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Noise conversion in delay-line optoelectronic microwave oscillators

A.L. Chizh, K.B. Mikitchuk

Abstract. **We report the results of theoretical and experimental studies of noise in a delay-line optoelectronic microwave oscillator with optical gain. The effect of various noise sources on the parameters of an optoelectronic microwave oscillator is considered, and, in addition to the noise of its individual components, several linear and nonlinear mechanisms for converting optical carrier noise into microwave signal noise are taken into account. It is shown that, due to the nonlinearity of the energy characteristics of high-power microwave photodiodes in an optoelectronic generator, the low-frequency components of the laser relative intensity noise are converted into microwave signal noise, as a result of which sources of correlated amplitude and phase noise appear in the oscillator loop.**

Keywords: *microwave optoelectronic oscillator, amplitude noise, phase noise, noise power spectral density, flicker noise.*

1. Introduction

The use of optical and optoelectronic generation methods makes it possible to obtain sinusoidal signals with a microwave frequency and low phase noise. Optoelectronic microwave oscillators are the most promising for the implementation of such methods as applied to modular-design devices [1, 2]. According to the principle of operation, these oscillators are autogenerators with positive feedback based on a fibre-optic delay line or a high-Q optical cavity [3]. The possibility of generating a quasi-harmonic microwave signal with ultra-low phase noise in delay-line microwave optoelectronic oscillators is due to duration up to tens of microseconds in fibre-optic delay lines, which is equivalent to the Q-factor of microwave resonators over 10^6 for X-band frequencies. The main advantages of delay-line microwave optoelectronic oscillators are the following: their phase noise level does not depend on the oscillation frequency (provided that optoelectronic components with an appropriate frequency band are used) and they are highly resistant to electromagnetic interference and vibrations.

Phase detectors are used in modern communication systems, radar and microwave measuring equipment, and so the most important characteristic of the oscillator is the phase noise, while the amplitude noise is considered insignificant [1]. However, in high-Q oscillators, the mutual conversion of amplitude and phase noise can occur when, for example, an amplifier in the gain compression regime is used in the oscillator loop, in which the power spectral density of the noise floor depends on the frequency as $1/f$ [4]. Since the source of disturbances in this case is the same baseband (low-frequency) noise process, the amplitude and phase noise become correlated, and both are characterised by a frequency-dependent power spectral density, approximately equal to $1/f$. Thus, reducing the amplifier noise floor in the optoelectronic microwave oscillator loop is the main way to reduce the phase noise. Earlier, optoelectronic microwave oscillators with both all-electronic and all-optical gain have been demonstrated [2, 5]. The use of an optical amplifier based on an erbium-doped fibre, on the one hand, can potentially provide low noise floor and, as a consequence, reduce the phase noise of the optoelectronic oscillator, while on the other hand, can lead to mutual conversion of amplitude and phase noise. In this case, special attention should also be paid to the suppression of the amplitude and phase noise of the optical carrier [6–8].

Thus, the development of an optoelectronic microwave oscillator with ultra-low phase noise requires comprehensive examination of a wide range of noise sources, as well as a set of mechanisms for converting optical carrier noise into phase noise in the microwave photodiode output in the positive feedback loop. In this work, we present the results of a theoretical and experimental study of the noise in a delay-line optoelectronic microwave oscillator with optical gain.

For experimental studies, a previously developed module of a double-loop optoelectronic microwave oscillator with all-optical gain [9] was used, which provides oscillation at a frequency of 10 GHz with an ultra-low phase noise level [–142 dBc Hz^{-1} (decibels relative to the carrier power per hertz)] at a frequency detuning of 10 kHz from the microwave carrier and a low level of spurs (–91 dBc) [9]. In the optoelectronic microwave oscillator module, an LDI-1550-DFB-2.5G (Laserscom) distributed-feedback laser diode was used as an optical source, and high-power Schottky photodiodes based on a double InAlAs/InGaAs/InP heterostructure with a photosensitive region having a diameter of 20 μm were used as microwave photodiodes [10].

Detailed theoretical studies on the delay-line double-loop optoelectronic oscillator with optical gain are performed using a nonlinear time-variant model based on the method of complex slowly varying amplitude of the oscillation signal [11]. Each circulation around the oscillator takes into account the sequential action of the oscillator components on the signal sample: a Mach–Zehnder optical modulator, fibre-optic delay lines, a fibre-optic amplifier, microwave photodiodes, and a microwave filter. This makes allows one to simulate the

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noises of the oscillator's individual components, linear and nonlinear mechanisms of optical carrier noise conversion, the nonlinearity of the oscillator components, the time-variant interaction of the oscillator signal with the noise components in the spectrum, as well as the combined effect of various combinations of noise sources. It should be noted that in this work, the term 'flicker noise' refers to noise floor with a power spectral density that depends on the frequency as b_{-1}/f, where b_{-1} is the noise weight factor [1].

2. Noise sources

Figure 1 shows the classification of noise sources in an optoelectronic microwave oscillator, in which, in addition to the noise of individual components, a conversion of the optical carrier noise into the noise of the microwave signal at the microwave photodiode output occurs due to a number of linear and nonlinear mechanisms:

– phase noise of the optical carrier caused by the interference of re-reflected and/or scattered optical signal (Rayleigh and Brillouin scattering) is converted into additive noise at the microwave photodiode output;

– dispersion in the optical fibre deteriorates the deterministic relationship between the phases of the components of the intensity-modulated optical signal, which also leads to the conversion of the optical carrier phase noise into the noise of the microwave signal; and

– optical intensity fluctuations are converted in the photodiode into the microwave signal noise both as a result of direct detection and the nonlinearity of the energy characteristics of the microwave photodiode.

Figure 2 shows the dependences of the phase-noise power spectral density on the length of the main fibre-optic delay line at offset frequencies of 1 and 10 kHz from the microwave carrier for an optoelectronic oscillator with optical gain and an oscillation frequency of 10 GHz, calculated for various noise sources. It is seen that the main noise sources are the optical amplifier noise, noise caused by dispersion in the optical fibre, and multiplicative flicker noise. At an offset frequency of 1 kHz, flicker noise with a weight factor $b_{-1} = -110$ dB determines the output signal phase noise and, due to the multiplicative property, does not depend on the signal delay time in the fibre-optic line [11]. For fibre-optic lines longer than 10 km, the main noise source is the noise of the optical amplifier or the noise caused by the optical fibre dispersion. At a 10 kHz frequency offset from the microwave carrier, the main noise source for fibre-optic lines less than 4 km long is the noise of the optical amplifier, while for lengths over 4 km, noise due to dispersion in the optical fibre is added. At an offset frequency of 10 kHz, flicker noise does not significantly affect the phase noise of the output signal; in this case, there is a length of the fibre-optic delay line, above which the phase noise ceases to decrease due to an increase in the noise floor associated with the combined effect of optical amplifier noise and noise caused by dispersion and/or Rayleigh scattering in the optical fibre.

3. Dynamic effects of noise conversion

Figure 3 shows the spectral power densities of the phase and amplitude noise of the output signal of the optoelectronic

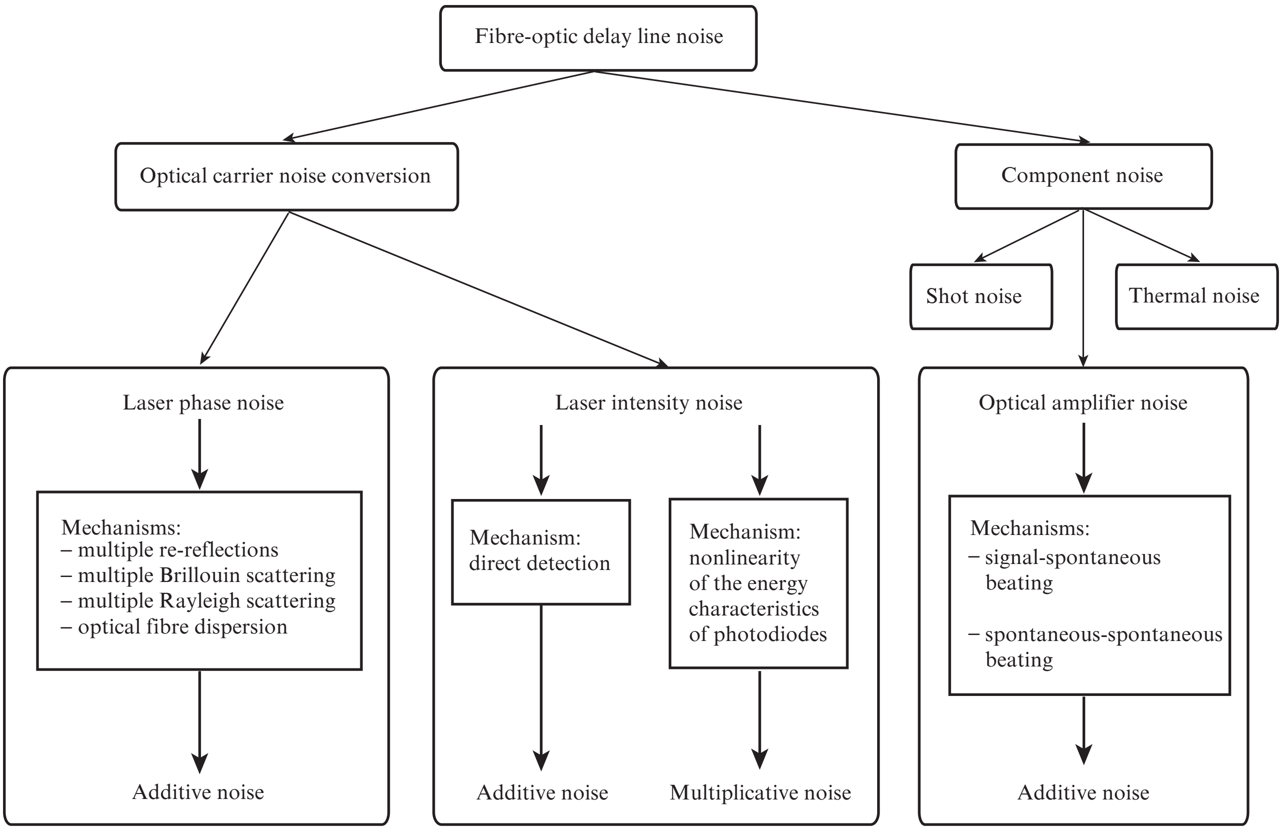

Figure 1. Classification of noise sources in optoelectronic oscillators.

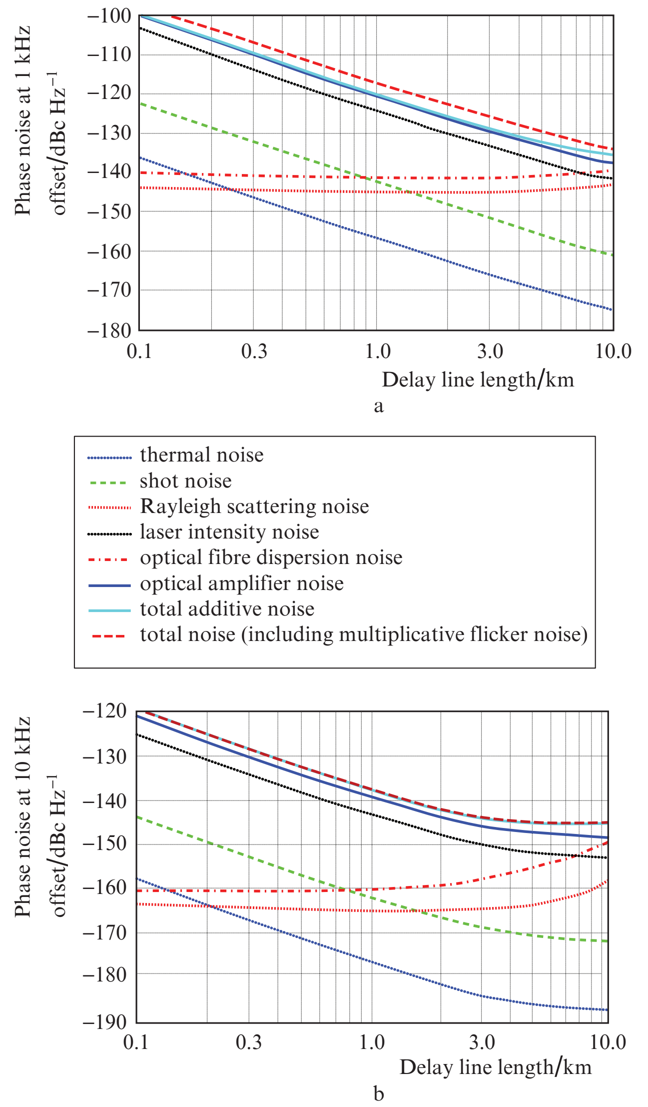

Figure 2. (Colour online) Phase noise power spectral density of the optoelectronic generator vs. the fibre-optic delay line length at offset frequencies of (a) 1 and (b) 10 kHz from the microwave carrier for various noise sources (oscillation frequency 10 GHz, microwave filter bandwidth 2 MHz, flicker noise weight factor $b_{-1} = -110$ dB).

oscillator for various temperatures of the laser diode being the optical carrier source in the optoelectronic oscillator loop. In the phase noise spectrum at a low frequency offset from the microwave carrier due to the effect of multiplicative flicker noise sources, the phase noise power density is inversely proportional to the third power of frequency offset, while at high frequencies, due to the effect of additive noise sources with uniform spectral density, the phase noise power density is inversely proportional to the second power of frequency offset. It is seen that the power spectral density of the phase noise at 10 kHz frequency offset from the microwave carrier is -140 dBc Hz^{-1}, while the power spectral density of spurs in the oscillation spectrum does not exceed -120 dBc Hz^{-1}. As the laser operating temperature decreases, the power spectral density of the amplitude noise at an offset frequency close to the microwave carrier also decreases, which is due to a decrease in the laser diode relative intensity noise used for optical carrier generation.

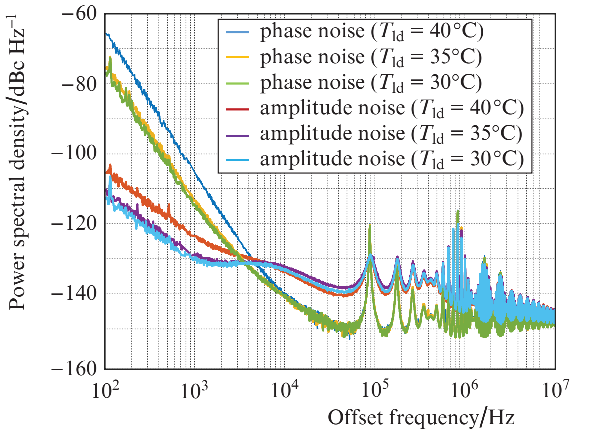

Figure 3. (Colour online) Measured power spectral densities of the phase and amplitude noise of the optoelectronic oscillator output signal at various temperatures T_{ld} of the laser diode being the optical carrier source in the optoelectronic oscillator loop.

The phase and amplitude noise of the optoelectronic oscillator at an offset frequency close to the microwave carrier is determined by conversion of the low-frequency components of the laser relative intensity noise into the noise of the output microwave signal. In order to look in more detail at the mechanisms of this conversion, it is necessary to consider the ‘electro-optical conversion – opto-electronic conversion’ complex. Conversion of the laser intensity noise in microwave photodiodes is a consequence of the combined effect of the nonlinear dependences of the photodiode impedance and the charge carrier transport time on the electric field distribution in the semiconductor structure of the microwave photodiode. For this reason, the low-frequency components $\mathrm{RIN}_{ld}(\Delta f)$ of the laser relative intensity noise at low offsets Δf from the optical carrier are converted into the phase noise with the same offsets Δf from the frequency f_{osc} of the photodiode output microwave signal. The power spectral densities of the excess phase and amplitude noise at the microwave photodiode output can be represented as [12]

$$L_\varphi(\Delta f) = \mathrm{RIN}_{ld}(\Delta f) K_\varphi(f_{osc}), \tag{1}$$

$$L_a(\Delta f) = \mathrm{RIN}_{ld}(\Delta f) K_a(f_{osc}), \tag{2}$$

where $K_\varphi(f_{osc})$ is the conversion coefficient of the optical intensity noise into the phase noise of the microwave signal at the photodiode output, i.e., the amplitud – phase conversion coefficient for the frequency f_{osc} (AM – PM conversion); and $K_a(f_{osc})$ is the conversion coefficient of the laser intensity noise into the amplitude noise of the microwave signal at the photodiode output (AM – AM conversion).

The AM – AM and AM – PM conversion coefficients in the microwave photodiode were estimated using a specially designed setup for measuring the dependence of the phase φ_{pd} and amplitude A_{pd} of the output microwave signal at frequency f on the constant component of the optical power P_{opt} as follows [9]:

$$K_\varphi = P_{opt}^2 \left(\frac{\partial \varphi_{pd}}{\partial P_{opt}}\right)^2 = I_{dc}^2 \left(\frac{\partial \varphi_{pd}}{\partial I_{dc}}\right)^2, \tag{3}$$

$$K_a = \left[\frac{1}{2}\frac{P_{opt}}{A_{pd}}\left(\frac{\partial A_{pd}}{\partial P_{opt}}\right)\right]^2 = \left[\frac{1}{4}\frac{I_{dc}}{P_{mw}}\left(\frac{\partial P_{mw}}{\partial I_{dc}}\right)\right]^2, \quad (4)$$

where P_{mw} is the microwave signal power at the microwave photodiode output; and I_{dc} is the constant photocurrent strength.

Figure 4 shows the AM – AM and AM – PM conversion coefficients for high-power InGaAs photodiodes being a part of the microwave optoelectronic oscillator as functions of the constant photocurrent strength. It should be noted that when using single-frequency LDI-1550-DFB-2.5G (Laserscom) laser diodes with a power of 13 dBm at a wavelength of 1.55 μm, the loop gain g_{ss} exceeds its threshold value (0 dB) at the Mach – Zehnder modulator phase 140° – 170°. For this reason, a signal with a power of ~0 dBm and a modulation depth of ~100 % is formed at the optical amplifier input, which, in turn, provides a constant photocurrent in the range of 10 – 20 mA. It can be seen that the AM – AM conversion coefficient is in the range from –2 to –6 dB, while the AM – PM conversion coefficient is less than –40 dB for typical operating photocurrents in an optoelectronic oscillator with all-optical gain.

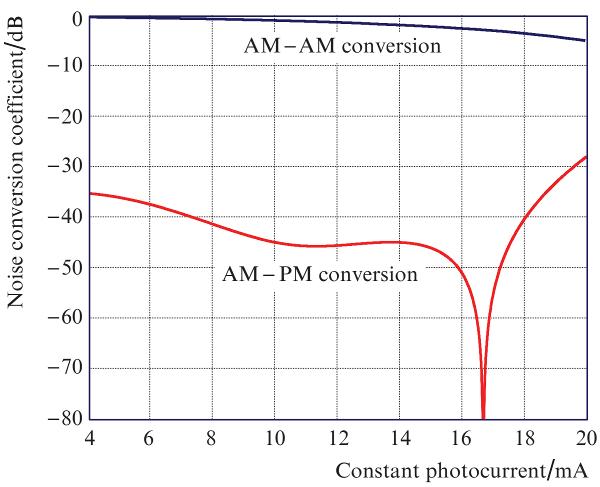

Figure 4. AM – AM and AM – PM noise conversion coefficients at a 10 GHz frequency for high-power InGaAs pin-photodiodes vs. the constant photocurrent strength.

It follows from relations (1) and (2) that the excess phase and amplitude noises arise from the same source (baseband relative intensity noise). For distributed-feedback laser diodes, the power spectral density of the baseband relative intensity noise depends on the frequency as $1/f$ at small offsets from the optical carrier [5]. Given the difference of more than 30 dB between the spectral densities of excess amplitude and phase noise, it can be argued that an optoelectronic oscillator with optical gain, designed using the microwave photodiodes under consideration, contains a sufficient high-power source of amplitude flicker noise. As the simulation shows, there is a nonlinear time-variant interaction between the amplitude and phase noises in the oscillator loop and their mutual conversion.

To illustrate the relationship between amplitude and phase noise, an optoelectronic oscillator was simulated in the time domain in the presence of the source of the multiplicative phase flicker noise. After the numerical simulation of the complex envelope of the oscillation signal, the correlation function of amplitude and phase fluctuations was calculated. It should be noted that when describing the dynamic regime of an optoelectronic oscillator with optical gain, it is convenient to use the loop gain coefficient in the small signal regime [5, 11]. To ensure stationary oscillation, it is necessary that the small-signal loop gain g_{ss} be in the range of 0 – 10.3 dB, since at $g_{ss} < 0$ dB the amplitude oscillation condition is not satisfied, while at $g_{ss} > 10.3$ dB the regime of dynamic instabilities occurs [11].

Figure 5 shows the cross-correlation functions of amplitude and phase fluctuations calculated for various values of the small-signal loop gain. It is seen that in the stationary oscillation regime $g_{ss} = 4$ dB, the cross-correlation function represents a noise 'pedestal' monotonically decaying to zero. In the case of correlated amplitude and phase fluctuations, this function should be quasi-periodic [11]. It is also seen that near the optoelectronic oscillator oscillation threshold, the cross-correlation function of the oscillation signal fluctuations in the amplitude and phase is nonmonotonic. In other words, the amplitude and phase fluctuations are correlated. For example, in an optoelectronic oscillator, the phase noise floor depends on the oscillation amplitude, which, in turn, due to the nonlinearity of the Mach – Zehnder modulator, depends on the amplitude fluctuations. Thus, near the optoelectronic oscillator oscillation threshold (g_{ss} = 0 – 3 dB), a time-variant interaction of the amplitude and phase noise and their mutual conversion occurs in the oscillator loop. This dynamic oscillation effect is enhanced as the noise weight factor b_{-1} increases.

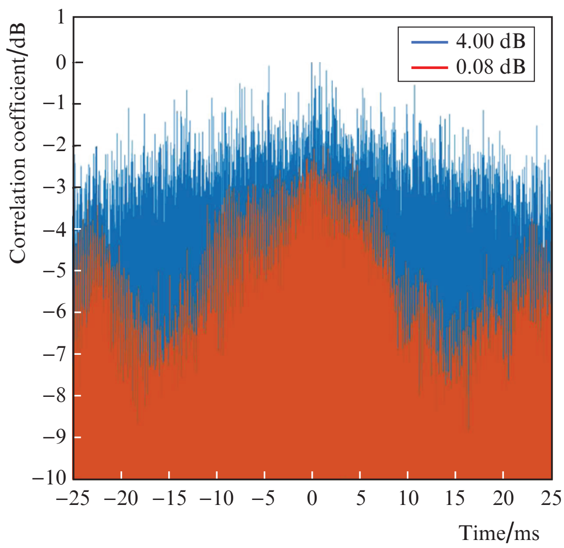

Figure 5. (Colour online) Cross-correlation functions of the amplitude and phase fluctuations calculated for various values of the small-signal loop gain.

Given that the laser baseband relative intensity noise is mainly converted into the amplitude noise of the microwave signal, the observed decrease in the amplitude noise with a decrease in the laser baseband relative intensity noise can be considered as a reason for reducing the phase noise. The mechanisms of mutual conversion of the amplitude and phase noise in the optoelectronic oscillator with all-optical gain are illustrated in Fig. 6. It is seen that there are two main ways to reduce the mutual effect of amplitude and phase noise. Firstly, the optoelectronic oscillator should be used in a stationary oscillation regime with a loop gain of more than 3–4 dB, when its threshold value is significantly exceeded. Secondly, it is necessary to take actions in order to suppress sources of amplitude noise (for example, the use of a laser with a low relative noise intensity). Figure 7 shows the spectral power densities of phase and amplitude noise measured for optoelectronic oscillators with optical gain for cases without suppression and with suppression of mutual conversion of amplitude and phase noise. We can see that a simultaneous decrease in the baseband relative intensity noise and an increase in the loop gain by increasing the pump power in an optical amplifier based on erbium-doped fibre allows us to reduce the output signal's phase noise of the optoelectronic oscillator by 8–9 dB at a frequency offset from the microwave carrier up to 2 kHz.

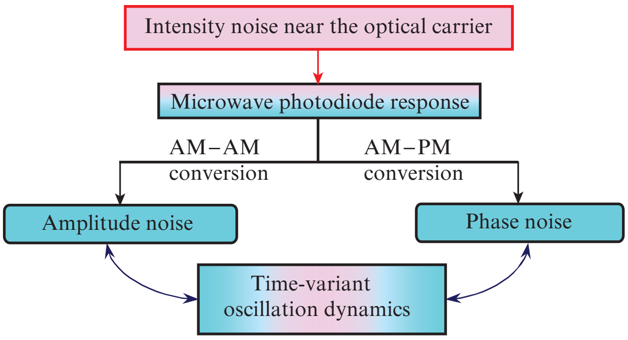

Figure 6. Mechanisms of mutual conversion of amplitude and phase noise in the optoelectronic oscillator with all-optical gain.

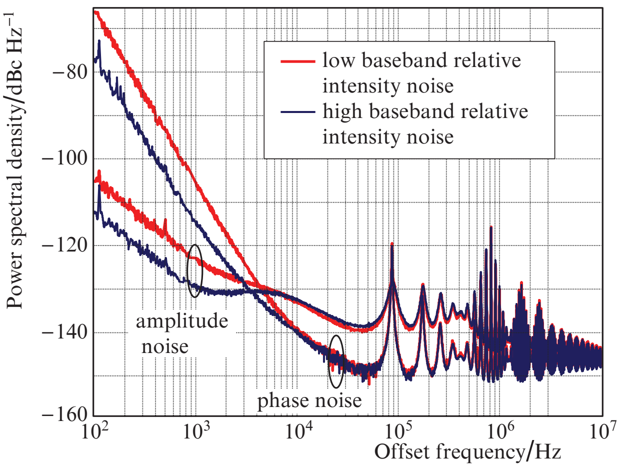

Figure 7. (Colour online) Power spectral densities of phase and amplitude noise measured for optoelectronic oscillators with all-optical gain for cases without suppression and with suppression of mutual conversion of amplitude and phase noise.

4. Conclusions

To obtain oscillation with the lowest phase noise in a delay-line optoelectronic oscillator with optical gain, it is necessary to carefully take into account a complex of noise sources and noise conversion mechanisms in the oscillator components. It has been established that, due to the nonlinearity of the energy characteristics of high-power microwave photodiodes in the optoelectronic oscillator, the baseband relative intensity noise is converted into the noise of the microwave signals, as a result of which sources of correlated amplitude and phase noise appear in the oscillator loop. Moreover, a nonlinear time-variant interaction of the amplitude and phase noises in the oscillator loop and their mutual conversion may occur in the optoelectronic oscillator near the oscillation threshold. The suppression of the mutual noise conversion is attained by reducing the laser baseband relative intensity noise and increasing the loop gain by increasing the pump power in an optical amplifier based on an erbium-doped fibre. It has been experimentally shown that the suppression of the noise conversion in the optoelectronic oscillator reduces the output signal phase noise of the optoelectronic oscillator by 8–9 dB for the offset from the microwave carrier up to 2 kHz.

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