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Optoelectronic reference X-band oscillator for radar systems

A.L. Chizh, K.B. Mikitchuk, I.V. Skotorenko

Abstract. **We present the design and results of studying the characteristics of an optoelectronic microwave oscillator in the free-running regime are presented, propose a method for synchronising it with a signal of a highly stable crystal oscillator using a phase-locked loop, and analyse the results of an experimental study on the frequency instability of an optoelectronic microwave reference oscillator. The optoelectronic microwave reference oscillator with optical gain and a 10 GHz oscillation frequency simultaneously provides ultra-low phase noise (less than –142 dB Hz^{-1}) at a 10 kHz frequency offset from the microwave carrier and a low level of spurs in the oscillation spectrum (no more than –94 dBc). In this case, the temperature coefficient of the oscillation frequency is determined by the temperature instability of a highly stable crystal oscillator.**

Keywords: *optoelectronic microwave oscillator, reference oscillator, phase noise, phase-locked loop.*

1. Introduction

Low phase-noise microwave oscillators are of great importance for many commercial and special applications, such as wireless and optical communication systems, radar systems and microwave measuring equipment. The measurement limits of spectrum analysers are determined by the phase noise of the reference oscillator, while in modern radar stations, rather stringent requirements are imposed on both short-term and long-term stability of the reference oscillator frequency. For example, the need to ensure short-term frequency stability in Doppler radars is associated with a small effective target scattering area [1]. The requirements for long-term frequency stability, in turn, arise from the need to ensure the possibility of accumulation and correlation processing of signals in the receiving paths of radar stations, as well as unconditional locking with the reference oscillator frequency by frequency synthesis systems.

The short-term stability of the oscillator frequency is characterised by the phase-noise power spectral density. Typically, low phase noise signals are generated by electronic circuits containing high-Q electromagnetic, magnetoelectric, or acoustoelectric resonatros in a positive feedback loop. In the X-frequency range, the Q-factor of almost all microwave resonators is significantly reduced compared to that in the lower frequency range, which leads to an increase in phase noise, the level of which limits the maximum oscillation frequency [2, 3]. An alternative method for generating sinusoidal microwave signals with low phase noise is the use of fibre-optic delay lines (FODLs) in microwave optoelectronic oscillators, which, according to the principle of their operation, are autogenerators with positive feedback [3, 4]. The ultra-low phase noise in such oscillators is due to the high equivalent Q-factor of the optical fibre in the microwave range, as well as the possibility of using optical amplifiers with ultra-low phase noise floor instead of transistor amplifiers. Erbium-doped fibre amplifiers in the saturation regime with an optical carrier input power of more than 1 mW allow us to attain a noise floor of less than –150 dBc Hz^{-1} (decibels relative to the carrier power per hertz), while the equivalent microwave signal gain can be more than 30 dB [5, 6]. The delay-line X-band optoelectronic microwave oscillators with optical gain provide the generation of signals with a phase noise less than –140 dBc Hz^{-1} at a 10 kHz frequency offset from the microwave carrier [4, 7].

The main disadvantage of microwave optoelectronic oscillators, which limits their use in communication systems, radars, and microwave measuring equipment as a reference oscillator, is the insufficient long-term stability of the oscillation frequency in relation to changes in the ambient temperature. The temperature coefficient of the optoelectronic oscillator frequency is determined by the temperature coefficient of the signal delay time in the optical fibre, which for a silica single-mode optical fibre ranges from -0.7×10^{-5}°C^{-1} to -1.4×10^{-5}°C^{-1} [8, 9]. In modern radar systems, for example, a temperature instability of no more than $\pm10^{-6}$ is required in the operating temperature range from –50°C to +50°C, which is equivalent to a temperature frequency coefficient of less than $\pm10^{-8}$°C^{-1}.

In this work we present the design and results of studying the characteristics of an optoelectronic microwave oscillator in the free-running regime, a method for synchronising an optoelectronic oscillator with a signal from a highly stable crystal oscillator using a phase-locked loop, and also the results of an experimental study on the frequency instability of an optoelectronic reference microwave oscillator.

2. Optoelectronic oscillator design

Figure 1 shows a block diagram of a microwave optoelectronic oscillator with optical gain. Electro-optical conversion in an optoelectronic oscillator is performed by intensity mod-

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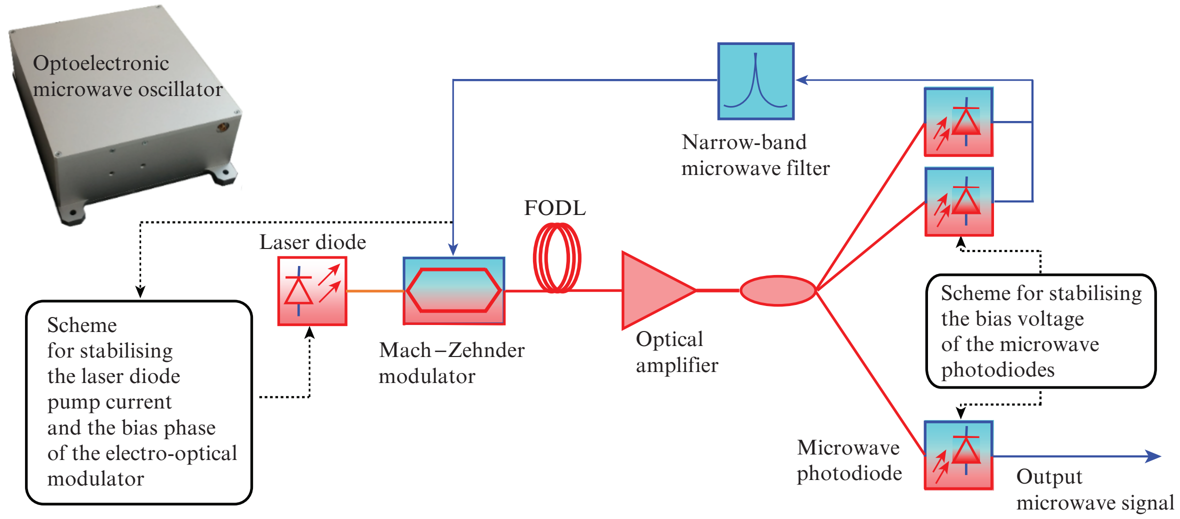

Figure 1. Structural scheme of a double-loop optoelectronic microwave oscillator based on the FODL with optical gain (the inset shows a photograph of an optoelectronic oscillator with an oscillation frequency of 10 GHz and overall dimensions of 257 × 197 × 84 mm).

ulation of a laser diode with a distributed feedback and an output power of 20 mW (lasing wavelength 1550 nm, lasing linewidth ~300 kHz) using an electro-optical Mach–Zehnder modulator with a half-wave voltage of 6 V at a frequency of 10 GHz. The optical signal is delayed in the main FODL that is a fibre-optic coil made of a silica single-mode optical fibre with a length of 2 km, which provides a delay time of ~10 μs. An optical amplifier based on an erbium-doped fibre is used to compensate for losses occurring in the optoelectronic oscillator loop. When using a 1 × 3 fibre-optic splitter, additional FODLs with a signal delay time difference of 1.2 μs in the oscillator loop are connected to the optical amplifier output, which is necessary to increase the frequency selectivity of the optoelectronic oscillator loop and significantly reduce the level of spurs in the oscillation spectrum [7]. The optoelectronic conversion of the intensity-modulated optical signal into a microwave signal in the optoelectronic oscillator loop is performed using high-power InGaAs pin-photodiodes with a microwave combiner. A first-order filter based on a hollow metal cavity with a bandwidth of 10 MHz is used as a narrow-band microwave filter. The oscillation signal is coupled out directly from the FODL using a high-power InGaAs pin-photodiode, which provides complete galvanic isolation of the microwave oscillator output. This design has the following advantages over the traditional multi-loop one:

– the equivalent phase noise of the fibre-optic amplifier is significantly lower than the phase noise of electronic microwave amplifiers, which reduces the phase noise at the frequency offset near the microwave carrier compared to an optoelectronic oscillator with all-electronic gain [8, 9]; and

– the output oscillation signal is formed using a fibre-optic splitter and a high-power microwave photodiode, which provide complete galvanic isolation from the external load and the possibility of implementing an optoelectronic oscillator with several identical outputs.

A theoretical study of the optoelectronic oscillator under consideration is performed using a nonlinear time-variant model, in the frame of which unidirectional circulations around a closed active positive feedback loop are described by a single sample of a complex slowly changing amplitude of the microwave signal [10, 11].

2.1. Optical gain in the optoelectronic oscillator loop

Figure 2 shows a schematic of an optical amplifier in an optoelectronic oscillator. The optical amplifier in the optoelectronic generator loop is designed on the basis of an erbium-doped fibre, four laser diodes (lasing wavelengths of 1470 and 1490 nm, and a power of 15 dBm) and four fibre-optic wavelength multiplexers used for bidirectional pumping. Spurious optical generation in the optical oscillator is suppressed by fibre-optic isolators.

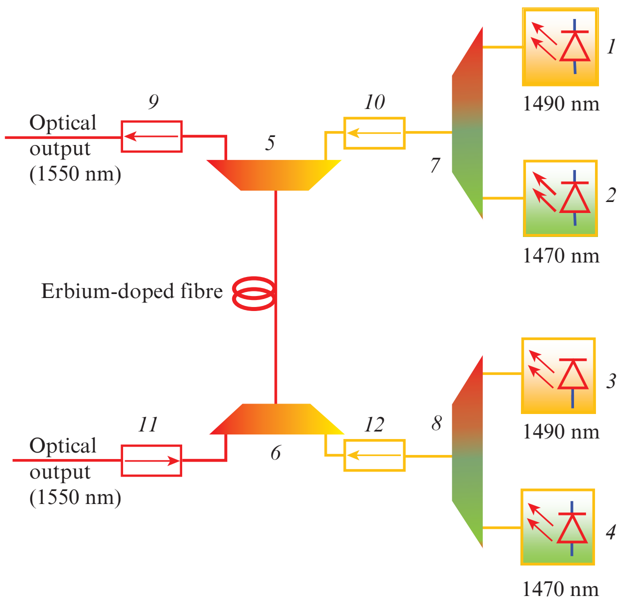

Figure 2. Schematic of an optical amplifier based on an erbium-doped fibre in an optoelectronic microwave oscillator:
(*1–4*) distributed-feedback laser diodes; (*5–8*) fibre-optic wavelength multiplexers; (*9–12*) fibre-optic isolators.

The equivalent noise floor of an optical amplifier based on an erbium-doped fibre, caused by optical signal beats and amplified spontaneous radiation, is one of the main phase noise sources in an optoelectronic oscillator with optical gain [6]. Figure 3 shows the results of measuring the gain and equivalent phase noise floor of an optical amplifier based on an erbium-doped fibre as a function of the counter-pump power. It can be seen that the equivalent gain of the microwave signal can be changed in the range of 17–27 dB by adjusting the counter-pump power in the range of 0–15 dBm (while the direct pump power remains constant), which is quite simply achieved by changing the pump current of the laser diodes.

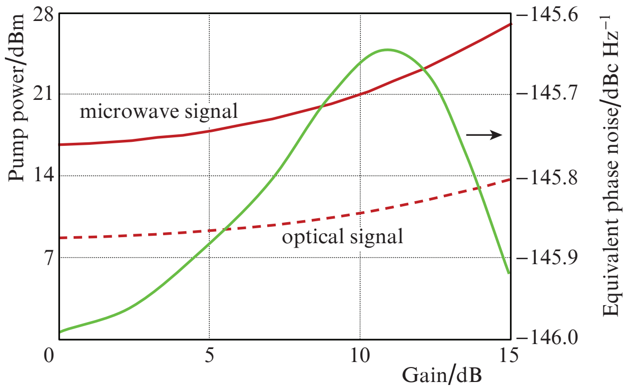

Figure 3. Dependences of the gain and equivalent phase noise floor of the optical amplifier based on an erbium-doped fibre on the counter optical pump power (direct optical pump power 15 dBm, erbium-doped fibre length 10 m, optical modulation depth 100%).

It should be noted that the gain of low phase-noise transistor microwave amplifiers does not exceed 8–15 dB, and the equivalent gain of an optical amplifier for microwave signals reaches 30 dB, while the gain remains constant for the entire frequency range of the FODL in an optoelectronic oscillator, tup to 50 GHz. The equivalent phase noise floor varies by no more than 0.4 dB over the entire gain range of the optical amplifier.

2.2. Double-loop configuration

To reduce the level of spurs in the oscillation spectrum, it is necessary to increase the frequency selectivity of the optoelectronic oscillator feedback loop, which is achieved by using a double-loop configuration [4, 7]. Figure 4 shows the level of spurs in the oscillation spectrum of a double-loop optoelectronic oscillator versus the difference of the signal delay time $\Delta\tau$ in additional FODLs, normalised to the signal delay time in the main FODL for various ratios η_Q of the equivalent Q-factor of the FODL to the Q-factor of a narrow-band microwave filter:

$$\eta_Q = \pi\tau\Delta f,$$

where Δf is the bandwidth of the narrow-band microwave filter. It can be seen that the level of spurs monotonically decreases by more than 50 dB with an increase in the normalised difference $\Delta\tau/\tau$ in the signal delay times in additional FODLs to the optimal values of 5%–12%. With a further increase in the value of $\Delta\tau/\tau$, a quasi-periodic dependence is observed, when the level of spurs increases by 5–10 dB, and then decreases to a value exceeding the minimum level of spurs by 0.2–2 dB.

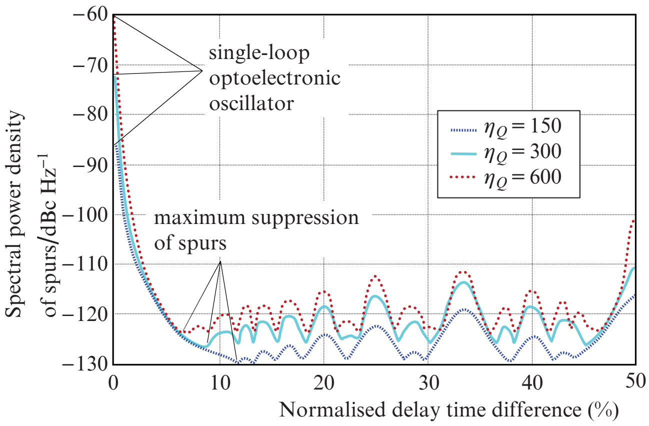

Figure 4. Dependences of the level of spurs in the oscillation spectrum of a two-loop optoelectronic microwave oscillator on the difference in the signal delay time in additional FODLs, normalised to the signal delay time in the main FODL, for different ratios η_Q of the equivalent Q-factor of the FODL to the Q-factor of a narrow-band microwave filter (oscillation frequency 10 GHz, the delay time in the main FODL 5 μs).

The optimal value of $\Delta\tau/\tau$ decreases with increasing η_Q, while the maximum amount of suppression of spurs also decreases. In this case, the suppression of spurs is ensured according to the principle of periodic filtering, while in the case $\Delta\tau/\tau > 0.5$, according to the principle of frequency vernier, for which the requirements for the accuracy of determining the lengths of additional FODLs required for a given level of spur suppression in the optoelectronic oscillator spectrum significantly increase.

3. Dynamic instabilities

Depending on the small-signal loop gain g_{ss}, the microwave optoelectronic oscillator with optical gain can operate in the following regimes: no oscillation ($g_{ss} < 0$ dB), stationary oscillation (0 dB $\leqslant g_{ss} \leqslant$ 10.3 dB), dynamic instabilities ($g_{ss} > 10.3$ dB). In the absence of oscillation (or subthreshold oscillation), the feedback loop gain is insufficient to compensate for losses in the optoelectronic oscillator. In the stationary oscillation region, the amplitude of the generated microwave signal increases monotonically with an increase in the feedback loop gain, and the generation of a microwave signal with low phase noise is achieved. In the region of dynamic instabilities, the relationship between the oscillator loop gain and the amplitude of the generated microwave signal is ambiguous, and several signals with different quasi-stationary values of amplitude and frequency are simultaneously generated.

Figure 5 shows the signal spectrum in the stationary oscillation regime of a double-loop optoelectronic microwave oscillator with optical gain and a 10 GHz oscillation frequency measured by the Rohde&Schwarz FSW26 spectrum analyser. It can be seen that stationary oscillation takes place, and the power of the spurs in the spectrum does not exceed –94 dBc. Note that the measured oscillation spectrum near the microwave carrier frequency ($\Delta f <$ 500 kHz) is distorted by the noise floor of the spectrum analyser. As was shown earlier in work [7], dynamic instabilities occur in an optoelectronic oscillator with optical gain at a small-signal loop gain $g_{ss} > 10.3$ dB, i.e., to ensure stationary oscillation in such an oscillator, a coefficient g_{ss} = 0 – 10.3 dB is required. The relative instability of the oscillation power is determined by the optical amplifier and lies within the range of ±0.05 dB for 4 – 8 h of continuous operation after reaching the regime in 30 min. Figure 6 shows the power spectral densities of the phase and amplitude noise of the output signal of the optoelectronic oscillator at different time moments (the optoelectronic microwave oscillator worked continuously, the interval between measurements was 4 h). It can be seen that during the time between measurements, both the phase and amplitude noises did not change by more than 1 – 2 dB.

Figure 7 shows the oscillation spectra of an optoelectronic oscillator with optical gain in the regime of dynamic instabilities, when the small-signal loop gain was 10.9 dB. It is seen that the spectrum contains a set of spurs, the frequency of which does not coincide with the eighenfrequencies of the optoelectronic oscillator, and the spectral distribution changes significantly over time, i.e. the spectral composition instability is observed.

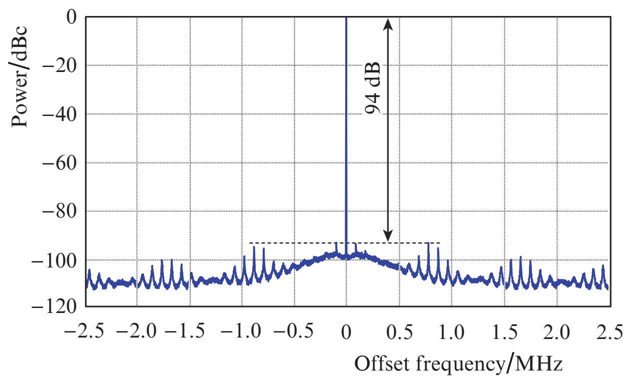

Figure 5. Measured signal spectrum of a double-loop optoelectronic microwave oscillator with optical gain and an oscillation frequency of 10 GHz.

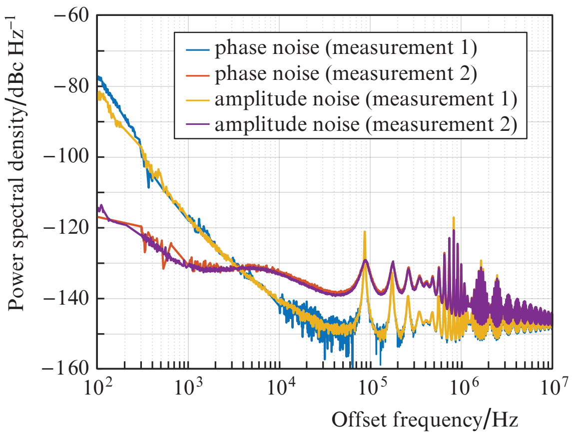

Figure 6. (Colour online) Spectral power densities of the phase and amplitude noise of a double-loop optoelectronic microwave oscillator at different time moments (the optoelectronic oscillator was operating continuously; the interval between measurements was 4 h).

4. Long-term frequency instability

An optoelectronic oscillator is characterised by complex oscillation dynamics, and so, when studying the effect of environmental factors on the oscillator output characteristics, it is necessary, for example, to take into account how the oscillator temperature changes. In general, a change in temperature leads to a change in the delay time in the optical fibre segments in the FODL due to a change in the effective refractive index of the fibre core, as well as to a shift in the centre frequency of the microwave filter. If the temperature coefficients of the delay time and centre frequency of a narrow-band microwave filter are close in magnitude but different in sign, the oscillation frequency dependence on temperature is piecewise continuous, and within the temperature range of the oscillation frequency continuity, the temperature coefficient of the oscillation frequency coincides with the temperature coefficient of the signal delay time in an optical fibre, taken with the opposite sign [9]. In general, two regimes of the effect of temperature changes on the optoelectronic oscillator are possible:

– temperature change before switching on the oscillator (temperature changed – thermal equilibrium established – optoelectronic oscillator turned on – stationary oscillation established – optoelectronic oscillator turned off); and

– temperature change of the operating optoelectronic oscillator (at a certain temperature, the optoelectronic oscillator is turned on – the temperature change occurs simultaneously with the oscillation process in the oscillator).

Figure 8 shows the calculated deviations of the oscillation frequency from its value at a temperature of 20 °C versus the temperature of a double-loop optoelectronic oscillator for the temperature change regime before switching on the oscillator and the temperature change regime of the operating oscillator. It can be seen that for the regime of changing the temperature before turning on the oscillator, the oscillation frequency dependence on temperature has a piecewise-continuous character, and in the intervals of continuity, the temperature coefficient of the oscillation frequency coincides with the temperature coefficient of the signal delay time in the optical fibre, taken with the opposite sign. In this case, the value of the temperature interval of the oscillation frequency continuity is close to that for the case when the temperature coefficients of the signal delay time and the centre frequency of the narrow-band microwave filter are close in magnitude, but different in sign. It can also be seen that for the temperature change regime of an operating optoelectronic oscillator, the value of the continuity intervals is generally arbitrary and, as the simulation shows, strongly depends on the temperature change rate.

It follows from the experimental results that when the ambient temperature changes from 5 °C to 40 °C, the oscillation frequency changes piecewise continuously in the range of 10.04×10^3 MHz ± 1.757 MHz. It should be noted that the oscillation power in the entire temperature range varied by no more than 3 dB. When the optoelectronic oscillator temperature changes, transient processes with a duration being 100 times longer than the signal delay time in the main FODL are possible, with the oscillation signal phase changing by several tens of degrees. Thus, a change in the optoelectronic oscillator temperature generally leads to a piecewise continu-

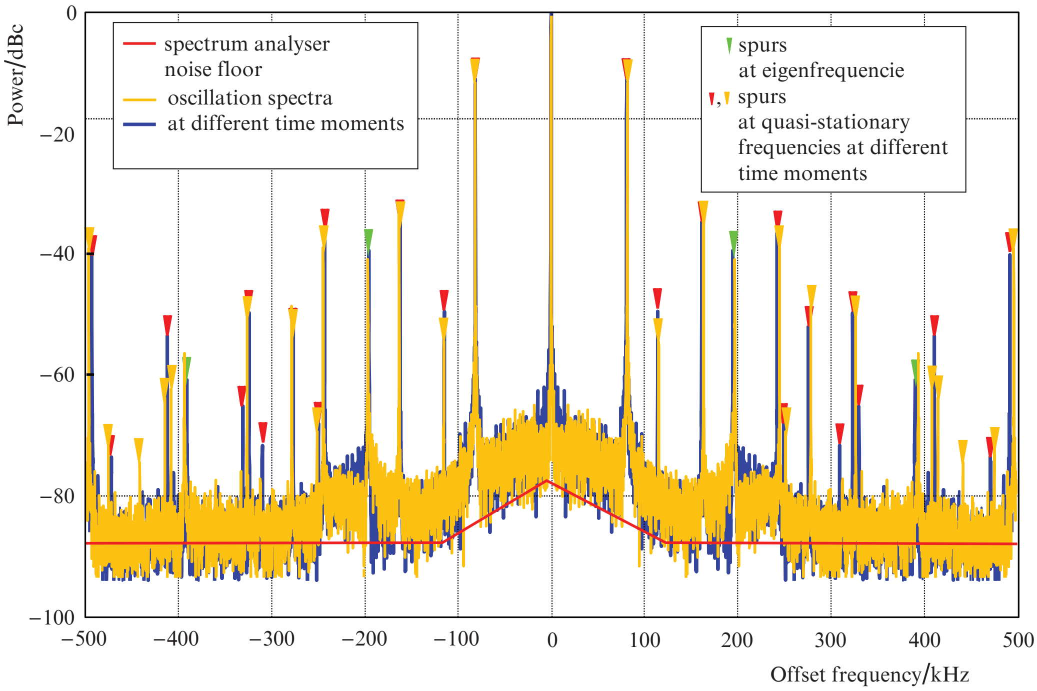

Figure 7. (Colour online) Oscillation spectra of the microwave optoelectronic oscillator measured at various time moments in the regime of dynamic instabilities. The analysed spectrum analyser bandwidth is 100 Hz.

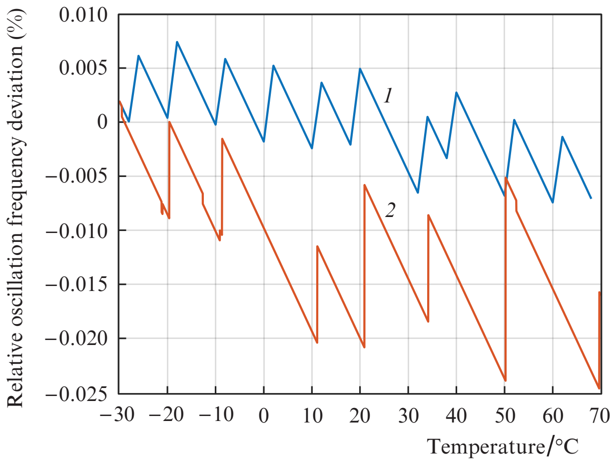

Figure 8. Relative oscillation frequency deviation of a double-loop optoelectronic oscillator as a function of its temperature for the temperature change regime before switching on the oscillator (*1*) and the temperature change regime of the optoelectronic oscillator in operation (*2*) (oscillation frequency 10 GHz, narrow-band microwave filter bandwidth 10 MHz, small-signal loop gain 8 dB, temperature frequency coefficient of the narrow-band microwave filter 1.2×10^{-6} °C^{-1}).

ous temperature dependence of the oscillation frequency, and when the temperature changes during the oscillator operation, the continuity interval value depends on the temperature change rate.

5. Ensuring long-term stability

Optoelectronic oscillators are delay-line autogenerators, and so they have a discrete set of eigenfrequencies, the spectral position of which is determined by the delay time, which, in turn, depends on the ambient temperature. In the case of frequency offset between eigenfrequencies, when the optoelectronic oscillator temperature changes, there is no quenching or fading of the microwave oscillation signal, and the spectral purity of the generated signal does not decrease. This allows the use of a phase-locked loop system to stabilise the optoelectronic oscillator frequency in the free-running regime. Figure 9 shows a diagram of an optoelectronic reference oscillator with a frequency stabilisation device with phase-locked tuning. The phase-locked loop system performs the function of stabilising the frequency difference between the optoelectronic oscillator operating in the free-running regime and the frequency of a voltage-controlled high-frequency oscillator by comparing it in a phase-frequency detector with the frequency of a high-stable oscillator [12, 13], in the capacity of which a crystal oscillator with a frequency instability 3×10^{-9} in the temperature range from −40 °C to +70 °C was used. This method allows us to stabilise the output frequency of the reference oscillator, while the optoelectronic oscillator still operates in the free-running regime.

Figure 10 shows the phase noise of an optoelectronic reference oscillator, measured with an Agilent E5052B phase noise analyser. It is seen that at offset frequencies above 300 Hz, the phase noise of the optoelectronic reference oscillator with a stabilised frequency coincides with the phase noise of the optoelectronic oscillator in the free-running regime. It should be noted that at offset frequencies from the microwave carrier above 10 kHz, the spectrum is distorted by the analyser noise floor.

The study of the frequency stability of the optoelectronic reference oscillator was performed in a heat and cold chamber in the temperature range from 5 °C – 40 °C.

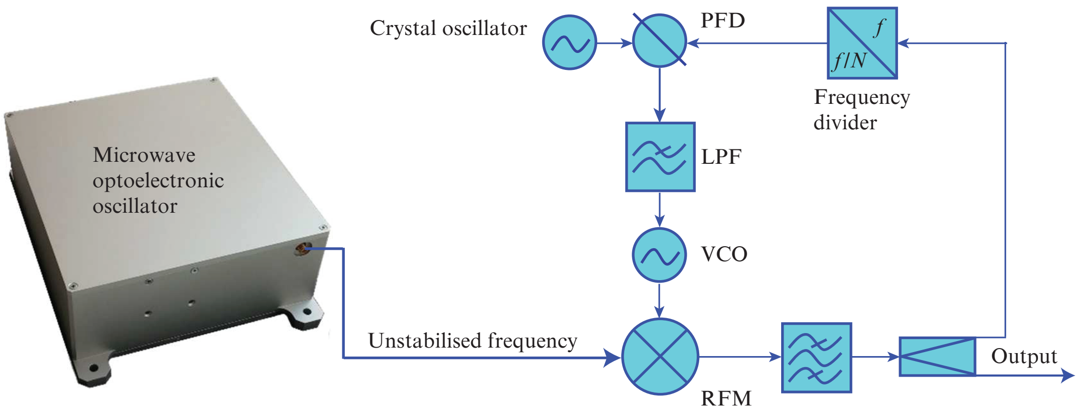

Figure 9. Schematic of an optoelectronic reference microwave oscillator scheme:
(RFM) radio-frequency mixer; (BPF) band-pass filter; (PFD) phase-frequency detector; (LPF) low-pass loop filter; (VCO) voltage-controlled oscillator.

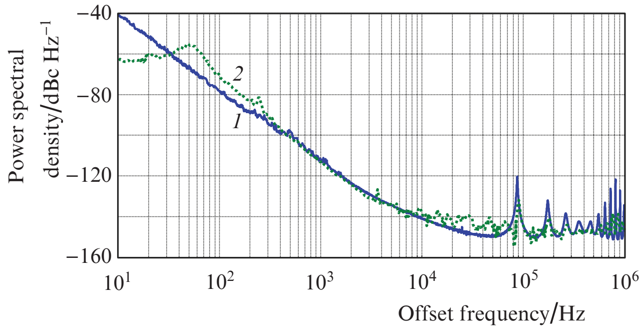

Figure 10. Measured phase noise of a double-loop optoelectronic microwave oscillator in the free-running regime (*1*) and in the case of its synchronisation with a crystal oscillator (*2*).

In the entire temperature range under consideration, the oscillation frequency drift did not exceed 11 Hz, i.e. the relative frequency instability did not exceed 3×10^{-9} and corresponded to the crystal oscillator frequency stability. The temperature frequency coefficient of the optoelectronic reference oscillator with the proposed architecture of the frequency stabilisation system is determined by the temperature instability of the high-stable crystal oscillator used, while maintaining a high spectral purity of the output signal.

6. Conclusions

The developed double-loop optoelectronic microwave reference oscillator with optical gain and a 10 GHz oscillation frequency simultaneously provides ultra-low phase noise (less than –142 dBc Hz^{-1}) at a 10 kHz frequency offset from the microwave carrier and a low level of spurs in the oscillation spectrum (no more than –94 dBc). The phase-locked loop system performs the function of stabilising the frequency difference of the optoelectronic oscillator operating in the free-running regime and the frequency of the voltage-controlled high-frequency oscillator by comparing it with the high-stable crystal oscillator frequency in the phase-frequency detector. In this case, the temperature frequency coefficient of the reference optoelectronic oscillator with the proposed architecture of the frequency stabilisation system is determined by the temperature instability of the high-stable crystal oscillator used.

References

1. Sokolov A.V. (Ed.) *Obnaruzhenie i raspoznavanie ob'ektov radiolokatsii* (Detection and Recognition of Radar Objects) (Moscow: Radiotekhnika, 2006).
2. Urick V.J., Williams K.J., McKinney J.D. *Fundamentals of Microwave Photonics* (New York: Wiley, 2015).
3. Oldyniec M. *RF and Microwave Oscillator Design* (Boston: Artech House, 2002).
4. Levy E.C., Horowitz M., Menyuk C.R. *J. Opt. Soc. Am. B*, **26**, 1 (2009).
5. Mikitchuk K., Chizh A., Malyshev S. *Proc. 24th Int. Conf. on Noise and Fluctuations (ICNF-2017)* (Vilnius, 2017).
6. Mikitchuk K.B., Chizh A.L., Malyshev S.A. *Trudy VI Vseros. nauchn. konf. 'Elektronika i mikroelektronika SVCh'* (Proc. VI All-Russian Sci. Conf. 'Microwave Electronics and Microelectronics) (Saint Petersburg, 2017).
7. Mikitchuk K., Chizh A., Malyshev S. *IEEE J. Quantum. Electron.*, **52**, 10 (2016).
8. Tseng W.H., Feng K.M. *Opt. Express*, **20**, 2 (2012).
9. Mikitchuk K., Chizh A., Malyshev S. *Proc. IEEE Int. Top. Meeting on Microwave Photonics (MWP2015)* (Paphos, 2015).
10. Mikitchuk K.B., Chizh A.L., Malyshev S.A. *Trudy VII Vseros. nauchn. konf. 'Elektronika i mikroelektronika SVCh'* (Proc. VII All-Russian Sci. Conf. 'Microwave Electronics and Microelectronics) (Saint Petersburg, 2018).
11. Mikitchuk K., Chizh A., Malyshev S. *Proc. IEEE Int. Conf. on Numerical Electromagnet., Modeling and Optimiz. for RF, Microwave, and Terahertz Appl. (NEMO-2014)* (Pavia, 2014).
12. Razavi B. *IEEE J. Solid-State Circuits*, **42**, 12 (2007).
13. Yanhong Zhu et al. *IEEE Photonics Technol. Lett.*, **28**, 22 (2016).