VCSELs in Various Sensor Applications

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  ▪ What is a VCSEL? Where is it used? Why?

► VCSEL Sensor Attributes
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► Types of Sensors
  ▪ Reflective, transmissive, scattering, etc.

► VCSEL Horizons
AOC (née Honeywell)

1993 Honeywell VCSEL Research Begins

1995 Technology Transfer to Richardson

1996 SC sleeve VCSEL

1996 TO-46 VCSEL

1996 First Commercial VCSEL Product

1996 1,000,000 VCSELs shipped

1997 Red VCSELs demonstrated

1998 LC & MTRJ OFEs

1998 Oxide VCSEL R&D

1999 SC sleeve VCSEL

2000 4 & 12 Channel Arrays

2000 850nm SM VCSELs

2001 Production oxide VCSELs

2002 850nm MM2 VCSELs

2002 850nm 10GB VCSELs

2002 780nm VCSELs

2002 1310 & 1550nm VCSELs

2003 850nm MM2 VCSELs

2004 1300nm VCSELs

2004 Finisar Purchase-AOC Formed

2004 35,000,000 VCSELs shipped

2005 Q1 2005

2006 2001 25,000,000 VCSELs shipped

2006 2000 20,000,000 VCSELs shipped

2006 Honeywell VCSEL Optical Products SBE Formed

2006 10,000,000 VCSELs Shipped

2006 Industry Benchmark VCSEL Reliability Study

2008 2001 1300nm VCSELs

2008 2000 1300nm VCSELs

2008 2001 850nm SM VCSELs

2008 850nm MM2 VCSELs

2008 850nm 10GB VCSELs

2008 780nm VCSELs

2008 1310 & 1550nm VCSELs

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2008 Honeywell VCSEL Optical Products SBE Formed

2008 10,000,000 VCSELs Shipped

2008 Industry Benchmark VCSEL Reliability Study
What is a VCSEL?

- Vertical Cavity Surface Emitting Laser (VCSEL) first commercialized by Honeywell in 1996
- Primary application was high speed data communications on multimode optical fiber
  - More than 50M VCSELs shipped by multiple vendors, AOC has shipped 35M+ VCSELs
- VCSEL filled market need for high reliability
Semiconductor Optical Sources

**LED**
- Incoherent
- Lambertian emission from all facets

**VCSEL**
- Coherent
- Symmetrical, low divergent optical beam
- Mirrors formed vertically during growth

**EEL**
- Coherent
- Elliptical, astigmatic optical emission
- Mirrors formed by cleaving and coating

All sources are grown by either MOCVD or MBE
Semiconductor Optical Sources

### VCSEL Advantages
- Planar structure with vertical emission can be tested in wafer form before sawing and building higher level assemblies
- High efficiency
- High degree of usable optical emission
- Reliability

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Symbol</th>
<th>Units</th>
<th>SM VCSEL</th>
<th>MM VCSEL</th>
<th>EE Laser</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power</td>
<td>$P_{\text{elec}}$</td>
<td>mW</td>
<td>5</td>
<td>20</td>
<td>60</td>
<td>60</td>
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<tr>
<td>Optical Power</td>
<td>$P_{\text{opt}}$</td>
<td>mW</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency at $P_{\text{opt}}=1\text{mW}$</td>
<td>$h$</td>
<td>%</td>
<td>20</td>
<td>10</td>
<td>5</td>
<td>2*</td>
</tr>
<tr>
<td>Wavelength</td>
<td>$l$</td>
<td>nm</td>
<td>760-860</td>
<td>670-870</td>
<td>630-1300</td>
<td>400-1300</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>$\Delta \lambda$</td>
<td>nm</td>
<td>0.01</td>
<td>0.5</td>
<td>2</td>
<td>50</td>
</tr>
<tr>
<td>Spectral Tuning (Temperature)</td>
<td>$\Delta \lambda / \Delta T$</td>
<td>nm/°C</td>
<td>0.06</td>
<td>0.06</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Spectral Tuning (Current)</td>
<td>$\Delta \lambda / \Delta I$</td>
<td>nm/mA</td>
<td>0.25</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Angle (full width at half of maximum value)</td>
<td>$\angle$</td>
<td>°</td>
<td>&lt;15</td>
<td>~15</td>
<td>15 par. 35 perp</td>
<td>120</td>
</tr>
</tbody>
</table>
VCSEL Value in Sensors

- High efficiency for battery powered applications
- Single optical wavelength, high coherence
- High radiance optical source
- Flexible packaging options
- Reliability
In other words, the “ilities”

- **Manufacturability** – all-vertical construction enables the use of traditional semiconductor manufacturing equipment

- **Integrability** – compatible with semiconductor manufacturing and wafer integration of the emitters with detectors and circuitry

- **Reliability** – without the failure modes of traditional laser structures such as dark line defects and catastrophic optical damage; very long wearout life

- **Testability** – complete testing and burn-in in wafer form

- **Arrayability** – VCSELs can be easily fabricated into one or two dimensional arrays

- **Packageability** – VCSELs allow use of traditional low cost LED packaging; chip on board technology for VCSEL-based sensors

- **Low power consumption** (OK, not strictly an ility) – extends battery life and reduces thermal design constraints in larger equipment systems
Efficiency

- Measuring efficiency with the total emitted optical power
  - VCSELs are typically 20%
  - LEDs are typically 20%
  - EELs are typically 10%
Power variation in a VCSEL can be made very minor over temperature and process with simple passive electrical components.

Pulsing a VCSEL with short electrical pulses reduces the joule heating, and allows for much higher optical power emission. Powers more than 10x the DC limits are readily achievable.
VCSELs can be made to emit at a single wavelength.

Some EELs can be made to emit a single wavelength. LEDs are broadband emitters.
850nm Single Mode VCSELs

- Single longitudinal and spatial mode
- High efficiency
VCSEL Optical Properties

- Symmetrical beam
- No Astigmatism
- Low divergence
- Simple, low cost optics
VCSELs are fast!

A VCSEL can turn on and off again in ~100 ps, producing a pulse of light short both in time and in space.
VCSEL Packaging Flexibility

- Can be put in any form factor of an LED and most EEL form factors.
- 2D Arrays
Optical Sensor Applications

Many techniques for optical sensing
- Reflection
- Transmission
- Absorption
- Scattering
- Interference
- Self Mixing
- Remote power
Some Optical Sensors

Taken from www.balluff.com
VCSEL Application examples exploit:

- Narrow wavelength and stability
  - Differential absorption sensors, *e.g.* blood gas
  - WDM and fiber sensors

- Narrow beam and small source
  - Wide-gap transmissive and reflective sensors
  - Photoelectronics
  - Scatterometers, *e.g.* turbidity sensor
  - Light guide illumination

- Low current and high speed
  - Hand-held optical ranging
  - Air data links

- Low current, size, and coherence
  - High-precision encoders
  - Speckle-based sensors

- Integration
Reflective Sensor

- Reflective sensors can work on either specular or scattering reflections
- Most ubiquitous optical sensor
  - Automatic flush
  - Proximity sensors
VCSEL photoelectric control

- With little scattered light, VCSEL is 10x more efficient than LED in similar package
- Increased discrimination to background light
- Improved precision on object location
- Lower power dissipation
- Surface mount on board, direct replacement of LED
A transmission sensor is an unfolded reflective sensor that can provide a higher degree of discrimination.

Transmission sensors can also quantitatively measure the amount of transmission, absorption, or other losses.
Absorption Sensor for Oxygen

\[ I_\nu = I_\nu^0 \exp[-S(T,P)g(\nu - \nu_0)NL] \]

- \( I_\nu \): Intensity at frequency \( \nu \)
- \( I_\nu^0 \): Initial intensity at frequency \( \nu \)
- \( S(T,P) \): Temperature, Pressure dependent linestrength
- \( G(\nu-\nu_0) \): Linenshape function
- \( N \): Number density of absorber
- \( L \): Path length

Scattering sensors measure the amount of light scattered relative to the amount of light transmitted

- Colloidal suspensions are uniform scatterers
- Some suspensions preferentially scatter into particular angles (blood, for example)

Cabuz, et al, DARPA contract MDA-972-00-C-0029

Applications
- Dishwashers
- Laundry machines
- Pool/Spa water
- Process controls
- Mixing controls

Figure 3. (a) Scatterogram showing the separation of 5 and 6 um beads; (b) Data showing the separation of 3 types of white blood cells – lymphocytes, neutrophils, and monocytes, obtained from a whole blood sample after lysing the red blood cells.
Speckle Sensor

- Speckle is induced by coherent sources
- Speckle is the summation of waves with a definite phase relationship
- Speckle patterns translate with the reflecting surface
- Image correlation can be used to determine direction and amount of motion
- Speckle sensors are statistical sensors, not absolute measurements

(Photo courtesy of Kanitech)
Interference Sensor

Uses the property of coherence to create an interference of the laser electric field. Typical example is a Michelson interferometer

- Variation (vibrations, movement, etc) in one of the optical paths will translate to fringe patterns

- Practical examples
  - Ellipsometry (measurement of thin optical and semiconductor films) is a practical example
  - Surface flatness measurement
MicroE Interferometric Sensor

- LED encoder uses slotted mask and detects on/off signal
- Laser encoder uses diffraction grating which produces interference pattern (requires coherence of laser)
- Resolutions:
  - rotary: LED: 1M counts/revolution; MicroE: 300M counts/revolution
  - linear: LED: up to 0.1 µm; MicroE: up to 0.0006 µm

MicroE’s Patented Position Sensor

VCSEL Advantages
- Compact Package
- High coherence
- Low power dissipation
- Low beam divergence
MicroE VCSEL encoder

- Ultra high resolution encoder
- Packaging of the laser is key to the application
- Single mode VCSEL

Photos courtesy of MicroE Natick, MA
Atomic Clocks

- Traditional Atomic Clocks use an optical source to interrogate an Alkali vapor in an RF cell. The RF cell is tuned to the hyperfine transition of the ground state.

- Coherent Population Trapping (CPT) eliminates the need for an RF chamber by placing the RF signal on the interrogating laser beam.
Atomic Clocks

Optics include $\lambda/4$ waveplate, attenuator, and collimating lens

<table>
<thead>
<tr>
<th>Alkali</th>
<th>Center Wavelength</th>
<th>$\nu_{HF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>894nm</td>
<td>9.2GHz</td>
</tr>
<tr>
<td></td>
<td>852nm</td>
<td></td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>852nm</td>
<td>6.834GHz</td>
</tr>
<tr>
<td></td>
<td>795nm</td>
<td></td>
</tr>
<tr>
<td>$^{85}$Rb</td>
<td>795nm</td>
<td>3.036GHz</td>
</tr>
</tbody>
</table>

From Lutwak, et. al, Symmetricon website

From Knappe, et al, Optics Express, vol. 13, pp. 1249ff, 2005
A weak signal is fed back into the laser from a distant reflector. The feedback causes instability in the laser. When the reflector is in motion, a Doppler signal is incorporated on the feedback which can be used to determine movement and direction of the reflector.

\[
\Delta P \approx \frac{\kappa}{L} \cos \left( \frac{4\pi \nu \nu t}{c} + \frac{4\pi L_0 \nu}{c} \right)
\]

Duijve, et. al SID 2003
Self Mixing Sensor

- Self mixing can be used to measure a position and movement of an object.
- Self mixing can directly measure velocity using the Doppler shift in the laser.

Duijve, et al SID 2003

Remote Power Sensor I

- In some applications for sensors, it is impractical or dangerous to have electrical wiring
  - Magnetic Resonance Imaging
  - Hazardous material processing (e.g. flammable materials)
  - Oil wells and pipelines
  - Harsh EMI environments

- One common example is the optocoupler (optoisolator)

- Ground Isolators
- DC Isolators
- AC coupling of signals
One way to achieve remote power is to deliver energy optically to a detector, which converts the optical energy to electrical energy.

- The electrical energy can be used to charge a battery, or it can be used to directly power an electrical circuit.
- Several detectors can be connected in series to gain voltage multiplication.

The major drawback to remote power devices today is that the return signal must be generated in a separate optical component. This requires additional fibers, power drain, and another optical component.

http://www.photonicpower.com
VCSELs in Remote Power Solutions

The power conversion photodiodes and the VCSEL can be monolithically integrated. More than 3V and 25mA can be supplied to an external circuit. The VCSEL requires less than 5mW to send optical signals.

- Requires only a single fiber to operate
- Can power almost any type of sensor
- Can be made very small (less than 7Fr) for in vitro applications

Various types of side views of one possible embodiment.

US Patent publication 200030223756 – Optical Transceiver
VCSELs in Laser Printing

- VCSELs enable 2 dimensional arrays to be used for printing
  - Increases speed and resolution
  - Allows faster color reproduction
  - Excellent beam quality
- Competition from various SLMs

![Graph showing comparison ofPages Per Minute vs Resolution (dpi) for different beam configurations: 1 Beam, 4 Beam, and 32 Beam.](image)

FujiXerox DocuColor 1256 GA
Future VCSEL Directions

- Other wavelengths
  - 650nm to 1550nm
- Higher power, better efficiency
- Integration of functions on chip
  - Photodiodes
  - Lenses
- Packaging with control electronics
The value of VCSELs in optical sensors has been demonstrated with practical examples

- High efficiency
- Optical beam quality
- Optical spectrum
- Packaging flexibility
- High speed