Semiconductor Lasers

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MSc in Photonics, Europhotonics
Outline

1. Introduction
2. Types of semiconductor lasers (SCLs) and their applications
3. Opto-Electronic Characteristics of SCLs
4. Dynamic characteristics of SCLs
5. The next frontiers of semiconductor laser research
The development of SCLs and applications

- Lasing in semiconductor diodes was first observed in 1962 (pulsed operation, cryogenic temperatures), only two years after the first demonstration of a laser.

- Semiconductor lasers (SCLs or diode lasers) are electrically pumped, and convert electrical power into optical power.

- SCLs appeared in telecom networks in the 1970s, in compact disc players in the 1980s, and high-power diodes emerged in the 1990s for optical pumping, medicine, and materials processing.

- After 50 years, the diode laser market is over $3 billion, and new technology and applications are still appearing.
Semiconductors

(Adapted from J. Faist, course on quantum electronics, ETHZ)
Direct and indirect semiconductors

Optical transitions between continuous energy bands (not discrete levels)

E_g typically < 4 eV

Inefficient light sources, efficient photon detectors

(Adapted from J. Faist, course on quantum electronics, ETHZ)
Semiconductors wavelengths

\[ \lambda_0 = \frac{hc}{E_g} \]
The first generation of SCLs

1962: First GaAs SCLs (pulsed operation, cryogenic temperatures) developed at General Electric Research Labs

1970: GaAs-based emitting, cw RT in the 800-900 nm range, developed at Bell labs.

- The devices used hetero-barriers to confine carriers to an active layer of GaAs, on the of order 0.1 μm in thickness, which had higher band gap layers of AlGaAs on either side.
- High operating currents (400 mA) and very short lives.

Source: Optics and Photonics News May 2012
SCLs: the first generation

By late 1974, the laser had been operating continuously for more than a year at room temperature (typically 30 °C) with power outputs exceeding 1 mW.

Source: Optics and Photonics News May 2012
Early applications

- The first applications (1977) within Bell labs: demonstrated data rates of 45-90 Mb/s.
- Next: short-distance trials carrying live traffic (fibers were used to connect three telephone central offices in downtown Chicago).
- Next: February 1980 at the Winter Olympics at Lake Placid an experimental optical fiber system was used to broadcast TV around the world.

The second generation of SCLs (~1986): improved devices with buried heterostructures for use in the 1.3 μm window.
SCLs in communications: then to now

• Today, all terrestrial and undersea telecommunications, data and television traffic above the local distribution level is carried in fibers using SCLs as light sources.

• The Internet would not be possible without SC lasers.

• Continuously-wave (cw) operating lasers, which carry no signal information, are used to pump fiber amplifiers that are periodically spaced under the sea.

• With very-high-speed modulation and wavelength division multiplexing (WDM), now information speed can approach 1 Tb/s—20,000 times higher that the initial 45 Mb/s rates.

• Present record for single-channel bit rate (?): 10.2 Tbit/s (2011 OFC)

Source: Optics and Photonics News May 2012
SCLs also in consumer products

Printers, scanners, CD/DVD players, etc — a dramatic price reductions made possible these applications (the VCSEL in a computer mouse costs about 10 cents of US dollar to manufacture)
Diode lasers represent 50% of the worldwide laser market.

Source: Laserfocusworld.com
Why diode lasers are so popular?

• Their output is very bright considering their small size. Hundreds of watts of power are commercially available from laser diodes operating under continuous wave (CW) conditions in packages as small as a few cubic inches. Their small size allow laser diodes to be used in environments and spaces in which other types of lasers cannot operate.

• Compared to other types of lasers, laser diodes use very little power. Overall efficiencies greater than 30% are typical.

• Since laser diodes are made of semiconductor materials, they do not require the fragile glass enclosures or mirror alignment (typical of gas lasers).
Also popular because

- Coherence and single wavelength characteristics of laser diodes enable the outputs of these devices to be focused to a diffraction limited spot size. The size of the resultant spot is dependent on the wavelength of the laser - the shorter the wavelength of light, the smaller the size of the spot.

- Operation at shorter blue and UV wavelengths makes smaller spot sizes possible, allowing more information to be stored on optical disks at a higher density.

- They can be directly modulated at high frequencies. By modulating the drive current, the laser output is modulated at GHz frequencies in high-speed data communications.
FABRICATION STEPS FOR A SEMICONDUCTOR LASER

1- SUBSTRATE

2- EPITAXIE

3- LASER PROCESSING

4- FACETS CLEAVING

5- SINGLE CHIP PREPARATION

6- MOUNTING, BONDING

Adapted from J. Faist, ETHZ
In today’s laser marketplace

SCLs main applications:
- Telecommunications
- Optical Storage

But also:
- Image Recording, laser printers
- Pumping of solid-state lasers (such as Nd:YAG), fiber lasers and Erbium Doped Fiber Amplifiers (EDFAs)
- Material Processing
- Biomedical instruments (spectroscopy, ophthalmology)
- Entertainment and display (light shows, digital cinema, projectors, laser pointers)
- Sensing, Instrumentation (optical mice, barcode readers, gesture recognition)

Source: Laserfocusworld.com
Types of SCLs and applications

- Wavelength
- Output power
- Cavity geometry
- Gain medium
Wavelengths

➢ Short wavelength

• $\lambda = 635 - 980$ nm
• Fabrication by epitaxial growth on gallium arsenide (GaAs) substrates
• Optical data storage

➢ Long wavelength

• $\lambda = 980 - 1550$ nm
• Fabrication by epitaxial growth on indium phosphide (InP) substrates
• Telecom

$\lambda = 980$ nm
Pumping of Erbium Doped Fiber Amplifiers (EDFAs)
Band-gap energy and wavelength of semiconductor materials

- Blue laser diodes are based on gallium nitride (GaN) or indium gallium nitride (InGaN) technologies.
- Blue lasers can also be constructed using frequency-doubling of infrared laser wavelengths.

SUEMATSU & IGA: SEMICONDUCTOR LASERS IN PHOTONICS, JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, NO. 9, MAY 1, 2008
Optical data storage

• Has led to revolutionary advances in information processing.
• One of the key challenges is to meet the demand for storage capacity.
• ‘Bit-by-bit’ optical data storage systems are
  – compact discs (CDs)
  – digital video discs (DVDs)
  – Blu-ray discs (Blu-rays)
• Advantages
  – compact and portable devices (high tolerance to vibrations)
  – high memory density
  – high resistance to intense electromagnetic radiation.
• Key advantages with respect to holographic data storage systems (capable recording and reading millions of bits in parallel)
‘Bit by bit’ Optical data storage

Information is retrieved back by detecting the intensity variation of a reading beam when the optical disc is scanned.

Source: Optics and Photonics News July/August 2010
Evolution of optical data storage systems

First generation: CDs
• CDs emerged in the 1980s.
• The information is in a 2D surface of a recording medium.
• The information occupies less than 0.01 percent of the volume of a CD.
• \( \lambda = 780 \) nm
• Due to the limitation of the recording wavelength and the numerical aperture (NA) of the recording lens, the maximum data capacity is about 650 to 750 megabytes for each CD.

(1 MB = 1 million bytes; 1 byte = 8 bits).
The second generation of optical data storage systems

Digital versatile disks (DVDs)
- invented and developed by Philips, Sony, Toshiba, and Panasonic in 1995
- $\lambda = 650$ nm
- Resolution $= 0.61 \times \frac{\lambda}{NA}$
- Storage capacity $= 4.7$ GB/disc

Blue DVDs (Blu-rays)
- $\lambda = 405$ nm
- 23.5 GB/disc
What is next?

3D systems, multidimensional systems, 2-photon absorption (to decrease depth of field for more layers), shorter $\lambda$ (frequency doubling), supra-resolution imaging methods (stimulated emission depletion STED), holographic data storage, etc...

Source: Optics and Photonics News July/August 2010
Major achievements (as in 2010)

<table>
<thead>
<tr>
<th>Group</th>
<th>Year</th>
<th>Achievements</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parthenopoulos</td>
<td>1989</td>
<td>Demonstration of 2P-induced 3-D storage with a two-beam approach</td>
<td>--</td>
</tr>
<tr>
<td>et al.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strickler et al.</td>
<td>1991</td>
<td>Demonstration of 2P-induced memory with a single-beam approach</td>
<td>--</td>
</tr>
<tr>
<td>Glezer et al.</td>
<td>1996</td>
<td>2P-induced 3-D voids recording in silica</td>
<td>17 Gbits/cm³</td>
</tr>
<tr>
<td>Kawata et al.</td>
<td>1998</td>
<td>Rewritable 2P recording in a photorefractive crystal</td>
<td>33 Gbits/cm³</td>
</tr>
<tr>
<td>Gu et al.</td>
<td>1999</td>
<td>Realization 2P recording using a CW laser</td>
<td>3 Gbits/cm³</td>
</tr>
<tr>
<td>Day et al.</td>
<td>1999</td>
<td>Rewritable 2P recording in a photorefractive polymer</td>
<td>5 Gbits/cm³</td>
</tr>
<tr>
<td>Kawata et al.</td>
<td>2000</td>
<td>2P recording in photochromic materials by a confocal reflection microscope</td>
<td>--</td>
</tr>
<tr>
<td>McPhall et al.</td>
<td>2002</td>
<td>Polarization-sensitive 2P recording in polymer dispersed liquid crystal</td>
<td>205 Gbits/cm³</td>
</tr>
<tr>
<td>Day et al.</td>
<td>2002</td>
<td>2P-induced voids recording in polymers</td>
<td>2 Gbits/cm³</td>
</tr>
<tr>
<td>Walker et al.</td>
<td>2007</td>
<td>2P-induced photochromic recording in a multilayer disc</td>
<td>250 GB/disc</td>
</tr>
<tr>
<td>Walker et al.</td>
<td>2008</td>
<td>2P-induced photochromic recording in a 200-layer disc</td>
<td>1,000 GB/disc</td>
</tr>
</tbody>
</table>

A long way from the beginning...
Storage Capacity: about 0.01 byte / mm²
(adapted from K. Tatebe)
Due to their narrow spectral bandwidth SCLs have replaced LEDs as light sources in most applications of optical fibers.

SCLs have much faster response times than LEDs, which is crucial to the development of ultrafast networks and computers.

LEDs also fail to meet the power requirements of high-speed fiber systems (but they are still used with large-core multi-mode fibers in some short-range applications).
The most important transmission window is the C or “conventional” band from 1,530 to 1,565 nm, at which single-mode fibers have the least signal loss.

It is also called the “erbium window” because it is the best suited for erbium-doped fiber amplifiers, which are crucial to long-haul communications.

Other important bands are
- the L or “long” band from 1,565 to 1,625 nm for long-haul telecom,
- the O or “original” band at 1,310 nm,
- the S or “short” band at 1,490 nm, for intermediate distances, and
- the unnamed region centered on 850 nm, for short-range data applications.
SCLs in optical communications

• Over the past 20 years tunable SCLs have been developed, whose operating wavelength can be adjusted within the relevant communications band.

• The SCLs used in optical communications are Distributed Feedback lasers (DFBs) and vertical-cavity surface-emitting lasers (VCSELs), more latter.

• The lasers must send out a signal within the optimum transmission windows of the fibers with enough power to reach the receiver or repeater with a sufficient signal-to-noise ratio (but not so much as to create undesirable nonlinearities).
SCLs in optical communications

The different types of networks have their own requirements for semiconductor lasers and modulation schemes.

- **Long-haul** (telecommunications, > 100 km),
- **Metropolitan** (~10 km),
- **Access** (communications links between subscribers and their telecom or datacom service provider: the link to your Internet, cable-television and/or phone company: “fiber to the home” or FTTH, < 10 km)
- **Interconnects** (of short-haul data communications or datacom < 100 m)
### Modern laser modules incorporate tunable lasers with an integrated semiconductor optical amplifier

### Summary of Characteristics

<table>
<thead>
<tr>
<th>Network Type</th>
<th>Long-Haul</th>
<th>Metro</th>
<th>Access</th>
<th>Interconnect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance (scale)</strong></td>
<td>&gt;100 km</td>
<td>10 km</td>
<td>Limited to 20 km by International Telecommunications Union (ITU) standard; often &lt;10 km</td>
<td>&lt;100 m</td>
</tr>
<tr>
<td><strong>Laser type</strong></td>
<td>Primarily DFB</td>
<td>DFB, VCSEL</td>
<td>Downstream: DFB Upstream: DFB or Fabry-Pérot</td>
<td>VCSEL</td>
</tr>
<tr>
<td><strong>Wavelength</strong></td>
<td>1,550 nm (C-band); 1,565 to 1,625 nm (L-band)</td>
<td>1,310 nm; 1,550 nm</td>
<td>Downstream: 1,490 nm and/or 1,550 nm Upstream: 1,310 nm</td>
<td>850 nm; 1,310 nm</td>
</tr>
<tr>
<td><strong>Modulation scheme</strong></td>
<td>Direct or external</td>
<td>Direct</td>
<td>Direct</td>
<td>Direct</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>10 Gbps</td>
<td>10 Gbps</td>
<td>Downstream: ≤2.5 Gbps Upstream: ≤1.24 Gbps</td>
<td>10GigE; 40GigE and 100GigE standards expected mid-2010</td>
</tr>
<tr>
<td><strong>Multiplexing scheme</strong></td>
<td>WDM, DWDM or coarse WDM</td>
<td>Coarse WDM or DWDM</td>
<td>WDM</td>
<td>Governed by Fiber Channel and Ethernet protocols</td>
</tr>
</tbody>
</table>

Source: Optics & Photonics News March 2010
Wavelength division multiplexing (WDM)

Channels need to be separated in frequency far enough such that the modulation sidebands of “neighboring channels” don’t overlap.

Adapted from D. Natelson, Rice University
Passing multiple independently modulated carriers of differing wavelengths down a single fiber is called \emph{wavelength division multiplexing}.

Dense WDM (DWDM), and has channels spaced by numbers like 1.6 nm, 0.8 nm, 0.4 nm (200 GHz, 100 GHz, and 50 GHz, respectively).
Types of SCLs and applications

- Wavelength
- Output power
- Cavity geometry
- Gain medium
SCL output power

- Low power (< 1 W)
  - Telecommunications
  - Optical Storage

- High power (> 1 W)
  - Optical pumping of solid-state lasers, such as the Nd:YAG. High-power laser diodes are tuned to the absorption band of the dielectric crystal resulting in much more efficient pumping

  Pump sources for Erbium Doped Fiber Amplifiers (EDFAs, 980 nm).

  Such optical amplifiers are used in direct optical amplification of the 1550 nm wavelength telecommunication signals propagating along the long haul telecommunication lines.
Low power diode lasers

5.6 mm or 9 mm diameter base
Telecom lasers

- Vertical Cavity Surface Emitting Lasers (VCSELs)

- dual-in-line 14 pin
- butterfly package
High-power broad-area SCLs

• Recent progress in SCL technology has enabled the use of SCLs in materials-processing applications such as welding, soldering and cutting.

• Laser diode mirrors are formed by cleaving the semiconductor along crystal planes, where the exposed semiconductor surface can oxidize and create optically absorbing defects at the mirror facet.

• The oxidation and generation of defects is a photosensitive and temperature-driven reaction.

• Therefore, during high-power laser operation, the mirror can degrade, become more absorbing, and eventually lead to catastrophic optical mirror damage.

• In the early 2000s optical power was limited to 5W

• Several new techniques have arisen over the past decade and high-power AlGaAs diodes in the 900 nm range can now reach >20 W per emitter
High-power broad-area SCLs

- Typically a high-power SCL is bonded onto a **heat sink** that has a **coefficient of thermal expansion** (CTE) matched to that of GaAs.

- Lateral wide $w \approx 100 \, \mu m$; cavity length $L \approx 4 - 6 \, mm$

multimode emission:
- # longitudinal modes: 100-200
- each longitudinal mode has 20 – 30 lateral modes

- Diode laser arrays allow for output powers in the range of kilowatts and are used for industrial welding and precision cutting of metals and various other materials.

Optics and Photonics News, October 2010
The maximum power in a single spatial mode is in the range of 100 – 150 mW and total cw power can approach 200 mW
Types of SCLs and applications

- Wavelength
- Output power
- Cavity geometry
- Gain medium
Optical cavities

Edge-Emitting Lasers (EELs)

- Two cleaved surfaces that serve as mirrors
  \[ L \approx 300 \, \mu m \]

- Injected current
- Wire bond
- Stripe contact
- Cladding layer
- Active layer \( \sim 100 \, \text{Å} \)
- Bottom contact
- Highly divergent output beam

Adapted from J. Mulet, PhD thesis, Universitat de les Illes Balears (2002)

VCSELs

- \( L = 1-2 \, \mu m \)

Adapted from Suematsu and Iga, J. Lightwave Tech. 26 1132 (2008)
Astigmatism is a condition in which the apparent focal points of the two axes do not coincide. It limits the ability to focus the laser beam to a small spot size and complicates focusing the output beam to a sharp well-defined point.
VCSEL advantages

- Low drive current (a few mA)
- Low output power (a few mW)
- High efficiency
- Low divergence, circular beam
- High speed modulation at low currents
- Low manufacturing cost (on-wafer testing)

Drawbacks: thermal and polarization effects.

Since 1988 VCSELS have gone a long way: the VCSEL in your computer mouse probably cost its manufacturer US$ 10 cents to make (OPN March 2010).
VCSEL advantages

- Can be fabricated in 2D arrays
- Their laser structure has a circular aperture allowing the output beam to be easily collimated using a simple spherical lens.
- They emit a very narrow spectral output.

Scanning electron micrograph of a 2D VCSEL array (Axel Scherer, Picolight).
Power-efficient answer

Eli Kapon\textsuperscript{1,2} and Alexei Sirbu\textsuperscript{2}

\textbf{Figure 1} | Long-wavelength VCSELs. \textbf{a}, On a wafer. \textbf{b}, Individually. These have a lower power consumption than their edge-emitter counterparts at similar optical power level. In addition, their vertical-cavity design leads to better coupling to single-mode fibres (by a factor of 2–4) and enables on-wafer characterization, which greatly reduces manufacturing costs.
Another type of low-power SCL: Ring Laser

- The dominant resonant mode is a *whispering-gallery mode* that propagates around the edge of the disk with very low loss due to *total internal reflection* at the boundary between the high index semiconductor medium and its surrounding medium (either air or glass).


- Ring lasers support two counter-propagating modes:
  - Clockwise mode (CW)
  - Counterclockwise mode (CCW)
Figure 1.7: Semiconductor ring lasers with different geometries: (a) a racetrack cavity with evanescent out-coupling [23], (b) a square mirror based design [24], (c) a triangular mirror based design [25], (d) two coupled micro-squares [26], (e) two coupled rings [6], (f) a racetrack cavity with a S-bend coupler [27].
A fast low-power optical memory based on coupled micro-ring lasers

Martin T. Hill¹, Harmen J. S. Dorren¹, Tjibbe de Vries¹, Xaveer J. M. Leijtens¹, Jan Hendrik den Besten¹, Barry Smalbrugge¹, Yok-Siang Oei¹, Hans Binsma², Giok-Djan Khoe¹ & Meint K. Smit¹

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NATURE | VOL 432 | 11 NOVEMBER 2004 |

two such ring lasers by an optical fiber, which also serves to carry input and output signals.

When a picosecond input pulse is sent through the connecting fiber in the CW direction, the pulse adds to the CW signal from the left-hand ring laser to lock the right-hand laser into a strong, mode-locked CW oscillation. In this state, (which could be identified with a “0” memory bit) the right-hand laser produces triple the output of the left-hand laser, which is running with both CW and CCW modes.

A picosecond input pulse in the opposite direction reverses the situation, making the oscillation CCW and causing the left-hand laser to be the more powerful, mode-locked one, producing the opposite memory state (a “1” bit). The two states can be distinguished by the output light that leaks back into the
Types of SCLs: lateral confinement

Gain guided

\[ \Delta n \approx 0.001 \]

multimode

\[ n = n(\lambda, I, N, T) \]

Index-guided (buried hetero-structure)

\[ \Delta n < 0.01 \]

Single mode

\[ \Delta n > 0.1 \]

Stable single mode

Optical confinement (1/2)

Higher band gap materials have a lower refractive index & AlGaAs layers provide lateral optical confinement.

This difference in refractive index is what establishes an optical dielectric waveguide that ultimately confines photons to the active region.

Dr. Khanh Kieu (University of Arizona)

15/03/2013 C. Masoller, LSA 2013 51
Optical confinement (2/2)

Homostructure

Heterostructure
First continuous wave SCLs operating at room temperature were hetero-structures

**Heterostructure**

- AlGaAs
- GaAs
- AlGaAs

**Advantages**

- Improved confinement of the injected electrons and holes reduces threshold current and reduces thermal effects.
- It also improves the confinement of the photons, reducing optical loss.
- This allows to operate continuous-wave at room temperature.
- It is possible to modify the dimensionality of gain media to increase the gain and further reduce threshold current:
  - 2D: Q Well
  - 1D: Q Wire
  - 0D: Q Dot

Dr. Khanh Kieu (University of Arizona)
Heterostructures

The **2000 Nobel Prize in Physics** was awarded

"*for basic work on information and communication technology*

with one half jointly to Zhores I. Alferov (Iaffe Physico-Technical Institute, St. Petersburg, Russia) and Herbert Kroemer (University of California, USA)

"*for developing semiconductor heterostructures used in high-speed- and opto-electronics*"
Optical spectrum

Multimode gain guided
670 nm laser diode

Single-mode index guided
780 nm laser diode

Relative intensity

Wavelength $\lambda$ (nm)

Relative intensity

Wavelength $\lambda$ (nm)
Types of SCLs and applications

• Wavelength
• Output power
• Cavity geometry
• Gain medium
  – quantum-wells (QWs)
  – quantum dots (QDs)
  – quantum cascade laser (QCL)
Bulk vs quantum well

Electrons

Holes

n-AlGaAs cladding 1000 Å GaAs active region p-AlGaAs cladding

Electrons

AIGaAs GRIN SCH

GaAs quantum well

Holes
Nowadays most SCLs are multi-quantum-wells (MQWs)

A MQW structure is fabricated with alternating layers of AlGaAs and GaAs

Saleh & Teich, Fundamentals of Photonics
Quantum dot lasers (QDLs)

• While quantum wells are essentially thin layers of active material, quantum dots are (as the name suggests), dots or islands of material surrounded by another material.

• The dots have a lower-energy bandgap than the surrounding material.

• Because they possess very different structures, QW and QD lasers can have very different properties even though they may be made from the same materials (such as InAs and GaAs).
QDL wavelengths

• The natural wavelength of bulk GaAs is 870 nm. To achieve longer wavelengths (for example, 980nm) an increasing amount of indium has to be added to the quantum-well structure.

• As indium is a large atom, a lot of stress is induced in the layer and a limit is reached at around 1,100 nm.

• Because quantum dots are not layers, but islands, they may accommodate more strain, so more indium can be introduced, leading to a longer wavelength.
QDL Tunability

• The lasing wavelength is determined by the size of the quantum dots.

• By controlling the size distribution of the quantum dots, QDLs offer a broad lasing spectrum.

• The tunability offered by changing the size and shape of the QDs allows these devices to reach wavelengths that are unachievable through other semiconductor laser technologies.

• This makes them ideal as a source for optical clock technology in optical computing.
QDs fabrication

- Atom-like islands of 10-20 nm diameter, each one containing about $10^5$ atoms
- Geometry parameters (density of QDs, size distribution) can be controlled by growth parameters.

Brighter Tutorials: http://www.ist-brighter.eu
Quantum Cascade Lasers: Intersubband laser diodes

Illustration of the differences between traditional (interband) laser diodes and intersubband laser diodes such as the quantum cascade laser. Unlike the interband laser, the intersubband makes use of an electronic transition (yellow) solely within the conduction band.
A semiconductor injection laser that differs in a fundamental way from diode lasers has been demonstrated. It is built out of quantum semiconductor structures that were grown by molecular beam epitaxy and designed by band structure engineering. Electrons streaming down a potential staircase sequentially emit photons at the steps. The steps consist of coupled quantum wells in which population inversion between discrete conduction band excited states is achieved by control of tunneling. A strong narrowing of the emission spectrum, above threshold, provides direct evidence of laser action at a wavelength of 4.2 micrometers with peak powers in excess of 8 milliwatts in pulsed operation. In quantum cascade lasers, the wavelength, entirely determined by quantum confinement, can be tailored from the mid-infrared to the submillimeter wave region in the same heterostructure material.
Quantum Cascade Lasers

Among the most recent semiconductor lasers, QCLs\(^1\) can be tailored to emit throughout most of the IR spectrum. Therefore, they are key photonic tools for an expanding range of applications. Unlike conventional semiconductor lasers, where lasing is a result of recombination of electron-hole pairs across the band gap, they operate through intersubband transitions in a stack of quantum wells. Since their demonstration, QCLs had been thought to exhibit a very narrow intrinsic linewidth, considerably

Continuous Wave Operation of a Mid-Infrared Semiconductor Laser at Room Temperature

Mattias Beck,\(^1\) Daniel Hofstetter,\(^1\) Thierry Aellen,\(^1\) Jérôme Faist,\(^1\) Ursula Oesterle,\(^2\) Marc Ilegems,\(^2\) Emilio Gini,\(^3\) Hans Melchior\(^3\)

Continuous wave operation of quantum cascade lasers is reported up to a temperature of 312 kelvin. The devices were fabricated as buried heterostructure lasers with high-reflection coatings on both laser facets, resulting in continuous wave operation with optical output power ranging from 17 milliwatts at 292 kelvin to 3 milliwatts at 312 kelvin, at an emission wavelength of 9.1 micrometers. The results demonstrate the potential of quantum cascade lasers as continuous wave mid-infrared light sources for high-resolution spectroscopy, chemical sensing applications, and free-space optical communication systems.

SCIENCE VOL 295 11 JANUARY 2002
QCLs applications

- Proteins and other large biomolecules have very strong and unique vibrational characteristics in the 10 to 100 THz (THz=10^{12} Hz) range.

- **QCLs applications**: nowadays emitting in a wide range of wavelengths in the infrared, being compact, efficient and operating at room temperature, QCLs are suitable light sources for "lab-on-a-chip" biosensors that are noninvasive, portable and accurate.

*Figure 2.0-1* Optical frequencies and wavelengths.
Since the first CW demonstration in 2002 (about 10 mW of power), QCLs have experienced rapid and dramatic improvements in power, efficiency and wavelength range.

The wavelength region accessible with quantum cascade lasers and the developing applications of this technology.
Design of fabrication of microfluidics over the facet of the quantum cascade laser integrated with plasmonic antenna. (a) The 2-mm QCL is first chipped and mounted onto a standard gold-coated c-mount that has been thinned to less than 1 mm. (b) The packaged laser is then submerged in PDMS and patterned for inlet and outlet ports. (c) Finally, the hoses are connected to the microfluidic channel, and liquid is pumped through the device.
Summary

• By engineering the band gaps of semiconductor materials, laser emission can be obtained in a wide range of wavelengths (from mm–THz to ultraviolet).
• A variety of optical cavity structures leads to a variety of semiconductor laser devices.
• Key advantages are their inexpensive fabrication, and they are compact and reliable.
3. Opto-Electronic Characteristics

- Output Light vs. Input Current Curve (L.I. Curve)
- Longitudinal modes and optical spectrum
- Lateral and transverse modes
The efficiency of the diode laser in converting electrical power to light power is determined by the slope of the L.I. curve, \( \Delta P/\Delta I \).
Thermal effects are device-dependent
Longitudinal modes

$L = m(\lambda/2)$, where $L$ is the cavity length, $\lambda$ is the wavelength of light in the semiconductor, is related to the free space wavelength through the index of refraction $n$: $\lambda = \lambda_o/n$

$$\Delta \lambda = (\lambda_o)^2/2nL$$

For semiconductors: $n=3.6$  \hspace{1cm} \textbf{Gain bandwidth: $\Delta \nu_g = 5 \text{ -} 50 \text{ THz}$}

**Typical values for EELs**: $L = 300 \mu m \Rightarrow \Delta \nu_n = 150 \text{ GHz} = 0.15 \text{ THz}$

**Typical values for VCSELs**: $L=1-2 \mu m \Rightarrow \Delta \nu_n = 1500 \text{ GHz} = 1.5 \text{ THz}$
Optical spectrum

**Single mode (VCSEL)**

![Graph of single mode VCSEL](image1)

**Multi mode (EELs)**

![Graph of multi mode EELs](image2)

For high-data-rate optical fiber transmission single mode SCLs are required because each mode travels with its own group velocity. Thus, the optical pulses emitted by a multimode laser broaden with propagation distance, which gradually loses the distinction between binary ‘zero’ and ‘one’.
Spatial modes

EELs: lateral modes

VCSELs: transverse modes
Effects of operating current level on the optical spectrum

**Multi longitudinal mode**  
*(gain guided)*

<table>
<thead>
<tr>
<th>Power (mW)</th>
<th>Relative optical power</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>1</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>3</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>5</td>
<td>778, 780, 782</td>
</tr>
</tbody>
</table>

**Single longitudinal mode**  
*(index guided)*

<table>
<thead>
<tr>
<th>Power (mW)</th>
<th>Relative optical power</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>1</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>3</td>
<td>778, 780, 782</td>
</tr>
<tr>
<td>5</td>
<td>778, 780, 782</td>
</tr>
</tbody>
</table>

15/03/2013  
C. Masoller, LSA 2013  
76
Temperature variation of the center wavelength

The temperature allows tuning the wavelength, which is useful for spectroscopy applications.
Why the optical spectrum varies with the pump current and with the temperature?

• Because in semiconductors optical transitions occur between continuous energy bands (and not discrete levels)
• Fermi-Dirac distribution:
  \[ f(E) = \left[ 1 + \exp\left(\frac{E - E_f}{k_b T}\right) \right]^{-1} \]
  \[ k_b = \text{Boltzmann constant, } E_f = \text{Fermi level} \]
Conduction and valences bands

- If $E_f$ lies between two energy bands, when $T \to 0$ the lower bands are filled (valence bands) and the higher bands are empty (conduction bands).
- When $T \neq 0$ the probability of finding electrons in the lowest conduction band is a function of $E_g/k_b T$: it increases with $T$ and decreases with $E_g$.
- Electrons in the conduction band leave ‘holes’ in the valence band.
- A ‘hole’ behaves as a particle with positive charge.
The electrons in the conduction band (CB) and the holes in the valence band (VB) are both carriers that contribute to the electrical conductivity of the semiconductor.

A semiconductor is an isolator at $T=0$, and its conductivity increases with $T$.

In most semiconductors, $E_g$ decreases with $T$.

Because the “carriers” (electron-hole pairs) are distributed in the CB and VB, which have opposite and different curvatures the semiconductor has a broad gain spectrum.
Semiconductor Gain

The semiconductor gain is wavelength dependent with a peak gain that shifts as a function of the carrier density.
### Table 12.1 Properties of some important semiconductors$^a,b$

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Type$^c$</th>
<th>Bandgap, $E_g$ (eV)</th>
<th>$\lambda_g$ (nm)</th>
<th>Refractive index</th>
<th>Lattice constant ($\text{Å}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>At 0 K</td>
<td>At 300 K</td>
<td>At 300 K</td>
<td>At $\lambda_g$</td>
</tr>
<tr>
<td>IV C$^d$</td>
<td>I</td>
<td>5.48</td>
<td>5.47</td>
<td>227</td>
<td>2.71</td>
</tr>
<tr>
<td>Si</td>
<td>I</td>
<td>1.17</td>
<td>1.12</td>
<td>1110</td>
<td>3.58</td>
</tr>
<tr>
<td>Ge</td>
<td>I</td>
<td>0.74</td>
<td>0.66</td>
<td>1880</td>
<td>4.12</td>
</tr>
<tr>
<td>IV–IV SiC</td>
<td>I</td>
<td>2.39–3.33</td>
<td>2.36–3.30</td>
<td>380–530</td>
<td>–</td>
</tr>
<tr>
<td>Si$<em>x$Ge$</em>{1-x}$</td>
<td>I</td>
<td>0.74–1.17</td>
<td>0.66–1.12</td>
<td>1110–1880</td>
<td>–</td>
</tr>
<tr>
<td>III–V$^e$ AlN</td>
<td>D</td>
<td>6.29</td>
<td>6.20</td>
<td>200</td>
<td>2.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlP</td>
<td>I</td>
<td>2.49</td>
<td>2.41</td>
<td>515</td>
<td>2.96</td>
</tr>
<tr>
<td>AlAs</td>
<td>I</td>
<td>2.23</td>
<td>2.17</td>
<td>572</td>
<td>3.19</td>
</tr>
<tr>
<td>AlSb</td>
<td>I</td>
<td>1.69</td>
<td>1.62</td>
<td>768</td>
<td>3.50</td>
</tr>
<tr>
<td>GaN</td>
<td>D</td>
<td>3.50</td>
<td>3.44</td>
<td>360</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaP</td>
<td>I</td>
<td>2.34</td>
<td>2.26</td>
<td>549</td>
<td>3.43</td>
</tr>
<tr>
<td>GaAs</td>
<td>D</td>
<td>1.52</td>
<td>1.42</td>
<td>871</td>
<td>3.63</td>
</tr>
<tr>
<td>GaSb</td>
<td>D</td>
<td>0.81</td>
<td>0.73</td>
<td>1700</td>
<td>3.75</td>
</tr>
<tr>
<td>InN$^f$</td>
<td>D</td>
<td>1.92</td>
<td>1.90</td>
<td>653</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InP</td>
<td>D</td>
<td>1.42</td>
<td>1.35</td>
<td>919</td>
<td>3.40</td>
</tr>
<tr>
<td>InAs</td>
<td>D</td>
<td>0.43</td>
<td>0.35</td>
<td>3540</td>
<td>3.52</td>
</tr>
<tr>
<td>InSb</td>
<td>D</td>
<td>0.24</td>
<td>0.17</td>
<td>7290</td>
<td>4.00</td>
</tr>
</tbody>
</table>

---

from J. M. Liu, Photonic devices (Cambridge University Press)
Band-gap energy \( (E_g) \) and refractive index \( (n) \)

\textbf{GaAs}

\[ E_g = 1.5216 - \frac{5.405 \times 10^{-4} T^2}{T + 204} \text{ (eV)} \]

At 300 K:

\[ n^2 = 8.950 + \frac{2.054\lambda^2}{\lambda^2 - 0.390} \]

\[ \frac{1}{n} \frac{dn}{dT} = 4.5 \times 10^{-5} \text{ K}^{-1} \]

\textbf{InP}

\[ E_g = 1.4206 - \frac{4.906 \times 10^{-4} T^2}{T + 327} \]

\[ n^2 = 7.255 + \frac{2.316\lambda^2}{\lambda^2 - 0.3922} \]

\[ \frac{1}{n} \frac{dn}{dT} = 2.7 \times 10^{-5} \text{ K}^{-1} \]

from J. M. Liu, Photonic devices (Cambridge University Press)
A main goal in the development of tunable lasers is to avoid mode-hopping.
Electrons and holes concentrations

- Concentration: number of electrons in the CB (or holes in the VB) per unit volume.
- Is determined by the type of semiconductor, the temperature and the external pumping (electrical or optical, injection of electrons or photons)
- In an intrinsic semiconductor all electrons in the CB come from thermal excitation from the VB, electron concentration= hole concentration
- In an extrinsic (doped) semiconductor there are impurities: atoms that can be positively ionized to contribute to a conduction electron (donors) and negatively ionized to contribute a hole to the VB (acceptors).
- In an intrinsic semiconductor the Fermi level is very close to the middle of the band gap
- In an extrinsic semiconductor the Fermi level is a function of the concentration of impurities:
  - In a n-type (e majority of carriers) is close to the CB
  - In a p-type (h majority of carriers) is close to the VB
- In thermal equilibrium the concentrations are described by the Fermi-Dirac distribution.
**p-n junctions**

In a **homo-junction** the semiconductors on the two sides have the same band-gaps; in a **hetero-junction** they have different band gaps (different semiconductors).

A bias voltage modifies the energy barrier causing an electric current to flow. A **depletion layer** is created by the diffusion of holes from the p side and of electrons from the n side.

Other types of homojunctions:
- i-n: undoped intrinsic region and n region
- p-i: p region and undoped intrinsic region

Adapted from Khanh Kieu (University of Arizona)
Homo-junction vs hetero-junction

Two types of hetero-junctions:
- p-N: the n side has a larger band-gap
- P-n: the p side has a larger band-gap

(The uppercase letter represents the large band gap semiconductor)

Double-hetero (DH) junctions:
- P-p-N
- P-n-N

The active layer in a DH structure is typically 100-300 nm.
If is thinner than 50 nm: quantum effects (QW)
Quasi-equilibrium concentrations: relaxation processes

• With current injection or optical excitation electrons and holes in excess of the equilibrium values can be generated.
• The carriers relax towards the equilibrium distribution with
  – **Intraband** relaxation processes (1fs-1ps)
    electron-electron or hole-hole collisions, electron/hole-phonon interactions
  – **Interband** relaxation processes
    Electron-hole recombination processes (100 ps-1 ms)
• Due to the different time-scales: intraband equilibrium, interband not in equilibrium
• Quasiequilibrium distributions: electrons and holes concentrations are described by two Fermi levels.
Electron-hole recombination processes

They lead to the annihilation of one electron with one hole

- **Shockley-Read process**: an electron or a hole is captured by an impurity. If an electron is captured, to conclude the recombination process then a hole has be to ba captured. The recombination process can be either radiative or non-radiative.

- **Bimolecular processes**: band-to-band recombination and exciton recombination (an exciton is a pair e/h held together by Coulomb attraction, in the same way as the pair e/p forming a hydrogen atom. Radiative processes.

- **Auger processes**: three particles involved (either 2 e & 1h or 1 e and 2 h). The energy released by band to band recombination of an electron and a hole is picked up by a third carrier, as kinetic energy. Is a nonradiative process.

**Carrier recombination rate**: $R = A \ n + B \ n^2 + C \ n^3$

**Carrier lifetime**: when the carrier concentration is higher than the equilibrium value, it will decay with a characteristic time constant, $\tau_N = (n-n_0)/R$

\[
1/\tau_N \approx A
\]
Radiative efficiency, optical transition rates

- \( R = R_{\text{rad}} + R_{\text{nonrad}} \)
- **Radiative efficiency** or internal quantum efficiency: \( \eta = \frac{R_{\text{rad}}}{R} \)
- \( R \) includes spontaneous electron-hole recombination processes but not the recombination rate due to stimulated recombination.
- The rate of stimulated electron-hole recombination can be calculated from the optical transition rates: absorption, stimulated emission and spontaneous emission
- \( R_a(\nu) d\nu = R_e(\nu) d\nu + R_{sp}(\nu) d\nu \)
Absorption and gain coefficients

- $R_a(\nu)d\nu = R_e(\nu)d\nu + R_{sp}(\nu)d\nu$

- $\alpha(\nu) = h \nu [R_a(\nu) - R_e(\nu)]/I(\nu)$

- $g(\nu) = h \nu [R_e(\nu) - R_a(\nu)]/I(\nu)$

- $g(\nu) = -\alpha(\nu)$

- Excess carrier density $N = n - n_o = p - p_o$

- High electron and hole concentrations, $n >> n_o$, $p >> p_o$, lead to a positive optical gain coefficient.

- **Transparency** carrier density, $N_{tr}$: minimum carrier density required for gain.
Carrier dependence of the gain

Gain only for photon energies larger than the band-gap and carrier density larger than the transparency value.

Typical gain bandwidth: \(2k_B T - 4k_B T\)
At room temperature: 50 - 100 meV  -- 12-24 THz

Peak value of the optical gain coefficient:

\[ g_{\text{max}} = g_o (N - N_{\text{tr}}) \]

Typical values of \(g_o\) are \(1-5 \times 10^{20} \text{ m}^2\)
\(N_{\text{tr}} \approx 10^{24} \text{ m}^{-3}\)
In a QW: \(g_{\text{max}} = g_o N_{\text{tr}} \ln N/N_{\text{tr}}\)
SCLs design goals

- To obtain optimal injection properties
- To optimize optical confinement
- To minimize optical loss and heating
- To obtain maximum gain at a given injection power
- To obtain optimal spectral output
Single-mode EELs

Distributed Bragg Reflector (DBRs)

Incorporate a grating, that reflects light only when the grating period $\Lambda$ satisfies $\Lambda = q\lambda/2$.

Distributed Feedback lasers (DFBs)

Incorporate a distributed grating that acts as a distributed reflector. The end surfaces are antireflection coated to avoid reflections.

DFBs (first developed in 1972) are the light source of choice in long-haul networks.

Adapted from Saleh and Teich
Another way to obtain single-frequency emission: with an external cavity

With controlled feedback the laser emission can “lock” to a mode of the external cavity. Additional advantages:
- a very narrow and stable spectral linewidth
- lower threshold.
However, uncontrolled feedback conditions: instabilities and chaotic output
Why the need of narrow stable spectral linewidth?

• The ever-growing demand for increased data rates is pushing optical communications towards coherent communications, whereby information is carried primarily in the phase of the optical wave rather than in its amplitude.

• For example, a single optical pulse that can possess any one of N optical phases can transmit \( \ln 2(N) \) bits per pulse; binary amplitude modulation, can transmit only two bits.

• Achieving phase coherent communications require great phase stability; i.e., a SCL with a narrow spectral linewidth.

• Nowadays DFBs have typical spectral linewidths of 0.5 MHz.
Summary single mode EELs
VCSELs

- $\lambda=1.5\mu m$
- $n=3$
- $L = \lambda/2n = 0.25 \mu m$
- Small cavity $\Rightarrow$ need highly reflective mirrors ($r > 98\%$)
- These are distributed Bragg mirrors based on paired quarter-wave semiconductor layers.
- The gain medium in these structures are several quantum wells of GaAs placed at the peak of the resonant mode electric field in the center of the $\lambda/n$ layer.
- First RT operation: K. Iga (1988)

VCSEL geometry

Distributed Bragg Reflectors (DBRs)

Fig. 1. Vertical VCSEL resonator and the longitudinal confinement of the optical field by the DBRs. Blue indicate n-type material and red indicate p-type.

Fig. 3. Formation of a waveguide for transverse optical confinement in an oxide-confined VCSEL.
VCSEL geometry

Oxide Confined (OC)

Buried tunnel junction (BTJ)

Fig. 2. (a) Basic design of an oxide-confined VCSEL and (b) a BTJ VCSEL.

LARSSON: ADVANCES IN VCSELS FOR COMMUNICATION AND SENSING
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 17, NO. 6, NOVEMBER/DECEMBER 2011
### TABLE I

**Summary of Highest Power Single-Mode VCSELs at Short and Long Wavelengths (OC = Oxide Confined)**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Wavelength (nm)</th>
<th>Single mode power (mW)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs-OC (small aperture)</td>
<td>670</td>
<td>2.8</td>
<td>74</td>
</tr>
<tr>
<td>GaAs-OC (surface relief)</td>
<td>760</td>
<td>2.0</td>
<td>75</td>
</tr>
<tr>
<td>GaAs-OC (metal aperture)</td>
<td>780</td>
<td>3.4</td>
<td>76</td>
</tr>
<tr>
<td>GaAs-OC (small aperture)</td>
<td>840</td>
<td>4.8</td>
<td>58</td>
</tr>
<tr>
<td>GaAs-OC (surface relief)</td>
<td>850</td>
<td>6.3</td>
<td>72</td>
</tr>
<tr>
<td>GaAs-OC (disordering)</td>
<td>850</td>
<td>7.3</td>
<td>70</td>
</tr>
<tr>
<td>GaAs-OC (metal aperture)</td>
<td>850</td>
<td>4.7</td>
<td>69</td>
</tr>
<tr>
<td>GaAs-OC (extended cavity)</td>
<td>980</td>
<td>5.4</td>
<td>68</td>
</tr>
<tr>
<td>GaAs-antiguided</td>
<td>980</td>
<td>7.1</td>
<td>73</td>
</tr>
<tr>
<td>GaAs-OC (PhC)</td>
<td>990</td>
<td>5.7</td>
<td>60</td>
</tr>
<tr>
<td>InP-BTJ</td>
<td>1310</td>
<td>6.0</td>
<td>65</td>
</tr>
<tr>
<td>InP-BTJ</td>
<td>1550</td>
<td>6.7</td>
<td>63</td>
</tr>
<tr>
<td>InP-BTJ</td>
<td>2365</td>
<td>0.5</td>
<td>64</td>
</tr>
<tr>
<td>GaSb-BTJ</td>
<td>2355</td>
<td>0.7</td>
<td>64</td>
</tr>
<tr>
<td>GaSb-BTJ</td>
<td>2420</td>
<td>0.3</td>
<td>10</td>
</tr>
<tr>
<td>GaSb-BTJ</td>
<td>2600</td>
<td>0.3</td>
<td>67</td>
</tr>
</tbody>
</table>
4. Dynamic characteristics of SCLs

- Relaxation oscillations, modulation bandwidth
- Intensity noise, laser linewidth
- Optical injection and injection locking
- Optical feedback
- Light polarization
Resonance frequency: relaxation oscillation frequency \((f_{ro})\)

SCLs turn on with a delay and relaxation oscillations of frequency \(f_{ro}\)

Free-running semiconductor lasers emit a stable output (class B lasers), but they can be destabilized by external perturbations (optical injection, feedback).

T. Heil, PhD thesis (Darmstadt 2001)
Multi-mode SCL turn on: relaxation oscillations

Fig. 3.2. Time evolution of carrier density $n$ and photon population $S$ under relaxation oscillations (after Marcuse D, Lee TP (1983); © 1983 IEEE)
Rate equations for a single-mode SL

\[
\begin{aligned}
\frac{dS}{dt} &= GS - \frac{S}{\tau_p} + \frac{\beta_{sp} N}{\tau_N} \\
\frac{dN}{dt} &= \frac{I}{eV} - \frac{N}{\tau_N} - GS
\end{aligned}
\]

- Two coupled non-linear first-order ordinary differential equations (ODEs)
- Further sources of nonlinearities: the carrier lifetime depends on the carrier density because of various carrier recombination processes; the gain is power-dependent (gain saturation):
  \[
  \frac{1}{\tau_N} = \frac{1}{\tau_{nr}} + BN + CN^2
  \]
  \[
  G = a\left(N - N_{tr}\right)
  \]
  \[
  G = aN_{tr} \ln\left(\frac{N}{N_{tr}}\right)
  \]
- When stochastic noise sources are included, these equations form the basis for the discussion of laser modulation response and intensity noise.
- To understand the laser linewidth, we need to write an equation for the complex laser field \(E\) \((S=|E|^2)\) & take into account the linewidth enhancement \(\alpha\) factor.
Direct modulation of the SCL drive current: modulation response

\( f_{ro} \) increases with the pump current

\[ \text{Frequency response (dB)} \]

\[ \text{Frequency (GHz)} \]

\( f_{ro} \) resonance frequency

\[ \omega_R = 5 \text{ GHz} \]

\[ \omega_R = 3 \text{ GHz} \]
In VCSELs the resonance frequency depends on the size of the device.
VCSELs: modulation bandwidths

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Technology</th>
<th>Bandwidth @ RT (GHz)</th>
<th>Bit rate (Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1310</td>
<td>InP – BTJ</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>InP – BTJ</td>
<td>&gt;6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>InP – BTJ</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>GaAs – OC</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>GaAs – OC</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>~1550</td>
<td>InP – BTJ</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>InP – BTJ</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>InP – BTJ</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

(State of the art: 50 GHz)

Fig. 8. Evolution of single channel speed in some LAN, SAN, HPC, and consumer standards [48]. Open symbols indicate predictions.

The output from a SCL is detected by a photo-detector, converted to an electric signal and analyzed by a spectrum. The RIN is a measure of the relative noise level to the average dc signal power.

\[ f_{ro} = \text{relaxation oscillation frequency} \]

Fig. 3.3. Intensity noise spectrum for several power levels
Laser linewidth and \( \alpha \) factor

- Due to spontaneous emission noise single-mode lasers have a finite linewidth.
- The fundamental limit of the linewidth can be calculated by the Schawlow and Townes formula, that gives a good approximation for solid-state lasers.
- But in SCL the linewidth is significantly higher than the value predicted by the Schawlow and Townes formula.
- The larger linewidth is due to the intensity and phase noise coupling, caused by a dependence of the refractive index on the carrier density in the semiconductor.
- Henry introduced the linewidth enhancement factor \( \alpha \) (also called alpha factor) to quantify this amplitude–phase coupling mechanism.
- The \( \alpha \) is an important parameter of SCLs and is a proportionality factor relating phase changes to changes of the gain.

\[
\Delta \nu = (1 + \alpha^2) \Delta \nu_{ST}
\]

4. Dynamic characteristics of SCLs

- Relaxation oscillations, modulation bandwidth
- Intensity noise and linewidth
- Optical injection and injection locking
- Optical feedback
- Light polarization
Optical Injection and Injection Locking

Parameters:
- Injection ratio
- Frequency detuning \( \Delta \nu = \nu_s - \nu_0 \)

Dynamical regimes:
- Injection locking (cw output)
- Period-one oscillation
- Period-two oscillation
- Chaos

Detection system (photo detector, oscilloscope, spectrum analyzer)
Injection locking increases $f_{\text{ro}}$ and the laser modulation bandwidth

Strong optical injection-locked semiconductor lasers demonstrating > 100-GHz resonance frequencies and 80-GHz intrinsic bandwidths

Erwin K. Lau$^{1,*}$, Xiaoxue Zhao$^1$, Hyuk-Kee Sung$^2$, Devang Parekh$^1$, Connie Chang-Hasnain$^1$, and Ming C. Wu$^1$

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$^2$School of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea
*Corresponding author: elan@eecs.berkeley.edu

High Power Master Laser

1.55-μm VCSEL

```
Response (dB)
-100 -80 -60 -40 -20  0  20  40  60  80  100
Frequency (GHz)
```

```
Detuning Frequency [GHz]
-100 -80 -60 -40 -20  0  20  40  60  80  100
Injection Ratio [dB]
```

#90115 - $15.00 USD  Received 26 Nov 2007; revised 17 Mar 2008; accepted 20 Mar 2008; published 24 Apr 2008  (C) 2008 OSA  28 April 2008 / Vol. 16, No. 9 / OPTICS EXPRESS  6609

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All-optical memory based on injection-locking bistability in photonic crystal lasers

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15/03/2013

1.55 μm Tunable Laser (Injection)

Free-running

Mode-B  Mode-A

Output [dBm]

Wavelength [nm]

1.31 μm Laser (Pump)

Bias

Injection

Output

Burried heterostructure photonic cristal laser
Outside the injection locking region: ultra-high intensity pulses

4. Dynamic characteristics of SCLs

- Relaxation oscillations, modulation bandwidth
- Intensity noise and linewidth
- Optical injection and injection locking
- Optical feedback
- Light polarization
Optical feedback effects

(a) Output Power vs Time

(b) Output Power vs Time

(c) Output Power vs Time

Laser Diode $E_A(t)$

External Mirror $E_B(t)$

$451$ MHz

$480$ MHz

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Feedback effects on the LI curve

Coherent feedback

Incoherent feedback

Adapted from R. Ju et al,

Experimental setup – UPC Terrassa lab

- Laser Diode
- Beamsplitter
- Grating
- External cavity - 45 cm
- Detector
- to Oscilloscope
- Temperature and pump current combi controller
- to Optical Spectrum Analizer
Feedback-induced Low Frequency Fluctuations

Low pump current

High pump current

Courtesy of A. Aragoneses, DONLL research group, UPC, Terrassa
Optical spectra

Low pump current

No feedback

High pump current

With feedback

Courtesy of A. Aragoneses, DONLL research group, UPC, Terrassa
Feedback effects depend on the feedback strength and the pump current.

Adapted from T. Heil, PhD thesis (Darmstadt 2001)

Figure 3.21: Intensity time series for $I=60 \text{ mA}$ and $\gamma=45 \text{ ns}^{-1}$ showing a transition from LFF to stable emission on a high-gain external-cavity mode (HGM). Obviously, the intensity stabilizes on a level higher than the intensities reached during the LFF cycles. The inset depicts the optical spectrum of the stable emission state recorded by the scanning Fabry-Perot interferometer. Note that the system remains in the stable state for the time of several milliseconds required to scan the optical spectrum.
LFFs: fast pulsing intensity

Irregular pulses

Regular pulse packages
4. Dynamic characteristics of SCLs

- Relaxation oscillations, modulation bandwidth
- Intensity noise and linewidth
- Optical injection and injection locking
- Optical feedback
- Light polarization
Polarization of the emitted light

Edge-Emitting Lasers: TE, TM

VCSELs:

$I_{th} = \text{threshold current}$

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In VCSELs: Polarization switching

[Graph showing intensity vs. time for different polarizations]

Hong and Shore, un published (Bangor university, UK)

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Polarization bistability and hysteresis

“Current-driven” Polarization Switching

Stochastic Polarization Switching

PS due to thermal modification of the net gain


Polarization bistability can be exploited for all-optical square-wave switching

Orthogonal feedback

The repetition rate is controlled by the feedback delay time.

Gavrielides et al, PRE 81, 056209 2010
A one-bit data can be stored as one of two orthogonal polarization states of a VCSEL. The polarization state is transferred from the VCSEL to another VCSEL which is optically connected in cascade.
THE NEXT FRONTIERS OF SEMICONDUCTOR LASER RESEARCH
Green SCLs

• In 1996 the first electrically pumped blue InGaN semiconductor laser diode was demonstrated (405 nm).
• Since then, researchers have found it extremely difficult to push toward longer wavelengths. Due to the physical and material properties of the InGaN QWs, efficiency drops drastically as diodes move towards green.
• And, unfortunately, this spectral region cannot be reached with other III-V materials, such as AlGaAs or InGaAlP from the long wavelength side.
• In 2009, however, three companies simultaneously demonstrated the first green laser diodes in the range of 515 nm to 530 nm, where the human eye is most sensitive.
• Potential applications are in biophotonics and the life sciences, such as special microscopy techniques, where laser diodes across the visible spectrum are needed as excitation sources.
• Another application for green laser diodes is expected to be laser-based miniature projectors.
Pico-projector: laser-based projectors that are compatible in size to the iPhone

Optics and Photonics News, September 2011
Another application of blue & green diode lasers: *optogenetics*

- The laser can be used for selective optical excitation of nerve cells.
- Optogenetics uses “opsin” molecules (light-sensitive proteins) that act as tiny solar cells.

*Nature* Vol. 465, 6 May 2010,
*Optics and Photonics News*, August 2011
SIX STEPS TO OPTOGENETICS

With optogenetic techniques, researchers can modulate the activity of targeted neurons using light.

**STEP 1**
Piece together genetic construct.
- Promoter to drive expression
- Gene encoding opsin (light-sensitive ion channel)

**STEP 2**
Insert construct into virus.

**STEP 3**
Inject virus into animal brain; opsin is expressed in targeted neurons.

**STEP 4**
Insert ‘optrode’, fibre-optic cable plus electrode.

**STEP 5**
Laser light of specific wavelength opens ion channel in neurons.

**STEP 6**
Record electrophysiological and behavioural results.

With blue light: www.youtube.com/watch?v=88TVQZUfYGw
Hybrid silicon lasers

Building lasers from silicon—the inexpensive core of computer chips—will allow to drastically increase the speed and capacity of data channels inside and between chips and computers.

Optics and Photonics News, March 2011
Hybrid silicon lasers

- Goal: bonding lasers made with light emitting semiconductors (III-V materials) to silicon chips.
- Problem: because of the different atomic structures of silicon and the semiconductors that are efficient light emitters, growing those typically require temperatures in the range of 700°C. Such temperatures would destroy the other features on the chip.
Hybrid Silicon Lasers

The Final Frontier to Integrated Computing

Silicon wafer showing integration of hybrid silicon lasers with low-loss waveguides, passive splitters, switches, arrayed waveguide routers, optical amplifiers and 2R regenerators.
Long-wavelength InAs/GaAs quantum-dot laser diode monolithically grown on Ge substrate

Huiyun Liu\textsuperscript{1*}, Ting Wang\textsuperscript{1}, Qi Jiang\textsuperscript{2}, Richard Hogg\textsuperscript{2}, Frank Tutu\textsuperscript{1}, Francesca Pozzi\textsuperscript{1} and Alwyn Seeds\textsuperscript{1}

Figure 2 | InAs QD laser diode on a Ge substrate. Schematic showing the layer structure of an InAs/InGaAs DWELL laser diode on a Ge substrate.

- N-electrode
- 300 nm n-GaAs contacting layer
- 1.5 \( \mu \text{m} \) n-Al\textsubscript{0.7}Ga\textsubscript{0.3}As cladding layer
- 55 nm Al\textsubscript{0.7}Ga\textsubscript{0.3}As guiding layer
- 5-layer InAs/InGaAs DWELL
- 55 nm Al\textsubscript{0.7}Ga\textsubscript{0.3}As guiding layer
- 1.5 \( \mu \text{m} \) p-Al\textsubscript{0.7}Ga\textsubscript{0.3}As cladding layer
- 1.5 \( \mu \text{m} \) P+ s-v buffer layer
- Ge (000) P + substrate
- P-electrode

Room temperature
Continuous-wave

a

Intensity (dB)

1,200 1,250 1,300 1,350 1,400

Wavelength (nm)

b

Output power (mW)

0 10 20 30 40 50

Current (mA)

100 mA 200 mA 300 mA 400 mA 500 mA

Temperature

20°C 30°C 40°C 50°C 60°C
Demonstration of Blue and Green GaN-Based Vertical-Cavity Surface-Emitting Lasers by Current Injection at Room Temperature

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Received May 10, 2011; accepted June 11, 2011; published online June 29, 2011

We realized room-temperature lasing of blue and green GaN-based vertical-cavity surface-emitting lasers (VCSELs), for the first time, by current injection. The blue GaN-based VCSEL had a threshold current of 1.5 mA and a threshold voltage of 3.3 V under continuous-wave operation. Its maximum output power was 0.70 mW and its laser emission wavelength was 451 nm. The green GaN-based VCSEL had a threshold current of 22 mA and a threshold voltage of 6.3 V under pulsed current operation. Its maximum output power was estimated to be over 0.80 mW and the laser emission wavelength was 503 nm. © 2011 The Japan Society of Applied Physics
Nanolasers

• Miniaturization to the nanoscale offers the advantages of lower power consumption (due to a lower threshold current), single-frequency and single-mode operation, and faster modulation response.

• A key advantage is the incorporation of metal cavities. The radiation loss of dielectric (semiconductor) cavities increases as their size approaches the wavelength of visible light.

• Metals provide effective optical confinement and thus dramatically reduce radiation losses.

• Subwavelength-scale semiconductor nanolasers have been demonstrated using metal-based cavities.

• Electrical injection at room temperature under continuous-wave operation has also been demonstrated.
Nanolasers grown on silicon

Roger Chen, Thai-Truong D. Tran, Kar Wei Ng, Wai Son Ko, Linus C. Chuang, Forrest G. Sedgwick and Connie Chang-Hasnain*

For the world’s smallest nanolaser (so far?) see Science 27 July 2012
Single-Nanowire Single-Mode Laser

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Supporting Information

ABSTRACT: We demonstrate single-mode laser emission in single nanowires. By folding a 200 nm diameter CdSe nanowire to form loop mirrors, single-mode laser emission around 738 nm wavelength is obtained with line width of 0.12 nm and low threshold. The mode selection is realized by the vernier effect of coupled cavities in the folded nanowire. In addition, the loop structure makes it possible to tune the nanowire cavity, opening an opportunity to realize a tunable single-mode nanowire laser.

KEYWORDS: Nanowire, laser, single mode, Vernier effect, coupled cavity, loop mirror

dx.doi.org/10.1021/nl1040308 | Nano Lett. 2011, 11, 1122–1126
Recommended literature for further reading

• Saleh and Teich, Fundamentals of photonics
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• J. M. Liu, Photonic devices (Cambridge University Press 2005)
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• Integrated silicon photonics, OPN March 2011
• High-power high-brightness direct-diode lasers, OPN October 2010