Fiber-based femtosecond optical frequency comb stabilized to iodine frequency standard

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Abstract. A fiber-based femtosecond optical frequency comb spanning wavelengths from 1 to 2 μm was stabilized precisely to an iodine frequency standard by means of heterodyne optical phase-locked loops. It enables transfer of frequency stability across electromagnetic spectrum and implementation of compact optical clocks with $\sim10^{-15}$ long-term instability.

1. Introduction

Modern techniques of time and frequency metrology take advantage of so-called optical frequency combs (OFCs) generated by femtosecond laser systems which are precisely stabilized to reference frequency standards [1, 2]. These OFCs are used to solve such tasks as precise measurements of optical frequencies, transfer of stability and accuracy from frequency standards to required frequencies (frequency synthesis), implementation of optical clocks, and timing of ultrafast processes [3-5]. Further expansion of metrological applications of highly-stable femtosecond OFCs beyond labs will become possible with more compact and reliable design of the OFC-based devices. Thus, the use of fiber-optic femtosecond OFC generators with stabilization to compact optical frequency standards is now regarded as a promising approach for development of transportable (or even mobile) versions of optical frequency synthesizers and optical clocks [6-8].

2. Experimental

Our experimental study was aimed at precise stabilization of a fiber-based octave-spanning OFC to an iodine optical frequency standard. The comb was generated by means of a home-made femtosecond erbium fiber laser similar to [9] and a hybrid highly-nonlinear fiber [7, 8]. Optical phase-locked loops (OPLLs) were applied to stabilize the comb teeth to the optical standard as depicted in figure 1. The corresponding short-wavelength (λ_1~1 μm) and frequency-doubled long-wavelength (λ_2~2 μm) teeth were locked to the fundamental laser wavelength (λ_{os}~1 μm) of the optical standard.

To ensure reliable and tight locking of the relatively noisy optical frequency comb to the optical standard, the used OPLLs must be fast enough and feature broadband noise suppression [10]. On this basis we designed feedback loops which incorporate a miniature intracavity electro-optic phase modulator [11] and an extracavity fiber-coupled acousto-optic frequency modulator (Brimrose). These elements allowed fast frequency control and implementation of OPLLs with bandwidths of ~220 kHz and ~100 kHz for the short-wavelength and long-wavelength sides of the OFC, respectively. In order to extend the effective dynamic range of the OPLLs and provide continuous long-term stabilization of the comb, the fast frequency controls were assisted by the relatively slow controls: PZT-based cavity length control, pump power control, and temperature control.

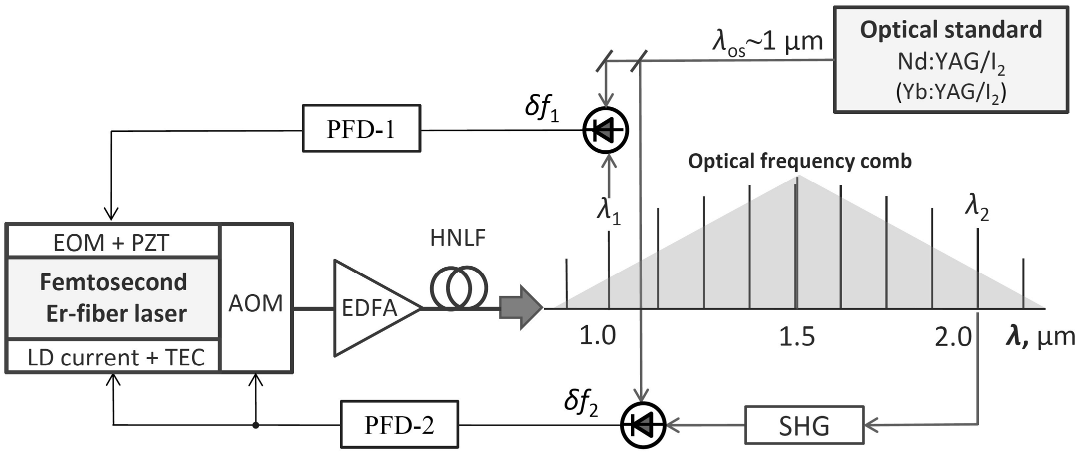

Figure 1. Implemented scheme of precise stabilization of a fiber-based femtosecond OFC to an iodine optical frequency standard: EOM – electro-optic phase modulator, PZT – piezoelectric translator, AOM – acusto-optic frequency modulator, LD – pumping laser diode, TEC – thermoelectric converter, EDFA – erbium-doped fiber amplifier, HNLF – highly-nonlinear fiber, PFD-1,2 – phase-frequency detectors, SHG – second harmonic generation; δf_1 and δf_2 stand for the beat radiofrequencies controlled by the PFDs.

To the best of our knowledge, such combination of controls including a fiber-coupled acousto-optic frequency modulator was not yet used for stabilization in the early experimental and commercial OFCs generated by femtosecond erbium fiber laser systems. Therefore, stabilization performance in those systems was limited by the relatively slow pump power control of erbium fiber lasers. The millisecond life time of the upper laser level limits the bandwidth of the corresponding laser frequency control via population inversion variation to a value less than 10 kHz [12].

The optical standard is based on a home-made frequency-doubled Nd:YAG (optionally Yb:YAG) laser stabilized to a narrow nonlinear saturated absorption resonance in the hyperfine structure of molecular iodine. Its long-term frequency instability was measured to be as low as $\sim 10^{-15}$ [13].

3. Results and discussion

The implemented design of OPLLs has ensured tight locking of the OFC to the reference optical standard. Simultaneous continuous measurements (with a 1 second rate) of the beat frequencies δf_1 and δf_2 have revealed just millihertz-scale residual random deviations of the corresponding short-wavelength ($\lambda_1 \sim 1$ μm) and frequency-doubled long-wavelength ($\lambda_2 \sim 2$ μm) comb teeth against the optical standard frequency (figure 2). The residual root-mean-square phase errors (measured in the same way as in [10]) were sufficiently less than 1 rad^2 in both of the OPLLs.

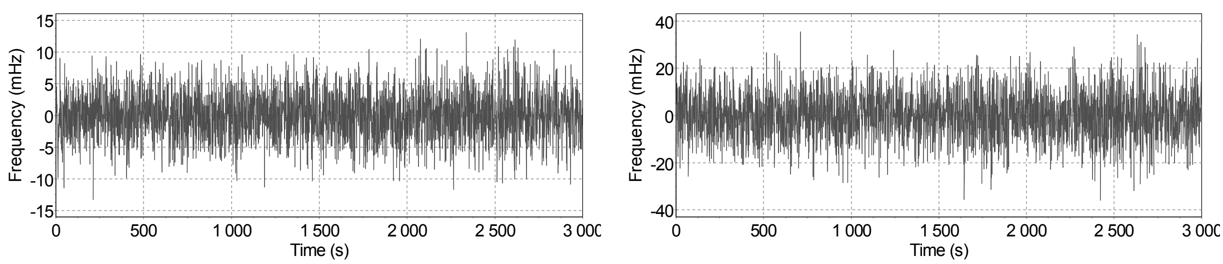

Figure 2. Residual random deviations of the OFC teeth against the optical standard frequency: the left graph – measurement of the beat frequency δf_1 (at 20 MHz) obtained with the short-wavelength tooth ($\lambda_1 \sim 1$ μm); the right graph – measurement of the beat frequency δf_2 (at 10 MHz) obtained with the frequency-doubled long-wavelength tooth ($\lambda_2 \sim 2$μm). Gate time of the frequency counters was 1 s.

An original measurement approach was used to evaluate transfer of stability from the optical standard frequency ($f_{os} \approx 2.8\times10^{14}$ Hz) to the octave comb width ($\Delta f_{comb}=f(\lambda_1) - f(\lambda_2) \approx 1.4\times10^{14}$ Hz). We mixed the second harmonic of the beat frequency δf_1 with the beat frequency δf_2 to obtain the corresponding difference radiofrequency f_{rf} that can be defined as:

$$f_{rf} = 2\delta f_1 - \delta f_2 = 2\Delta f_{comb} - f_{os}.$$

Instability of this easily measurable radiofrequency (f_{rf} ~30 MHz) can be attributed to residual random deviations of the doubled comb width ($2\Delta f_{comb}$) against the optical standard frequency (f_{os}). It is important to note that the comb offset contribution to the frequency f_{rf} is reduced to zero. Continuous measurement of the frequency f_{rf} has provided us with necessary data for calculation of the Allan deviation shown in figure 3. It characterizes an added instability (resulting from imperfection of the comb width stabilization by OPLLs) which is additive to the instability of the optical standard. Since the comb width is a multiple of the intermode frequency spacing (f_{im} ~10^8 Hz), the added instability for the frequency f_{im} is the same as for the comb width. This feature allows evaluation of the stability transfer also to the radio frequency band by the OFC-based optical clock. Since the added instability in our setup is a few orders of magnitude less than the inherent instability of the used iodine frequency standard [13] (at least at averaging times from 1 to 1000 s), we suppose that our setup transfers stability of the optical standard frequency to the OFC with negligible impairment. Continuous locking of the comb teeth to the optical standard frequency was maintained for hours during experiments. It was limited mainly by the finite range of a PZT-based slow frequency control.

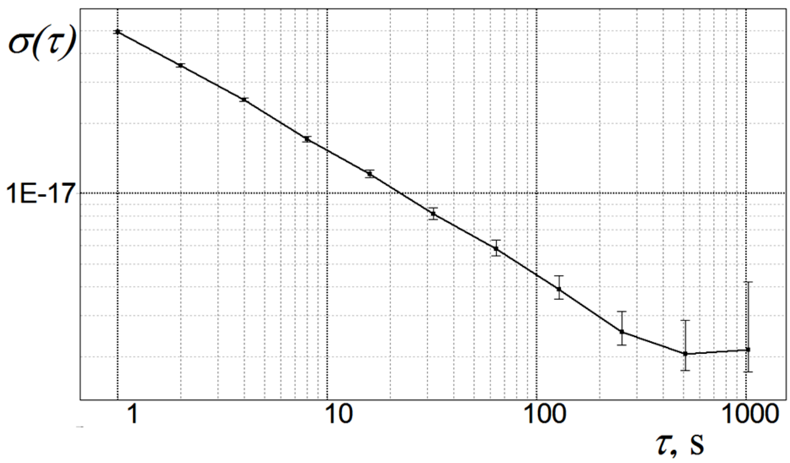

Figure 3. Allan deviation calculated for residual random deviations of the doubled comb width ($2\Delta f_{comb}$) against the optical standard frequency (f_{os}).

4. Conclusion

We have demonstrated precise and reliable stabilization of a compact fiber-based octave-spanning OFC to an advanced iodine optical frequency standard with ~10^{-15} long-term instability. The original arrangement of high-bandwidth OPLLs employing fast EOM- and AOM-based controls has enabled stability transfer from the optical standard to the OFC with negligible impairment. Unlike conventional stabilization of octave-spanning OFCs, the applied stabilization scheme does not employ any nonlinear interferometer. This feature results in compactness and reduced complexity of the setup. Such stabilized fiber-based OFC allows implementation of a compact transportable optical clock.

References

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