Quantum Electronics **35** (9) 787 – 790 (2005)

LASERS

PACS numbers: 42.55.Px
DOI: 10.1070/QE2005v035n09ABEH009165

Spectral perturbations in a semiconductor laser: I. Anomalous splitting in the mode-beating spectrum

P.G. Eliseev, C. Liu, H. Cao, M. Osinski

***Abstract*. Mode-beating spectra and their current and temperature dependences are studied in a semiconductor laser. In the mode-beating spectrum of InGaAs quantum well lasers, the anomalous splitting of the difference-frequency line into three components f^0, f^+ and f^- is observed. The splitting increases with increasing optical power above the threshold. The component f^0 is less mobile and shifts to the red with increasing temperature. The component f^+ shifts to the blue, whereas the weak f^- component shifts to the red. The difference $f^+ - f^0$ amounts to 400 MHz, which is $\sim 5\,\%$ of the value of f^0 in a 5-mm long diode cavity. No anomalous splitting was observed in quantum dot lasers.**

Keywords: *semiconductor lasers, nonlinear mode interaction, mode-beating spectrum.*

1. Introduction

The mode-beating frequency in lasers is a sensitive parameter determined by the properties of an active medium and nonlinear processes proceeding in it in a strong electromagnetic field. The difference frequencies in the radio-frequency range can be measured quite accurately, which allows one to detect frequency pulling much simpler than in the optical range. Wave beats are used in the heterodyne detection and generation of ultrashort pulses by the mode-locking method. Beats between counter-propagating waves in gyroscopic sensors can be used to measure the rotation velocity with the navigation accuracy. In semiconductors lasers, this method is not often used because the difference frequencies f in standard (short) lasers lie in the terahertz range. One of the methods for generating electromagnetic waves in this range is based on the use of mode beating in a semiconductor laser.

The beating frequency in a semiconductor laser with an external cavity may lie in the radio-frequency range [1], which allows one to measure mode widths and to study related effects such as self-mode locking. The nonlinear interaction between modes [2] results in their self-stabilisation [3, 4], frequency pulling, and spectral splitting [5]. Recently the anomalous frequency splitting was observed in the beating spectrum of a monolithic ring semiconductor laser [6]. Such phenomena can affect the applications of lasers in systems sensitive to difference frequencies. For example, in gyroscopic applications it is necessary to exclude the frequency pulling for counterpropagating modes, otherwise a signal will be distorted due to the Sagnac effect.

In this paper, we studied the mode-beating spectrum in long laser diodes (with the cavity length $L = 5$ mm) with the frequency $f \sim 8$ GHz, which can be measured, as its $2f$ and $3f$ harmonics, with a microwave spectrum analyser. The anomalous splitting was observed in Fabry – Perot resonators. We obtained some additional data concerning the symmetrical component of the splitting. Mode pulling is analysed in paper [7] using the theory of their nonlinear interaction in semiconductor laser.

2. Experimental

We investigated InGaAs quantum well (QW) and InAs/InGaAs quantum dot (QD) laser diodes. The separate-confinement double InGaAs/GaAs/AlGaAs QW laser heterostructures ($\lambda = 1016$ nm) were grown by the MOS hydride method on a GaAs substrate. Similar QD structures (six DWELL InAs/InGaAs layers [8, 9], $\lambda \sim 1250$ nm) were grown by the method of molecular beam epitaxy. The diodes had the ridge stripe geometry (the stripe width was 3 μm) providing spatially single-mode lasing.

Thus, we studied the structures of two types: quantum wells and quantum dots. The optical characteristics of these structures were compared recently in paper [9]. The length of a Fabry – Perot resonator with end faces having a highly reflecting dielectric coating was 5 mm. The diodes were mounted in a thermally stabilised holder on the substrate side. The beating spectra were measured with a fast Newport 1417 photodetector, microwave amplifiers, and an HP 7000 spectrum analyser with the resolution better than 100 Hz in the range from 1 to 24 GHz. Optical measurements were also performed for lasers with identical structures but different cavity lengths. A Nicolet Magna-IR 760 Fourier spectrometer with the spectral resolution 0.0125 nm was used.

3. Results

Comparative results of measurements and calculations for lasers of the two types are presented in Table 1. Figure 1a

P.G. Eliseev P.N. Lebedev Physics Institute, Russian Academy of Sciences, Leninskii prosp. 53, 119991 Moscow, Russia;
e-mail: eliseev@chtm.unm.edu;
P.G. Eliseev, C. Liu, H. Cao, M. Osinski Center for High Technology Materials, University of New Mexico, Albuquerque, NM, USA

Received 2 June 2005
Kvantovaya Elektronika **35** (9) 787 – 790 (2005)
Translated by M.N. Sapozhnikov

presents the radio-frequency survey spectrum of a QW laser, which exhibits the lines at frequencies f, $2f$, and $3f$, where f is the fundamental beating frequency (between the adjacent longitudinal modes). The spectrum corresponds to multifrequency generation, whereas, according to the observation of the spatial distribution of radiation, only the fundamental axial mode is excited. All the data on the beating spectra are related to the beats between longitudinal modes v_q (q is the longitudinal mode index). The frequency f measured in the beating spectrum is the difference frequency

$$f = v_q - v_{q+1} = c/(2n^*L), \tag{1}$$

where $n^* = n + v\,dn/dv$ is the group refractive index. The phase refractive index n means here the refractive index of a mode obtained from the propagation constant of a wave in a multilayer waveguide structure.

Table 1. Parameters of QW and QD lasers.

Parameter	QW laser	QD laser
Threshold current/mA	105	50
Central wavelength/nm[1)]	1015	1259
Spectral width/nm[2)]	1.5	3
f/GHz (for $L = 5$ mm)	7.69	8.53
n^*	3.8–3.9	3.513
dn^*/dv/ Hz^{-1}	6.1×10^{-15}	$\sim 2 \times 10^{-16}$
Mode interval in the optical spectrum/nm	0.027	0.046
Number of modes[1)]	40	200–250
Minimal width of the beating line/MHz	10	0.33
df^+/dI/MHz mA^{-1}	2.95	line is absent
df^0/dI/MHz mA^{-1}	−0.0555	−0.075
df^-/dI/MHz mA^{-1}	−2.9	line is absent

[1)] For the twofold excess over the threshold current; [2)] the formal width of the envelope of a multifrequency spectrum.

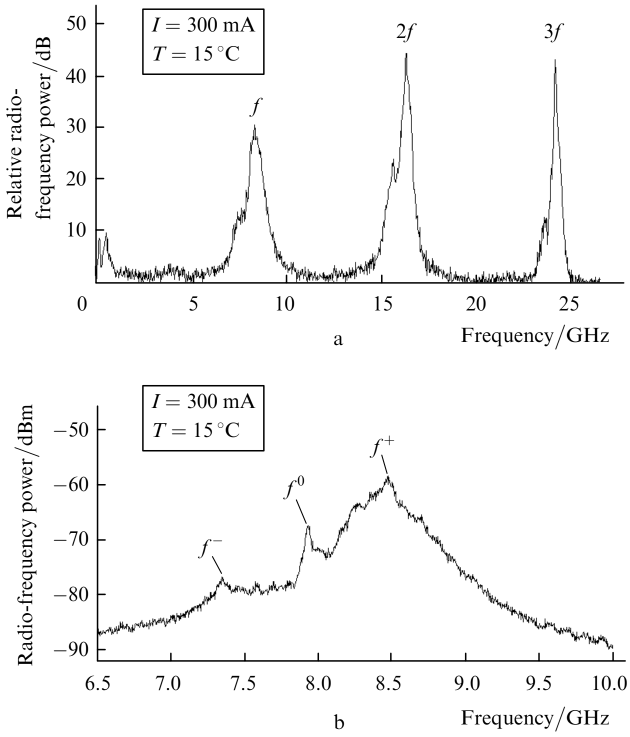

Figure 1. Mode-beating spectra of the QW laser: the survey spectrum (a) and the f band (b) (the cavity length is 5 mm). The three splitting components are observed (b).

Figure 1b shows the structure of the f band containing at least three components. These components were observed in some current range approximately up to the threefold excess over the threshold.

Splitting of the fundamental f band. Figure 2 shows the dependence of the positions of the components of the 8-GHz f band on current. The central f^0 component is most stable, shifting weakly to the red. The f^+ and f^- lines shift stronger and almost symmetrically with respect to the central line. The f^- line is rather weak, its intensity being smaller by 10–15 dB than that of the f^+ line. In the interval from the threshold current approximately up to 300 mA, these lines shift almost linearly with current; however, the linearity is violated at high currents. Therefore, this experiment confirms the appearance of the f^+ splitting component, as in a ring laser [6], and also demonstrates the appearance of the almost symmetrical f^- line. For a moderate excess of the threshold, the f^+ and f^- lines shift proportionally to the optical power. In particular, the position of the f^+ line can be written in the form

$$f^+ = f^0 + \delta f_1(P), \tag{2}$$

where $\delta f_1(P)$ is the addition to the frequency proportional to the radiation power P. The experimental frequencies and shift coefficients are presented in Table 1. The $2f$ and $3f$ bands exhibit the following properties:

(i) The f^0 lines are rather accurate multiples of the frequency f^0, namely, $f_2^0 = 2f^0$ и $f_3^0 = 3f^0$. These lines exhibit the corresponding (double or triple) red shift with increasing current and temperature.

(ii) Sometimes the f_2^0 and f_3^0 lines reveal the fine structure consisting of narrower lines of width of the order of 200 kHz.

(iii) The f^+ lines with frequencies that are not multiples of f^+ are present (which exhibit the blue shift). The frequencies of these lines f_2^+ and f_3^+ are

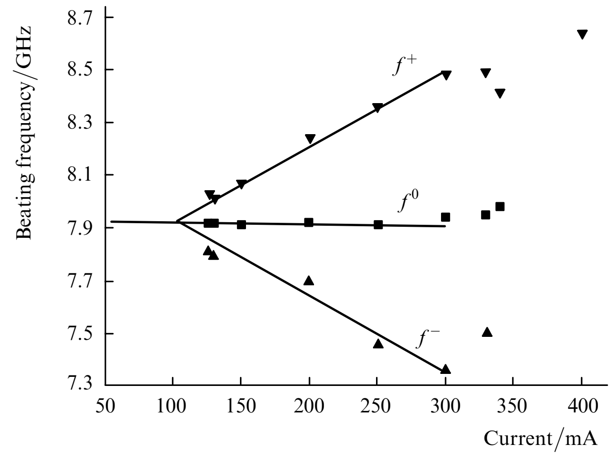

Figure 2. Positions of the beating lines in the f band as functions of current in the QW laser ($L = 5$ mm, $T = 15°$ C).

$$f_2^+ = 2f^0 + \delta f_2(P), \quad f_3^+ = 3f^0 + \delta f_3(P), \tag{3}$$

where $\delta f_2(P)$ and $\delta f_3(P)$ are the positive additions depending on the optical power P. These additions are somewhat smaller than $\delta f_1(P)$.

No splitting of this type was observed in 1.25-μm QD lasers. The optical spectrum above the threshold exhibits many (100–300) longitudinal modes, and the beating spectrum contains the f^0 line experiencing a weak red shift. Note that although the f^0 line contains contributions of many mode pairs, its width is much smaller than in a QW laser. Figure 3 shows the beating line in a QD laser approximated by a Lorentzian. The full-width at half maximum of this line is ~ 330 kHz.

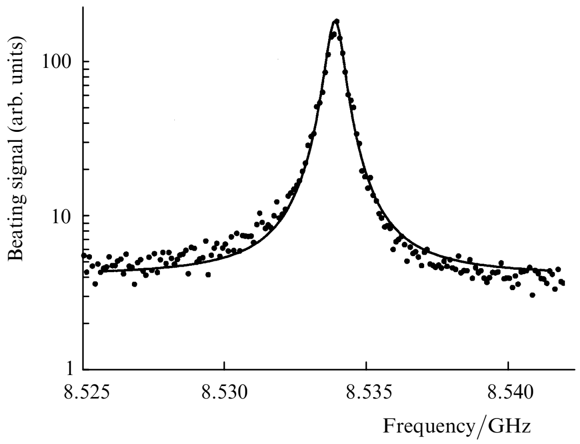

Figure 3. Beating spectrum of the QD laser approximated by a Lorentzian with the FWHM 330 kHz ($L = 5$ mm, $T = 15\,^\circ$ C, $I = 150$ mA).

4. Discussion

Difference between the QW and QD structures. The behaviour of lasers based on the structures of these two types is substantially different (see Table 1). The beating frequency of the adjacent longitudinal modes in a QD laser is noticeably higher, which corresponds to a lower group refractive index. The emission wavelength of the QD laser is located at a greater distance from the absorption edge of materials forming the waveguide. This results in a decrease in the effective refractive index and its dispersion. Due to a lower dispersion, the nonequidistance of longitudinal modes equal to

$$\frac{\mathrm{d}f}{\mathrm{d}q} = -\frac{f^2}{n^*}\frac{\mathrm{d}n^*}{\mathrm{d}\nu} = -\frac{f^2}{n^*}\left(2\frac{\mathrm{d}n}{\mathrm{d}\nu} + \nu\frac{\mathrm{d}^2 n}{\mathrm{d}\nu^2}\right) \tag{4}$$

is much smaller in the QD laser. Therefore, the total width of the f^0 line determined by the summation of the beating signal from many mode pairs is a few times smaller in the QD laser, although a total number of mode pairs in it is larger.

The beating band in the QW laser is split into three components, whereas no splitting is observed in the QD laser. The splitting increases with current approximately proportional to the radiation power.

Temperature effect. Consider the expected effect related to the temperature dependence and dispersion of the refractive index. Because the refractive index n (and n^*) at a fixed frequency increases with temperature, the optical frequency and mode interval decrease in this case (if the central optical frequency remains fixed).

However, on the other hand, there exist the dispersion of the refractive index and the temperature shift of the operating point. The results of optical measurements of the dispersion of n^* in structures of both types are presented in Table 1. For the QW laser,

$$\frac{\mathrm{d}n^*}{\mathrm{d}\nu} = 2\frac{\mathrm{d}n}{\mathrm{d}\nu} + \nu\frac{\mathrm{d}^2 n}{\mathrm{d}\nu^2} \approx 6.1 \times 10^{-15}\ \text{Гц}^{-1}, \tag{5}$$

which corresponds to the increase in the mode interval with decreasing the optical oscillation frequency. The calculation of $\mathrm{d}n^*/\mathrm{d}\nu$ in the QD laser from optical measurements is complicated, first, because of a small nonequidistance of modes and, second, because perturbations caused by the coupling with the substrate modes (see [10]) are comparable with the dispersion effect. Therefore, the error in this case is rather large, of the order of 20 %. The temperature variation of the beating frequency f has the form

$$\frac{1}{f}\frac{\mathrm{d}f}{\mathrm{d}T} = -\alpha_T - \frac{1}{n^*}\frac{\mathrm{d}n^*}{\mathrm{d}T}, \tag{6}$$

where

$$\frac{\mathrm{d}n^*}{\mathrm{d}T} = \frac{\partial n^*}{\partial T} + \frac{\mathrm{d}n^*}{\mathrm{d}\nu}\frac{\mathrm{d}\nu}{\mathrm{d}T} + \frac{\mathrm{d}n^*}{\mathrm{d}N}\frac{\mathrm{d}N}{\mathrm{d}T} + \frac{\mathrm{d}n^*}{\mathrm{d}P}\frac{\mathrm{d}P}{\mathrm{d}T}; \tag{7}$$

α_T is the thermal expansion coefficient (TEC); and N is the carrier concentration. It is taken into account that the parameters N and P change implicitly with temperature, which can affect the value of n^*. The measured values of $\mathrm{d}n^*/\mathrm{d}T$ are presented in Table 2.

Table 2. Temperature effects.

Parameter	QW	QD
$\mathrm{d}n^*/\mathrm{d}\nu/$ Hz^{-1}	6.1×10^{-15}	$\sim 2 \times 10^{-15}$
$\mathrm{d}\nu/\mathrm{d}T/$GHz K^{-1} (over the energy gap)	-104.2	-70.6
Expected dispersion shift $\mathrm{d}f/\mathrm{d}T/$MHz K^{-1}	5	1.2
$\mathrm{d}f^0/\mathrm{d}T/$MHz K^{-1} (experimental value)	-2.5	-6.5
$\mathrm{d}n^*/\mathrm{d}T/$ K^{-1} (experimental value)	1.18×10^{-3}	2.66×10^{-3}
$\alpha_T/$K^{-1} (TEC, GaAs substrate)	5.7×10^{-6}	5.7×10^{-6}

The red shift of the central frequency of the laser spectrum due to the temperature dependence of the energy gap leads to a decrease in n^* and the blue shift of the beating frequency. In the general case, the result will correspond to the competition of the red shift due to the temperature dependence of n^* (at a fixed frequency) and the blue shift caused by the dispersion and shift of optical frequencies. Note that the blue shift of the repetition frequency during mode locking in a semiconductor laser was observed in [11] and was explained by the influence of dispersion. This frequency corresponds to the intermode beats of the group of longitudinal modes in the phase-locking state.

Note that some mutual compensation of temperature effects affecting f reflects the fact that, as temperature changes, the spectral operating point of the laser tends to preserve its position on the dispersion curve $n(\nu)$, which also is displaced with temperature. However, this rule is not strict due to different displacements of oscillators determining $n(\nu)$ and the action of carriers on n.

On the reasons for splitting. By comparing the behaviour of splitting components, we see that the most stable f^0 line shifts not to the blue but to the red with increasing temperature and current (which obviously heats somewhat the active region). We explain this by the fact that the f^0 line is formed due to summation of beats of many mode pairs because the optical spectrum contains several tens of weak longitudinal modes. Therefore, the position of the f^0 line is determined by averaging over a large ensemble. Because this concerns only weak modes, the effect of the optical power is unimportant. The temperature shifts of different components may have different signs, resulting in a weak red shift of the f^0 line. The value of $\mathrm{d}n^*/\mathrm{d}T$ obtained from these temperature measurements (Table 2) corresponds to the combined effect. The red shift of the f^0 line with increasing current suggests that the temperature effect dominates over the dispersion effect. The presence of the structure of the f^0 line is confirmed by the fact that its higher harmonics $2f^0$ and $3f^0$ reveal sometimes the 'fine structure' containing several closely spaced components (separated by ~ 200 kHz).

The f^+ line shifts with current in the opposite direction. It seems that this shift cannot be explained by the dispersion effect. First, the experimental shift is greater than that calculated above and, second, one can see that the extrapolated positions of the f^+ and f^0 lines intersect at the point corresponding to the lasing threshold. This suggests that the blue shift of the f^+ line is related to the optical power rather than to temperature.

The red shift of the f^- line, which is much greater than that of the f^0 line, is obviously also determined by the optical power. We assume that each of the lines f^+ and f^- is produced by one mode pair, one of which is more intense ('strong' mode); therefore, these pairs consist of a strong mode and its weak neighbours on both sides. It is known that the nonlinear interaction of modes, which was first considered in [2], has the spectral asymmetry, which is manifested in the suppression of the high-frequency mode and the enhancement of the low-frequency mode. Because the f^+ line is stronger by 10 – 15 dB than the f^- line, we can assume that a pair of modes giving rise to the f^+ line is located on the low-frequency side of the strong mode. Therefore, it seems that the pulling of neighbouring modes occurs because the weak low-frequency mode repels from the strong mode, while the even weaker high-frequency mode is attracted to the strong mode. As for the QD laser, the absence of the f^+ and f^- lines in it can be explained by the fact that this laser does not contain sufficiently 'strong' modes and has many modes. These lasers are characterised by a small dispersion of the refractive index and a low index of amplitude-phase coupling [8, 9, 12].

5. Conclusions

We have shown that the behaviour of mode beatings in QW and QD lasers with the one-dimensional transverse structure of the field is different. The beating spectrum in QW lasers is split into components separated by a distance which increases with increasing optical power. The split lines are apparently produced by different mode sets: the f^0 line (weak red shift) corresponds to many pairs of low-intensity modes, while the f^+ line corresponds to a pair of modes, of which one is stronger than the other. The shift of modes in this pair depends on the optical power. The $f^+ - f^-$ splitting does not exceed 600 MHz. The splitting in the beating spectrum is 5 % – 8 %. The main parameters of frequency pulling have been determined. Theoretical analysis is performed in paper [7].

Acknowledgements. This work was supported by NASA (Grant NAG5-10372). The authors thank Dr. G.M. Pick and Prof. K. Malloy for their help in the study. P.G.E. acknowledges the support of the Leading Scientific Schools Program of the Russian Federation.

References

1. Bahert H., Bogatov A.P., Gurov Yu.V., Eliseev P.G., Okhotnikov O.G., Pak G.T., Rakhval'skii M.P., Khairetdinov K.A. *Kvantovaya Elektron.*, **8**, 1957 (1981) [*Sov. J. Quantum Electron.*, **11**, 1184 (1981)].
2. Bogatov A.P., Eliseev P.G., Sverdlov B.N. *Kvantovaya Elektron.*, **1**, 2286 (1974) [*Sov. J. Quantum Electron.*, **4**, 1275 (1974)].
3. Bogatov A.P., Eliseev P.G., Okhotnikov O.G., Rakhval'skii M.P., Khairetdinov K.A. *Kvantovaya Elektron.*, **10**, 1851 (1983) [*Sov. J. Quantum Electron.*, **13**, 1221 (1983)].
4. Bogatov A.P., Eliseev P.G., Okhotnikov O.G., Rakhval'skii M.P., Khairetdinov K.A. *Trudy FIAN.*, **166**, 52 (1986).
5. Bogatov A.P., Eliseev P.G., Kobiljanov O.A., Madgazin V.R. *IEEE J. Quantum. Electron.*, **23** (6), 1064 (1987).
6. Liu C., Cao H., Eliseev P.G., Osinski M. *Electron. Lett.* (in press).
7. Eliseev P.G. *Kvantovaya Elektron.*, **35**, 791 (2005) [*Quantum Electron.*, 35, 791 (2005)].
8. Liu G.T., Stintz A., Li H., Malloy K.J., Lester L.F. *Electron. Lett.*, **35**, 1163 (1999).
9. Ukhanov A.A., Stintz A., Eliseev P.G., Malloy K.J. *Appl. Phys. Lett.*, **84** (7), 1058 (2004).
10. Eliseev P.G., Drakin A.E. *Laser Phys.*, **4** (3), 485 (1994).
11. Sato K. *IEEE J. Sel. Top. Quantum Electron.*, **9** (5), 1288 (2003).
12. Eliseev P.G., Li H., Liu G.T., Stintz A., Newell T.C., Lester L.F., Malloy K.J. *IEEE J. Sel. Top. Quantum Electron.*, **7** (2), 135 (2001).