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# THERMAL MANAGEMENT IN VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASERS: AN ANALYTICAL APPROACH

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ABSTRACT

This paper tackles with thermal management in optically pumped vertical-external-cavity surface-emitting lasers. The considerations are based on one-dimensional, stationary solution of heat conduction equation. It is shown that even such simplified model can provide useful hints for designing devices of this type.

## 1. Introduction

Optically pumped vertical-external-cavity surface emitting lasers (VECSEL's) appeared in 1997 and quickly attracted attention of many researchers [1]. They are prized due to the possibility of generation of high continuous-wave output power and near-diffraction-limited beam quality. The versatility of semiconductor gain materials allows to obtain the emission from wide spectral range. The external cavity enables the use of different intra-cavity elements, like filters or non-linear crystals for achieving such effects as narrowing linewidth, short pulse generation and frequency conversion [2], [3].

The major constraints on the VECSEL performance are thermal [4]. Uncontrollable temperature rise leads to the following undesired effects:

- structure deformation,
- band gap modification.

As a result there is the lost of the resonant periodic gain, the decrease of pumping efficiency and the misalignment between the quantum well peak gain and minimal reflectivity of the Bragg reflector. All these phenomena significantly reduce the device performance and thus designing an efficient heat removal system is crucial in VECSELs.

## 2. Brief characterization of the device

A simplified scheme of a VECSEL is presented in Fig. 1. The active region consists of a periodic array of quantum wells, spaced at half-wavelength intervals by barrier/spacer layers. The positive feedback is provided by DBR mirror and external mirror. Quantum wells are optically pumped with usage of a diode or other laser source.

Thanks to optical pumping the structure may be undoped – there is no need for the DBR to incorporate composition grading schemes, which reduce electrical impedance, but impair the optical efficiency. However such solution is a source of another problem: the structure is heated due to absorption of pumping light in the gain region and DBR.

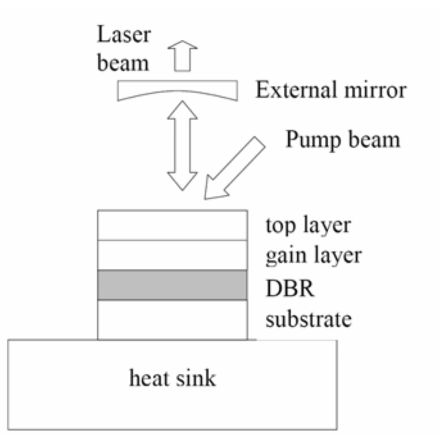


Fig. 1. Schematic representation of a VECSEL system.

In case of standard device (Fig. 1) waste heat can be removed to the heat sink only through the substrate. This path is not efficient because of large thickness of this layer and its low thermal conductivity. Two main approaches are known in this case. The first is called a thin-device approach: the substrate is almost removed with thin layer (approximately 6 microns) left. Then the structure is soldered directly to the heat sink. The second approach uses so-called heat spreader, which is a transparent crystal of high thermal conductivity bonded to the upper surface (Fig. 2). Such an element creates a new path for heat flow, effectively bypassing the DBR and the substrate.

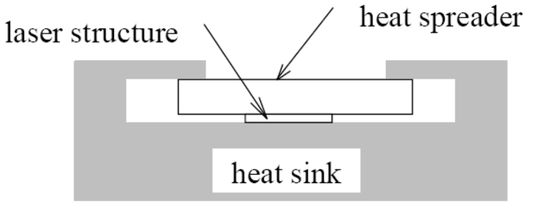


Fig. 2. VECSEL with a heat spreader.

## 3. Model

From thermal point of view VECSEL is a stratified medium heated at the top by almost circular beam. Therefore the choice of cylindrical coordinates with two variables (radial and axial) taken into account seems to be fully justified. Such two-dimensional models have already been developed. In Ref. [5] analytical approach using Hankel transformation of the 0-th order has been described. In Ref. [4] an advanced commercial software based on Finite Element Method has been used.

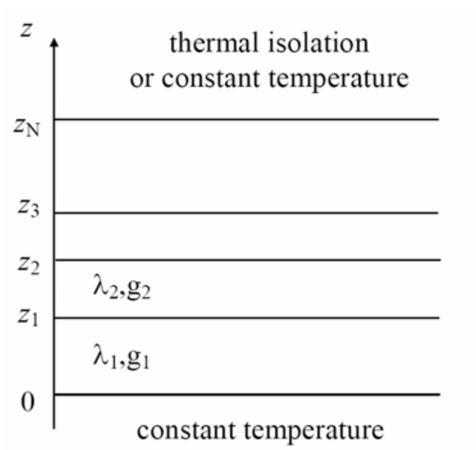


Fig. 3. VECSEL geometry considered theoretically.

In this work a very simplified, one-dimensional, analytical approach is presented. The reduction of dimensionality is considered due to conditions:

a) the diameter of pumping beam is much larger than the total thickness of the device,

b) the weak radial heat flow.

In case of a thin device approach both conditions are satisfied. The assumed diameter of the pumping beam is 100 μm, so it exceeds the device thickness by order of magnitude. The condition b) is expected to be satisfied according to the analogy with an edge-emitting laser, where weak lateral heat flow has been found [6]. In case of a device with heat spreader the situation is bit controversial. For diamond heat spreader (of high thermal conductivity) it is possible to lower its thickness assumed in calculations, for sapphire one (of low thermal conductivity) the approximation is rather based on condition b).

All calculations are provided for the same devices as considered in Ref. [4].

### *3.1. Heat conduction equation*

A stack of layers of different thickness and thermal conductivities is schematically depicted in Fig. 3. It is assumed that in each layer there is a heat source $g_n$ = const. In this case the heat conduction equation reduces to the one-dimensional, time-independent form:

$$\frac{d}{dz}\left(\lambda(z)\frac{d}{dz}T(z)\right)=-g(z) \qquad (1)$$

where $T$ denotes relative temperature (the temperature exceeding the ambient temperature), $\lambda$ is the thermal conductivity and $g$ – a step-like function describing the heat source. For the $n$-th layer (1) can be written as:

$$\frac{d^2}{dz^2}T_n(z)=-\frac{g_n}{\lambda_n} \qquad (2)$$

and the solution reads

$$T_n(z)=-\frac{g_n}{2\lambda_n}z^2+A_n z+B_n. \qquad (3)$$

Note that in a system of $N$ layers there are $N$ solutions of the form (3) containing $2N$ constants ($A$ and $B$). On the other hand there are $N$–1 interfaces. At each interface continuity condition for the temperature and heat flux must be satisfied. In addition, taking into account boundary conditions at $z = 0$ and $z = z_N$, a nonhomogeneous, $2N \times 2N$ set of linear equations is obtained. Unknowns $A_n$ and $B_n$ are determined by elimination of variables.

### *3.2. Solution for a thin-device approach*

For a thin device one can assume that the temperature of bottom surface of the structure is constant and the top surface is thermally insulated

$$T(z=0)=T_b, \quad \frac{\partial}{\partial z}T(z_N)=0. \qquad (4)$$

Then the coefficients $A_n$ and $B_n$ can be determined separately. For the top layer (layer $n = N$):

$$A_N=\frac{g_N}{\lambda_N}z_N, \qquad (5)$$

while for downwards successive layers the recursive expression can be used:

$$A_n=\frac{\lambda_{n+1}}{\lambda_n}A_{n+1}-\frac{z_n}{\lambda_n}\left(g_{n+1}-g_n\right). \qquad (6)$$

For the bottom layer (layer $n = 1$):

$$B_1=T_d, \qquad (7)$$

while for upwards successive layers the recursive expression can be used:

$$B_{n+1} = \left( \frac{g_n - 0.5\, g_{n+1}}{\lambda_{n+1}} - \frac{g_n}{2\lambda_n} \right) z_n^2 + \\ + \left( 1 - \frac{\lambda_n}{\lambda_{n+1}} \right) A_n z_n + B_n. \quad (8)$$

### *3.3. Solution for a device with a heat spreader*

For a device with heat spreader the assumption of constant temperature of the bottom surface is still justified, but the upper boundary condition should be changed to isothermal one:

$$T(z=0) = T_b, \quad T(z=z_N) = T_{up}. \quad (9)$$

Then the coefficients $A_n$ and $B_n$ are related with each other. In this case elimination of variables is done by elimination of all unknowns except $A_1$. Thus it is assumed that all coefficients depend on $A_1$ in the following way:

$$A_n = \overline{w}_n A_1 + \overline{\overline{w}}_n, \; B_n = \overline{u}_n A_1 + \overline{\overline{u}}_n \quad (10)$$

where

$$\overline{w}_1 = 1, \overline{\overline{w}}_1 = 0, \quad \overline{u}_1 = 0, \overline{\overline{u}}_1 = T_0. \quad (11)$$

For successive layers ($n > 1$) recursive relations must be used

$$\overline{w}_n = \frac{\lambda_{n-1}}{\lambda_n} \overline{w}_{n-1}$$
$$\overline{\overline{w}}_n = \frac{\lambda_{n-1}}{\lambda_n} \overline{\overline{w}}_{n-1} + \frac{g_n - g_{n-1}}{\lambda_n} z_{n-1}$$
$$\overline{u}_n = (\overline{w}_{n-1} - \overline{w}_n) z_{n-1} + \overline{u}_{n-1}$$
$$\overline{\overline{u}}_n = \frac{1}{2}\left( \frac{g_n}{\lambda_n} - \frac{g_{n-1}}{\lambda_{n-1}} \right) z_{n-1}{}^2 + (\overline{\overline{w}}_{n-1} - \overline{\overline{w}}_n) z_{n-1} + \overline{\overline{u}}_{n-1} \quad (12)$$

The upper boundary condition allows to calculate $A_1$:

$$A_1 = \frac{T_{up} + \frac{g_N}{2\lambda_N} z_n{}^2 - \overline{\overline{w}}_N z_n - \overline{\overline{u}}_N}{\overline{w}_N z_N + \overline{u}_N}. \quad (13)$$

## 3. Results

In this paper an InGaAs VECSEL is considered. The detailed description of the device can be found in Table 1 in Ref. [4]. It is assumed that pump absorption and hence heat loading occur in the gain region and DBR. The radial- and *z*-dependent expressions for the heat load were given in Ref. [4] as Eqs. (1) and (2). Here mean values for each layer have been calculated with usage of package Mathematica [7].

Figure 4 presents calculations for the device with a heat spreader. It is well seen that silicon carbide ($\lambda = 0.49$ W/mmK) or diamond ($\lambda = 2$ W/mmK) may be the recommended heat spreader materials, while

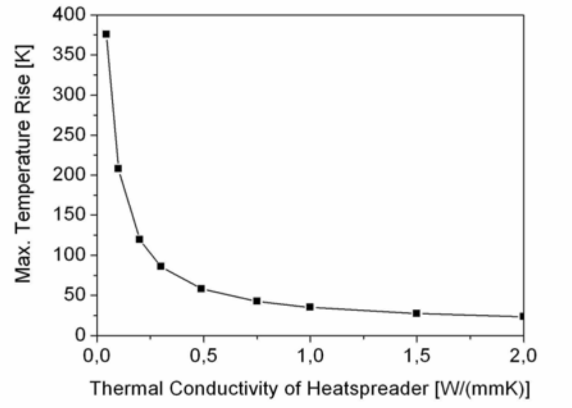


Fig. 4. Dependence of the maximum temperature rise in the laser structure on the thermal conductivity of the heat spreader.

sapphire ($\lambda = 0.044$ W/mmK) should be rather avoided in this application.

Figure 5 shows the comparison of maximum device temperature for a VECSEL with and without the diamond heat spreader. Over the range of DBR thermal conductivities considered, the heat spreader approach seems to outperform the thin-device approach. In addition, one can say, that the heat spreader transfers heat so effectively that considering sophisticated models of the heat transport through DBRs as in Ref. [5] is questionable.

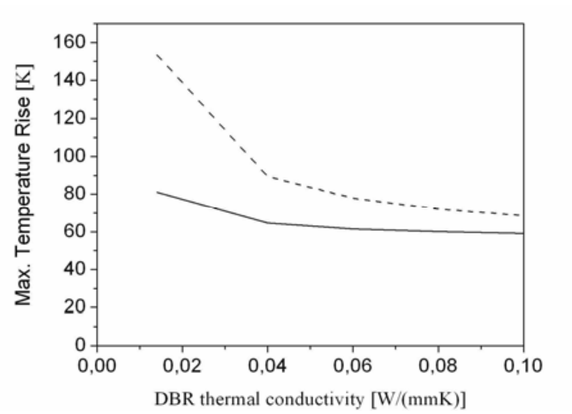


Fig. 5. The effect of DBR thermal conductivity. The solid line deals with a device with a heat spreader, dashed – is calculated for a thin device.

It is interesting to compare Figs. 4 and 5 with Figs. 4 and 11 from Ref. [4]. The diagrams here and there lead to similar conclusions, although the results differ quantitatively. These differences can be explained in terms of substitution of radial- and *z*-dependent expressions for the heat load by mean values.

## 4. Conclusion

A simple, one-dimensional, analytical model of heat flow has been presented. It is based on heat conduction equation, so it is applicable in structures containing layers of thickness much larger than phonon mean-free path. For thin layers the heat flow looses its diffusive character and the heat conduction equation must be modified [8].

In this work, as in Ref. [4], the Bragg reflector is treated as one layer of thermal properties described by an effective thermal conductivity. Then the thinnest layer in the considered VECSEL is the 0.5-micron top layer and heat conduction equation can be used.

Another question may be asked about the dimensionality of the model. However detailed investigations on the range of application of conditions a) and b) mentioned in Section 3 are not within the scope of this work. Here, it is shown that such simple one-dimensional analytical expressions can provide results similar to those obtained by much more complicated analytical or numerical models and hence may be a useful tool for designing VECSEL cooling systems.

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