Stabilization of actively mode-locked Er-doped fiber lasers in the rational-harmonic frequency-doubling mode-locking regime

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Stabilization of an actively mode-locked fiber laser in the frequency-doubling rational-harmonic mode-locking regime is demonstrated experimentally for the first time to the authors' knowledge. The stabilization is achieved by a method based on minimization of the average optical power at the second output of a dual-output Mach–Zehnder modulator used as a mode locker. This method produces long-term stable operation of the laser with ~35-dB suppression of the pulse-to-pulse amplitude fluctuation caused by rational-harmonic frequency doubling. © 1999 Optical Society of America

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Actively mode-locked Er-doped fiber lasers are attractive sources of picosecond pulses in the gigahertz region.[1–5] The high repetition rate of the pulse train generated by actively mode-locked fiber lasers is achieved through the well-known technique of harmonic mode locking[1] and rational-harmonic mode locking (RHML).[4] For harmonic mode locking the laser cavity loss is modulated at a frequency equal to $p\Delta f$, where Δf is the free spectral range (FSR) of the laser cavity and p is an integer. A harmonically mode-locked laser generates a pulse train with a repetition rate equal to the modulation frequency. An optical pulse train with a repetition rate of $(np \pm 1)\Delta f$ can be produced by a rational-harmonic mode-locked fiber laser when the modulation frequency is equal to $(p \pm 1/n)\Delta f$, where n is an integer. An important advantage of the RHML technique is its ability to generate a pulse train with a repetition rate significantly higher than the modulation frequency. Unfortunately, an inherent drawback of RHML with the multiplication factor $n \geq 3$ is a strong pulse-to-pulse amplitude fluctuation caused by the unmatched harmonics of the modulation frequency.[5] Such a fluctuation can be eliminated only by special pulse amplitude equalization techniques[6,7] that involve optical nonlinearities, and therefore are rather complicated, intrinsically set a limit on the maximal repetition rate through the available pump power, or both. However, frequency doubling ($n = 2$) by RHML does not suffer from this drawback and, for this reason, is more attractive for applications. As was demonstrated in Ref. 5, a stable low-noise optical pulse train without pulse dropout or pulse-to-pulse amplitude fluctuation can be generated by frequency-doubling RHML, provided that the modulation frequency is adjusted with high precision to $(p \pm 1/2)\Delta f$. However, the length and consequently the FSR of the laser cavity are influenced by environmental perturbations. For this reason, a stabilization scheme that compensates for detuning of the laser cavity length is required.

Several stabilization methods have been demonstrated for fiber lasers that operate in the harmonic mode-locking regime. They rely on locking the pulse phase with that of the drive source,[2] suppressing the relaxation oscillation rf power of the laser output,[8] or detecting the differential noise increases at the relaxation oscillation frequency and the supermode beat frequency.[9] Harmonic regenerative mode locking by feedback of the harmonic longitudinal beat signal was also demonstrated.[3] Recently we demonstrated a novel and simple stabilization method for fiber lasers operating in harmonic mode-locking regime that is based on minimization of the average interpulse noise power.[10]

In the case of frequency-doubling RHML the repetition rate of the pulses is not equal to the modulation frequency and does not match an integer multiple of the laser cavity FSR. Because of this fundamental difference from harmonic mode locking, the applicability of the stabilization methods mentioned above to frequency-doubling RHML will be questionable until it is experimentally demonstrated. To the best of our knowledge, stabilization of fiber lasers operating in the RHML regime had not been reported. In this Letter we demonstrate, for the first time to our knowledge, stabilization of an actively mode-locked fiber laser in the frequency-doubling RHML regime.

The experimental configuration of the actively mode-locked fiber laser with the stabilization scheme is shown in Fig. 1. The laser is fabricated in a σ configuration.[11] This is the same σ laser that was previously used to demonstrate the stabilization in the harmonic mode-locking regime.[10] The 20-m-long Er-doped fiber [440 parts in 10^6 (ppm)] is placed in the single-mode (SM) part of the σ laser and pumped by a 980-nm laser diode. To compensate for the high normal dispersion of the Er-doped fiber [~−50 ps/(nm km)], we insert a 29-m piece of standard SM fiber into the SM part of the cavity. Part of the dispersion-compensating fiber is wound around a piezo drum that is used to tune the cavity length. A 3-nm FWHM bandwidth-tunable optical filter is tuned to run the laser at ~1540 nm. The mode locker is a lithium niobate dual-output intensity Mach–Zehnder

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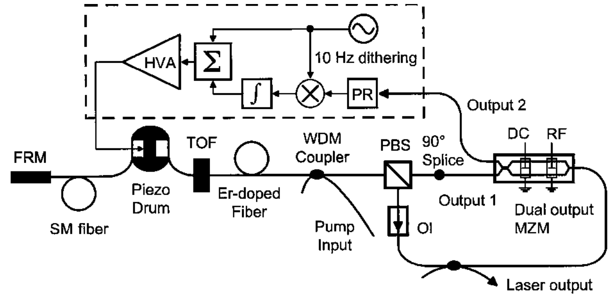

Fig. 1. Actively mode-locked Er-doped fiber σ laser and stabilization scheme: PR, narrow-band photoreceiver; PBS, polarization beam splitter; FRM, Faraday rotation mirror; OI, optical isolator; TOF, tunable optical filter; HVA, high-voltage amplifier; WDM, wavelength-division multiplexing.

modulator (MZM) with an insertion loss of ~3 dB and a 3-dB bandwidth of ~3 GHz. The MZM is operated in the linear part of its modulation characteristic.

If the laser operates in the harmonic mode-locking regime, the principle of stabilization is rather clear, as explained in Ref. 10. In this case the modulation frequency is approximately equal (ideally equal) to an integer multiple of the laser cavity FSR, and the pulse repetition rate is the same as the modulation frequency. Therefore the average optical power at the MZM second output represents the average interpulse noise power, which is minimal if the modulation frequency is exactly an integer multiple of the laser cavity FSR.[10] Thus for stabilization of a harmonically mode-locked laser the average optical power at the MZM second output must be minimized. However, for RHML the average optical power at the MZM second output no longer represents pure interpulse noise power, and it is not evident that the stabilization method is also applicable if the laser operates in the RHML regime. Indeed, in the case of RHML with a repetition rate multiplied by a factor n, each pulse circulating in the cavity is completely switched to the first MZM output only once every n round trips.[4] At every other $(n - 1)$ round trip the pulses make a considerable contribution to the MZM second output. Nevertheless, we demonstrate here that in the case of frequency-doubling RHML the average optical power at the MZM second output is still a good index of the laser cavity length detuning.

The detuning characteristic of the average optical power at the MZM second output is shown in Fig. 2. We obtained this characteristic by changing the modulation frequency f_M at a fixed cavity length. Because the detuning characteristic is a periodic function of the modulation frequency with the period equal to the FSR of the laser cavity, the measurements were performed only for the modulation frequency range that coincided with the FSR. The deepest minima [marked (1) in Fig. 2] appear at the modulation frequencies that satisfy the condition $f_M = p\Delta f$ and correspond to harmonic mode locking. Other minima [(2), (3), and (4)] in the detuning characteristic are numbered in order of depth decrease. These minima appear at the modulation frequencies that satisfy the conditions $f_M = (p \pm 1/2)\Delta f$, $f_M = (p \pm 1/3)\Delta f$, and $f_M = (p \pm 1/4)\Delta f$ and correspond to frequency doubling, tripling, and quadrupling RHML, respectively. The laser output was detected by a 25-GHz photoreceiver and monitored by a 20-GHz sampling oscilloscope and a 25-GHz rf spectrum analyzer. When the modulation frequency was tuned to minima (1), (2), (3), or (4), typical oscilloscope traces and rf spectra corresponding to harmonic mode locking and to frequency doubling, tripling, and quadrupling RHML, respectively, were observed. We were not able to achieve effective RHML with a multiplication factor higher than 4 and did not observe corresponding minima in the detuning characteristic. We believe that these minima are too shallow to be resolved in the experiment. The decrease of the minimum depth with increase of the RHML multiplication factor n is in agreement with the model of RHML presented in Ref. 4. As we mentioned above, in accordance with this model the residual optical power at the RHML minima results from the contribution of the pulses to the MZM second output that occurs at $(n - 1)$ round trips of every n round trips. Therefore the contribution of the pulses to the MZM second output and the residual optical power at the RHML minima is higher for higher n.

When the modulation frequency was tuned to run the laser in the frequency-doubling RHML regime ($f_M \approx 3.00141$ GHz), a 6.00282-GHz pulse train was generated. The average optical power at the laser output was ~1.5 mW. The FWHM pulse width, estimated by Gaussian fitting of the second-harmonic generation autocorrelation trace, was ~13.5 ps. The FWHM optical bandwidth measured by an optical spectrum analyzer was ~0.28 nm and yielded a time–bandwidth product of ~0.47. The pulse width and the time–bandwidth product were not influenced by the pump power. We believe that there was no average soliton formation in the cavity. The dependencies of the average optical power at the MZM second output, of the pulse width, and of the difference between rf powers of the f_M and $2f_M$ frequency components in the rf spectrum of the laser output on laser cavity length detuning were measured simultaneously. For these measurements the modulation frequency was fixed ($f_M \approx 3.00141$ GHz) and the cavity

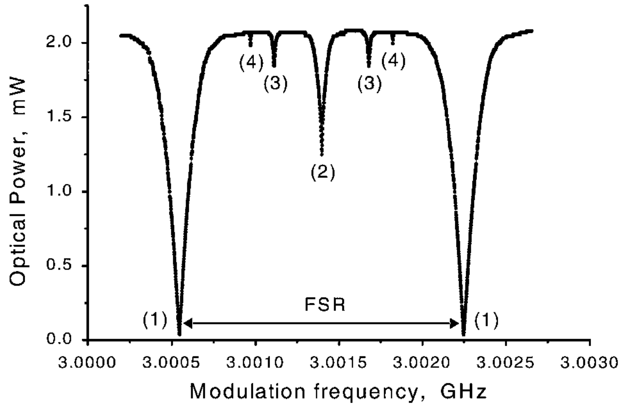

Fig. 2. Detuning characteristic of the average optical power at the MZM second output. The FSR is ~1.704 MHz.

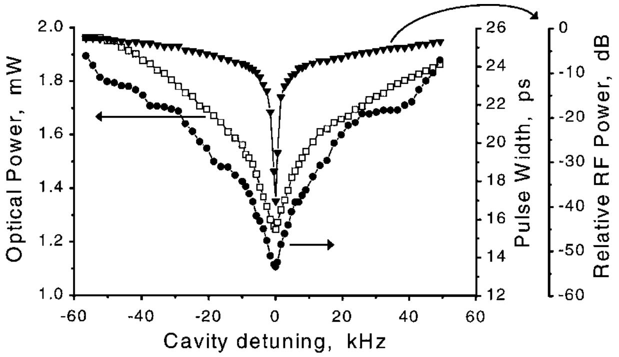

Fig. 3. Dependencies of the average optical power at the MZM second output (open squares), the pulse width (filled circles), and the difference between rf powers of the f_M and $2f_M$ frequency components (filled triangles) on laser cavity detuning.

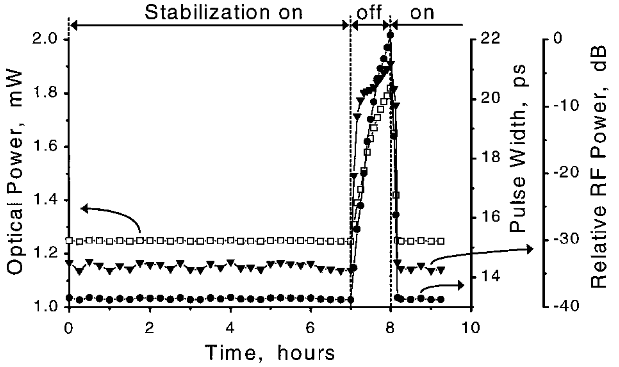

Fig. 4. Long-term temporal evolution of the average optical power at the MZM second output (open squares), the pulse width (filled circles), and the difference between rf powers of the f_M and $2f_M$ frequency components (filled triangles).

length was changed by the piezo drum. All dependencies are shown in Fig. 3. The cavity length detuning is recalculated in the corresponding frequency detuning. Zero frequency detuning corresponds to the cavity length that provides generation of the shortest pulses. Figure 3 demonstrates that the optical power measured at the MZM second output is a good index of the laser cavity length detuning. Indeed, minimal pulse width, best suppression of the f_M component in the rf spectrum of the laser output, and minimal optical power at the MZM second output are achieved simultaneously. This means that optical power at the MZM second output is minimal when perfect frequency-doubling RHML is achieved. To stabilize the laser in the frequency-doubling RHML regime one should keep the optical power at the MZM second output at the corresponding minimum of the detuning characteristic by controlling the laser cavity length.

For experimental demonstration of this stabilization principle, a simple feedback loop was constructed. To generate the error signal that is related to both direction and magnitude of laser cavity detuning, we applied a 10-Hz small-amplitude dithering signal to the piezo drum. Intensity modulation of the average optical power at the MZM second output produced by dithering of the laser cavity is detected by a 1-kHz-bandwidth photoreceiver. Its 10-Hz component is converted through phase-sensitive detection into an error signal. The error signal is integrated and summed with the dithering signal. The resultant signal is amplified by a high-voltage amplifier and applied to the piezo drum.

Figure 4 demonstrates the long-term stable operation of the laser in the frequency-doubling RHML regime that was achieved with this stabilization scheme. The stabilization was turned on for 6 h, and a stable pulse train with a pulse width of ~13.5 ps was generated during that time. The ≈35-dB suppression of the unmatched f_M frequency component demonstrated in Fig. 4 confirms that pulse-to-pulse amplitude fluctuation caused by the rational-harmonic frequency-doubling mechanism is strongly suppressed by the stabilization scheme. Moreover, the rf spectra of the pulse trains showed that relaxation oscillation noise was completely suppressed and supermode beat noise was ~50 dB below the $2f_M$ frequency component, at the same level as for the optimally tuned laser without stabilization. After 6 h the stabilization was turned off (the voltage at the piezo drum was fixed at a constant level) and, consequently, the average optical power at the MZM second output, the f_M frequency component in the rf spectrum of the laser output, and the pulse width increased. When stabilization was turned on again, the laser returned to the stable operation.

In conclusion, we have demonstrated, for the first time to our knowledge, the long-term stabilization of an actively mode-locked Er-doped fiber laser in the frequency-doubling rational-harmonic mode-locking regime.

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