Complete suppression of the pulse-to-pulse amplitude fluctuations in pulse train generated by rational harmonic repetition rate doubling actively mode-locked Er-doped fibre lasers

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We demonstrate experimentally that pulse-to-pulse amplitude fluctuations are completely suppressed in pulse train generated by rational harmonic repetition rate doubling actively mode-locked Er-doped fibre laser if modulation frequency is properly tuned. Irregularity of the pulse position in the train is found to be the only drawback of this regime. A theoretical model is developed to explain the experimental results. We obtain analytical expressions for pulse train parameters and derive stability conditions for rational harmonic repetition rate doubling pulse train. We found that the irregularity could be reduced to value acceptable for applications by increasing the bandwidth of the optical filter installed in the laser cavity.

Introduction

Rational harmonic mode locking (RHML) is attractive for its potential to multiply the repetition rate of the pulse train generated by actively mode-locked Er-doped fiber lasers [1]. The best pulse train quality was obtained in repetition-rate-doubling (RRD) RHML regime. Indeed, in RRD-RHML regime, about 35 dB suppression of an unmatched component at the modulation frequency f_M in the radio-frequency (RF) spectrum of the pulse train was observed experimentally [2] when the modulation frequency detuning, $\delta f_M = f_M / f_{FSR} - n - 1/2$, was equal to zero (f_{FSR} is the free spectral range of the laser cavity, n is an integer). However, the nature of the f_M - component is not completely elucidated and ultimate limitations on the parameters of the pulse train in RRD-RHML regime are not determined.

In this paper, a detailed experimental and theoretical investigation of the parameters of the pulse train in RRD-RHML regime of Er-doped fiber lasers is presented. For the reason of clarity we consider the case of a dispersion-compensated laser cavity and we do not take into account Kerr nonlinearity in the optical fiber.

Theory

For theoretical analysis we consider an actively mode-locked fiber laser in unidirectional ring configuration. The laser cavity is formed by Mach-Zehnder modulator (MZM) followed by output coupler, Fabry-Perot filter (FPF) and Er-doped fiber as amplification medium. All elements are connected by optical fiber to form a ring. The cavity dispersion is compensated. The saturated gain of the Er-doped fiber is assumed to be equal to intracavity loss, spectrally flat within the FPF's transmission bandwidth and time independent. The parameters of the FPF are optical frequency at maximal transmission of the FPF ν_0, FPF's free spectral range ν_{FSR}, FPF's FWHM bandwidth

$\Delta\nu$ and finesse $k_F = \nu_{FSR}/\Delta\nu$. The time dependent transfer function of the MZM is $M(t) = M_0 \sin(\psi_0 + \pi R \sin(\theta))$, where $\theta = 2\pi f_M t$ is normalized time, M_0 is MZM's maximal transmission, ψ_0 is the phase factor, $R = V_M / V_\pi$, V_π is π–voltage of the MZM, V_M is amplitude of the modulation voltage. For RRD-RHML, two conditions must be satisfied: $0 \le \psi_0 \le \pi/2$ and $0 \le \pi R \le \min(\psi_0;\ \pi/2 - \psi_0)$.
For analysis of RRD-RHML, Kuizenga and Siegman's theory [3] is applied, assuming a Gaussian pulse circulating inside the laser cavity. Both MZM's transmission in time and FPF's transmission in frequency are approximated by Gaussian functions using quadratic expansions. A self-consistent steady-state solution is obtained after two complete cavity round-trips. For two sequential cavity round-trips, electrical field of the optical pulse at MZM's output is expressed in the following form: $E_m(t) = E_{0m} \exp(2\pi i \nu_0 (t - t_m)) \exp(-2\ln 2 (t - t_m)^2 / \tau_m^2)$ where $m = 1, 2$ corresponds to the first and the second cavity round-trips, E_{0m} is the complex amplitude of the pulse, t_m is the temporal position of the pulse peak and τ_m is the FWHM pulse width. Normalized time $\theta_0 = \pi\left((t_2 + t_1)/T_M - n - 1/2\right)$ is introduced that represents temporal position of the middle point between pulse positions at the first and the second round trips. Temporal shift of the pulse from this middle point is described by dimensionless parameter $\Delta\theta = \pi\left((t_2 - t_1)/T_M - n - 1/2\right)$. Pulse-to-pulse amplitude fluctuation is characterized by the parameter $\delta I = \left(|E_{02}|^2 - |E_{01}|^2\right) / \left(|E_{02}|^2 + |E_{01}|^2\right)$. Simple analytical expressions can be obtained in first order on small parameter $k = f_M / \Delta\nu$ for pulse train parameters at the MZM output, namely:

$$\Delta\theta = -(\pi k / k_S)\ R\ \sin(2\psi_0)\ \cos(\theta_0) / \left(2 a \sqrt{\alpha_{M12}}\right) \tag{1}$$

$$\delta I = -\ ctg(\psi_0)\ tg(\pi R \sin(\theta_0))\ \left(1 - k \pi^2 R^2 \cos^2(\theta_0) / \left(k_S\ a \sqrt{\alpha_{M12}}\right)\right) \tag{2}$$

$$\tau_m = \frac{1}{\pi} \sqrt{\frac{2\ln 2}{k_S\ f_M\ \Delta\nu \sqrt{\alpha_{M12}}}} \left(1 - \frac{k}{k_S} \frac{\alpha_{Mm}}{\sqrt{\alpha_{M12}}}\right) \tag{3}$$

where $k_S = 2 k_F \sin(\pi / 2 k_F) / \pi$, $a = M(\theta_0) M(\theta_0 + \pi) / M_0^2$, $\alpha_{M12} = \alpha_{M1} + \alpha_{M2}$, $\alpha_{M1} = \alpha_M(\theta_0)$, $\alpha_{M2} = \alpha_M(\theta_0 + \pi)$, $\alpha_M = -(1/2)\left(d^2 \ln(M(\theta)) / d\theta^2\right)$. Temporal parameter θ_0 can be calculated from the following transcendental equation:

$$k_S\ \delta\ f_M / k = R\ \cos(\theta_0)\ \sin(2\pi R \sin(\theta_0)) / \left(2 a \sqrt{\alpha_{M12}}\right) \tag{4}$$

Stability condition for RRD-RHML pulse $\alpha_{M12}(\theta_0) > 0$ could be obtained by linear stability analysis. This condition is satisfied for any reasonable values of laser parameters.

Experiment

For experimental investigation of the RRD-RHML regime, we used an actively mode-locked Er-doped fiber laser in sigma configuration. Detailed description of the laser is given in ref. [2]. In present experiment, intracavity dispersion was compensated by inserting a piece of dispersion compensating fiber to be consistent with the theoretical model. All measurements were carried out at 1545 nm. The intracavity dispersion was estimated to be about (0.01±0.01) ps/nm at 1545 nm by measurement of the dependence of mode-locking frequency on operational wavelength. Free spectral range of the laser cavity was about 1.567443 MHz. The phase factor of the MZM ψ_0 was measured to be about 0.19π. Optical filter double-pass FWHM bandwidth was $\Delta\nu = 2.2$ nm and $k_S = 1$. In present experiment, value of the small parameter is $k = 0.065$. Laser output was detected by photo-receiver with 25-GHz bandwidth and monitored by a 20-GHz sampling oscilloscope. Oscilloscope was triggered by the modulating signal applied to the MZM. In order to allow measurement of the pulse timing in the cavity with respect to cavity loss modulation, additional time delay was introduced for triggering signal. This additional delay was tuned to equalize total delay of measured signal (optical delay plus electrical delay after photo-receiver) and delay of triggering signal. In order to determine the instant corresponding to maximal transmission of the MZM, modulation frequency was tuned for harmonic mode locking (HML) at $f_M \approx 2.699614627$ GHz. For optimally tuned HML, pulses circulating in the cavity are synchronized with instants of the MZM's maximal transmission, providing with reference points in oscilloscope trace. In the presented theoretical model, these instants correspond to $\theta = \pi/2 + 2\pi l$ where l is integer. Then modulation frequency was detuned by half of the laser cavity's FSR to achieve RRD-RHML regime. Oscilloscope traces were recorded for different values of the modulation frequency detuning δf_M. Pulse-to-pulse amplitude fluctuation δI and temporal parameters θ_0, $\Delta\theta$ were measured from the oscilloscope traces. Resulting experimental dependencies are shown in Fig. 1, 2 for normalized modulation amplitudes $R = 0.07$, 0.10, 0.14. The theoretical dependencies calculated for actual laser parameters are shown in the same figures. Quite good agreement between experimental results and theoretical model is observed.

Conclusion

We have demonstrated experimentally and theoretically that pulse-to-pulse amplitude fluctuations occurring in the repetition-rate-doubling rational-harmonic regime of actively mode-locked fiber lasers are eliminated if the modulation frequency is properly tuned. However, a component at modulation frequency is still present in the RF spectrum due to the irregularity of the pulse's temporal position in the train. This irregularity can be reduced to value acceptable for applications, but it can not be completely eliminated.

Acknowledgements

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References

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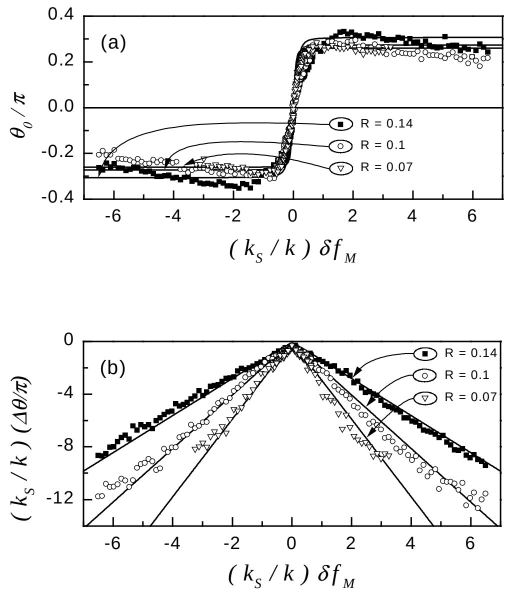

Figure 1. Experimental and theoretical dependencies of the temporal parameters θ_0 (a) and $\Delta\theta$ (b) on the normalised modulation frequency detuning.

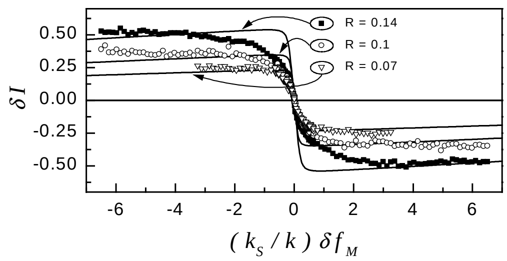

Figure 2. Experimental and theoretical dependencies of the pulse-to-pulse fluctuations δI on the normalised modulation frequency detuning.