Quantum Electronics **32** (9) 809 – 814 (2002)

PACS numbers: 42.55.Px; 42.60.Mi
DOI: 10.1070/QE2002v032n09ABEH002296

Low-frequency intensity fluctuations in high-power single-mode ridge quantum-well InGaAs/AlGaAs heterostructure semiconductor lasers

A.P. Bogatov, A.E. Drakin, S.A. Plisyuk, A.A. Stratonnikov,
M.Sh. Kobyakova, A.V. Zubanov, A.A. Marmalyuk, A.A. Padalitsa

***Abstract*.** **It is shown that for an average output power of 60 mW, the spectral density of low-frequency intensity fluctuations in single-mode semiconductor lasers lies in the interval $6 \times 10^{-17} - 10^{-15}$ W^2 Hz^{-1}. This fluctuation level is caused by the presence of subthreshold longitudinal modes and mode hopping, leading to the emergence of a noticeable $1/f$ component in their spectrum.**

Keywords: *quantum-well laser, single-mode lasing, intensity fluctuations, 1/f-noise.*

1. Introduction

Intensity fluctuations in lasers are of interest for two reasons. First, these fluctuations serve as a characteristic of laser radiation defining the lower limit of sensitivity of any laser-based device. Second, intensity fluctuations may contain physical information about the processes occurring in the laser itself.

Investigations of intensity fluctuations in semiconductor lasers have been carried out for a long time. However, the main attention in the low-frequency spectral region was paid to the so-called $1/f$-noises, and the noise measurements were made in lasers with an output power up to 10 mW (see, for example, Refs [1 – 3] and references therein). The amplitude of fluctuations in the low-frequency region is sensitive, to the technical quality of the lasers and the operating conditions, e.g., the number of transverse and longitudinal modes excited in them, etc. For this reason, the level of low-frequency fluctuations in the semiconductor lasers investigated earlier had a considerable spread from sample to sample, which extremely complicated the analysis of noises. The behaviour of lasers with an output power exceeding several milliwatts was especially intricate. As a rule, such lasers operated in a multimode regime and the number of excited modes could vary strongly from laser to laser.

The progress achieved at present in the development of single-mode lasers enables us to cast a fresh glance at the potentialities of low-frequency fluctuation studies. Indeed, modern quantum-well heterostructure lasers with ridge optical waveguides are capable of operating at a single transverse mode, and sometimes at a single longitudinal mode, with an output power of hundreds of milliwatt [4, 5]. The modern level of technical advancement ensures the fabrication of lasers with reproducible parameters. The high quality of radiation from such lasers with a divergence close to the diffraction limit, as well as a strong time coherence (single-frequency operation) render these lasers quite useful for various applications whose range keeps on widening continuously.

One can expect that the behaviour of intensity fluctuations in such lasers will be determined not by their technical features, but by the physical factors. Consequently, the fluctuation level in them will be fairly reproducible for analysis. The aim of the this paper is to measure the level of low-frequency fluctuations in high-power single-mode ridge lasers and to determine the closeness of this level to the theoretical limit, i.e., to the level of natural fluctuations.

2. Experimental

We studied quantum-well InGaAs/GaAs/AlGaAs heterostructure lasers. Table 1 shows the parameters of the layers. The optical waveguide in the layer plane was created by a ridge having a width $w = 3.5$ μm in its upper part. Outside the ridge, the residual thickness of etching down to the waveguide layer was 0.1 – 0.2 μm. These structures were used for fabricating laser diodes with a resonator length $L = 600 - 800$ μm and a reflectivity ~ 10 % and 95 % of the mirrors deposited on the diode facets. The emission wavelength was ~ 980 nm.

Fig. 1 shows a simplified scheme of the setup for recording the emission intensity fluctuations. Fluctuations were measured with a photodetection circuit containing a FD-24K photodiode. The signal from the photodiode was fed to a low-noise Unipan 233-6 preamplifier from which it was fed to a Unipan 232B nanovoltmeter-amplifier with a pass band 500 – 15000 Hz, and then to a computer via an analogue-to-digital converter. A Peltier element and a thermistor mounted on the laser holder allowed measurements in the temperature range 10 – 40 °C.

A.P. Bogatov, A.E. Drakin P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prosp. 53, 119991 Moscow, Russia;
S.A. Plisyuk, A.A. Stratonnikov Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141700 Dolgoprudnyi, Moscow oblast', Russia;
M.Sh. Kobyakova, A.V. Zubanov, A.A. Marmalyuk, A.A. Padalitsa M.F. Stel'makh Polyus Research and Development Institute, ul. Vvedenskogo 3, 117342 Moscow, Russia

Received 17 July 2002
Kvantovaya Elektronika **32** (9) 809 – 814 (2002)
Translated by Ram Wadhwa

Table 1.

Layer		Thickness/nm
GaAs:Zn	p^+	500
$Al_{0.45}Ga_{0.55}As$: Zn	p	1500
$Al_{0.3}Ga_{0.7}As$	ul	400
GaAs	ul	7
$In_{0.2}Ga_{0.8}As$	ul	5.3
GaAs	ul	10
$In_{0.2}Ga_{0.8}As$	ul	5.3
GaAs	ul	7
$Al_{0.3}Ga_{0.7}As$	ul	400
$Al_{0.45}Ga_{0.55}As$: Si	n	3000
GaAs : Si	n	500
GaAs : Si	n	350×10^3

Note: ul – undoped layer.

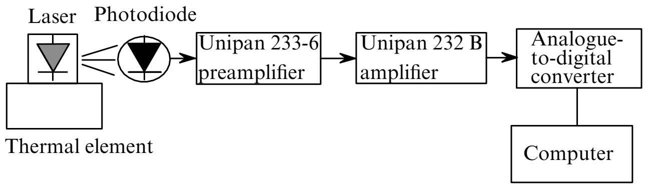

Figure 1. Schematic of the experimental setup.

The automated setup described above was used for collecting data for one or several realisations of a random process corresponding to the variation in the emission power P in time. The data processing was carried out by choosing as the initial parameter the deviations δP from the average power $\bar{P}$ measured at successive instants of time t_i:

$$\delta P = P(t) - \bar{P}. \tag{1}$$

The data array consisted of N values of $\delta P_i = \delta P(t_i)$ measured at instants of time $t_i = \Delta i$, where $\Delta = 25$ µs and $0 \leqslant i \leqslant N-1$. The value $N = 1024$ was used in the measurements. Then, the discrete Fourier transform

$$C^n(f_j) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \delta P_k \exp\left(\frac{2\pi \mathrm{i} kj}{N}\right), \tag{2}$$

was performed, which gave the discrete spectrum of one realisation of the process at frequencies $f_j = j/\Delta N$, where j lies in the interval $-N/2 \leqslant j \leqslant N/2$; and n is the number of the random process realisation. As a result, we obtained the spectral density of fluctuations:

$$g(f_j) = \Delta\left[\overline{C^2(f_j) + C^2(f_{N-j})}\right],$$

where $j = 0, ..., N/2$. The averaging was carried out as the arithmetic mean over the number n of realisations of the process. For most measurements, the value $n = 64$ was used.

The main emission parameters (spectrum, far field, and watt–ampere characteristic) of lasers were measured. The spectrum was recorded with a computer-controlled MDR-41 monochromator. A signal from the exit slit of the monochromator was detected with a photodiode and fed to the computer. The emission intensity distribution in the far-field zone was detected with an automated setup described earlier in [6].

3. Experimental results

Fig. 2 shows the typical emission characteristics of the lasers. The threshold currents I_{th} of the diodes ranged from 20 to 35 mA. The FWHMs of the radiation pattern in the directions perpendicular and parallel to the layers in the laser structure were ~ 34° and ~ 9°, respectively. The data for intensity distribution in the far-field zone (Fig. 2b) are in satisfactory agreement (with an error not exceeding 1° for the half-width) with the results of numerical calculations of the waveguide structure of the laser for the layer parameters presented in Table 1.

Lasing at a single lowest transverse mode was observed in samples studied, as a rule, for currents I below 160 mA. In this case, the output power was more than 60 mW. This lasing regime led to a linear watt–ampere characteristic

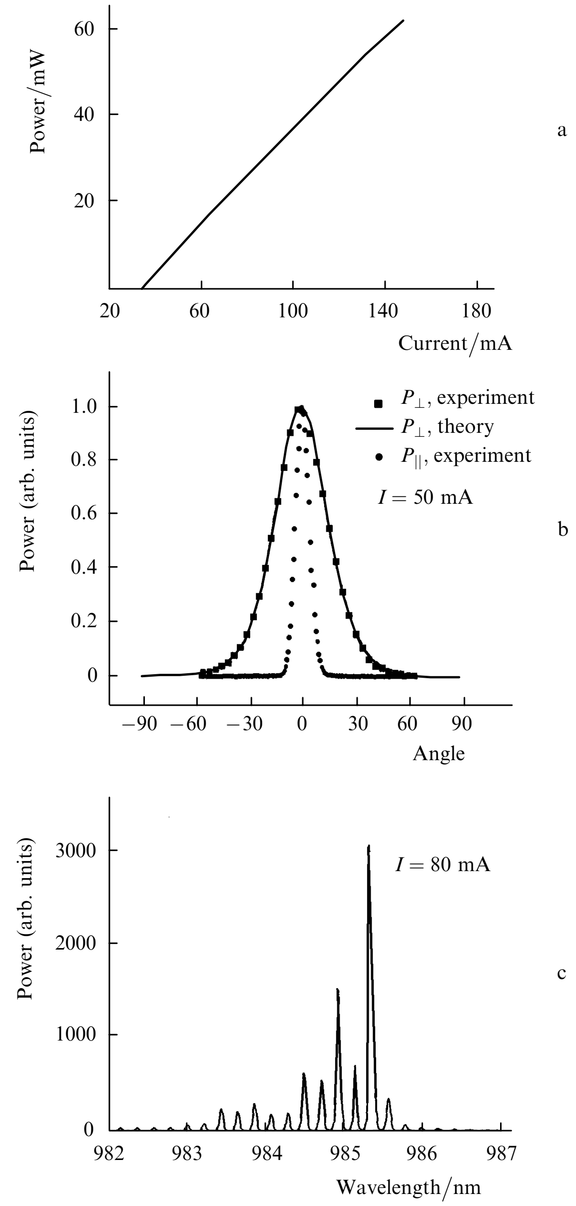

Figure 2. Emission characteristics of the laser: watt–ampere characteristic (a), distribution of emission power in the far-field zone in the vertical plane $P_\perp$ (perpendicular to the structure layers) and in the horizontal plane $P_\|$ (parallel to the structure layers) (b), as well as laser emission spectrum for a current 80 mA (c).

(Fig. 2a). Fig. 2c shows a typical emission spectrum consisting of several longitudinal modes. Note that the spectrum was recorded for ~ 1 min, therefore representing an averaged spectrum. The 'instantaneous' spectrum in such measurements could be similar to the single-frequency spectrum.

Fig. 3 shows the results of processing of the intensity fluctuations. One can see that the fluctuation spectrum has the shape of $1/f$-noise in the frequency range $f \leqslant 5$ kHz, and the shape of white noise (with spectral density in the form of a plateau) at frequencies $f > 5$ kHz. The distribution of the probability density ρ of fluctuations δP is close to normal, as can be seen in Fig. 4. Because the pass band of the recording system is 500 – 15000 Hz, the mean-square fluctuation $\overline{\delta P^2}$ corresponds to the integral of $g(f)$ in the above frequency range. The normal fluctuation amplitude distribution law indicates that the random quantity $P(t)$ being measured is the result of summation of a large number of smaller partial variations of power.

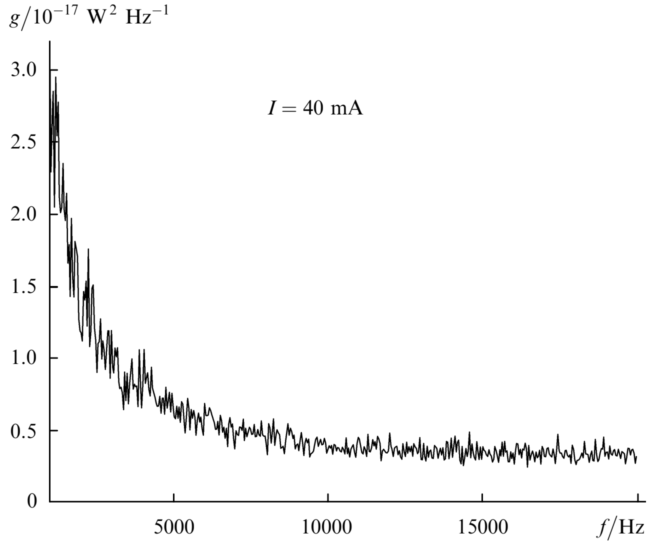

Figure 3. Spectral density of the intensity fluctuations for a current 40 mA.

The spectral component $g(f)$ having a frequency dependence $1/f$ in the low-frequency range also depends on the lasing conditions and is not reproduced from sample to sample. The appearance of the $1/f$-noise is caused by single sharp power fluctuations, which can be seen from Fig. 5 showing three realisations of a random process for the same laser. Although the mean power (~ 30 mW) and the pump current (~ 90 mA) are the same for all the three realisations, they correspond to different lasing regimes from the fluctuation point of view. The realisation shown in Fig. 5a corresponds to the 'steady' lasing process in which no sharp and significant fluctuations δP of power are observed. In this case, the fluctuation amplitude distribution $W(\delta P)$ is close to normal, while the spectrum $g(f)$ has a shape resembling white noise. On the contrary, Fig. 5c shows the lasing regime with sharp and significant fluctuations of power. In this case, the fluctuation amplitude distribution differs considerably from the normal law, and the spectrum contains a clearly manifested $1/f$-noise component. The realisation shown in Fig. 5b corresponds to the intermediate case.

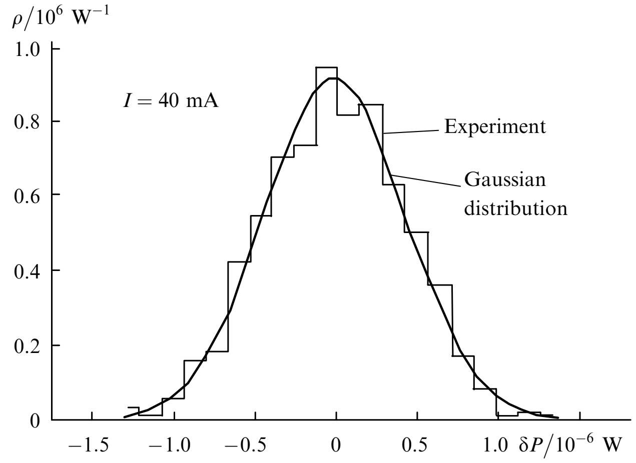

Figure 4. Dependence of the distribution of the probability density ρ on the fluctuation amplitude δP of the laser intensity for a pump current 40 mA. The histogram shows the experimental distribution; the smooth curve is a Gaussian distribution with a variance equal to the spread of the experimental data.

Thus, the $1/f$-noise component in the frequency range up to 5 kHz is associated in our measurements with sharp and large-amplitude fluctuations. As for the $g(f)$ component in the frequency range corresponding to the plateau, the spread in its value was much smaller, and the values of this component were determined mainly by the lasing conditions.

Fig. 6 shows the spectral density at a frequency $f \approx 10$ kHz corresponding to the plateau on the spectral curve as a function of the pump current. As a rule, the increase in the spectral density with current (average laser power) is nonmonotonic. One can see from Fig. 6 that a large peak on the dependence $g(I)$ is observed in the current range $I \approx 70 - 80$ mA, which corresponds to a larger than an order of magnitude increase in fluctuations (up to 10^{-15} W^2 Hz^{-1}). As the pump current is further increased, the spectral density tends to saturate, and the value of $g(I)$ does not exceed 6×10^{-17} W^2 Hz^{-1} for a current $I \approx$ 140 mA corresponding to an output power of 60 mW.

The presence of the peak in Fig. 6 indicates to the existence of an additional parameter determining the fluctuation amplitude. It was found that this parameter is the temperature of the active region of the laser. This was confirmed by direct measurements of the dependence of g on the temperature of the cold finger of the laser at a fixed frequency $f = 10$ kHz; the results of these measurements are shown in Fig. 7. Despite the irregular form of this dependence, it exhibits some oscillations with a characteristic scale of temperature variation about of 3 K. Such a variation ΔT corresponds to the temperature rearrangement of the lasing frequency at an individual longitudinal mode by a mode interval.

Because we did not stabilise the laser diode temperature in our experiments; slow variations in the temperature of the active region during the measurements (the duration of each measurement was 5 – 10 s) could lead to some irreproducibility of the results. This was especially noticeable when the average temperature of the laser was close to the 'boundary' region corresponding to a sharp increase in fluctuations. The data presented in Fig. 5 in the form of various realisations of a random process correspond namely to such a situation.

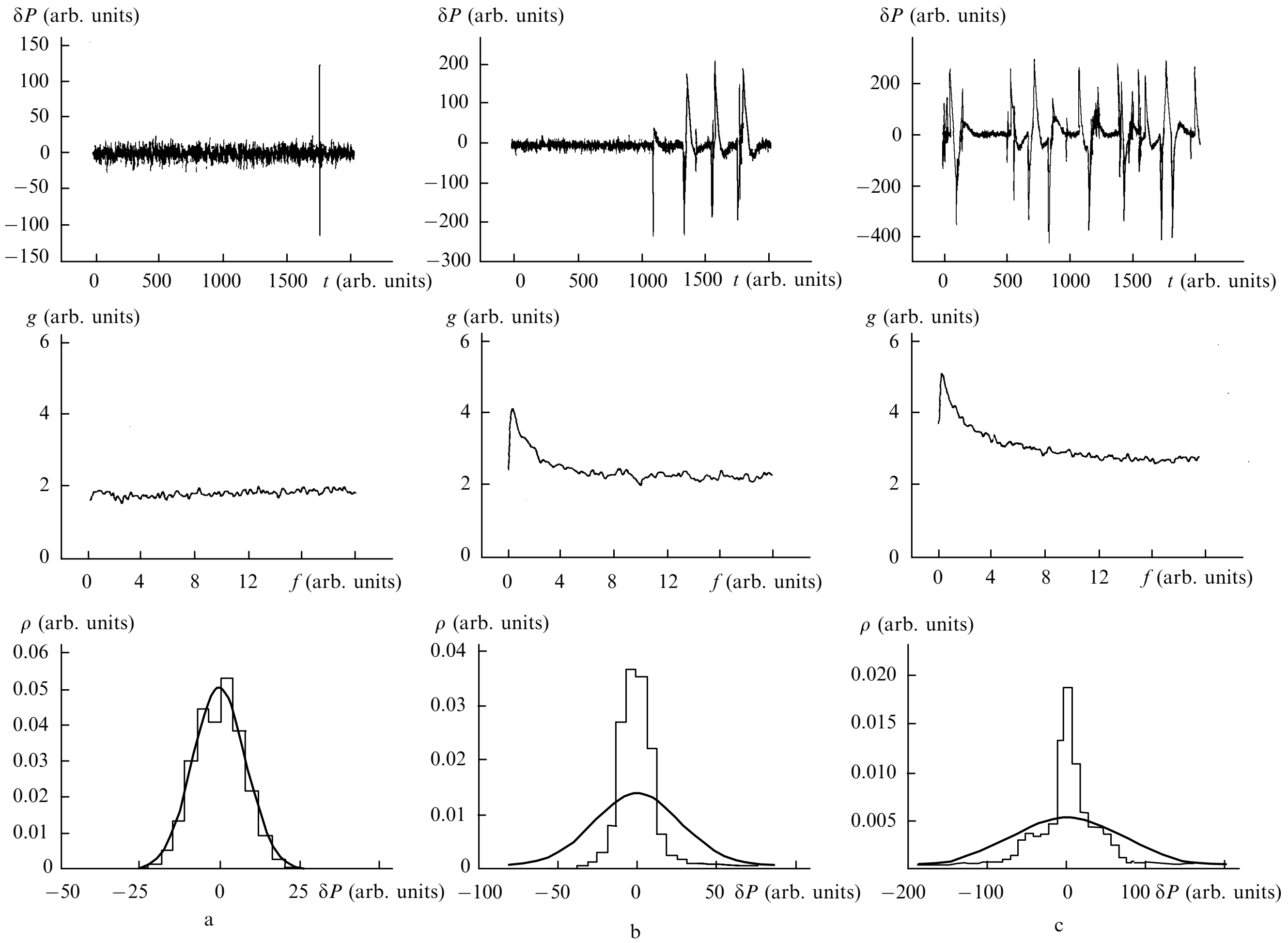

Figure 5. Emission intensity fluctuations (upper row), spectrum of intensity fluctuations (middle row), and the probability intensity distribution for three realisations of the process and the Gaussian distribution (solid curve) with a variance equal to the spread of the experimental data (lower row).

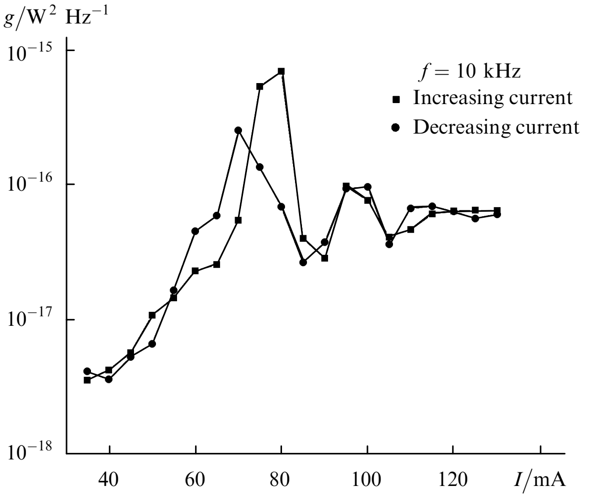

Figure 6. Dependence of the spectral density (frequency 10 kHz) on the pump current.

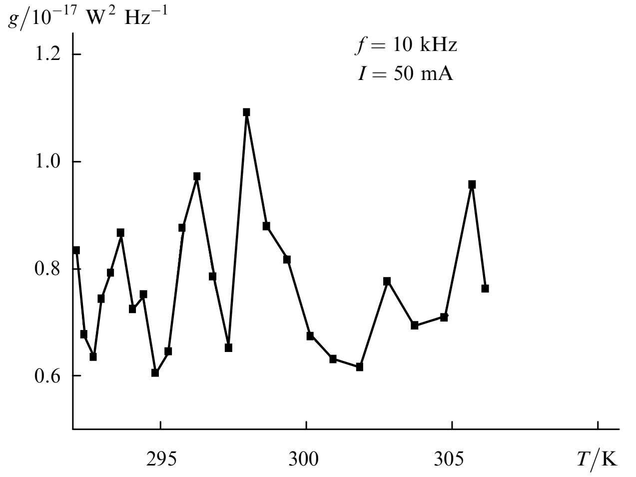

Figure 7. Dependence of the spectral density of intensity fluctuations (current 50 mA, frequency 10 kHz) on the temperature of the cold finger.

4. Discussion

Thus, we have detected in this work the low-frequency fluctuations of the laser radiation intensity, both of the $1/f$- or white noise type. Depending on the laser operation regime, the spectral density of the latter type of fluctuations lies in the range $4 \times 10^{-18} - 10^{-15}$ $\mathrm{W}^2\ \mathrm{Hz}^{-1}$. It was found that temperature is the parameter most sensitive to the fluctuation level variations, which are of the oscillatory type. Because an increase in the pump current is always accompanied by an increase in temperature, fluctuation level variations caused by an increase in the average optical power are always accompanied by an implicit variation in the fluctuation level due to a change in the temperature. This is manifested as a sharp peak in the curve describing a continuous increase in fluctuations with increasing average output power.

The power fluctuation oscillations observed upon a temperature variation are apparently caused by mode hopping [7]. The mode-hopping rate depends on the stability of lasing at a spectral mode. In turn, this stability is determined by the position of the mode relative to the maximum of the spectral profile of the gain curve of the laser medium. The temperature variation is accompanied by a successive passage of longitudinal mode frequencies through the spectral profile maximum; accordingly, the lasing stability also varies periodically.

When the longitudinal mode frequency coincides with the maximum of the gain curve, the stability is the highest and mode hopping is unlikely. On the contrary, when two adjacent modes are located symmetrically relative to the spectral maximum, the stability is minimum, and the mode hopping probability increases sharply. This can explain the quasi-periodic nature of fluctuation variations with temperature, which is caused by a quasi-periodic variation in the mode-hopping rate. Note that a similar situation was observed earlier in Ref. [8] and was also attributed to mode hopping.

A comparison of the fluctuation amplitude in the most 'steady' lasing regime, i.e., outside the peak $g(I)$, with the results obtained in Ref. [8] for a less powerful laser (5–12 mW) shows that the maximum values of the fluctuation amplitude are close in both works and amount to $\sim 6\times10^{-17}$ W^2 Hz^{-1}. This means that a manifold increase in the average power in our work did not lead to a significant increase in the maximum fluctuation level; i.e., the relative power fluctuations in our lasers were an order of magnitude smaller than for the lasers used in Ref. [8].

It is also interesting to compare the experimental values of fluctuations with the theoretical limit set by the 'natural' fluctuations due to spontaneous emission for the single-frequency lasing. According to Ref. [9], the spectral frequency in the low-frequency limit is given by

$$g(f)=\frac{2a(1+\eta)^2P^2\tau}{\eta^3}, \qquad (3)$$

where a is the spontaneous emission factor from Ref. [10] ($a\approx10^{-5}$ in our case); $\eta=(I-I_{\rm th})/I_{\rm th}$ is the relative excess of the pump intensity over the lasing threshold; P is the laser output power; and τ is the photon lifetime in the resonator ($\tau\approx3.3\times10^{-12}$ s in our case). For the maximum output power $P=60$ mW (Fig. 2a) and for $\eta=3.2$, we obtain $g(f)\approx1.3\times10^{-19}$ W^2 Hz^{-1}, which is two orders of magnitude smaller than the experimental value.

It follows from this estimate that the spontaneous emission itself is not responsible for intensity fluctuations in the lasers studied. However, it may play an indirect role by inducing mode hopping at an unstable working point. Relation (3) was derived for a laser with a single-frequency resonator and, hence, it does not take into account other subthreshold modes. In our case, however, the laser operated at several modes, and mode hopping turned out to be the main source of fluctuations. Therefore, the theoretical estimate obtained from (3) can provide only the limiting value of the spectral density of fluctuations for the case when mode hopping is suppressed and the subthreshold modes are insignificant.

5. Conclusions

Thus, our study has shown that the low-frequency output power fluctuations in single-mode lasers are in the range $6\times10^{-17}-10^{-15}$ W^2 Hz^{-1} for an average output power of ~60 mW and are determined by the lasing stability. The lower limit corresponds to the 'steady' lasing regime at a spectrally stable working point, while the upper limit is set by a high-rate mode hopping. In the 'steady' lasing regime, the $1/f$ flactuation component is minimal, and the fluctuation amplitude is distributed according to the normal law. However, even in the 'steady' lasing regime, the spectral density of fluctuations is two orders of magnitude higher than the theoretical limit set by spontaneous emission for a single-mode laser. This indicates that the presence of subthreshold modes in a real laser apparently leads to a considerable increase in fluctuations.

It is shown that the $1/f$-noise component in the lasers investigated by us is related to transitions from the 'steady' lasing regime to the high-rate mode hopping. The white noise component also increases in this case, and the fluctuation amplitude distribution no longer follows the normal law.

A further decrease in the fluctuation level can be achieved by using not only spatially, but also spectrally single-mode waveguides. This would eliminate mode hopping and considerably suppress the subthreshold modes, thereby reducing their role in the laser.

Acknowledgements. This work was performed under the special Federal Programmes 'Quantum and Nonlinear Processes' and 'Physics of Solid Nanostructures' as well as under the programme 'Integration' (Project 'Fundamental Optics of Quantum-Well Semiconductor Structures'), and was partly supported by the programme 'Leading Research Schools' (Grant No. 00-15-96624).

References

1. Bessonov Yu.L., Kurlenkhov S.S., Morozov V.N., Sapozhnikov S.M., Chan Min Tchai, Shidlovskii V.R. *Kvantovaya Electron.*, **12**, 347 (1985) [*Sov. J. Quantum Electron.*, **15**, 220 (1985)].
2. Bessonov Yu.L., Kornilova N.B., Kurnosov V.B., Morozov V.N., Narolenko S.D., Chan Min Tchai, Shidlovskii V.R. *Kvantovaya Electron.*, **12**, 2370 (1985) [*Sov. J. Quantum Electron.*, **15**, 1569 (1985)].
3. Fronen R.J., Vandamme L.K.J. *IEEE J. Quantum Electron.*, **24**, (5) 724 (1988).
4. Schmidt B., Pawlik S., Mauschek N., Miller J., Pliska T., Troger J., Lichtenstein N., Wittmann A., Moldriek S., Sverdlov B., Harder C. *Proc. Opt. Fiber Commun. Conf. OFC-2002. Techn. Digest* (Anaheim, USA, 2002, THGG64) p. 702.
5. Popovichev V.V., Davydova E.I., Marmalyuk A.A., Simakov A.V., Uspenskii M.B., Chelnyi A.A., Stratonnikov A.A., Plisyuk S.A., Bogatov A.P., Drakin A.E. *Kvantovaya Electron.*, **32** (12) (2002) [*Quantum Electron.*, **32** (12) (2002)].
6. Bogatov A.P., Drakin A.E., Stratonnikov A.A., Konyaev V.P. *Kvantovaya Electron.*, **30**, 401 (2000) [*Quantum Electron.*, **30**, 401 (2000)].
7. Ohtsu M., Teramachi Y., Otsuka Y., Osaki A. *IEEE J. Quantum Electron.*, **22**, (4), 535 (1986).
8. Vasil'ev V.V., Hollberg L., Keilbach K., Velichansky V.L. *Issledovaniye nizkochastotnykh fluktuatsii poluprovodnikovykh lazerov*

(Study of Low-Frequency Fluctuations of Semiconductor Lasers) (private communication).
9. Bogatov A.P. *Preprint FIAN* (256) (Moscow, 1988).
10. Newstein M. *IEEE J. Quantum Electron.,* **20** (11), 1270 (1984).