Universal femtosecond fiber-optic clockwork

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Abstract— we report on development of a universal optical clockwork based on a fiber-optic femtosecond frequency comb generator with an advanced stabilization system. The comb generator employs a highly-stable mode-locked erbium-fiber laser and an original hybrid highly-nonlinear fiber. The implemented concept of frequency stabilization provides universality of the clockwork and allows frequency stability transfer from different types of optical standards to the generated radio and optical frequencies. The clockwork can ensure ultra-low relative instability (less than \(10^{-15}\)) of generated frequencies provided that a proper optical frequency standard is applied. The clockwork is approved for operation with molecular (\(\mathrm{H}_2\)) and single-ion (\(\mathrm{Yb}^+\)) optical standards.

Keywords— femtosecond optical clock; mode-locked fiber laser; hybrid highly-nonlinear fiber; frequency stability.

A highly-stable femtosecond frequency comb generator is an essential part of femtosecond optical clocks (FOCs) [1]. The comb serves as a clockwork, being synchronized with an atomic oscillator employed into an optical frequency standard. Such clockwork enables direct delivery of the optical standard frequency stability to synthesized radio frequencies and time marks. The optical standard stability can be also delivered to optical frequencies derived from the comb itself. The FOC systems are in demand for applications both in fundamental research and engineering (global navigation systems, telecom). However, to make FOCs as easy-to-operate multipurpose tools available for all interested institutions, it is necessary to design compact and reliable clockworks with a universal architecture capable of locking to and referencing against different optical standards. It will allow flexible configuration of FOC systems depending on resources, purposes and conditions of use.

Here we report on the design and characterization of an original prototype of universal femtosecond fiber-optic clockwork developed at the Institute of laser physics SB RAS.

Fig. 1 illustrates concept of the implemented clockwork.

It consists of a femtosecond frequency comb generator (FFCG) and optical phase-lock loops (OPLLs). FFCG is based on a mode-locked erbium fiber laser with a length-controlled linear-ring cavity [2]. The laser is assisted with a fiber-optic amplifier and a highly-nonlinear fiber (HNLF) that allows generation of an optical frequency comb covering the huge spectral range \(0.9\pm2.2\) \(\mu\)m. A dispersion-managed hybrid HNLF is used to achieve optimal spectral profile and ensure acceptable intensity and coherence even at the comb edges [3].

The FFCG is stabilized by applying pump-power, temperature and cavity-length automatic control to the femtosecond fiber laser and using a proper laser line from an optical standard as the reference frequency. Digital OPPL technique is used to ensure tight locking of the selected comb lines to the reference frequency, and, thus, to translate the optical standard stability to the comb. To characterize inaccuracy of the OPPL which forces a matching comb line to repeat the optical standard frequency, we made long-term measurements of the comb line frequency deviations (Fig. 2).

Fig. 2. Characterization of random frequency deviations of the comb line against the reference optical standard: a – a measured trace of the frequency deviation values; b – the calculated standard Allan deviation.

One can see that long-term instability of the comb locking to an optical frequency reference is not worse than parameters of existent optical standards. Thus, their stability can be reliably delivered to FOCs based on the above clockwork.

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