09

Auto-oscillation of a low-noise microwave signal in an optoelectronic oscillator with passive optical amplification

I.Yu. Tatsenko, A.B. Ustinov

St. Petersburg State Electrotechnical University „LETI“,
197022 St. Petersburg, Russia
e-mail: ustinov_rus@yahoo.com

Received July 11, 2023
Revised September 5, 2023
Accepted September 11, 2023

A detailed study of an optoelectronic oscillator with passive optical amplification has been carried out. A key feature of studied oscillator circuit is the absence of any optical or microwave amplifiers. The circuit parameters that affect the phase noise are determined. A modified Yao-Maleki model is proposed that more adequately describes the phase noise spectrum of an optoelectronic oscillator without amplifiers. The minimum phase noise obtained was -135 dBc/Hz at a 10 kHz offset from a carrier frequency of 3.5 GHz for a fiber length of 600 m. Dependence of the flicker noise coefficient on the laser power is determined, which makes it possible to characterize more accurately the phase noise of an optoelectronic oscillator with passive optical amplification.

Keywords: optical fiber, optoelectronic oscillator, phase-noise, flicker-noise, Yao-Maleki Model.

DOI: 10.61011/TP.2023.11.57505.176-23

Introduction

Currently, very high frequency (VHF) signal oscillators are used in radar and communication system, navigation devices and instruments. The main objectives of VHF oscillator development are to increase the stability of the generated signal frequency and to reduce phase noise. Development of optoelectronic VHF oscillators (OEO) is one of the promising solutions.

To make a low-noise oscillator, a high-Q resonator is required [1]. It is well known that Q factor is defined as the ratio energy stored in the system to the energy lost in one cycle of oscillation. There are currently two main methods to achieve the maximum Q factor that form the basis for OEO development. The first method is based on the use of optical resonators with whispering gallery modes that have a giant Q factor [2]. The second method is based on the use of a ring circuit with fiber optic delay line (FODL) [3–5], that is actually an component for optical radiation energy storage.

From the point of view of radio engineering, OEO is a low-noise device due to high steepness of phase-frequency response characteristic of FODL (due to long delay time amounting to units−tens of microseconds) with record-breaking low loss of optical radiation in optical fiber (about 0.04 dB/μs). For self-exciting oscillation to occur, a constant energy source is required to compensate the loss in the system [6]. In most designed optoelectronic oscillators, loss compensation is implemented either in the VHF path by transistor VHF amplifiers [7], or in the optical path by fiber-optic or semiconductor optical amplifiers [8], and FODL serves to provide long delay time.

To transmit a radio signal via optical fiber, OEO uses a fiber-optic transmission line (FOTL) whose key components are laser, electrooptic modulator, optic fiber itself and photodetector (Figure 1, a). VHF signal propagates in FOTL in the form of optical radiation amplitude modulation. VHF signal loss in FOTL (by power is defined by a standard expression $H_P = 10 \cdot \log(P_{out}/P_{in})$, where$P_{in}$ is the VHF signal power at FOTL input (i.e. at the electrooptic modulator control input), log is the common logarithm, and P_{out} is the VHF signal power at the photodetector output calculated using the following equation [9]:

$$P_{out} = R\left(P_{las} S J_1\left(\frac{\pi V_0}{V_\pi}\right)\sin\left(\frac{\pi V_b}{V_\pi}\right)\right)^2. \qquad (1)$$

This equation uses the following notations: R — photodetector load resistance, P_{las} —laser power, S — photodetector sensitivity, $J_1(.)$ — first-order Bessel function of the first kind, V_0 — modulating VHF signal amplitude applied to the electrooptic modulator input, V_b — modulator operating point offset voltage, V_π — electrooptic modulator half-wave voltage. Equation (1) shows that the FOTL output power P_{out} depends not only on P_{in} (in terms of V_0), but also on other FOTL parameters such as laser power P_{las} and modulator half-wave voltage V_π. Therefore, even a fixed value of P_{in} gives increasing values of P_{out} due to a decrease in V_π and an increase in P_{out}. Thus, our recent study [10] has shown experimentally that increasing optical radiation power and the use of a high-photocurrent photodetector allows the VHF signal loss in FOTL to be reduced. At some combination of V_π and P_{las}, a situation may be achieved when the FOTL transmission coefficient H_p becomes positive. Such technical effect is hereinafter referred to as „passive optical amplification“

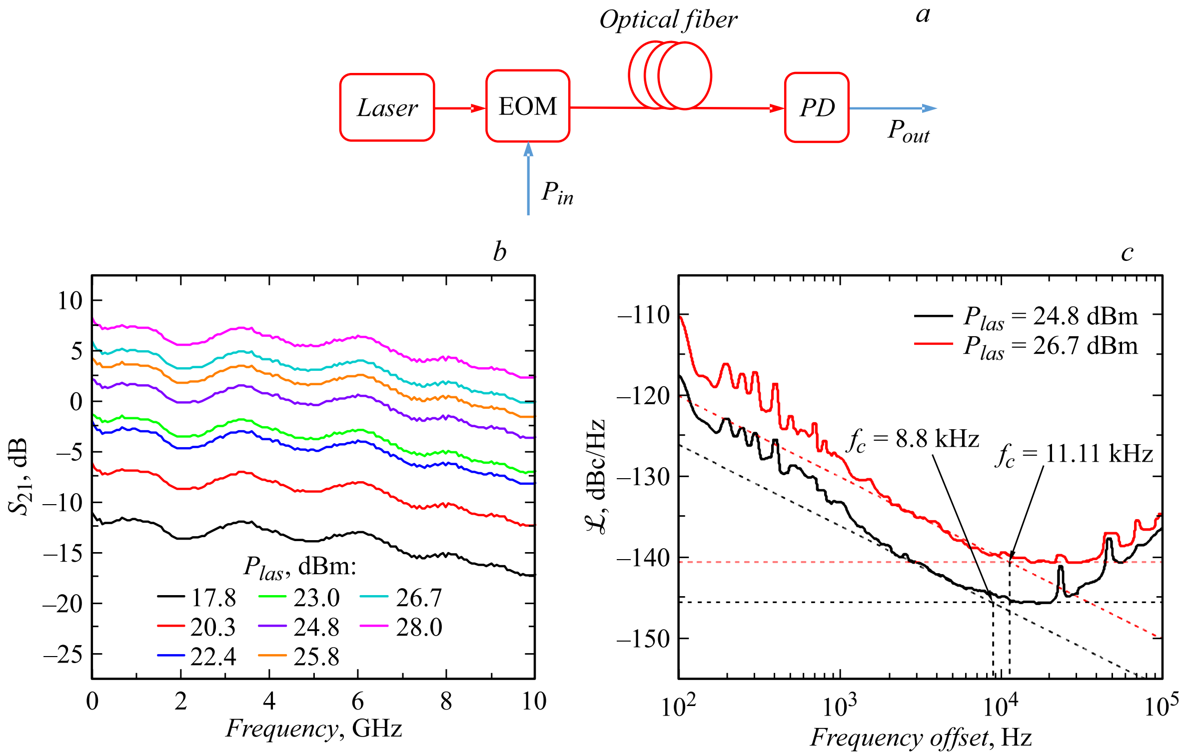

Figure 1. FOTL flow chart (a), FOTL amplitude-frequency response (b) and added phase noise spectra at 3.5 GHz (c) measured at various laser powers.

(as opposed to optical amplification provided by an active component, e.g. semiconductor or erbium optical amplifier).

When the FOTL output with positive transmission coefficient is connected to the FOTL input, then VHF signal self-oscillation occurs in the resulting ring system. To chose the oscillating frequency, a VHF filter shall be used for loss insertion. VHF signal loss will also occur at the oscillator output. This loss may be compensated by passive optical amplification of FOTL. Such self-excited oscillator is be hereinafter referred to as passive optical amplification OEO.

In terms of physics, VHF signal self-oscillation in passive optical amplification OEO will be provided by the optical radiation energy stored in the optic fiber. Laser and photodetector power supply is the source of such energy. VHF signal self-oscillation in passive optical amplification OEO has been investigated inadequately by now. there are just a few studies on this topic [11,12] that mainly show a fundamental possibility of VHF signal self-oscillation in such systems.

The objective of this study was to investigate in detail the VHF signal self-oscillation in passive optical amplification OEO. As a result, this is the first time when correlation between the added phase noise in FOTL and the OEO phase noise has been established. This allowed to modify the Yao-Maleki model describing the OEO phase noise spectrum. The first section of the paper describes the FOTL measurements that influence the OEO phase noise, investigation of which is described in the second and third sections herein. The fourth section of the paper compares the specifications of the given OEO with other optoelectronic oscillators that use VHF or optical amplifiers in their circuits. The Summary provides the main findings.

1. Investigation of the fiber-optic transmission line depending on the laser power

First, we investigated the FOTL model and determined the parameters that are necessary to design an optoelectronic oscillator. Diagram of the fiber-optic VHF signal transmission line is shown in Figure 1, a. This consisted of 1550 nm laser with an emission power of 1 W, Mach-Zender modulator with a half-wave voltage of $V_\pi \approx 1.6$ V, optic fiber and photodetector with a sensitivity of 0.8 A/W in the frequency range of 0–12 GHz.

Operating principle of FOTL is as follows. Continuous laser emission functioning as a carrier signal is subjected to intensity modulation by the monochromatic VHF input signal sent to the Mach-Zender modulator control port. Then, the modulated optical radiation propagates in the fiber-optic cable and is detected by the photodetector. Depending on the FOTL transmission coefficient, the photodetector input signal is a VHF signal attenuated or amplified with respect to the VHF input signal.

As described in the Introduction, the FOTL loss decreases with the increase in laser power P_{las}. Therefore, we have, first, measured the FOTL amplitude-frequency response (AFR) at various values of P_{las}. The results are shown in Figure 1, b, where it can be seen that loss in FOTL is about -13 dB at low frequencies when the laser power is $P_{las} = 17.8$ dBm. They grow with growing frequency due to the decrease in the photodetector sensitivity [10]. The loss in FOTL decreases with increasing laser power. When the laser power is higher than $P_{las} = 26.7$ dBm, the FOTL transmission coefficient becomes positive almost in the full frequency range up to 10 GHz. When laser power is $P_{las} = 28$ dBm, the transmission coefficient is about 7 dB at low frequencies and about 3 dB at 10 GHz. Such measurements indicate that VHF signal self-oscillation can occur in the ring circuit formed by shunting the FOTL output with input.

Then, the added phase noise in FOTL was measured. These measurements will be necessary for future analysis of the OEO phase noise. In addition, FOTL must have low added phase noise to provide low OEO phase noise.

The FOTL added phase noise spectra $\mathscr{L}(f')$ measured at various laser powers are shown in Figure 1, c. The curves show that flicker-noise (or $1/f$ noise) prevails below the flicker-noise cutoff frequency f_c. Its spectral power density is described by $S_{1/f} = b_{-1} f^{-1}$ where b_{-1} is the coefficient of proportionality of the flicker-noise that is determined phenomenologically. Recall that $\mathscr{L} = \frac{1}{2} \cdot S\varphi$. Analysis of the findings has shown that, when the laser power is $P_{las} = 24.8$ dBm, the cutoff frequency f_c is 8.8 kHz, and b_{-1} is equal to$2.5 \cdot 10^{-11}$ rad^2/Hz. If the laser power is increased, then at $P_{las} = 26.7$ dBm these values are equal to $f_c = 11.11$ kHz and $b^{-1} = 1 \cdot 10^{-10}$ rad^2/Hz.

At offset frequencies higher than f_c, white noise is prevailing. Its spectral power density is described as follows

$$S_\varphi = b_0 f^0. \qquad (2)$$

The graph of this function is a horizontal line. However, the experimental dependence of the phase noise spectrum shown in Figure 1, c is horizontal initially and then starts growing. This may be attributable to non-uniformity of the laser RIN at higher offset frequencies [13]. The experimental data review suggests that, when the laser power is$P_{las} = 24.8$ dBm, the white noise level in the wide-band FOTL is about $\mathscr{L} = -145.5$ dBc/Hz, that corresponds to $S_\varphi = -142.5$ dBrad^2/Hz and$b_0 = 5.34 \cdot 10^{-15}$ rad^2/Hz, and when the laser power is $P_{las} = 26.7$ dBm, the white noise level is about $\mathscr{L} = -141$ dBc/Hz, that corresponds to $S_\varphi = -138$ dBrad^2/Hz and $b_0 = 1.59 \cdot 10^{-14}$ rad^2/Hz.

Using the findings for $P_{las} = 24.8$ dBm, we have calculated the laser RIN N_{RIN} as follows. General spectral power density of the FOTL white noise may calculated as follows

$$\rho_0 = \rho_T + \rho_{shot} + \rho_{RIN}, \qquad (3)$$

where $\rho_T = 4kT$ is the spectral power density of the white noise; $\rho_{shot} = 2qI_{ph}R$ is the spectral power density of the shot noise; $\rho_{RIN} = N_{RIN} I_{ph}^2 R$ is the spectral power density of the noise induced by the laser RIN contribution; k is the Boltzmann constant; T is the absolute temperature; q is the electron charge; $I_{ph} = \alpha P_{las} S/2$ is the photodetector output photocurrent; α is the loss of optical radiation power in the optical path consisting of the loss in the Mach-Zender modulator (when the working point is at the maximum transmission ratio) and in the optic fiber, and expressed in relative units; N_{RIN} — laser RIN.

b_0 included in equation (2) is related to ρ_0 by the following expression: $b_0 = \rho_0/P_{in}$, whereP_{in} is the VHF signal power at the FOTL input. By applying ρ_0 from this expression to equation (3), we derive an equation where N_{RIN} is the only value that is unknown. Using the following parameter values of the experimental FOTL model: $T = 293$ K, $R = 50\,\Omega$, $\alpha = 0.171$ (that correspond to the loss in the Mach-Zender modulator 4.5 dB, total loss in optical fiber 0.18 dB and total loss on three optical connectors ≈ 3 dB), $S = 0.8$ A/W, $P_{las} = 302$ mW (that corresponds to 24.8 dBm); $P_{in} = 10$ dBm; and experimental value $b_0 = 5.34 \cdot 10^{-15}$ rad^2/Hz for $P_{las} = 24.8$ dBm, we find $N_{RIN} = -146$ dB/Hz.

Then, for the resulting value of N_{RIN}, equations (2) and (3) were used to calculate the spectral white noise density S_φ at the laser power of $P_{las} = 26.7$ dBm. $b_0 = 1.12 \cdot 10^{-14}$ rad^2/Hz and$S_\varphi = -139$ dBrad^2/Hz were calculated that are in good agreement with the measurements (Figure 1, c). This value of N_{RIN} will be further used to calculate the OEO phase noise spectrum.

2. Investigation of OEO oscillation and phase noise spectra without amplifiers

The flow chart of OEO on the basis of FOTL with positive transmission coefficient is shown in Figure 2, a. SMF-28 optical fibers with lengths from 100 m to 2 km were used for the measurements. The laser power was varied from 24.8 to 27.1 dBm. The lower limit is derived from the self-oscillation activation threshold in the ring circuit. The upper limits is due to the fact that, when the laser power is higher than 27.1 dBm in OEO, the quasi-monochromatic oscillation was transformed into multi-frequency oscillation. To output the VHF signal from the ring circuit, the VHF directional tapper with tapping ratio 10 dB was used. The OEO model used a band-pass filter with a carrier frequency of 3.5 GHz and a bandwidth of 30 MHz measured at 3 dB. Such frequency was caused by the local peak of FOTL AFR at 3.5 GHz (Figure 1, b). Therefore, the VHF signal self-oscillation occurred at 3.5 GHz.

First, we turn our attention to the measurements made for the optic fiber length of 600 m, because the oscillator demonstrated the lowest phase noise at such optic fiber length. Figure 2, b shows the self-oscillation spectrum that occurred a little higher than the threshold at the laser power of $P_{las} = 24.8$ dBm. Additional noise harmonic with power reduced by about 60 dB can be seen around the fundamental harmonic.. In addition, it should be noted that the fundamental oscillation harmonic power was equal to

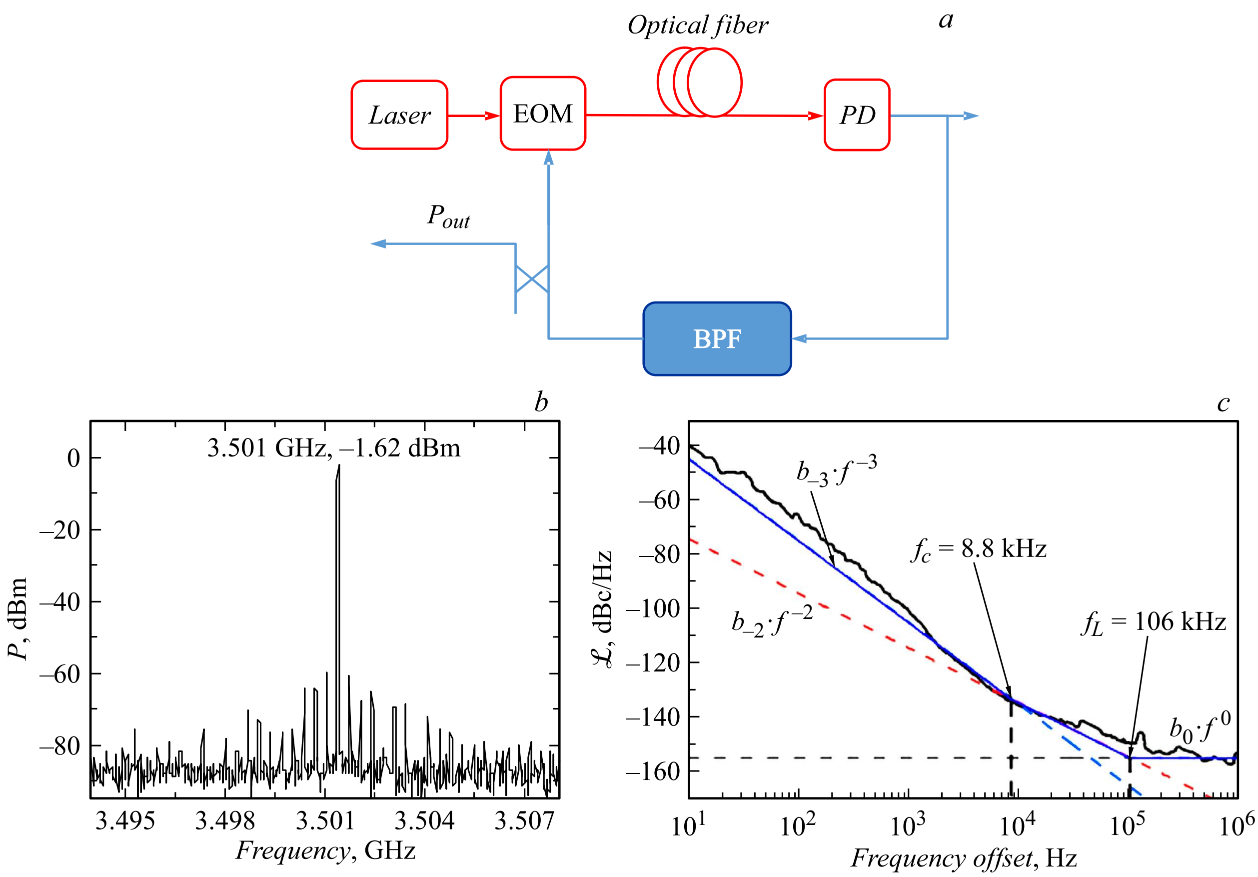

Figure 2. Flow chart of OEO on the basis of FOTL with positive transmission coefficient (*a*), OEO oscillation spectrum (*b*), OEO phase noise spectrum (*c*). The measurements were carried out at the laser power of 24.8 dBm.

-1.62 dBm. This means that the power entering the Mach-Zender modulator control port is approximately equal to 10 dBm that is similar to the measurement of the FOTL added phase noise. Thus, FOTL in the OEO circuit runs in the same mode as during the added phase noise measurement.

Figure 2, *c* shows the OEO phase noise spectrum. The curve sows that, at the offset frequency of 10 kHz, the OEO phase noise was quite low and equal to -135 dBc/Hz. This spectrum was initially analyzed using the Leeson phenomenological model [14,15]. The spectrum was approximated using the following polynomial: $S_\varphi = \sum_{i=-3}^{0} b_i \cdot f^i$, where$b_0 = 3.16 \cdot 10^{-16}$, $b_{-1} = 0$ (because there is no f^{-1} slope), $b_{-2} = 3.56 \cdot 10^{-6}$, $b_{-3} = 0.031$. It is shown that , above the Leeson frequency (is calculated for OEO as $f_L = 1/\pi\tau$, where τ is the signal delay time in the „open“ ring), the phase noise spectrum has a zero slope f^0, and the noise is equal to $\mathscr{L} = -155$ dBc/Hz (that corresponds to $S_\varphi = b_0 \cdot f^0 = -152$ dBrad^2/Hz). This value agrees quite well with the minimum FOTL phase noise determined above. For the optic fiber length of 600 m, the Leeson frequency is equal to $f_L = 106$ kHz, as shown in Figure 2, *c*. Below f_L, the phase noise spectrum slope changes from f^0 to f^{-2} and is described by expression $S_\varphi = b_{-2} \cdot f^{-2}$. The phase noise spectrum slope changes from f^{-2} to f^{-3} at the offset frequency of $f_c = 8.8$ kHz, that agrees well with the FOTL flicker-noise cutoff frequency determined in the previous section. Spectrum at such offsets is described by expression $S_\varphi = b_{-3} \cdot f^{-3}$.

Then numerical calculation of the phase noise spectrum was calculated. Such calculation is usually performed using the Yao-Maleki model [9]. This model assumes that only thermal noise, shot noise and laser RIN are the phase noise sources in OEO, therefore the phase noise spectrum is calculated as follows

$$S(f') = \frac{\delta}{(2 - \delta/\tau) - 2\sqrt{1 - \delta/\tau}\cos(2\pi f'\tau)}, \qquad (4)$$

where $\delta = \rho_0 \cdot G_A/P_{osc}$ is the OEO noise-to-signal ratio, ρ_0 is calculated using equation (3), G_A is the VHF power gain of the amplifier (for OEO without VHF amplifiers $G_A = 1$), P_{osc} is the power of the oscillated VHF signal. The spectrum of the phase noise simulated using the standard Yao-Maleki model is shown by the dotted line in Figure 3. It can be seen that the standard model agrees quite well with the experimental data at high offset frequencies, however, the disagreement with the experimental curve is rather considerable at the offset frequencies below 1 kHz.

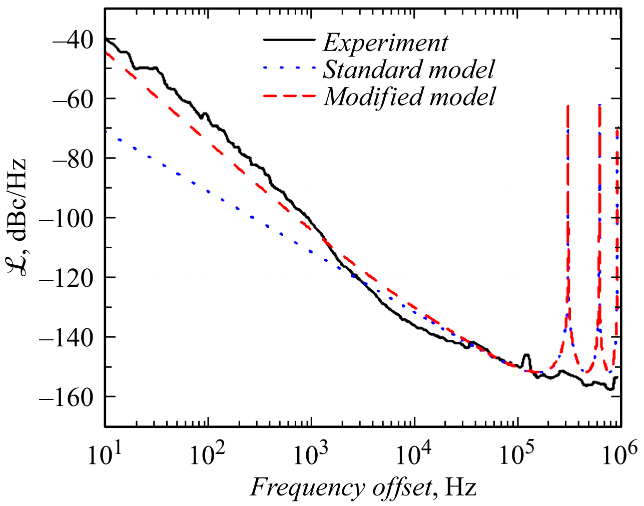

Figure 3. Passive optical amplification OEO phase noise spectrum (solid line), spectrum of phase noise simulated using the standard Yao-Maleki model (dotted line), spectrum of phase noise simulated using the modified Yao-Maleki model (dashed line).

We have modified the Yao-Maleki model by adding the FOTL flicker-noise. As a result, the noise-to-signal ratio was written as $\delta = \rho_0 \cdot G_A/P_{osc} + b_{-1} \cdot f^{-1}$, b_{-1} is the coefficient of proportionality of the FOTL flicker-noise that was determined in the previous section. The phase noise spectrum simulation using the modified Yao-Maleki model is shown by the dashed line in Figure 3. The Figure shows that the modified model describes the phase noise spectrum much better than the standard model from [9].

3. The effect of OEO design parameters without amplifiers on the phase noise

First, let's consider how the laser radiation power affects the OEO phase noise. Measurements of phase noise at various offsets from the oscillation frequency $f_0 = 3.501$ GHz at various laser powers are marked with signs in Figure 4, *a*. The measurements show that the OEO phase noise increases with the laser power growth. For example, with when the laser power increases from 24.8 to 27 dBm, the phase noise at offset frequency 10 kHz increases from −135 to −118 dBc/Hz. Such phase noise behavior is explained by the fact that, when the laser power P_{las} grows, noises ρ_{shot} and ρ_{RIN} included in equation (3) are also growing. As a result, the noise-to-signal ratio included in equation (4) is growing.

To confirm the obtained experimental data, the OEO phase noise was calculated using equation (4) taking into account the introduced modification (i.e. considering the FOTL flicker-noise). moreover, it shall be noted that the dependence of b_{-1} on the laser power P_{las} was additionally considered in the calculation. This dependence was derived from the analysis of the FOTL added phase noise spectra in Figure 1, *c* on the assumption that $b_{-1} = 2.5 \cdot 10^{-11}\,\mathrm{rad}^2/\mathrm{Hz}$ at the laser power of 24.8 dBm (302 mW), and $b_{-1} = 1 \cdot 10^{-10}\,\mathrm{rad}^2/\mathrm{Hz}$ at the power of 26.4 dBm (468 mW). The linear approximation was made by these two points and functional dependence of b_{-1} on P_{las} was derived: $b_{-1}(P_{las}) = 4.52 \cdot 10^{-10} \cdot P_{las} - 1.11 \cdot 10^{-10}$, where$P_{las}$ is the laser power in watts. Then the derived dependence of $b_{-1}(P_{las})$ was used to calculate the dependence of the phase noise on the laser power using equation (4). The calculation data is shown in Figure 4, *a* with solid lines. For comparison, the dependence of the phase noise on the laser power was calculated without considering the dependence of b_{-1} on P_{las}, the calculation data is shown in Figure 4, *a* with dashed lines. It is shown that the dependence of b_{-1} on P_{las} considered in the simulation provides better coincidence with the experimental data. At the offset frequency of 100 Hz, the agreement of the simulation data with the experimental data is worse, because the experimental phase noise spectrum at the offset frequency below 1 kHz has a slope that is a bit steeper than f^{-3} (Figure 3).

Then the effect of the optic fiber length on the OEO phase noise was investigated. It should be noted that the laser power P_{las} at which self-oscillation started depended on the optic fiber length, because the loss in OEO grow with the growth of the optic fiber length, and the FOTL transmission coefficient must be increased by increasing the laser power.

To measure the phase noise, $P_{las}$was chosen such that to ensure self-oscillation at all optic fiber lengths from 100 m to 2 km. It was equal to $P_{las} = 26.4$ dBm. The results are shown in Fig. 4, *b*. The curves show that the increase in the optic fiber length results in the decrease in the phase noise similarly to the standrad OEO with amplifiers [16].

The study uses relatively high laser powers and long optic fiber lengths, therefore the stimulated Mandelstam-Brillouin scattering (SMBS) threshold will be estimated. When $P_{las} = 26.4$ dBm, the radiation power at the optic fiber input is $P_{opt} = 18.9$ dBm (77.6 mW). For such power, the length limit of SMF-28 optic fiber beyond which SMBS may occur can be easily calculated. It is shown in Figure 4, *b* with the dashed line and is equal to $L_{th} \approx 900$ m.

4. Discussion of findings

The obtained minimum values of OEO phase noise for OEO with the optic fiber length of 600 m were compared with other literature on OEO. The comparison data is shown in the Table. The Table shows that OEO without amplifiers in [11] demonstrated phase noise −133 dBc/Hz with offset 10 kHz from the carrier frequency 1.25 GHz and−130 dBc/Hz with the same offset from the carrier frequency 10 GHz. To reduce the phase noise, 6 km optic fiber and laser frequency modulation were used. In addition, this OEO used additional electronic circuit for Lase RIN suppression. In [12], a double-ring OEO with optical fiber

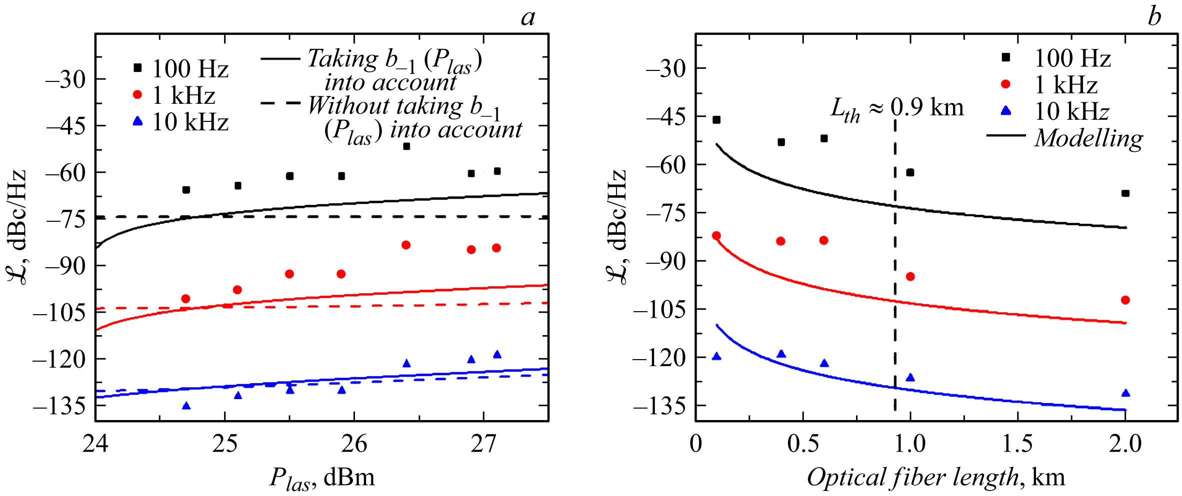

Figure 4. *a* — dependences of the phase noise on the laser power at the optic fiber length of 600 m; *b* — dependences of the phase noise on the optic fiber length at the laser power of $P_{las} = 26.4$ dBm.

Phase noise of optoelectronic VHF oscillators

Optic fiber length/Oscillation frequency	Phase noise, dBc/Hz		
	100 Hz	1 kHz	10 kHz
[11] (6 km)/(1.25 GHz), without amplifiers	−80	−105	−133
[11] (6 km)/(10 GHz), without amplifiers	−70	−100	−130
[12] (2.3 km)/(10 GHz), without amplifiers	−70	−105	−120
[17] (2.2 km)/(4 GHz), with VHF amplifier	–	−100	−143
[17] (600 m)/(4 GHz), with VHF amplifier	–	−75	−112
[18] (3.2 km)/(4 GHz), with optical amplifier	–	−115	−139
[18] (55 m)/(4 GHz), with optical amplifier	–	−80	−108
This study (600 m)/(3.5 GHz), without amplifiers	−65	−101	−135

lengths of 2.3 km and 1.4 km was designed. The oscillator demonstrated the phase noise of −120 dBc/Hz with offset 10 kHz from the carrier frequency 10 GHz. Comparison of findings shows that the OEO studied herein (the last line in the table) has lower phase noise with an offset of 10 kHz at simpler design and much shorter optic fiber length. However, at offset frequencies 100 Hz and 1 kHz, the oscillator phase noise from [10] is a little bit lower due to the use of longer optic fiber.

According to the data from the review [3], a OEO with VHF amplifier and the lowest noise level has the phase noise of −143 dBc/Hz with offset 10 kHz from the carrier frequency 4 GHz [17]. It uses 2.2 km optical fiber. The same study showed that the phase noise with offset 10 kHz increases to −112 dBc/Hz when 600 m optical fiber is used in the same OEO. Comparison of these findings with the findings of this study obtained for 600 m optical fiber shows that avoidance of a VHF amplifier in the OEO circuit reduces the phase noise considerably.

For OEO with optical amplifier, the data of [3] suggest that the most low-noise OEO demonstrates the phase noise of −139 dBc/Hz with offset 10 kHz from the carrier frequency 4 GHz at the optical fiber length of 3.2 km [18]. The oscillator studied herein demonstrates a comparable phase noise level at a much shorter optic fiber length.

Conclusion

The investigation shows that avoidance of amplifiers from the OEO circuit, i.e. the use of passive optical amplification allows you to reduce the OEO phase noise. It is shown that the laser power shall be reduced and optic fiber length shall be increased in order to decrease the phase noise. However, when laser power decreases, the passive optical amplification effect in FOTL disappears and the VHF signal self-oscillation in OEO becomes impossible. Therefore, the laser power and optic fiber length are competing parameters, consequently, these parameters shall be selected correctly to design OEO with low phase noise.

To describe the OEO phase noise spectra, we have proposed a modified Yao-Maleki model that considers the FOTL flicker-noise effect and dependence on the laser power. Such modification provided accurate description of the OEO phase noise spectrum and the laser power effect on it.

Thus, OEO with passive optical amplification is a low-noise device and may be used in radar and communication systems.

Funding

This study was partially supported by the Ministry of Science and Higher Education of the Russian Federation (project „State Assignment", grant FSEE-2020-0005).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.A. Savchenkov, V.S. Ilchenko, W. Liang, D. Eliyahu, A.B. Matsko, D. Seidel, L. Maleki. Opt. Lett., **35** (10), 1572 (2010). DOI: 10.1364/OL.35.001572

[2] M.L. Gorodetsky, *Opticheskie microrezonatory s gigantskoj dobrotnost'yu* (Fizmatlit, Moskva, 2011) (in Russian).

[3] Y.K. Chembo, D. Brunner, M. Jacquot, L. Larger. Rev. Modern Phys., **91** (3), 035006 (2019). DOI: 10.1103/RevModPhys.91.035006

[4] A.B. Ustinov, I.Yu. Tatsenko, A.A. Nikitin, A.V. Kondrashov, A.V. Shamrai, A.V. Ivanov. Fotonika, **15**, 3 (228) (in Russian). DOI: 10.22184/1993-7296.FRos.2021.15.3.228.237

[5] A.B. Ustinov, I.Yu. Tatsenko, A.A. Nikitin, A.V. Kondrashov, A.V. Shamrai, A.V. Ivanov. Fotonika, **15**, 4 (334) (in Russian). DOI: 10.22184/1993-7296.FRos.2021.15.4.334.346

[6] X.S. Yao, L. Maleki. Electron. Lett., **30** (18), 1525 (1994). DOI: 10.1049/el:19941033

[7] M.E. Belkin, A.V. Loparev, Y. Semenova, G. Farrell, A.S. Sigov. Microwave Opt. Technol. Lett., **53** (11), 2474 (2011). DOI: 10.1002/mop.26304

[8] K. Mikitchuk, A. Chizh, S. Malyshev. IEEE J. Quant. Electron., **52** (10), 5000108 (2016). DOI: 10.1109/JQE.2016.2600408

[9] X.S. Yao, L. Maleki. JOSA B, **13** (8), 1725 (1996). DOI: 10.1364/JOSAB.13.001725

[10] I.Yu. Tatsenko, T.K. Legkova, A.V. Ivanov, A.B. Ustinov. Izv. vuzov Rossii. Radioelektron., **23** (4), 48 (2020) (in Russian). DOI: 10.32603/1993-8985-2020-23-4-48-56

[11] C.W. Nelson, A. Hati, D.A. Howe, W. Zhou. In: *2007 IEEE International Frequency Control Symposium Joint with the 21st European Frequency and Time Forum* (Geneva, Switzerland, 2007), DOI: 10.1109/FREQ.2007.4319233

[12] W. Zhou, O. Okusaga, C.W. Nelson, D.A. Howe, G. Carter. Optoelectron. Integrated Circuits X, **6897**, 68970Z (2008). DOI: 10.1117/12.760479

[13] V.J. Urick, J.D. McKinney, K.J. Williams. *Fundamentals of Microwave Photonics.* (John Wiley & Sons, Hoboken, New Jersey, 2015)

[14] D.B. Leeson. Proceed. IEEE, **54** (2), 329 (1966). DOI: 10.1109/PROC.1966.4682

[15] E. Rubiola. *Phase Noise and Frequency Stability in Oscillators* (Cambridge University Press, 2008)

[16] A.B. Ustinov, A.V. Kondrashov, A.A. Nikitin, V.V. Lebedev, A.N. Petrov, A.V. Shamrai, B.A. Kalinikos. J. Phys.: Conf. Series, **1326** (1), 012015 (2019). DOI: 10.1088/1742-6596/1326/1/012015

[17] A.B. Ustinov, A.A. Nikitin, V.V. Lebedev, A.A. Serebrennikov, A.V. Shamray, A.V. Kondrashov, B.A. Kalinikos. J. Phys.: Conf. Series, **1038** (1), 012033 (2018). DOI: 10.1088/1742-6596/1038/1/012033

[18] Y. Liu, T. Hao, W. Li, J. Capmany, N. Zhu, M. Li. Light: Sci. Applications, **7** (1), 38 (2018). DOI: 10.1038/s41377-018-0035-8

Translated by Ego Translating