Current induced mode competition in microdisk lasers

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Abstract. A phenomenon of mode competition in microdisk lasers under various injection currents was studied. The increase of the injection current causes rise of the internal temperature. The modeling has shown that this increase leads to the shift of the gain spectrum. That may be enough to cause drastic redistribution of emitted power between microdisk modes. This effect has been studied in the experiment and by the numerical simulation.

Keywords: microdisk lasers, thermal mode shift, mode competition.

1. Introduction

The light has several advantages over electricity in data transmission thus today long-range communications are using light exclusively. Short-range (such as chip-to-chip) transmission is still being worked on, as it requires compact and energy efficient photonic devices with high response rate and in-plane signal extraction. Semiconductor lasers with microdisk resonators are a promising solution to this problem and its high Q-factor together with small effective mode volume allow for low threshold current [1].

It is well known that as temperature increased, energies of modes decreased nearly linearly. For example, lasing mode spectral shift under ambient temperature variation was observed [2]. However, our experiment has demonstrated similar behavior with constant external temperature, but variable injection current. Moreover, the emitting power transfer between neighboring laser modes was observed.

Many practical applications such as wavelength-division multiplexing (WDM) [3] require power stability of radiated light into each mode. Thus, observed mode switching is undesirable and so we aim to investigate the underlying physics of that phenomenon.

The general idea of the paper is schematically illustrated in the Figure 1. We discuss two modes that are close to each other in spectral domain. Due to thermal shift of the material gain spectrum, the maximum modal gain that can be achieved for each mode is also varying. In fact, at different temperatures of the active area of the laser the material gain spectrum can be favourable for lasing at different modes. Since the modes 'compete' for the same carriers in the

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active area the favorable conditions for one mode may results that another mode would cease completely. When we consider laser heating with the increase of the injection current the close picture of mode competition can be obtained. Below we provide theoretical modeling relevant for this scheme and compare numerical results with the experiment.

2. Theory

2.1. General rate equations

In our experiment laser's active area contains multiple QWDs layers (see [4] and references wherein). Due to inhomogeneous broadening QDs have different sizes (and thus, optical transition energies). Transition energy distribution can be approximated by a Gauss function [5]:

$$\rho(E) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right). \tag{1}$$

Here E_0 is an energy of the transition with the highest probability. Each QD with transition energy E creates a Lorentzian gain profile around E [5]:

$$F(\delta E) = \frac{1}{1 + (\delta E/\Gamma)^2}, \tag{2}$$

where Γ is a homogeneous broadening parameter.
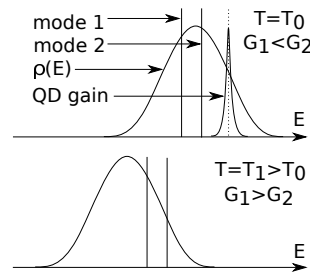

Figure 1. Gain spectra and laser modes shift under temperature variation. $G_{1,2}$ are modal gains of modes 1 and 2.

The theory of charge carrier statistics in QWD structures are not well developed up to now and detailed discussion of QWD filling factor $f(E)$ could be complicated. Hence, we will assume that all QDs are filled equally and that concentrations of electrons and holes are equal. This way $f(E) = \langle f \rangle$ and the carrier dynamics boils down to the one parameter - captured electron concentration n:

$$n = n_{QD}\langle f \rangle/d, \tag{3}$$

where n_{QD} is surface density of QDs over all layers and d is effective active area thickness. In this case phenomenological approach [6] to laser dynamics can be used:

$$\frac{dn}{dt} = \frac{\eta J}{ed} - \frac{n}{\tau} - V_A^{-1}(G_1 S_1 + G_2 S_2). \tag{4}$$

where η — injection efficiency, that also considers effective surface of the microdisk mode, J — injection current density, d — active area effective thickness, V_A — the volume of active area, τ — electron lifetime, G_k — gain of mode k (measured in s^{-1}) and S_k is the number of photons in mode k.

If we denote rate of spontaneous emission into the mode k as $R_{sp,k}$ then rate equations for modes photon number can be written as [5]:

$$
\begin{cases}
\dfrac{dS_k}{dt} = \Big(G_k - \alpha(E_k)\Big)S_k + R_{sp,k} \\[2ex]
G_k = G_{max}\dfrac{\sigma}{\Gamma}\sqrt{\dfrac{2}{\pi}}\int dE\rho(E)F(E-E_k)\Big(2f(E)-1\Big) \\[2ex]
R_{sp,k} = G_{max}\dfrac{\sigma}{\Gamma}\sqrt{\dfrac{2}{\pi}}\int dE\rho(E)F(E-E_k)f(E).
\end{cases}
\tag{5}
$$

where α — internal and extraction losses, and G_{max} — gain spectra peak, which is usually known from experimental data. We have no means of evaluating α since numerous technological factors have an impact on it. Let us assume that losses α_k are equal for all modes and its values will be taken from similar experimental setups [4].

Typically, $\sigma \approx 20$ meV and $\Gamma \approx 5$ meV at $T = 300$ K in the structures studied. Using that values, and following $f(E) = \langle f \rangle$ approximation one can simplify integrals in (5) via Taylor expansion by Γ/σ and discarding terms of higher order of magnitude than linear.

$$
\int dE\rho(E)F(E-E_k) \approx \pi\Gamma\rho(E_k) = \sqrt{\frac{\pi}{2}}\frac{\Gamma}{\sigma}\exp\left(-\frac{1}{2}\left[\frac{E_k-E_0}{\sigma}\right]^2\right).
\tag{6}
$$

2.2. Shift of laser modes and gain spectrum

The experiment has shown that for both modes wavenumber reduces linearly as the injection current increases (see Figure 2). Thus mode energy reduces linearly as well — $E_k(J) = \chi(J - J_k) + E_k(J_k)$.
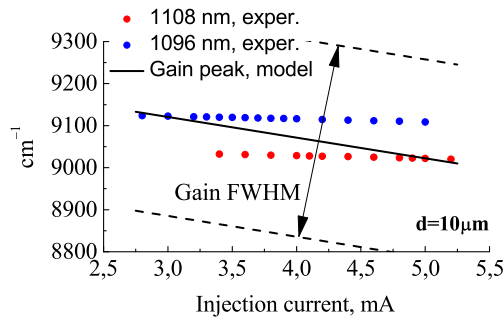

Figure 2. The wavenumber ($1/\lambda$, cm^{-1}) of laser modes at different injection current (dots). Position of gain maximum and FWHM limits of gain spectra are also shown by solid and dashed lines respectively.

Similar shift was observed in [2], but ambient temperature was varied instead. Also it was concluded that the gain spectra shifts with temperature as well due to band gap variation. This way, we introduce $E_0(T)$ and $E_k(T)$ functions and together with (5) and (6) we can write down for G_k and $R_{sp,k}$ following expressions:

$$
G_k(T) = G_{max}\left(2\frac{n}{n_{QD}/d}-1\right)\exp\left(-\frac{1}{2}\left[\frac{E_k(T)-E_0(T)}{\sigma}\right]^2\right)
\tag{7}
$$

$$
R_{sp,k}(T) = G_{max}\frac{n}{n_{QD}/d}\exp\left(-\frac{1}{2}\left[\frac{E_k(T)-E_0(T)}{\sigma}\right]^2\right).
\tag{8}
$$

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The experiment in [2] has shown that the temperature dependency of wavelength λ_k can be approximated by a linear function $\lambda_k(T) = \gamma(T - T_0) + \lambda_k(T_0)$. Here $(T_0; \lambda_k(T_0))$ is a point in the experimental data and $\gamma \approx 0.07$ nm/K. Also it was estimated that the wavelength of a gain peak λ_0 changes linearly $\lambda_0(T) = \gamma_0(T - T_0) + \lambda_0(T_0)$ and $\gamma_0 \approx 0.4$ nm/K. All these changes are small relative to a common wavelength $\lambda \approx 1080$ nm, so corresponding energies E_0 and E_k change linearly with coefficients $-(hc/\lambda^2)\gamma_0$ and $-(hc/\lambda^2)\gamma$ respectively. This way, we can write estimates for $E_0(T)$ and $E_k(T)$

$$E_0(T) = -\frac{hc}{\lambda^2}\gamma_0(T - T_0) + E_0(T_0) \tag{9}$$

$$E_k(T) = -\frac{hc}{\lambda^2}\gamma(T - T_0) + E_k(T_0) \tag{10}$$

Since E_k reduces linearly as T and J increase, one can conclude that T increases linearly as J increases.

$$T(J) = -\frac{\chi\lambda^2}{hc\gamma}(J - J_0) + T_0 \tag{11}$$

Most likely, it happens via Joule heating in the laser that is linear with the current that is accompanied with non-radiative recombination in the active area. The value T_0 is found via (10) and measured $E_k(J_0)$ as J_0 corresponds to T_0.

2.3. Calculation results

Overall, in order to find the laser state under given injection current, the following system of nonlinear equations should be solved:

$$\begin{cases} \dfrac{\eta J}{ed} - \dfrac{n}{\tau} - V_A^{-1}(G_1 S_1 + G_2 S_2) = 0 \\[2mm] (G_k - \alpha) S_k + R_{sp,k} = 0 \\[2mm] G_k = G_{max}\left(2\dfrac{n}{n_{QD}/d} - 1\right)\exp\left(-\dfrac{1}{2}\left[\dfrac{E_k(T) - E_0(T)}{\sigma}\right]^2\right) \\[3mm] R_{sp,k} = G_{max}\dfrac{n}{n_{QD}/d}\exp\left(-\dfrac{1}{2}\left[\dfrac{E_k(T) - E_0(T)}{\sigma}\right]^2\right) \\[3mm] E_0(T) = -\dfrac{hc}{\lambda^2}\gamma_0(T - T_0) + E_0(T_0) \\[2mm] E_k(T) = -\dfrac{hc}{\lambda^2}\gamma(T - T_0) + E_k(T_0) \\[2mm] T(J) = -\dfrac{\chi\lambda^2}{hc\gamma}(J - J_0) + T_0 \end{cases} \tag{12}$$

At Fig.3 experimental data are shown for 10 μm diameter microdisk with electrical injection [4]. The active region is of conventional type with 5 layers of QWD emitting near 1.1 μm. At the figure the mode's power are shown as a dependence on an injection current density. Spectral analyses (not shown here) let us conclude that these are two adjacent modes with spectral spacing of 12 nm. The experiment was carried out at the room temperature.

Since we are interested in the relation between S_1 and S_2 but not their absolute values, the accuracy of d and G_{max} does not matter much. On the other hand, that is not the case for γ_0, γ, τ, α and especially $E_0(T_0)$ as they are directly related to the currents for onset and cease of the lasing. The accuracy of $E_0(T_0)$ should be of order of 1 meV.

Table 1. Parameter values in the numerical solution of the system

Parameter	Value	Source
η	$5 \cdot 10^{-2}$	threshold current and microdisk geometry
τ	0.25 ns	threshold current
d	50 nm	typical thickness of 5 QWD layers
n_{QD}	$5 \cdot 10^{11}$ cm^{-2}	QWD surface density 10^{11} cm^{-2}
γ_0/γ	5.3	[2]
J_0	4000 A/cm^2	experiment
$E_0(J_0)$	1129.3 meV	model adjustment
σ	25 meV	[5]
G_{max}	510 ns^{-1}	[7]
α	45 ns^{-1}	FWHM of linewidth in [4]

Despite the simplicity, the model, described above, managed to closely capture the experimentally observed effect. The switching between modes are well seen at the current density around 5300 A/cm^2. That corresponds to injection current value 4.15 mA where according to Fig. 2 peak of the gain spectrum becoming closer to the mode with higher wavelength. This shows that an injection current may indeed cause a microdisk temperature to increase and change the lasing wavelength through the modes competition.
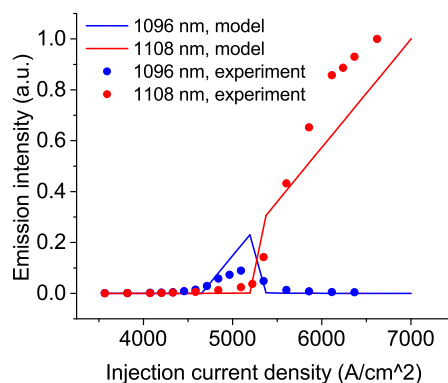
Figure 3. Dependence of emitting power via two laser modes on the injection current density: theory (dots) and experiment (lines).

3. Conclusion

We have proposed the cause of the observed current induced mode competition. Injection current increase leads the microdisk temperature to rise, that, in turn, causes laser modes and gain spectra to shift. As a result, we observe the behavior similar to one in [2]. However, in this work we have relied on the experimental data and provide rough estimates of microdisk internal parameters, which are fairly specific and are tied to a particular design.

As a conclusion, we can state that temperature shift alone, without other supporting effects, may cause switching between modes in microdisks and should be taken into account in relevant multimode models of the laser with electrical injection.

Acknowledgement

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