 

***OPTICAL FREQUENCY STANDARDS***

https://doi.org/10.1070/QEL16909

# Methane microwave optical master oscillator for fountain references

A.S. Shelkovnikov, A.I. Boiko, A.N. Kireev, A.V. Tausenev, D.A. Tyurikov, D.V. Shepelev, A.V. Konyashchenko, M.A. Gubin

***Abstract.*** **We have demonstrated a microwave master oscillator operating on optical principles and based on a He–Ne/$CH_4$ optical frequency standard ($\lambda$ = 3.39 μm) and femtosecond fibre laser system ($\lambda$ = 1.54 μm). The output signal spectrum of the oscillator has the form of an equidistant frequency comb in the range 60 MHz to 10 GHz with a 60-MHz step. Comparison of the frequencies of two master oscillators shows that the short-term output frequency instability for the comb components in the range 0.8–1.5 GHz is under $1 \times 10^{-14}$ at an averaging time of 1 s. We have tested microwave signals from the oscillator using apparatus in the reference facility at the State Time and Frequency Service, All-Russia Research Institute of Physical and Radio Engineering Measurements. A signal at a nominal frequency of 100 MHz synthesised from one comb component was compared to signals from two hydrogen masers with enhanced short-term stability in the reference facility. The short-term frequency stability of the synthesised signal has been shown to be twice better than the stability of the masers and to be limited by the intrinsic instability of the commercial synthesiser of a 100-MHz nominal frequency. Our experiments confirm that the proposed microwave optical master oscillator is potentially attractive for use in systems with increased requirements for short-term frequency stability, in particular in time and frequency fountain references.**

***Keywords:*** *He–Ne/$CH_4$ frequency standard, femtosecond optical frequency divider, femtosecond fibre laser, ultralow-phase-noise microwave oscillator, atomic fountain.*

**A.S. Shelkovnikov, A.N. Kireev, D.A. Tyurikov** P.N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; e-mail: shelkov@x4u.lebedev.ru;
**A.I. Boiko** All-Russia Research Institute of Physical and Radio Engineering Measurements, 141570 Mendeleevo, Moscow region, Russia;
**A.V. Tausenev, A.V. Konyashchenko** P.N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; Avesta Project Ltd., Fizicheskaya ul. 11, Troitsk, 108840 Moscow, Russia;
**D.V. Shepelev** Avesta Project Ltd., Fizicheskaya ul. 11, Troitsk, 108840 Moscow, Russia;
**M.A. Gubin** P.N. Lebedev Physical Institute, Russian Academy of Sciences, Leninsky prosp. 53, 119991 Moscow, Russia; All-Russia Research Institute of Physical and Radio Engineering Measurements, 141570 Mendeleevo, Moscow region, Russia; Bauman Moscow State Technical University, Vtoraya Baumanskaya ul. 5, 105005 Moscow, Russia

Received 18 November 2018; revision received 24 January 2019
*Kvantovaya Elektronika* **49** (3) 272–277 (2019)
Translated by O.M. Tsarev

## 1. Introduction

At present, fountain references and frequency keepers based on cold Cs (transition frequency $\nu$ = 9.2 GHz) and Rb ($\nu$ = 6.8 GHz) atoms are used as primary frequency and time standards forming a global time scale and national time scales [1]. The accuracy of the best Cs references is at a level of $1 \times 10^{-16}$, which is two orders of magnitude better than the accuracy of the preceding generation of Cs references based on thermal atoms. Basic to the progress made to date have been laser cooling methods, which have made it possible to obtain a Ramsey fringe width $\Delta\nu \sim 1$ Hz (relative linewidth $\Delta\nu/\nu \sim 10^{-9}$). Studies of noise characteristics of passive frequency standards, including fountains, demonstrate that, because of the Dick effect [2, 3], the time needed to reach such accuracy depends significantly on the short-term frequency stability of the interrogation signal generator, or master oscillator (MO) because, in detecting a narrow reference line signal and finding its centre it is necessary to average the noise arising from frequency fluctuations in the MO.

The time needed for obtaining one data point of a reference Ramsey fringe in fountains is determined by the 'elementary' cycle duration $T_c$, which includes the preparation (cooling) of a bunch of atoms, flight along a trajectory and detection of photons emitted by the atoms, and amounts to a total of ~1 s. A point of vital importance is the ability to maintain microwave field coherency during this time interval i.e. an MO with a high short-term frequency stability is necessary.

The fractional frequency instability of an atomic fountain depends on the noise and measurement time $\tau > T_c$ as follows [4]:

$$\sigma_y = \frac{1}{\pi Q_{at}}\sqrt{\frac{T_c}{\tau}}\sqrt{\frac{1}{N_{at}} + \frac{1}{N_{at}N_{ph}} + \frac{2\sigma^2_{\delta N}}{N^2_{at}} + \gamma}\,, \quad (1)$$

where $Q_{at}$ is the quality factor of the line ($Q_{at} = \nu_0/\Delta\nu$). The first three terms under the square root, which include the number of atoms in the cloud ($N_{at}$) and the number of photons ($N_{ph}$) in luminescence detection, determine intrinsic noise in the fountain; the last term, $\gamma$, represents the contribution of the instability of the interrogation signal generator; and $\sigma_{\delta N}$ is the uncorrelated rms fluctuations in the number of atoms in the detection channel.

Intrinsic instability [$\sigma_y(\tau)$ in (1) at $\gamma = 0$] in the existing fountains varies in the range $(10^{-14}-10^{-13})/\sqrt{\tau/1\,\mathrm{s}}$, depending on the particular realisation of the standard [5, 6]. If precision quartz oscillators or H masers having a characteristic short-term frequency instability of $1 \times 10^{-13}$ at $\tau$ = 1 s are used as sources of an interrogation signal fed to a microwave oscillator, the noise averaging time needed to reach an accuracy of $1 \times 10^{-16}$ is $(1-2) \times 10^6$ s (three to four weeks). Therefore, in the case of low-noise fountains with an intrinsic instability of $(1-3) \times 10^{-14}/\sqrt{\tau/1\,\text{s}}$, it is extremely important to use a master oscillator with a short-term instability within $1 \times 10^{-14}$ at $\tau$ = 1 s (an order of magnitude lower than that of quartz or a H maser), because this allows the time needed for a fountain to reach its nominal accuracy to be reduced by two orders of magnitude. Radically reducing the measurement time reduces the systematic error in the reference frequency, because this enables high-speed control over operation of the fountain and allows one to correct the time scale being formed.

For example, using an MO with an instability of $7.8 \times 10^{-15}$ at $\tau$ = 1 s, Lipphardt et al. [6] were able to lower the instability of the CSF2 fountain by almost one order of magnitude, to a level of $2.5 \times 10^{-14}/\sqrt{\tau/1\,\text{s}}$, reducing the time needed for the fountain to reach a level of $1 \times 10^{-16}$ from weeks to 17 h. The instability value obtained corresponded to intrinsic noise in the fountain and the contribution of noise in the MO was negligible.

The problem of making a microwave master oscillator with a high short-term stability (low phase noise level at a small detuning from the carrier) is important for a number of other applications: for designing precision spectrum analysers and phase noise meters, improving the signal detection sensitivity of radio telescopes and space monitoring systems etc. (see Refs [7, 8] and references therein).

In foreign laboratories, two approaches are mainly used for making high-stability MOs for fountains: based on a cryogenic microwave sapphire oscillator, which is a rather complex and expensive system [9], and based on lasers stabilised to ultrahigh-quality-factor Fabry–Perot interferometers, with optical-to-microwave frequency division by a femtosecond laser system [10]. The advances made by Russian researchers in producing and utilising interferometers for fundamental metrology were summarised in Refs [11, 12].

In this study, a different approach is used for making a high-stability MO based on optical principles: a He–Ne/$CH_4$ optical standard is employed as a stable frequency source and, like in the case of ultrahigh-$Q$ interferometers, its frequency is divided to the microwave domain by a femtosecond laser system.

Attractive aspects of the approach under development is that it requires no cryogenic equipment and that there is no direct influence of thermal vibrations of the cavity or mirror surface on frequency instability, because a quantum reference (spectral line of methane) is used instead of optical resonance determined by the geometry of the macroscopic system. Its low-frequency stability depends on its thermal expansion coefficient and the stability of external conditions (temperature, pressure and vibrations). The use of a methane quantum reference allows one to achieve high short- and long-term stability, at least on a timescale up to several hours, because frequency drift of a spectral line is substantially smaller than interferometer resonance drift.

At present, the short-term frequency instability of the He–Ne/$CH_4$ standard, which determines limiting characteristics of the MO, is $7 \times 10^{-15}$ at an averaging time of 1 s. The He–Ne/$CH_4$ optical frequency standard (OFS) is inferior in this parameter to systems with Fabry–Perot interferometers fabricated from the ULE material ($\sim 1 \times 10^{-15}$ at $\tau$ = 1 s), but there are possibilities of improving the short-term stability of the methane OFS and maintaining its level at averaging times up to $\tau \sim 10^4 - 10^5$ s. If a He–Ne/$CH_4$ MO is used as an interrogation signal generator for Cs and Rb fountains, the OFS stability reached to date is sufficient as the intrinsic instability of the best fountains is at a level of $(2-3) \times 10^{-14}$ when extrapolated to $\tau$ = 1 s.

The first versions of a methane MO were demonstrated experimentally by Foreman et al. [13], using a femtosecond Ti:sapphire synthesiser, and then by Gubin et al. [14, 15], who used a compact femtosecond synthesiser based on an erbium-doped fibre laser. The intrinsic instability of an optical frequency divider (OFD) was measured by Kireev et al. [16], who obtained $1 \times 10^{-14}$ at an averaging time of 1 s for a 3-Hz bandwidth. In this paper, we report further development of the methane MO. A direct comparison with masers indicates that the MO is superior in short-term stability to the H masers with improved short-term stability that are used in fountains at the All-Russia Research Institute of Physical and Radio Engineering Measurements (VNIIFTRI).

We describe the basic components of a new generation of methane MOs and present results of microwave signal frequency stability measurements at the Laboratory of Quantum Radiophysics, P.N. Lebedev Physical Institute, Russian Academy of Sciences, and on a reference facility at the Main Metrological Center, State Time and Frequency Service, VNIIFTRI.

## 2. General scheme of the master oscillator

The methane MO (Fig. 1) consists of two main components: He–Ne/$CH_4$ OFS ($\lambda$ = 3.39 μm) and OFD. The latter includes an erbium fibre laser ($\lambda$ = 1.54 μm) based femtosecond laser system and an optical interface that ensures the generation of a difference frequency comb in a periodically poled lithium niobate crystal at OFS wavelengths in the range 3.3–3.4 μm [15].

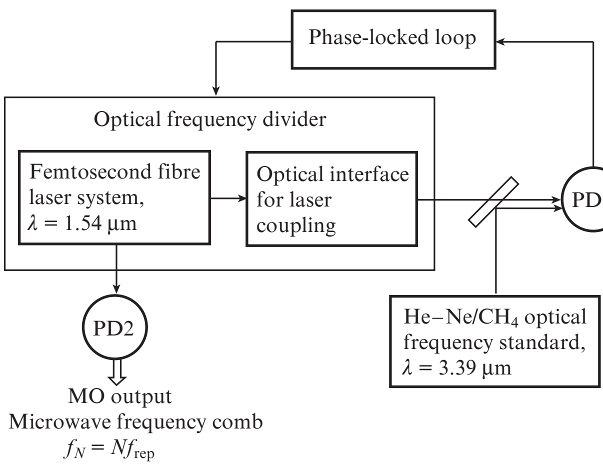


**Figure 1.** Schematic of the MO based on a He–Ne/$CH_4$ optical frequency standard.

The component frequencies $\nu_n$ of the difference frequency comb are only determined by the pulse repetition rate $f_{\text{rep}}$ of the femtosecond laser, $\nu_n = nf_{\text{rep}}$ (where $n$ is an integer), as the comb frequency detuning from zero, $f_0$, is subtracted in the difference frequency generation process. This considerably simplifies the femtosecond part of the device because no additional channel for $f_0$ stabilisation is required, i.e. the beat signal between the frequency of one component of the difference frequency comb and the He–Ne OFS frequency is sufficient for $f_{rep}$ frequency locking to an optical reference.

Below, we briefly describe the key features of the main components of the methane MO.

### 2.1. He–Ne/$CH_4$ optical frequency standard

The optical frequency standard consists of two cw lasers: a two-mode He–Ne/$CH_4$ reference laser stabilised to the $F_2$ line of methane and a single-mode heterodyne He–Ne laser locked to the reference laser by a phase lock loop system. The latter generates two modes with mutually orthogonal linear polarisations and a frequency difference $\omega_{12} = \omega_1 - \omega_2 \approx$ 5 MHz. The intermode beat frequency $\omega_{12}$ is used for detecting the sub-Doppler saturated dispersion resonance in methane, to which the laser frequency is locked [17]. For locking, we use the saturated dispersion resonance, separated out by a frequency detector, and its second harmonic, separated out by a synchronous detector (Fig. 2). The modulation frequency is $f_m$ = 8 kHz.

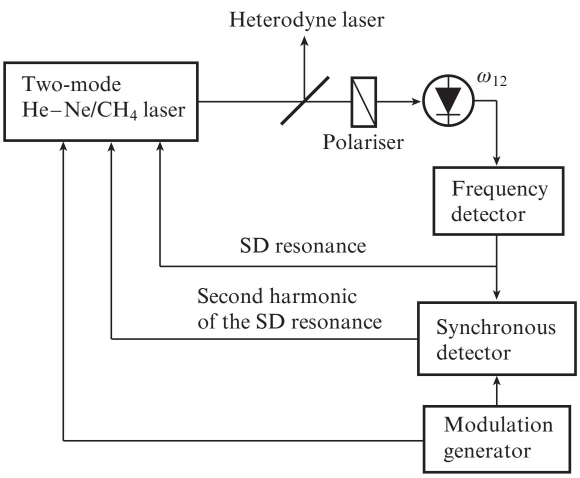


**Figure 2.** Schematic of the stabilisation of the two-mode He–Ne/$CH_4$ reference laser frequency to saturated dispersion (SD) resonances; $\omega_{12}$ is the intermode beat frequency.

The amplitude (peak-to-peak height) of the resonance is ~130 kHz and its full width is $2\gamma \approx$ 440 kHz (Fig. 3). The intermode beat frequency noise spectral density at the output of the frequency detector at the second harmonic of the modulation frequency ($2f_m$) is 0.15 Hz $Hz^{-1/2}$. This value is roughly equally contributed by natural frequency noise in the laser, noise in the frequency detector and additive noise in the InAs photodetector. The above parameters of the resonance allowed us to reach an optical frequency instability (relative Allan deviation) of $7 \times 10^{-15}$ at an averaging time of 1 s. Frequency stability was assessed by comparing heterodyne lasers in two identical OFS's. The output of the heterodyne laser does not contain the frequency modulation used in the reference laser and it has an increased output power (~1 mW), sufficient for use in a femtosecond divider.

Structurally, the optical cavities of both the reference and heterodyne lasers have the form of glass-ceramic monoblocks [18]. The monoblock laser design and the absence of liquid-nitrogen-cooled photodetectors allowed us to make a relatively compact device, with the possibility of subsequently improving its performance, in particular by enhancing its long-term frequency stability, e.g. through thermal stabilisation.

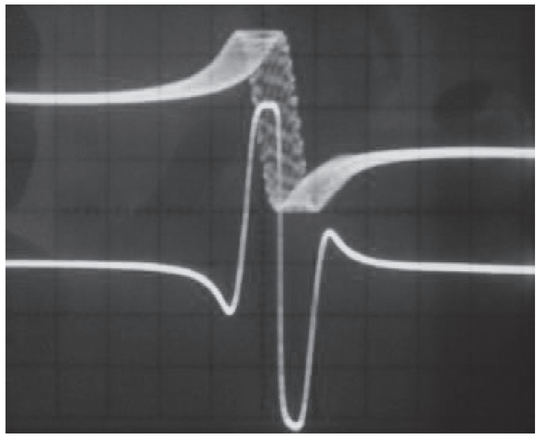

**Figure 3.** Saturated dispersion resonance of the $F_2$ line of methane. The upper trace represents the output signal of the frequency detector and the lower trace represents the output signal of the synchronous detector at the second harmonic of the modulation frequency.

Figure 4 compares two monoblock He–Ne/$CH_4$ OFS's. At an averaging time of 1 s, the Allan deviation is $7 \times 10^{-15}$ per laser. The measurements were performed with an HP53132A universal counter operated in Π mode.

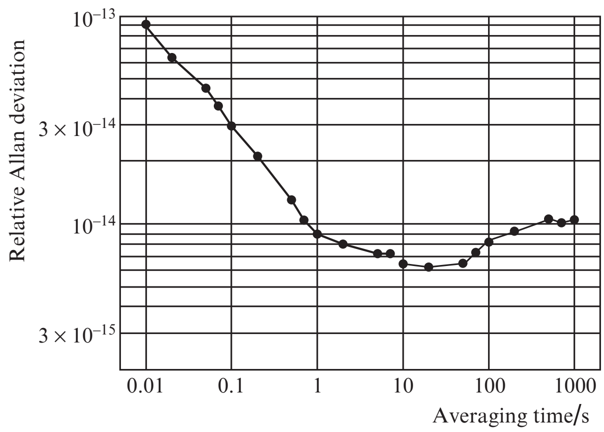


**Figure 4.** Relative Allan deviation obtained for two independent OFS's by directly comparing the heterodyne lasers in the OFS's. The beat frequency was 2.6 MHz at a carrier frequency of 88 THz.

### 2.2. Femtosecond fibre laser system

Optical frequencies were divided to the microwave domain using a femtosecond $Er^{3+}$ fibre laser-based system. The laser was made using polarisation-maintaining fibre. Self-phase modulation in it was ensured by Kerr nonlinearity. The pulse repetition rate $f_{rep}$ of the laser was ~60 MHz. Compared to previous work [14, 15], two more channels for active control over the repetition rate were added to the laser design: an electro-optical modulator and a Peltier element for controlling the temperature of the laser fibre segment. The use of the electro-optical modulator in combination with a piezoceramic translator allowed us to extend the feedback band of the phase lock loop frequency control system to 150 kHz, which was sufficient for reaching an instability level of $1 \times 10^{-14}$ at an averaging time of 1 s.

A detailed description and specific features of the operation of the femtosecond system in question, which includes a femtosecond oscillator, fibre amplifiers, and a supercontinuum generator, will be presented in a subsequent report. Note here that data obtained by comparing the MO output frequency with H maser frequencies allowed us to identify problematic components and achieve stable multi-day independent operation of the femtosecond system and MO on the whole after additional corrections.

The MO output signal is a continuous train of picosecond pulses with a stabilised repetition rate at the PD2 photodetector output (Fig. 1). The pulse duration is determined by the response time of the photodetector and is ~100 ps in our case. The spectrum of a continuous pulse train has the form of a microwave frequency comb: $f_N = Nf_{\rm rep}$. Any component of the spectrum can be separated out by radio engineering techniques and utilised as an output signal of the MO. However, the components differ in relative stability. Stability first improves with increasing harmonic order and then begins to decrease as a result of the reduction in the signal-to-noise ratio due to the finite bandwidth of the photodetector. Based on the above and taking into account the available components, we used the $N = 14$ (834 MHz) and $N = 26$ (1.55 GHz) harmonics.

To obtain limiting characteristics of the MO, one should also take into account the possible saturation of the photodetector with the high energy of a femtosecond pulse. The saturation problem can be resolved via extracavity multiplication of the repetition rate of femtosecond pulses, which is equivalent to the decimation (filtering) of the optical comb, with a power redistribution between its components [19].

## 3. Comparison of the frequencies of two independent master oscillators

To date, two experimental prototypes of methane MOs have been made, which allowed us to assess the stability of their output microwave signals via direct comparison. The oscillator signals were compared at a frequency of 1.55 GHz (26th harmonic of the $f_{\rm rep}$ frequency). The repetition rates of the two femtosecond lasers in the MOs differed by 400 Hz, which led to a frequency difference of 10 kHz at the 26th harmonic. At a carrier frequency of 1.55 GHz, this small difference enabled frequency measurements with required accuracy. The experimental setup is schematised in Fig. 5.

The frequency difference between the two MOs was measured with the HP53132A in two counting modes: in Π mode, using a 300-Hz bandwidth filter at the counter input, and in Λ mode. Figure 6 shows the relative Allan deviation (open circles) as a function of averaging time for the two MOs. At averaging times shorter than 10 s, the data show $1/\tau$ behaviour, characteristic of white phase noise. The contribution of such noise to instability depends on the pass-band width at the frequency counter input. In a standard maser instability measurement procedure, a 3-Hz bandwidth filter is used. Converting the Allan deviation to that for a 3-Hz bandwidth filter at an averaging time of 1 s, we obtain no more than $1 \times 10^{-14}$. The filled squares in Fig. 6 represent a two-sample 'triangle' deviation, i.e. the deviation calculated from the data obtained with the frequency counter operating in Λ mode [20]. In Λ mode, an input signal is further processed in the frequency counter according to a certain algorithm with data filtering. It is inadequate to use the data thus obtained for calculating the Allan deviation. Nevertheless, the 'triangle' deviation can be used for estimating the lower limit of oscillator instability. Frequency instability per oscillator in Λ mode at $\tau = 1$ s does not exceed $1 \times 10^{-14}$. The obtained short-term frequency instability of the methane MO is substantially better than the stability of H masers, which are typically used as interrogation signal sources for fountains.

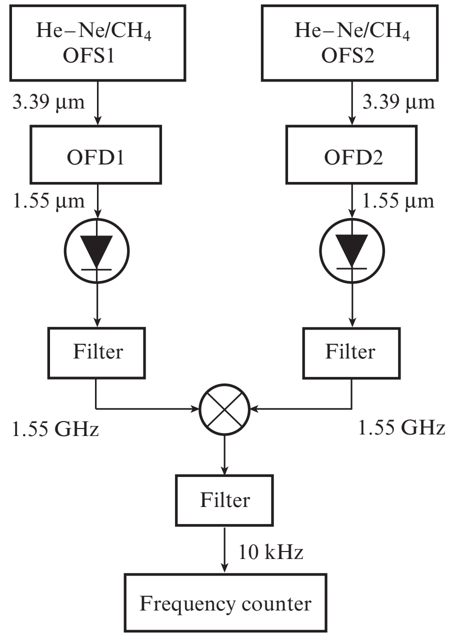


**Figure 5.** Block diagram of MO output frequency stability measurements.

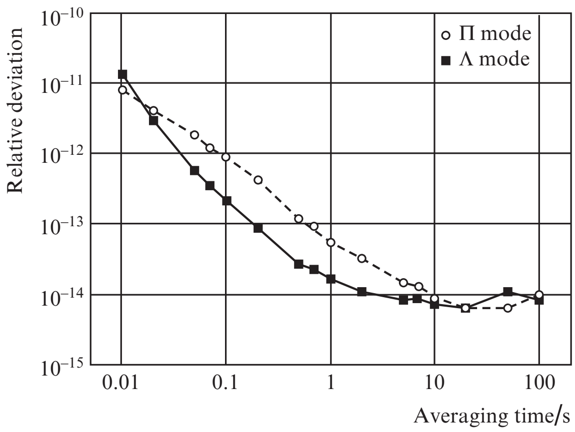


**Figure 6.** Relative frequency instability of the two MOs at a carrier frequency of 1.55 GHz. The measurements were performed using a 300-Hz bandwidth filter at the frequency counter input.

## 4. Comparison of the master oscillator with H masers of a reference facility

To continue studies with precision measuring electronics, one of the MOs was delivered to the reference facility at VNIIFTRI. Our main purpose was to assess the feasibility of using the methane MO as a interrogation signal generator for fountains with the aim of improving reference frequency stability.

Proceeding from the requirement that the methane MO be compatible with the fountains operating at VNIIFTRI, we designed and implemented a scheme for the synthesis of a reference signal for fountains (Fig. 7).

In the electronic apparatus that ensures the synthesis of an interrogation signal for Cs/Rb atoms, coupling between the fountain and a set of H-maser-based keepers and frequency stability control, standard frequencies of 5 and 100 MHz are used as references. To bring the MO output frequency to one of these values, a nominal frequency synthesiser was included in the scheme. As an input signal for it, we used a comb component with a frequency of 834 MHz ($N = 14$). To produce an interrogation signal for the Cs/Rb fountain at a frequency of 9.1/6.8 GHz, a precision SDI synthesiser is employed at VNIIFTRI (Fig. 7). A 5-MHz signal is used as a standard reference signal for it, but in the case of switching of inner units of the synthesiser a 100-MHz reference signal can be used. Instability measurements for this synthesiser at a frequency of 6.8 GHz show that, in the case of the 5-MHz reference signal, its intrinsic instability is $5 \times 10^{-14}$ in a 5-Hz band. With the 100-MHz reference signal, instability is an order of magnitude lower: $5 \times 10^{-15}$. Because of this, we used a nominal frequency of 100 MHz. Moreover, the synthesis of frequencies under 50 MHz from comb components while maintaining the initial instability level, $5 \times 10^{-14}$ at $\tau = 1$ s, is a complex radio engineering problem, though solvable in principle [21].

A second condition for carrying out experiments on a fountain is that long-term stability of the methane MO be ensured. For this purpose, at long times the MO was locked to a H maser used on a fountain. Digital phase locking was ensured by adding a frequency comparator (Fig. 7) as a phase detector and a device for adjusting the frequency of the heterodyne laser in the OFS. As a result, the MO–fountain match scheme ensured 100-MHz nominal frequency synthesis and slow locking of the MO (with a time constant from 20 to 50 s) to one of the H masers in the reference facility.

This configuration allowed us to assess frequency stability of the synthesised 100-MHz reference signal by comparing it to signals from H masers specially designed at the Vremya-Ch JSC for the system of fountains at VNIIFTRI and having short-term frequency instability at a level of $(6-8) \times 10^{-14}$ at $\tau = 1$ s. Three 100-MHz signals were simultaneously fed to the inputs of a VCH-314 frequency comparator: from the methane MO and two masers. The 'three corner hat' method makes it possible to assess instability of each signal from the data thus obtained. The measurement results are presented in Fig. 8 (the filter bandwidth is 3 Hz).

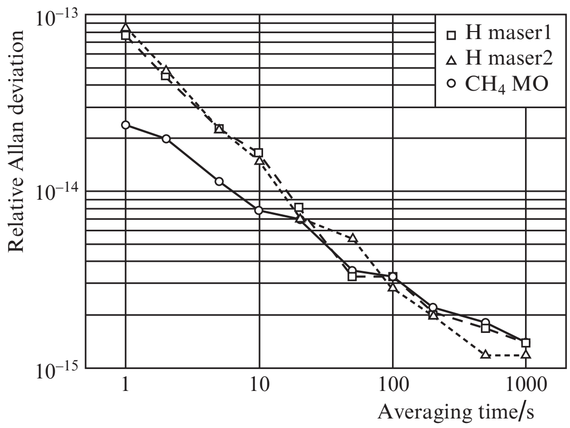


**Figure 8.** Relative Allan deviation as a function of averaging time for two hydrogen masers and the methane MO in the case of slow locking to one of the masers.

The relative Allan deviation obtained for the signal from the He–Ne/$CH_4$ MO, $3 \times 10^{-14}$ at $\tau = 1$ s, is a factor of 2 smaller than that in the case of masers but three times larger than MO instability at microwave frequencies (Fig. 6). Stability degradation is due to the noise produced by the commercial nominal frequency synthesiser, which generates a 100-MHz signal.

The intrinsic instability of the synthesiser was assessed in a separate experiment using a Microsemi 5125A phase noise and Allan deviation test set. To this end, we used two identical synthesisers and fed a signal from one high-stability oscillator to their inputs. The instability was measured to be $3 \times 10^{-14}$ in a 5-Hz band at $\tau = 1$ s, in agreement with the above value. Currently, a new synthesiser is under development, with output frequencies of 9.1/6.8 GHz and an intrinsic instability level no higher than $5 \times 10^{-15}$ at $\tau = 1$ s.

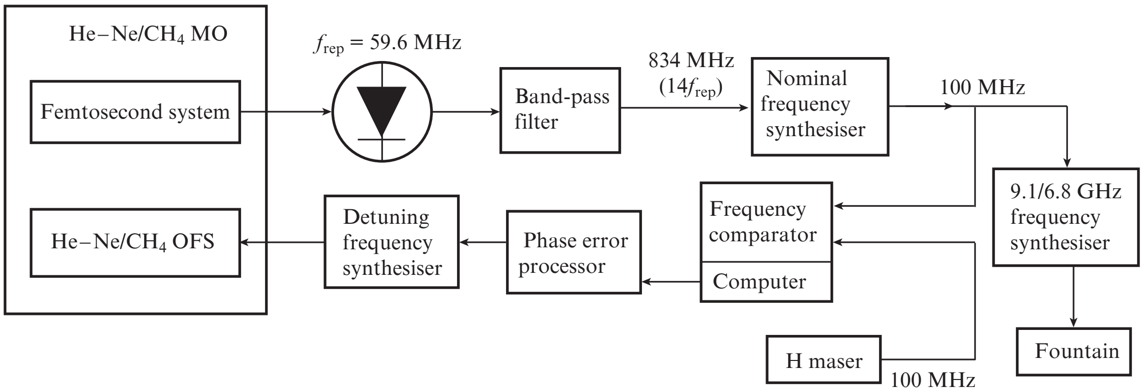


**Figure 7.** Block diagram of 100-MHz reference signal synthesis for Cs/Rb fountains.

## 5. Conclusions

We have demonstrated an oscillator whose short-term stability surpasses that of the hydrogen masers with enhanced short-term stability in the reference facility at VNIIFTRI. In the output frequency range 0.8–1.5 GHz, the oscillator instability is under $1 \times 10^{-14}$ at an averaging time of 1 s.

Based on this oscillator, we have designed and implemented a scheme for the synthesis of a reference signal with a nominal frequency of 100 MHz for the generation of an interrogation signal for the Cs/Rb fountains at VNIIFTRI. The instability of the synthesised 100-MHz frequency is $3 \times 10^{-14}$ at an averaging time of 1 s and it is limited by the intrinsic instability of the commercial microwave synthesiser used.

The next step in our research will be to test the master oscillator directly on fountains.

***Acknowledgements.*** We are grateful to Yu.S. Domnin for his many valuable comments regarding the operation of the reference facility.

This work was supported by the Russian Science Foundation (Project No. 16-19-10694).

## References

1. Riehle F. *Frequency Standards: Basics and Applications* (New York: Wiley, 2005; Moscow: Fizmatlit, 2009).
2. Dick G.J., in *Proc. 19th Precise Time and Time Interval (PTTI) Applications and Planning Meeting* (Redondo Beach, CA, 1987) p.133.
3. Santarelli G. et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **45**, 887 (1998).
4. Santarelli G., Laurent P., Lemonde P., Clairon A., Mann A.G., Chang S., Luiten A.N., Salomon C. *Phys. Rev. Lett*., **82**, 4619 (1999).
5. Guéna J. et al. *IEEE Trans. Ultrason, Ferroelect., Freq. Control*, **59**, 391 (2012).
6. Lipphardt B., Gerginov V., Weyers S., et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **64**, 761 (2017).
7. Zagorodnov A.P., Yakunin A.N. *Nauchn. Priborostr*., **22**, 19 (2012).
8. Kim J., Cox J., Chen J., Kartner F. *Nat. Photonics*, **2**, 733 (2008).
9. Fluhr C. et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **63**, 915 (2016).
10. Fortier T.M. et al. *Nat. Photonics*, **5**, 425 (2011).
11. Kolachevsky N.N., Khabarova K.Yu. *Usp. Fiz. Nauk*., **184**, 1354 (2014).
12. Vishnyakova G.A. et al. *Usp. Fiz. Nauk*., **186**, 176 (2016).
13. Foreman S., Marian A., Ye J., Petrukhin E., Gubin M., Mücke O., Wong F., Ippen E., Kaertner F. *Opt. Lett*., **30**, 570 (2005).
14. Gubin M.A. et al. *Quantum Electron*., **38**, 613 (2008) [*Kvantovaya Elektron*., **38**, 613 (2008)].
15. Gubin M.A. et al. *Appl. Phys. B*, **95**, 661 (2009).
16. Kireev A.N. et al. *Quantum Electron*., **46**, 1139 (2016) [*Kvantovaya Elektron*., **46**, 1139 (2016)].
17. Gubin M.A., Protsenko E.D. *Quantum Electron*., **27**, 1048 (1997) [*Kvantovaya Elektron*., **24**, 1080 (1997)].
18. Gubin M.A. et al., in *Proc 2017 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFC)*(Besancon, France, 2017) p. 452.
19. Haboucha A., Zhang W., Li T., Lours M., Luiten A.N., Le Coq Y., Santarelli G. *Opt. Lett*., **36**, 3654 (2011).
20. Dawkins S.T., McFerran J.J., Luiten A.N. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **54**, 918 (2007).
21. Hatti A. et al. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, **60**, 1796 (2013).