09.2;09.7;11.3;13.4

Quantum noise source based on shot noise of a balanced photodetector with a tunable integrated optical beam splitter

© V.V. Lebedev[1,2], V.M. Petrov[1], I.V. Ilichev[1,2], P.M. Agruzov[1,2], A.V. Shamrai[1,2,¶]

[1] ITMO University, St. Petersburg, Russia
[2] Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia
[¶] E-mail: achamrai@mail.ioffe.ru

Received May 14, 2021
Revised July 14, 2021
Accepted July 15, 2021

A broadband quantum noise source based on detection of shot noise of a balanced photodetector is demonstrated. Precise electro-optical tuning of the balanced photodetector circuit was carried out by an integrated optical beam splitter constructed in the form of the dual output Mach–Zehnder interferometer on a lithium niobate substrate. The classical component of the detected noise related to the relative intensity noise of a laser diode was suppressed by more than 15 dB. At the maximum laser power of 100 mW, the power spectral density of detected shot noise was 12 dB higher than the level of technical noise of the measuring system in the frequency band above 3 GHz.

Keywords: quantum random number generator, vacuum fluctuations, shot noise measurements, integrated optics, lithium niobate

DOI: 10.21883/TPL.2022.14.52066.18870

True random number generators are demanded for solving a great number of practical tasks [1–3]. Detection of the balanced photodetector shot noise is one of the most efficient techniques for constructing analog parts of such generators, namely, the quantum noise source [4–10]. As a physical source of entropy, quantum vacuum fluctuations are used, the engineering realization being based on their homodyne detection in the form of the balanced photodetector shot noise during the laser radiation passage through a beam splitter. The balanced photodetector suppresses the common-mode component of the laser radiation intensity classical noise and enables detecting the shot noise that considerably exceeds the measurement system technical noise in the case of high optical power. An important parameter is the frequency band of the detectable shot noise [6]. The experimentally achieved maximal frequency band of quantum noise sources based on detecting the balanced photodetector shot noise is ~ 1 GHz [8,9], which is caused by technical difficulties in precise phasing and balancing the circuits based on the so-called „volume" optics.

Integrated optical beam splitters based on silicon optical waveguides [10] are characterized by high absorption and photosensitivity at the telecommunication wavelengths range (1500–1600 nm), which gives rise to sources of additional classical noise and limits the maximal optical power, while the thermoelectric control used in [10] for active tuning is highly inertial and unsuitable for broadband devices.

We have proposed and implemented experimentally a broadband quantum noise source employing as a controllable beam splitter a double-output Mach–Zehnder integral optical modulator (MMZ) fabricated based on optical waveguides in a crystalline lithium niobate substrate (Fig. 1). This technique has already confirmed its efficiency in constructing various quantum devices [11]. The optical waveguides were fabricated according to a well-developed method of the titanium thermal diffusion [12]. Electrooptical control via planar electrodes ensured fast amplitude and phase tuning in the balanced photodetector channels. As the laser radiation source, a single-frequency distributed-feedback laser diode with the wavelength of 1552 nm, radiation line width of 170 kHz and power of 100 mW was used. The MMZ output radiation was fed through the fiber-optic assembly to the InGaAs *pin*-photodiodes forming a balanced photodetector. Each photodiode band was 10 GHz, which ensured the balanced photodiode band of above 3 GHz. For this purpose, photodiodes with maximally close frequency characteristics and equal sensitivity of ~ 0.78 A/W were selected. The high saturation current (~ 30 mA) and low dark current ($< 1\,\mu$A) defined a large dynamic range of the detected signals. The system

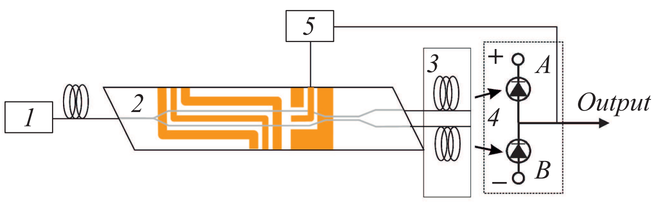

Figure 1. The circuit scheme of a broadband quantum noise source based on detecting shot noise of the balanced photodetector employing as a controllable beam splitter a double-output integral optical Mach–Zehnder modulator. *1* — single-frequency laser diode, *2* — MMZ, *3* — fiber-optic assembly, *4* — balanced photodetector, *5* — stabilization system for the MMZ operating point.

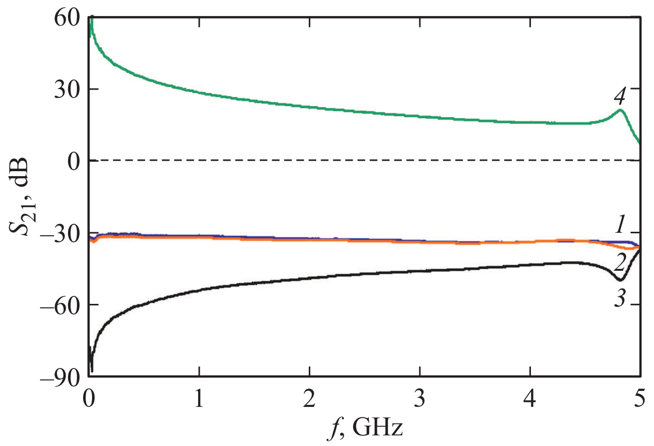

Figure 2. Suppression of the common-mode noise with a balanced photodetector. *1*, *2* — each photodiode (*A* and *B*) response S_{12} to the common-mode signal, *3* — the balanced photodetector response to the common-mode signal, *4* — common-mode noise suppression.

of the MMZ operating point stabilization [13] provided precise balancing of the output powers ($< 0.1\%$). To suppress the classical intensity noise, antiphase subtraction of the synchronous signals was performed by aligning the optical and electrical paths in the balanced detection system. The efficiency of the classical intensity noise suppression was estimated by that of suppression of the common-mode interference. For this purpose, the laser radiation was modulated by the amplitude (common-mode signal), while the MMZ electrodes were fed with a differential signal. The suppression was defined as a ratio between the frequency response to the differential signal and the frequency response to the common-mode signal and was > 15 dB in the frequency band of $f > 3$ GHz (Fig. 2). Reduction of the suppression efficiency with increasing frequency was caused by more severe requirements for the precision of phasing and balancing.

Measurements of the output noise signal of the balanced photodetector equipped with a preamplifier showed that the power spectral density of the optical noise detected in the frequency band of > 3 GH exceeds the technical noise (electronics noise) by more than 12 dB (Fig. 3, *a*). Classical noise caused by the laser diode intensity noise was invisible against the quantum shot noise, which was confirmed by the linear dependence of the detected noise signal power P_{el} on the total laser radiation power P_{opt} at the inputs of the balanced photodetector photodiodes (pic. 3, *b*). The power of the detected shot signal agrees well with the theoretical estimate [14]:

$$N(f) = 2qP_{opt}AR_0\left|H_{pd}^2(f)\right|, \quad (1)$$

where $N(f)$ is the noise power spectral density, q is the electron charge, A is the photodiode direct current sensitivity, $H_{pd}(f)$ is the balanced photodetector frequency characteristic normalized by the direct current sensitivity, R_0 is the load resistance at the photodetector output.

Thus, we have developed a broadband quantum noise source based on detecting shot noise of the balanced photodetector employing a controllable beam splitter based on the waveguide Mach–Zehnder interferometer on the lithium niobate substrate and a high-frequency balanced photodetector.

Experimentally obtained exceedance of quantum noise over the classical one appeared to be more than 12 dB in the frequency band of > 3 GHz, which is the best characteristic for the sources of this type known from literature. Estimation of efficiency of the true random number generator employing that noise generator gives an unprecedentedly high rate of ($\sim$ (10–20) $\cdot 10^9$ bit/s).

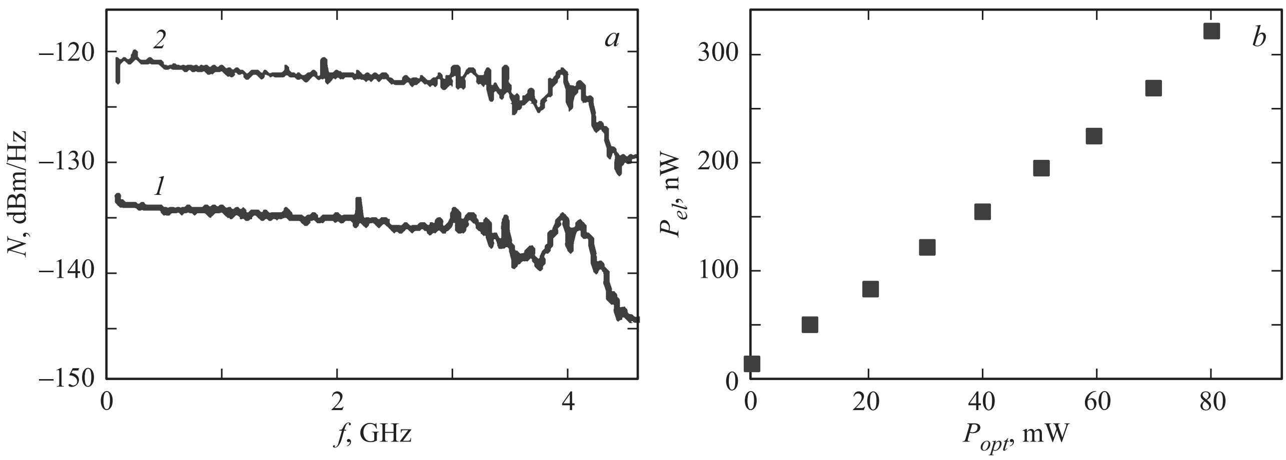

Figure 3. *a* — noise signal *N* at the balanced photodiode output after the preamplifier: *1* — at the switched-off laser diode (the level of the measuring system technical noise), *2* — at the laser power of 100 mW (quantum shot noise). *b* — the output noise power (in the band of 0.01 to 3 GHz) versus the laser power.

Financial support

In the ITMO University, the work was financially supported by the RF Ministry of Science and Higher Education (State Assignment N 2019-0923).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] M. Herrero-Collantes, J.C. Garcia-Escartin, Rev. Mod. Phys., **89** (1), 015004 (2017). DOI: 10.1103/RevMOdPhys.89.015004

[2] A.V. Gleim, V.V. Chistyakov, O.I. Bannik, J. Opt. Technol., **84** (6), 362 (2017). DOI: 10.1364/JOT.84.000362

[3] Y. Liu, Q. Zhao, M.H. Li, Nature, **562** (7728), 548 (2018). DOI: 10.1038/s41586-018-0559-3

[4] C. Gabriel, C. Wittmann, D. Sych, Nature Photon., **4** (10), 711 (2010). DOI: 10.1038/nphoton.2010.197

[5] T. Symul, S.M. Assad, P.K. Lam, Appl. Phys. Lett., **98** (23), 231103 (2011). DOI: 10.1063/1.3597793

[6] T. Gehring, C. Lupo, A. Kordts, D.S. Nikolic, N. Jain, T. Rydberg, T.B. Pedersen, S. Pirandolo, U.L. Andersen, Nature Commun., **12**, 605 (2021). DOI: 10.1038/s41467-020-20813-w

[7] H. Zhou, P. Zeng, M. Razavi, X. Ma, Phys. Rev. A, **98** (4) 042321 (2018). DOI: 10.1103/PhysRevA.98.042321

[8] J.Y. Haw, S.M. Assad, A.M. Lance, N.H.Y. Ng, V. Sharma, P.K. Lam, T. Symul, Phys. Rev. Appl., **3** (5), 054004 (2015). DOI: 10.1103/PhysRevApplied.3.054004

[9] B. Xu, Z. Chen, Z. Li, J. Yang, Q. Su, W. Huang, Y. Zhang, H. Guo, Quant. Sci. Technol., **4** (2), 025013 (2019). DOI: 10.1088/2058-9565/ab0fd9

[10] L. Huang, H. Zhou, J. Opt. Soc. Am. B, **36** (3), B130 (2019). DOI: 10.1364/JOSAB.36.00B130

[11] O. Alibart, V. D'Auria, M. De Micheli, F. Doutre, F. Kaiser, L. Labonté, T. Lunghi, E. Picholle, S. Tanzilli, J. Opt., **18** (10), 104001 (2016). DOI: 10.1088/2040-8978/18/10/104001

[12] V.M. Petrov, A.V. Shamrai, I.V. Ilichev, P.M. Agruzov, V.V. Lebedev, N.D. Gerasimenko, V.S. Gerasimenko, Fotonika, **14** (5), 414 (2020) (in Russian). DOI: 10.22184/1993-7296.FRos.2020.14.5.414.423

[13] A. Petrov, A. Tronev, P. Agruzov, A. Shamrai, V. Sorotsky, Electronics, **9** (11), 1861 (2020). DOI: 10.3390/electronics9111861

[14] V.J. Urick, D.J. McKinney, K.J. Williams, *Fundamentals of microwave photonics* (John Willey & Sons, Hoboken, N.J., 2015).