Quantum Electronics **35** (9) 821 – 824 (2005)

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Px; 42.60.Da
DOI: 10.1070/QE2005v035n09ABEH003404

Study of the spectral width of intermode beats and optical spectrum of an actively mode-locked three-mirror semiconductor laser

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Abstract. **Various oscillation regimes of an actively mode-locked semiconductor laser are studied experimentally. Two types of regimes are found in which the minimal spectral width ($\sim$3.5 kHz) of intermode beats is achieved. The width of the optical spectrum of modes is studied as a function of their locking and the feedback coefficients. The maximum width of the spectrum is $\sim$3.7 THz.**

Keywords: *active mode locking, semiconductor laser, feedback, microwave pumping.*

1. Introduction

New possibilities for developing frequency synthesis systems from radio-frequency to optical range have appeared in recent years. For this purpose, femtosecond mode-locked lasers, which generate a wide range of frequencies, are used [1 – 3]. The intermode frequency lies in the microwave spectral range, while the difference of frequencies of arbitrary modes may achieve several hundred terahertz [3]. Locking of the intermode and optical frequencies of a laser allows absolute measurements of frequencies in various ranges with a high degree of precision. Semiconductor lasers, which have a comparatively broad gain line and can be mode locked to generate ultrashort pulses, are also interesting from the point of view of frequency synthesis [4 – 13]. The use of semiconductor lasers is especially important for frequency synthesis in the radio and far-IR frequency ranges, when it becomes necessary to use one or two lasers.

However, further investigations are needed for using semiconductor lasers for this purpose. This is especially true for actively mode-locked semiconductor lasers. In this case, it is necessary to investigate the possibility of obtaining high-stability ultrashort pulses and operation regimes leading to optimal conditions for generating a set of equidistant frequencies.

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Received 24 January 2005, revision received 7 July 2005
Kvantovaya Elektronika **35** (9) 821 – 824 (2005)
Translated by Ram Wadhwa

In this paper, we present the results of our further investigations of the semiconductor laser described in [5].

2. Experimental technique and results

We studied the dependence of the spectrum of intermode beats on the following factors: detuning of the frequency of the microwave pump oscillator from the intermode frequency, pump parameter $r = (I - I_{\rm th})/I_{\rm th}$ (where I is the pump current and $I_{\rm th}$ is the threshold laser current), and the coupling factor in the three-mirror cavity. In addition, the microwave oscillator frequency used for studying the intermode-beat spectrum was approximately equal to double the intermode frequency of the external cavity. Because the amplitude modulation of the laser output power takes place in this case, the detector used for recording the signal could detect not only the intermode beat components, but also a signal from the microwave pump oscillator. An appropriate choice of such a microwave pump frequency prevented the overlap of the intermode beat frequency (odd harmonics) with the frequency of the microwave pump oscillator, and also made it possible to observe new mode-locking regimes.

Figure 1 shows schematically our experimental setup for studying the operating regimes of an actively mode-locked semiconductor laser. The setup consists of semiconductor laser (*1*) (the reflectivity of the output face of the laser is $\sim$3% – 5 %) with collimating objective (*2*) and external mirror (*3*), high-stability current source (*4*) (with a relative

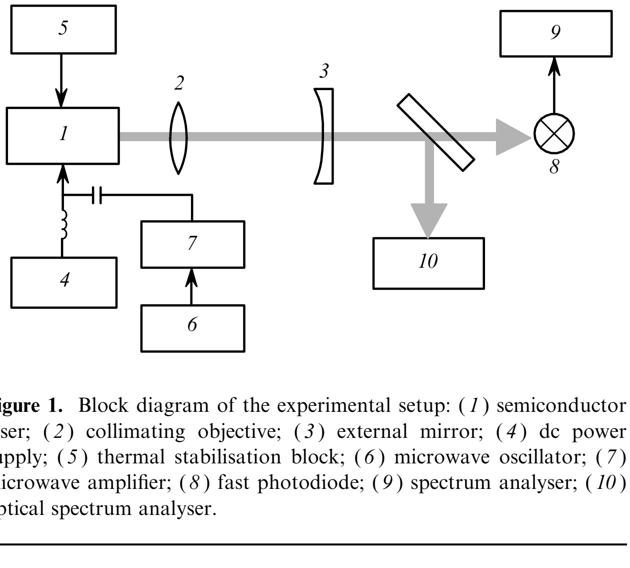

Figure 1. Block diagram of the experimental setup: (*1*) semiconductor laser; (*2*) collimating objective; (*3*) external mirror; (*4*) dc power supply; (*5*) thermal stabilisation block; (*6*) microwave oscillator; (*7*) microwave amplifier; (*8*) fast photodiode; (*9*) spectrum analyser; (*10*) optical spectrum analyser.

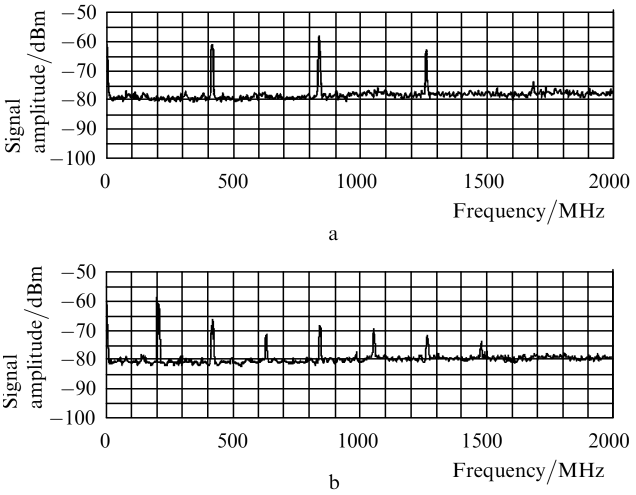

Figure 2. Intermodal beat spectra for detunings $\Delta f < 10$ MHz (a) and $\Delta f > 10$ MHz (b).

stability of 10^{-4}), thermal stabilisation block (*5*) (with a stabilisation to within 10^{-2} °C), microwave pump oscillator (*6*), microwave amplifier (*7*) for coupling out the oscillator from the semiconductor laser, fast photodiode (*8*) (with a working band ~1.5 GHz), spectrum analyser (*9*), and optical spectrum analyser (*10*). Note that in contrast to [6] (where a diffraction grating was used) and [7] (where selective elements were introduced into the external cavity of the laser), we used a nonselective feedback, i.e., the reflectivity of the external mirror remains almost unchanged within the gain band of the semiconducting medium. In the present investigations, we used ILPN-820-100 lasers with a threshold current of ~58 mA.

Experiments were performed for various values of operating parameters of the semiconductor laser and the external cavity, as well as for various microwave pump powers and frequencies. Preliminary experimental studies [5] revealed that the interval in which the pump parameter r varies from −0.2 to 0.2 is interesting for investigations. In

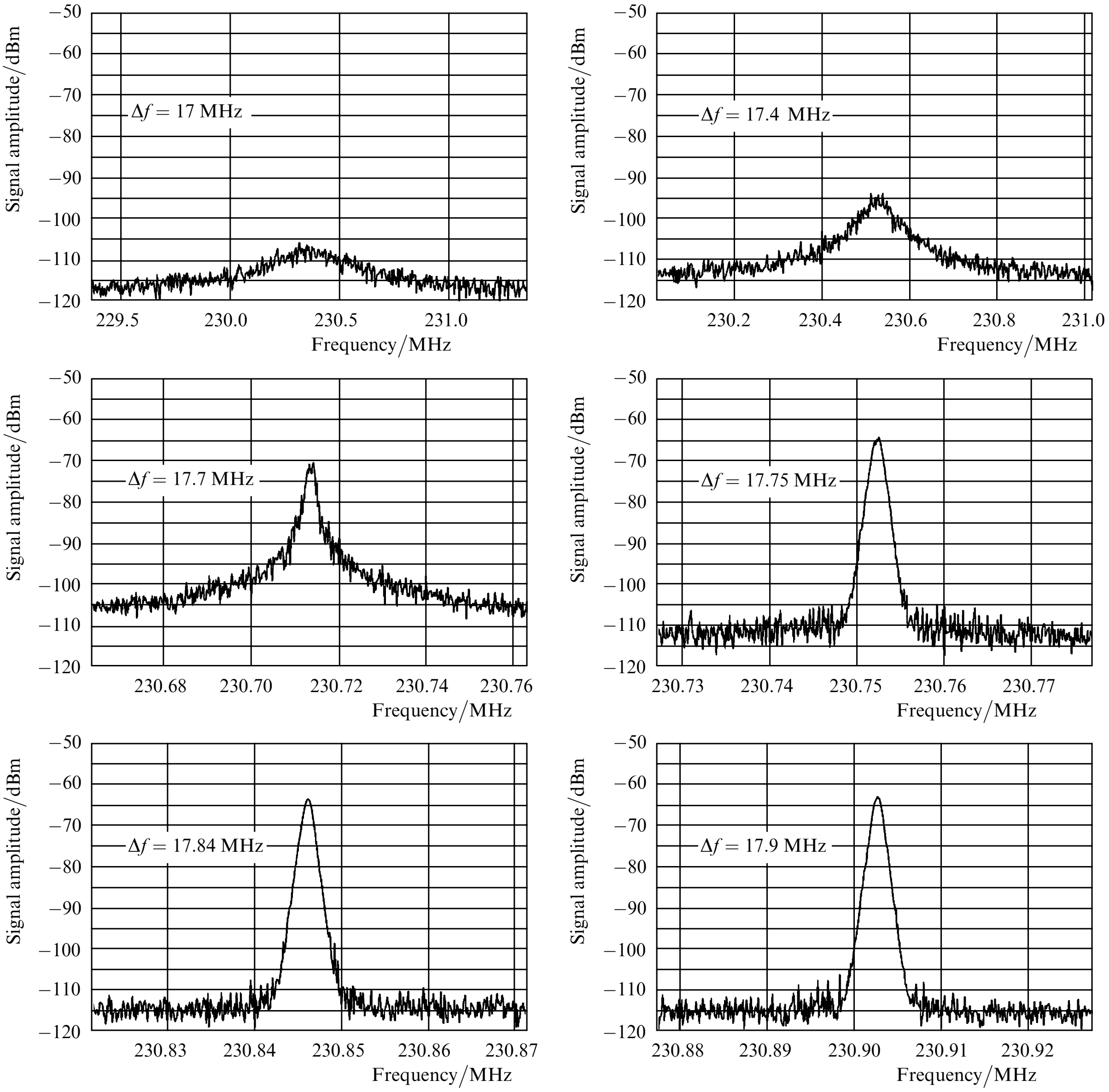

Figure 3. Dynamics of subthreshold mode excitation at frequencies $kf_{\rm im}$ for various detunings Δf of the microwave oscillator frequency $f_{\rm mw}$ from the intermode frequency $f_{\rm im}$ of the external cavity.

order to study the effect of the coupling factor on the intermode beat spectral width, we used the mirrors of the external cavity with reflectivities 0.1, 0.5 and 0.9. This means that the coupling factor $T = \tau^2\rho_{\rm m}/\rho$ (where τ and ρ are the coefficients of transmission and reflection from the output face of the semiconductor laser and $\rho_{\rm m}$ is the reflectivity of the external mirror [7]) varied over a wide range. In our experiments, the intermode frequency $f_{\rm im}$ was ~212.5 MHz, while the pump frequency $f_{\rm mw}$ varied in the interval 400–470 MHz. We studied the intermode beat frequency spectra as functions of the detuning Δf of the microwave oscillator frequency from the intermode frequency of the external cavity of the semiconductor laser, which is described by the expression

$$\Delta f = \left|\frac{f_{\rm mw}}{n} - f_{\rm im}\right|, \tag{1}$$

where n is an integer.

Different intermode beat spectra are observed for different values of detuning Δf of frequency $f_{\rm mw}$ from frequency $f_{\rm im}$. For comparatively small detunings $\Delta f = \pm(0-10)$ MHz, a regime of the first type is observed and the beat spectrum consists of equidistant frequencies separated by $f_{\rm mw}$ (Fig. 2a), i.e., the lasing frequency is determined by the frequency of the microwave field. A further increase in the detuning ($\Delta f > 10$ MHz) leads to the regime of the second type, and additional components (Fig. 2b) associated with the presence of the subthreshold mode emerge in the intermode beat spectrum [11]. The beat spectrum is a set of equidistant frequencies, the interval between these frequencies being determined by frequency $f_{\rm mw}$:

$$\frac{f_{\rm mw}}{n} = f'_{\rm im} = \pm(212 - 230)\ \text{MHz}, \tag{2}$$

where $f'_{\rm im}$ is the new intermode frequency taking frequency pulling into account.

Figure 3 shows the dynamics of emergence of new beats for frequency detunings $\Delta f > 10$ MHz at frequencies $\sim kf_{\rm im}$ (where k is an odd number). These beats appear first as a broadband ($\Delta f_{\rm sig} \sim 2 - 0.5$ MHz) noisy signal, and a further increase in the detuning leads to a rapid decrease in the spectral width of the signal and an increase in its amplitude. Experiments show that the minimum spectral width of the signal $\Delta f_{\rm sig} \sim 3.5$ kHz is attained for a certain interval of optimal values of Δf (Fig. 4). The frequency detuning Δf varies in an interval of 0.9 MHz from the instant of emergence of beats until the attainment of the minimum spectral width. Upon a further increase in the frequency detuning, the amplitude of the signal at frequencies $kf_{\rm im}$ decreases at first, the signal width increases, and the beat signal vanishes again for $\Delta f > 20$ MHz (this is not shown in Fig. 3).

The dependence of the amplitude and width of the intermode beat spectra are shown in Fig. 4 for different reflectivities R of the external mirror (i.e., different coupling parameters T). One can see that the amplitude distributions and the regions with a minimum beat spectrum width almost coincide for $R = 50\,\%$ and $90\,\%$, while they are considerably shifted for $R = 10\,\%$. It should be noted, however, that as a whole, the position of curves in Fig. 4 weakly depends on the coupling parameter T.

We found that the second type of intermode beat spectra emerges in a certain interval of currents, starting from $I_{\rm min}$, for various reflection coefficients of the external mirror: for $R = 10\,\%$, $50\,\%$ and $90\,\%$, beats emerge for a current $I_{\rm min} = 48$ mA, ~57 mA and ~63 mA, respectively.

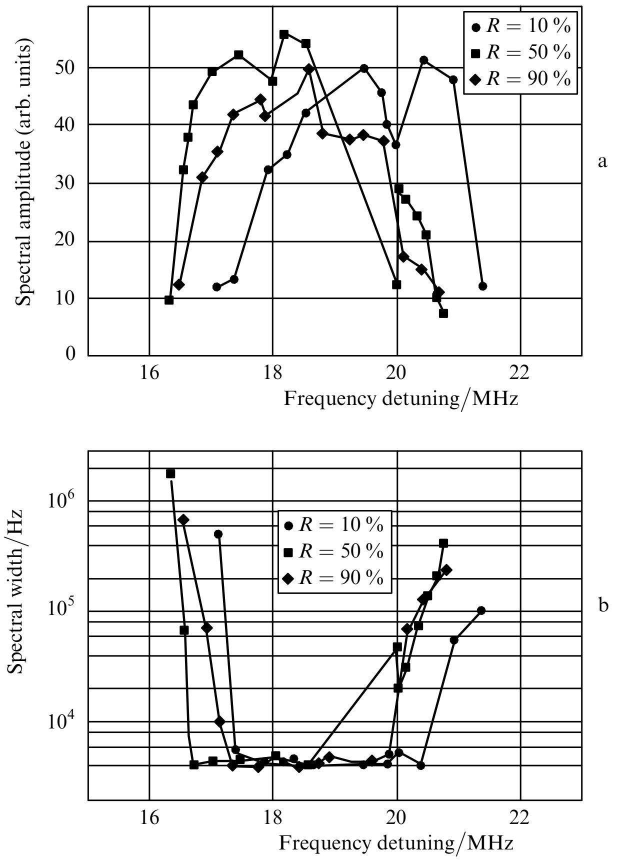

Figure 4. Dependence of the amplitude and width of the intermode beat spectrum on the detuning Δf of the microwave oscillator frequency $f_{\rm mw}$ from the intermode frequency $f_{\rm im}$ of the external cavity.

In our experiments, we studied the optical spectra of a mode-locked semiconductor laser for different reflectivities of the external mirror. Figure 5 shows the normalised spectra of the output radiation of a free-running semiconductor laser, as well as an actively mode-locked semiconductor laser for different reflectivities of the external

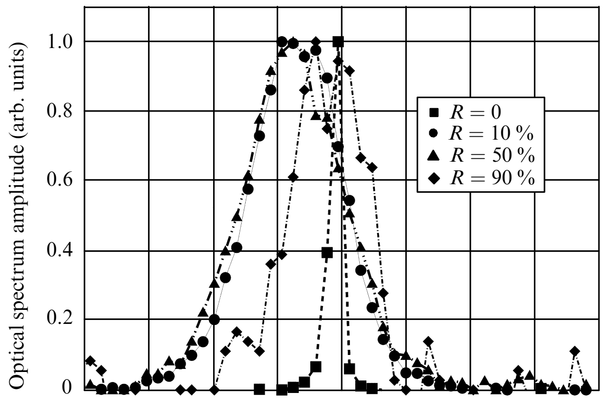

Figure 5. Normalised optical spectra of the output radiation of a semiconductor laser in free-running (■) and active mode-locking (●, ▲, ◆) regimes for different reflectivities of the external mirror.

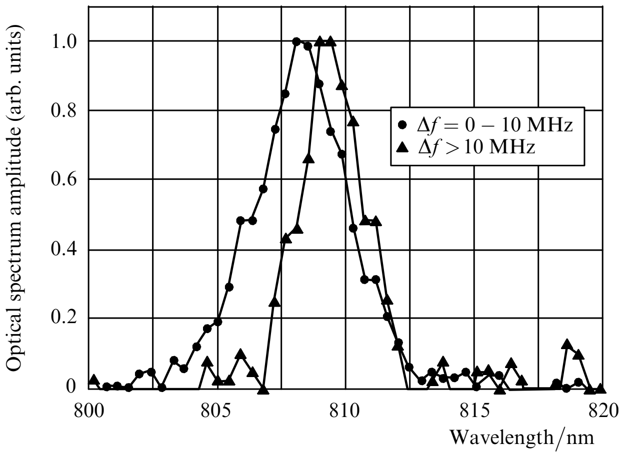

Figure 6. Normalised optical spectra of the output radiation of an actively mode-locked semiconductor laser for different detunings Δf of the microwave oscillator frequency f_{mw} from the intermode frequency f_{im} of the external cavity.

mirror. It was found that in the active mode-locking regime, the optical spectrum is broadened about 12-fold, i.e., from 0.5 to 6 nm. The maximum width of the spectrum was achieved (see Fig. 5) for external mirrors with reflectivities 50 % and 10 %.

We also studied the optical spectra of the output radiation for various detunings of the microwave pump oscillator frequencies from the intermode frequency of the external cavity (Fig. 6). The width of the optical spectrum of the semiconductor laser modes was ~6 nm for detunings $\Delta f = \pm(0 - 10)$ MHz and ~4 nm for $\Delta f > 10$ MHz.

3. Discussion of results

Unlike [11], an experimental method allowed us to observe two types of intermode beat spectra of a semiconductor laser pumped by microwave radiation at a frequency f_{mw}, which is almost a multiple of the intermode beat frequency f_{im} of the external cavity. For detunings $\Delta f = \pm(0 - 10)$ MHz, intermode beat components were observed, whose frequencies depended on f_{mw} and were approximately equal to $2nf_{\text{mw}}$ (where n is an integer). For $\Delta f > 10$ MHz, the spectrum consisted of intermode beat components with a frequency interval $f'_{\text{im}} \approx kf_{\text{im}}$ (where k is an integer). In this case, mode frequency pulling was observed and the frequency interval between intermode beats was not exactly equal to the intermode frequency of the external cavity, but was determined by the quantity f_{mw} for the first type of the spectrum or expression (2) for the second type of the spectrum. The dynamics of the excitation and narrowing of the subthreshold mode spectrum was reminiscent of that obtained in [11].

The evolution of the mode excitation process is shown in detail in Fig. 3. One can see that a slight variation in the microwave modulation frequency leads to a narrowing of the beat spectrum and an increase in its amplitude. This is probably due to an increase in the pump current for a detuning $\Delta f > 10$ MHz and a mutual phase modulation. A distinguishing feature of this process is the absence of an excitation threshold. The minimum spectral width of an individual component of the intermode beats (~3.5 kHz) was achieved in the interval of laser working currents $I = (0.8 - 1.2)I_{\text{th}}$ (pump parameter $r = -0.2 \div 0.2$). The maximum width of the optical mode spectrum, which amounts to ~6 nm (the central wavelength is ~810 nm) is attained for $\Delta f = \pm(0 - 10)$ MHz under the same operating conditions of a semiconductor laser; for $\Delta f > 10$ MHz, it decreases to 4.3 nm.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 04-02-17167).

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