Efficient method of designing optically-pumped vertical external cavity surface emitting lasers having equally excited quantum wells

Abstract

Even distribution of carriers allows to maximize optical gain of the Optically-Pumped Vertical External Cavity Surface Emitting Laser. In this paper we show how to distribute the quantum wells and blocking layers in order to compensate the exponential decay of the pumping beam intensity. Our model says whether it is possible at all (for an assumed length of the device) and, if it is, allows to find positions of the blocking layers. No iterations nor numerical calculations more sophisticated than a standard calculator can do are required to use the model.

1. Introduction

The Optically Pumped Vertical External Cavity Surface Emitting Lasers (OP-VECSELs) are able to emit high quality beams of multi-watt powers [1], thus combining the most important advantages of Edge-Emitting and Vertical Cavity Surface Emitting Lasers (EELs and VCSELs). Moreover their external cavity may contain additional elements like non-linear crystals or semiconductor saturable absorber mirrors (SESAMs), which may be used for instance for frequency doubling and short pulse generation. Usually, optical gain is provided by several quantum-well (possibly double- or multi-quantum-well) active regions, located at the successive anti-nodes of the standing wave. The cavity is formed by a Distributed Bragg Reflector (DBR) and an external mirror [2].

The pumping beam penetrates the device in the direction nearly perpendicular to the layers. Absorption of the pumping beam generates carriers necessary to achieve optical gain, but also causes exponential decay of the intensity in the deeper regions. If we simply placed, at each anti-node, the same number of wells, the gains provided by the active regions would differ significantly. Since optical gain is a concave function of carrier concentration (roughly $\sim \log(N/N_0)$, where $N$ is the carrier concentration and $N_0$ is the transparency concentration), the highest possible total gain (for a fixed, arbitrary number of the carriers) is highest when all the wells provide the same material gain. If the temperatures of the wells can be assumed to be equal, we should try to have the same carrier concentration in each well. The temperature rise in the VECSEL can be high, most of the temperature drop takes place in the substrate and DBR as these part are much thicker than the active part. Generally, we want to direct the same number of carriers to all the wells.

In order to do so, we have to increase the volume from which the distant wells collect the carriers or increase the number of the wells in the stronger pumped regions. To do the first thing one can use so called blocking layers—thin wide-gap layers which block carrier diffusion (in case of AlAs blocking layers in GaAs, the thickness of a few nanometers is sufficient to block the carrier diffusion). They define the volume from which the well(s) between them collect the carriers [3]. The question how to place them is not trivial, mainly because positions of the wells are restricted to the anti-nodes, which strongly restricts positions of the blocking layers.

If there are two or more anti-nodes between two subsequent blocking layers, one has to take into account the carrier diffusion in order to find the actual carrier concentration in the two (or more) active regions. This makes the analysis more complicated [3]. Our goal is to build an analytical model which allows to construct the desired scheme without using complicated calculation.

2. The model

As we mentioned, in order to avoid consideration of carrier diffusion, we restrict our interest to the case, where in each segment (area bounded by the neighbouring blocking layers) there is only one active region (we treat the DBR as the 0th blocking layer, see Fig. 1), and the active regions are placed at each anti-node. The window layer acts as the last blocking layer and due to the optical reasons must be located at an anti-node. This means that the last segment must be thicker than $d$ (see Fig. 1). Therefore, in order to have the same number of generated carrier per a QW, we have to put more wells in this segment and treat it in a different manner in our calculations.
In order to obtain a handy result we base our model on the following simplifying assumptions:
1. Widths of the wells and blocking layers are negligible. More precisely, their presence (the blocking layers do not absorb the pump, on the other hand the wells have higher absorption than the adjacent bulk material) introduces a tolerable error.
2. The blocking layers block totally carrier diffusion.
3. We neglect reflection of the pumping light from the DBR and from the blocking layers.
4. Carrier losses in the absorbing barrier are negligible (relative to the losses in the QWs).

In Fig. 1 a scheme of theVECSEL is presented. Distance $d$ must be a multiple of a half of the emitted wavelength. Usually $d \approx \lambda/(2n_r)$, where $\lambda$ is vacuum wavelength and $n_r$ is refractive index of the barrier. Small deviations from the exact equality come from the presence of the wells and blocking layers. In our scheme the pumping light comes from the right, so under our assumptions the pumping wave intensity is described by the following formula:

$$I(z) = I_0 \exp(\alpha z)$$

(1)

where $\alpha$ is the absorption in the barriers, $I_0$ is a normalisation constant, defining the pump power. Number of the carriers generated in $n$-th segment is simply

$$P_n = I_0(\exp(\alpha z_n) - \exp(\alpha z_{n-1}))$$

(2)

We assume that in segments $1, 2, \ldots, N$ there are the same number of wells (in this paper—just one well), and in the last segment, $N + 1$, we put $k$ wells. We want to distribute the blocking layers such that

$$P_1 = P_2 = \cdots = P_N = \frac{1}{k} P_{N+1}$$

(3)

As we have $k$ times more wells in the last segment, we want to have $k$ times more carriers generated there. Possible values of numbers $N$ and $k$ will be determined in our calculations. Position $z_n$ can be written as (see Fig. 1)

$$z_n = nd + \delta_n$$

(4)

Then we have

$$P_1 = I_0\left[\exp\left(\alpha(d + \delta_1)\right) - 1\right] = \frac{1}{k} P_{N+1}
$$

$$P_2 = I_0\left[\exp\left(\alpha(2d + \delta_2)\right) - \left[\exp\left(\alpha(d + \delta_1)\right)\right]\right] = \frac{1}{k} P_{N+1}\left[\exp(2\alpha d)\exp(\alpha \delta_2) - \exp(\alpha d)\exp(\alpha \delta_1)\right]
$$

$$P_3 = I_0\left[\exp\left(\alpha(3d + \delta_3)\right) - \left[\exp\left(\alpha(2d + \delta_2)\right)\right]\right] = \frac{1}{k} P_{N+1}\left[\exp(3\alpha d)\exp(\alpha \delta_3) - \exp(2\alpha d)\exp(\alpha \delta_2)\right]
$$

Let us introduce the following symbols:

$$a = \exp(-\alpha d) \quad x_n = \exp(\alpha \delta_n)$$

(5)

Note that $0 < a < 1$, regardless of $\alpha$ and $d$. Using these symbols we can write the system of equations (3) as:

$$0 = x_2 - 2ax_1 + a^2$$

$$0 = x_3 - 3ax_2 + a^2x_1$$

$$0 = x_4 - 2ax_3 + a^2x_2$$

$$\vdots$$

$$0 = x_N - 2ax_{N-1} + a^2x_{N-2}$$

$$0 = x_{N+1} - (k + 1)ax_N + ka^2x_{N-1}$$

$$\frac{1}{a} = x_{N+1}$$

because $\delta_{N+1} = d$

As one can see, thanks to the extraordinary properties of exponential function we got something as simple as a system of $N + 1$ linear equations with $N + 1$ unknowns. Because we do not know what are the values of $N$ and $k$, it is convenient to consider first only equations concerning first $N$ segments, i.e. those defined by the blocking layers which position we can choose. Thus we consider the system of $N - 1$ equation with $N$ unknowns:

$$x_2 - 2ax_1 + a^2 = 0$$

$$x_3 - 3ax_2 + a^2x_1 = 0$$

$$x_4 - 2ax_3 + a^2x_2 = 0$$

$$\vdots$$

$$x_{N} - 2ax_{N-1} + a^2x_{N-2} = 0$$

If we treat one of the unknowns as a parameter we can solve the system. As the parameter we choose $x_1$ as the first blocking layer must be always present. This way we obtain:

$$x_2 = a(2x_1 - a)$$

$$x_3 = a^2(3x_1 - 2a)$$

$$\vdots$$

$$x_{N} = a^{N-1}(Nx_1 - (N - 1)a)$$

(8)

Although the system (7) has always the solution in real numbers, we must check if the solution fulfils the additional conditions, i.e.:

$$1 < x_n < 1/a \quad \forall n = 1, 2, \ldots, N$$

(9)

The above conditions say simply that $0 < \delta_n < d$. It assures that in each segment there is one active region.
Substituting (8) to (9) we get:

\[
1 < x_1 < \frac{1}{a} \\
\frac{1}{2} \left( a + \frac{1}{a} \right) < x_1 < \frac{1}{2} \left( a + \frac{1}{a^2} \right) \\
\frac{1}{3} \left( 2a + \frac{1}{a} \right) < x_1 < \frac{1}{3} \left( 2a + \frac{1}{a^2} \right) \\
\vdots \\
\frac{1}{N} \left( (N - 1)a + \frac{1}{a^{N-1}} \right) < x_1 < \frac{1}{N} \left( (N - 1)a + \frac{1}{a^N} \right) \tag{10}
\]

If the above inequalities are inconsistent, it is impossible to build a system of \(N\) active regions (of the same number of QWs), having equal carrier concentrations.

The above system can be significantly simplified. Let us denote

\[
L_n = \frac{1}{n} \left( (n-1)a + \frac{1}{a^{n-1}} \right) \tag{11}
\]

\[
R_n = \frac{1}{n} \left( (n-1)a + \frac{1}{a^n} \right) \tag{12}
\]

being just the left and right hand side of the \(n\)-th inequality. Basic calculations show that:

\[
L_{n+1} - L_n = \frac{1}{n(n+1)a^n} \left( a^{n+1} - (n+1)a + n \right) \tag{13}
\]

The sign of the difference is determined by polynomial \(l_n(a) = a^{n+1} - (n+1)a + n\). It is easy to see that \(l_n(1) = 0\), \(l_n'(a) = (n+1)(a^n - 1) \leq 0\ \forall a \in [0,1]\). It means that \(l_n(a) \leq 0\ \forall a \in [0,1]\) (in our case \(0 < a < 1\)), and hence

\[
L_1 < L_2 < \cdots < L_N \tag{14}
\]

Now we can write the system of inequalities (10) in a more compact way:

\[
\frac{1}{N} \left( (N - 1)a + \frac{1}{a^{N-1}} \right) < x_1 < \frac{1}{N} \left( (N - 1)a + \frac{1}{a^N} \right) \tag{15}
\]

Which of the right hand sides is the actual minimum depends on \(a\) (i.e. on the material absorption and distance between the active regions).

If for a certain \(N L_N \geq \mathcal{R}(N)\), it is impossible to build \(N\) (and any greater number, since \(L_N\) is increasing and \(\mathcal{R}(N)\) is non-increasing with \(N\)) equally pumped segments. This way we can find the possible values of \(N\). When we choose one of them, we can return to the full system of equations (8). Solving it we can find values of all \(x_1, x_2, \ldots, x_N\), but now we are interested only in \(x_1\):

\[
x_1 = \frac{1}{(N+k)\alpha^{N+1} + a} = \frac{N + k - 1}{N + k} \tag{16}
\]

If, for the chosen \(N\), we can find a natural number \(k\) such that \(x_1\) calculated with the above formula fulfills condition:

\[
L_N < x_1 < \mathcal{R}(N) \tag{17}
\]

we know that we can build \(N\) one-well segments concluded by one \(k\)-well segment, having equally pumped quantum wells. If there is no such \(k\), or it is too high from the practical point of view, one has to decrease number \(N\) and repeat the procedure.

Finally, when we have suitable \(N, k\) and hence \(x_1\), we can calculate all the other \(x_2, x_3, \ldots, x_N\) using (8) and then the actual positions \(z_n, n = 1, 2, \ldots, N+1\) of the blocking layers using formulae (11) and (12).

3. Example

Let us consider an important example: a VECSEL with GaAs barriers, emitting at 980 nm, pumped by a 808 nm laser. Assuming \(\alpha = 1.3 \cdot 10^4\) 1/cm [14] and \(n_r = 3.52\) we get the following parameters:

\[
d \approx 139.2\,\text{nm} \quad a \approx 0.8345 \tag{18}
\]

![Figure 1. Scheme of wells and blocking layers distribution in a VECSEL. Wells are blue (downwards), blocking layers red (upwards). Numbers 1, 2, ..., N + 1 denote the segments.](image)
Of course in a real calculations one should use more precise values, because the optical properties of the structure are more sensitive to the distances between the wells. First we will check whether it is possible to have seven one-well segments. We calculate, using (11):

\[ L_7 = 1.13837 \]

\[ R(7) = \min_{n=1,...,7} R_n = R_3 = 1.12997 \]

(19)
We see that \( L_7 > R(7) \), so we cannot construct seven such segments. But since

\[ L_6 = 1.10730 < R(6) = R_3 = 1.12997 \]

(20)
we can find out if we can close such 6-segment sequence by the multi-well one. Using (16) for \( N = 6 \) we calculate:

\[
x_1(k = 3) = 1.13612 > R(6)
\]

(21)
\[
x_1(k = 4) = 1.10595 < L_6
\]

(22)
Since \( x_1 \) is a decreasing function of \( k \), there is no possibility to find a suitable \( k \). It means that we cannot build the final segment with an integer number of wells such that it has the same carrier concentration as in all the others. The non-integer values of \( k \) could have physical meaning as \( k \) is actually the ratio between number of wells in the last segment and number of wells in the other ones. If we assumed the other segments to contain not one, but two wells each, we could consider \( k = 3.5 \). But it would mean that we have to put as many as seven quantum wells in the last segment, which is too many, because the peripheral wells would be placed far from the anti-node of the standing wave.

If not 6, let us try \( N = 5 \). Now we have \( L_5 = 1.08005, R(5) = 1.12997 \). For the new \( N \):

\[
x_1(k = 2) = 1.13837 > R(5)
\]

(23)
\[
x_1(k = 3) = 1.10038 < R(5)
\]

(24)
\[
x_1(k = 4) = 1.07083 < L_5
\]

(25)
Number \( x_1(k = 3) \) fulfills all the conditions, so we can build 5 one-well segments and one 3-well segment on the top, with all the 8 wells equally pumped. Now we calculate \( x_2, \ldots, x_N \) using (9), extract \( \delta_n \) given by:

\[
\delta_n = \frac{\log(x_n)}{\alpha}
\]

(26)
Finally we get \( z_1, \ldots, z_{N+1} \) from formula (14). Positions of the wells (which are independent on \( x_1 \)) and blocking layers are presented in table 1. One should remember that positions of the wells \((nd)\) and hence numbers \( z_n \) are only approximations. The reliable values are \( \delta_n \)—positions of the blocking layers relative to the adjacent quantum well (see Fig. 1).

Looking at the values in the table one can see that the lowest distance between a well and a blocking layer is 37 nm. This is a safe distance from the technological point of view, even taking into account non-zero thicknesses of the wells and the blocking layers. The total thickness of the absorbing area is \( 7d, \exp(-7do) \approx 0.28 \), and hence over 70% of the pumping power is absorbed. As the blocking layers are generally located near the nodes of the standing wave, and their thickness can be as low as a few nanometers, their presence modifies the optical properties of the resonator in a very limited degree.

4. Summary

We have shown an efficient and simple way to design the VECSEL structure such that the carrier concentration, and hence optical gain (with the assumption that the temperature differences between the wells are not high), is equal in all the quantum wells. This configuration gives the highest modal gain for given number of carriers, so is highly desirable.

We presented an example of a GaAs-based structures with 6 active regions in subsequent anti-nodes of the standing wave. This is the longest possible design in which one use 1-well segments except the last one. Our calculations can be easily modified to describe segments with different number of wells. In this case longer absorbing areas can be achieved, if necessary. However, the longer the area is, the higher temperature differences appear there, which spoils the desired gain uniformity.

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References

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| \( n \) | \( x_n \) | \( \delta_n \) | \( nd \) | \( z_n \) | \( (n+1)d \) |
|---|---|---|---|---|---|
| 1 | 1.10038 | 74 | 139 | 213 | 278 |
| 2 | 1.14012 | 101 | 278 | 379 | 418 |
| 3 | 1.13656 | 98 | 418 | 516 | 557 |
| 4 | 1.10293 | 75 | 557 | 632 | 696 |
| 5 | 1.10578 | 37 | 696 | 733 | 835 |
| 6 | 1.19837 | 139 | 835 | 974 | 974 |
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