High-power VCSEL arrays for next-generation LiDAR Systems

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Agenda

- Lumentum introduction
- Today’s automotive LiDAR requirements and challenges faced
- Vertical-cavity surface-emitting lasers (VCSELs) as the solution
- Introduction to multi-junction VCSELs
- LiDAR approaches
- Motivation for multi-junction VCSELs and improved performance
- Lumentum VCSEL array performance for 1D + matrix addressable arrays
- Summary
Lumentum – A Leading 3D Sensing Optical Solutions Provider

$1.74B
FY21¹ revenue, 5600 employees

Markets Served:
• Telecom + Datacom
• Consumer + Industrial includes 3D Sensing
• Lasers for manufacturing

1. Fiscal year ended July 3, 2021

- Highest quality and reliability
- Established high-volume, manufacturing infrastructure
- Largest global supplier of 3DS illuminators
- Laser chips, integrated packages, reference designs
- Integrated packages reference designs

Markets Served:
- Wearables
- AR VR
- Automotive
- AI Facial Recognition
- IoT Markets
- Smartphones

Markets include:
- Wearables
- AR VR
- Automotive
- Smartphones
- AI
- IoT

¹ FY21 revenue: $1.74B, 5600 employees
Lumentum Automotive Synergy

- Lumentum history lends itself well to automotive industry
  - High quality, reliable products
  - Proven product excellence under challenging conditions (temperature, vibration)
  - High volume manufacturing – Millions of VCSELs shipped every week

- Lumentum’s Kaizen quality culture
- Submarine proven fiber optical component history
- >1B units of VCSEL chips shipped, zero field failures!

- Scale, quality and cost structure to support automotive LiDAR requirements
- IATF 16949-2016 certified VCSEL fab
- VCSEL module for automotive in-cabin applications completed AEC-Q102 qualification
Automotive LiDAR

- High Power VCSEL arrays are enabling LiDAR system performance...
  - Long range
  - Best field of view (FoV)
  - High resolution
  - High object detection accuracy (<10 cm)

- … While meeting strict implementation requirements...
  - Eye safety limits
  - High reliability, no moving parts
  - Environmental robustness
  - Compact, easy to integrate in a vehicle
  - Low cost

- … making visions of the future reality
  - Robotaxis
  - Fully autonomous vehicles
Challenges for the ToF LiDAR Illuminator

**LiDAR Requirement**

- Longer reach
- Stay within eye safety limits
- No moving parts
  - Compact, easy to integrate
- Automotive reliability
- Cost Effective

**Challenges for LiDAR Illuminator**

- Highest possible power
  - Pulse power > 100 W at <30 A (10 ns, 0.1% DC)
  - Slope efficiency > 3 W/A over temp range
  - Power density of up to 800 W/mm²
- Nano second pulses capability (<10 ns)
- Addressable VCSEL sections
- Small chip, illumination matched to SPAD read-out
- Low wavelength shift over temp (<0.07nm/°C) without cooling
- Chip must pass AEC-Q qualification
- IATF16949 certified fab
- Proven manufacturing and test processes
- Scale!
Why Lumentum VCSELs?

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<tr>
<th>Versatility</th>
<th>Cost</th>
<th>Stability</th>
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<tr>
<td>Scalable power, from just a few mW to hundreds of watts</td>
<td>High volume fab shipping millions of VCSELs every week</td>
<td>Performance stability over temperature with minimal power drop</td>
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<tr>
<td>Almost infinitely configurable and adaptable</td>
<td>Already scaled to meet coming LiDAR demand</td>
<td>Wavelength stability over operating temperature range &lt;10nm shift; no need for TEC or other means</td>
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<td>Easy packaging and integration with existing and future detector, driver, and optical technologies</td>
<td>Proven semiconductor manufacturing and test processes</td>
<td>Multi-junction technology reduces loss at higher currents</td>
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<td>Addressable, which paves the way to truly solid-state systems with no moving parts!</td>
<td>Lower cost on optics - lens and DOE</td>
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<td>Small size (and decreasing!) and performance enable higher density and flexibility</td>
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<th>Excellence</th>
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<td>Market leading slope efficiency and power density</td>
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<td>World’s leading supplier of 3D sensing illuminators</td>
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<td>Proven kaizen history and quality culture</td>
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<td>Over 1B shipped with zero field failures</td>
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<td>VCSEL chips and modules undergo AEC-Q102 qualification</td>
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<td>IATF16949 certified fab</td>
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- High power with nanosecond pulse capability (<10 ns) and low duty cycles
- High efficiency with low power consumption and thermal load
- Proven high quality and reliability
- Ideal for d-ToF applications with increasingly Longer sensing range
- No Burn-in required
Multi-Junction for High Power VCSELs

- More junctions → More photons (higher output power) for the same input current and area
- Higher power normally requires Higher current → Higher $I^2R$ losses
- Adding more junctions improves efficiency of laser at higher output power enabling higher output power
- Reducing current improves driver efficiency
- At low (~<0.1% duty-cycle)
  - 200mW to 3W/emitter
  - High power density (100W/mm$^2$ to 1.5 kW/mm$^2$)
Increasing Peak Power with Multi-Junction VCSEL Design and Short Pulses

- More junctions increases voltage → Lower current to reach same power
- Lower current -> Lower $I^2R$ losses → Peak wall-plug efficiency extends to higher power
- Higher power purely from efficiency increase limited … need to reduce heating with shorter pulses
Multi-Junction for LiDAR: 905 nm

- 905 nm array for LiDAR application
- 6 Junction EPI design
  - Aperture diameter 17.3 um
  - 152 emitters
- 8 ns pulse width, 0.05% duty cycle, using commercial high-speed driver which limits maximum current to 25A
- 140W peak power at 25A peak current at 25°C, >1500 W/mm² power density (0.85W/emitter at 75°C)
- High slope efficiency
  - 6.1 W/A peak SE at 25°C
  - 5.9 W/A peak SE at 75°C
LiDAR Architectures

**Mechanical Scanning**

**1D Addressable Line Scan**

**Flash ToF**

**2D Addressable**
Electronic vs. Mechanical scanning

- **Mechanical Scan LiDAR:**
  - More complex, costly and larger optics
  - Smaller laser diode chip

- **All electronic scan LiDAR:**
  - Simple, compact, robust optics
  - Already employed in consumer electronics for few meter range
  - Larger laser chip required vs. mechanical scan approach
Electronic Scan – Matching to Detector Array

- All electronic scan requires match between VCSEL array and single photon avalanche detector (SPAD) array
- Low complexity of optical solution(s) possible
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- All electronic scan requires match between VCSEL array and single photon avalanche detector (SPAD) array
- Low complexity of optical solution(s) possible
- Coaxial designs possible and already demonstrated!

Reflection from object in field-of-view

**Line readout SPAD array**

**Multi-channel VCSEL array**
Matching to Single-Photon Avalanche Photodiode (SPAD) Arrays

- SPAD arrays may have hundreds of columns
- VCSEL array also requires hundreds of channels
- Newer SPADs can readout in blocks rather than lines
- Block readout different from macro-pixels. *Pixels not summed, but read-out individually*

Both read-out zone same # of pixels. 
*SPADs same size, resolution*
Matching Column Addressable VCSEL to Line Read-Out SPAD

- Trade-offs with line readout for column VCSEL arrays

**Image only x, diffuse in y:**
- VCSEL channel lower aspect ratio, smaller chip
- Requires more complex optics
- Requires near 100% fill-factor of SPAD sensor pixel

**1 to 1 match – many narrow VCSELs channels, large chip**

- VCSEL channel emitter pattern
  - Projection of emitter onto SPAD array
  - VCSEL emitter pattern within channel
  - Projection of emitter onto SPAD array
Addressable VCSEL Array Geometries

**Column addressable**
- Typ. config front side anodes, backside cathode
- Conductive substrate

*Pro / Cons:*
- Simple fabrication
- Works with commonly available line read-out SPADs
- Large chips or many bond-pads often required
- Trade-off for width / number of channels
  - Narrow -> higher resistance, worse uniformity + better overlap with SPAD column
  - Wider -> lower resistance, better uniformity, worse overlap with SPAD column

**Matrix addressable**
- Frontside anode and cathodes – overlapping
- Isolated substrate

*Pro/Cons:*
- More complex fabrication but can be smaller than column addressable for similar number of channels
- Requires detector to have block read-out
- Current flows over wider path, better uniformity over sub-array
- More efficient with optical power, enables longer distance
- Fewer contact pads (M+N) pads for M x N sub-arrays
High-Power 1D Addressable Array

- 1d addressable chip
- 100 channels
- Chip size **16mm x 4.5mm** > 70mm²
- 940nm, 5J

6 ns pulse, 0.1% duty-cycle, 25°C
Results 2D Array, Individual Sub-Array (in array of ~200 elements)

- 905nm, 6J
- ~7ns pulse, 0.1% duty-cycle.
- Sub-array size ~0.05 mm² Overall chip ~12mm²
Summary

- The latest generation of high-power, multi-junction VCSEL chips are the light sources of choice for automotive ToF LiDAR architectures

- Addressability of individual emitter sections allows a perfect match of the emitter to available and future detector devices

- These VCSEL laser chips are highly reliable and the infrastructure for cost efficient volume production is in place today

- Addressable VCSEL arrays for LiDAR
  - Simpler optics + no need for TEC
  - Proven at consumer volumes for shortest distances
  - Higher peak power densities > 1kW/mm² (low-duty-cycle, few ns pulse) permit extension to longer distances
  - Matrix addressability opens additional options for LiDAR architectures
Thank You