Injection current minimization of InAs/InGaAs quantum dot laser by optimization of its active region and reflectivity of laser cavity edges

V V Korenev$^{1,3}$, A V Savelyev$^{1,3}$, A E Zhukov$^{1,2,3}$, M V Maximov$^{2,1}$
$^1$Saint–Petersburg Academic University RAS, Saint–Petersburg 194021, Russia
$^2$Ioffe Physico–Technical Institute RAS, Saint–Petersburg 194021, Russia
$^3$Peter the Great St. Petersburg Polytechnic University, St. Petersburg 195251, Russia
E-mail: korenev@spbau.ru

Abstract. The ways to optimize key parameters of active region and edge reflectivity of edge-emitting semiconductor quantum dot laser are provided. It is shown that in the case of optimal cavity length and sufficiently large dispersion lasing spectrum of a given width can be obtained at injection current up to an order of magnitude lower in comparison to non-optimized sample. The influence of internal loss and edge reflection is also studied in details.

1. Introduction

Compact lasers emitting in broad wavelength range near 1.3 μm are needed for the wide range of practically important applications, from medicine to high-speed data transfer [1 – 3]. The usage of InAs/InGaAs quantum dots (QDs) having long-wavelength emission spectra allows not only to cover the required wavelength range, but also to simplify the production process and decrease costs in comparison to the distributed-feedback (DFB) lasers [4 – 5]. Therefore, the task of injection current minimization of such QD lasers at a given lasing spectrum width tends to play prominent role. In this paper we show how to tackle this issue using the active region having optimized structure and size as well as reflection coefficients of its edges.

2. The ways to optimize laser active region and reflection of the edges

In the case of MBE-grown InAs/InGaAs QD laser there is a series of parameters, which can be varied even during the growth process. These parameters are QD layers number in laser active region ($Z$), dispersion of inhomogeneous broadening ($\sigma$) and laser cavity length ($L$). Moreover, the reflectivity of laser cavity edges, which can be also varied by using coatings of different types, may also affect characteristics of such lasers. Thus, the key goal of current paper is to figure out at which parameters it is possible to obtain lasing spectrum of a given width ($\Omega$) at minimum injection current.

To study the influence of laser cavity length ($L$) on the injection current ($I_{inj}$), we have calculated the dependence of $I_{inj}$ on $L$ for different numbers of QD layers in laser active region ($Z$) at a given dispersion ($\sigma$) and lasing spectrum width ($\Omega$) – see Fig. 1, where $\sigma = 20.5$ meV and $\Omega = 18$ meV, while the other parameters are in accord with [4, 6 – 9]. As it can be seen from the figure there is always an optimal laser cavity length allowing one to attain lasing spectrum of a given width at minimum injection current given $\sigma$ and $Z$. This is because of high injection current in the case of sufficiently short or long cavity. Indeed, as laser cavity length is too small, output loss tends to increase resulting in the increase of injection current required to attain given $\Omega$. In the case of long...
In laser active regions. Fractional Z, e.g. Z= 1.5, means integer layers number, but adjusted QD density in laser active region.

![Graph](image)

**Figure 1.** The dependence of the injection current ($I_{inj}$) on laser cavity length ($L$) for different values of QD layers number in laser cavity ($Z$) varying from 1.5 to 9. Dashed line corresponds to the optimal injection currents ($I_{L_{opt}}$) at optimal length ($L_{opt}$) for different $Z$. Here $\Omega= 18$ meV and $\sigma= 20.5$ meV.

As it can be seen from the figure the larger is $Z$, the smaller is injection current and corresponding cavity length. This is due to the increase in maximum gain ($G_{max}$), which is directly proportional to $Z$, that allows to obtain lasing spectrum of the same width $\Omega$ at lower injection current and even higher output loss, i.e. at shorter laser cavities.

In order to elucidate how the variation of inhomogeneous broadening may influence injection current, which is already optimized by laser cavity length ($I_{L_{opt}}$), we have calculated the dependence of $I_{L_{opt}}$ on the value of dispersion ($\sigma$) of inhomogeneous broadening varying from 10 meV to 35 meV for the different values of $Z$. Dashed line corresponds to the minimum of $I_{L_{opt}}$ at different values of $Z$.

![Graph](image)

**Figure 2(a, b). (a)** The dependence of injection current ($I_{L_{opt}}$), which is optimized by laser cavity length ($L$), on the value of dispersion ($\sigma$) of inhomogeneous broadening varying from 10 meV to 35 meV for the different values of $Z$. Dashed line corresponds to the minimum of $I_{L_{opt}}$ at different values of $Z$. **(b)** The dependence of optimal length $L_{opt}$ corresponding to the minimum of $I_{L_{opt}}$ on dispersion for different numbers of QD layers in laser active region ($Z$). In both cases $\Omega= 18$ meV.
The rate equation model used to model dynamics of charge carriers in QDs as well as values of the other parameters is chosen to be in accord with [6 – 9]. As it can be seen from the figure 2a (e.g., see curve $Z = 1$), there is always an optimal value of dispersion ($\sigma$) minimizing $I_{\text{L, opt}}$ for lasing spectrum of a given width. Indeed, if dispersion is sufficiently small, lasing spectrum is narrow and, therefore, the injection current ($I_{\text{inj}}$), as well as optimal injection current ($I_{\text{L, opt}}$), should both increase in order to maintain lasing spectrum of a given width $\Omega$. At large dispersions maximum gain ($G_{\text{max}}$) turns out to be sufficiently small and can be even lower than the total loss ($\alpha$) at certain dispersion due to its reciprocal proportionality to the value of dispersion ($G_{\text{max}} \sim 1/\sigma$). This results in higher values of $I_{\text{L, opt}}$, which is needed to attain given $\Omega$, as $\sigma$ increases. Therefore, there is always an optimal value of dispersion ($\sigma_{\text{opt}}$) that allows one to attain lasing spectrum of a given width at minimum injection current ($I_{\text{L, opt}}(\sigma_{\text{opt}})$ – see figure 2a, e.g. curve $Z = 1$). Furthermore, as it is shown in the figure 2b, such an optimal value of injection current ($I_{\text{L, opt}}(\sigma_{\text{opt}})$) corresponds to the attainable cavity length that does not exceed 1.5 cm.

As it can be seen from the comparison of figure 1 and figure 2a, optimization of dispersion plays the key role, while optimization of laser cavity length is only fine tuning of injection current value corresponding to the lasing spectrum of a given width. Indeed, the usage of optimal cavity length allows one to decrease injection current by 30% from 30 mA for $L = 0.5$ cm to 20 mA for $L = 0.1$ cm – see figure 1 for $Z = 9$. At the same time, the increase of dispersion ($\sigma$) from 15 to 25 meV results in the decrease of injection current from 35 to 18 mA, i.e. practically by 48%.

In order to elucidate if there is an optimal number of QD layers ($Z$) in laser active region, which allows one to decrease $I_{\text{L, opt}}(\sigma_{\text{opt}})$ further at the same width of lasing spectrum ($\Omega$), we studied the dependence of $I_{\text{L, opt}}(\sigma_{\text{opt}})$ on $Z$ in the case of different internal ($\alpha_{\text{in}}$) and external ($\alpha_{\text{out}}$) loss in laser cavity. The output loss was changed by the variation of reflectivity of laser cavity edges that, in its turn, can be achieved by the usage of different coatings – see figure 3(a, b).

**Figure 3(a, b).** (a) The dependence of the injection current ($I_{\text{L, opt}}(\sigma_{\text{opt}})$), which is optimized by laser cavity length and dispersion, on the number of QD layers in the laser cavity ($Z$) for different values of internal loss ($\alpha_{\text{in}}$) and fixed output loss $\alpha_{\text{out}} = 6.6$ cm$^{-1}$. (b) The dependence of $I_{\text{L, opt}}(\sigma_{\text{opt}})$ on the number of QD layers in the laser cavity ($Z$) for different values of external loss ($\alpha_{\text{out}}$), which is varied by the selection of different coatings to change reflectivity of cavity edges, and at fixed internal loss $\alpha_{\text{in}} = 2.5$ cm$^{-1}$. The number of QD layers in laser active region ($Z$) and lasing spectrum width ($\Omega$) were the same for both figures and equal to 5 and 18 meV respectively.

As it is seen from the figure 3a, the variation of $\alpha_{\text{in}}$ from 3.5 to 1.5 cm$^{-1}$ results in smaller values of $I_{\text{L, opt}}(\sigma_{\text{opt}})$ required to achieve lasing spectrum of a given width $\Omega$. This is because of the decrease in $\alpha = \alpha_{\text{in}} + \alpha_{\text{out}}$, which results in smaller threshold population inversion in average QDs $\gamma_0 = \alpha/\Gamma_{\text{max}}$. 
which should be maintained in order to involve these QDs into lasing. The increase in the number of QD layers in laser active region \((Z)\) has the same effect on the value of injection current \(I_{L,\sigma_{\text{opt}}}\) and also leads to its decrease as \(\gamma_0 = \alpha / G_{\text{max}}\) decreases due to the increase in \(G_{\text{max}} \sim Z\).

As it is shown in the figure 3b, the decrease of \(\alpha_{\text{out}}\) from 10.3 to 4.5 cm\(^{-1}\) due to variation of cavity edge reflectivity also results in smaller injection current \(I_{L,\sigma_{\text{opt}}}\) at a given lasing spectrum width \(\Omega\) due to the same reason: the decrease in \(\alpha_{\text{out}}\) results in lower population inversion \(\gamma_0 = \alpha / G_{\text{max}}\), which is required for the lasing start in average QDs.

3. Conclusion

It is shown that in the case of InAs/InGaAs quantum dot lasers, there always exists an attainable value of laser cavity length realizing lasing spectrum of a given width at minimum injection current for any given dispersion of inhomogeneous broadening. At the same time, the optimization of dispersion of inhomogeneous broadening plays the major role for the minimization of injection current, while the optimization of laser cavity length is only fine tuning of its value. In the case of multi-layered structures, the increase of dispersion as well as decrease of internal and external loss leads to further decrease of injection current corresponding to the lasing spectrum of a given width.

As a result, in order to minimize injection current realizing lasing spectrum of a given width, one should always increase the number of QD layers in laser active region and dispersion using multi-layered structures with broad distribution of QDs over the sizes, while internal and external loss should both decrease. The decrease of external loss should be realized by the usage of special coatings for laser cavity edges, while the length of laser cavity should be chosen in such a way that it has an optimal value, which minimizes the value of injection current for the given lasing spectrum width.

Acknowledgements

This work was supported by the Russian Scientific Foundation (project 14-42-00006). One of the authors (VVK) is also supported by the Committee for Science and Higher Education of the Government of Saint-Petersburg.

References

[1] Zhukov A E, Kovsh A R 2008 Quantum Electronics 38 409
[2] Zhukov A E, Kovsh A R, Nikitina E V, Ustinov V M, Alferov Zh I 2007 Semicond. 41 606
[3] Sugawara M, Mukai K, Nakata Y, Ishikawa H, Sakamoto A 2000 Phys. Rev. B 61 7595.
[4] Savelyev A V, Novikov I I, Maximov M V, Shernaykov Yu M, Zhukov A E 2009 Semicond. 43 1597.
[5] Zhukov A E, Maximov M V 2009 Modern Injection Lasers (St. Petersburg: Publishing House of St. Petersburg State Polytechnical University)
[6] Korenev V V, Savelyev A V, Zhukov A E, Omelchenko A V, Maximov M V 2012 Semicond. 46 645
[7] Korenev V V, Savelyev A V, Zhukov A E, Omelchenko A V, Maximov M V, Shernyakov Yu M 2013 Proc. of SPIE 8772 84320W
[8] Korenev V V, Savelyev A V, Zhukov A E, Omelchenko A V, Maximov M V 2014 Appl. Phys. Lett. 102 112101
[9] Korenev V V, Savelyev A V, Zhukov A E, Maximov M V, Omelchenko A V 2015 Proc. of SPIE 9503 950305