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Synchronisation of the radiation frequency of diode lasers with the mode frequency of a highly stable femtosecond Ti:sapphire laser

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***Abstract*. The phase locking of diode lasers to the frequency component (mode) of the output radiation of a highly stable femtosecond Ti:sapphire laser, resulting in the amplification of the mode power by several orders of magnitude, is reported. The possibilities of using femtosecond lasers for creation of a new generation of miniature optical clocks and for synthesis and measurements of absolute laser frequencies are discussed.**

Keywords: *femtosecond laser, synthesis of optical frequencies, optical clock, stabilisation of the laser frequency.*

The prospects for using femtosecond lasers in metrology for creation of an optical clock [1–3] and highly accurate measurements of the absolute values of optical frequencies [4, 5] have been recently demonstrated. These applications are based on the property of a mode-locked femtosecond laser to generate a broad spectrum of equidistant frequencies. It was shown in Refs [1, 2] that the intermode frequency of self-mode-locked lasers could be stabilised by phase locking the intermode beat frequency to the frequency of an external highly stable oscillator. In this case, the equidistance of the intermode intervals is provided by the process of self-mode-locking itself with accuracy of no worse than 10^{-16} [6]. In such a way, a highly stable array of equidistant frequencies with a step of 100 MHz–1 GHz can be produced, covering the frequency range up to several hundreds of terahertz.

The use of such a frequency scale allows one to perform very precise measurements of broad frequency intervals in the systems for synthesis and absolute measurements of optical frequencies, which substantially simplifies the structure of these systems [5]. Indeed, if it is necessary to measure precisely the frequency interval between the known frequency ν_0 and the frequency $\nu_{\rm m}$ being measured, and both these frequencies fall in the region covered by the modes of a femtosecond laser, it is sufficient to measure beat frequencies f_0 and $f_{\rm m}$ between these frequencies and nearest laser modes and to determine, with the help of additional rough measurements, the number N of intermode intervals between them. Then, the frequency interval being measured can be determined from the relation $|\nu_{\rm m} - \nu_0| = N\Delta\nu \pm f_0 \pm f_{\rm m}$, where $\Delta\nu$ is the intermode frequency.

If the intermode frequency is coupled to the radio-frequency standard, while one of the synchronised laser modes is simultaneously coupled to the frequency of an optical standard, we obtain a scale of standard frequencies, which are known with the accuracy of primary frequency standards. In this case, any frequency in the spectral range under study can be measured without using special schemes for frequency synthesis. Any laser frequency lying within the interval covered by the scale of standard frequencies can be measured from the beat frequency between the frequency being measured and the nearest standard frequency.

The creation of an optical clock assumes the transfer of frequency characteristics of an optical standard to the radio-frequency range. In the optical clock created earlier [7], this transfer was performed using harmonic generation and a chain of mutually synchronised lasers with successively decreasing frequencies. Such a clock represents a complex stationary setup. In Ref. [3], a simpler scheme was proposed, based on the use of a femtosecond laser.

Fig. 1 illustrates the physical principle of this clock. A femtosecond laser used in the clock should generate the spectrum of modes, which covers the frequency interval that is equal to the laser standard frequency. A He–Ne/CH_4 laser standard used in the clock emits at the frequency 88.5 THz, which corresponds to the pulse duration equal to 10 fs. The difference frequency between the modes of a femtosecond laser, whose intermode interval is equal to the frequency of the He–Ne/CN_4 standard, is generated with the help of a nonlinear crystal. Then, this difference frequency is stabilised by phase locking to the standard frequency. In this case, the intermode frequency $\Delta\nu$, which lies in the radio-frequency range, is also stabilised, i.e., a single-stage transfer of the frequency characteristics of the optical standard to the radio-frequency region occurs. Note that, although the

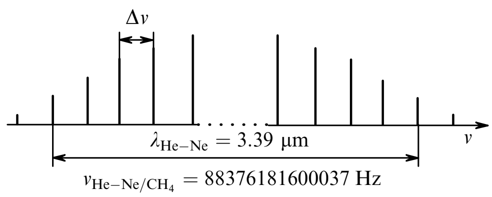

Figure 1. Physical principle of a femtosecond optical clock.

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intermode frequency is stabilised, the absolute frequency of the modes can be unstable; however, this circumstance is inessential for the scheme under study.

However, the direct use of the modes of a femtosecond laser in the schemes discussed above, in particular, for obtaining the difference frequency in a nonlinear crystal in the optical clock is substantially hindered due to the low power of an individual mode. For example, if the average power of a femtosecond laser is 200 mW, $\Delta\nu = 10^8$ Hz, and $N \approx 885000$ (for $\nu_{\rm He-Ne} = 88.5$ THz), then the power of a single mode will be only $0.2/N \approx 2 \times 10^{-7}$ W.

In this paper, we propose to 'increase' the power of separated modes of a femtosecond Ti:sapphire laser by using the radiation from additional single-frequency tunable diode lasers with an external cavity, which are phase-locked to the frequency of the separated modes of the femtosecond laser. We describe the design of diode lasers and their basic characteristics; substantiate the choice of the operating parameters of the phase offset lock (POL) system for automatic frequency tuning; and present the results of the experimental study of phase locking. In conclusion, we consider a functional scheme of the femtosecond optical clock based on the method described.

We studied phase locking of laser diodes to the modes of a femtosecond laser on the setup representing a part of the optical clock (Fig. 2). We used a highly stable femtosecond Ti:sapphire laser that was similar to that described in Ref. [2]. The laser was pumped by a cw argon laser. The average output power was about of 300 mW upon 7-W all-line pumping. The duration of femtosecond pulses was about of 100 fs, which corresponds to their spectral width ~ 10 nm. The beat frequency of adjacent modes was stabilised by phase locking to the frequency of a highly stable oscillator. The error signal was minimised with the help of a piezoelectric ceramics on which one of the cavity mirrors was mounted, i.e., by varying the laser cavity length. The relative root-mean-square deviation of the intermode frequency from its average value was 1.17×10^{-12} and 5.6×10^{-14} for the averaging times equal to 10 and 100 s, respectively.

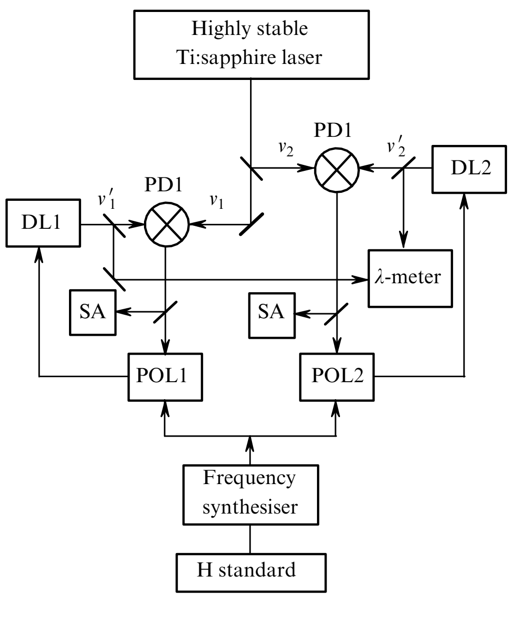

Figure 2. Scheme of the experimental setup: (DL) diode laser; (SA) spectrum analyser; (PD) photodiode; (POL1,2) automatic phase tuning of frequency; (H standard) hydrogen frequency standard.

The radiation of a Ti:sapphire laser containing modes with frequencies ν_1 and ν_2 was mixed with the help of beamsplitters with radiation from diode lasers DL1 and DL2 emitting at frequencies ν_1' and ν_2' that were close to the frequencies of separated modes. Each of the mixed radiation beams was directed on photodiodes PD1 and PD2, which detected beat signals between the frequency of the corresponding diode laser and the adjacent mode of the Ti:sapphire laser. The amplitude of the beat signal was determined by the power of one separated mode. The power of the rest of the modes contributed to noise.

To increase the signal-to-noise ratio, the spectrum of modes incident on the photodiode was narrowed. For this purpose, the mixed radiation was directed after the beamsplitter to a diffraction grating, and a part of the diffracted radiation beam with the required frequency was separated by a slit and directed to the photodiode. The position and width of the slit were adjusted to the maximum of transmission of the diode laser emission. The frequencies of diode lasers were controlled with a λ-meter and the spectra of the beat signal and beat frequencies were recorded with a Rohde & Schwarz FSEK analyser. The beat signal from photodiodes was fed to systems POL1 and POL2, whose error signal was used for tuning the frequencies of DL1 and DL2 lasers.

We used in our experiments diode lasers SDL-5411 and ILPN-820 with output powers 100 and 50 mW, respectively. The linewidth of the lasers operating in the free-running mode exceeded 10 MHz and their frequency was determined by the diode temperature and injection current. To tune the laser to the required frequency and narrow down its line, an external cavity was used. The feedback was implemented with the help of a 1800 mm^{-1} diffraction grating placed at a distance of 35 mm from the laser diode in the autocollimating mounting. The diode emission was collimated with an aspherical lens with a focal length of 4.3 mm and a numerical aperture of 0.47.

The laser design is shown in Fig. 3. Laser diode (*1*) and lens (*3*) are mounted on holder (*2*). The holder design allows one to mount on it lasers having housings of different shapes. The distance between the laser diode and the lens could be precisely regulated by adjusting screw (*4*). The diffraction grating (*8*), which was glued to piezoelectric ceramics (*7*) via intermediate holder (*9*), was mounted on alignment head (*6*). The output emission represented the emission reflected in the zero order of the diffraction grating. Mirror (*10*) was used to compensate for the angular displacement of the output beam upon grating rotation. Aligning units (*2*) and (*6*) were mounted on a common base (*12*).

The entire construction was thermally stabilised with an accuracy of 0.01°C with the help of thermoelectric element (*13*) mounted on a massive base (*14*), which was used for heat removal. The entire cavity was placed inside a soundproof case to protect the laser against external acoustic perturbations. The course tuning of the laser within 30 nm was performed by rotating the diffraction grating. The fine tuning was provided by a piezoelectric ceramics within ~ 4 GHz, which is approximately equal to the intermode interval.

In the case of a careful isolation of the lasers from acoustic perturbations, the output emission linewidth measured from the beat spectrum for two identical lasers was

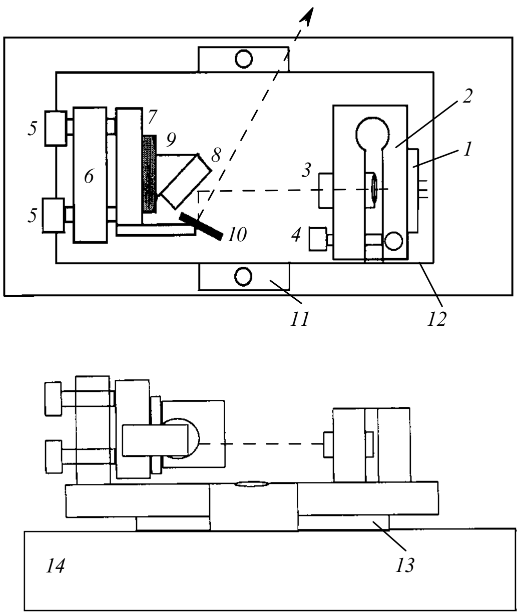

Figure 3. External cavity diode laser: (*1*) diode laser; (*2*) diode and objective holder; (*3*) aspheric lens; (*4*, *5*) adjusting screws; (*6*) adjusting head; (*7*) piezoelectric ceramics; (*8*) diffraction grating; (*9*) holder; (*10*) mirror; (*11*) thermally insulated holder; (*12*) cavity base; (*13*) thermoelectric element; (*14*) laser base.

about of 300 kHz. The output power in a single-frequency mode was 30 mW for SDL-5411 laser diodes and about 13 – 15 mW for ILPN-820 lasers.

Phase locking of the diode laser frequency was performed with the help of a piezoelectric element and by controlling the current. The current control provided a high rate of tuning with frequencies up to $\sim$ 300 kHz, the sensitivity by current in the static regime was 70 MHz m^{-1} A^{-1}. The control of the cavity length with the help of the piezoelectric element provided a sufficiently broad dynamic range of phase locking. The sensitivity of the piezoelectric element control was 10 MHz V^{-1}.

The POL system producing the error signal, which was proportional to the phase difference between the beat frequency and the reference frequency, included an amplifier, a phase detector, and two feedback circuits for the frequency control: a fast one and a slow one. In the fast circuit, the error signal from the phase detector passed through a filter and was used to control the laser diode current. In the slow circuit, a high-voltage signal was produced to control the piezoelectric ceramics. The reference frequency was fed to the POL system from a frequency synthesiser, which was stabilised relative to the hydrogen frequency standard. The beat signal frequency and, hence, the reference frequency were chosen to be 12 MHz. The characteristics of the POL system were chosen in accordance with the parameters of the beat signal obtained.

The beat signal power was about of – 90 dBm. Taking into account that the output power of the diode and Ti:sapphire lasers was $\sim 10^{-3}$ and 10^{-6} W, respectively, this indicated to a poor matching of the wave fronts. However, this parameter should not be optimised at this stage. To suppress amplitude perturbations, a signal was amplified to the restriction level using an amplifier with the gain $\sim$ 90 dB. In addition, to limit the band of phase perturbations of the frequency F_{p} within $\sim$ 20 kHz ($F_{\mathrm{d}}/F_{\mathrm{p}} < \pi < 2$, where F_{d} is the frequency deviation at the frequency F_{p}), we used the frequency divider (division by 12), because the bandwidth of frequency perturbations can reach $\sim$ 300 kHz in the free-running (without division) mode.

To achieve a stable phase locking of the diode laser frequency to the frequency of a certain mode of the Ti:sapphire laser, several conditions should be satisfied: the signal-to-noise ratio should be no less than 20 dB; the spectral width of the beat signal in the free-running mode should lie within the limits determined by the phase locking circuit, while slow deviations of the signal frequency from the mean value caused by external perturbations should not exceed $\sim$ 10 MHz. These conditions were realised by separating a narrow spectral range ($\sim$ 0.1 nm) from a broad ($\sim$ 10 nm) output spectrum of the Ti:sapphire laser, acoustically isolating lasers from external perturbations, and stabilising power supplies and thermally stabilising the diode laser.

Spectral parameters of the beat signal were recorded with a spectrum analyser. Fig. 4 shows beat signals recorded by averaging for 1 and 100 s. In both cases, a narrow spectrum of the beat signal is observed and a characteristic noise pedestal caused by the amplitude–phase noise of diode lasers. Because the signal was fed to the spectrum analyser from the photodetector without an amplifier-limiter, it was accompanied by the amplitude noise (Fig. 4a). As the averaging time increased (in our case, to 100 s), the noise tended to the minimum level (Fig. 4b). The noise pedestal represents the frequency–phase perturbations. One can see from Fig. 4b that to suppress them to the resolution level of the analyser, a high transfer coefficient of the phase locking circuit is required (more than 20 dB).

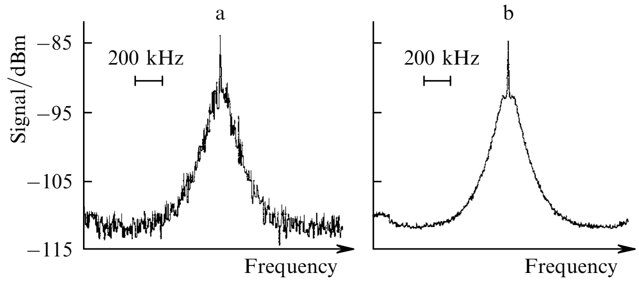

Figure 4. Spectrum of the beat signal between a mode of a femtosecond Ti:sapphire laser and emission of a single-frequency diode laser upon phase locking of the latter to this mode. The averaging time is 1 (a) and 100 s (b) and the pass band is 10 kHz.

In our case, the error signal from the POL system was minimised by the diode laser current. Such a control of the frequency results in the amplitude modulation of the output power of the diode laser. In addition, amplitude fluctuations of the output power of the Ti:sapphire laser caused by the instability of the Ar laser output also contribute to the amplitude noise.

Fig. 4 shows that the achieved operation band is $\sim$ 30 – 40 kHz. It is mainly determined by the depth of suppression of the amplitude noise, which is described by the expression $A \sim \exp(U_{\mathrm{s}}^2/U_{\mathrm{n}}^2)$ [8], where U_{s} is the signal amplitude at the 0.7 level in the synchronisation band and U_{n} is the amplitude noise level in the same band. Later, we obtained a signal at the difference frequency $|\nu_k - \nu_n|$ using a Schottky diode. However, these studies are of independent interest and are not discussed here.

Thus, we achieved a reliable phase locking of diode lasers to the mode frequencies of the Ti:sapphire laser and obtained a highly stable beat signal between these diode lasers. If necessary, any number of diode lasers can be phase locked by this method to the modes of a femtosecond Ti:sapphire laser.

In conclusion, we discuss briefly a femtosecond optical clock, in which the above-described scheme was used. Fig. 5 shows the scheme of an optical clock with the He–Ne/CH_4 laser frequency standard. Diode lasers serve as power 'amplifiers' for modes of the femtosecond Ti:sapphire laser at frequencies ν_1 and ν_2 (at wavelengths 0.75 and 0.96 μm, respectively). The emission at the difference frequency $|\nu_1 - \nu_2| \approx \nu_{CH_4}$, which appears behind a nonlinear crystal, is mixed with the emission of the He–Ne/CH_4 standard at the frequency ν_{CH_4} and these two emissions are incident on the photodiode. The low-frequency beat signal from the photodiode at the frequency $||\nu_1 - \nu_2| - \nu_{CH_4}|$ is fed to the POL system, whose error signal is fed to the Ti:sapphire laser for minimising. As a result, the frequency interval $|\nu_1 - \nu_2|$ in its spectrum and, hence, $\Delta\nu$ prove to be stabilised over the frequency of the He–Ne/CH_4 standard.

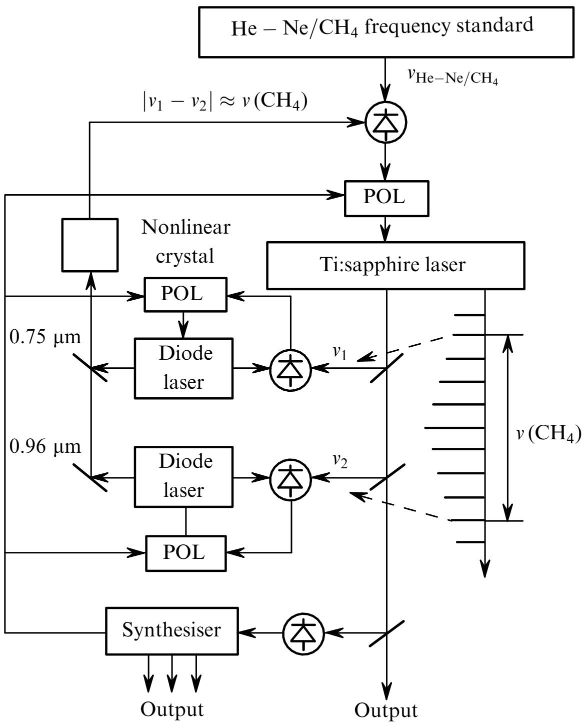

Figure 5. Scheme of a femtosecond optical clock.

Therefore, frequency characteristics of the He–Ne/CH_4 standard are transferred to the radio-frequency range without using any intermediate stages. The scheme is autonomous, i.e., it does not require an external reference oscillator. By using the beat frequency between the modes separated by different intermode intervals, we can obtain 'a comb' of stable frequencies in the optical range, which are strongly locked with frequencies in the radio-frequency range. If necessary, the width of the emission spectrum of the Ti:sapphire laser can be increased with the help of a single-mode optical of photonic crystal fibre.

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