Numerical investigation of longitudinal spatial hole burning (LSHB) in high-power semiconductor lasers

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Abstract. Longitudinal spatial hole burning (LSHB) and its effect on output power of broad-area semiconductor lasers are examined using one-dimensional rate equations. It is shown that direct LSHB can be separated into two mechanisms – an increase in the effective threshold current and a decrease in the output efficiency. The LSHB dependence on laser diode parameters is analysed. In particular, a large optical confinement factor $\Gamma$ is shown to suppress the LSHB-induced power decrease.

1. Introduction
Semiconductor lasers are highly efficient light sources. In particular, broad-area (stripe width $\sim 100 \mu m$) GaAs-based devices achieve $>60\%$ power conversion efficiency in a wide range of output power levels [1, 2]. Longitudinal spatial hole burning (LSHB) is a well-known effect of an inhomogeneous free carrier density distribution along the Fabry–Perot resonator axis and is generally considered [3–5] to play a significant role in limiting the maximum achievable output power of diode lasers. Therefore, a detailed analysis of how different diode laser parameters affect LSHB is of great importance.

LSHB effect on output power can be divided into a direct effect, which itself causes power decrease, and an indirect one, which enhances other mechanisms of power decrease (internal optical loss, carrier leakage, heating, etc.). The former is generally quite small ($\sim 1\%$), but the root cause of two effects is the same. Therefore, an analysis of the direct LSHB effect (which can be much simpler) can still provide helpful insight into optimizing the design of a semiconductor laser.

A detailed analysis of the direct LSHB effect is given in [6, 7]. However, these papers mostly focus on giving a simple analytical estimate, hence the information on how different diode laser parameters affect LSHB is rather limited. This defines our main goal – to figure out which semiconductor lasers are most susceptible to LSHB and how their design can be changed to alleviate this problem.

2. Simulation approach
As in [6, 7], in our analysis we use a system of rate equations, describing the distributions of free electron density $n$ and photon density $S$ along the resonator axis $z$:

$$\frac{\eta I}{qV_a} = R_{sp}(n) + v_{gf}(n)(S^- + S^+),$$

(1)
\[
-\frac{dS^-}{dz} = (\Gamma g(n) - \alpha_i) S^-, \quad (2)
\]
\[
\frac{dS^+}{dz} = (\Gamma g(n) - \alpha_i) S^+. \quad (3)
\]

Here \( S \) is divided into \( S^+ \) and \( S^- \) that denote photons moving forwards and backwards along \( z \), respectively. To calculate the optical gain, we use the two-parameter logarithmic formula \( g(n) = g_0 \ln(n/N_{tr}) \), while for the spontaneous emission rate we neglect Shockley–Read–Hall recombination to write \( R_{sp} = Bn^2 + Cn^3 \). The active region volume is \( V_a = d_a W L \) and the group speed is \( v_g = c/\tilde{n} \). Other model parameters and their values are listed in Table 1.

| Parameter                  | Value  | Units   |
|----------------------------|--------|---------|
| Wavelength \( \lambda \) | 1060   | nm      |
| Active region thickness \( d_a \) | 9      | nm      |
| Stripe width \( W \)     | 100    | \( \mu m \) |
| Resonator length \( L \)  | 3000   | \( \mu m \) |
| Back mirror \( z = 0 \) reflectivity \( R_1 \) | 0.95   |         |
| Front mirror \( z = L \) reflectivity \( R_2 \) | 0.01   |         |
| Injection efficiency \( \eta_i \) | 1.0    |         |
| Spontaneous emission rate \( B \) | \( 1 \cdot 10^{-10} \) | \( cm^3/c \) |
| Auger recombination rate \( C \) | \( 5 \cdot 10^{-30} \) | \( cm^6/c \) |
| Gain coefficient \( g_0 \) | 2140   | \( cm^{-1} \) |
| Transparency carrier density \( N_{tr} \) | \( 1.77 \cdot 10^{18} \) | \( cm^{-3} \) |
| Optical confinement factor \( \Gamma \) | \( 0.87 \cdot 10^{-2} \) |         |
| Effective refractive index \( \tilde{n} \) | 3.44   |         |
| Internal optical loss \( \alpha_i \) | 1.0    | \( cm^{-1} \) |

Equations (1–3) are accompanied by boundary conditions \( S^+(0) = R_1 S^-(0) \) and \( S^-(L) = R_2 S^+(L) \). In order to solve the resulting system, we implement a finite difference scheme to discretize the spatial derivatives, which transforms equations (1–3) to a system of \( 3m \) equations, where \( m \) is the number of grid points. Then, the output power can be easily calculated from the photon density values at the resonator boundaries.

The values listed in Table 1 correspond to a common high power semiconductor laser design [1] and were partially obtained by analysing experimental results. As a reference point (the absence of LSHB), we use the zero-dimensional diode laser rate equations (see, for example, Chapter 2 in [8]), which assume a uniform carrier distribution along the resonator axis and result in a linear P-I curve, given \( \alpha_i \) and \( \eta_i \) are held constant.

### 3. Results and discussion

Figure 1 shows typical P-I curves obtained by the above method. As we can see from the blue lines, the introduction of LSHB does not lead to power saturation. At high currents, its effect can be to a reasonable degree approximated as a small decrease in the differential efficiency \( \eta \) (P-I curve slope).

To demonstrate that this effect can lead to a large power loss, we also present the P-I curves obtained using a model with an increasing internal absorption (red lines in figure 1). Here, we use the approximate formula \( \alpha_i = \alpha_i^0 + kJ \), where \( J \) is the current density and
$k = 1.2 \cdot 10^{-4} \text{ cm/A} \ [9, 10]$. In this case, the LSHB power penalty is much larger. This result is of great significance since the rise in internal absorption is widely recognised [3, 4, 9] as one of the main factors limiting the laser diode efficiency. Moreover, it is reasonable to assume that other power saturation mechanisms, such as carrier leakage, two-photon absorption, and local heating, are also amplified by LSHB.

Figure 2 compares free carrier and photon distributions with and without LSHB. These curves are intrinsically connected to the two mechanisms of output power decrease due to LSHB. The first one is an increase in spontaneous recombination, which can be expressed as a rise in effective threshold current $I'_{th}$:

$$I'_{th} = \frac{qWd_a}{\eta_i} \int_0^L R_{sp}(n)dz.$$  \hspace{1cm} (4)

As it was demonstrated in [6], $I'_{th}$ will exceed the value obtained from 0D rate equations as long as either $R_{sp}(n)$ or $g(n)$ are nonlinear.

The second mechanism is a decline in output efficiency $\eta'$, which is a ratio of the output power to the total power loss (output + internal absorption). The output power is determined by the photon densities at the resonator boundaries $S^+(L)$ and $S^-(0)$, while the internal absorption is proportional to the average photon density $\overline{S}$. From figure 2 it is apparent that in the presence of LSHB $\overline{S}$ is larger, therefore, $\eta'$ is smaller. This holds true as long as $\alpha_i \neq 0$. To calculate $\eta'$, we can use the following formula:

$$\eta' = \frac{E_{ph}}{q} \frac{S^+(1 - R_2) + S^-(1 - R_1)}{\Gamma \int_0^L g(n)(S^+ + S^-)dz}.$$  \hspace{1cm} (5)

Here $E_{ph}$ is the photon energy, and $q$ is the elementary charge.

The curves obtained using eq. (4, 5) are plotted in figure 3. Here they are compared to the values of threshold current and differential efficiency calculated using regular 0D rate equations. A rapid change in the values of $I'_{th}$ and $\eta'$ near threshold can lead to a strong power decline, which can be seen in figures 4 and 5.

Figure 4 demonstrates how the resonator length $L$ affects the LSHB power penalty. A high $L$ leads to smaller values of $\eta'$, which plays the main role at high currents. Meanwhile, low $L$ improves laser efficiency at high currents, while simultaneously degrading performance near
threshold. This is due to an increased threshold carrier density that makes a rise in $I'_{th}$ more significant.

Figure 5 illustrates the effect of changing the optical confinement factor $\Gamma$. These curves are particularly interesting because $\Gamma$, unlike many other epitaxial design parameters, can be easily adjusted without sacrificing laser performance [5]. We can see that in order to suppress LSHB it is advisable to increase $\Gamma$, particularly if it is small to begin with.

The dashed curve in figure 5 represents a laser with an increased Auger recombination rate. Here we increased $C$ by a factor of 10, which is roughly equivalent to a transition from GaAs-based lasers operating near $\lambda = 1 \mu m$ to $1.55 \mu m$ lasers on InP substrates. As we can see, such an increase in $C$ leads to stronger LSHB, though this effect is by no means dramatic.

The effect of other parameters on LSHB is of less importance. The gain coefficient $g_0$ and the spontaneous recombination rate $B$ act on LSHB similarly to $\Gamma$ and $C$, respectively, though $g_0$ can not be altered as much as $\Gamma$, while the effect of $B$ is very small. The internal loss $\alpha_i$ and the front mirror reflectivity $R_1$ play a large role in LSHB, but these facts are self-evident and have already been thoroughly examined in [6, 7].

4. Conclusion

The obtained results demonstrate that longitudinal spatial hole burning depends not only on the output mirror reflectivity and internal optical loss, but also on a number of other
parameters, some of which can be adjusted during the manufacturing process. As its effect on the output power can be quite significant, we suggest that it should be taken into consideration when designing high power semiconductor lasers. In particular, our calculations indicate that increasing optical confinement factor $\Gamma$ can successfully weaken LSHB. This is an important fact since $\Gamma$ is often kept small in order to minimize free-carrier absorption. A positive overall effect of a stronger optical confinement was experimentally demonstrated in [5].

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