.¹¹ Therefore pulse-repetition

rates of several gigahertz with corresponding cw output powers of several tens of milliwatts seem very feasible. Higher repetition rates will also further reduce the pulse jitter.

In conclusion, we have demonstrated passive harmonic mode locking in a double-clad fiber laser for the first time to our knowledge. The double-clad fiber structure permits the use of high-power diode-array pump lasers. The cavity design should eventually permit the generation of pulse trains at gigahertz repetition rates with average output powers of several tens of milliwatts.

Note added in proof: We recently obtained output powers as great as 20 mW and repetition rates of as much as 400 MHz from laser systems similar to those described above.

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