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Femtosecond Er^{3+} Fiber Laser for Application in an Optical Clock

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Abstract—The main elements needed for the realization of a compact femtosecond methane optical clock are developed and studied. A femtosecond laser system on an Er^{3+} fiber ($\lambda = 1.55$ μm) contains an oscillator, an amplifier, and a fiber with a relatively high nonlinearity in which the supercontinuum radiation is generated in the range 1–2 μm. In the supercontinuum spectrum, the fragments separated by an interval that is close to the methane-optical reference frequency ($\lambda = 3.39$ μm) exhibit an increase in intensity. The supercontinuum radiation is converted into the difference frequency in a nonlinear crystal to the range of the methane-reference frequency ($\lambda = 3.3$–3.5 μm), so that the frequency components of the transformed spectrum have sufficient intensities for the subsequent frequency–phase stabilization with respect to the methane reference. A system that stabilizes the pulse repetition rate of the femtosecond Er^{3+} laser is also employed. Thus, the repetition rate of the ultrashort pulses of the femtosecond fiber laser is locked to the methane reference. The pulse repetition rate is compared with the standard second. Thus, the scheme of an optical clock is realized.

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INTRODUCTION

In modern schemes of a high-precision optical clock, the oscillators that determine the accuracy represent ultranarrow resonances obtained using laser spectroscopy. The frequencies of these resonances belong to the optical range. Therefore, a fundamental problem lies in the determination of these frequencies by comparing them with the frequency of the international standard second (a cesium frequency standard in the 9.8-GHz range).

A time measurement (clock) is reduced to the recalculation of the number of oscillations for a stable oscillator. The accuracy of the time measurements increases with an increasing number of oscillation periods. Hence, a shorter measurement interval is needed at higher frequencies. This can be illustrated using the example of the classical mechanical clock. A stable pendulum serves as the oscillator that determines the clock accuracy. Normally, its oscillation period is about one second. Its frequency is compared with the standard frequency determined by the Earth’s rotation around its axis. This comparison is realized with a system of gears (a number ratio of the gear teeth in a pair of gears determines the frequency ratio). Thus, a relatively low standard frequency is compared using a high-frequency oscillator (the frequency ratio is about 10^4). The frequencies of narrow optical resonances are also higher than the cesium microwave standard frequency by a factor of 10^4–10^5. Precise measurements of optical resonances will make it possible to create a high-precision optical clock. However, the methods for the measurement of the frequency of the electromagnetic wave are unavailable in optics (the wavelength is measured in experiments) in contrast to radio physics. It is known that the wavelength is one-to-one related to the frequency, but the velocity of light must be determined with a high accuracy (this represents a fundamental problem). The measurement of an optical frequency is reduced to its comparison with the frequency of the international standard second. Figuratively speaking, a mechanism similar to the gear system in a mechanical clock is needed for the direct measurement of the optical frequency. Thus, a chain of frequency converters is needed to transform the optical frequency to the RF range, where the frequency can be accurately measured using the comparison with the cesium standard.

For this purpose, chains containing lasers, nonlinear converters, klystrons, frequency mixers, etc. have been developed. They represent extremely complicated systems for the measurement of a single optical frequency. Therefore, few setups have been created in well-equipped national metrological laboratories. The advent of ultrashort laser pulses made it possible to remove such chains.

It is known that cw lasers with passive-mode locking can generate radiation whose spectrum represents a comb consisting of narrow equidistant lines. Note that the total width of such a comb is determined by the duration of the ultrashort pulse in the cw train. In modern lasers, the comb spectral width can reach hundreds of terahertz. The comb spectral width can additionally be increased using the supercontinuum generation in hollow optical fibers and fibers with a relatively high nonlinearity. Broadband phase-coherent frequency combs generated with femtosecond lasers and specific optical fibers have stimulated a revolution in the precision metrology of optical frequencies [1–4].

The interval between the comb components is determined by the pulse repetition rate f_r in a cw train, and the position of the spectrum relative to the zero frequency (comb shift f_0) depends on the mismatch of the phase and group velocities of the femtosecond pulse carrier and envelope. Thus, the frequency of the nth line of the optical comb (ν_n) is determined with high accuracy using the following simple expression:

$$\nu_n = nf_r + f_0. \tag{1}$$

Note that $0 < f_0 < f_r$. Frequencies f_r and f_0 belong to the RF range and can easily be measured using the methods of radio electronics with respect to the existing microwave frequency standards. Thus, optical frequency ν_n can be determined.

Hall, and Hänsch were awarded the Nobel Prize in 2005 for the application of the femtosecond comb for the precision metrology of optical frequencies. Ti:sapphire lasers and photonic-crystal fibers were used in these works. Relationship (1) makes it possible to construct an optical clock whose work is determined by stable oscillations of the optical (laser) frequency standard (OFS) and the mechanism for the stability transfer to the RF range (frequency division) is realized with a femtosecond comb. Many works have been devoted to the creation of an optical clock (see, for example, [5–8]).

Various schemes for the stability transfer from the optical range to the RF range can be realized with regard to the relative position of the OFS frequencies and the spectrum of the femtosecond comb. We choose the methane standard ν_{CH_4}, whose frequency belongs to the mid-IR range (88.4 THz, $\lambda = 3.39$ μm), as the stable reference. The methane standard (He–Ne/CH_4) represents an He–Ne laser ($\lambda = 3.39$ μm) whose cavity contains a cell with methane. One of its vibrational–rotational transitions is used to stabilize the laser frequency [9]. Due to the fact that the output power of He–Ne lasers is relatively low, the simplest scheme involves a decrease in the frequency of the femtosecond comb (i.e., a spectral transfer of the comb components from the visible/near-IR range to the mid-IR range of the methane standard). This can be realized with the generation of the difference frequency.

For this purpose, the supercontinuum radiation generated using the femtosecond laser is directed to a nonlinear crystal, which exhibits phase matching for the generation of the difference frequency (DF) spectrum in the range $\lambda = 3.39$ μm. Note that the DF spectrum (ν_n^{DF}) generated in such a scheme does not contain shift f_0, which enables one to substantially simplify the clock, since it is not necessary to stabilize frequency f_0:

$$\begin{aligned} \nu_n^{DF} &= \nu_{m'} - \nu_{m''} \\ &= (m'f_r + f_{ceo}) - (m''f_r + f_{ceo}) = nf_r, \\ n &= m' - m''. \end{aligned} \tag{2}$$

The radiation with the DF spectrum is mixed with the single-frequency radiation of the frequency standard at a photodetector and the beat signal δ for the frequencies ν_{CH_4} and the nearest kth component of the DF spectrum,

$$\delta = \nu_{CH_4} - kf_r, \tag{3}$$

is used by the system for the frequency–phase self-tuning (FPST) to control the cavity length of the femtosecond laser (i.e., to stabilize the pulse repetition rate f_r). Thus, the stability of the optical frequency of the methane standard is transferred to the repetition rate of the femtosecond pulses. This is needed for the realization of an optical clock.

If expression (3) is used to calibrate the optical reference frequency with respect to the cesium frequency standard (for absolute measurements of the optical frequency), integer k is preliminarily determined using the interferometric measurement of the wavelength (and, hence, frequency) on λ meters. The accuracy of such measurements (about 10^8) is sufficient to correctly determine k.

The scheme of the methane femtosecond optical clock based on the above analysis was experimentally demonstrated in 2004 [10]. The repetition rate (78 MHz) of the femtosecond sapphire laser used to generate the supercontinuum (0.5–1.0 μm) was stabilized using the methane standard (He–Ne/CH_4 laser) with a relatively high (about 10^{-14}/s) short-term frequency stability. The nonlinear frequency conversion of the supercontinuum to the mid-IR spectral range was performed with a periodically poled lithium niobate (PPLN) crystal.

The stabilized repetition rate ($f_r = 78$ MHz) of the femtosecond sapphire laser was compared with either the frequency of a hydrogen maser or the repetition rate of another femtosecond sapphire laser stabilized with the iodine optical frequency standard (Nd:YAG/I_2 laser [4]). It was demonstrated that the frequency stability of the methane optical clock ($f_r^{CH_4}$) is higher than the stability of the H maser at averaging times of less than 50 s. The measurement of the phase noise of the fre-

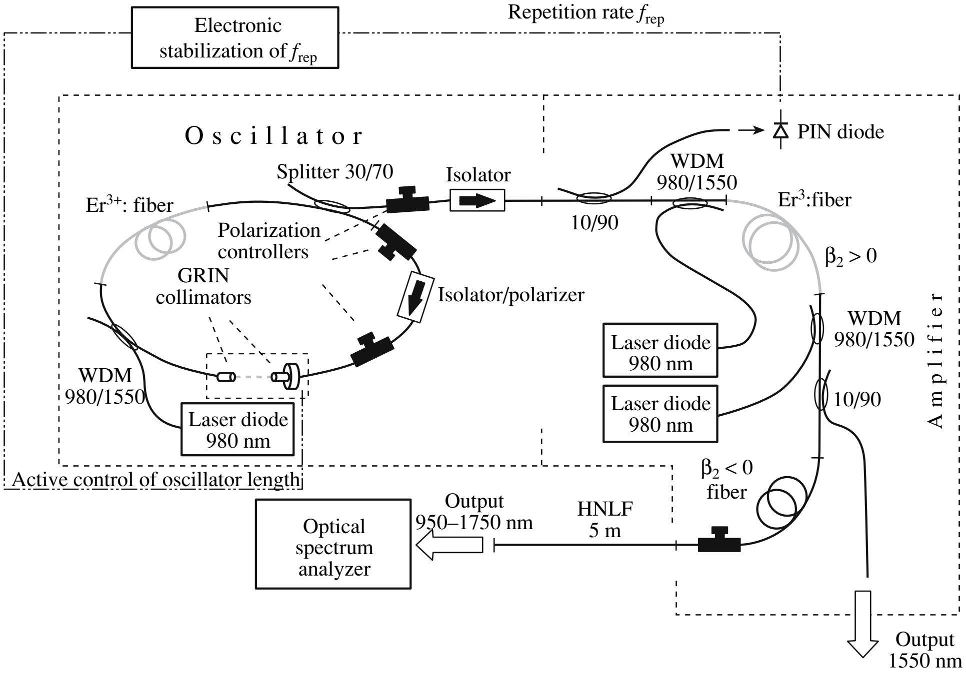

Fig. 1. Scheme of the laser system.

quency difference for two optical clocks ($f_r^{CH_4}$ and $f_r^{I_2}$) demonstrated that their total noise spectral density in the low-frequency range is less than the noise spectral density of the best quartz oscillators by 30–50 dB.

Thus, it was demonstrated that methane femtosecond optical clocks are promising for the creation of the RF master oscillators whose frequency stability and spectral width are significantly superior to those of conventional oscillators.

However, femtosecond sapphire lasers exhibit substantial disadvantages. Their price is high, their sizes are large, and their efficiency is relatively low. In addition, cw lasing is difficult to realize over several days or, even, weeks, which is one of the main requirements on an optical clock. Thus, the possibility of the creation of an optical clock based on compact femtosecond fiber lasers (e.g., lasers on fibers doped with Er^{3+} ions) has been actively investigated.

In spite of the fact that fiber lasers exhibit significantly higher (in comparison with sapphire lasers) high-frequency phase noise, they are superior with respect to several parameters. They are compact and can work for a long time in the absence of restarting: cw lasing with the generation of ultrashort pulses can be maintained over several weeks. Therefore, such lasers are promising candidates for metrological applications in a continuously working optical clock.

Systems based on Er-fiber femtosecond lasers and supercontinuum generation in fibers with a relatively high nonlinearity are demonstrated in [11–13]. These systems make it possible to generate completely phase-locked frequency combs over tens of hours. The DF spectrum in the range 1.5 μm is obtained from the supercontinuum spectrum of the Yb-fiber laser in [14].

The purpose of this work is to develop and to study the main components needed for the creation of a compact methane femtosecond optical clock: (i) Er-fiber femtosecond laser with an amplifier and a supercontinuum generator, (ii) a nonlinear converter of the mid-IR supercontinuum to the DF spectrum with the needed intensity in the range 3.39 μm, and (iii) a device for the stabilization of the repetition rate of the Er-fiber femtosecond laser.

Er^{3+}-FIBER FEMTOSECOND LASER WITH A SUPERCONTINUUM GENERATOR

Figure 1 demonstrates the scheme of the laser setup. It consists of the master oscillator (femtosecond-fiber laser), an amplifier, and a highly nonlinear fiber (HNLF) for the supercontinuum generation. The fiber laser with a unidirectional ring cavity works in the stretched-pulse mode with the nonlinear polarization rotation as the mechanism for mode locking [15]. The energy of the output laser pulses is 0.12 pJ, the pulse duration is 100 fs (the spectral width is 35 nm), and the pulse repetition rate is 62 MHz (the mean power is about 8 mW). The pulses of the master oscillator are amplified in a fiber amplifier to a mean power level of 120 mW. The amplifier represents a 3.5-m-long piece of fiber doped with Er^{3+}, which is pumped from both sides using laser diodes with a power of 300 mW and a wavelength of 980 nm. To minimize the duration of the output pulse, which is stretched due to the chirp related

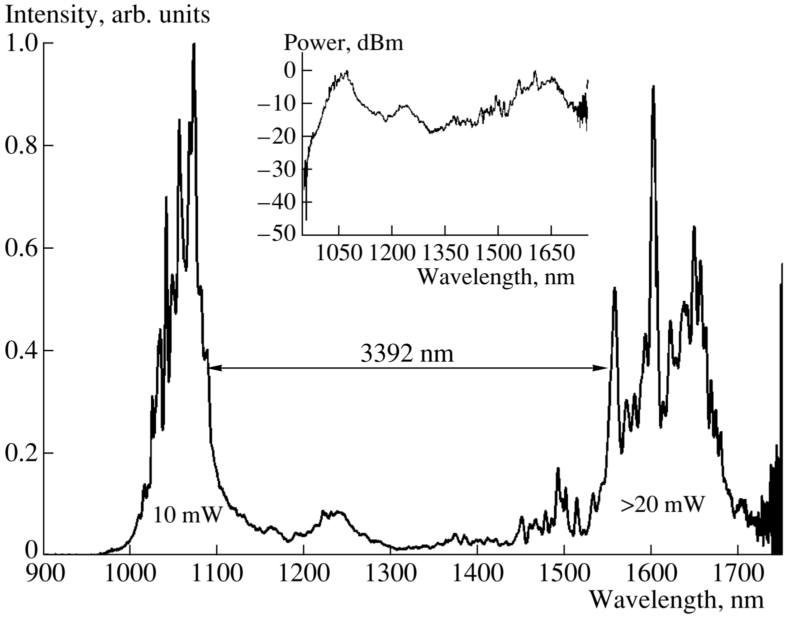

Fig. 2. Spectrum of the supercontinuum.

to the amplifier fiber, we employ a single-mode fiber with group velocity dispersion and the length needed for the chirp compensation. Amplified pulses with a duration of less than 100 fs and a spectral width of 50 nm are fed to the HNLF with a length of about 4 m. The characteristics of this fiber are as follows: the concentration of germanium oxide in the core is about 25 mol %, the mode field diameter is about 4 μm, the cutoff wavelength is $\lambda_{\text{cut off}} = 1.48$ μm, and the zero-dispersion wavelength is $\lambda_0 = 1.45$ μm. At the lasing wavelength ($\lambda = 1.55$ μm), the dispersion is $D = 2.7$ ps/nm km. The supercontinuum spectral range is 980–1750 nm (Fig. 2 [16]).

STABILIZATION OF THE REPETITION RATE OF THE FEMTOSECOND Er-FIBER LASER WITH AN RF SYNTHESIZER

Sapphire lasers consist of localized elements, so that the repetition rate is easy to monitor and control using the displacement of one of the cavity mirrors with a piezoelectric translation stage. In fiber lasers, which represent ring systems with distributed elements, the control of the repetition rate can be a problem. On the other hand, fiber lasers do not suffer from the problem of heat sink as sapphire lasers do (high-rate water cooling is not needed in fiber lasers).

To determine the stability of lasing with the active control of the cavity length and to determine the needed dynamic range of the system for frequency stabilization, we experimentally stabilize the repetition rate of the femtosecond Er-fiber laser using an external precision RF synthesizer. For this purpose, the laser cavity contains an optical system that makes it possible to vary the cavity length. It represents two gradient index (GRIN) lens collimators placed at a distance of several millimeters. One of them is mounted on a piezoelectric translation stage. The total range of the repetition-rate tuning with the piezoelectric translation stage is 60 Hz. The laser remains mode-locked across the entire range of the piezoelectric translation stage.

To eliminate environmental effects on the drift of the repetition rate f_r, we place the system in a closed box with a metal plate that is thermally stabilized with an accuracy of 0.1°C.

To stabilize the repetition rate $f_r = 62$ MHz using the RF synthesizer, we deliver the photodetector signal to a double balance mixer, where this signal is compared with the reference signal of the synthesizer. The error signal is amplified using a high-voltage amplifier and is fed to the piezoelectric unit that controls the laser cavity length. Figures 3 and 4 demonstrate the measured laser repetition rate. Figure 3a shows the residual fluctuations of the repetition rate for the averaging time $\tau = 1$ s. The corresponding standard deviation of the repetition rate is 0.22 mHz. For comparison, Fig. 3b demonstrates the frequency fluctuations of the reference synthesizer. Figure 4 shows the instability (Allan deviation) of the repetition rate of the free-running laser and the laser locked to the reference synthesizer and the frequency of the reference synthesizer (the averaging times are up to 100 s). It is seen from the data presented that the stability of the laser repetition rate is completely determined by the stability of the reference quartz oscillator.

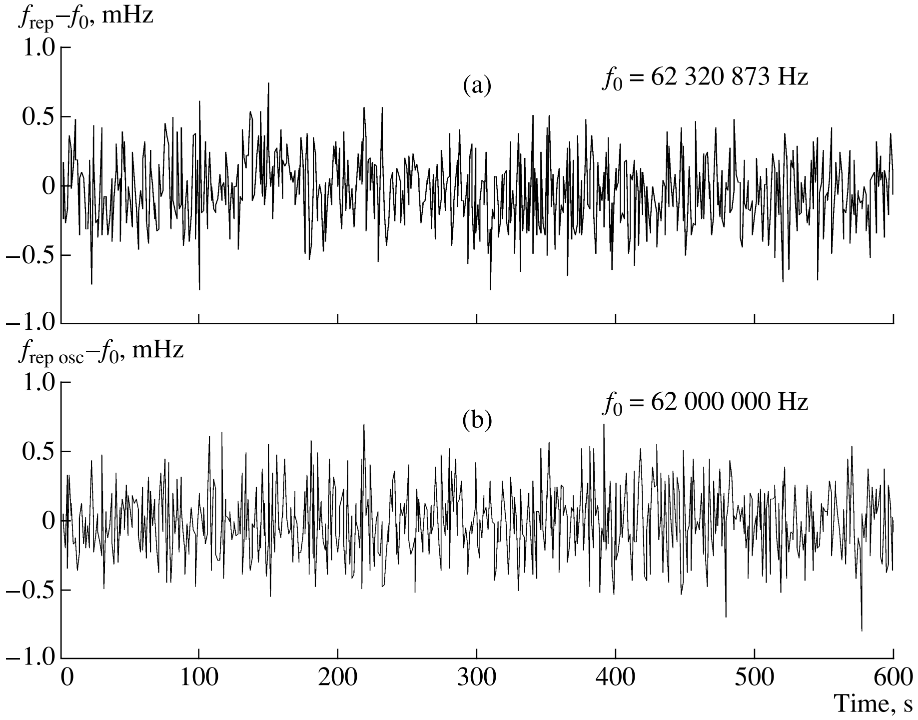

Fig. 3. Fluctuations of (a) the repetition rate of the stabilized Er laser and (b) the frequency of the reference synthesizer.

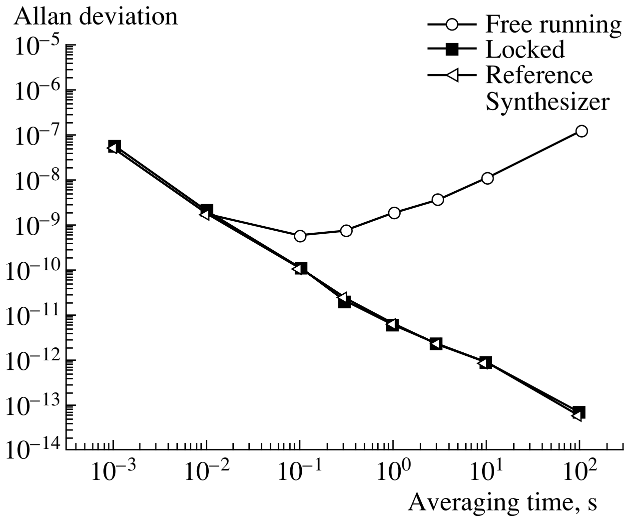

Fig. 4. Allan deviation for the repetition rate of the Er laser.

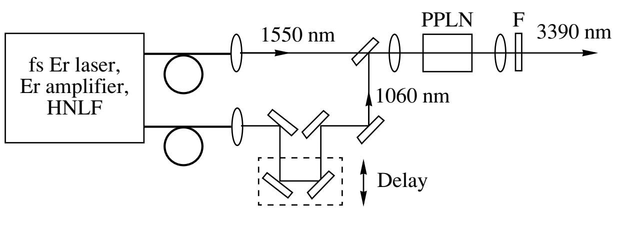

Fig. 5. Optical scheme of the DFG setup (F is the optical filter).

GENERATION OF THE DF SPECTRUM

Figure 5 shows the optical scheme of the setup for the supercontinuum generation at DFs in the wavelength range 3.39 μm. We use about 10% of the output power of the Er-fiber amplifier at a wavelength of 1550 nm for the DF generation (DFG). The main part of the radiation is delivered to the HNLF for the supercontinuum generation. A spectral component with a wavelength of 1060 nm, which is selected from the supercontinuum, is used as the second component for the DFG process in the PPLN crystal that exhibits phase matching for the above waves. In the experiments, we employ the PPLN crystal with the MgO impurity (5 mol %). Its length is 8 mm and the lattice period is 30.45 μm for the DFG in accordance with the relationship 1/1060 nm (*e*) – 1/1550 nm (*e*) = 1/3390 nm (*e*).

The radiation power incident on the crystal is 10 mW at λ = 1550 nm in a band with a width of about 50 nm and 8 mW at λ = 1060 nm in a band with the same width. The power of the resulting DF radiation (3390 nm) is 1.5 μW. Figure 6 shows the optical spectrum of the DF radiation. The spectral width is about 35 nm. For an interval of 62 MHz between the femtosecond comb components, the power of a single spectral component is $P_n \sim 100$ pW.

We plan to realize the beating of the frequency components of the resulting spectrum that are close to a wavelength of 3.39 μm and the methane frequency reference at a sensitive InSb photodetector whose detec-

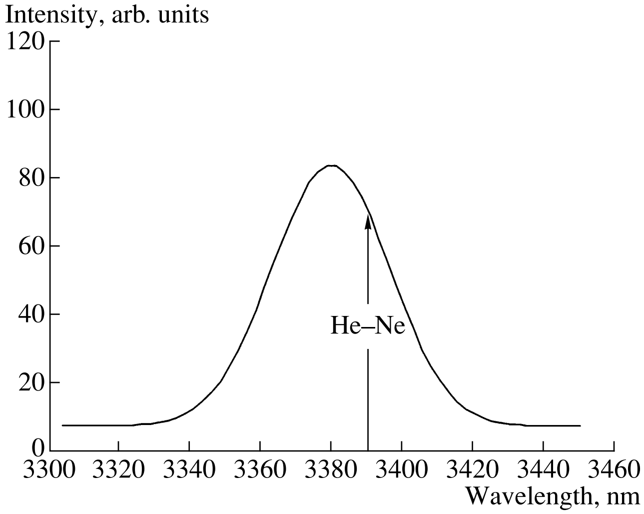

Fig. 6. DF radiation spectrum.

tion limit is about 10^{-11} W/Hz$^{1/2}$). For an output power of the methane reference of about 1 mW, the power of the RF beat signal must be about 1 μW, which yields a signal-to-noise ratio of about 50 dB/Hz$^{1/2}$ or about 20 dB for a band of 100 kHz. This corresponds to a conventional requirement on the stable (without phase slip) operation of the PLL system that controls the cavity length of the femtosecond Er-fiber laser. Thus, the stability of the methane reference will be transferred to the repetition rate of the laser pulses (i.e., to the RF spectral range).

CONCLUSIONS

The results needed for the realization of a compact femtosecond methane optical clock are presented: the supercontinuum with high-intensity spectral fragments is obtained in the Er-fiber laser radiation and the supercontinuum from the range 1.0–1.5 μm is transformed to the DF spectrum in the range 3.39 μm, so that the intensities of the DF spectral components are sufficient for the stabilization of the femtosecond laser repetition rate using the He–Ne/CH_4 reference. The proposed devices for the passive and active stabilization of the pulse repetition rate of the Er-fiber laser provide a stabilization accuracy of about 10^{-3} Hz at a response time of 10^{-3} s and the possibility of continuous daily operation.

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