Regenerative mode locking of fiber lasers with the use of a tracking generator

B.N. Nyushkov[1,2], A.V. Ivanenko[3], S.A. Farnosov[1], V.S. Pivtsov[1,2], V.I. Denisov[1], S.M. Kobtsev[3]

[1] *Institute of Laser Physics of SB RAS, 13/3 Lavrentyev Str., Novosibirsk, 630090 Russia;*
[2] *Novosibirsk State Technical University, 20 Karl Marx Str., Novosibirsk, 630073 Russia;*
[3] *Novosibirsk State University, 2 Pirogov Street, Novosibirsk, 630090, Russia;*

E-mail: nyushkov@laser.nsc.ru

Actively mode-locked (AML) fiber lasers are an attractive source for a regular train of ultra-short pulses. Such lasers normally consist of a fiber-based cavity and an intensity modulator. The modulator is driven by an external RF generator at a frequency f_{mod}, which is set equal to an integer multiple of the fundamental pulse repetition frequency f_{rep} governed by the cavity length. Despite high stability of the used RF generator an AML laser itself requires stabilization for long-term performance. The motivation for stabilizing an AML laser is to ensure that the detuning between the laser repetition frequency at nf_{rep} and the modulation frequency f_{mod} is kept within a tolerance, which is typically less than 0.1% [1]. This is required to maintain mode locking in the presence of mechanical relaxation, thermal drift, and other environmental perturbations that affect the cavity length. Traditional approach is stabilizing the laser cavity via piezo-electric control, while the external modulation function f_{mod} is kept constant. Thus, the oscillation frequency f_{rep} remains constant. The regenerative approach allows f_{rep}, in principal, to drift freely and force the modulation frequency to follow f_{rep}. However a typical regenerative feedback, which has a clock extraction circuit based on a high-Q dielectric filter and a high-gain electrical amplifier, is designed to operate only at a selected harmonic of the fundamental repetition rate f_{rep} [2]. The frequency tuning range is very limited due to the narrow band filtration. Another problem is the coupling of the amplitude noise back to the cavity through such a regenerative feedback.

In this paper we propose and preliminary explore a novel technique of AML with a regenerative feedback which is based on the concept of a tracking generator. Such an approach ensures permanent mode locking, allows on-the-run continuous tuning of the pulse repetition rate as well as changing of the order of harmonic mode locking. Basically the developed regenerative scheme employs a simple phase lock loop (PLL) to control a widely-tunable RF oscillator used as a clock for the laser intensity modulator.

A simplified schematic diagram of the developed regeneratively mode-locked fiber laser system is shown in Fig. 1. The laser has a unidirectional ring cavity composed of an erbium-doped fiber amplifier (EDFA), a Mach-Zehnder intensity modulator (MZIM), and supplementary components. All the fiber components are polarization maintaining (PM) that enhance environmental stability of the laser. The regenerative feedback circuit employs a voltage-controlled oscillator (VCO) which can be tuned in a wide frequency range (exceeding manifold f_{rep}) by varying the reference voltage (V_{REF}). A digital phase-frequency detector (PFD) detects detuning between the VCO and a signal at the laser repetition rate frequency, which is extracted by means of a fast photodiode (PD) and a tunable band pass filter (TBP). The error signal yielded by PFD is used to control the VCO via PLL. Thus, in the closed-loop conditions the VCO frequency, which is actually $f_{mod,}$, remains tightly locked to a selected harmonic of the instantaneous repetition rate frequency (f_{rep}) of the laser, even if the cavity optical length changes with time. This enables permanent maintenance of AML even in an unstabilized laser despite environmental perturbations. This feature allows also continuous tuning of the pulse repetition rate in a wide range (by adjusting the cavity length) without interruption of mode locking.

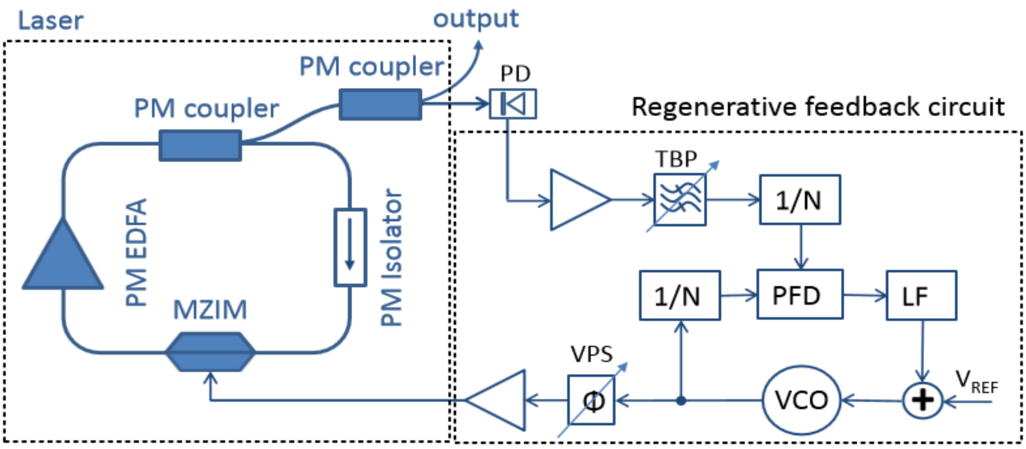

Fig.1. Schematic of the regeneratively mode-locked fiber laser system: MZIM – Mach-Zehnder intensity modulator; EDFA – erbium doped fiber amplifier; PD –photodiode; TBP – tunable band pass filter; 1/N – prescaler; PFD – phase-frequency detector; VCO – voltage-controlled oscillator; VPS – variable phase shifter.

For preliminary experiments we built a laser cavity with a fundamental repetition frequency of approximately 13 MHz. Using a single sample of a wide-range VCO based on commercial integrated circuit, we managed to obtain regenerative mode-locking alternatively at the 1st, 2nd, and 3rd harmonics of the fundamental frequency. To trigger mode-locking it was necessary to set roughly the VCO frequency in the vicinity of the selected harmonic of the frequency f_{rep} and close the PLL. The system tolerates an initial detuning between f_{mod} and f_{rep} as large as few MHz (in excess of 10%). In the closed loop conditions the residual phase error does not exceed 30 mrad (in the band 0,1 Hz to 60 kHz). The mode locking can be maintained permanently without any attendance. The generated pulses have duration of order of 100 ps. The highest per-pulse energy was achieved in a single-pulse mode-locking regime (at the fundamental repetition rate) and reached approximately 2 nJ. The Fig. 2 demonstrates optical spectra of the laser, while Fig.3 represents a radio-frequency spectrum of the laser intermode beats upon mode locking at the fundamental frequency.

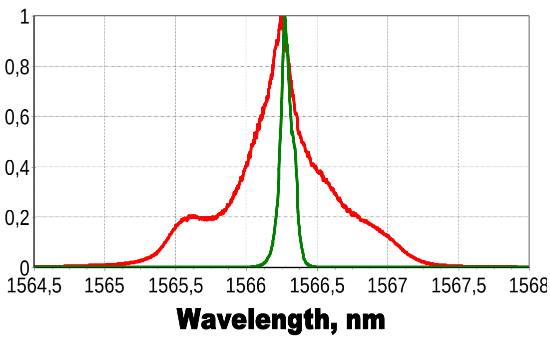

Fig.2. Optical spectra: the green trace – free-running cw lasing; the red – mode-locked lasing.

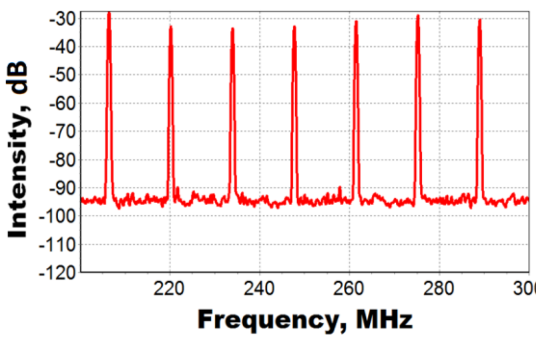

Fig.3. RF spectrum of intermode beat notes upon mode locking.

Thus, we have preliminary tested a novel technique of regenerative mode locking in a fiber laser. The technique employs a concept of a tracking generator for feedback circuit. It features a simple design, permanent maintenance of mode locking despite environmental perturbations, and possibility of on-the-run continuous tuning of the pulse repetition rate. It also allows switching the order of harmonic mode-locking. Such a regenerative technique may greatly facilitate developing of mobile and unattended pulsed laser systems.

References

1. N.A. Koliada et al., *Quantum electronics* **43,** 95-98 (2013).
2. Masato Yoshida et al., *Optics Letters* **32**, 1827-1829 (2007).