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Stabilisation of a fibre frequency synthesiser using acousto-optical and electro-optical modulators

N.A. Koliada, B.N. Nyushkov, V.S. Pivtsov, A.S. Dychkov,
S.A. Farnosov, V.I. Denisov, S.N. Bagayev

Abstract. **A fibre-optic frequency synthesiser is developed that is stabilised to the optical frequency standard based on molecular iodine (Nd : YAG/I$_2$). The possibility of transferring stability of the optical frequency standard to other optical frequencies in the IR range 1–2 μm and to the RF range by using synthesiser phase-locked loops (PLLs) with acousto-optical and electro-optical modulators is experimentally demonstrated. The additive instability introduced into the optical frequency comb of the synthesiser (which arises due to PLL residual random errors) is several orders less than the intrinsic instability of the reference optical frequency standard employed (i.e., is noticeably less than 1×10^{-13} for 1 s and 5×10^{-15} for 1000 s).**

Keywords: *fibre frequency synthesiser, optical frequency standard, optical clock, femtosecond fibre laser, comb of equidistant optical frequencies.*

A femtosecond frequency synthesiser is a basis of the clock mechanism in a modern femtosecond optical clock (FOC) [1–4]. It is used to directly divide an optical frequency of an atomic oscillator (optical frequency standard) and thus to provide a possibility of a direct synthesis of standard radiofrequencies and formation of time marks with stability and accuracy of the optical standard. The main unit in any femtosecond frequency synthesiser is a driving femtosecond laser operating in the mode-locked regime with a system of active stabilisation. Such a laser should provide stable generation of a comb of equidistant optical frequencies (corresponding to laser longitudinal modes). Presently, the most promising approach to fabrication of mobile FOCs is employment of fibre optics as the base of a femtosecond frequency synthesiser. A principal possibility of using fibre laser systems for these purposes was demonstrated in a series of works [5–9]. Fibre femtosecond lasers are compact, possess high efficiency and low energy consumption. In addition, such laser systems are less prone to misalignment because employment of discrete adjusted optical elements in such systems can be minimised or even excluded.

In the present work, we experimentally study possible precise stabilisation of an octave optical frequency comb generated by a femtosecond erbium laser [10, 11] to an optical frequency standard Nd : YAG/I$_2$. The phase-locked-loop (PLL) method is used for controlling boundary spectral components of the comb ($\lambda_1 \approx 1064$ nm, $f_1 \approx 2.8 \times 10^{14}$ Hz and $\lambda_2 \approx 2128$ nm, $f_2 \approx 1.4 \times 10^{14}$ Hz) with respect to the frequency of fundamental radiation ($\lambda_{\rm os} \sim 1064$ nm) of the optical standard (Fig. 1). Reliable frequency locking and efficient noise suppression require a PLL system that should have a sufficiently fast response and process perturbations in a wide frequency band. Therefore, the system developed uses such adjusting elements as a miniature intracavity electro-optical phase modulator [12] and fibre-coupled (Brimrose) acousto-optical frequency modulator (AOFM) placed at the output from the femtosecond erbium fibre laser. In this way, the bandwidths of approximately 200 and 100 kHz were realised for the feedback (FB) loops that stabilise the short-wavelength and long-wavelength boundaries of the optical frequency comb. Such a combination of wide-band feedbacks was for the first time realised in a femtosecond erbium fibre generator-synthesiser of optical frequencies. In earlier works and commercial systems (for example, Menlo Systems), this approach based on AOFM has not been used and the quality of stabilisation was limited by a substantially slower (the bandwidth was less than 10 kHz) automatic frequency control system that varied the pump power (population inversion) of the active medium in the driving femtosecond fibre erbium laser [13].

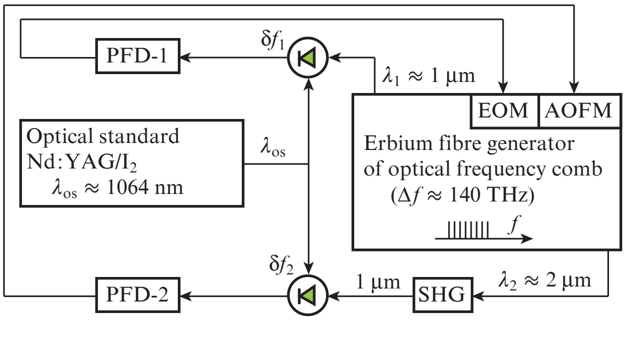

Figure 1. Schematic of stabilisation of the optical frequency comb of the synthesiser: (PFD-1,2) phase frequency detectors; (EOM) electro-optical modulator; (AOFM) acousto-optical frequency modulator; (SHG) second harmonic generator on a PPLN nonlinear crystal.

N.A. Koliada, A.S. Dychkov, S.A. Farnosov, V.I. Denisov, S.N. Bagayev Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: n.koliada@mail.ru;
B.N. Nyushkov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State University, ul. Pirogova, 2, 630090 Novosibirsk, Russia; e-mail: nyushkov@laser.nsk.ru;
V.S. Pivtsov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; Novosibirsk State Technical University, prosp. Karla Marksa, 20, 630092 Novosibirsk, Russia;
e-mail: clock@laser.nsk.ru

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In the experiment, we have simultaneously performed long-term precise measurements of beat frequencies δf_1 and δf_2 between the reference optical frequency standard and the stabilised boundary components of synthesiser optical frequency octave comb ($f_1 \approx 2.8 \times 10^{14}$ Hz and $f_2 \approx 1.4 \times 10^{14}$ Hz). The intervals between comb modes are equidistant and form the output radio-frequency of the FOC. The used stabilisation approach provided a millihertz-scale accuracy of optical frequency comb lock-in (Fig. 2). An optical standard on a Nd:YAG laser was used with the frequency stabilised at the level of 10^{-15} (relative long-term frequency instability) to narrow nonlinear resonances of saturated absorption on hyperfine structure components of molecular iodine [14].

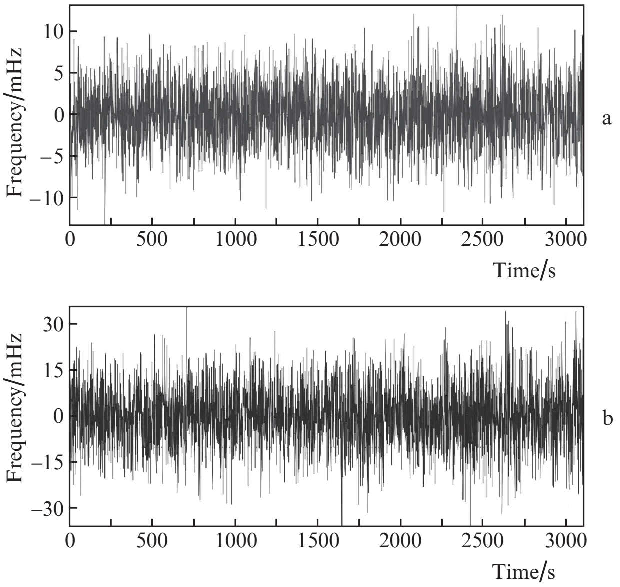

Figure 2. Time diagrams of (a) the frequency of the beat signal δf_1 between the reference optical frequency standard and the short-wavelength comb component stabilised to it ($\lambda_1 \approx 1064$ nm, $f_1 \approx 2.8 \times 10^{14}$ Hz) and (b) frequency of the beat signal δf_2 between the reference optical frequency standard and the frequency-doubled long-wavelength comb component stabilised to it ($\lambda_2 \approx 2128$ nm, $f_2 \approx 1.4 \times 10^{14}$ Hz) for the octave optical frequency comb of synthesiser. The single measurement time is 1 s.

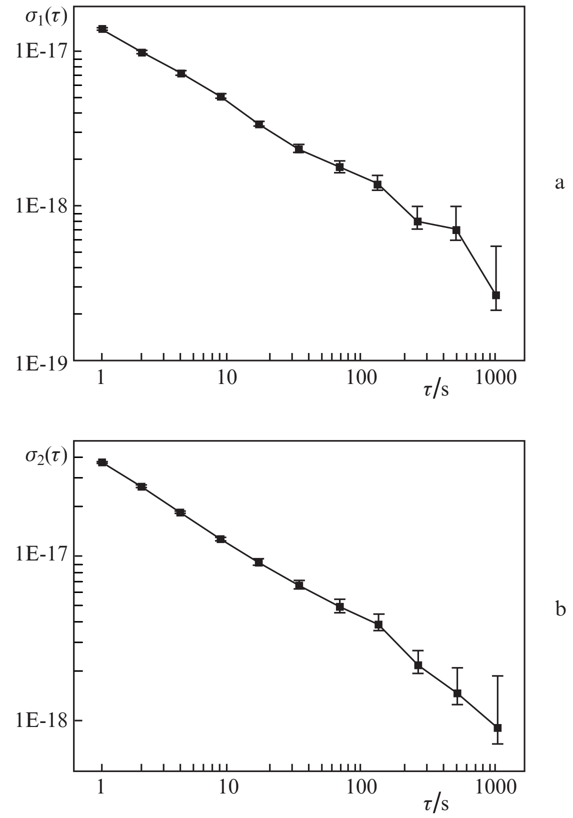

Figure 3. Allan deviation calculated for (a) residual random deviations of the short-wavelength component ($f_1 \approx 2.8 \times 10^{14}$ Hz) and (b) frequency-doubled long-wavelength component ($f_2 \approx 1.4 \times 10^{14}$ Hz) of the synthesiser optical frequency comb with respect to the reference optical frequency standard (~2.8×10^{14} Hz) used for their stabilisation.

In Fig. 3 one can see the corresponding Allan deviations that were calculated from results of simultaneous measurements of beat frequencies δf_1 and δf_2 and normalised to the corresponding value of the optical frequency (approximately 2.8×10^{14} Hz). Residual random frequency deviations relative to the reference optical frequency standard are slightly greater for the long-wavelength boundary of the comb ($f_2 \approx 1.4 \times 10^{14}$ Hz) (Fig. 3b) than for the short-wavelength boundary ($f_1 \approx 2.8 \times 10^{14}$ Hz). This is explained by the difference between realised PLL systems for these frequency comb components and by different operation bandwidths in the corresponding FB loops. However, even the worst Allan deviation values fit within the interval from 4×10^{-17} for 1 s to 1×10^{-18} for 1000 s.

The stabilisation random inaccuracy for the entire optical frequency comb is determined by the sum of stabilisation random inaccuracies for the long-wavelength and short-wavelength boundaries of the comb. In realising the FOC, this inaccuracy can be interpreted as the introduced instability that is additive to the instability of reference optical frequency standard. By using values of Allan deviation obtained in the present study (see Fig. 3) the total random inaccuracy of stabilisation can be evaluated by the formula:

$$\sigma_{\Sigma}(\tau) = \sqrt{\sigma_1^2(\tau) + \sigma_2^2(\tau)}, \tag{1}$$

where $\sigma_1(\tau)$ and $\sigma_2(\tau)$ are the Allan deviations for the short-wavelength boundary component ($\lambda_1 \approx 1064$ nm, $f_1 \approx 2.8 \times 10^{14}$ Hz) and for the frequency-doubled component of the long-wavelength boundary ($\lambda_2 \approx 2128$ nm, $f_2 \approx 1.4 \times 10^{14}$ Hz) of the synthesiser optical frequency comb, respectively. The range of approximate values of the Allan deviation estimated in this way for the stabilisation random inaccuracy of the FOC based on the developed synthesiser is from 4.2×10^{-17} for 1 s to 1.1×10^{-18} for 1000 s.

To estimate experimentally the possibility of using the developed synthesiser in the FOC regime, we have preliminarily measured instability of the intermode frequency (the interval between modes in the synthesiser optical frequency comb). For this purpose, the radio-frequency signal was detected by a photodetector at the synthesiser intermode frequency ($f_{\rm rep} \sim 107$ MHz). Then, we performed the long-term measurement of the low difference frequency (~3 kHz) between the synthesiser radio-frequency mentioned above and the frequency of an auxiliary reference RF generator (Rohde&Schwarz 1090.3000.11) stabilised to a passive hydrogen frequency standard Ch1-1006. Values of instability calculated from the measurement results (Fig. 4) actually coincide with passport instability characteristics of the hydrogen standard employed. This testifies that the main contribution into the value of measured mutual instability is made by the hydrogen frequency standard (in conjunction with the generator stabilised to it). Instability of the output frequency of the FOC itself should be substantially less than the values of the Allan deviation obtained. A rough estimation of this instability can be made from relation (1) and issuing from that known values in this case are the measured mutual (sum) instability, passport instability of hydrogen frequency standard, and introduced instability of the auxiliary reference RF generator. Such an estimate yields values close to the instability of the employed reference optical frequency standard ($\sim 2 \times 10^{-13}$ for 1 s and $\sim 6 \times 10^{-15}$ for 1000 s).

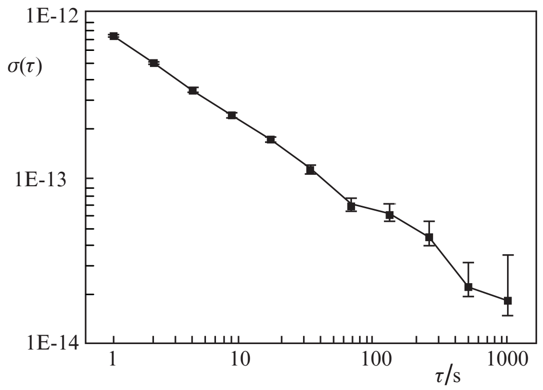

Figure 4. Allan deviation calculated for the mutual instability of the FOC output radio-frequency $f_{\rm rep}$ and the frequency of auxiliary reference RF generator stabilised to a passive hydrogen frequency standard.

Instability of the output radio-frequency for the FOC based on the developed fibre-optical frequency synthesiser can be estimated more accurately by comparing the output radio-frequencies of two independent FOC samples. Such investigations will be performed in the future.

Hence, the results obtained confirm the possibility of employing the developed synthesiser for transferring stability of the optical frequency standard to other optical frequencies (to the wavelength range of 1–2 μm) and to the RF range. Thus, for the first time, the combination of a miniature intracavity electro-optical phase modulator [12] with an acousto-optical fibre-coupled frequency modulator (Brimrose) has been used for stabilising the erbium fibre frequency synthesiser. The high-stable optical frequency comb obtained can be used for solving practical problems in precise metrology: optical frequency measurements, spectroscopy, fabrication of a femtosecond optical clock, and development of new communication technologies. A fibre-based generator-synthesiser of the optical frequency comb allows one to develop reliable, compact and mobile metrological equipment.

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