The analytical approach to optimization of active region structure of quantum dot laser

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Abstract. Using the analytical approach introduced in our previous papers we analyse the possibilities of optimization of size and structure of active region of semiconductor quantum dot lasers emitting via ground-state optical transitions. It is shown that there are optimal length, dispersion and number of QD layers in laser active region which allow one to obtain lasing spectrum of a given width at minimum injection current. Laser efficiency corresponding to the injection current optimized by the cavity length is practically equal to its maximum value.

1. Introduction

Efficient semiconductor lasers having broadband emission spectra, which correspond to the transparency window of standard silicon optical fibre, can be used for the wide range of practical applications, such as optical coherence tomography and ultrafast data transmission [1 – 3]. Long-wavelength InAs/InGaAs quantum dot (QD) lasers, emitting via ground state (GS) optical transitions of QDs near 1.3 μm, allow one not only to overlap this wavelength range, but also to decrease operation current of such a laser realizing lasing spectra of a given parameters [4].

At the same time, due to the possibility of usage of such semiconductor QD lasers in compact portable devices, the task of optimization of its energy consumption plays an important role. In particular, it is important to find out the ways to optimize all the key parameters of laser’s active region, such as number of QD layers (Z) in it, dispersion of inhomogeneous broadening (σ) and laser cavity length (L), to obtain lasing spectrum of a given width (Ω) at minimum injection current (I_{inj}).

2. Optimization of laser active region

To elucidate the influence of the inhomogeneous broadening and of the number of QD layers in laser’s active region (Z) on the injection current we have calculated the dependence of injection current optimized by the laser cavity length (I^{L}_{opt}) on the dispersion (σ) corresponding to the lasing spectrum of the given width Ω=12 meV for different values of Z – see figure 1a. The other parameters are in accord with [4 – 5]. The calculation is performed in the scopes of the model proposed in [4 – 5].
Figure 1(a, b). (a) The dependence of injection current optimized by the laser cavity length ($I_{opt}$) corresponding to the lasing spectrum of the given width ($\Omega = 12$ meV) on dispersion for the different numbers of QD layers ($Z$). (b) The dependence of optimal cavity length ($L_{opt}$) corresponding to the $I_{opt}$ on dispersion for different values of $Z$.

As it can be seen from the figure 1a (see curve $Z=1$), there is always an optimal value of dispersion ($\sigma$) realizing the minimum of optimal injection current ($I_{opt}$), which corresponds to the lasing spectrum of a given width. Indeed, at sufficiently small dispersion, lasing spectrum is sufficiently narrow and, therefore, the injection current ($I$), as well as optimal injection current ($I_{opt}$), should increase in order to attain lasing spectrum of a given width. At large dispersion, the maximum gain ($G_{max}$) turns out to be sufficiently small and can be even lower than the total loss ($\alpha$) at a certain dispersion due to reciprocal proportionality of the maximum gain to the dispersion ($G_{max} \sim 1/\sigma$). This, in the case of large dispersions, results in the increase of $I_{opt}$ with the increase of $\sigma$. Therefore, there is always an optimal value of dispersion ($\sigma_{opt}$) that allows one to realize lasing spectrum of a given width at minimum injection current – see figure 1a, e.g. curve $Z=1$.

The larger is the number of QD layers in laser’s active region ($Z$), the higher is the maximum gain ($G_{max} \sim Z$) and the less pronounced are the lasing spectrum narrowing, which takes place at sufficiently low dispersions, and $G_{max}$ decrease, which is important at sufficiently high dispersions. This, in its turn, results in higher values of optimal dispersion ($\sigma_{opt}$) and lower values of injection current corresponding to the lasing spectrum of a given width. As a result, for $Z > 3$ the simple increase of dispersion leads to the decrease of optimal injection current ($I_{opt}$) and the higher is $\sigma$, the lower is $I_{opt}$ in all accessible range of dispersion – see figure 1a.

It is important to notice that the optimal values of dispersion realizing minimal injection current shown in the figure 1a correspond to the technologically accessible range of laser cavity lengths – see figure 1b. This, in its turn, makes the considered optimization very useful from the practical point of view. At the same time, in the case of extremely large dispersions exceeding 30 meV and sufficiently high output powers, the lasing via first excited optical transitions can take place and, thus, should be taken into account [6]. As it can be seen from the figure 1b at fixed $Z$, e.g. at $Z=5$, the increase of dispersion leads to the increase of optimal cavity length corresponding to the optimal injection current ($I_{opt}$). Indeed, the higher is $\sigma$, the lower is $G_{max}$, which is reciprocally proportional to $\sigma$ ($G_{max} \sim 1/\sigma$). Therefore, the total loss ($\alpha$) should decrease in order to maintain the lasing condition of the equality of the gain ($G$) and total loss ($\alpha$): $G = \alpha$, where $G \sim G_{max}$. This, in its turn, corresponds to the laser samples with longer cavities that is in accord with the figure 1b and our further calculations – see figure 2 ($Z=5$).
Figure 2. The dependence of the injection current ($I$) as a function of laser cavity length ($L$) for the different values of dispersion ($\sigma$) varying from 10 meV to 35 meV. Dashed line corresponds to the optimal injection current ($I_{\text{opt}}$) at optimal length ($L_{\text{opt}}$). Here $\Omega= 12$ meV and $Z= 5$.

It is interesting to notice that at sufficiently high dispersions, when the values of $G_{\text{max}}$ and $\alpha$ are practically equal, the slope of $L_{\text{opt}}(\sigma)$ dependence sharply increases above $\sigma_{\text{opt}}$. As it can be distinctly seen from the figure 1b (curve $Z= 1$), there is such an increase of $L_{\text{opt}}$ for all the dispersions exceeding 19.25 meV that is equal to $\sigma_{\text{opt}}$ for $Z= 1$ as it follows from the figure 1a. However, such an increase in the slope is not enough to increase lasing spectrum width significantly and, therefore, $I_{\text{opt}}$ for $Z= 1$ also tends to increase – see figure 1a. The same situation is for large values of $Z$ – see figure 2 for $Z= 5$. The dashed line in the latter figure corresponds to the $I_{\text{opt}}$ decreasing with the increase of $\sigma$ practically in all range of dispersions that is due to sufficiently high values of $\sigma_{\text{opt}}$ because of large $Z$.

Thus, there are always optimal values of laser cavity length ($L_{\text{opt}}$) and dispersion ($\sigma_{\text{opt}}$) of inhomogeneous broadening allowing one to attain lasing spectrum of a given width at minimum injection current. However, at sufficiently large numbers of QD layers in laser active region ($Z$), the optimal value of dispersion becomes so high that the simple increase of dispersion leads to the decrease of injection current corresponding to the lasing spectrum of a given width in all accessible range of dispersions – see figure 1a. The increase of a priori given laser spectrum width ($\Omega$) from $\Omega_a$ to $\Omega_b$ ($\Omega_b > \Omega_a$) results in the increase of optimal injection current ($I_{\text{opt}}$) as well as of optimal dispersion ($\sigma_{\text{opt}}$) because the wider is the lasing spectrum, the higher injection and dispersion are needed in order to realize it. Such an increase corresponds to the movement from left-down to the right-top corner of the figure – see figure 3.

Figure 3. The dependence of optimal injection current ($I_{\text{opt}}$), which corresponds to the lasing spectrum of the given width ($\Omega$), on dispersion ($\sigma$) for the different values of QD layers in laser active region ($Z$). $I_{\text{opt}}$ corresponding to $\Omega_a= 12$ meV are depicted with curves $Z_a$ and to $\Omega_b= 15$ meV are $Z_b$. 
At the same time, it is very important for the practice to reveal how strong is the influence of laser cavity length \((L)\) and dispersion of inhomogeneous broadening \((\sigma)\) on the injection current realizing the lasing spectrum of the given width \((\Omega)\). More precisely, it is important to reveal optimization of which parameter \((L\ or \ \sigma)\) is most crucial for the achievement of minimum injection current corresponding to the lasing spectrum of the given width \((\Omega)\) and optimization of which parameter is just fine-tune. In order to answer this question we have calculated the dependence of injection current optimized by the cavity length on dispersion \(I_{\text{L}}^{\text{opt}}(\sigma)\) – see figure 1a, and the dependence of injection current optimized by the dispersion on cavity length \(I_{\sigma}^{\text{opt}}(L)\) – see figure 4, for the different numbers of QD layers in laser active region \((Z)\).

**Figure 4.** The dependence of the injection current \((I_{\text{opt}}^{\sigma})\), which is optimized by the dispersion, as a function of laser cavity length \((L)\) for the different numbers of QD layers \((Z)\) in laser active region.

As it can be seen from the figure 1a for \(Z=5\) the variation of dispersion from 7.0 meV to 21.5 meV results in the decrease of optimal injection current \(I_{\text{L}}^{\text{opt}}\) practically by 500 mA. At the same time, the variation of the cavity length from 0.1 cm to 0.5 cm in the case of \(Z=5\) results in decrease of \(I_{\sigma}^{\text{opt}}\) only by 50 mA – see figure 4. Therefore, the optimization of dispersion plays the key role and, in the case of multi-layered structures, the dispersion should be increased in order to decrease optimal injection current \(I_{\text{L}}^{\text{opt}}\). However, the optimization of laser cavity length is the task of fine-tuning of injection current that is in accord with our previous results [7]. Thus, the usage of multi-layered structures (with \(Z > 3\)) and high dispersions (exceeding 17 – 20 meV) allow one to decrease the optimal injection current \(I_{\text{L}}^{\text{opt}}\) corresponding to the lasing spectrum of a given width \(\Omega\) significantly.

**Figure 5.** Laser power conversion efficiency (PCE) as a function of dispersion of inhomogeneous broadening \((\sigma)\): blue curve corresponds to the PCE at the injection current optimized by the laser cavity length \((I_{\text{L}}^{\text{opt}})\), which realizes lasing spectrum of a given width \((\Omega)\); red curve corresponds to the peak value of PCE at \(Z=5\) and \(\Omega = 12\) meV.
Finally, it occurs that in the case of multi-layered structures having 3 – 5 layers of QDs, power conversion efficiency (PCE) of QD laser $\eta_{\text{opt}}$ corresponding to the optimal injection current $I_{\text{L opt}}$ is practically equal to its peak value $\eta_{\text{max}}$, corresponding to the specific value of laser cavity length ($L_{\text{max}}$), for all attainable values of dispersion, where diode opening voltage, serial diode resistivity and internal quantum efficiency are equal to 1.02 meV, $10^{-4}$ Ohm cm$^2$, 0.9 that is in accord with [8] – see figure 5. Thus it, is important to use multi-layered laser structures having sufficiently high dispersion in order to obtain lasing spectrum of a given width at minimum injection current and maximal dispersion which can be also further fine-tuned by the optimization of laser cavity length.

3. Conclusion

It was shown that in the case of quantum dot lasers having a small number of quantum dot layers in its active region, in particular in the case of a single plane of quantum dots, there are always optimal values of dispersion and laser cavity length allowing one to realize lasing spectrum of a given width at minimum injection current. At the same time, the usage of multi-layered structures results in the decrease of the injection current, corresponding to the lasing spectrum of the given width. The operation current can be also decreased by the increase of dispersion in all practically accessible range of dispersions.

Moreover, the optimization of dispersion plays the key role, while the optimization of laser cavity length, which has its optimal value corresponding to the minimum operation current for single- as well as for multi-layered structures, is just a fine-tune. The usage of laser structures optimized by the length allows one to decrease injection current on more than 45% on the scale $\sim$ 0.1 A, however the optimization of dispersion takes place on the scale of $\sim$ 1 A.

As a result, the usage of laser active regions having several layers of quantum dots and the increase of dispersion, as well as fine-tune optimization of the laser cavity length, allow one to obtain lasing spectrum of a given width at minimum operation current at power conversion efficiency practically equal to its maximum value.

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