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Femtosecond optical-to-microwave frequency divider with a relative instability of $10^{-14} – 10^{-16}$ (τ = 1 – 100 s)

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Abstract. **We have developed a low-noise optical-to-microwave frequency divider based on a femtosecond erbium fibre laser. The source of an optical signal was a He – Ne/CH$_4$ frequency standard. Comparison of two frequency dividers showed that the relative instability of output microwave signals, introduced by the dividers, is $10^{-14} – 10^{-16}$ for the averaging time τ = 1 – 100 s. The instability obtained corresponds to the requirements imposed on interrogative oscillators for time and frequency standards based on Cs or Rb atomic fountains.**

Keywords: *femtosecond optical-to-microwave frequency divider, fibre laser, He – Ne/CH$_4$ frequency standard, ultralow phase noise microwave generator.*

1. The development of various radio-technical systems (universal time, GLONASS, communication, radiolocation) requires the creation of radio-frequency master oscillators (MOs) with a high short-term frequency stability and low-level phase noise. In particular, MOs with the relative frequency instability (Allan deviation) of $\sigma_{\rm MO} = 1\times10^{-14}$ – 1×10^{-15} (at the averaging time of τ = 1 s) are needed for frequency standards and time keepers of 'fountain' type on Cs and Rb atoms, which make the basis for national and international time scales. The accuracy of fountains is $(1 – 2)\times10^{-16}$; however, the time needed to reach such an accuracy depends on stability of the microwave field, with which an ensemble of cold atoms interacts (Dick effect [1]). The short-term instability of the best hydrogen masers (H maser) is $\sigma_{\rm maser} \sim 1\times10^{-13}$ (τ = 1 s). Being employed as MOs, those require more than 10 days ($\sim10^6$ s) for reaching the mentioned accuracy. Due to the inverse square-root dependence of the fountain instability on the averaging time [2], the reduction of the MO instability by an order of magnitude to $\sigma_{\rm MO} = 1\times10^{-14}$ (τ = 1 s) results in a two-order shorter time needed for the fountain to reach the nominal accuracy. Under further reduction of the MO instability, the fountain stability is determined by other noise sources.

Studies performed in recent years show that the problem can be successfully solved by using high-stability lasers and femtosecond optical frequency dividers (OFDs), which transfer the frequency stability from the optical-to-microwave spectral range [3 – 5]. Obtaining highly stable optical radiation is not now a problem. The common approach is stabilising the frequency of a semiconductor laser by a high-Q Fabry – Perot resonator according to the Pound – Drever – Hall technique [2, 6]. As for reliable low-noise femtosecond OFDs not worsening the optical stability, these are still being actively developed. The temporal jitter of OFD output signals is affected by a number of factors, in particular, the mode locking stability of the fibre laser and the feedback frequency band of the system for the cavity length control; at the stage of converting optical femtosecond pulses into electrical picosecond pulses, photodetector properties also contribute into this effect.

In detecting femtosecond pulses there are fundamental limitations on the frequency stability of a microwave signal: Schottky noise of photodetectors and conversion of input pulse intensity fluctuations to the phase noise. Special measures can suppress contributions related to these limitations to a level of 1×10^{-16} (τ = 1 s), which is important in various radio-photonics applications [3, 4].

In the present work, for the first time in Russia the problem of creating an OFD with a short-term frequency instability of $\sigma_{\rm OFD} \approx 1\times10^{-14}$ (τ = 1 s) has been solved, which is sufficient for radical reduction of the time needed for reaching the nominal accuracy in Cs and Rb atomic fountains. No special measures were taken for suppressing contribution from the noise arising in photodetection and no corresponding complication of the OFD scheme was needed for solving the problem.

2. The source of highly stable optical radiation was an optical He – Ne/CH$_4$ frequency standard (OFS) at the wavelength λ = 3.39 μm possessing a short-term frequency instability $\sigma_{\rm OFS} < 1\times10^{-14}$ (τ = 1 s) [7]. The frequency of the He – Ne/CH$_4$ OFS (88 THz) is lower than the radiation frequency of a femtosecond Er^{3+} fibre laser (190 THz) used in the OFD, which gives a chance to employ a simplified scheme of the divider based on generating a comb of difference frequencies in a nonlinear crystal. In this scheme, a single parameter is stabilised, namely, the femtosecond pulse repetition rate $f_{\rm rep}$ [8 – 10].

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The scheme of the OFD in the 'methane optical clock' based on the He–Ne/CH_4 OFS and femtosecond Er^{3+} fibre laser was thoroughly described in [9, 10] where a single OFD was investigated. The instability of the obtained microwave signal was determined by comparing its frequency with that of the H maser; however, it was impossible to find the intrinsic instability of output frequency at the averaging times $\tau <$ 30 s, where it is substantially less than that of the H maser. In the present work, we report the measurements with two newly developed independent femtosecond OFDs with substantially redesigned Er^{3+} fibre lasers [11].

In contrast to [9, 10], Er^{3+} lasers utilise polarisation-maintaining fibres. The laser has a linear cavity, one end of which has a nonlinearly reflecting optical mirror. At the other end of the cavity, there is an air gap where collimated radiation is reflected from a highly reflecting end mirror placed on a piezoelectric transducer. In front of the mirror, there is an electro-optical phase modulator on a $LiNbO_3$ crystal. The employment of the intracavity modulator allows one to broaden the band of the pulse repetition rate stabilisation system. In the present work, the feedback band was 150 kHz. The laser was mode-locked at $f_{\rm rep} \sim$ 60 MHz, the average radiation power was 40 mW, and the spectral width was 38 nm.

Laser radiation (at the wavelength λ = 1550 nm) was amplified in a fibre amplifier and then compressed in a section of fibre possessing a negative dispersion of group velocities. The duration of amplified pulses was 150 fs, and the average power was 220 mW. Part of radiation (10 %) was separated by a fibre splitter, collimated, and used as output radiation with a wavelength of 1550 nm. The other part (90 %) passed into the fibre section with high nonlinearity and a length of 4 cm, where super-continuum radiation was generated with a spectral width of 1000–2000 nm. This radiation was also collimated and its short-wavelength part (1060 nm) was mixed in a nonlinear crystal with the initial radiation (1550 nm) for obtaining the difference frequency comb in the range of 3400 nm.

Employment of the femtosecond laser described above provided stable twenty-four-hour operation of the OFD.

3. The scheme of experiment for studying instability of two OFDs is shown in Fig. 1. In Fig. 2 one can see a comb of radio-frequency components with $f_{\rm rep} \sim$ 60 MHz ($f_N = Nf_{\rm rep}$, where N is the harmonic number) at the output from the photodetector that records femtosecond pulses of the Er^{3+} fibre laser comprised in the OFD. Upper frequencies of the spectrum are limited by an operation range of the analyser (3 GHz). Optical femtosecond pulses at the OFD output are detected by a wide-band linear InGaAs pin-photodiode with the band of 10 GHz at the level of –3 dB. From Fig. 2 one can see that the signal/noise ratio for the comb components falls moderately with frequency; thus, for obtaining a highly stable signal it is reasonable to use harmonics of higher orders N. Taking into account the output characteristics of the photodetector and the available elemental base we have chosen components with $N = 26$ at a frequency of ~1.55 GHz. The frequency difference between the 26th harmonics of two OFDs equal to ~10 kHz was measured by a frequency counter.

4. The relative Allan deviation for averaging times τ = 0.01– 500 s is shown in Fig. 3. The dependence shown by black squares is the intrinsic instability of two OFDs. Measurements were performed with a 100-Hz-band filter at the frequency counter input. The dependence behaves as $\sim 1/\tau$, which is typical for white phase noise [2]. The contribution of such noise into the measured instability depends on the transmission bandwidth of a channel at the frequency counter input. The result of the recalculated Allan deviation for a 3-Hz-band filter that is used in the standard procedure of maser instability measurements is shown in Fig. 3 by triangles.

Thus, from Fig. 3 one can see that the obtained instability of frequency division for the He–Ne/CH_4 OFS to the micro-

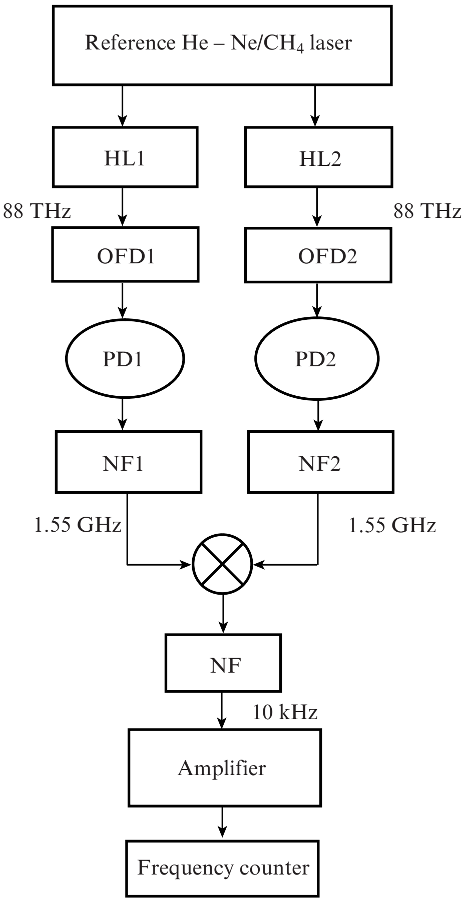

Figure 1. Scheme of the experiment: (OFD) optical frequency divider; (HL) heterodyne laser; (PD) photodetector; (NF) narrow-band filter.

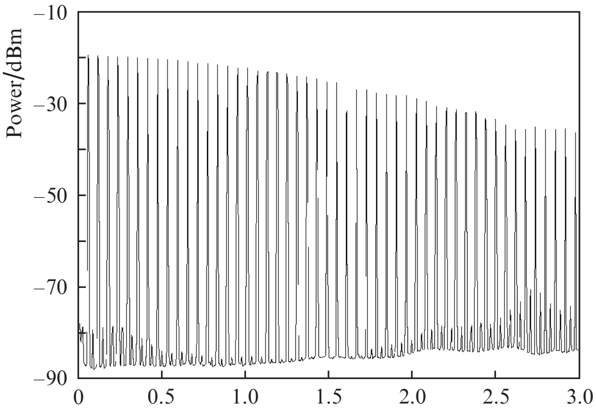

Figure 2. Radio-frequency comb of harmonics of the pulse repetition rate for a femtosecond Er^{3+} fibre laser at the output from a photodetector. The spectral analyser bandwidth is 1 MHz.

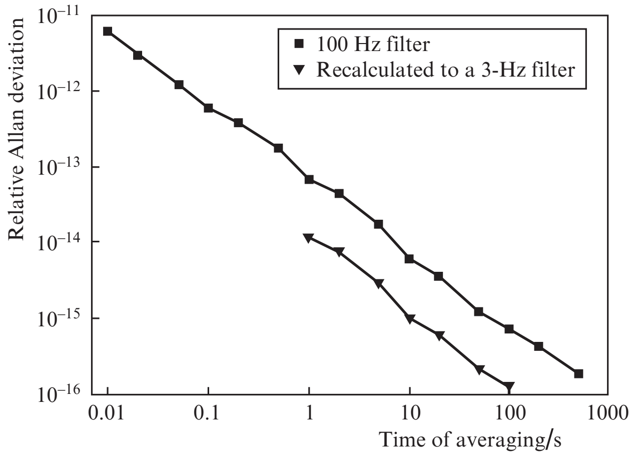

Figure 3. Relative Allan deviation vs. averaging time for two OFDs (the carrier frequency is ~1.55 GHz, the 26th harmonic of the pulse repetition rate of the femtosecond Er^{3+} laser).

wave range is $1\times10^{-14} - 1\times10^{-16}$ in the time averaging interval of 1 – 100 s (for a 3-Hz-band filter). The dependence is approximated by the function $\sigma(\tau) = 1\times10^{-14}/\tau$. For employing the OFD in master oscillators of frequency standards on fountains of Cs or Rb atoms, the stability at the averaging time $\tau = 1$ s is important. The level of the instability obtained at the averaging time $\tau = 1$ s is close to results of Ref. [5], where an optical MO on a fountain of Cs atoms allowed the time of the fountain reaching the accuracy of 2×10^{-16} to be reduced from 10 days (by using a H maser) to one day.

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