Coupled-Cavity Bottom-Emitting VCSELs — a New Laser Design for Increased Single-Transverse-Mode Output Power

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March 11, 2005

Keywords: VCSEL, CCBE-VCSEL, semiconductor laser, high output power, mode-discrimination, single-mode, single-transverse-mode.

Abstract

A new type of VCSEL, called the coupled-cavity bottom-emitting VCSEL, is presented. The optical properties of CCBE-VCSELs are investigated theoretically using a 3-dimensional optical field model, and it is concluded that such devices may be capable of providing increased single-transverse-mode output power.

Introduction

Since the beginning of the 1990's, *vertical-cavity surface-emitting lasers* (VCSELs) have been the subject of increasing research interest. Today, VCSELs are commercially available and have successfully entered the short-range data-communications market, due to several attractive characteristics, including single-transverse-mode operation, rotationally symmetric output and the possibility of on-wafer testing.

In order to expand into other areas of optoelectronics, *e.g.* laser line-of-sight data-communication, optical interconnects, high-density optical storage and laser printing, VCSELs must provide high optical output power while maintaining these characteristics. The former requires the use of large apertures, in order to provide a large gain area, from which photons can be added to the optical field. The latter, unfortunately, is non-compatible with the use of large apertures, since large apertures make single-transverse-mode operation impossible in current VCSEL designs.

*The work described in this article was carried out at Research Center COM at the Technical University of Denmark in cooperation with Odense University College of Engineering and Alight Technologies A/S. The author is currently affiliated with the Nano-Science Center at the University of Copenhagen and Atomistix A/S.

In this article, a new type of VCSEL, called the *coupled-cavity bottom-emitting VCSEL* (CCBE-VCSEL), is presented. This device may be capable of providing increased optical output power, while maintaining a single transverse mode, due to two beneficial effects: 1) Efficient cooling of the device is possible, and 2) discrimination of higher order modes allows for single-transverse-mode operation, even for large apertures.

The discussions of this article are purely theoretical, and the results are mainly based on simulations performed using a 3-dimensional optical field model, which has been developed specifically for the purpose of analyzing CCBE-VCSELs. The article focuses on the transverse optical properties of the device, but the longitudinal properties have been examined as well. The model is described in details in [1], along with further information about the analyses of this article.

The CCBE-VCSEL

Figure 1 shows a schematic of a CCBE-VCSEL. This novel device consists of two optical cavities, formed by three distributed Bragg reflectors (DBRs). The passive substrate cavity is much longer than the active cavity, in which optical gain is provided by a quantum well. The top DBR has higher reflectivity than the middle- and bottom DBRs combined, and the device is therefore bottom-emitting; the optical field is emitted through a hole in the bottom contact. The bottom-emitting structure allows for efficient cooling, since a heat sink can be attached to the top contact, which is close to the active region, in which the heat is generated (≈ 5 μm). In current top-emitting VCSEL designs, efficient cooling is difficult, since heat sinks can only be attached at the bottom, which is far away from the active region (≈ 500 μm).

Above the active cavity, an aperture is placed in the center of a thin oxide layer. The aperture serves a dual purpose: 1) It provides optical confinement, since the refractive index in the aperture is much larger than in the surrounding oxide layer, and 2) it provides electrical confinement, since the oxide layer is non-conducting, while the aperture region is conducting. In other words, both the optical field and the electrical current are confined to the center of the device by the aperture.

The aperture gives rise to diffraction of the optical field, and due to the long substrate cavity this causes a "discrimination" of higher order modes. The mode-discrimination can be qualitatively described as follows: Most of the optical field is confined to the short active cavity, due to the middle DBR, but a fraction of the field propagates in the long substrate cavity. Due to the diffraction at the aperture, the field "spreads out" transversally as it traverses the substrate cavity, and as it returns, after being reflected at the bottom DBR, some of the field is not coupled back into the active cavity. The higher order modes diffract more than the fundamental mode; they therefore experience higher diffraction losses, and they are therefore discriminated.

The idea of using a coupled-cavity geometry to introduce mode discrimination in VCSELs is not new. Several coupled-cavity geometries have been investigated experimentally [2, 3, 4], and theoretical investigations also exist [5]. The CCBE-VCSEL differs from these designs by the use of the substrate as a long, coupled cavity. It does *not* require external optical components,

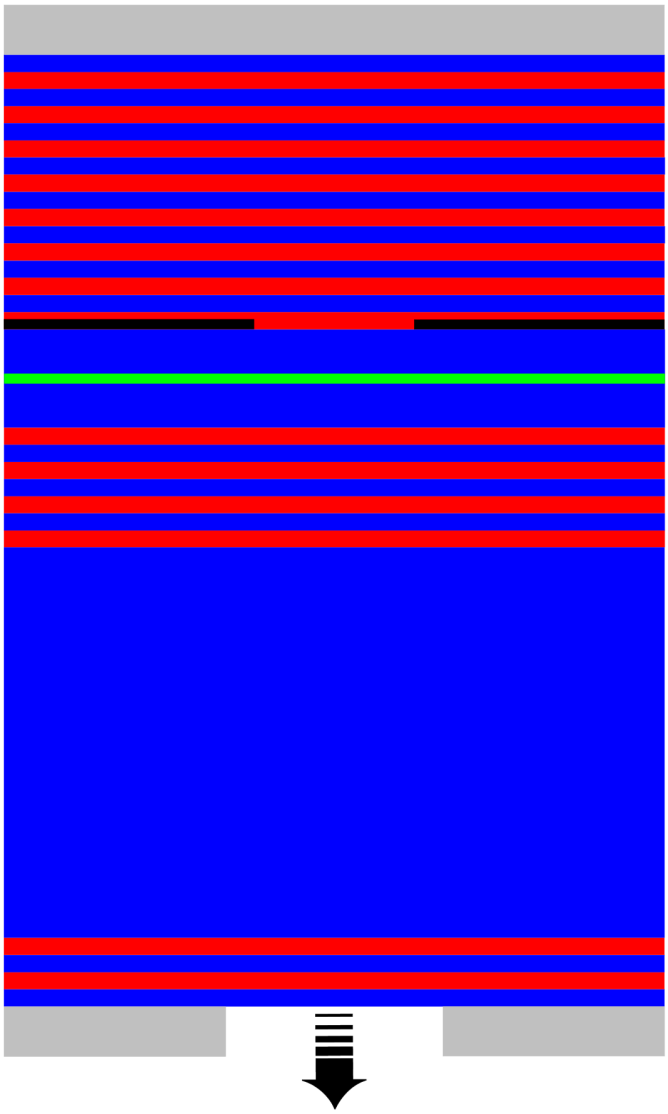

Figure 1: Schematic of the benchmark CCBE-VCSEL structure, consisting of two optical cavities (blue), formed by three DBRs (red and blue stripes). The passive substrate cavity is much longer than the active cavity, in which optical gain is provided by a quantum well (green). The optical field is emitted through a hole in the bottom contact (grey), and a heat sink can be attached to the top contact (also grey). Above the active cavity, an aperture is placed in the center of a thin oxide layer (black). Both the quantum well and the aperture are placed in antinodes of the optical field.

which make alignment tedious and mass-production expensive, and the bottom-emitting geometry makes efficient cooling possible.

Due to the diffraction effects in CCBE-VCSELs, effective index models, such as the one described in [6], do not accurately describe the optical field in such devices. The 3-dimensional optical field model, used for the analysis of the optical field in CCBE-VCSELs described in the next section, is a so-called eigenmode expansion model, and it is fully capable of describing these diffraction effects. Similar models are described in [7] and [8], and the model has been successfully tested against the results found in [9].

Optical Properties of CCBE-VCSELs

Three parameters determine the diffraction losses in CCBE-VCSELs, and thus the degree of mode-discrimination in such devices: 1) The substrate cavity thickness, 2) the aperture diameter, and 3) the reflectivity of the middle DBR. A long substrate cavity results in large diffraction losses, and therefore in high mode-discrimination; a small aperture diameter has the same effect, as does a low reflectivity in the middle DBR. The explanations are straight forward: A long substrate cavity provides the optical field with plenty of space to "spread out", which means that a substantial fraction of the field is not coupled back into the active cavity. A small aperture diameter leads to large diffraction, which means that the optical field "spreads out" significantly over short distances. Finally, a low reflectivity in the middle DBR allows for a substantial fraction of the optical field to propagate in the substrate cavity, which means that a large fraction of the field "spreads out" and gets lost.

In order to get a first qualitative analysis of the optical properties of CCBE-VCSELs, a benchmark CCBE-VCSEL structure has been defined. The benchmark CCBE-VCSEL structure has been based on the benchmark VCSEL structure from [9], and the following extensions have been made: 1) The number of periods in the top DBR has been increased, to make the structure bottom-emitting, and 2) the bottom DBR has been split into a middle DBR and a bottom DBR, separated by a long substrate cavity. The benchmark CCBE-VCSEL structure has the following design characteristics: The top DBR contains 33.5 periods, and the oxide-aperture is placed in an antinode of the optical field. The optical cavity is one wavelength thick, and has a 5 nm quantum well placed in the optical field maximum in the center. The quantum well provides gain within the diameter of the aperture and loss outside this diameter. The total number of periods in the middle- and bottom DBRs is 24.5, and the half period is placed in the middle DBR. The number of periods in the bottom DBR is then $N_2 = 24.5 - N_1$, where N_1 is the number of periods in the middle DBR (a half-integer number). All the layers in the structure have the same diameter, d_0, which is five times as large as the aperture diameter, d[1]. The CCBE-VCSEL is designed for lasing near $\lambda = 980$ nm.

A layer-by-layer description of the benchmark CCBE-VCSEL structure is provided in Table 1. It should be emphasized, that the benchmark CCBE-VCSEL is a test structure, upon which calculations can be easily made, and from which qualitative device trends can be deduced. The aim of this article is

[1]Due to model specific considerations, the layer diameter for $d = 1$ μm is $d_0 = 10$ μm, *i.e.* ten times the diameter of the aperture [1].

Layer(s)	Thickness	Material	Refractive Index
Ambience	-	Air	1
Top DBR	69.49 nm	GaAs	3.53
(33.5 periods)	79.63 nm	AlGaAs	3.08
Buffer	63.71 nm	AlGaAs	3.08
Aperture	15.93 nm	AlAs	2.95 for $r < d/2$
		AlOx	1.60 for $r > d/2$
Active Cavity	136.49 nm	GaAs	3.53
	5.00 nm	QW	3.53
	136.49 nm	GaAs	3.53
Center DBR	79.63 nm	AlGaAs	3.08
(N_1 periods)	69.49 nm	GaAs	3.53
Passive Cavity	L	GaAs	3.53
Bottom DBR	79.63 nm	AlGaAs	3.08
(N_2 periods)	69.49 nm	GaAs	3.53
Ambience	-	Air	1

Table 1: Layer-by-layer description of the benchmark CCBE-VCSEL structure, which has been analyzed to find the qualitative device trends of CCBE-VCSELs.

not to provide a detailed description of a structure for actual implementation, but to examine what characteristics CCBE-VCSELs can be expected to exhibit.

The structure has been analyzed using a 1-dimensional optical field model [1], and it has been concluded, that a single longitudinal mode exists for substrate cavity thicknesses below $L = 70$ μm. Since this article focuses on the transverse optical properties, only structures with $L < 70$ μm are discussed.

Figure 2 shows the threshold gain of the fundamental- and first order modes of the benchmark CCBE-VCSEL structure for different substrate cavity thicknesses, L, as found using the 3-dimensional optical field model[2]. At small thicknesses, the first order mode actually has smaller threshold gain than the fundamental mode, which indicates that the first order mode "fits" the active cavity better than the fundamental mode. As the substrate cavity thickness is increased, the threshold gain of both the fundamental- and the first order mode increases. The threshold gain of the first order mode increases more than that of the fundamental mode, and at $L \approx 24$ μm the two curves cross each other, and the threshold gain of the first order mode becomes increasingly larger than that of the fundamental mode, thus providing a means of mode-discrimination. This is due to the diffraction of the optical modes at the aperture, and the diffraction losses encountered upon each cavity-round-trip through the substrate cavity.

The threshold gain of the fundamental- and first order modes for different aperture diameters, d, is shown in Figure 3. The figure shows that the difference in threshold gain between the two modes increases for decreasing aperture size. As the aperture becomes smaller, the diffraction grows and the substrate cavity losses increase. The diffraction of the first order mode grows more than that of the fundamental mode, and the mode-discrimination is increased.

[2]The threshold gain of the optical modes actually varies significantly for small variations in the substrate cavity thickness. This "fine structure" is *not* shown in Figure 2, in which only some of the minima of the "fine structure" are plotted; it is discussed in [1].

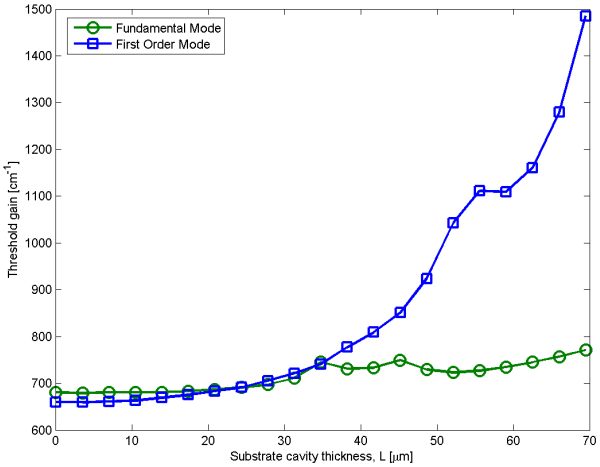

Figure 2: Threshold gain of the fundamental- and first order modes of the benchmark CCBE-VCSEL for different substrate cavity thicknesses. The threshold gain of the first order mode increases much more than that of the fundamental mode for increasing L. (Simulation with $N_1 = 14.5$ and $d = 8$ μm).

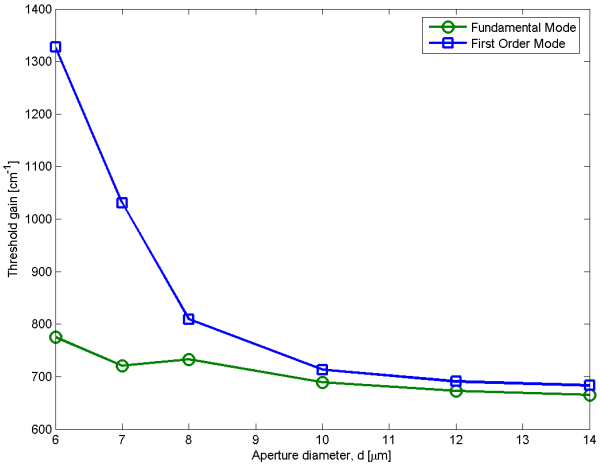

Figure 3: Threshold gain of the fundamental- and first order modes of the benchmark CCBE-VCSEL for different aperture diameters. The threshold gain of the first order mode increases much more than that of the fundamental mode for decreasing d. (Simulation with $N_1 = 14.5$ and $L = 41.7$ μm).

The threshold gain of the fundamental- and first order modes of the benchmark CCBE-VCSEL structure for different numbers of periods in the middle DBR, N_1, is shown in Figure 4. The figure shows that at large N_1 the threshold

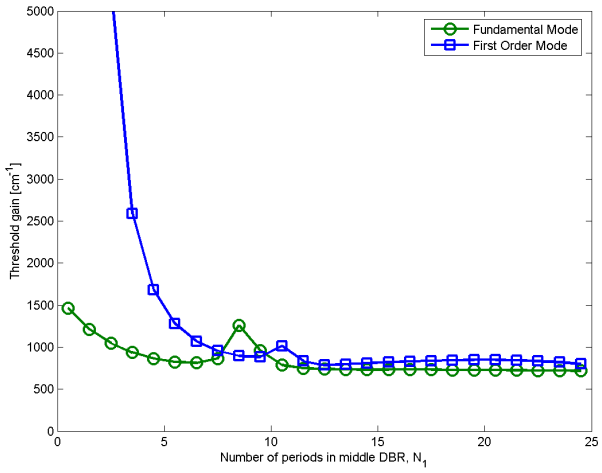

Figure 4: Threshold gain of the fundamental- and first order modes of the benchmark CCBE-VCSEL for different numbers of periods in the middle DBR. The threshold gain of the first order mode increases much more than that of the fundamental mode for decreasing values of N_1. (Simulation with $d = 8$ μm and $L = 41.7$ μm).

gain of the two modes is approximately the same, and that it increases for a decreasing number of periods. The threshold gain of the first order mode increases more than that of the fundamental mode, which — again — provides a means of mode-discrimination. This is due to the larger influence of the substrate cavity for smaller N_1, *i.e.* when a larger fraction of the optical field is confined in the substrate cavity.

Conclusions and Perspectives

A new type of VCSEL, called the *coupled-cavity bottom-emitting VCSEL*, has been presented. The device trends of CCBE-VCSELs have been investigated theoretically, and it has been shown that the CCBE-VCSEL may be capable of providing increased output power, while maintaining a single transverse mode. This important feature is due to the mode-discrimination caused by diffraction effects in the long substrate cavity of CCBE-VCSELs. Efficient cooling of the device is also possible, and it therefore appears that the CCBE-VCSEL may be a serious candidate for the high-power semiconductor lasers needed for the further expansion of the optoelectronics market.

Acknowledgements

I would like to thank Ole Albrektsen, Odense University College of Engineering, and Bjarne Tromborg, Research Center COM, for their contributions to this article and the work described herein.

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