Quantum Electronics 30 (10) 867 – 872 (2000)

PACS numbers: 42.55.Px; 42.60.Mi
DOI: 10.1070/QE2000v030n07ABEH001838

Emission of optically coupled semiconductor lasers

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Abstract. The emission characteristics of a system consisting of two coherently coupled semiconductor lasers are studied. It is found that different lasing regimes are realised in the system depending on its parameters. In the case of strong coupling, deep stochastic pulsations of the radiation intensity are formed in certain ranges of frequency detuning. There exist critical pump currents above which fluctuations are observed for all detunings and a catastrophic decrease (collapse) in coherence takes place. The power spectrum of noise contains two independent low- and sublow-frequency components. Suppression of noise in a system with spectrally selective coupling is obtained.

1. Introduction

A study of the optical interaction between two semiconductor lasers is important for an understanding of properties of ensembles of optically coupled lasers. Numerous experimental and theoretical investigations have been devoted to coupled injection lasers whose two flat cavities were separated by a narrow gap (of the order of several wavelengths of the light wave). Such lasers are called C^3 lasers (see references in Refs [1 – 4]).

The behaviour of two lasers with a large coupling length, in which the time of propagation of the light wave from one laser to another is comparable with the characteristic inner laser times, has not been adequately studied. In this case, because of the delay, the dynamics of the system becomes strongly complicated [5 – 9]. In particular, such systems exhibit deep stochastic pulsations of the output power accompanied by a catastrophic decrease in coherence [7].

A study of the interaction between two lasers is of practical interest, for example, for producing phase screens consisting of an array of coherent emitters controlled by a single source. The aim of experiments performed in this paper was to study the influence of parameters of a system of two coupled lasers on their emission properties.

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Received 25 July 2000
Kvantovaya Elektronika 30 (10) 867 – 872 (2000)
Translated by M N Sapozhnikov

2. Dynamic equations of coupled lasers

Methods for analysis of coupled lasers have been considered in review [10]. However, theoretical models used for lasers of other types cannot be adequately applied to semiconductor lasers because of a strong optical nonlinearity of their active medium, the high intensity of spontaneous emission, and a comparatively low reflectivity of cavity mirrors, which make the assumption about the conservative nature of the system in the search for mode solutions incorrect. For this reason, the adequate theory of coupled lasers is still absent. Here, we restrict ourselves to a simple model of two lasers with flat cavities coupled via the intermediate optical elements. The electric field strengths E_j ($j = 1, 2$) of each of the lasers satisfy the equations

$$\begin{aligned}\frac{dE_1(t)}{dt} &= \left[-i\omega_1 + \frac{1}{2}\Delta G_1(1 - i\alpha_1)\right]E_1(t)\\ &\quad + k_1E_2(t-\tau) + F_1(t),\\ \frac{dE_2(t)}{dt} &= \left[-i\omega_2 + \frac{1}{2}\Delta G_2(1 - i\alpha_2)\right]E_2(t)\\ &\quad + k_2E_1(t-\tau) + F_2(t),\end{aligned} \tag{1}$$

where ω_j is the resonance angular frequency of the jth individual laser; ΔG_j is the difference between the laser gain and the threshold gain; α_j is the line broadening factor; F_j is the Langevin force; τ is the time of propagation of the light wave between lasers; and the coupling coefficient k_j describes the addition to the field due to the emission injection and the efficiency of optical matching of the lasers. The electric field strength is normalised by the relation $|E_j|^2 = I_j$, where I_j is the photon density in the cavity.

The concentration N_j of charge carriers satisfies the equation

$$\frac{dN_j}{dt} = J_j - \frac{N_j}{\tau_{ej}} - G_j|E_j|^2, \tag{2}$$

where J_j is the pump rate; G_j is the gain; and τ_{ej} is the spontaneous lifetime of carriers. We assume that the system is in a synchronised state, i.e., lasing occurs at the common frequency. To separate the complex equation into two real equations for slowly varying functions of time (the intensity I_j and phase ω_j), we will write $E_j(t) = \sqrt{I_j}\exp(-i\varphi_j - i\omega t)$, where $\varphi_1(t) - \varphi_2(t-\tau) = \Delta\varphi_1$ and $\varphi_2(t) - \varphi_1(t-\tau) = \Delta\varphi_2$.

Let us expand the gain G_j in a series in the carrier concentration near the threshold $N_{j\,\mathrm{th}}$ with an accuracy to the linear term

$$G_j(N_j) = G_j(N_{j\,\mathrm{th}}) + g_j \Delta N_j,$$

where $g_j = \partial G_j / \partial N_j$; $\Delta N_j = N_j - N_{j\,\mathrm{th}}$; and $G_j(N_{j\,\mathrm{th}})$ is equal to the loss Γ_j in the cavity. Under stationary conditions for a small deviation of the gain from the threshold gain $|g_j \Delta N_j| \ll G_j(N_{j\,\mathrm{th}})$, we obtain from (2)

$$I_j = I_{0j} - \frac{\Delta N_j}{\Gamma_j}\left(\frac{1}{\tau_{ej}} + g_j I_{0j}\right), \tag{3}$$

where I_{0j} is the photon density in the individual jth laser. It follows from (2) that $I_{0j} = (J_j - J_{j\,\mathrm{th}})/\Gamma_j$, where $J_{j\,\mathrm{th}} = N_{0j}/\tau_{ej}$ is the threshold pump rate.

Under stationary conditions, $\Delta\varphi_1 = -\Delta\varphi_2 = \Delta\varphi$, $I_j(t-\tau) = I_j(t) = I_j$. Then, introducing the notation $\tan\psi_j = 1/\alpha_j$, we obtain the system of six equations describing the stationary state of two semiconductor lasers upon optical interaction:

$$\begin{aligned}
&I_1 = I_{01} - \frac{\Delta G_1}{\Gamma_1}\left(\frac{1}{g_1\tau_{e1}} + I_{01}\right),\\
&I_2 = I_{02} - \frac{\Delta G_2}{\Gamma_2}\left(\frac{1}{g_2\tau_{e2}} + I_{02}\right),\\
&\Delta G_1 + 2k_1\left(\frac{I_2}{I_1}\right)^{1/2}\cos(\omega\tau + \Delta\varphi) = 0,\\
&\Delta G_2 + 2k_2\left(\frac{I_1}{I_2}\right)^{1/2}\cos(\omega\tau - \Delta\varphi) = 0,\\
&\omega_1 - \omega = k_1\left(\frac{I_2}{I_1}\right)^{1/2}(\alpha_1^2+1)^{1/2}\cos(\omega\tau + \Delta\varphi - \psi_1),\\
&\omega_2 - \omega = k_2\left(\frac{I_1}{I_2}\right)^{1/2}(\alpha_2^2+1)^{1/2}\cos(\omega\tau - \Delta\varphi - \psi_2).
\end{aligned} \tag{4}$$

Here, I_1, I_2, ΔG_1, ΔG_2, ω and $\Delta\varphi$ are unknowns and $\Delta G_j = g_j \Delta N_j$. This system has a solution set. Note that not all of the solutions can be stable.

To simplify the analysis, we will assume that that the ratio I_2/I_1 remains constant upon small variations of the laser parameters. Then, it is sufficient to consider only the last four equations from (4). Fig. 1 shows the dependences of ω_1, ω_2, ΔG_1, and ΔG_2 on ω plotted in this approximation. The horizontal dashed straight lines correspond to the specified resonance frequencies ω_1 and ω_2. As the phase difference $\Delta\varphi$ changes, curves *1* and *2* shift to the opposite sides and the intersection points of dashed straight lines with curves ω_1 and ω_2 are found one under another at a certain value of $\Delta\varphi$ (Fig. 1). The corresponding frequency ω and gains ΔG_1 and ΔG_2 are one of the solutions of the system of equations. There can exist several intersection points, but lasing appears at the frequency corresponding to the maximum gain.

When the difference $\omega_2 - \omega_2$ between the natural frequencies of cavities is large (larger than the cosine amplitude), there is no frequency ω at which the simultaneous lasing can occur. We can obtain from the last two equations of the system (4) the condition for the frequency detuning at which the simultaneous lasing can occur:

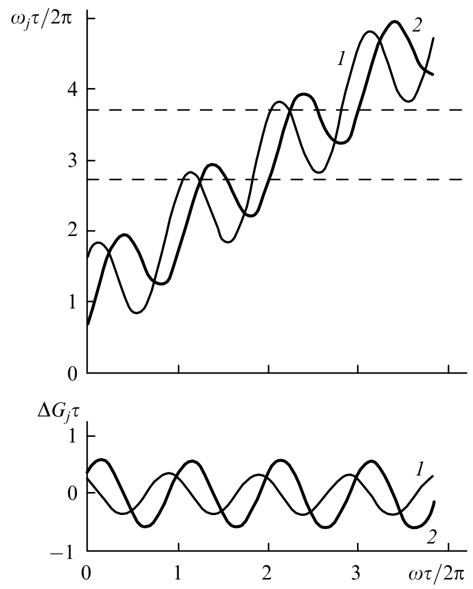

Figure 1. Normalised functions ω_1, ω_2, ΔG_1, and ΔG_2 of the normalised frequency ω for $I_2/I_1 = 0.8$, $\Delta\varphi = 0$, $\alpha = 4$, $\tau = 10$.

$$|\omega_1 - \omega_2| \leqslant \left[k_1^2\frac{I_2}{I_1}\left(\alpha_1^2+1\right) + k_2^2\frac{I_1}{I_2}\left(\alpha_2^2+1\right)\right]^{1/2}. \tag{5}$$

To obtain more than one frequency ω of simultaneous lasing, the negative derivative of the function $\omega_j(\omega)$ should exist, i.e., the conditions $\tau^2 k_1^2 (I_2/I_1)(\alpha_1^2+1) > 1$ and $\tau^2 k_2^2 (I_1/I_2)(\alpha_2^2+1) > 1$ should be satisfied. By multiplying these inequalities, we obtain

$$\tau^4 k_2^2 k_1^2\left(\alpha_1^2+1\right)\left(\alpha_2^2+1\right) > 1. \tag{6}$$

If this condition is not satisfied, then there exist the only phase difference $\Delta\varphi_0$ and the only frequency ω_0 at which simultaneous lasing can occur for the specified natural frequencies ω_2 and ω_1 of the cavities. If for this phase difference $\Delta\varphi_0$ and the simultaneous lasing frequency ω_0 the condition $\Delta G > 0$ is satisfied, no stable lasing will occur at one frequency. Therefore, no lasing takes place at one common frequency at any pump currents for certain parameters of the system even when the natural frequencies are very close to each other and satisfy the condition (5). It is for this reason that synchronisation of lasers with close emission wavelengths ($\Delta\lambda < 1$ nm) cannot be achieved in some cases.

As the system parameters are changed, the curves in Fig. 1 also change, resulting in the change in frequency ω and the gain. Let laser diodes be pumped by rectangular current pulses. Then, they are heated during the laser pulse, which causes the increase in the optical length of their cavities, resulting in a change in the frequency detuning $\omega_2 - \omega_1$ and the phase difference $\Delta\varphi$. This, in turn, leads to a change in the frequency and, according to the first two equations of the system (4), to the modulation of the emission power. A similar situation takes place upon continuous variation in the pump current, which results in a strong nonlinearity of watt-ampere characteristics, as will be discussed below.

The applicability of a single-mode model can be doubted because it is known that semiconductor lasers tend to multimode lasing and, in addition, the system of two widely separated lasers has a very high density of spectral modes.

However, a complex configuration of a composite resonator provides drastic differences in the mode-dependent loss, and the single-mode approximation appears adequate upon lasing at one frequency.

3. Method and experimental results

Two lasers in our experiments were optically coupled with the help of microobjectives. A fraction of radiation from each of the lasers was directed with beamsplitters to a monochromator, which allowed us to observe spectra visually with the help of an electrooptical converter and to detect the intensities of spectral lines using an avalanche photodiode. The high-resolution measurements were performed by placing a Fabry – Perot etalon in front of the monochromator. The degree of optical coupling was continuously controlled with the help of an attenuator. The distance l between the lasers can be varied from 2 to 80 cm. Care was taken to prevent the entry of radiation reflected from the optical scheme elements back to the laser in order to eliminate its influence on the laser operation.

We studied AlGaAs semiconductor lasers with flat cavities of length from 200 to 800 μm, which emitted in the region of 0.8 μm. The lasers had a usual active region or an active layer with a single quantum well. Initially, pairs of lasers were chosen emitting at close wavelengths whose difference did not exceed 1.5 nm. These lasers operated in the free running regime at one or several longitudinal modes. The tuning to the optical coupling was performed using the photocurrent signals in each of the lasers, and more accurately, by monitoring the variation in the emission spectrum and power. The relative position of natural frequencies was adjusted by varying the temperature of diodes and also by changing the delay between pulses when the pulsed modulation of the current was used.

In order to change the spectrum in some experiments, one of the lasers had an external resonator of length 2 cm with a diffraction grating operating in the autocollimation scheme. Signals from photodiodes were fed into an oscilloscope or a spectrum analyser.

The coherent interaction of lasers decreases the lasing threshold and changes the emission spectrum and power. Fig. 2 shows a typical threshold curve. Lasing takes place when the pump currents i_1 and i_2 of the first and the second laser, respectively, lie outside the region bounded by the curve. The stronger coupling, the farther the threshold curve from the straight lines corresponding to threshold currents $i_{1\mathrm{th}}$ and $i_{2\mathrm{th}}$ in the free running mode. The data in Fig. 2 were obtained for the maximum coupling level attained in experiments.

Upon optical interaction, watt-ampere characteristics exhibit undulations whose amplitudes depend on currents and coupling coefficients. In the free running mode, watt-ampere characteristics were linear above the threshold, and if one of the coupled lasers was not pumped, the undulations were small, which implies that reflection of light from its mirror was of minor importance if the system has been properly aligned.

The emission parameters of one of the lasers become substantially dependent on another laser when the pump current of the latter exceeds approximately 80% of the threshold current in the free running mode, i. e., when a sufficient amplification of the input radiation is achieved in its active medium.

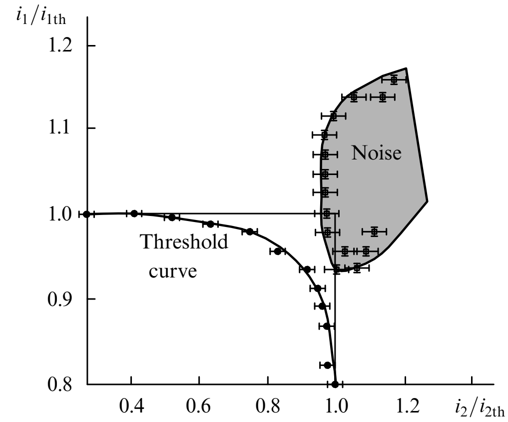

Figure 2. Threshold diagram of two coupled lasers (the calculated curve and experimental points) and the boundary of the coherence collapse region for $l = 0.8$ m.

In the case of weak coupling, as the current increases (resulting in the change in the frequency detuning), the emission power and wavelength exhibit continuous and weak oscillations (undulations) with respect to the power and wavelength in the free running mode. The undulations occupy only a part of watt-ampere characteristics because in this case the interval of detunings (5) in which the synchronisation of the system takes place is small. As the optical coupling increases, undulations take the form of steps (Figs 3a, b) that appear due to the mode switching (the second lasing mode). In the general case, switching between the modes in some current interval occurs repeatedly, i. e., the integrated power exhibits jumps. If the current at which switchings occur is fixed, the output power will look like a random telegraphic signal, i.e., its value will jump to another value in a random manner.

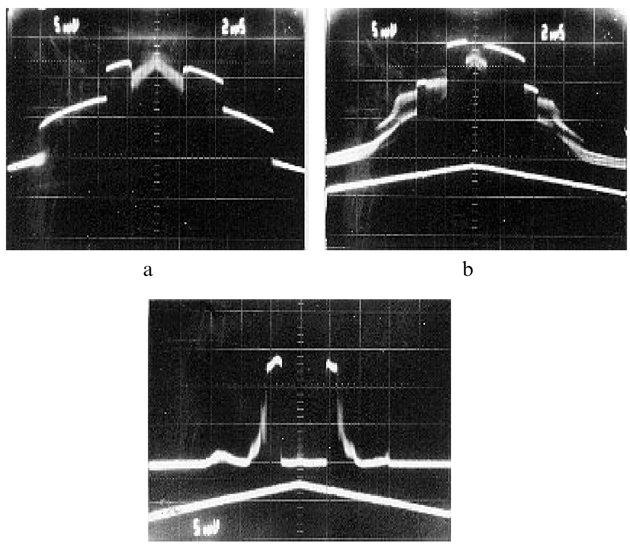

Figure 3. Oscillograms (watt-ampere characteristics) of the output power of a laser (a, b) obtained upon a linear increase in the pump current i_1 from 30.5 to 37.5 mA, $i_2 = 23$ (a) and 25 mA (b), $i_{1\mathrm{th}} = 33$ mA, $i_{2\mathrm{th}} = 18$ mA, $l = 2.5$ cm, and the oscillogram of power in the mode (c) upon changing i_2 from 16 to 32 mA, $i_1 = i_{1\mathrm{th}} = 34$ mA, $i_{2\mathrm{th}} = 22$ mA, $l = 3.8$ cm. The lower traces in Figs. 3b and 3c show the current variation. The scale division on the abscissa is 2 ms.

Mode jumps can occupy large intervals of the pump current, resulting in an apparent ambiguity in watt-ampere characteristics (Fig. 3b). The width of these intervals depends on the current, as shown in Fig. 3b, and some other parameters.

It is known that mode jumps are also observed in individual lasers. However, the accompanying oscillations of the output power in coupled lasers are much greater because of the spectral selectivity, and mode jumps can be completely suppressed by an appropriate choice of the system parameters. On flat parts of watt-ampere characteristics (Fig. 3a), except small intervals where the mode switching occurred, the stable single-mode lasing was observed. An increase in the current i_2 near the threshold affects the watt-ampere characteristic similarly to an increase in the coupling level, which is explained by the fact that the amplification compensates for the loss in the gap between lasers.

Note the asymmetry of the watt-ampere characteristic in Fig. 3a. It can be explained by the nonlinear dependence of temperature on current and, hence, by an asymmetric change in the frequency detuning, which determines the moment of mode switching. Another reason is optical nonlinearity of the medium [the dependence of the power on detuning in (4) is ambiguous because $\alpha_{1,2}$ are nonzero]. This explains the hysteresis of the watt-ampere characteristic in a laser with an external cavity [11]. A strong asymmetry of the watt-ampere characteristic in the regime of mode self-stabilisation in a laser with the external cavity was observed in Ref. [12].

However, this effect appears when the mode interval is smaller than the inverse lifetime of carriers, which does not correspond to the case in Fig. 3 where the distance between lasers is quite small. A strong hysteresis, which was probably caused by self-stabilisation, was observed in a laser with an external mirror in Ref. [13], however, in this case, watt-ampere characteristics had a distinct anomalous form, which differed from that shown in Figs. 3a, b. The dependence of the width of the hysteresis loop on the frequency of the saw-tooth modulating current observed in our case demonstrates an important role of the temperature mechanism.

As the current was increased, stochastic power pulsations appeared in the region of mode switching [7], which were accompanied by broadening of the emission spectrum (the third lasing regime). These pulsations first appeared in a weaker mode, whereas a stronger mode remained stable during a short period until the moment of switching.

Initially, pulsations look like sharp downward intensity jumps with a short leading edge and a comparatively slow intensity increase. However, they acquire a random shape with increasing current, and the interval of detunings in which they were observed expands. Beginning from a certain critical current i_{1cr}, which depended on the optical coupling level, the distance between the lasers, and the current i_2, the system transfers to the regime of coherence collapse when pulsations occupy all frequency detunings. In this case, the width of the spectral line of the mode increased up to several gigahertz, whereas upon lasing at one mode in the second regime, this width decreased by a factor of ten and more, down to 10 MGz (the value limited by the spectral resolution of our setup) compared to that observed in the free running mode.

The average emission power decreased during the coherence collapse. The part of the watt-ampere characteristic near its top in Figs. 3a, b corresponds to the collapse regime. In this part, the power decreases by step with increasing current, while the oscillogram lines broaden because of fluctuations that occur faster than the sweep rate. The current i_{1cr} decreases with increasing coupling level and the length of the coupling region (approximately as $1/l$).

Fig. 2 shows the region of the injection current in which this regime was observed for one of the pairs of lasers. In general, the positions of boundaries of the pulsation regions for different pairs of lasers from the same batch do not coincide. The lasing modes considered above are also distinctly observed when one or both lasers are excited by rectangular current pulses when the frequency detuning varies in time due to heating. Note that we have failed to obtain synchronisation for some lasers or observed only the first of the lasing regimes considered.

The type of variation of the power in modes depending on the frequency detuning is illustrated in Fig. 3c, which shows the dependence of the emission power in one of the modes of the first laser on the current in the second laser. The current i_1 is equal to the threshold current in the free running mode, while the current i_2 changes linearly. The other modes behave similarly. As the power of one of the modes decreases, that of another one increases, i.e., mode switching takes place.

Mode switching can occur softly when the mode power changes continuously with detuning, or sharply when the mode power changes abruptly and it is impossible to obtain the intermediate power even for very slowly varying current. Thus, the oscillogram in Fig. 3c exhibits a soft switching on of the mode with increasing current and its sharp switching off (jump) after the passage of the maximum. Upon soft switching of two modes, a strong intermode noise appears produced by anticorrelated fluctuations of power in modes.

The emission spectrum of the system as a whole depends on its parameters in the complicated way. Nevertheless, the stable single-mode lasing was achieved in some current intervals, as was mentioned above. We managed to obtain more or less consecutive discrete frequency tuning over 6 – 8 modes when the current in one of the lasers did not exceed its intrinsic threshold current.

Consider now the situation when the first laser has an external dispersive resonator. In this case, the Q factor increases and the laser becomes less sensitive to the emission from the second laser, whose frequency is locked by the injected signal when the threshold is slightly exceeded so that it emits in one mode imposed by the first laser.

The emission wavelength was tuned in this scheme within the range 4 – 6 nm by rotating a diffraction grating. As the pump current of the second laser was increased, the influence of the injected radiation gradually reduced: except of the imposed mode, its eigenmodes became excited, and then it itself began to affect the first laser. In this case, the system also passed to the regime of stochastic pulsations upon exceeding a critical current.

The width $\Delta\nu$ of the frequency band in which the system is synchronised to one mode depends on the level of optical coupling. To measure the width of the synchronisation band, one of the pump currents was slowly modulated with a small-amplitude (4 mA) saw-tooth signal. Because of the increase in the refractive index with temperature, this resulted in the variation in the frequency detuning in time. The presence of synchronisation was manifested in an increase in the emission power. The rate of the frequency shift was measured in the absence of interaction using the Fabry – Perot etalon. Fig. 4 shows the dependence of $\Delta\nu$ on the relative level of optical coupling k. For $k \leqslant 0.9$, the band almost linearly broadens with the optical coupling level, in accordance with (5), and its width becomes several orders of magnitude larger than the width of the spectral line of the mode. For larger values of k, $\Delta\nu$ increases faster, which can be explained by the fact that in the case of strong coupling the multiple passages of light between the lasers, which were neglected in the model, become substantial.

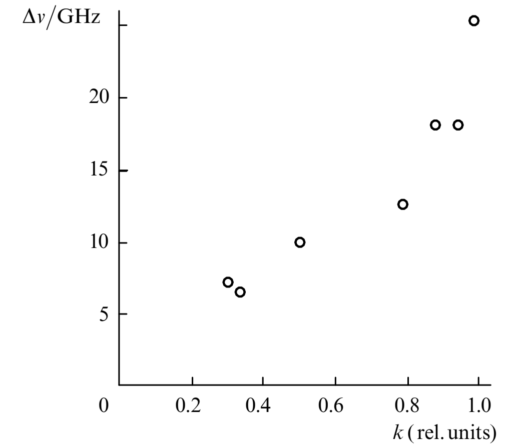

Figure 4. Dependence of the synchronisation bandwidth on the relative level of optical coupling for $l = 0.8$ m, $i_1 = 1.2i_{1\text{th}}$ and $i_2 = i_{2\text{th}}$.

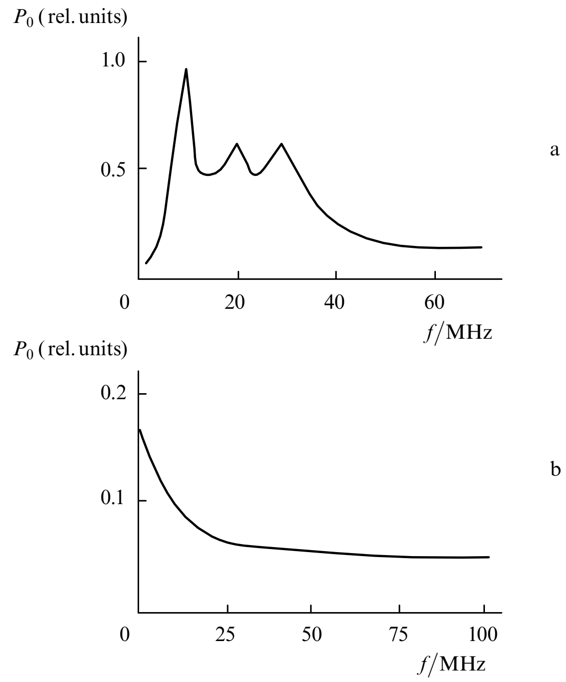

Figure 5. Normalised spectral power density of the low-frequency (a) and sublow-frequency (b) noise of coupled lasers for the filter transmission bandwidth equal to 300 kHz, $l = 0.8$ m, $i_1/i_{1\text{th}} = 1.27$, $i_2/i_{2\text{th}} = 0.96$ (a) and $i_1/i_{1\text{th}} = 0.50$, and $i_2/i_{2\text{th}} = 0.95$ (b).

When devising synchronised sets of laser emitters, it is important to know the influence of the current on the deviation of the emitted-wave phase because one can control the wave front form by tuning the phase. To determine the phase shift appearing upon a change in the current, the quasi-parallel light beams from both lasers were directed on the same photodetector, where they interfered. A change in the emitted-wave phase estimated from the shift of interference bands upon continuous variation of the current i_2 within the synchronisation band was about 30°. This value is noticeably lower than the maximum phase deviation obtained upon variation of the current in the laser locked by an independent source [13] but it is sufficient for small correction of the wave front of an emitter.

In the general case, the spectrum of the noise power upon optical interaction (Fig. 5) has a complex structure. However, three components of this spectrum can be distinguished: the high-frequency component (with characteristic frequencies in the region of relaxation vibrations in the free running mode), the low-, and sublow-frequency components. The low-frequency component corresponds to low-frequency pulsations, which we discussed above. For sufficiently high currents and the coherence collapse, its distribution represents a broad band at the characteristic frequency, which is 10 – 20 times lower than $1/\tau$. For lower pump powers, the low-frequency component can have a complex structure, as for example, in Fig. 5a, and its shape depends on the frequency detuning. In addition, the spectrum exhibits sometimes lower-frequency bands, whose nature is not known so far.

The spectrum of the sublow-frequency noise is shown in Fig. 5b. The power spectral density decreases with the frequency as f^2. The frequency beginning from which the power spectral density starts to decrease rapidly (the cut-off frequency) depends on the pump power and detuning but does not exceed 10 MHz. This noise is caused by random mode switching. It is similar in the form of the output-power signal and the spectrum to noise in a laser with an external optical feedback [14] and to the explosion noise that appears upon injection locking of the laser frequency by the external radiation [15]. The latter fact suggests that these noises have the common nature. They results from random transitions between two metastable states caused by the spontaneous emission noise. The sublow- and low-frequency components can be present in the spectrum separately or simultaneously. Thus, in the second lasing regime, only the first component is present, whereas it is absent during the coherence collapse. In the third lasing regime, both components can be present at a certain frequency detuning.

One can see from Fig. 2 that when the distance between lasers is large enough, they can readily pass to the collapse state, resulting in a drastic deterioration of their emission parameters. We tried to use the spectrally selective coupling to reduce the noise. For this purpose, we placed between lasers separated by the distance 0.8 m a Fabry – Perot interferometer transmitting at the lasing frequency.

The first laser in this experiment had an external resonator, i. e., it was used as a master laser. In the absence of the interferometer, a high-power low-frequency noise appeared in the system with a maximum at 50 MHz (whether or not the external resonator of the first laser was used) when the current exceeded the critical value. In the presence of the interferometer, the power of a beam from the first laser transmitted by the interferometer and directed to the second laser decreased, whereas the output power of the second laser, both in the mode and integrated over the spectrum, did not change. The emission noise of the second laser decreased down to its noise in the absence of optical coupling, and the noise power of the master laser reduced by an order of magnitude, the sublow-frequency noise also decreasing.

We found that the spectrally selective coupling increases the stability of a single-mode lasing upon modulation. Thus, when rectangular 2-μs current pulses superimposed on a constant bias were applied to the second laser, its output power was modulated at the mode frequency imposed by the master laser. The relative modulation coefficient defined as the ratio of the light-pulse amplitude to the constant light signal was equal to 5. In the absence of the interferometer, the modulation of the output power at a single mode could be only obtained upon pumping the second laser below the threshold, and the relative modulation coefficient did not exceed unity.

It was shown in [7] that the coherent interaction of lasers is metastable. Pulsations are caused by finite phase and amplitude fluctuations of the electric field strength produced by spontaneous radiation, which lead to the system instability. The Fabry – Perot interferometer placed between the lasers reduces the spectral width of the optical interaction. As a result, fluctuations in one laser do not affect another laser, which reduces the noise of simultaneous lasing and decreases the probability of its quenching.

4. Conclusions

The emission properties of two coherently coupled semiconductor lasers strongly depend on the system parameters (the coupling level, the distance between lasers, and pump currents). We can distinguish four characteristic lasing regimes. When the parameters are adequately chosen, the simultaneous (synchronous) lasing at one mode can be realised and the lasing frequency can be tuned discretely by varying the pump current. The frequency bandwidth within which the synchronisation of lasers can be achieved amounts to ten and more gigahertz.

However, in the case of high output power, a system of coupled lasers can readily pass to the regime of stochastic pulsations of the emission intensity accompanied by a drastic decrease in the emission coherence. This can be avoided by placing the lasers near to each other or, if it is impossible for technical reasons, by using the spectrally selective optical coupling.

References

1. Tsang W (Ed.) *Semiconductor Injection Lasers. I* (Orlando, San Diego, New York, London: Academic Press Inc., 1985)
2. Goldobin I S, Luk'yanov V N, Malakhova V I, Prokof'eva S P, Solodkov A F, Tambiev Yu A, Yakubivich S D *Kvantovaya Elektron.* **11** 1859 (1984) [*Sov. J. Quant. Electron.* **14** 1247 (1984)]
3. Bykovskii Yu A, Dedushenko K B, Zverkov M V, Likhachev I G *Kvantovaya Elektron.* **21** 414 (1994) [*Quant. Electron.* **24** 381 (1994)]
4. Bykovskii Yu A, Dedushenko K B, Likhachev I G *Kvantovaya Elektron.* **19** 1062 (1992) [*Sov. J. Quant. Electron.* **22** 986 (1992)]
5. Motosugi G *Jpn. J. Appl. Phys.* **16** 2221 (1977)
6. Brosson P, Ruhle W, Patel N B, Rippwe J E *IEEE J. Quantum. Electron.* **17** 714 (1981)
7. Dedushenko K B, Mamaev A N *Kvantovaya Elektron.* **17** 393 (1990) [*Sov. J. Quant. Electron.* **20** 357 (1990)]
8. Nishizawa J I, Ishida K *IEEE J. Quantum. Electron.* **11** 515 (1975)
9. Iwashita K, Nakagawa K *IEEE J. Quantum. Electron.* **18** 1669 (1982)
10. Likhanskii V V, Napartovich A P *Usp. Fiz. Nauk* **160** 101 (1990)
11. Lang R, Kobayashi K *IEEE J. Quantum. Electron.* **16** 347 (1980)
12. Akul'shin A M, Bazhenov V Yu, Velichanskii V L, Zverkov M V, Zibrov A S, Nikitin V V, Okhotnikov O G, Sautenkov V A, Senkov N V, Yurkin E K *Kvantovaya Elektron.* **13** 1391 (1986) [*Sov. J. Quant. Electron.* **16** 912 (1986)]
13. Dedushenko K V, Mamaev A N *Laser Phys.* **3** 967 (1993)
14. Bykovskii Yu A, Dedushenko K B, Zverkov M V, Mamaev A N *Kvantovaya Elektron.* **19** 657 (1992) [*Sov. J. Quant. Electron.* **22** 606 (1992)]
15. Dedushenko K V, Mamaev A N *Opt. Commun.* **96** 78 (1993)