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Effect of pump reflections in vertical external cavity surface-emitting lasers

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Abstract. A numerical analysis of the influence of pump reflections on the carrier generation rate and the uniformity of carrier population in the quantum wells (QWs) of vertical-cavity surface-emitting lasers is presented. We have applied an approach allowing us to study the carrier distribution over the absorbing layers and the QW layers of the structure which is quite general and for an arbitrary function of the local carrier generation rate. When analysing the dual-wavelength VECSEL (Leinonen T et al 2007 Opt. Express 15 13451–6), we have found that application of carrier transport blocking layers can result in a highly uniform QW carrier population. The pump reflections are shown to have a great impact on the carrier distribution in the device under study.

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Vertical-cavity surface-emitting lasers (VECSELs) are a subject of growing interest for a variety of applications. VECSELs have been shown to emit nearly diffraction-limited Gaussian beams, have potential for power scaling up to multi-watt level and can operate in a wide wavelength range with the aid of semiconductor band-gap engineering [1]. Additionally, VECSELs allow for intracavity nonlinear frequency conversion enabling high efficiencies [2, 3].

Until recently, nonlinear frequency conversion was constrained mainly to second harmonic generation due to the lack of VECSELs emitting at multiple wavelengths. However, a VECSEL emitting two coaxial beams at different wavelengths simultaneously, with good spatial overlap, and with high power, could act as a source for multifrequency mixing and thus enable generation of difference frequency radiation at mid- or far-infrared wavelengths. Applications for coherent light in the said wavelength ranges are found in spectroscopy, line-of-sight communication and for the remote detection of chemical warfare agents [4, 5]. Laser sources emitting in these ranges are available, namely quantum-cascade lasers. However, these lasers are subject to considerable drawbacks: they require cryogenic cooling and operate only in pulsed mode, the wavelengths exceeding 10 µm [6].

The design of a two-colour VECSEL with a wavelength separation of tens of nanometres is complicated by two main difficulties. The first problem is concerned with unequal ‘living conditions’ for the wavelengths: the emission at the short wavelength ($\lambda_S$) could be absorbed strongly in the quantum wells (QWs) emitting at the long-wavelength ($\lambda_L$). The second problem stems from having two sets of non-identical QWs capturing carriers from the same reservoir, resulting in competition for the available gain. Both of the above problems have to be solved in order to design an efficient dual-wavelength VECSEL.

Recently, two variants of dual-wavelength VECSELs have been proposed by our groups [7, 8]. In the first one the problem of optical field interaction (the absorption of $\lambda_S$ emission in the deeper QWs) was solved by positioning $\lambda_L$ QWs at the nodes of the standing wave at $\lambda_S$. This approach allowed for the first observation of dual-wavelength emission with optical modes sharing a common VECSEL cavity. The laser output remained cw until the pump power exceeded a critical value. Intensity instability was observed beyond this pump power. The reason for pulsed operation at high-power emission is as yet not clearly understood. By hypothesis, the observation could likely be attributed to residual short-wavelength absorption due to lack of coincidence of the QW positions with the nodes of the short-wavelength pattern.

The second approach for reaching dual-wavelength emission resembled a coupled-cavity VCSEL, with an intermediate mirror acting as an optical long-wave-pass filter to prevent absorption of short-wavelength emission in the long-wavelength gain area [8]. The mirror consisted of alternating AlAs and Al$_{0.3}$Ga$_{0.7}$As layers and was designed to be transparent for pump radiation and highly reflective for $\lambda_S$. The layer structure of the mirror resulted in resonant effects for the pump light. In other words, the pump reflections from the interfaces should be taken into account when analysing optical pumping of such a dual-wavelength VECSEL. Usually, when a more conventional VECSEL is modelled, only the exponential decay of the pump power along the gain region is taken into consideration [9]–[11].

In this paper, we perform a theoretical analysis and a numerical simulation of optical pumping of both a conventional single-mode and a dual-wavelength VECSEL’s active region. Our approach takes into consideration pump-light reflections inside the active region, where the carrier generation rate is assumed to be an arbitrary function of geometrical length. The
resulting intensity distribution is quite different from what would be obtained by following the monotonous exponential decay given by the Beer–Lambert law. A similar theoretical analysis could be applied to the modelling of in-well optical pumping, as the pump intensity attenuation is small and resonant effects for the pump radiation are significant [12].

2. Mathematical model and simulations

A general optical pumping configuration is shown in figure 1. The active region of the structure includes $N$ sections separated by blocking layers that prevent carrier transport between the sections. The section, identified by the index $i$, consists of $m_i$ QWs. The QWs are assumed to have the same width and the same composition in each section. These parameters are not required to be the same in different sections. The pump beam is incident upon the structure from the left side and is absorbed by the QWs’ barrier layers. Our model allows for interference of the reflected pump wave with the incident pump radiation.

Assuming absence of electric bias applied to the VECSEL structure and charge neutrality, one can derive the carrier distribution along the absorber region:

$$D_a \frac{d^2n}{dx^2} - \frac{n}{\tau} + G = 0.$$  

Here $n$ is the carrier density, $D_a$ the ambipolar diffusion coefficient, and $\tau$ the ambipolar carrier lifetime (related to the diffusion length by $L_a = \sqrt{D_a \tau}$) due to the spontaneous recombination. The carrier generation rate $G$ is

$$G(x) = -\frac{dS}{dx} \frac{\lambda_p}{\hbar c}.$$
where $S(x)$ is the pump power density, $\lambda_p$ the pump wavelength, $h$ Planck’s constant, and $c$ the speed of light. When the Beer–Lambert law is satisfied, $S(x)$ is

$$S(x) = \frac{P_{in}}{\pi r^2} e^{-\alpha x},$$  \hspace{1cm} (2)

where $P_{in}$ is the pump power at the onset of the absorber region, $r$ the beam radius, and $\alpha$ the absorption coefficient. In the general case, pump power density differs from (2) and should be found as a solution to the pump wave equation inside the active region. Examples of such a solution are presented in the following.

The diffusion equation (1) for an arbitrary function $G$ can be solved to give:

$$n(X) = C_1 \sinh(X) + C_2 \cosh(X) + \int_0^X F(\zeta) \sinh(X - \zeta) \, d\zeta,$$

where $X = x / L_a$, $F(X) = -\tau G(L_a X)$, $C_{1,2}$ are constants dependent on the boundary conditions. Formula (3) holds for any $X$ inside the absorber region, i.e. the homogeneous layer between two QWs or between a QW and a blocking layer. The constants $C_{1,2}^{(j)}$ are unique for the $j$-th barrier region. Moreover, these constants are interdependent in each section because of the diffusion carrier flux into unbound states above the QWs. One can derive the following expression, which links $C_{1,2}$ iteratively in the adjoining barriers of the same section:

$$
\begin{pmatrix}
C_1^{(j+1)} \\
C_2^{(j+1)}
\end{pmatrix} = M \begin{pmatrix}
C_1^{(j)} \\
C_2^{(j)}
\end{pmatrix} + \xi \int_0^{X_{QW}^{(j)}} F(\zeta) \sinh(X_{QW}^{(j)} - \zeta) \, d\zeta \begin{pmatrix}
\cosh(X_{QW}^{(j)}) \\
-\sinh(X_{QW}^{(j)})
\end{pmatrix},
\end{equation}

When deriving the last equations, the carrier density, specified by (3), was supposed to be continuous across a QW layer (see appendix A of [11] for more detail). A similar equation is written in [11] where a special case of the carrier generation rate $G$ satisfying the Beer–Lambert law has been applied.

Thus, the problem is reduced to finding the $C_{1,2}^{(1)}$ values. By neglecting the carrier flux over the blocking layer at $X = 0$, we obtain:

$$\left. \frac{dn}{dX} \right|_0 = C_1^{(1)} = 0.$$

To determine $C_2^{(1)}$, one must find a value, which together with the known value of $C_1^{(1)}$, disables carrier transport across the right blocking layer in the section:

$$\left. \frac{dn}{dX} \right|_{X_{b1}} = C_1^{(m+1)} \cosh(X_{b1}) + C_2^{(m+1)} \sinh(X_{b1}) + \int_0^{X_{b1}} F(\zeta) \cosh(X_{b1} - \zeta) \, d\zeta = 0.$$

Corresponding calculations can be repeated for other sections by shifting the origin of the $X$-axis to the position of the left blocking layer in the section concerned.

Let us examine a few examples. First, we discuss a typical optically pumped single-mode VECSEL structure, e.g. like that described in [10]. The resonant-gain active region of the laser consists of nine QWs made of In$_{0.16}$Ga$_{0.84}$As separated by barriers made of GaAs.
Figure 2. Carrier density distribution in the QWs ($n_{QW}$) and the normalized carrier generation rate ($G/G_{\text{max}}$) in the barrier layers.

The semiconductor Bragg mirror comprises 30 pairs of alternating GaAs/AlAs layers. The Al$_{0.3}$Ga$_{0.7}$As output window layer and the capping layer of GaAs are grown over the active region. We assume that the VECSEL is operating at the wavelength of 980 nm. The structure consists of a single section terminated by two blocking layers in accordance with the model shown in figure 1.

Figure 2 displays $G$ normalized to its maximum value and the carrier density distribution in the QWs. The parameters used in the simulation are summarized in table 1. To calculate $G$, we have used a transfer matrix approach within a plane wave approximation. The pump power density was calculated as $S = 0.5 \text{Re}[E^*H]$, where $E$ and $H$ are the complex amplitudes of the pump field’s transversal components. It can be easily seen from the graph that the behaviour of $G/G_{\text{max}}$ differs substantially from the exponential decay generally adopted in simulations [9]–[11]. The pulsations of $G$ are due to pump wave reflections in the multi-layered structure of the laser. According to our calculations, the carrier distribution non-uniformity over the QWs exceeds 9% (we determine the factor of non-uniformity as $\eta = \sigma/a$, where $\sigma$ is the standard deviation and $a$ is the mean value of the QW carrier distribution). The deeper the QWs involved, the higher the non-uniformity of the carrier distribution. For example, if In$_{0.25}$Ga$_{0.75}$As QWs are used instead of In$_{0.16}$Ga$_{0.84}$As, $\eta$ should amount to 20%. To equalize the QW carrier concentration, insertion of blocking layers into the barriers separating the QWs has been proposed [7]–[9]. These blocking layers should be transparent for pumping but impenetrable to carrier motion. Moreover, the role of the blocking layers is greatly increased if the optically pumped structure comprising of QWs of different composition is considered [7, 11]. As has been shown in [7, 11], if the carrier generation (barrier) regions for the nonidentical QWs are not separated into sections, almost all carriers are captured by the deep QWs and the shallow QWs are hardly pumped enough to reach the threshold value of lasing.

As a second example, we consider a dual-wavelength VECSEL structure with a long-wave-pass filter specially designed to prevent absorption of short-wavelength emission in the
Table 1. List of parameters used in the simulation.

| Parameter               | Value | Units |
|-------------------------|-------|-------|
| QWs of the conventional single-mode VECSEL | $\tau_c$ | 0.25 | ps |
|                         | $\tau_e$ | 10 | ps |
|                         | $\tau_r$ | 2 | ns |
|                         | $t_{QW}$ | 8 | nm |
| QWs of the short-wavelength gain area of the dual-wavelength VECSEL | $\tau_c$ | 0.3 | ps |
|                         | $\tau_e$ | 5 | ps |
|                         | $\tau_r$ | 2 | ns |
|                         | $t_{QW}$ | 7 | nm |
| QWs of the long-wavelength gain area of the dual-wavelength VECSEL | $\tau_c$ | 0.15 | ps |
|                         | $\tau_e$ | 20 | ps |
|                         | $\tau_r$ | 2 | ns |
|                         | $t_{QW}$ | 7 | nm |
| Barriers                | $\tau$ | 5 | ns |
|                         | $D_a$ | 10 | cm$^2$ s$^{-1}$ |
|                         | $\alpha$ | 13200 | cm$^{-1}$ |
| Pumping                 | $P_{in}$ | 0.2 | W |
|                         | $\lambda_p$ | 808 | nm |
|                         | $d$ | 100 | $\mu$m |

long-wavelength gain area [8]. Figure 3 shows the refractive index profile and the electric field distributions inside the laser chip. The structure contains shallow and deep QWs which were designed to emit at the short wavelength $\lambda_S \approx 966$ nm and at the long wavelength $\lambda_L \approx 1047$ nm, respectively. The short-wavelength gain region is located close to the surface of the device and is separated from the long-wavelength gain region by the long-wave-pass filter. According to the general scheme presented in figure 1, the short-wavelength gain area includes four sections of paired In$_{0.14}$Ga$_{0.86}$As QWs. The strain-compensating layers of GaAs$_{0.7}$P$_{0.3}$, located between the sections act also as carrier blocking layers. Seven In$_{0.25}$Ga$_{0.75}$As QWs forming three clusters of two QWs and one more QW are placed in a total of four sections of the long-wavelength gain region. Again, wide-bandgap layers of GaAs$_{0.7}$P$_{0.3}$ are used to block carrier transport between the sections and for strain compensation. The long-wave-pass filter made of alternating AlAs and Al$_{0.3}$Ga$_{0.7}$As layers is transparent for the pump light and strongly reflective for the short-wavelength radiation. Moreover, the stop-band of the filter is chosen to have $\lambda_L$ at one of the reflection minima of the filter. The graphs shown at the bottom of figure 3 confirm that short-wavelength emission is negligible in the long-wavelength gain area.

By varying the location of the blocking layers inside the active regions, one can equalize the QW populations. Figure 4 displays the carrier density distribution in the barriers and QWs of the short- and long-wavelength gain regions. The barrier carrier concentration demonstrates a step-wise profile with jumps corresponding to the positions of the blocking layers. Such behaviour is caused by the impenetrability of those layers for carriers. The results shown in figure 4 have been calculated for s-polarized pump light at an incident angle of 35°. The non-uniformity of QW carrier populations was evaluated to be about 0.05 and 0.22% for the $\lambda_S$ and $\lambda_L$ gain areas, respectively. The positions of the QW clusters correspond approximately to
Figure 3. Amplitude of the electric field at \( \lambda_S \) (solid line) and \( \lambda_L \) (dashed line) along with the refractive index profile.

Figure 4. Carrier density distribution \( n \) in the barriers and QWs \( n_{QW} \) for (a) the short-wavelength and (b) the long-wavelength gain areas.

Antinodes of the standing wave patterns thus providing a resonant periodic gain active structure. In order to increase the absorption length for the pump light in the third and the fourth sections of the \( \lambda_L \) gain region, the QWs’ positions were shifted by double the distance as compared to that of the QWs in other sections.

Figure 5 shows \( G \) normalized to its maximum value inside the active regions of the device. The graphs in figure 5 have been calculated with parameters corresponding to those in figure 4. The reflections of the pump light manifest themselves as pulsations of \( G \), which evidently are
of a higher value in the $\lambda_S$ gain area. The amplitude of these pulsations is quite comparable with the mean value of $G$ inside the sections. As mentioned earlier, strong reflections of the pump light in the laser structure, especially in the long-wave-pass filter, is the main reason for such pulsations.

In figure 6, we show the effect of the pump incidence angle on the non-uniformity factor $\eta$. As the incidence angle deviates from the optimal value, $\eta$ increases rapidly, especially in the $\lambda_S$ active region. This is just one more striking illustration of the pump reflection’s role in the laser performance. The reflections are evidently weaker in the $\lambda_L$ gain area, thus providing
a less noticeable carrier non-uniformity variation. As before, the calculations were performed for s-polarized pump light. A simulation of p-polarized pump light results in qualitatively similar behaviour.

3. Conclusions

We have numerically studied the optical pumping of VECSELs, both conventional single-wavelength and dual-wavelength. The theoretical approach allows us to analyse the carrier density distribution along a gain region of a quite general laser structure. The structure is supposed to contain an arbitrary number of sections divided by blocking layers. Each section may include an arbitrary number of QWs. Because of pump light reflections, the carrier generation rate may differ from what follows from the Beer–Lambert law.

For a single-wavelength VECSEL with common structure parameters, the non-uniformity of QW carrier distribution is calculated to be more than 9%. We have shown that the carrier generation rate profile demonstrates quite considerable pulsations superimposed on an exponential decay that results from the Beer–Lambert law.

The important role of pump reflections in creating a local carrier generation rate in a dual-wavelength VECSEL with a long-wave-pass filter has been demonstrated. We have shown that the carrier non-uniformity in QWs can be radically reduced to a value far below 1% if blocking layers are inserted into appropriate positions in the active region. The QW carrier distribution, especially in the short-wavelength gain area, is a strong function of the pump beam’s incidence angle, thus emphasizing the importance of pump reflections.

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