Quantum correlations of the pump and radiation noise of a semiconductor laser near its threshold

A. S. Trifonov and P. A. Usachev

A. F. Ioffe Physicotechnical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia
(Submitted 6 May 1995)
Zh. Éksp. Teor. Fiz. **108**, 1253–1262 (October 1995)

Investigations have been made of the correlation between the photon flux noise and the noise of the voltage across the junction of a quantum-well semiconductor laser near its threshold. The correlation measurements were made by means of a delay line. Complete negative correlation in the threshold region was found. The influence of the optical losses on the correlation is discussed. © *1995 American Institute of Physics.*

1. INTRODUCTION

In the investigation of quantum-mechanical systems, measurement of the correlations between two conjugate variables has fundamental importance. If correlations are found, they can be used to obtain new states of the quantum system. In particular, in optical experiments they can be used to generate amplitude-squeezed ("noise-free") light. Besides the use of squeezed light in physics experiments, there are several other fields in which its use is very promising. For example, in optical communication systems there is a possibility of increasing the maximum capacity of the channels, and in interferometry it can be used to improve considerably the optical characteristics of devices.

The possibility of obtaining amplitude squeezing by pumping was first predicted theoretically in the study by Golubev and Sokolov,[1] and the first experiments to obtain amplitude-squeezed light using the suppression of the noise of the pump current of a semiconductor laser were described in Refs. 2–5. These experiments were made possible primarily by the development of single-frequency *cw* injection lasers operating at pump currents several times higher than the threshold value. Later,[6,7] it was shown that the fluctuations of the photon flux of a semiconductor laser are negatively correlated with the noise of the voltage across the $p-n$ junction and that the spectral density of the combined noise of the photon flux and the noise of the voltage across the laser junction is less than the spectral density of the photon flux noise. The mechanism for the occurrence of this correlation is due to the dipole interaction between the internal field and electron–hole pairs. In the same investigations, a measurement was made of the correlation between the noise of the intensity and the noise of the voltage across the junction of a laser pumped by a current an order of magnitude greater than the threshold current at temperature 66 K.

In the measurement of the characteristics of amplitude-squeezed light, the main difficulty is in carrying out accurate calibration relative to the level of the shot noise, and therefore in such investigations one uses a balanced homodyne detector that includes a correlator of the two noise voltages and a delay line.[3,7–9]

The aim of the work reported here was to investigate the correlation between the noise of the photon flux and the noise of the voltage in the pump circuit of a semiconductor laser in the threshold regime at room temperature and also to study the effect of the optical losses on the noise characteristics of the emitted radiation and the correlation coefficient. We have investigated the noise of a InGaAsP/GaAs semiconductor laser based on a buried double heterostructure with separate confinement and radiation wavelength 0.8 μm. Among various lasers, we chose one that operates in the single-frequency regime (one longitudinal radiation mode) up to a pump current of order 100 mA. The threshold current of the chosen laser was 48 mA. A detailed description of such lasers can be found in Ref. 10. For the measurement of the correlation coefficient, we used a correlator of the noise voltages based on a delay line.

In the theoretical part of the paper, we analyze the conditions for the occurrence of correlation, consider the equivalent noise circuit of the semiconductor laser, discuss the possibility of measuring the noise in the pump circuit, calculate the correlation coefficient, and analyze the effect of the optical losses on the statistical characteristics of the photon flux of the output radiation. The analysis is based on the results of Refs. 6 and 7. We then consider the low-frequency spectral density of the measured quantities, justify the choice of the range of measurements, and describe the experiment.

The results of measuring the correlation of the noise of the voltage across the junction and the noise of the laser radiation intensity confirm the theoretical prediction that the correlation of these noise signals is essentially completely negative in the threshold region. Neither the low laser–photodetector current gain (in our experiment, it was 7%) nor the introduction of additional optical losses destroyed the total negative correlation by a measurable amount.

The observed correlation can be used to suppress the excess quantum noise slightly above threshold, for example, by means of an external light modulator controlled by the noise voltage taken from the junction.

2. PUMP NOISE AND RADIATION INTENSITY NOISE

2.1 Conditions for occurrence of correlation

A semiconductor laser is pumped by the injection of electrons. If a correlation is to arise between the pump noise and the radiation intensity noise, the statistical properties of the pump electron flux must be transformed into the statistical properties of the flux of the emitted photons. This can be

 1063-7761/95/100687-05$10.00

achieved if the quantum efficiency of the laser is near unity, i.e., each electron pump corresponds to the appearance of a coherent photon in a laser radiation mode. This becomes possible only if the electron lifetime τ_e in the cavity is much less than the time constant $\tau_{CR}=CR_s$ of the control circuit and the lifetime τ_{st} of a stimulated-emission electron is much shorter than the lifetime of the electrons that participate in nonradiative recombination or in spontaneous emission in a nonlasing mode. It is also necessary for the rate at which the photons leave the cavity to exceed the rate of the intracavity losses, including the losses through escape from the opposite end of the laser. With regard to this last point, the laser with separate confinement of the carriers and photons that we used has significant advantages, since it is characterized by a low level of intracavity loss.

The processes of stimulated emission and of the escape of photons from the cavity are random in nature. This means that the delay between the times of electron injection and of coherent photon emission changes from case to case. However, if the measurement time is considerably greater than this delay, the probability that a photon does not leave the cavity during the time of measurement is negligibly small. By virtue of this close relationship between the pump current and the flux of the emitted photons, the voltage across the junction of the semiconductor laser will fluctuate. The noise voltage v_n across the junction is uniquely related to the fluctuations ΔN_e in the number of electrons N_e in the active region of the laser through the diffusion capacitance C of the junction:

$$v_n=q\,\frac{\Delta N_e}{C}, \tag{1}$$

where q is the elementary charge.

The correlation between the voltage across the junction and the number of photons in the cavity will be negative.

2.2 Noise of the voltage across the junction and noise of the current through the junction

We consider the equivalent noise circuit of a $p-n$ heterojunction with differential resistance R, diffusion capacitance C, and internal source of the noise current i:

$$R=\frac{2V_T}{I}=\frac{2V_T\tau_e}{qN_e}, \tag{2}$$

$$C=\frac{\partial Q_e}{\partial V_n}=\frac{qN_e}{2V_T}, \tag{3}$$

where I is the constant current through the junction, $V_T=k_BT/q$ is the thermal potential, k_B is Boltzmann's constant, T is the absolute temperature, ∂Q_e is the change in the total charge in the active region, and ∂V_n is the change in the voltage across the junction.

Let the power source of the junction have an internal resistance R_s and a source of thermal noise current i_s associated with this resistance. The low-frequency power spectra of the noise sources of the currents can be written as

$$S(i)=2qI+4qI_0, \quad S(i_s)=\frac{4k_BT}{R_s}, \tag{4}$$

where I_0 is the reverse current through the diode.

Using Kirchhoff's law, we obtain the current i_n and the voltage v_n across the junction,

$$i_n=-\frac{R}{R+R_s}\,i-\frac{R_s}{R+R_s}\,i_s, \quad v_n=\frac{RR_s}{R+R_s}\,(i_s-i), \tag{5}$$

and the power spectra of the noise current $S(i_n)$ and of the noise voltage $S(v_n)$:

$$S(i_n)=S(i)\left(\frac{R}{R+R_s}\right)^2+S(i_s)\left(\frac{R_s}{R+R_s}\right)^2,$$

$$S(v_n)=\left(\frac{RR_s}{R+R_s}\right)^2(S(i_s)+S(i)). \tag{6}$$

In the case $R_s\ll R$, the diode operates in the constant-voltage pump regime, and we have

$$S(i_n)=S(i)=2qI+4qI_0, \quad S(v_n)=R_s^2(S(i_s)+S(i)). \tag{7}$$

The dependence of the noise in the external circuit on the current I satisfies the expression for shot noise both for the voltage across the junction and for the current through the junction.

In the case $R_s\gg R$, the diode operates in the constant-current pump regime, and

$$S(i_n)=S(i_s)=\frac{4k_BT}{R_s}, \quad S(v_n)=R^2(S(i_s)+S(i)). \tag{8}$$

For $I\gg I_0$

$$S(v_n)\approx 2qIR^2\approx 2k_BTR. \tag{9}$$

Although the noise of the voltage across the junction corresponds to the expression for shot noise, the noise is measured using a large measurement resistance R_s, and as a result of normalization with respect to it the noise of the voltage across the junction is reduced by the factor $(R/R_s)^2$. To detect this noise, it is necessary to cool the resistance R_s or to use synchronous methods of measurement, or both of these methods. Lasers based on a double heterostructure have large bulk resistance in the p- and n-type regions (base resistance), which plays the role of R_s. At a threshold current of tens of milliamperes, the laser operates in the constant-current pump regime, since its differential resistance R is small compared with the base resistance. The constant-voltage pump regime should be feasible in lasers based on a homojunction, since in them the base resistance can be fairly small.

The total noise current of the laser consists of four parts: the pump noise, the noise of the generation and recombination of carriers in the $p-n$ junction, the noise of the internal field of the cavity, and the noise of the output radiation. If the pump current slightly exceeds the threshold value, the output radiation of the laser contains not only the shot noise but also strong excess noise of the photon flux due to spontaneous emission. Because of the presence of the correlation, this excess noise is present in the noise voltage across the junction and can be measured.

2.3 Correlation between the noise of the photon flux and the noise of the voltage across the junction of the laser

The noise spectrum of the fluctuations p_e of the number of photons per unit time in the output radiation of the semiconductor laser for the range of frequencies low compared with the relaxation frequency is flat, with noise power equivalent to a variance in the number of photons in unit time equal to[7]

$$S(p_e)=\langle p_e^2\rangle=\frac{2+r}{r^2}\,p_e=\gamma p\,\frac{2+r}{r^2}, \tag{10}$$

where $r=I/I_{th}-1$ is the pump parameter, I_{th} is the threshold current of the laser, p is the mean number of photons in the cavity, and γ is the rate at which photons leave the cavity.

The power spectrum of the noise of the voltage across the laser junction[7] has the form

$$S(v_n)=4q^2\gamma pR^2\left(1+\frac{1}{r}\right)^2. \tag{11}$$

The correlation spectrum of the noise of the external radiation p_e and of the voltage across the junction v_n can be written as

$$S(v_n,p_e)=-2\sqrt{2}q\gamma pR\,\frac{1+r}{r^2}. \tag{12}$$

The low-frequency coefficient of the correlation between the voltage across the junction and the emitted photon flux of the laser in the limit $R_s\to\infty$ is[7]

$$C(v_n,p_e)=-\sqrt{\frac{2}{r+2}}, \tag{13}$$

and for near-threshold pumping ($r\ll 1$) it is

$$C(v_n,p_e)=-1. \tag{14}$$

For operation far beyond the lasing threshold ($r\to\infty$), we obtain $C(v_n,p_e)=0$, and the correlation disappears.

If the pumping slightly exceeds the threshold, the presence of the complete correlation (14) makes it possible to use the noise of the voltage across the junction to suppress the excess noise in the laser radiation.

2.4 Effect of losses on the correlation

If in the path of the photon flux there is a divider with transmission coefficient μ, then the noise spectrum of the power of the transmitted radiation $p_{e1}=\mu p_e$ has the form

$$S(p_{e1})=\langle p_{e1}^2\rangle=\mu^2\gamma p\,\frac{2+r}{r^2}+\mu(1-\mu)\gamma p. \tag{15}$$

The correlation spectrum $S(v_n,p_{e1})$ of the voltage v_n and the radiation p_{e1} can be written in the form

$$S(v_n,p_{e1})=-\mu 2\sqrt{2}q\gamma pR\,\frac{1+r}{r^2}, \tag{16}$$

and the coefficient of the correlation between v_n and p_{e1} is

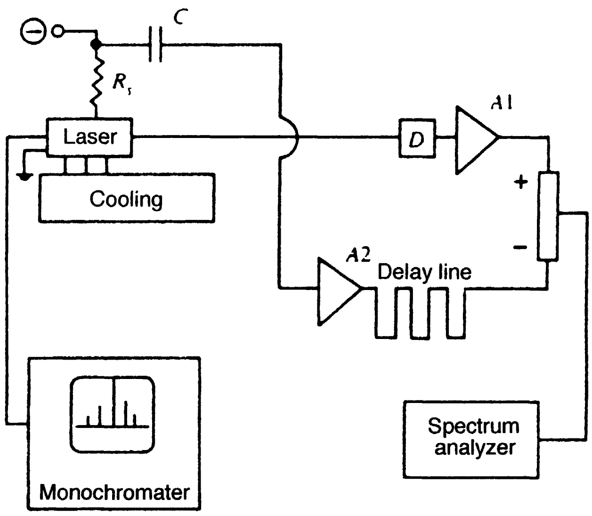

FIG. 1. Circuit for measuring the correlation of the pump noise and the radiation noise of a semiconductor laser. Explanations are given in the text.

$$C_1=-\sqrt{\frac{2}{r+2+r^3\,\dfrac{1-\mu}{\mu}}}. \tag{17}$$

In the case of pumping near the threshold ($\mu\gg r^3$), we have

$$C_1=C(v_n,p_{e1})=-1. \tag{18}$$

Thus, if the transmission coefficient satisfies $\mu\gg r^3$ the correlation remains complete even in the presence of optical losses. In the limit $\mu\to 0$ (strong losses), the power spectrum of the transmitted radiation (15) becomes a Poisson spectrum,

$$S(p_{e1})=\mu\gamma p=p_{e1}, \tag{19}$$

and the correlation between v_n and p_{e1} disappears.

3. DESCRIPTION AND STRUCTURAL CIRCUIT OF THE EXPERIMENT

The structural circuit of the experiment is shown in Fig. 1. The semiconductor laser radiation is collected by a focusing lens and directed onto a photodiode. The blocks $A2$ and $A1$ are amplifiers of the noise signals obtained from the $p-n$ junction of the laser and from the photodiode, respectively. The delay line is made of a coaxial cable with resistance 50 Ω and length 30 m. It ensures a delay of the signal by T_d=0.12 μs, giving an interval between the maxima on the screen of the spectrum analyzer of 8 MHz. The signal levels are equalized by means of attenuators, which make it possible to regulate smoothly the degree of attenuation. The signal from the differential amplifier, which is proportional to the difference of the input signals, reaches an SK-4-59 spectrum analyzer. The voltages, which are proportional to the power spectrum of the measured signal and the scan of the spectrum analyzer, are recorded by an automatic plotter.

The power spectra of the pump and radiation noise are flat in the frequency range beginning at 5 MHz ($1/f$ noise and mode-switching noise are absent) up to frequencies of

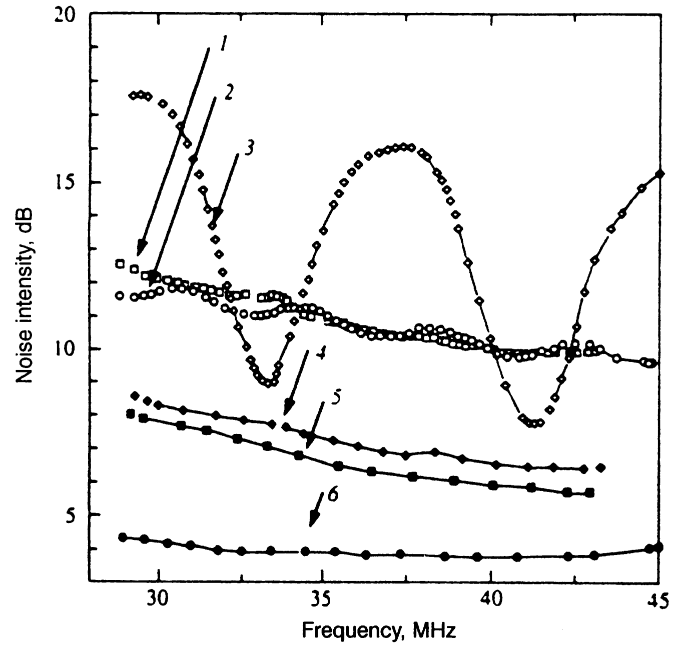

FIG. 2. Results of measurement of the correlation between the pump noise and the radiation noise of a semiconductor laser in its threshold region: *1*—power spectrum of the noise of the voltage across the junction; *2*—power spectrum of the noise of the photon flux; *3*—power spectrum of the combined noise of the voltage across the junction and the time-delayed noise of the photon flux; *4*—intrinsic total noise of the measuring circuit (f_n+f_i); *5*—intrinsic noise of the channel for measuring the noise of the voltage across the junction (f_n); *6*—intrinsic noise of the channel for measuring the noise of the photon flux (f_i).

order 1 GHz (the frequency of relaxation oscillations in the threshold regime). In these measurements, we selected the frequency range from 30 to 50 MHz, which is the range that is least affected by external radio interference. Two and a half periods of the spectrum of difference of the direct and delayed signals fit into this frequency interval.

The c-w differential quantum efficiency of the measurement circuit μ, defined as the ratio of the increment of the constant photocurrent to the increment of the pump current, was 7% for differential efficiency of the laser of order 20%.

To estimate the degree of suppression of the in-phase voltage across the differential amplifier, completely positively correlated direct and delayed signals, whose levels were equalized, were sent to the inputs of the amplifier from a white-noise source. The difference between the maximum and minimum values of the power spectrum of the difference of these signals was more than 20 dB, indicating good suppression of the in-phase signal at the inputs of the differential amplifier.

4. INVESTIGATION OF QUANTUM CORRELATIONS

4.1 Correlation between the radiation intensity noise and the noise in the pump circuit

Because of the presence of optical losses, the nonideal quantum efficiency of the photodetector, and the intrinsic noise in the measurement channels, the power spectra of the measured noise signals have additional terms. Figure 2 shows the following results of measurement of the correlation of the pump noise and the radiation noise in the above-threshold region. Curve *1* is the power spectrum of the noise of the voltage across the junction, $S(v_n)+f_n$, where f_n is the intrinsic noise in the channel for measuring the voltage noise. Curve *2* is the power spectrum of the noise of the photon flux deduced from the drop of the voltage v_i across the load resistance R_m of the photodetector:

$$S(v_i)=2qI_i\mu g^2\,\frac{2+r}{r^2}\,R_m^2+2qI_i(1-\mu)g^2R_m^2+f_i, \tag{20}$$

where g is the ratio of the gains of the channels for measurement of the voltage noise and the radiation intensity noise, μ is the c-w differential quantum efficiency of the measurement circuit, and f_i is the inherent noise of the channel for measuring the radiation intensity noise. Curve *3* is the power spectrum of the combined noise of the voltage across the junction and the time-delayed noise of the photon flux:

$$S(\Omega)=S(v_n)+f_n+S(v_i)-2S(v_i,v_n)\cos(\Omega T_d), \tag{21}$$

where

$$S(v_i,v_n)=-4qI_ig\,\frac{1+r}{r^2}\,RR_m, \tag{22}$$

is the correlation spectrum. Curve *4* is the total intrinsic noise of the measurement circuit (f_n+f_i). Curve *5* is the intrinsic noise of the channel for measuring the noise of the voltage across the junction (f_n). Curve *6* is the intrinsic noise of the channel for measuring the noise of the photon flux (f_i). For laser pump current $I=49$ mA, the photocurrent was $I_i=70\ \mu$A. The range of measurement was 28–46 MHz in a frequency band $\Delta f=300$ kHz.

The sinusoidal variation of curve *3* in Fig. 2 indicates the presence of correlation between the noise of the photon flux and the noise of the voltage across the laser junction. In the absence of correlation, curve *3* would be flat at the level of the noise power, which is numerically equal to the sum of the noise powers of curves *1* and *2*.

To determine the correlation coefficient C_m, it is necessary to find the ratio

$$C_m=\frac{S(v_i,v_n)}{\sqrt{S(v_i)S(v_n)}}, \tag{23}$$

where we determine $S(v_i,v_n)$ from the difference between the maximum and minimum values of $S(\Omega)$:

$$S(v_i,v_n)=\frac{\max(S(\Omega))-\min(S(\Omega))}{4}. \tag{24}$$

The correlation coefficient C_m, calculated in accordance with (23) and (24), was -1.06 ± 0.1, indicating total correlation between the measured noise signals. This agrees well with the theoretically predicted[6] value [see Eqs. (17) and (18)].

4.2 Effect of optical losses on the correlation spectrum

We measured the power spectrum of the total signal (21) when an absorbing light filter with transmission coefficient $\chi=0.4$ was introduced between the laser and the photodiode.

The constant photocurrent of the detector was changed from $I_{i1}=68\ \mu A$ to $I_{i2}=25\ \mu A$. The transmission coefficient χ was

$$\chi=\frac{I_{i2}}{I_{i1}}=0.37. \tag{25}$$

The ratio of the differences between the maximum and minimum values of $S(\Omega)$ in the presence of losses and in their absence was

$$\frac{\Delta_2}{\Delta_1}=0.43\pm0.08\approx\chi. \tag{26}$$

Thus, this ratio is practically equal to the ratio (25) of the photocurrents, in agreement with the theoretical conclusion about the behavior of the correlation spectrum (16) and the correlation coefficient (17) and (18).

5. CONCLUSIONS

In the work reported here, we have investigated the correlation between the noise of the photon flux and the noise of the voltage across the junction of a semiconductor laser in the threshold regime, and we have also investigated the effect of optical losses on the statistical properties of the output radiation. We have obtained expressions for the low-frequency power spectra of the noise of the output radiation and the noise of the voltage across the junction as functions of the pump level of the semiconductor laser. We have shown that at room temperature, when the threshold current is tens of milliamperes, the laser operates in the regime of current stabilization through the junction. We have obtained an expression for the coefficient of correlation of the noise voltage across the junction and the noise of the output laser radiation as a function of the pump current. We have shown that in the presence of strong optical losses the statistics of the detected photon number becomes a Poisson distribution and that the noise created by the losses is shot noise irrespective of the variance of the number of photons of the original radiation. At the same time, the correlation with the noise of the voltage across the laser junction disappears. The introduction of optical losses small compared with the pump parameter ($\mu\gg r^3$) does not affect the total correlation between the radiation noise and the laser pump noise.

From the results of the measurements, the following conclusions can be drawn.

1. The measurement of the correlation between the noise of the voltage across the junction and the noise of the laser photon flux confirm the theoretical conclusion (18) that these noise signals are negatively correlated in the threshold region.

2. The measurement of the effect of optical losses on the correlation spectra (25) and (26) confirms the prediction obtained in Sec. 2.4 that the correlation coefficient does not change and indicates that neither the low quantum efficiency of the measurement circuit (7%) nor the introduction of additional optical losses destroys the complete negative correlation.

We thank I. S. Tarasov, who kindly supplied the lasers for the investigations, and V. P. Valyukhov for numerous discussions that helped us to improve the arrangement of the experiment.

This work was done with the support of the Russian Fund for Fundamental Research (Grant No. 94-02-06255) and the International Science Foundation (Grant No. R5X000).

[1] Yu. M. Golubev and I. V. Sokolov, Zh. Éksp. Teor. Fiz. **87**, 408 (1984) [Sov. Phys. JETP **60**, 234 (1984)].
[2] Y. Yamamoto and S. Machida, Phys. Rev. A **35**, 5114 (1987).
[3] Y. Yamamoto and S. Machida, Phys. Rev. Lett. **58**, 1000 (1987).
[4] Y. Yamamoto and S. Machida, Phys. Rev. Lett. **60**, 792 (1988).
[5] W. Richardson and R. Shelby, Phys. Rev. Lett. **64**, 400 (1990).
[6] W. Richardson and Y. Yamamoto, Phys. Rev. Lett. **66**, 1963 (1991).
[7] Y. Yamamoto, W. Richardson, and S. Machida, in *Quantum Measurements in Optics*, edited by P. Tombesi and D. F. Walls (Plenum Press, New York, 1992), p. 65.
[8] W. Richardson, S. Machida, and Y. Yamamoto, Phys. Rev. **66**, 2867 (1991).
[9] Y. Yamamoto and H. Haus, Phys. Rev. A **45**, 6596 (1992).
[10] D. Z. Garbuzov, I. E. Berishev, Yu. V. Il'in, *et al.*, J. Appl. Phys. **72**, 319 (1992).

Translated by Julian B. Barbour