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Comparison of polarization fading compensation methods for broadband microwave photonic links by introduced noise and achievable dynamic range

© V.V. Lebedev,[1] A.N. Petrov,[1,2] M.V. Parfenov,[1,2] E.N. Velichko,[2] A.V. Shamray[1]

[1] Ioffe Institute,
194021 St. Petersburg, Russia
[2] Peter the Great St. Petersburg Polytechnic University,
195251 St. Petersburg, Russia
e-mail: vladimir_l@mail.ru

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Two methods for compensation of polarization fading in microwave photonic links have been studied. Comparison of noise characteristics has been performed and factors limiting the dynamic range of microwave photonic link have been analyzed on an example of a link with an external remote electrooptic modulator. The possibility of reaching spurious-free dynamic range close to the shot-noise limit $\mathrm{SFDR}_3 \approx 116\,\mathrm{dB\,Hz}^{-2/3}$ has been demonstrated for 1000 m microwave photonic link.

Keywords: Optical polarization, polarization fading, fiber-optic links, optical noise, dynamic range, balanced detection, microwave photonics, integrated optical modulator, polarization control

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Introduction

Fiber-optic communication links(FOCL) are widely used for transmitting analog signals over long distances, for example, in distributed systems of fiber-optical sensors [1] or radio-photonic systems [2]. The most important parameters of an FOCL are the dynamic range [3], for the expansion of which coherent techniques based on interference of optical signals [4] are often used. The interference signal in such systems depends on the polarization state, the change of which leads to fading — the so-called polarization feeding [5]. Usually, to suppress polarization feeding, a special fiber is used with the preservation of polarization, providing one constant state of polarization along the FOCL [6]. This approach leads to a significant increase in the cost of FOCLs and does not allow the use of already deployed networks based on standard fiber without preserving polarization. These limitations become especially critical for mass applications, such as the distribution of an ultrahigh frequency carrier over a FOCL network in fifth and sixth generation telecommunications networks [7]. To address this problem, various techniques of compensation for polarization feeding have been developed [8]. For example, in modern digital FOCL with differential quadrature phase-shift keying format (DQPSK), two orthogonal polarizations [9] are used simultaneously, and in fiber-optical sensor systems, active adjustment of the polarization state of optical radiation is used using a polarization controller (polarization scrambler) [10].

The objective of this study was to compare the polarization feeding compensation technique using orthogonal polarization components of optical radiation with the technique based on active adjustment of the polarization state in terms of introduced noise and achievable dynamic range of transmission of analog broadband signals.

1. FOCL configuration with remote external modulator

A radio-photonic line with a remote Mach–Cender electro-optical modulator based on optical waveguides in lithium niobate was chosen as the object of research (Figure 1, *a*). This FOCL configuration is well suited for polling remote antenna posts [14] of distributed radio reception systems, when equipment with high energy consumption in the form of a laser radiation source and a microwave signal processing system is located at the base station, and antenna posts at reception points are maximally unloaded and contain only a modulator with a working point stabilization system, the energy consumption of which can be reduced to level 5 mW or lower [12], that allows it to be powered by a photoelectric converter from signal optical radiation in the telecommunication wavelength range (1500–1600 nm) with an average power of less than 15 mW.

A specially designed Mach–Cender modulator was used with a dual output [14] with a modulation frequency band $B = 20\,\mathrm{GHz}$, half-wave voltage $V_\pi \approx 5\,\mathrm{V}$ and optical losses $\mathrm{OL} = 3.5\,\mathrm{dB}$. The modulation of the optical signal at different outputs of the modulator occurs in antiphase, which makes it possible to use balanced detection to suppress

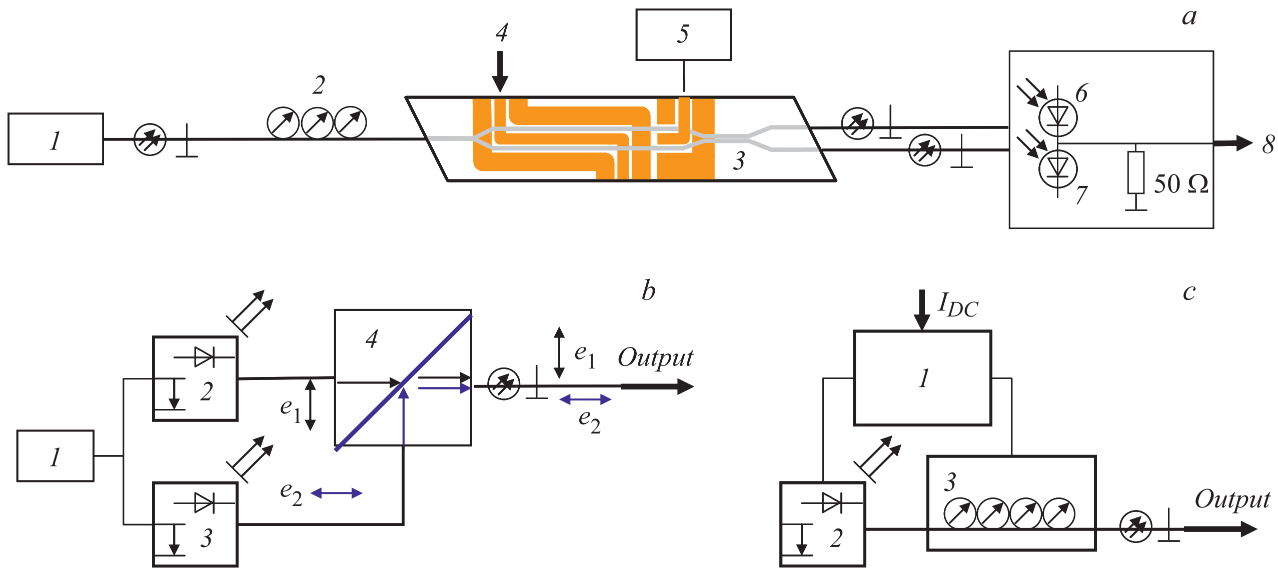

Figure 1. *a* — block diagram of a radio-photonic line layout with a remote external modulator and a balanced detector. *1* — laser source, *2* — manual fiber-optical polarization controller, *3* — MCM with dual output, *4* — microwave input, *5* — modulator operating point stabilization system, *6, 7* — photodiodes as part of a balanced photodetector, *8* — microwave output; *b* — block diagram of a depolarized laser source. *1* — control electronics, *2, 3* — single-frequency laser diodes with distributed feedback, *4* — polarizing divider/combiner; *c* — block diagram of a laser source with polarization adjustment. *1* — control electronics, *2* — single-frequency laser diode, *3* — polarization controller (scrambler).

common-mode interference and noise, such as the noise of the intensity of the laser source (RIN). In addition, the use of a modulator with a dual output at a quadrature operating point provides a gain in the transmission coefficient of the line of 6 dB [3] compared to a line without balanced detection with a standard modulator with one output.

It is the modulator interferometer, made on the basis of a birefringent lithium niobate crystal with a thin-film plasmon-polariton polarizer [13] at the input, which emits a polarization TE mode, that in this system is a polarization-dependent element that causes polarization feeding, when used to deliver optical radiation to the input of the modulator of a standard fiber- of an optical cable based on a single-mode telecommunication fiber (SMF 28) without preserving polarization. The length of the fiber-optical cable was about 1000 m. Additionally, a manual fiber-optical polarization controller was installed in front of the modulator, allowing to simulate a random change in polarization or to set the exact state of polarization at the input of the modulator.

The broadband analog signal transmitted over the FOCL using the amplitude modulation of the optical carrier was detected by a specially designed balanced photodetector. The balanced photodetector used case-free chips of high-frequency photodiodes with a frequency band of 10 GHz and a maximum sensitivity of about 0.6A/W in the telecommunication wavelength range of 1500–1600nm. In order to increase the transmission coefficient and reduce the FOCL noise factor, photodiodes with a high saturation current of 30 mA were selected, allowing the use of laser radiation sources with an optical output power of up to 100 mW. The frequency band of the signal detected by the balanced photodetector was about 3 GHz and was limited by the accuracy of the alignment of the optical paths between the outputs of the modulator and the photodiodes of the balanced photodetector. The relative error of alignment of optical paths was 10^{-5} with the length of the fiber-optical cable between the output of the modulator and the input of the balanced photodetector about 1000 m. Two types of laser sources were used to generate the optical carrier: the so-called „depolarized“ an optical radiation source [14] combining in one optical fiber the radiation of two independent laser diodes with orthogonal states of linear polarization, and a laser diode-based source with an output polarization state controller and a feedback control system [15].

2. FOCL characteristics with „depolarized“ source

In the „depolarized“ optical radiation source (Figure 1, *b*), two high-power (100,mW) single-frequency laser diodes with distributed feedback were used, the radiation from which in orthogonal linear components of polarization was combined at the FOCL input - of an optical polarization combiner (POBS-15-L-1, AFW Technologies) with polarization extinction coefficient $E > 25$ dB. In order to exclude the ingress of intermodulation components below 5-th order into the frequency band of the transmitted signals [15], the selected laser diodes were emitted at adjacent frequencies of

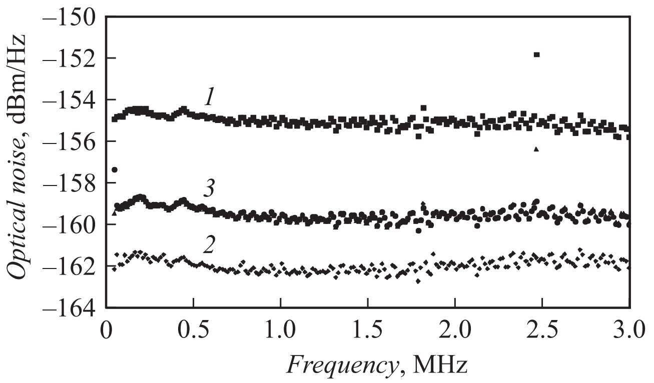

Figure 2. Spectral dependences of the power density of optical noise of a depolarized laser source after passing the modulator (polarizing element): *1* — direct detection, orthogonal polarization components are oriented at an angle of 45° relative to the surface and optical axis of the crystal substrate of the integrated optical modulator; *2* — direct detection, one of the orthogonal polarization components is parallel to the optical axis of the crystal substrate of the integrated optical modulator; *3* — balanced detection at different orientations of orthogonal polarization components.

the ITU telecommunication grid with a frequency difference of 100 GHz ($\lambda_1 = 1550.12$ nm, $\lambda_2 = 1550.92$ nm). This wavelength difference can be used for systems with a frequency band up to 20 GHz. With precise alignment of the optical powers of laser diodes at the output of „depolarized“ the constant component of the optical power detected by the balanced photodetector did not change even with a strong polarization mode dispersion modeled by the restructuring of the polarization controller in front of the modulator, i.e. the polarization feeding was suppressed. However, measurements of the spectral density of noise by the Y-factor [16] showed a strong influence of the state change of the polarization controller on the noise characteristics of the FOCL (Figure 2). The maximum noise is observed when the radiation of laser diodes at the input of the modulator has orthogonal linear polarizations oriented at an angle of 45° relative to the surface and optical axis of the crystal substrate of the integrated optical modulator. The maximum increase in the noise level of the intensity „of a depolarized“ source with direct detection relative to the noise of a single laser diode is about 8 dB. The source of these noises is presumably interference of the main line of generation of one laser diode with strongly crushed side lines of the second laser diode. Experiments have shown that this type of noise is in-phase and can be effectively suppressed by a balanced detector to a level close to the limit of shot noise [17]:

$$N(f) = 10 \cdot \log(2qI_{DC}R|H(f)|^2) \approx -160\,[\text{dBm/Hz}], \quad (1)$$

where $q = 1.6 \cdot 10^{-19}$ With — electron charge, $I_{DC} \approx 20$ mA — constant component of the total photodiode current, R — load resistance (usually 50) and $H(f) \approx 0.5$ — spectral transfer function of the photodetector. The achievable dynamic range, free from nonlinear distortions, is estimated using the following theoretical formula [3]:

$$\text{SFDR}_3[\text{dB} \cdot \text{Hz}^{-2/3}] = -8.7 + \frac{40}{3}\log(I_{DC}[\text{mA}]) - \frac{2}{3}N[\text{dBm/Hz}], \quad (2)$$

and gives a very high value of $\text{SFDR}_3 \approx 116\,\text{dB/Hz}^{-2/3}$ when using balanced detection. The dynamic range value calculated by the formula [3]:

$$\text{SFDR}_3 = \frac{2}{3}(174 + \text{OIP}_3 - G - \text{NF}), \quad (3)$$

using the measurement results by the Y- technique of the factor of the transmission coefficient of the FOCL (G), the noise factor (NF) and the intersection point of the third order (OIP_3), defined by the two-tone technique [3], agree well with the theoretical estimates according to the formula (2) (Figure 3).

Thus, studies have shown that the use of balanced detection allows you to reduce the noise level of a depolarized “ source to a level close to the quantum limit of shot noise, increase the transmission coefficient of FOCL by 6 dB and as a result get a dynamic range of

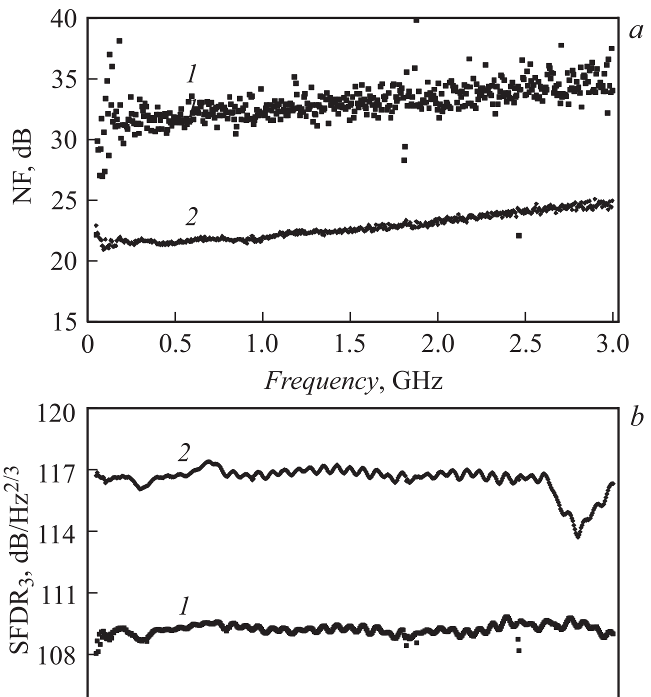

Figure 3. Frequency dependences of the noise factor (u) and the dynamic range (b) of a radio photon line with a depolarized laser source: *1* — simple direct detection, *2* — balanced detection.

FOCL above 116dB $Hz^{2/3}$. Without balanced detection, when one of the photodiodes of the balanced detector is turned off, the transmission coefficient of the FOCL drops by 6 dB (by 4 times, since the photocurrent drops by 2 times), and the noise of the depolarized" source becomes uncompensated, there is an increase in the noise factor by 10 dB and a narrowing dynamic range by 7 dB, to the level of 109 dB $Hz^{-2/3}$. It should be noted that in order to effectively suppress noise in a wide frequency range, the time delay of the signal between the arms of the balanced detector should be less than the inverse value of the maximum frequency of the transmitted broadband signal, which is 300 ps for the frequency band 3 GHz. It becomes more difficult to ensure a small delay between the shoulders, the longer the length of the FOCL, which makes it difficult to suppress noise in FOCL with a length of more than 1000 m.

3. FOCL characteristics with source with polarization adjustment

The second optical radiation source also used a powerful (100,mW) single-frequency laser diode with distributed feedback, and to compensate for the polarization feeding, an active adjustment of the polarization state was used (Figure 1, c), supporting linear polarization corresponding to the waveguide TE-mode at the input of the integrated optical modulator. This adjustment was implemented using a special device — controlled polarization controller (polarization scrambler), which is a fiber phase plates with temperature or piezoelectric control [18]. An electronic control system for a feedback polarization controller was developed, using the constant component of the current of the balanced photodetector (I_{DC}) as an input signal. An original algorithm for controlling the polarization scrambler wave plates was developed, which allows avoiding and effectively removing the control system from „dead" zones associated with the finite maximum amplitude of the control voltage [19]. The criterion for setting the optimal state of polarization at the input of the modulator was the maximum value of the constant component of the photocurrent I_{DC}. The reaction rate of the polarization adjustment system was about one second, which is sufficient for most applications, since the polarization state drift in a fiber-optical cable usually occurs much slower with a characteristic change time of several minutes [20]. To check the operability of the polarization state adjustment system, a polarization drift was simulated using a manual fiber-optical polarization controller. The element corresponding to the half-wave plate was slowly rotated in the entire available range of angles ($0-180^{circ}$). The system was able to maintain the maximum constant component of the current I_{DC} with a relative error of 0.2% when rotating the half-wave plate at a speed of less than 5°/show. With a faster drift of the polarization state, the constant component of the current I_{DC} began to change chaotically in a wide range, which was due to the insufficient speed of the automatic control system. After the rotation stopped after a few seconds, the system found the working point and captured it, while the constant component of the current I_{DC} was again set to the maximum value. Note that these limitations were due to the speed of the feedback signal processing system, the polarization controller used makes it possible to control the polarization state with a characteristic time of ~ 1 ms. The measurement of noise characteristics showed that the polarization state control system practically does not introduce additional noise. Experimentally measured noise factors for direct detection on one photodiode and for balanced detection (Figure 4, a) they did not change with external changes in the polarization state in the fiber-optical cable, when the polarization adjustment system was operating normally and managed to compensate for the polarization drift. The low noise level during detection by a single photodiode was achieved due to the low noise level of the intensity of the powerful laser diode used (RIN < -160 dBc/Hz). A slight narrowing of the dynamic range (Figure 4, b) to 114 dB $Hz^{-2/3}$ when detected by a single photodiode was due to a decrease in the transmission coefficient by 6 dB.

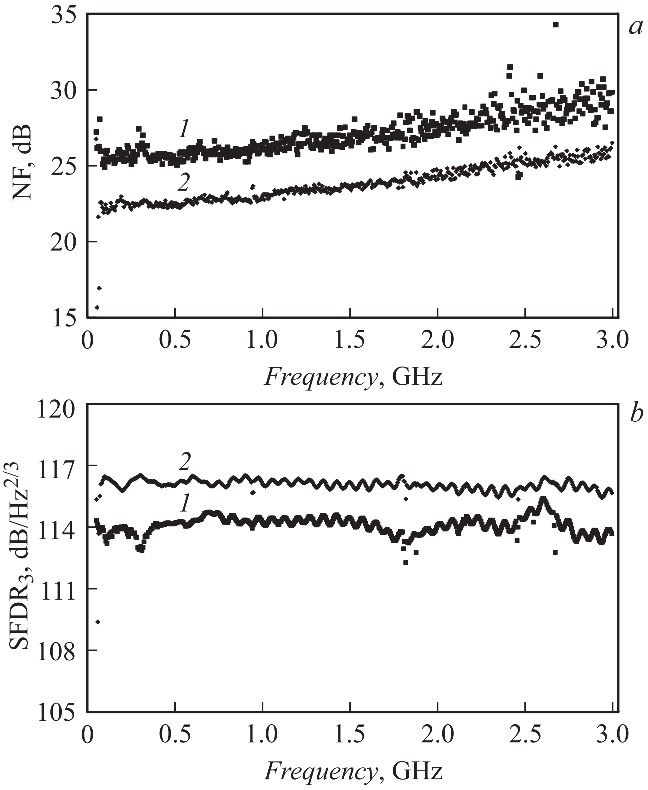

Figure 4. Frequency dependences of the noise factor (u) and the dynamic range (b) of a photon line radio with a laser source with polarization adjustment: *1* — simple direct detection, *2* — balanced detection.

Conclusion

Two types of laser sources have been investigated that allow to compensate for polarization feeding in analog FOCLs based on a standard fiber without preserving polarization. A source based on the polarization combination of radiation from two laser diodes with orthogonal linear polarization effectively compensates for the polarization feeding, however, it has polarization-dependent noises that can be suppressed when using balanced detection. For FOCLs with this source, a dynamic range free from third-order nonlinear distortions $\mathrm{SFDR}_3 \approx 116\,\mathrm{dB\,Hz}^{-2/3}$ has been experimentally demonstrated, close to the theoretical limit due to shot noise. High requirements for the accuracy of alignment of optical paths make it difficult to use balanced detection in long-length FOCLs. A source based on a laser diode with a polarization adjustment system makes it possible to effectively compensate for slow departures of the polarization state (with times more than 1 s characteristic of most practical applications) and does not introduce additional polarization-dependent noise, which makes it preferable for long-length FOCLs (more than 1000 m). When using a powerful (100,mW) single-frequency laser diode with distributed feedback, providing low relative intensity noise, the dynamic range of FOCL with a laser source with active polarization control is only 2 dB less with simple direct detection compared to detection with a balanced photodetector.

The results obtained determined the conditions for the applicability of the considered techniques of compensation for polarization feeding in FOCL with a remote stand-alone external electro-optical modulator, and showed the fundamental achievability of the noise level limited by the fundamental quantum limit of shot noise.

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Conflict of interest

The authors declare that they have no conflict of interest.

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