Modulation Properties of Vertical Cavity Light Emitters

Doctoral Thesis by
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Stockholm, November 2001
Singulièure fortune où le but se déplace,
Et, n'étant nulle part, peut être n'importe où !
Où l'Homme, dont jamais l'espérance n'est lasse,
Pour trouver le repos court toujours comme un fou !

Charles Baudelaire “Le voyage”
Renaud Stevens

Modulation properties of vertical cavity surface emitting lasers

Royal Institute of Technology, Department of Microelectronics and Information Technology, Kista, Sweden, 2001. ISRN KTH/MVT/FR-01/4-SE; TRITA-MVT REPORT 2001:4; ISSN 0348-4467.

Abstract

It is estimated that, between the year 2000 and 2003, the number of online Internet users will grow from 250 millions to 500 millions. This growth results in rapidly increasing demand for fibre-optic communication bandwidth, occurring at all levels: from access and local area networks (LANs) to metro-area networks (MANs). A now established solution for many applications such as interconnects and Gigabit Ethernet is the vertical cavity surface emitting laser (VCSEL). The advantages of VCSELs are numerous: low fabrication and coupling costs, large modulation bandwidth, array integration and tunability. VCSEL-based modules, with speed up to 2.5 Gbit/s are now commercially available for multimode fibre (MMF) based applications. However, devices operating at long wavelength and higher transmission rates (10Gbit/s and more) will be needed in the near future.

The purpose of the work presented in this thesis was to obtain an understanding of the high-speed properties of VCSELs, in order to extend the modulation frequency at which they can be used in fibre optical communication systems. An approach for systematic high-speed characterisation of VCSELs is presented and both its potential benefits and problems are discussed. It is shown that the VCSEL dynamics, under certain conditions, can be well described by a small number of parameters that can be extracted from small signal measurements and used for further optimisation. The calibrated small-signal modulation responses of VCSELs have been measured and fitted to an analytical transfer function allowing the estimation of the resonance frequency, damping factor and parasitic cut-off at different bias points. This data can be used to determine the relative importance of different bandwidth limiting effects due to damping, thermal heating and parasitics.

Small signal analysis and transmission experiments were performed with a large sample of VCSELs covering the various ranges of applications. Visible VCSELs and resonant cavity light emitting diodes (RCLEDs) for very short reach plastic optical fibre (POF) applications, 850nm datacom VCSELs for short distance multimode fibre networks, and long wavelength VCSELs for long haul single mode fibre transmission.

Keywords: Semiconductor lasers, VCSEL, high-speed modulation, fibre optic networks, datacom, RCLED, plastic optical fibre
List of papers

The thesis is based on the following papers, which are referred to by their numbers:

**Paper 1**


**Paper 2**


**Paper 3 (invited)**


**Paper 4**


**Paper 5**


**Paper 6**

“Influence of spatial hole burning and mode competition on the modulation response of vertical cavity surface emitting lasers”, R. Schatz, H. Isik, M. Peeters and R. Stevens, to be submitted.
The work has also resulted in the following publications which, however have not been included in the thesis:


Acknowledgement

I would not be here at the first place without Anders Karlsson: everything started while finishing my military service in the French Airforce. After a few contacts back and forth I finally got an offer to join the department, at the express condition to give my answer 24h later. After hours of deep thinking I finally said yes, to be told I was expected to be up and running on site one week later! Even though Anders has always been very busy with the research, the European networks' meetings, the lectures in Paris and the salsa lessons, he always took the time to pass by my office for a chat or ask for the latest results, merci Anders.

My deepest thanks go to my supervisor Dr Richard Schatz. I think the hardest thing throughout my Ph.D. has not been the long hours setting the experiments and trying to get some results, submitting articles, writing this thesis or trying to understand the theory, it has been to convince Richard that VCSELs are worth studying and can give amazing results! This thesis could have been named “How to convince an expert on high speed DBR lasers (30GHz and beyond) that one of the most attractive characteristic of VCSEL is their potential for high speed communication when the maximum bandwidth is “only” 4 GHz” (this was the first result obtained, luckily since, this number has improved to 10 GHz), but the title being a bit too long I decided for the shorter version. I am glad after all these years Richard is now one of the most dedicated experts in the VCSEL field! I could not have made it without his patient help on understanding and modelling the physics of semiconductor lasers, his enthusiastic and dedicated approach for experimental work and his never ended support throughout my Ph.D. There is only one thing I regret, specially as an ambassador of French cuisine in Sweden: my failure to convince Richard that the best cost effective, calorie efficient and tasty lunch is not made of crisps and soda…

Because research is mainly a team effort, being based on previous results and knowledge, and progressing thanks to other people's suggestions, needs or disagreements, I would like to thank all the people who helped me during these years: Edgard Goobar for his genuine experimental skills who helped getting started, Olle Kjebon for his expertise on high-speed lasers, Klaus Streubel for his incredible enthusiasm and ability to emulate other people's motivation, Mattias “Tabernac”! Dahlström for his friendship and support in the lab as well as on the rugby field, and Hussein Isic for his help on writing the Matlab computer model. And all the students and staff previously or currently at FMI and QEO: Gunnar, Eilert, Bo, Tedros, Peter, Per, Stefan, Robert, Urban, Mohammed, Rubens, Nadeem, Hussein, Erik. A special thank to the VCSEL group at the semiconductor laboratory for sharing valuable knowledge on the growth, fabrication and processing issues, and performance of devices. Klaus Streubel, Mattias Hammar, Sebastian Lourdudoss, and all the ex- or current fellow students: Stefan, Nicky, Sebastian, Fredrik, Jonas, Egbert, Carlos, Jurgen, Martin, Roberta, Sofia, Pia. I would like to thank Professor Lars Thylen for making it possible to study in an internationally recognised institute, in a challenging domain with state-of-the-art scientific, technical, material and human resources. Eva Andersson has had an essential part in these years of studies, being always helpful and friendly with all administrative matters.

Anita Lövqvist was my office room-mate when I first arrived here and made a lot to make me discover and appreciate the multiple aspects of the Swedish culture, customs, cookies and language! I also would like to thanks the VCSEL/RCLED group...
from Mitel (Zarlink) for their friendship, for providing me state-of-the-art components throughout the years, for sharing their valuable knowledge and expertise of industrial research and development and for the extra sessions at Photonics West: Thomas “Buddy” Aggerstam, Marco Ghisoni, Janet Sveijer, Jan Jönsson, Mariella Wallin, Mardjan Dubois, Rickard Marcks Von Wurtemberg and Bertil Kronlund.

There have been many successful collaborations in the course of this project, so my deepest thanks also go to all the people from our European partners involved in the VERTICAL, COST or other projects: Joel Jacquet, Jan Danckaert, Michael Peeters, Peter Bienstman, Christina Carlsson, John McInerney and Angel Valle, to name only a few.

On a more personal level I would like to thank all my friends who have made my time in Stockholm so enjoyable, through snowboarding week ends, midsommar pole dancing, windsurfing sessions, beach barbecues or dinners. Lena and Calvin “fantastissaucisson” for incredible dinners, single malts and singing sessions “under the bridge”. Adam, Marie, Cat and Nick for their cheekyness. Paul and Kim for “easy going” weekends up north or out east. Niclas and (Mrs.) Kate for the Easter egg hunts and Sunday roasts. Jessica for making me discover all the best and most beautiful places in Stockholm. Malin and Matthias for taking care of homeless frogs. The French contingent: Cyril, Glenn, Jerome, Olivier, Alexis, Franck, Micka, Chic, Tonio and Vero, Dim, Thomas and all the coquinoux. Charlotte for distracting me during the writing of this thesis and for keeping my spirit high at all times.

Finally I would like to deeply thank my family for their endless support and understanding.
Acronyms

BER  Bit Error Rate  
COD  Catastrophic Optical Damage  
CW  Continuous-Wave  
DBR  Distributed Bragg Reflector  
DFB  Distributed Feed Back  
DH  Double Heterostructure  
DWDM  Dense Wavelength Division Multiplexing  
EDFA  Erbium Doped Fibre Amplifier  
FP  Fabry-Perot  
FM  Frequency Modulation  
GI-POF  Graded-Index Plastic Optical Fibre  
HBT  Hetero-Bipolar Transistor  
LAN  Local Area Network  
LASER  Light Amplification of Stimulated Emission Radiation  
LED  Light-Emitting Diode  
LW  Long Wavelength  
MAN  Metro-Area Network  
MEMS  MicroElectroMechanical Structure  
MMF  Multimode Fibre  
MQW  Multi-Quantum Well  
OC192  Optical Carrier -192: standard for fibre-optic data transmission at 10Gbit/s  
PFO  Plastic Optical Fibre  
PRBS  Pseudo-Random Bit Sequence  
QD  Quantum Dot  
QW  Quantum Well  
RCLED  Resonant Cavity Light-Emitting Diode  
RIN  Relative Intensity Noise  
RT  Room Temperature  
SHB  Spatial Hole Burning  
SI  Semi-Insulating  
SMF  Single Mode Fibre  
SMSR  Side-Mode Suppression Ratio  
SONET  Synchronous Optical NETwork  
VCL  Vertical Cavity Laser, also referred as:  
VCSEL  Vertical Cavity Surface-Emitting Laser
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Papers I-VI
1 Introduction

In the last decade, the vertical cavity surface-emitting laser (VCSEL) has established itself as a reliable low-cost high-speed solution for data communication applications and interconnects and has started to challenge the well-established edge-emitting lasers in telecom and data storage applications. VCSEL-based modules, with speed up to 2.5 Gbit/s per channel for distances up to 300 meters are now commercially available. However, due the ever-increasing demand for bandwidth, devices operating at higher transmission rates (10 Gbit/s and more) and emitting at long wavelengths will be needed in the near future, in order to penetrate the telecommunication markets and metro-area network applications. This thesis describes work that has been done in order to understand the modulation properties of VCSELs, to identify the limiting parameters and ultimately to optimise the speed of operation into practical fibre networks. After a brief introduction to semiconductor lasers, optical communications and VCSELs in Section 1.1 and 1.2, the main applications for VCSELs are presented in Section 1.3, namely datacom, telecom and plastic optical fibre networks.

Chapter 2 introduces the basic principles of semiconductor in-plane and surface-emitting lasers, such as recombination processes and cavity requirements. The well-known rate equations are introduced to describe the steady state characteristics of a laser such as carrier density clamping, threshold current and output power. The main elements of a VCSEL structure are then presented namely the high reflectivity distributed Bragg reflectors (DBRs), the multi-quantum well (MQW) active layer and the electrical confinement schemes necessary to achieve high efficiencies. The VCSEL performance, i.e. output power, threshold current and temperature range of operation, depends highly on the alignment of the cavity resonance to the gain peak wavelength. The RCLED as an alternative optical source for plastic optical fibre (POF) applications is finally presented. In a RCLED, the microcavity effect enhances spontaneous emission and leads to improved extraction efficiency as opposed to conventional LED.

The dynamic properties of VCSELs are discussed in Chapter 3. It is shown that a small signal analysis of the single-mode rate equation model also provides good understanding of how the laser would work under large signal modulation. The VCSEL dynamics can, under certain conditions, be well described by a small number of key parameters that can be extracted from measurements. From this data the relative importance of different bandwidth limiting effects due to damping, thermal heating and parasitics can be deduced and used for further optimisation. The inhomogeneous carrier distribution due to an inhomogeneous photon distribution,
known as spatial hole burning, and its effects on the modulation response is briefly
discussed.

Chapter 4 presents the measurement and evaluation techniques used to analyse the
high-speed properties of VCSELs and RCLEDs. A detailed description of the small
signal modulation experiment is given, including practical discussions on the
calibration, the fitting to a theoretical response and the parameter extractions. The
experimental set-up used in Paper II for long distance single mode transmission using
long wavelength VCSELs is described. Finally the small and large signal analysis of
RCLEDs is presented and experimental results such as bandwidth measurements and
transmission over plastic optical fibre are discussed.

The thesis is concluded in Chapter 5. Finally, Chapter 6 is a guideline to the papers,
adding some issues on device performance and analysis that have not been addressed
in the publications.

1.1 Semiconductor lasers: background and history

1.1.1 Semiconductor laser

Since the first proposal of laser operation by Schawlow and Townes in 1958\(^1\) and the
first demonstration using a ruby crystal two years later\(^2\), laser technology has had
tremendous implications in everyday life. Applications today include high precision
medical surgery, industrial remote sensing, entertainment lightning, chemical
spectroscopy, radar scanning, three-dimensional microscopy and many more, the list
being constantly increased as new discoveries are made and technology improves\(^3-5\).

The main advantages of lasers compared with other light sources such as light bulbs
or neon tubes are that the emitted light is monochromatic, coherent, directional and
that the small spot size can give very high density of energy. One of the major
breakthroughs in laser technology occurred in 1962\(^6-7\) with the invention of
semiconductor lasers. Compared to other lasers such as gas or dye lasers,
semiconductor lasers combine compactness, higher efficiency and reliability, lower
cost, and ease of use.

One of the most important advantages of semiconductor lasers is that they can be
directly modulated, i.e. one can readily obtain optical pulses as short as a few
picoseconds by modulating the device current\(^8-9\). Such pulses may be used for time-
resolved dynamical studies as well as carrying information at high bit rates in fibre
and free-space optical communication systems\(^10-11\). Large gain bandwidth of
semiconductor materials allows wavelength tunability\(^12\) and the high light-current
linearity of the lasers makes them suitable for modulation over a wide range of
frequencies from DC to tens of GHz\(^13\).
1.1.2 Optical communications

Apart from being widely used for optical data storage and retrieval, e.g. in CD or DVD players, to read/write digital information, semiconductor lasers have rapidly evolved into the most appropriate and widely used light sources for optical communication. The combined development of high speed microelectronics and semiconductor lasers, together with the invention of optical fibre and fibre amplifier made the information technology revolution possible, allowing the huge amounts of data to be transmitted almost instantly from one side of the world to the other. The never ending increased demand for bandwidth by today’s applications such as video streaming through the internet is the main driving force behind the development of faster lasers.

Today, the most common devices for telecommunication applications are edge emitting lasers, typically distributed feedback (DFB) lasers. The two most important wavelengths are 1300nm, corresponding to minimum dispersion in single mode fibres and 1550nm, corresponding to minimum attenuation. The latter wavelength band is also the gain region for erbium doped fibre amplifiers (EDFA). In a DFB laser, the wavelength and mode selection is realised by horizontal gratings. Although this type of lasers exhibits high power, high side-mode suppression ratio (SMSR) and narrow linewidth, it also results in high manufacturing costs. The last five years have seen the development of vertical-cavity lasers and their maturation for shorter wavelength (850nm). Due to the combined advantages of low-cost, high-bandwidth and high-density, VCSELs are now used as the preferable light source for short distance communications (up to 300 m) such as access networks and local area networks (LANs). Recent achievements in Nitride-based materials, quantum dots and microelectromechanical technology also indicate that long wavelength VCSELs could start to challenge edge-emitting lasers in telecom and dense wavelength division multiplexing (DWDM) applications.

1.2 Vertical-cavity surface-emitting lasers

1.2.1 Structure

As its name indicates, the fundamental difference between an edge-emitting and a vertical cavity surface emitting laser is the fact that the laser oscillation as well as the out-coupling of the laser beam occur in a direction perpendicular to the epitaxial gain region and the surface of the laser chip. Figure 1.1 illustrates the typical differences between edge-emitting lasers and VCSELs. A VCSEL consists of an active medium, usually multiple quantum wells, placed between two DBR mirrors. The overall cavity length is much shorter for a VCSEL, typically a few µm, as opposed to some hundreds of µm in the case of an edge-emitting laser, resulting in larger longitudinal mode spacing and shorter gain region. In order to compensate for the shorter gain region, the light has to travel back and forth more times before coupled out, therefore the mirror reflectivity has to be much higher. The reflectivity of an output facet for an edge emitting laser, resulting from the change of refractive index at the cleaved interface semiconductor-air is typically around 30%. Laser operation in VCSELs requires reflectivities higher than 99%, using Bragg mirrors of alternating refractive index material.
The VCSEL was first proposed by Iga et. al. in 1979\textsuperscript{16}, demonstrated under pulsed conditions at room temperature (RT) by the same group five years later\textsuperscript{17}, and finally continuous wave (CW) operation at room temperature was achieved in 1988\textsuperscript{18}. Vertical cavity lasers have been commercially available since the mid-1990s\textsuperscript{19}.

1.2.2 Advantages and drawbacks

There are many reasons why VCSELs are becoming increasingly popular as light sources for applications such as datacom and optical interconnects. The monolithically integrated structure requires one single epitaxial run, making it easier to fabricate. Since the mirrors are formed during the epitaxial growth, each individual VCSEL can be tested already on the wafer, before it is cleaved into separate components, thereby drastically reducing the production cost. The use of DBRs eliminates the risk of catastrophic optical damage (COD) in the mirrors which can occur in edge-emitters where the active material close to the facets are depleted by surface recombination and thereby light absorbing. It also reduces the risk of mechanical mirror damage. The extremely short resonator leads to a longitudinal mode spacing that is large compared with the gain bandwidth and leads to inherent single longitudinal mode operation. The small active volume and high mirror reflectivity contribute to the very low threshold observed in VCSELs, as low as a few microamperes\textsuperscript{20}, resulting in low power consumption and reduced heating of the device. This feature, combined with the absence of CODs, explains the remarkable reliability of VCSELs. Lifetimes of more than 10000 hours have been reported by several groups\textsuperscript{21-22}.

The surface emission and the small size make it possible to fabricate very dense two-dimensional arrays of VCSELs, suitable for multi-channels parallel transmission modules\textsuperscript{23}. VCSELs do not need to be cleaved, it is therefore possible to integrate them monolithically with other optoelectronic components such as photodetectors, modulators or hetero-bipolar transistors\textsuperscript{24} (HBT). Because of the circular symmetry of the VCSEL structure, the light is emitted with a circular beam and very low divergence. This results in high coupling into optical fibres, up to 90\%\textsuperscript{25} and allows
for relaxed tolerance in alignment, further reducing the cost of installation. For comparison, the output light emitted from an edge-emitting laser is elliptical with a transverse and lateral divergence of about 40 and 10 degrees, respectively, making it cumbersome to couple the light into an optical fibre without significant optical loss or advanced optics.

In addition, VCSELs have an inherent single-wavelength structure that is well suited for wavelength engineering, making it possible to process multi-wavelength array or tuneable VCSELs. Although the manufacturing challenges are numerous, both types of devices have been demonstrated. By carefully designing the optical cavity, with the implementation of a small thickness variation in the bottom DBR, a record 140-wavelength VCSEL array has been reported. The thickness gradient created a cavity thickness variation, which in turn led to laser wavelength variation, the overall wavelength span across the array being 43 nm. Large wavelength tunability can be achieved by mechanically varying the VCSEL cavity length. This was demonstrated by placing a movable DBR on a microelectromechanical structure (MEMS) cantilever suspended over the VCSEL cavity, and by applying a voltage across the airgap. The electrostatic force, by attracting the top mirror, shortens the airgap, thus tuning the laser wavelength towards a shorter wavelength (blue shift). Wavelength tuning as high as 31.6 nm for a VCSEL operating at 950 nm was reported. Finally, VCSELs have demonstrated modulation speed up to 21 GHz bandwidth, and have been used for transmission up to 20 Gbit/s through 200 m of MMF.

However, VCSELs also have some drawbacks compared to edge-emitters. The manufacturing tolerances on VCSEL growth are much tighter than for edge-emitting lasers, the layer thickness having to be controlled within 1%. The perhaps major disadvantage with VCSELs is the strong tendency to operate on multiple transverse modes, due to the large transverse dimensions of the optical cavity. This results in emission spectra with multiple emission wavelengths, which limits the maximum achievable distance due to chromatic dispersion effects. Most commercial VCSELs of today operate multimode and are mainly used in short distance multimode fibre based optical data links, optical interconnects, optical storage, and laser printing. A lot of efforts are made to produce high power single mode VCSELs. This includes oxide confined VCSELs with current aperture small enough to support only the fundamental mode, index-guided structures such as regrown or surface relief VCSELs, and spatial mode filtering in an external cavity or extended cavity. Although the first and last of these techniques have produced high single mode power they are difficult to implement with high uniformity and yield. A more reliable technique is to combine a large-area oxidation (20 μm diameter aperture) with an etched shallow surface relief for mode selection. This implies only a small modification to the fabrication procedure but produces reasonably high single mode power (10 mW), with high uniformity and yield.
Currently, Metro and Access Networks are dominated by 1300 nm and 1550 nm FP and DFB lasers. A long wavelength VCSEL (LW-VCSEL) would be an ideal low-cost alternative to the DFB laser, particularly for the new standard IEEE 802.3ae currently under development, which will extend the existing Gigabit Ethernet into traditional SONET markets at OC-192 data rates. However, the performance specifications for such LW-VCSELs are challenging. If they are to be built into low-cost transceivers, they must operate over the 0 to 70°C temperature range for indoor applications and over the –40 to 85°C range for outdoor applications, without external temperature stabilisation. The laser power launched into the single mode fibre (SMF) must usually be more than 0.7 mW in order to support transmission distances of 10 km at 10 Gbit/s. Currently, of the two major classes of LW-VCSELs, optically-pumped and electrically-pumped, only the optically-pumped class has the required transceiver power, although its manufacturability is still a challenge. Despite intense research effort, the electrically pumped class has not yet met the requirements for commercial applications, though its potential value, if successfully developed, will be large.

The next section presents the various types and applications of VCSELs, both currently developed and commercially available.

1.3 VCSEL applications

1.3.1 Near infrared: 850, 780 and 980 nm

Although the first proposal for VCSEL was to use GaInAs/InP materials, the first results and the major development were obtained for VCSELs based on the more mature AlGaAs/GaAs material system, and operating at wavelength of 850-980 nm. The reason was mainly due to the fact that the GaAs material system allows the fabrication and integration of efficient active layers, lattice-matched to high reflectivity DBRs. GaAs also exhibits high thermal conductivity, allowing efficient heat removal, and a layer with a high Al-content can be selectively oxidised, providing optical and electrical confinement.

Today, datacom modules based on near-infrared VCSELs represent 95% of the VCSEL market, 80% of which are commercialised by a few companies: Agilent, Honeywell, Infineon and Zarlink (formerly Mitel). The remaining 20% are shared among numerous start-ups offering innovative designs. The market has recently exploded: it is evaluated to be worth USD 500 million at present, and is constantly growing due to the rapid deployment of Gigabit Ethernet and fibre channels. Reed Electronics Research forecasts the VCSEL transceiver market to reach over USD 1.4 billion by 2004. Others applications such as lighting products, optical interconnects, displays, sensors or printing represent at present a minor part of the market but are expected to gradually challenge the market dominance of datacom modules.

Most of today’s commercial datacom components are based on implanted 850 nm VCSELs. They are often packaged as single component or in parallel fibre modules of linear arrays, offering 4 to 12 channels at 2.5 Gbit/s per channel, with aggregate bandwidths up to 30 Gbit/s. The research and development efforts are focusing on the next generation of high speed VCSEL, and a number of groups have reported transmission at 10 Gbit/s or more for distances up to 300 m of 50 µm MMF.
Transmission at 10 Gbit/s through a record 2.8 km length of a new high bandwidth 50 µm-core-diameter MMF with a single longitudinal mode VCSEL has been recently demonstrated\textsuperscript{39}. The first commercially available 10 Gbit/s, 850 nm VCSEL was unveiled earlier this year for laboratory applications\textsuperscript{40}. These new products are based on a new type of VCSEL, for which electrical confinement is provided through the selective oxidation of one of the Bragg mirror layers, allowing smaller current aperture and better transverse mode control. Although the oxidation process was questioned a few years ago for its mass production uniformity and long time reliability, a numbers of companies now report similar characteristics as conventionally implanted VCSELs. Most of the new devices now use both implantation and oxidation. Paper 3 in this thesis describes the modulation properties of three types of state-of-the-art 850 nm VCSEL currently used or recently developed: an implanted VCSEL for speed up to 2.5 Gbit/s\textsuperscript{41}, the next generation oxidised VCSEL for 10 Gbit/s applications\textsuperscript{42}, and a recently developed buried-heterostructure VCSEL with semi-insulating (SI) GaInP regrowth showing very promising results\textsuperscript{43}.

The optical interconnect is considered by many to be inevitable in the computer technology. The performance of massively parallel computers is usually limited by the communication bottleneck between processors. Optic provides an effective mean to link these processors because of its high capacity, low crosstalk and attenuation, and the possibility to obtain three-dimensional architectures. Other potential applications include routers, switches and storage. The VCSEL is a strong candidate as the preferred optical light source for the emerging optical interconnect mass market, meeting the requirement of low cost, high density integration and low power dissipation. A 256-channel bi-directional optical interconnect using VCSELs and photodiodes on CMOS was recently demonstrated\textsuperscript{44}.

1.3.2 Long wavelength for telecom applications

Despite their impressive performances for multimode applications, 850 nm VCSELs suffer from the fact that they are not adapted to the existing metro or long haul networks consisting of single mode fibres, and cannot compete with the high-speed edge-emitting lasers on the telecom market. Due to the high level of dispersion and absorption at 850 nm in silica fibres, the maximum achievable speed and distance will always be lower than for long wavelength devices. Today, the interest in VCSEL is shifting towards the telecom market and in particular the development of VCSEL operating at wavelengths corresponding to the attenuation windows of the optical fibre.

While commercially available near infrared VCSELs show excellent performances, the characteristics of long wavelength devices are still significantly inferior. It is only recently that the first 1.3 µm and 1.55 µm VCSELs have been made commercially available. The dominant material systems for long-wavelength edge-emitting lasers are GaInAsP/InP or AlGaInAsP/InP. These InP-based alloys are suitable as active material for 1.3-1.55 µm VCSEL but cannot offer heterostructures with a large refractive index contrast for the fabrication of reflective Bragg mirrors. High reflectivities can be obtained but require a very large number of quarter-wavelength layers, and the increasing diffraction losses and thermal resistance make a monolithic full-cavity VCSEL structure difficult to achieve. Additional effects such as Auger
recombination, intervalence band absorption and carrier leakage over the heterobarriers explain the difficulties to fabricate long-wavelength VCSELs that operate CW at high temperature.

A number of different approaches have been proposed and realised to overcome these difficulties, and many groups have now demonstrated CW operation of 1.3 and 1.55 µm VCSELs.

### 1.3.2.1 1.55 µm VCSEL

One approach is to make use of one or two GaAs-based mirrors, providing high reflectivity and good thermal properties, by using either wafer-fusion or metamorphic epitaxial growth to attach them to an InP-based active region. Sub-milliampere threshold current and CW operation up to 71°C has been demonstrated at the University of California at Santa Barbara, USA, with double-fused devices. Researchers at Alcatel developed a fully integrated laser structure with a metamorphic n-typed GaAs/AlAs top mirror grown on an InGaAsP MQW active layer and an InP/GaInAsP DBR. Proton implantation provided current confinement and a built-in tunnel-junction was added. This allowed the substitution of a high-resistive p-doped DBR by a low-resistive n-doped DBR, therefore significantly reducing the series resistance and the heating in the device. CW operation up to 47°C and maximum RT output power of 1 mW have been demonstrated. The results of the modulation properties of this device are described in paper 2, demonstrating “error free” 2.5 Gbit/s transmission through 90 km of single-mode fibre. Another group has recently developed a 1.6 µm monolithic VCSEL consisting of a lattice-matched bottom DBR, an InGaAs QW active region, and a metamorphic top DBR. This structure was used for the first demonstration of a long-wavelength VCSEL based WDM transmission link at 10 Gbit/s over 50 km of standard single mode fibre, consisting of four individually modulated VCSELs, each transmitting at a speed of 2.5 Gbit/s.

Amorphous dielectric mirrors have also been used, demonstrating very high reflectivity with very few periods but suffering from the fact that they do not conduct the electrical current and have poor heat conductivity. Paper 1 of this thesis presents the small signal characteristics of a device based on an integrated bottom InP Bragg reflector and a semi-insulated regrown around the mesa, with a dielectric Si/SiO$_2$ top mirror. Measurements show a maximum 3dB bandwidth of 4.3 GHz. Another approach using a bottom dielectric mirror, a buried tunnel-junction and an epitaxial top mirror has shown very promising results. Performances such as submilliampere threshold at room temperature, single mode emission at 1.54 µm and CW laser operation up to 75°C have been demonstrated.

Finally, 1.55 µm VCSELs operating CW up to 88°C using AlAsSb-based DBRs lattice-matched to InAlGaAs QWs have been reported, demonstrating submilliampere threshold and maximum RT output power of 1 mW.
1.3.2.2 1.3 µm VCSEL

Capitalising on the current know-how of GaAs material system for Bragg mirrors, most of the recent efforts on 1.3 µm are focused on the design of InGaAsN active layer, which are lattice matched to AlGaAs/GaAs reflectors. A number of groups have now reported 1.3 µm VCSEL with single-mode CW operating power greater than 0.7 mW, and modulation up to 10 GHz, meeting the requirements for OC-48 SONET and 10 Gbit Ethernet applications for uncooled operation up to 85°C51-52. The main application target is for metro-area networks with link distances of 80 km or less. A totally different approach is a double wafer-fused structure in which the 1.3 µm laser is optically pumped by an integrated short-wavelength (850 nm) VCSEL. Output power up to 1.3 mW, threshold current of 5 mA and single mode operation up to 85°C have been demonstrated53.

Due to the recent development of high efficiency quantum dot (QD) active regions for 1.3 µm GaAs-based edge-emitting lasers54-55, long wavelength quantum dot VCSELs have started to attract much attention. The first demonstration of GaAs-based QD VCSELs has recently been achieved56. Devices consisting of InGaAs QDs active layer and GaAs/AlO DBRs operate pulsed at room temperature with threshold currents below 2 mA and emission wavelength near 1.3 µm. Although further optimisation is needed to achieve CW operation, these devices show very promising performances.

1.3.2.3 Tuneable VCSEL

Dense wavelength division multiplexing (DWDM) is the most deployed technology used to increase communication bandwidth. A DWDM system allows multiple wavelengths to be transmitted in the same fibre, as high as 200 channels, with an overall Terabits-per-second capacity. Tuneable lasers are recognised as highly desirable component for present DWDM systems, and tuneable VCSELs are potentially low-cost, compact and easy to wavelength-lock57. Bandwidth9 Inc. has recently reported one approach that overcomes the challenges of manufacturing tuneable 1.55 µm VCSELs, and demonstrated a monolithic electrically pumped VCSEL using an integrated microelectromechanical structure (MEMS) tuning58.

1.3.3 Visible wavelengths for plastic fibre networks: 650 and 670nm

While copper coaxial cable and glass fibre, the traditional solutions to data communications are well suited to specific applications, they each have inherent limitations for short range low cost applications. Copper is unsuitable for high-speed data transmission because of its cost, a high attenuation at high frequencies and susceptibility to electromagnetic interference. The small diameter and fragility of glass carries with it a high cost of installation and alignment. One alternative to the previous two solutions is plastic, in the form of optical fibre. Plastic optical fibre (POF) is a low-cost, easy-to-align, flexible and easy-to-use solution for short distance connections, and is already widely used in CD players, industrial electronics, PCs and car electronics. Mercedes and BMW now use POF in all the new car models for the communication system between all the multimedia applications, radio, navigation system, CD player, mobile phone system, and the safety features. The total amount of POF used is approximately 12m and the typical data rate is around 10Mbit/s59.
Figure 1.2 shows the absorption spectrum of POF, with minimum attenuation at 590 and 650 nm. The high level of absorption (100 dB/km) limits the overall fibre length to 100 m. A number of different light sources are currently used, LEDs, edge-emitting lasers, and more recently RCLEDs and VCSELs. While LEDs are cheap and reliable but slow, and edge-emitting laser exhibits high threshold currents and coupling limitations, RCLEDs present the combined advantages of improved directionality, speed, power, linewidth, and temperature stability. Paper 5 in this thesis presents the first 250 Mbit/s transmission through 30 m of POF using a 656 nm RCLED. Since then RCLEDs have been used at bit rates up to 500 Mbit/s but at higher speeds lasers are required, with VCSELs being the preferred choice.

There are however some technical difficulties into making a 650 nm VCSEL such as a lower index contrast in the AlGaAs/AlAs layers composing the DBRs, and a weak electron confinement in the GaInP/AlGaInP heterostructures. This makes it challenging to operate at the elevated temperature required for the applications. State of the art performance of selectively oxidised visible VCSELs includes sub-milliampere threshold current and CW operation up to 85°C, at an emission wavelength of 683 nm. Devices emitting at 670 nm and operating CW up to 45°C have shown 11 GHz modulation bandwidth and have been used for transmission up to 1.5 Gbit/s through 10 m of 50/125 graded index multi-mode fiber.

The typical red VCSEL is composed of alternate layers of high and low Al concentration AlGaAs layers to form the top and bottom quarter-wave mirrors, and a cavity based on AlGaInP with InGaP quantum wells. Paper 4 in this thesis present the high-speed performance of this type of VCSEL, including 1 Gbit/s transmission through 50 m of POF, demonstrating that red VCSELs are suitable candidates for IEEE 1394b-S800 standard. Recently 2 Gbit/s transmission using standard multimode fibre was achieved with an oxidised VCSEL.
1.3.4 Blue and near ultraviolet: 380-410 nm

The technological prospects for blue and near ultraviolet VCSELs and RCLEDs are at an early but exciting research stage. A collaboration among Brown University, Sandia, and Agilent Technologies has demonstrated RT quasi-CW VCSEL operation in the 380-410 nm wavelength range using optical pumping at modest levels of excitation to generate the population inversion, which established a working optical design for blue VCSELs.\(^6^5\)

The first blue VCSEL operating at room temperature was demonstrated in 1999.\(^6^6\) By exploiting recent progress in crystal growth technology, an active region of InGaN quantum wells and mirror surfaces of gallium and aluminium nitrides were grown on a sapphire substrate to make disc-shaped cavities. Each one was only 18 μm in diameter. When the cavities were illuminated by a HeCd laser, light was emitted at a wavelength of 399 nm. The present challenge is to make the optical resonator structure compatible with electrical injection. The mirrors themselves are poorly conducting, so carriers must be laterally fed into the active optical volume defined by the mirrors. The problem is especially severe on the p-side of the junction due to the low conductivity of p-type GaN. Song and co-workers at Brown University have solved the problem by inserting a thin transparent conductive layer of indium tin oxide within the optical cavity to enhance the lateral “current spreading”. Devices with this layer have been operated to date as robust RCLEDs.\(^6^7\) Although laser operation in these structures has yet to be observed, further developments of high-efficiency blue light emitters are expected in the near future.

While many technical improvements and an increased fundamental understanding will be required to bring the present blue and violet lasers into full technological bloom, it is clear that these devices are destined to fill an important role in future optoelectronics applications. Two-dimensional arrays of blue VCSELs could drastically reduce the read-out time in high-density optical data storage (for example, in CDs and DVDs) and increase the scan speed in laser printing technology. Blue GaN VCSELs have great potential in another market sector unrelated to telecom, commercial lighting and display applications, because the cost of manufacturing enable them to compete with the traditional solutions such as LEDs and RCLEDs.

1.4 Summary

In less than five years, VCSELs have established themselves as a reliable low-cost high-speed solution for data communication applications and interconnects and have started to challenge the well-established edge-emitting lasers in telecom and data storage applications. Near-infrared VCSELs, emitting at 850 nm, have demonstrated very large modulation bandwidth up to 21 GHz and 20 Gbit/s transmission through conventional multimode fibre. VCSEL-based modules, with speed up to 2.5 Gbit/s per channel for distances up to 300 meters, are now commercially available. However, due the ever-increasing demand for bandwidth, devices operating at higher transmission rates (10 Gbit/s and more) will be needed in the near future and have started to be demonstrated.
The development of VCSEL operating at wavelengths coupled to fibre-optic attenuation windows for telecom applications has also attracted much attention. A number of groups have now reported 1.3 $\mu$m VCSEL with single-mode CW operating power greater than 0.7 mW, and modulation up to 10 GHz, meeting the requirements for OC48 and 10 Gbit Ethernet applications. Recently the first 1.55 $\mu$m VCSEL-based WDM transmission link at 10 Gbit/s over 50 km of standard singlemode fibre was demonstrated.

In the visible range, red and blue VCSELs have also emerged, and thanks to their greater speed, lower beam divergence and advantageous economics could also threaten edge-emitting lasers and LEDs in some applications such as short distance POF communications, sensors, commercial lighting and displays, high-density optical data storage and printing.
2 VCSEL physics

This chapter describes the fundamental principles for laser operation in semiconductor lasers. The main conditions for laser operation are discussed for FP laser and VCSEL, followed by a brief description of the recombination mechanisms and the band structure. The well-known rate equations are then introduced to describe the steady state characteristics of a laser such as carrier density clamping, threshold current and output power. The different elements of a VCSEL structure are described: the high reflectivity DBRs, the MQW active layer, and the optical and electrical confinement schemes necessary to achieve high efficiency. Finally, the basic RCLED structure and the microcavity properties are discussed.

2.1 Principles of semiconductor laser operation

A laser consists in its simplest form of two mirrors with a light amplifying gain medium in between. The two mirrors partially reflect the light so it bounces back and forth through the amplifying region. If the gain is enough to compensate the optical losses, the laser will emit coherent light through the mirrors. This gain is called the threshold gain. The wavelength of the laser light is determined by the phase condition, which requires that the optical wave be reflected in phase after a round-trip in the cavity. The two conditions for lasing, related to the gain and the phase, can be expressed as follows

\[ \sqrt{R_1 R_2 e^{-2 \mu L + 2 \Gamma \alpha_l}} = 1 \]  \hspace{1cm} (2.1)

Where \( \lambda_0 \) is the oscillating wavelength, \( n \) the effective refractive index in the cavity, \( R_1 \) and \( R_2 \) the power reflectivities of the two mirrors and \( L \) the length of the cavity. \( \Gamma \) is the optical mode confinement factor and is defined as the fraction of the volume that the optical mode occupies overlapping the active volume. \( \alpha_l \) is the internal loss, \( g \) the gain in the cavity and \( k \) is the wave propagation constant (\( k=2\pi n/\lambda_0 \)).

The phase condition is \( 2kL = m2\pi \), where \( m \) is an integer, giving

\[ \lambda_0 = \frac{2nL}{m} \]  \hspace{1cm} (2.2)
The resonant wavelengths corresponding to different solutions of the phase conditions are normally referred as different longitudinal modes. Because the material gain and sometimes the optical losses are highly dependent on wavelength, the laser will in general only emit light at one or a few discrete wavelengths for which the gain is maximum. A laser oscillating at only one wavelength is therefore a single mode laser.

The threshold gain is derived from Eq. 2.1, to give the following expression:

\[
g_{th} = \frac{1}{\Gamma} \left[ \alpha_i + \frac{1}{2L} \ln\left( \frac{1}{R_1 R_2} \right) \right]
\]  

(2.3)

This equation explains why the short cavity length in a VCSEL requires very high mirror reflectivity in order to keep the threshold gain small.

Figure 2.1 shows how the longitudinal lasing mode is selected in an in-plane laser or in a VCSEL. In edge emitting FP lasers the lasing wavelength is mainly determined by the gain peak wavelength, whereas in a VCSEL it is determined by the resonance defined by DBR mirrors. The VCSEL wavelength axis covers a five times larger range, i.e., the gain curve has the same width in both cases. In the VCSEL case, the mode spacing is much larger, due to the short cavity length, which results in an intrinsic single-mode operation.

2.2 Semiconductor laser

2.2.1 Recombination mechanisms

Photon emission in semiconductor lasers is due to the electron-hole recombination in the active region. Radiative recombination occurs when an electron in the conduction band recombines with an empty state (hole) in the valence band and the excess energy is emitted in the form of a photon. The optical processes associated with radiative recombination in semiconductors are (i) spontaneous emission (ii) absorption and (iii)
stimulated emission. Stimulated emission occurs when an incoming photon stimulates an excited electron in the conduction band to fall down to the valence band, thereby emitting a new photon that has the same energy and momentum than the incident photon. This process forms the basis for laser operation and was first described by Einstein in 1917. Spontaneous emission, on the other hand, does not need any stimulus to occur. It will give incoherent light that has no correlation in phase or polarisation with the rest of the light in the cavity. The electronic radiative transitions that take place between the conduction and the valence band in a semiconductor are similar to atomic or molecular transitions in gas lasers. The main difference is that, for semiconductor lasers, the optical transitions are between continuous band of states within the valence and conduction bands. Fig. 2.2 shows a simplified energy versus wave-vector diagram for a direct band-gap semiconductor.

![Energy band diagram](image)

Fig. 2.2 A realistic band model for a direct band-gap semiconductor

An accurate description of the band structure requires sophisticated numerical techniques. A commonly used approximation of the exact band structure in a direct bandgap semiconductor is the parabolic band model. In this model, the energy versus wave-vector relation is assumed to be parabolic, following the equations

\[
E_c = \frac{\hbar^2 k^2}{2m_c} \quad \text{for electrons} \tag{2.4}
\]

\[
E_v = \frac{\hbar^2 k^2}{2m_v} \quad \text{for holes} \tag{2.5}
\]

where \( m_c \) and \( m_v \) are the effective masses for electron and holes, respectively, \( \hbar \) is the Planck constant and \( k \) is the magnitude of the wave vector \( \mathbf{k} \). In a direct-gap, the minimum of the conduction band and the maximum of the valence band occur at the same value of the wave vector \( \mathbf{k} \). Since a photon carries negligible momentum compared with the carrier momentum \( \hbar \mathbf{k} \), radiative transitions occur between free electrons and holes of essentially identical wave vector.
2.2.2 Basic structure

A double heterostructure (DH) edge-emitting semiconductor laser typically consists of a direct bandgap material sandwiched between two cladding layers of higher bandgap and lower refractive index. Electron-hole recombination provides the optical gain and the cleaved facets perpendicular to the junction provide the optical feedback. When the current through the junction is increased, more and more electrons are injected to the high-energy conduction band. At a certain current, the probabilities for stimulated emission and absorption become equal. This level is known as transparency. When the current is increased even more, population inversion is obtained and the structure provides optical gain for wavelengths corresponding to the bandgap energy. At a certain current the gain becomes large enough to compensate the optical losses of the cavity and the structure becomes an optical oscillator. The current when this occurs is called threshold current. Figure 2.3 shows a typical Fabry-Perot laser.

![Schematic illustration of a Fabry-Perot diode laser](image)

Fig. 2.3 Schematic illustration of a Fabry-Perot diode laser

2.3 Static characteristics

2.3.1 Rate equations

A single mode laser can be well described with a reservoir theory for the numbers of free carriers (electrons in the conduction band), and photons (optical energy in the laser cavity). The rates of change of carriers and photons numbers follow the expressions:

\[
\frac{dN}{dt} = I_{in} - I_{sp} - R_{sp}S \quad (2.6)
\]

\[
\frac{dS}{dt} = (R_{sp} - \gamma_{i} - \gamma_{m})S + R_{sp} \quad (2.7)
\]

The first equation states that the temporal increase of the number of carriers in the cavity, \(N\), equals the injection rate of carriers, \(I_{in}\), to which the rate of carriers
dissipated through spontaneous recombination, \( I_{sp} \), and stimulated emission, \( R_{st}S \), have to be subtracted. The second equation can be derived from the wave equation\(^6\). It states that the net increase of the number of photons, \( S \), is equal to the rate at which photons are created through spontaneous emission, \( R_{sp} \), and stimulated emission, \( R_{st} \), minus the photons lost due to internal, \( \gamma_iS \), and mirror losses, \( \gamma_mS \). The output coupling is represented by the term \( \gamma_mS \). The internal loss rate \( \gamma \) takes into account the absorption of photons through scattering and free carrier absorption. The term \( R_{sp} \) is the amount of spontaneous emission that is resonant with the cavity and within the same longitudinal mode as the coherent light. The spontaneous recombination current \( I_{sp} \) describes the recombination of the electrons in the conduction band with holes in the valence band. This recombination can be radiative, with the emission of a photon, or non-radiative. Carriers can recombine without emission of light in localised states due to defects in the crystal or at the surface of the crystal. Another possible non-radiative recombination process is Auger recombination where a third carrier absorbs as kinetic energy the energy liberated from an electron-hole recombination. The non-radiative recombination processes will generate heat and are therefore undesirable. All recombination processes increase with the number of carriers and \( I_{sp} \) is often approximated as:

\[
I_{sp} = \frac{N}{\tau_{sp}} \tag{2.8}
\]

where \( \tau_{sp} \) is the carrier lifetime.

The modal gain \( R_{st} \) is the stimulated emission rate per photon, and becomes positive when there is enough carriers to achieve population inversion, i.e. when the number of carriers is larger than a certain value \( N_0 \), known as the transparency carrier number.

\[
R_{st} = \frac{\Gamma v_g}{V} g(N) \tag{2.9}
\]

where \( \Gamma \) is the confinement factor, \( V \) is the volume, \( v_g \) the group velocity and \( g(N) \) the material gain. For most bulk materials, \( g(N) \) increases almost linearly with the number of carriers and can be approximated as:

\[
g = a(N - N_0) \tag{2.10}
\]

where \( a \) is the differential gain \( \partial g/\partial N \). For QW lasers and when the gain is positive, \( g \) is better approximated as proportional to the function \( \ln (N/N_0) \). At high photon density, gain compression can be observed due to effects such as spectral hole burning\(^7\) or carrier heating\(^7\). This gain saturation can be included in the gain expression as:

\[
g(N, S) = \frac{a}{1 + \frac{\Gamma \varepsilon g}{V} S} (N - N_0) \tag{2.11}
\]
where $\varepsilon$ is the non-linear gain factor (gain compression factor). Non-linear gain does not have a significant effect in the static characteristics of a laser, but limits the dynamic performances as it will decrease the differential gain and increase the damping of the resonance frequency.

### 2.3.2 Steady state

When the laser operates and is not modulated both Eqs. 2.6 and 2.7 are equal to zero. If the laser operates above threshold, the spontaneous emission term $R_{sp}$ can be neglected compared to the stimulated emission. The total power can then be easily derived:

$$P = \gamma_m S = \frac{\gamma_m}{\gamma_i + \gamma_m} (I - I_{sp})$$

(2.12)

For simplicity, power is here in unit photon/s and current in unit carrier/s.

The carrier number can also be derived, by considering a linear dependence of the gain:

$$N = \frac{\gamma_i + \gamma_m}{a} + N_0$$

(2.13)

Above threshold, the carrier number will therefore be independent of the bias current if the parameters $\gamma_i$, $\gamma_m$ and $N_0$ are also independent of the quantities that depend on the current, such temperature or photon density. This is not quite true but the clamping of the carrier number above threshold is still a good first approximation to understand the semiconductor laser. Since the carrier number is fixed to $N_0$, the spontaneous recombination current above threshold $I_{sp} = I_n = N_0/\tau_{sp}$ will be also constant. The difference $I - I_n$ will therefore be used for photon production by stimulated emission. $I_n$ is called threshold current and the power/current slope is called the quantum efficiency.

In reality, thermal effects, spatial hole burning, nonlinear gain and current leakage will modify this simple approach and affect for instance the power-current linearity or the carrier number clamping.

### 2.4 VCSEL

This section presents the different parts composing a VCSEL, and discusses some of the issues related to device fabrication and operation. Fig. 2.4 shows a typical VCSEL structure. A VCSEL typically consists of an active layer, usually multi-quantum wells, embedded between two DBR mirrors. Current confinement is provided either by ion implantation, or by the selective oxidation of a high Al-content of the top DBR.
2.4.1 Bragg reflectors

The Bragg mirrors consist of repeating $\lambda/4$-thick pairs of high and low refractive index layers. The basic principle is the constructive reflection of light at a series of subsequent interfaces, each of a refractive index step $\Delta n = n_{\text{high}} - n_{\text{low}}$, where $n_{\text{high}}$ and $n_{\text{low}}$ designate the materials with the higher and lower refractive indices, respectively. This effect leads to the formation of a so-called stop-band in the vicinity of the Bragg wavelength as shown in Fig. 2.5. More details about the theory of Bragg reflectors can be found elsewhere.\(^{72}\)

![Fig. 2.5 Stop band effect in DBRs](image)

The quality and the properties of DBRs employed in VCSELs are of major importance, the main requirement being to provide reflectivities greater than 99%. Whether this can be reached or not critically depends on the loss in the mirror. For an ideal mirror without any absorption, the reflectivity can reach any desired value.
simply by adding layer pairs and thereby decreasing the mirror transmission. In a real DBR, the peak reflectivity is limited by the absorption in the mirror stack. The amount of loss depends on the material absorption and the penetration depth of the light into the mirror stack. Another effect due to the penetration of light into the multilayer stack is that the reflectivity is reduced by diffraction. This is of no importance in infinite planar structure, but as the VCSEL occupies a finite area on the mirror it can considerably reduce the reflectivity. This increases the importance of lateral optical confinement in the VCSEL, i.e. in etched pillar structure or regrown designs, or favours the use of oxidation. As a rule of thumb, DBRs with high index contrasts are favourable to obtain wide stop bands, to reduce the penetration depth, and thereby mirror and diffraction losses.

One disadvantage of the repeating interfaces in DBRs is that the discontinuities in energy bands lead to a high series resistance. To reduce the series resistance the interfaces can be graded.

### 2.4.2 Active layer

The short optical length of the gain medium in a VCSEL is partly compensated by the very high reflectivity of the Bragg mirror. Despite this the active medium must still be capable of producing considerable gain. This is why quantum wells are used as active material in VCSELs. The structure of a QW is similar to that of a DH except that in the former case the thickness of the active region is kept much smaller. Fig. 2.6 shows the typical structure of a GaAs/AlGaAs quantum well, with the energy sub-bands in the valence and conducting band.

![Fig. 2.6 Structure of a GaAs/AlGaAs quantum well.](image)

Electrons and holes are confined to the central well region by the band structure at the interfaces. If the length of this region is made small enough (determined by de Broglie equation), the confinement of the carriers in one direction will result in energy sub-bands. The relation between the energy of the first sub-band and the QW width is given by the following expression:
\[ E = E_g + \frac{\hbar^2 \pi^2}{2m_r l^2} \] (2.14)

where \( E_g \) is the bandgap of the material and \( m_r \) is the reduced electron-hole pair mass. The main advantages of quantum well compared to a bulk material are increased material gain for equivalent current density, and increased differential gain. The use of strained QW will further increase the differential gain and reduce the transparency carrier density\(^7\).

### 2.4.3 Electrical confinement

There are two main types of electrical confinement: ion implantation and selective oxidation. An implanted VCSEL has a planar structure where the diameter of the active volume is defined by the region surrounded by areas implanted with ions, usually protons. The crystalline damage caused by the implantation of ions into the top DBR makes the region non-conductive and confines the injection carriers into the opening of the current aperture formed by the implanted area. Since there is no refractive index difference laterally in the structure, there is no index guiding mechanism for the light. The optical mode will therefore experience a transverse difference in gain, where gain is provided within the current aperture while the region outside will cause absorption. This will confine the guided mode into the gain region. This mechanism is known as gain guiding. As the laser is operated, heat is generated in the active region and in the p-doped DBR, and will spread longitudinally and transversally in the structure. Since the refractive index increase with temperature, a refractive index profile will be induced. The creation of a refractive index profile in the transverse direction is usually referred to as thermal lensing. This additional index profile will greatly affect the transverse mode behaviour of the VCSEL. Since ion-implantation is a rather simple and low-cost technique and further processing and packaging is simplified by the planarity, most of today’s commercially available VCSELs are implanted.

In the oxidation process, a high Al content AlGaAs layer in the DBR is exposed in a humid N\(_2\)-atmosphere. The Al-oxide formed during the process being non-conducting and having a lower refractive index than AlGaAs, acts as both a current aperture and an optical waveguide. This enables high electrical to optical conversion efficiency. By carefully monitoring the speed of the oxidation, current aperture as small as a few \( \mu m \) can be reached, creating a waveguide that supports only the fundamental optical mode. Oxide confined VCSELs have demonstrated threshold currents as low as a few tens of \( \mu m \)\(^2\), high power conversion efficiency\(^7\) and low drive voltage. The disadvantage of the process is that the oxidation of the high Al content AlGaAs layer is very sensitive to material and process parameters, The speed of oxidation is highly dependent on the Al concentration and the temperature of the furnace in which the oxidation takes place\(^7\). This makes reproducibility more difficult than for ion-implantation.
2.4.4 Gain-cavity detuning

Whereas in FP lasers the lasing wavelength is determined by the wavelength with maximum gain, in a VCSEL it is determined by the resonance defined by its DBR mirrors (cf. section 2.1). The gain-cavity detuning is defined by the respective alignment of the cavity resonance and the gain peak wavelength and is of crucial importance for the VCSEL performance. Because the gain peak of the quantum well emission and the resonance of the DBR change at different rates with temperature, the output power and threshold current will be highly dependent on the gain-cavity detuning and therefore on the temperature and drive current at which the VCSEL is operated.

Fig. 2.7 Schematic illustration of the spectral alignment of the gain spectrum and the cavity resonance for a VCSEL

The threshold in a VCSEL will reach a minimum at some temperature close to where the peak of the QW emission coincides with the DBR resonance. Figure 2.7 illustrates different cases of the detuning effect. If the cavity resonance is on the long or the short side of the gain peak (cases (a) and (c)), the threshold current is higher than when they coincide (case (b)). This feature is of the most importance not only for designing the VCSEL to operate at a given temperature, but also for the total temperature range of operation required. The cavity resonance is usually chosen to be on the long side of the gain spectrum at zero-drive current. In this way, the gain peak moves toward the cavity resonance as the device heats under operation. The threshold dependence on the temperature has an approximated parabolic shape in a VCSEL, unlike a typical edge-emitting laser for which the threshold increases linearly and monotonically with temperature.

2.5 RCLED

Many POF applications such as automotive or avionics communication systems require a robust, reliable, reasonably fast (10 MHz-1 GHz) and low cost source. The visible RCLED is an alternative solution to conventional LEDs or edge-emitting laser diodes. RCLEDs offer higher efficiency, narrower emission spectrum, enhanced directionality and higher modulation speed than conventional LEDs. Compared with edge-emitting lasers, RCLEDs exhibit a lower fabrication cost, higher reliability and threshold-less light emission.

The RCLED, also known as microcavity LED, consists of an active layer placed inside a Fabry-Perot resonator, where the optical cavity mode is in resonance with the spontaneous emission from the active layer. This structure is very similar to a VCSEL, but uses a lower reflective mirror (R<90%) on the emitting surface. The major difference with a VCSEL is that in a RCLED, the light is emitted due to resonantly amplified spontaneous emission, but laser operation does not occur. The
microcavity effect results in extraction efficiencies up to 10 times higher than in conventional LEDs\textsuperscript{77}. The gain-cavity detuning can be varied to optimise not only the temperature range of operation but also the emission profile in order to maximise the fibre coupling efficiency\textsuperscript{78}.

The fully monolithic planar RCLED structure is presented in Figure 2.8. It consists of two AlGaAs/AlAs-Bragg mirrors and an active layer of GaInP quantum wells and AlGaInP-barriers. The MQW structure is embedded in AlGaInP cladding layers forming a cavity of one optical wavelength. The current is confined by ion implantation in the top mirror.

Optical power up to 8.5 mW and maximum external efficiencies of 4.8\% have been reported, for devices exhibiting a narrow emission at 660 nm with a linewidth of around 3 nm\textsuperscript{60}. A combination of the microcavity effect and photon recycling has been used to demonstrate a record 22.3\% quantum efficiency\textsuperscript{79}.

2.6 Summary

This chapter described the fundamental principles for laser operation in semiconductor lasers such as recombination mechanisms and band structure. The structures of FP lasers and VCSELs were presented and compared. In the VCSEL case, the cavity mode spacing is much larger than in edge-emitters, due to the short cavity length, which results in an intrinsic single-mode operation. The rate equations for the photons and carriers were derived to describe the steady state characteristics of a laser such as carrier density clamping, threshold current and output power. The main elements of a VCSEL structure were presented and discussed, namely the high reflectivity DBR reflectors, the MQW active layer and the electrical confinement schemes, selective oxidation layer and ion implantation. Finally the basic principles of spontaneous emission enhancement in a RCLED were presented.
3 VCSEL dynamics

One of the main advantages of semiconductor lasers is the fact that they can be directly modulated, i.e. they can be used to convert an analogue or digital electronic signal to an optical signal. The main advantage is that the same current is used for bias and for modulation, which greatly simplify the external circuitry compared to an external or internal modulator where several currents are needed. The main drawback is that modulation of the device current leads simultaneously to phase or frequency modulation (FM) through carrier-induced refractive index changes and lattice heating. These phenomena can be used in coherent detection systems for frequency shift keyed (FSK) and phase shift keyed (PSK). However, the frequency modulation is a problem in intensity modulated long distance fibre optical systems since it causes a spectral broadening of the signal, making it more exposed to fibre dispersion.

For digital communication, the maximum speed at which information can be sent, the maximum bit-rate, depends on how fast the laser can be modulated, i.e. how fast it can turned on and off. The constantly increasing demand for bandwidth requires faster lasers. It is therefore of the utmost importance to understand the mechanisms occurring in a laser under modulation, to identify the limiting factors and ultimately to minimise them. The outline of this chapter will be as follows. First, a small signal analysis based on the rate equations in presented. It shows that the VCSEL dynamics, under certain conditions can be well described by a number of key parameters. The main three bandwidth-limiting factors, namely damping, thermal and parasitic effects are then identified. The next section presents some relevant characteristics and potential issues of RCLED.
3.1 Modulation response

3.1.1 Step response

If a current step is applied to the laser, the optical output power will exhibit damped periodic oscillations before settling down to its new steady state value. Such relaxation oscillations are due to an intrinsic resonance in the laser dynamics, in which the energy stored in the system oscillates back and forth between the electron and photon populations. The damping of these oscillations is dependent on non-linear gain and nonradiative recombination. The natural frequency of relaxation oscillations is in the GigaHertz range and plays an important role in determine the dynamic response of the laser. The damped relaxation oscillation frequency is not only dependent on the laser structure, but also varies with the current injection. Fig. 3.1 shows the current step, the carrier density and the output power responses for a typical VCSEL.

Fig. 3.1 Current step response of a VCSEL\textsuperscript{80}.

When the laser is operated such as the zero level of the modulation is well above threshold, the rising edge of the optical pulse trails the electrical pulse by a few tens of picosecond. This effect is called turn-on delay. If the zero level is reduced to threshold or lower, the difference increases and can become unacceptably large. Because this effect does not occur on the falling edge of the pulse, it can create pulse width distortion. For rapid modulation the laser will not turn-on after a sequence of zeros.

A good understanding of how the laser would work at large signal modulation, and an expression for the resonance frequency and decay rate can be obtained from a small signal analysis of the single-mode rate equation model\textsuperscript{81}.
3.1.2 Rate equations: small signal modulation

In the small signal analysis, a small sinusoidal perturbation in current, with time
dependence $e^{j\omega t}$ is assumed to initiate only small changes in the steady state values of
carrier and photon densities. Eqs 2.6 and 2.7 can be linearized by neglecting the
quadratic and higher power of $\Delta S$ and $\Delta N$, and can be written in the following matrix
form

$$
\begin{pmatrix}
  j\omega + A & B_0 \\
- C & j\omega + D_0
\end{pmatrix}
\begin{pmatrix}
  \Delta N \\
  \Delta S
\end{pmatrix} = 
\begin{pmatrix}
  \Delta I \\
  0
\end{pmatrix}
$$

(3.1)

where $A = R_{st,N} S_0 + I_{sp,N}$, $B_0 = R_{st,0} + R_{st,S} S_0$, $C = R_{st,N} S_0$ and $D_0 = -R_{st,S} S_0$. $R_{st}$ is
the stimulated emission rate while the spontaneous emission is neglected above
threshold. The subscripts $S$ and $N$ denote the partial derivatives with respect to the
photon and carrier numbers and the subscript $0$ denotes the steady state solutions of
the rate equations. By solving $\Delta N$ and $\Delta S$ from the above equation system, the
following solutions are obtained:

$$
\Delta N = \frac{j\omega + D_0}{Q_0(\omega)} \Delta I 
$$

(3.2)

$$
\Delta S = \frac{C}{Q_0(\omega)} \Delta I 
$$

(3.3)

with $Q_0(\omega) = -\omega^2 + j\omega(A + D_0) + B_0 C + AD_0$

(3.4)

The term $B_0 C + AD_0$ represents the resonance frequency $\omega_R^2$, and $A + D_0$ governs the
damping $\gamma$. The modulation intrinsic response of a laser is therefore

$$
\Delta S = \frac{C}{-\omega^2 + j\gamma \omega + \omega_R^2} \Delta I 
$$

(3.5)

The measured response will often, in addition to the two complex conjugated poles of
the intrinsic response, contain a third real pole. This parasitic-like roll-off is in general
due to the electrical capacitance of the metallic contact and the high conductive layers
below it. However, slow diffusion limited carrier transport through undoped layers
can also give rise to parasitic-like effects due to the charge pile.

From above discussion, the theoretical transfer function describing the modulation
response of a laser can be written a function of the frequency $f$:

$$
\Delta P = \frac{C_1}{(-f^2 + j\frac{\gamma}{2\pi} f + f_R^2)(if + f_p)} \Delta I 
$$

(3.6)
Where \( C_1 = 4\pi^2 Cf_p \frac{\gamma_m}{\gamma_m + \gamma_i} \) 

(3.7)

is a coefficient that depends on the coupling efficiency and the quantum efficiency. \( f_r \) and \( \gamma \) are the resonance frequency and damping rate of the relaxation peak, \( f_p \) is the parasitic-like roll-off frequency.

### 3.1.3 \( K- \) and \( D- \) factors

The angular resonance frequency defined in the previous section can be written as follows:

\[
\omega_R^2 = \frac{v_g aN_p}{\tau_p}
\]

(3.8)

where \( v_g \) is the group velocity, \( a \) the differential gain, \( N_p \) the photon density (\( \Gamma S/V \)) and \( \tau_p \) the photon lifetime in the cavity. This equation shows the importance of the differential gain in the modulation response of a laser.

The damping rate of the resonance peak, \( \gamma \), can be written

\[
\gamma = \frac{1}{\tau_{\Delta N}} + v_g aN_p + \frac{\varepsilon N_p}{\tau_p}
\]

(3.9)

where \( \varepsilon \) is the gain compression factor and \( \tau_{\Delta N} \) the spontaneous differential lifetime. The first two terms can be interpreted as the inverse differential stimulated carrier lifetime and the third is the excess damping associated with gain compression. Spontaneous emission rate, carrier transport effects and spatial hole burning effects will also affect the damping but are here neglected for simplicity. Using equation 3.8 the damping can then be expressed as function of the resonance frequency \( f_r \),

\[
\gamma = K f_r^2 + \gamma_0
\]

(3.10)

where \( K = 4\pi^2 \left[ \tau_p + \frac{\varepsilon}{v_g a} \right] \) and \( \gamma_0 = \frac{1}{\tau_{\Delta N}} \)

\( K \) describes here the damping of the response for high bias currents. \( \gamma_0 \) is the damping factor offset and determines the laser bandwidth at threshold. These two parameters can be extracted from the small signal response measurements described in the next chapter. Because the damping increases in proportion to \( f_r^2 \), the response flattens out as the laser is driven at high current, as shown in Figure 3.2. At some point, the damping becomes large enough that the response drops below the 3dB cut-off at frequencies smaller than \( f_r \). As a result, there is a maximum bandwidth that can be achieved.
By taking into account the steady state solution of the rate equations for the photon density, and assuming that all injected carriers above threshold, $I_{th}$, are converted to photons, Eq. 2.12 can be written:

$$N_p = \frac{\tau_p \Gamma}{qV}(I - I_{th})$$  \hspace{1cm} (3.11)

where $q$ is the electron charge, $\Gamma$ the confinement factor and $V$ the active region volume. Here, $I$ and $I_{th}$ are measured in Amperes.

By plugging equation (3.11) into equation (3.8) we can then write

$$f_r = D\sqrt{I - I_{th}}$$  \hspace{1cm} (3.12)

where the $D$-factor has been defined as

$$D = \frac{1}{2\pi} \sqrt{\frac{\Gamma V g \alpha}{qV}}$$  \hspace{1cm} (3.13)

3.2 Bandwidth limitations

At high relaxation frequencies the linear relation between $\gamma$ and $f_r^2$ implies a maximum possible bandwidth, the damping limit given by

$$f_{3\text{dB},\text{damp}} = \frac{2\sqrt{2}\pi}{K}$$  \hspace{1cm} (3.14)

![Graph showing damping effects](image)

The oxidised VCSEL depicted in paper III is limited by damping.
Often the laser is instead limited by thermal effects that gives a maximum relaxation frequency \( f_{r,max} \), that occurs at a current \( I_{\text{max}} \), before the damping limit is reached.

\[
f_{3\text{dB,therm}} = \sqrt{1 + \sqrt{2} f_{r,max}}
\]

(3.15)

The red VCSELs investigated in paper IV are one example for which the bandwidth is limited by the thermal effects in the device.

The parasitic and transport effects provide a low-pass filtering with a cut-off at \( \omega = 1/\tau_{\text{par}} \) where \( \tau_{\text{par}} \) is the time constant for the \( RC \)-like roll-off. The maximum 3dB frequency corresponding to the parasitic limit is

\[
f_{3\text{dB,par}} = (2 + \sqrt{3}) f_{\text{par}} \quad \text{where} \quad f_{\text{par}} = 1 / (2\pi \tau_{\text{par}})
\]

(3.16)

The reason why the maximum 3dB frequency corresponding to the parasitic is larger than the frequency associated with the \( RC \)-constant is because the resonance peak lifts the response at high frequencies as shown in Fig. 3.4.

The regrown 850 nm VCSEL discussed in paper III is an example of a parasitic-limited bandwidth.
Note that above equations are limits, i.e., each equation gives the true maximum 3-dB bandwidth only if the other two limits are significantly higher. By comparing the above limits it is possible to identify the physical mechanisms that is the main bandwidth limiting factor.

### 3.3 Spatial hole burning

Although VCSELs operate in single longitudinal mode there are often many transverse modes competing at large bias current, which can have dramatic effects on the static and dynamic behaviour of VCSELs. This mode competition causes both spatial and temporal fluctuations in the intensity of the emitted light. The appearance and coexistence of these transverse mode can be due to non-uniform current injection (for example for planar top emitting device with a ring contact) or spatial hole burning (SHB). SHB is the inhomogeneous carrier distribution due to an inhomogeneous photon distribution. In the region with a high photon density, the locally higher stimulated recombination will deplete the carriers. In order to maintain the threshold gain necessary for lasing, the carrier density will increase in the adjacent regions with lower intensity, creating a "hole" in the carrier distribution, as illustrated in Figure 3.5.

![Fig.3.5 Spatial hole burning: schematic illustration of the photon (P) and carrier (N) distribution](image)

This hole will reduce the lateral confinement for the main optical mode and increase the overlap with side-modes, leading to a mode-jump or multimode operation. Since the depth of the hole also varies during modulation, it will affect the dynamic response of the VCSEL. Paper VI in this thesis describes a simple but realistic dynamic model for multimode VCSELs. The model takes into account inhomogeneous injection, nonlinear gain, spatial hole-burning and carrier diffusion, and is based on the rate equations for the photon, carrier numbers and an additional equation for the inhomogeneous part of the carrier distribution.

### 3.4 Summary

This chapter described the modulation properties of VCSELs. Assuming a small sinusoidal perturbation in current, the variation of the carrier and photon densities from the steady state values were calculated using the rate equations. The theoretical transfer function describing the modulation response was derived as function of the frequency. The VCSEL dynamics can be described with a resonance frequency, a damping rate and a parasitic-like cut-off frequency. The main three bandwidth limiting factors, namely damping, thermal and parasitic effects were then calculated from the current dependence of these characteristics.
4 Measurement technique and evaluation

This chapter presents the measurement and evaluation techniques used to analyse the high-speed properties of VCSELS and RCLEDs. A detailed description of the small signal modulation experiment is given, including discussions on the calibration, the fitting procedure and extraction, and the parameter evaluation. This approach is illustrated with the measurements obtained from the long wavelength VCSEL described in Paper I of this thesis. The key parameters described in the previous chapter are extracted and analysed in order to assess the relative importance of the bandwidth limiting effects. In order to evaluate VCSELS in a system context, large signal modulation experiments have been performed. The experimental set-up used for 2.5 Gbit/s transmission through 90-km single-mode fibre depicted in Paper II is described. Finally the small and large signal analysis of RCLEDs is presented and experimental results such as bandwidth measurements and plastic optical fibre link are discussed.

4.1 Small signal measurements

The dynamic parameters of a VCSEL described in the previous chapter can be extracted from the small signal modulation response of the laser. In this method, the VCSEL is biased to given current, and a small signal modulation is added in order to modulate the output power. The amplitude of modulation is negligible compared with the bias current, to avoid nonlinearities. The output power modulation is measured as the frequency of the modulation signal is varied. Finally the Network Analyser compares the received optical modulation signal with the injected electrical modulation signal as functions of the frequency to obtain the modulation response of the VCSEL in dB. This method gives good dynamic range and also access to both magnitude and phase of the response, which make measurements at frequencies far above the relaxation peak possible. Other methods to measure the resonance frequency include relative intensity noise (RIN) measurements and pulse response.
4.1.1 Equipment and set-up

The measurement set-up for modulation measurements is shown in Figure 4.1 and typically consists of

- A broadband network analyser, which supplies a frequency swept electrical modulation signal
- A coaxial microwave probe for applying the modulation signal directly to the laser chip in order to avoid the external parasitics of a bonding wire
- A high-speed photo-detector with low noise preamplifier to increase the signal above the receiver noise level of the network analyser

Reflections back to a VCSEL should be avoided as much as possible. However, due to the high reflectivity of the VCSEL DBR mirrors, the feedback effects are less pronounced than for edge emitting lasers, where an optical insulator is necessary in the measurement set-up.

Both the probe and the detector should have 50-Ohm impedance, in order to be matched to the network analyser ports and therefore avoid reflections, losses and distortions of the signal.

4.1.2 Calibration

It is important to do an accurate calibration of the entire measurement system including the cabling, the probe, the detector and the pre-amplifier.

The high-speed coplanar probe commercially available can provide a low-loss, low-resistance contact with the device with frequencies up to 110 GHz\textsuperscript{83}. The frequency response is generally flat over the range of interest (up to 20 GHz) but a calibration of the probe using a calibration substrate is necessary to guaranty the accuracy of the measurements. The calibration substrate contains highly precise elements for calibrating out the unavoidable errors and losses in a microwave network analyser, its associated cabling, and the microwave probe to ensure accurate on-wafer testing. The
typical elements for calibrating a microwave measurement system consist of open, short, matched loads, and through. These four elements have electrical characteristics that are very different from one another so that each element contributes an important part to the overall calibration process.

The main difficulty with the commercially available coplanar probe is that the lateral spacing between the signal and the ground tips is generally limited to 1250 µm. Similarly, the depth difference is limited to a few microns, making it cumbersome to probe on a full VCSEL wafer, for which the total height is generally a few tens of microns. To overcome this issue, a flexible “in house” probe was designed and built for on-wafer probing. The signal and ground tips were made of very thin flexible copper wire with a few microns of lateral and depth pitch to allow contact from the top of the wafer to the substrate sub-mount. Figure 4.2 illustrates the principle. The frequency response of this probe was measured using a high bandwidth (25 GHz) DBR laser and calibrated out from the measurements.

In general the magnitude of the detector frequency response is available from the manufacturer and need to be calibrated out. In this case the phase of the response has to be recreated from the magnitude data, using causality and stability constraints of linear systems.

4.1.3 Experimental guidelines

Special attention must be paid to the modulation depth of the signal applied to the laser. High modulation amplitude increases the signal to noise ratio but can introduce distortions of the response due to nonlinearities and cause an artificial compression of the resonance frequency peak, especially with structures operating at very low bias currents such as oxidised VCSEL with sub-milliampere threshold.

For accurate parameter extraction it is also important to have a large signal-to-noise ratio. This can be achieved by using large temporal averaging factors during measurements. Averaging in the frequency domain, so-called smoothing is not recommended; it will reduce the frequency resolution of the signal and often corrupt the phase information.

A good rule is to measure the modulation response at 5 - 10 bias currents until a maximum current is reached where the resonance frequency peak saturates or starts to decrease.
At high frequencies the signal to noise ratio is often poor. This noise in the high frequency region is in general not only caused by ordinary amplifier noise but also noise due to calibration problems of the measurement set-up. Even slight movement of the measurement cables will change the phase of distant reflections, which can give a noisy appearance of the measurement curve. Crosstalk can also give similar effects. This type of noise is not uncorrelated at different measurement points and is difficult to distinguish from the signal. Hence, it is preferable to omit the highest frequency parts of the measurements where the signal-to-noise ratio is very poor.

The VCSEL chip has to be mounted on a module for commercial applications. The package has limitations at high frequencies and the measured bandwidth can be strongly decreased by the package parasitics. Resonance and filtering effects introduced by the inherent package parasitics can be significant sources of error. The inductive and capacitive elements associated with the physical geometry of the package will result in small parasitic LC circuits, which will in turn cause voltage or current peaking at the resonance frequencies and low pass or band rejection filtering effect at other frequencies.

4.1.4 Fitting procedure and extraction

The procedure for the parameter extraction consists of fitting the measured response to the transfer function defined by Eq. 3.6. It is achieved by minimising the difference using the least mean square method. More details about the method can be found in paper III.

It is in general advantageous to use both the magnitude and phase of the response for the parameter extraction. If only the magnitude is used, the noise will, especially at high modulation frequencies where the signal to noise ratio is poor, give a non-zero average contribution which is impossible to distinguish from the signal. The demand that both the magnitude and phase of the measured response should fit the theoretical model makes it also easier to dismiss abnormal measurements that are due to, e.g., self-pulsation or external reflections. The phase response makes it also possible to measure small changes in the delay of the modulated signal as a function of bias, which can provide valuable additional information about the laser dynamics.

From the extraction, the damping, the resonance frequency and the parasitic-like cut-off frequency can be deduced at each given bias.

4.2 Parameter evaluation

The K-factor introduced in Eq. 3.10 can be experimentally determined from the linear relation of the damping factor versus the resonance frequency squared. Similarly, the D-factor defined in Eq. 3.12 is given by the slope of the resonance frequency squared as a function of the current above threshold. Especially in the latter case it is important to only use points at low currents where thermal effects do not affect the results. At high currents the resonance frequency can saturate. The maximum resonance frequency is also an important parameter that is needed to fully describe the bias dependence of the transfer function parameters.
\[ H(f) = \frac{C}{\left(-f^2 + j\frac{\gamma}{2\pi} f + f_r^2\right)(jf + f_p)} \]

\[ \gamma = 2.6 + 0.30 f_r^2 \]

\[ f_{3dB,\text{damping}} = 30 \text{ GHz} \quad f_{3dB,\text{thermal}} = 5.7 \text{ GHz} \quad f_{3dB,\text{par}} = 7.8 \text{GHz} \]

Fig. 4.3 Parameterisation of the bias dependence of the extracted damping factor, resonance frequency and parasitic-like roll-off frequency. The resulting overall bandwidth is 4.5GHz

This approach is illustrated with the measurements obtained from the long wavelength VCSEL described in Paper I of this thesis. For the VCSEL response in Figure 4.3 the damping limit was found to be 30 GHz, the thermal limit 5.7 GHz and the parasitic limit 7.8 GHz yielding an overall bandwidth of 4.5 GHz.

### 4.3 Damping nonlinearities

The linear dependence of the damping as function of the resonance frequency introduced in Eq. 3.9 was found to be inaccurate in the case of oxidised VCSEL of small diameter (5 \( \mu \text{m} \)). Figure 4.4 shows the values of the damping extracted from the small signal measurements. The measured and extracted responses can be found in paper IV. The damping first decreases at very low bias currents. The exact reason for this behaviour is not clear but may be attributed to spatial hole burning effects. When the current is increased further, the damping increases linearly with the resonance frequency, and gives \( K = 0.25 \text{ ns} \), corresponding to a damping limited modulation bandwidth of 36 GHz. At higher bias currents, the damping increases much faster, limiting the maximum intrinsic bandwidth to about 11 GHz. Although the reason for this effect is not fully understood, it is believed it may due to the onset of higher order transverse modes at high current density and spatial hole burning. Other reasons could be gain saturation, carrier overflow or gain-cavity detuning due to heating of the device, each of these effects contributing to variations of the differential gain.
The same effect was also observed for small diameters 850nm oxidised VCSELs, and is briefly discussed in Paper III.

### 4.4 Large signal modulation

In order to evaluate VCSEL in a system context, transmission experiments were performed with conventional SMF. Figure 4.5 shows the experimental set-up used. The mounted VCSEL was kept at room temperature throughout the measurement. The light was directly coupled into a straight cleaved single-mode fibre, which was in turn alternatively coupled to an optical spectrum analyser, to the transmission link or directly to the high-speed receiver. Both eye diagram and error counts were measured.

**Fig. 4.5 VCSEL Transmission set up**
The VCSEL was modulated with a pseudo-random bit sequence (PRBS) of 2\(^7\)-1 at 622 Mbit/s and 2.5 Gbit/s. An erbium doped fibre amplifier and an optical band-pass filter were also used to compensate from the power penalty (10dB) at 2.5 Gbit/s. Bit-error rate (BER) was measured while varying the received optical power for distance of 0 km (back-to-back) and 90 km standard SMF. The eye diagram and the BER at both bit rates are shown in Paper II.

4.5 RCLED modulation and POF link

For the small signal analysis of the RCLEDs, the light was focused directly on a high-speed silicon detector, and the amplified electric signal was measured using a HP8510 Network Analyser. Fig. 4.6 shows the typical modulation response of a RCLED at various currents and the current dependence of the modulation bandwidth for different implantation diameters. As for the VCSEL measurements described in section 4.2, both the amplitude and the phase of the modulation response were measured and fitted using a 2-poles transfer function

\[
H(f) = \frac{\text{const}}{(jf + f_p)(jf + f_i)} \tag{4.1}
\]

where \(H(f)\) is the ratio of the small signal light output to the modulation current, \(f\) is the modulation frequency, \(f_p\) is the parasitic cut-off frequency and \(f_i\) is the intrinsic response. This model provided a very good fit for all current injection and the parasitic cut-off \(f_p\) was found to be independent of the current and equal to 650 MHz, indicating that the bandwidth is not limited by parasitics. The modulation bandwidths for all diameters increase with the current. A maximum 3dB bandwidth of 400 MHz was measured for the device with an implanted diameter of 30 \(\mu\)m.
Fig. 4.6 Measured and fitted small signal modulation response for a 50µm RCLED, and modulation bandwidth dependence on the current density for various implantation diameters
Eye diagram measurements were performed to assess the suitability of RCLEDs for high-speed data rate transmission. The RCLED emission was coupled directly into the 30 m graded-index POF (GI-POF) without additional optical elements. No additional amplification was used for the detected signal. The POF transmission system is shown in Figure 4.7. The RCLEDs were packaged in standard TO-46 cans with a 1 mm-diameter lens window.

Figure 4.8 shows the open eye diagram of a RCLED modulated with a PRBS of $2^{23}-1$, at a bit-rate of 500 Mbit/s, after transmission through 30 m GI-POF. The RCLED was biased at $I_{dc} = 66$ mA, and the amplitude of modulation was $V_{pp} = 2$ V.

4.6 Summary

This chapter presented the experimental techniques used for high-speed evaluation of VCSELs and RCLEDs. A description of the small signal modulation set-up was given, including discussions regarding technical considerations and calibration issues. The fitting of the measured responses to the analytic transfer function and the parameter extraction procedure were then described. To illustrate the approach, the key parameters introduced in the previous chapter were extracted and analysed in the case of the long wavelength VCSEL based on an integrated InP Bragg reflector depicted in Paper 1. From the bias dependence of the poles the relative importance of the three types of bandwidth limiting factors was discussed, namely damping, thermal and parasitic effects. In order to evaluate VCSEL in a system context, large signal
modulation was performed. The experimental set-up used for 2.5Gbit/s transmission through 90 km single-mode fibre depicted in Paper II was described. Finally the small and large signal analysis of RCLEDs was presented and experimental results such as bandwidth measurements and plastic optical fibre link were discussed.
5. Summary and conclusions

5.1 Summary

Vertical cavity lasers are promising sources for applications in telecommunications, in particular as low cost solutions for access network and interconnect. Presently, devices are being commercialised, with most of the research effort having been spent on achieving good static characteristics. However, as devices mature, it becomes more and more important to assess their static and dynamic properties in a system context, as well as develop/improve devices starting from established technologies. The purpose of the work presented in this thesis was to obtain an understanding of the high-speed properties of VCSELs, in order to extend the modulation frequency at which they can be used in fibre optical communication systems. It was shown that the VCSEL dynamics, under certain conditions, could be well described by a small number of parameters that can be extracted from small signal measurements and used for further optimisation. This data can be used to determine the relative importance of different bandwidth limiting effects due to damping, thermal heating and parasitics.

In the early stage of this work, the main bandwidth-limiting factor in long wavelength VCSEL was easily identified as thermal limits since the main challenge was to develop a VCSEL operating at room temperature. Paper I presents the first bandwidth measurements of a long wavelength InP:Fe semi-insulating regrown VCSEL based on an integrated InP-based reflector. The measurements were performed at a temperature stage of -60°C, at which the threshold current was minimum to optimise optical power and efficiency. The maximum 3dB bandwidth reported in the paper was 3.4 GHz. Measurements on a larger number of devices show the best lasers exhibit a maximum 3dB bandwidth of 4.3 GHz, which was comparable at that time to the best results reported with a double-fused VCSEL. Thermal management challenges also face the relatively new developed red VCSELs, for which wavelength emission at 650 nm corresponding to the minimum attenuation of Plastic Optical Fibre is at present difficult to achieve. As the wavelength is decreased towards visible emission AlGaAs/AlAs layers used in DBRs exhibit lower index contrast, and the electron confinement in GaInP/AlGaInP heterostructures becomes weaker. Paper IV describes the high-speed performance and evaluation of implanted and oxidised red VCSELs. VCSELs operating at 670 nm up to 50°C show good results but the thermally induced photon density saturation also lead to a thermally limited bandwidth of 4.5 GHz. These devices were used for transmitting 1Gbit/s signal through 50 m of graded-index
POF, demonstrating the suitability of red VCSEL for 1394b-S800 standard. Since then 2 Gbit/s performance of the component was achieved (paper 11, not included in this thesis), establishing the highest bit-rate red VCSEL POF transmission reported to date. Alternatively, for POF applications requiring less bandwidth but low cost reliable visible sources, RCLEDs have become commercially available over the past few years. Paper V reports on the error-free transmission at 250 Mbit/s over 30 m of POF. Since then, the use of a recently developed GI-POF allowed to increase the transmission bit rate to 500 Mbit/s.

Once the thermal challenges have been overcome and that the devices exhibit good temperature operation and reasonably high output power, the next challenge in VCSEL high speed operation is generally the parasitics reduction/control. Paper II describes the modulation characteristics of a 1.54 $\mu$m VCSEL fabricated at Alcatel with a top metamorphic GaAs/AlAs and bottom InP/InGaAsP Bragg reflectors with record 1mW output power. Although the relatively high level of capacitance limited the overall bandwidth to 1.2 GHz, this device was used for error-free 2.5 Gbit/s transmission through 90 km of single mode fibre.

Once the thermal and parasitics issues are addressed due to improved designs, resulting in higher bandwidths, it becomes more difficult to distinguish the main limiting factors as maximum bandwidth approaches the fundamental limit for direct modulation. Paper III reviews the dynamic properties of state-of-the-art datacom VCSEL, using implantation, oxidation or semi-insulating regrowth. The implanted devices, commercially available for transmission up to 2.5 Gbit/s, exhibits a maximum bandwidth of 3.3 GHz, limited by package-induced parasitics. The next generation oxidised VCSEL, with reduced threshold and higher efficiency, is found to be limited by the high level of damping to 10 GHz. This device was used for 10 Gbit/s transmission through multimode fibre (paper 12, not included in this thesis).

The analytic transfer function used in this work can generally well describe the VCSEL dynamics at low currents. However, at higher currents where multimode and spatial hole burning effects become more pronounced a more complex transfer function is often needed. These effects cause both spatial and temporal fluctuations in the intensity of the emitted light and can also have dramatic consequences on the dynamic behaviour of VCSELs such as competing resonance frequencies, increased damping or low-frequency fall-off. A simple but realistic dynamic model for multimode VCSELs was developed in order to understand why and how these phenomena occur. The model takes into account inhomogeneous injection, nonlinear gain, spatial hole-burning and carrier diffusion, and is based on the spatially independent rate equations for two modes. It was found that below a certain bias current, SHB is equivalent to a low-frequency enhancement of the nonlinear gain. In this region it gives an initial fall-off of the modulation response and an excessive damping of the relaxation peak. At higher currents, SHB leads to a slower increase of the resonance frequency with current. This model showed good qualitative agreement with the results observed from the oxidised red VCSEL. This model and its results are discussed in paper VI.
5.2 Conclusions and future work

From research performed in the thesis, we can conclude that the following features are required for high speed modulation of VCSELs:

a) Good thermal and static properties. Although apparently obvious, this “sine qua non” condition proves to be challenging for many applications for which wide temperature operation, high and stable output power, low and constant threshold current, low operating voltage and low power consumption are all required. A number of different solutions can address these issues: high mirror reflectivity, optical and electrical confinement, high efficiency.

b) High resonance frequency. This feature is directly related to the previous one, because of the dependence of the resonance frequency on the photon density. High resonance frequency is achieved at large photon density, which puts high demand on the optical/electrical efficiency and thermal dissipation. Another crucial parameter is the differential gain, which can be optimised when designing the active layer. The temperature dependence of the differential gain is an issue that needs to be addressed. Although careful design of the gain-cavity detuning can provide good thermal characteristics, the variation of the cavity peak with respect to the gain spectrum will also change the differential gain. This effect will also affect the Henry $\alpha$-parameter, which is of crucial importance for the chirp in long distance high-speed data transmission systems.

c) Low electrical chip parasitics. This can be achieved by minimising the resistance (e.g. with graded doped interfaces) and the capacitance (by e.g. proton implantation) in the Bragg reflectors and by carefully designing the contact pad. Other solutions such as intracavity contacts, mesa etching with polyimide/semi-insulating epitaxial regrowth have also been proven successful. In order to carefully evaluate the parasitic effects, an accurate 3D dynamic model of current injection and charge accumulation within the VCSEL is necessary. Results from such a model would also be helpful in designing a carefully impedance matched driving circuit.

d) Low damping of the resonance peak. As can be seen with the 10Gbit/s 850nm oxidised VCSEL, a high damping can drastically reduce the intrinsic maximum modulation bandwidth of a VCSEL. Low damping can be achieved by reducing the gain compression factor and increasing the differential gain. This is however far from trivial. The gain compression factor depends on a number of effects among which carrier heating and spectral hole burning are thought to be the most important. The damping is also increased by spatial hole burning, carrier transport effects and carrier overflow. Further investigations are needed to fully understand these effects.

e) For modulation speed faster than 10Gbit/s and long distance transmissions, single mode operation, low chirp and polarisation control are of crucial importance because of the modal dispersion, chromatic dispersion and polarisation mode dispersion in the fibre.
f) Due to the high reflectivity of the VCSEL DBR mirrors, optical feedback effects are less pronounced than for edge emitting lasers. However these effects have been shown to create additional noise which can limit the capacity in data transmission systems. Detailed studies of the importance of feedback on the noise and modal behaviour of VCSELs using RIN measurements would be necessary.
6. Guide to the papers

6.1 Paper I

Paper I investigates the on-wafer high-speed modulation characteristics at low temperature of InP:Fe semi-insulated regrown VCSELs based on an integrated InP Bragg reflector. The main advantage of this design was to take into account the possibility of using an InP/GaInAsP bottom mirror. Such devices are very attractive from a fabrication point of view, since only standard III-V full wafer-scale processing is involved. These VCSELs emit at 1.55 µm and operate continuous wave up to -9°C. The wafer was maintained throughout measurements at a temperature of -70°C, using a liquid nitrogen cooled set-up, where the threshold current is minimum. Measurements on a large number of devices show the best lasers exhibit a maximum 3dB bandwidth of 4.3 GHz at a bias current of 25 mA as shown in Fig. 6.1.

![Fig. 6.1 Small signal modulation response, measured (solid line) and fitted (dashed line)](image)

The analysis yields a maximum resonance frequency of 2.7 GHz, implying a parasitic-free thermally limited bandwidth of 6.2 GHz. However, the parasitic pole was found to be 1.2 to 1.7 GHz, limiting the overall bandwidth to 4.3 GHz. At high injection current (> 25 mA) the resonance frequency decreases, due to device heating. The maximum intrinsic bandwidth derived from the K-factor was found to be 30 GHz. The results of these VCSELs are comparable to other long-wavelength VCSELs.
6.2 Paper II

This paper presents the first 1.54 \( \mu m \) VCSEL single-mode fibre-optic transmission experiments using a fully monolithic structure operating CW at room temperature. This device was based on the combined use of a metamorphic GaAs/AlAs top mirror and a tunnel junction to limit the absorption in the p-doped mirror. Data rates of 622 Mbit/s and 2.5 Gbits/s were transmitted over 90 km on a single-mode fibre with bit-error rates better than \( 10^{-10} \). Small signal modulation parameter extraction indicates an ultimate intrinsic bandwidth of 20 GHz. However, high capacitance limits the bandwidth to 500 MHz. This device exhibits record 1mW output power at room temperature, and CW operation up to 47°C.

6.3 Paper III

This paper presents an approach for systematic high-speed characterisation of 850-nm datacom VCSELs and discusses both its potential benefits and problems. VCSELs using either ion implantation, selective oxidation or semi-insulating regrowth for current confinement are described and the relative advantages and issues of each current confinement schemes are discussed. The bandwidth of the implanted device appears to be limited by parasitics effects to 3.3 GHz. Due to a much smaller injection diameter, the oxidised VCSEL reaches 10 GHz, being mainly limited by the high damping. Finally the regrown VCSEL operates up to 5 GHz, limited by the parasitics.

6.4 Paper IV

This paper reports on two AlGaInP-based visible VCSEL designs based on different current confinement schemes, ion implantation and selective oxidation, and the respective performances are compared with a particular interest on the modulation properties. The implanted device operated CW up to 40°C. Threshold current of 7 mA, threshold voltage of 2.5 V and maximum optical power of 0.3 mW were measured at room temperature. The maximum 3dB-bandwidth was shown to be 2.1 GHz, limited both by thermal and parasitic effects. "Error-free" transmission at 1 Gbit/s was demonstrated through 50 meters of graded-index POF. The selectively oxidised devices achieve much higher output power (1.8 mW for the 10 \( \mu m \) opening diameter) with threshold current as low as 1.5 mA and threshold voltage of 2.1 V at room temperature, and operate CW up to 49°C. The maximum 3dB-bandwidth was 4.5 GHz. Modulation current efficiency factor up to 2.8 GHz/\( \sqrt{[mA]} \) was measured.
6.5 Paper V

In this Paper, POF transmission experiments using a RCLED emitting at 660 nm is reported. The light was directly coupled into the POF without additional optics. Operating the RCLED at a DC current of 60 mA generated 0.6 mW of fibre-coupled power measured after 1 m of POF. A high-speed receiver together with a digital communication analyser was used to detect and analyse the signal. The RCLEDs were biased at 80 mA and modulated using a $2^7 - 1$ pseudo-random bit sequence with peak-to-peak amplitude of 2 V. Transmission through 30 m of POF at a data rate of 250 Mbit/s was demonstrated.

6.6 Paper VI

A simplified dynamic multi-mode model for VCSEL is presented. By describing the shape of the carrier distribution with a sum of modal shapes, the original spatially resolved rate equation system is reduced to a set of spatially independent rate equations with a minimum of parameters. The model is used to study the influence of spatial hole burning, mode competition and carrier diffusion on the small signal modulation response. Despite the simplifications the model shows good agreement with spatially resolved models, and qualitative agreement with results obtained from oxidised GaAs-based VCSELs. The model shows that SHB has significant influence on the damping and the resonance frequency.
References


Paper I

High-speed modulation characteristics of long wavelength vertical cavity lasers based on an integrated InP Bragg reflector

R. Stevens, S. Rapp, R. Schatz, E. Goobar, K. Streubel and A. Karlsson

Paper II

90 km single mode fibre transmission using 1.54 μm vertical cavity lasers with top metamorphic GaAs/AlAs and bottom InP/InGaAsP Bragg reflectors


Paper III

Quest for very high-speed VCSELs: pitfalls and clues

R. Stevens, R. Schatz, A. Lövqvist, T. Aggerstam, C. Carlsson, C. Angulo Barrios, S. Lourdudoss and M. Ghisoni

Paper IV

High-speed visible VCSEL for POF data links

R. Stevens, A. Risberg, R. Marcks Von Wurtemberg, B. Kronlund, M. Ghisoni and K. Streubel

Paper V

250 Mbit/s plastic fibre transmission using 660 nm resonant cavity light emitting diode

K. Streubel and R. Stevens

Paper VI

Influence of spatial hole burning and mode competition on the modulation response of vertical cavity surface emitting lasers

R. Schatz, H. Isik, M. Peeters and R. Stevens

To be submitted