Navigating Automotive LIDAR Technology

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VP of Technology
October 22, 2019

Outline

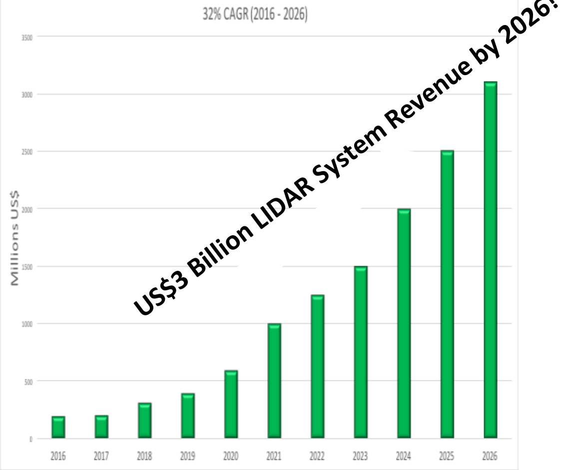
- Introduction to ADAS and LIDAR for automotive use
- Brief history of LIDAR for autonomous driving
- Why LIDAR?
- LIDAR requirements for (personal) automotive use
- LIDAR technologies
- VCSEL arrays for LIDAR applications
- Conclusions

What is the big deal?

- “The automotive industry is the largest industry in the world” (~$1 Trillion)
- “The automotive industry is > 100 years old, the supply chains are very mature”
- “The advent of autonomy has opened the automotive supply chain to new players” (electronics, optoelectronics, high performance computing, artificial intelligence)

(Quotations from 2015 by LIDAR program manager at a major European Tier 1 supplier.)

LIDAR System Revenue



The Automotive Supply Chain

OEMs (car companies)

↑

Tier 1 Suppliers
(Subsystems)

↑

Tier 2 Suppliers
(components)

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ADAS (Advanced Driver Assistance Systems) Levels

SAE and NHTSA

- **Level 0** No automation – manual control by the driver
- **Level 1** One automatic control (for example: acceleration & braking)
- **Level 2** Automated steering and acceleration capabilities (driver is still in control)
- → **Level 3** Environment detection – capable of automatic operation (driver expected to intervene)
- **Level 4** No human interaction required – still capable of manual override by driver
- **Level 5** Completely autonomous – no driver required

Level 3 and up need the full range of sensors. The adoption of advanced sensors (incl LIDAR) will not wait for Level 5 or full autonomy!

The Automotive LIDAR Market

Image courtesy of Autonomous Stuff

Emerging US $6 Billion LIDAR Market by 2024 (Source: Yole) ~70% automotive

Note: Current market is >$300M for *software test vehicles only*!

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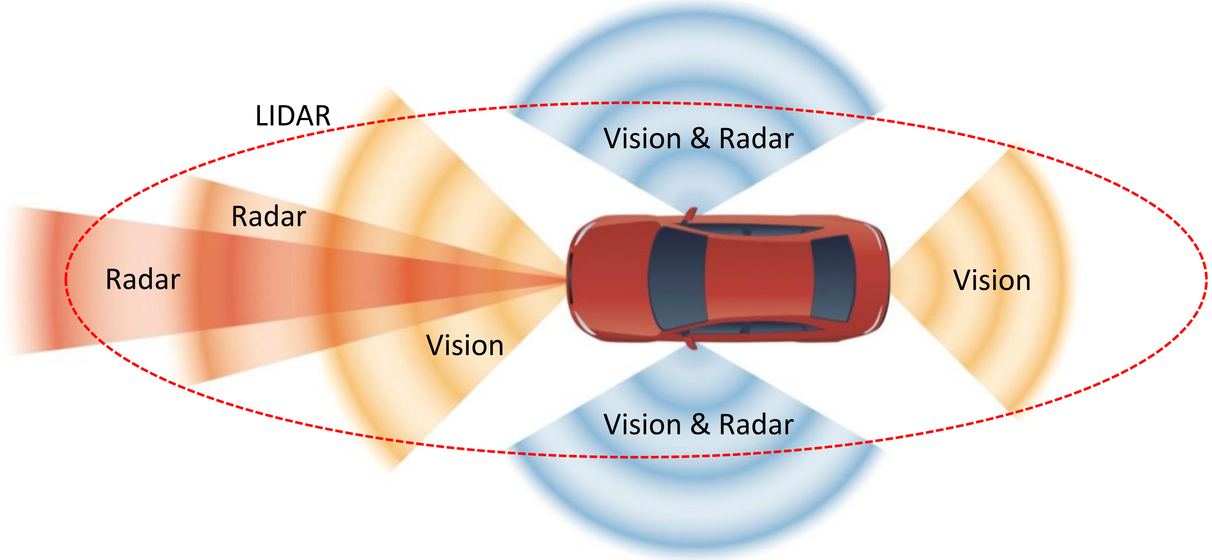
Sensor Fusion Approach to ADAS and Autonomous Vehicles

Much of the ADAS development is driven by NHTSA regulation



Each technology has weaknesses and the combination of sensors provides high confidence.

Radar has long range & weather immunity but low resolution	Cost of Radar modules ~ $50
Cameras have high resolution but 2D & much image processing	Cost of Camera modules < $50
LIDAR have day & night, mid res, long range, 3D, low latency	Cost of LIDARs ~ ?

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A (Very) Condensed History of LIDAR for Autonomous Vehicles

2004 DARPA Grand Challenge
No Winner – Several Laser Rangefinders

2005 DARPA Grand Challenge
Stanford's "Stanley" wins with 5 Sick AG Low-Res LIDAR units as part of system

DARPA

theverge.com

Velodyne Acoustics builds a Hi-Res LIDAR and enters their own car in 2005 DARPA GC
Does not finish but commercializes the LIDAR

5 of 6 finishers in 2007 DARPA Urban Challenge use Velodyne LIDAR

Ali Eminov
flickr

"Google Car" with $75K Velodyne HDL-64E first appears in Mountain View in 2011

Autonomy by Burns & Shulgan 2018

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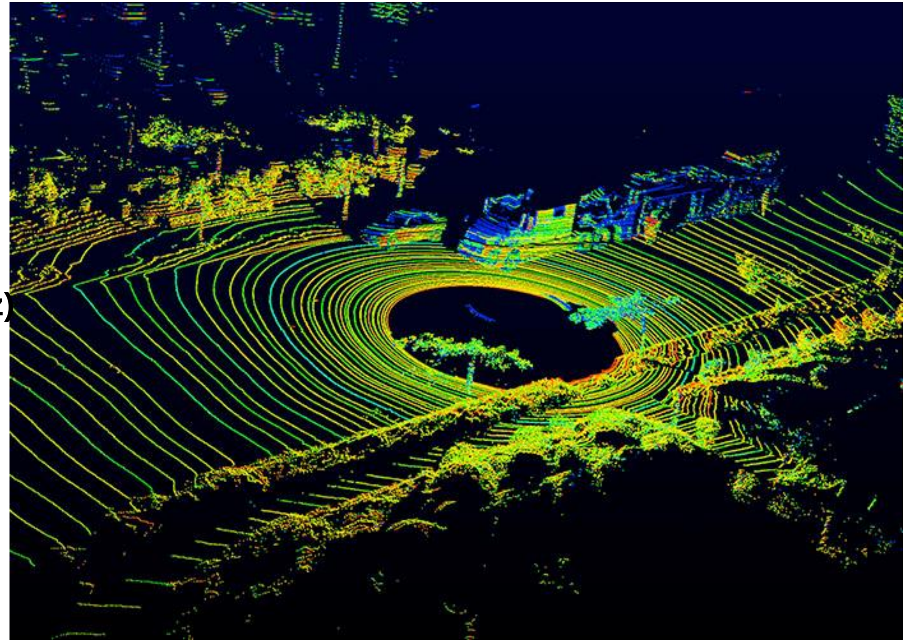
The Velodyne LIDAR

HDL-64E

- 64 Channels
- 120m range
- 288k pixels
- 360° Horiz FOV (5-20 Hz)
- 26.9° Vertical FOV
- 0.08° horiz angular res
- 0.4° vert angular res
- +/- 2cm accuracy



Also: Big, Ugly, Expensive, 60W Power Hog. However, the “gold standard” for 12 years.

Velodyne VLP-16

Images courtesy of Autonomous Stuff

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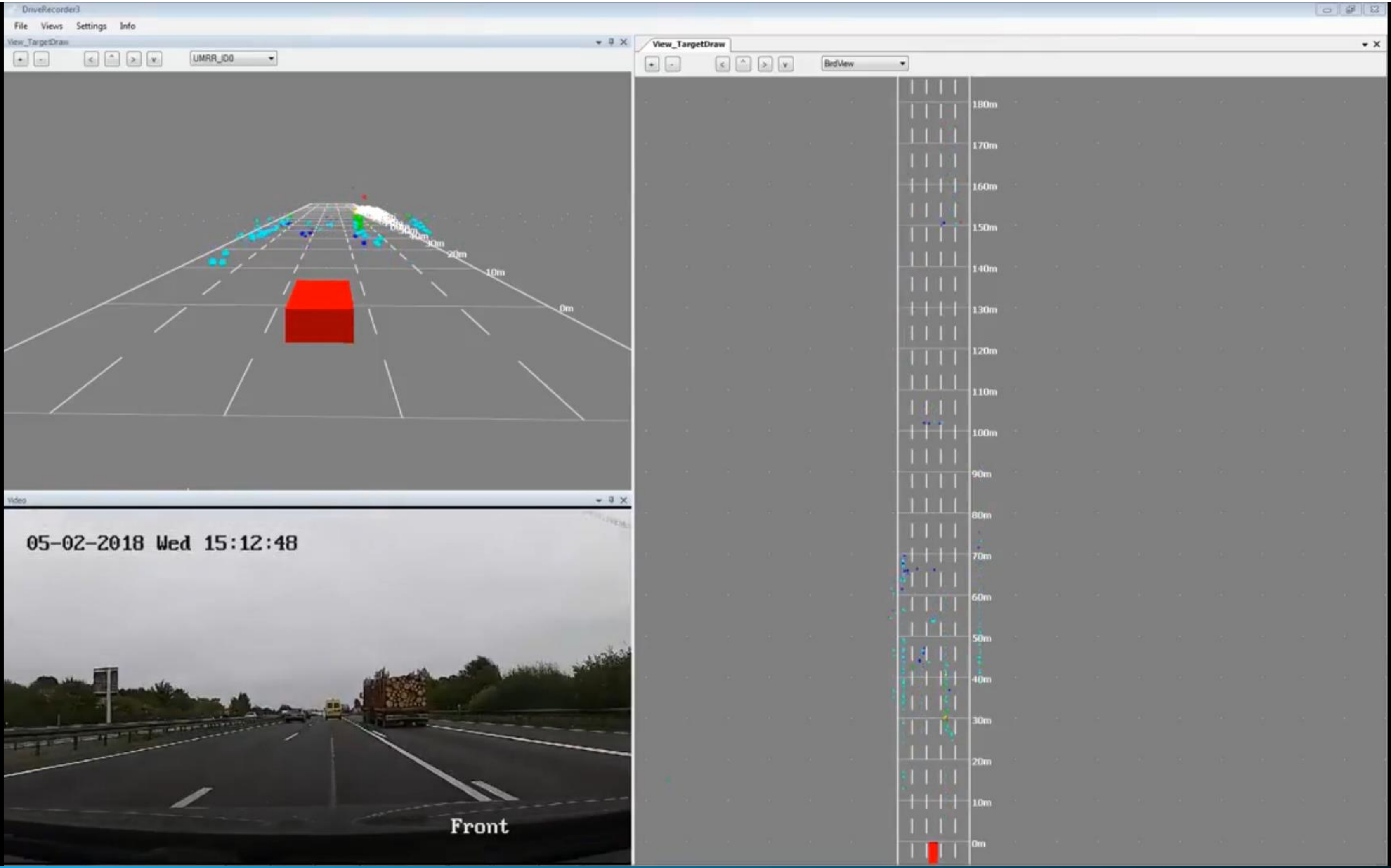
Do you really need LIDAR?

"Lidar is a fool's errand. Anyone relying on lidar is doomed. Doomed! [They are] *expensive* sensors that are unnecessary. It's like having a whole bunch of *expensive* appendices. Like, one appendix is bad, well now you have a whole bunch of them, it's ridiculous, you'll see."

Elon Musk at Tesla Autonomy Investor Day, April 22, 2019

Free-Images.com


DriveRecorder3
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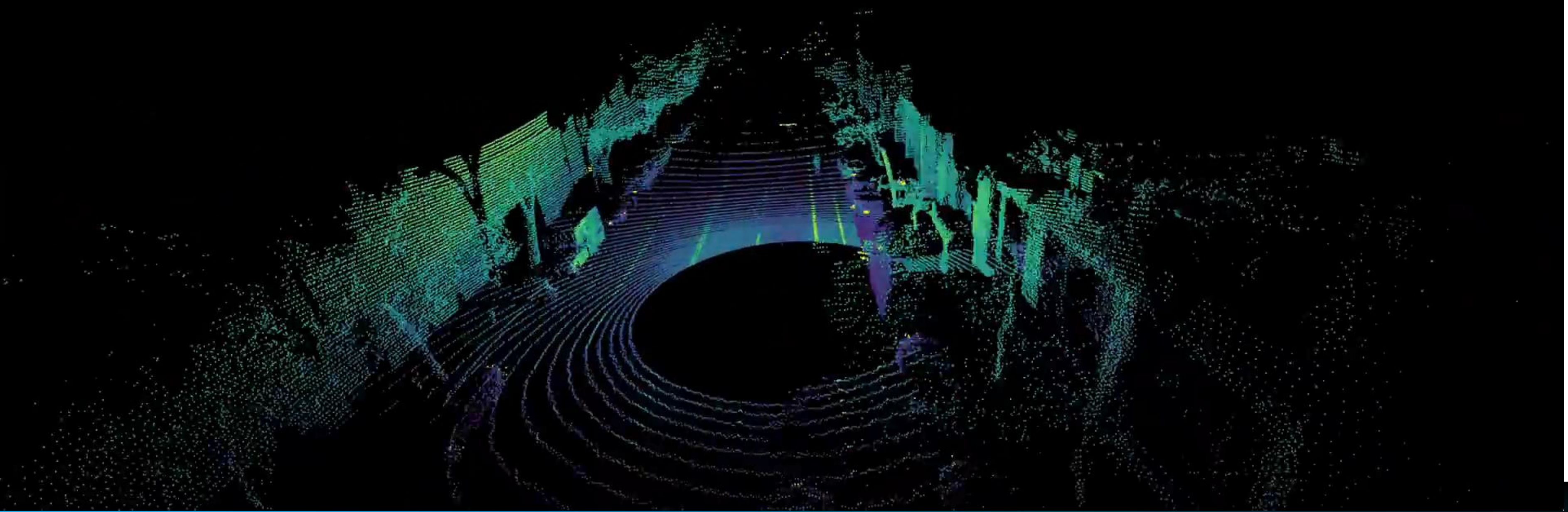

Consensus Requirements of Automotive LIDAR

	Short Range ~20-30m (side-looking)	Long Range ~200-300m (forward-looking)
FOV (varies)	> 90°	< 90°
x, y res	~1°	0.1° – 0.15° (~ width of person at 200m)
z res	a few cm (higher res is not needed)	
frame rate	≥ 25 Hz	
reliability	AEC-Q100 (severe shock and vibration, etc)	
Temperature	AEC-Q100 Grade 1 (-40C – 125C)	
Size	"how small can you make it?" or 100 – 200 cm^3	
Safety	IEC-60825-1 Class 1 "eye safe"	
Cost (System)	≤ $50	< $200

One problem in automotive sensing – there are no standards – object size? reflectivity? surface?

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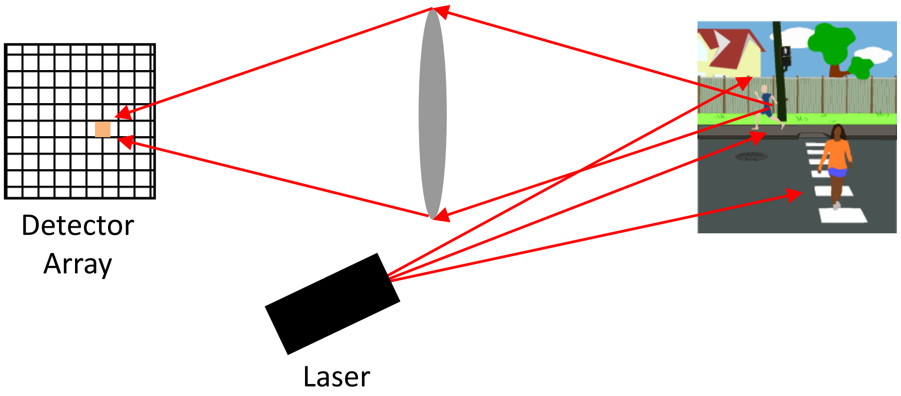
So will there be a LIDAR in every car?

- It won’t be from lack of trying! There are approximately **90** LIDAR start ups!
- In addition, every OEM and most of the Tier 1 suppliers are developing LIDAR
- Almost all the industry thinks it is necessary for autonomous driving
- There are many ways to build a LIDAR
- The real race is not for a “better” LIDAR, but for a good-enough *cheap* LIDAR!

Note: The Waymo robo-taxi model is a different use case. High cost of the vehicle is amortized over commercial use and a single urban area simplifies the navigation issues.

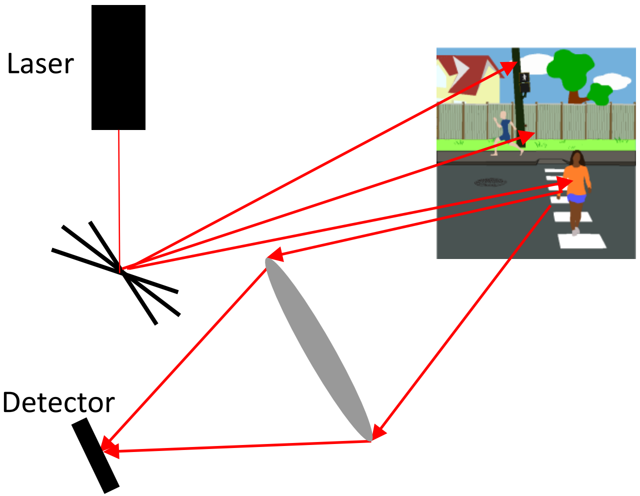
Flash LIDAR vs Scanned LIDAR

Flash



Array size & focal length define Field-Of-View (FOV)
Array element size defines resolution
High peak power for large FOV
Low coherence – Low brightness laser
No moving parts – basically a camera

Scanning



Scan angle defines FOV
Collimation of laser defines resolution - requires high brightness (radiance) laser
Can use single point or linear array of detectors
→ 1 or 2 axis scanning

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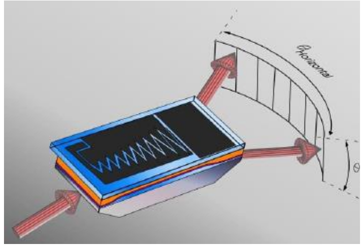
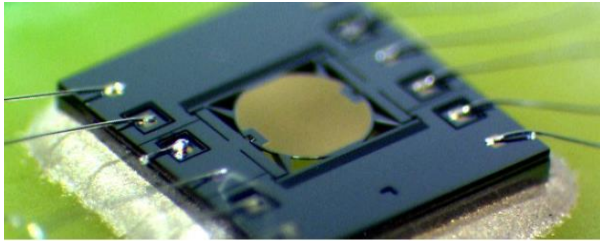
Scanning Issues

- Size, reliability and cost of mechanical scanning (spinning is actually not so bad)
- MEMS scanning imposes severe optical design constraints – clear aperture, scan angle
- Folded paths of various reflective scanning systems are a manufacturing problem
- Solid state scanning mechanisms (liquid crystal, silicon photonics, acousto-optic, electro-optic, etc) are all subject to limitations on clear aperture, scan angle, loss, laser coherence and temperature sensitivity



Liquid Crystal-Clad EO Waveguide Scanner
Davis Proc SPIE **9356 (2015)**



2-axis MEMS scanning mirror
Sanders Proc SPIE **7208 (2009)**

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Detection Options

Detection Process	LIDAR Type Compatibility
Direct Detection (PD, Linear APD)	Scan & Flash
Photon Counting Direct Detection (SPAD)	Scan & Flash
Coherent Detection	Scan Only (in practice)
Integrating Direct Detection (CMOS imager)	Flash Only

TriLumina lasers applicable

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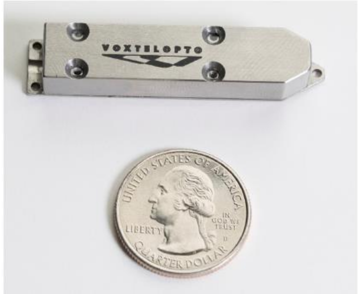
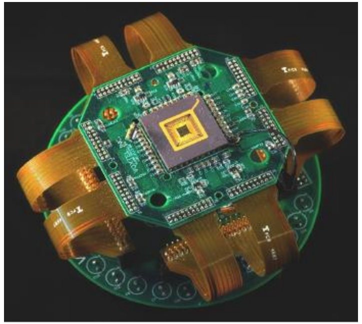
Direct Detection LIDAR

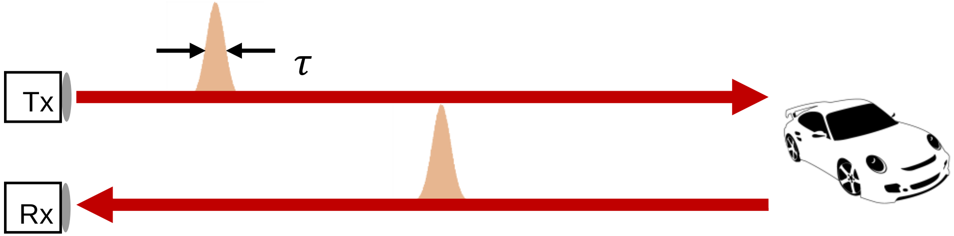
- Using photodiodes or avalanche photodiodes biased in linear range – Time of Flight: $t = 2R/c$
- Need fast risetime for range resolution: $\Delta R \approx \tau c$
- The major noise sources are background light and amplifier noise
- **Both scanning and flash designs in NIR (800 – 1000nm) are range-limited by eye safety considerations**
- Many systems are >1400nm (often 1550nm) because of eye safety advantages – still need a lot of power at 1550nm
- Long wavelength systems are mostly scanning - flash technology is very expensive - using military style FPAs



Voxtel 1535nm DPSS
20μJ @ 400kHz



Voxtel 128 X 128 InGaAs APD Array F-C bonded to Active Si IC



Williams Opt.Eng. **56 03224 (2017)**

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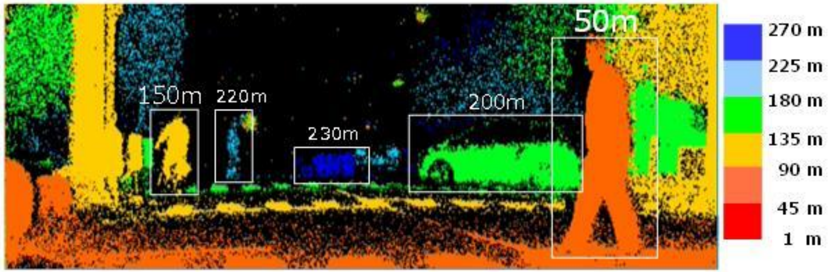
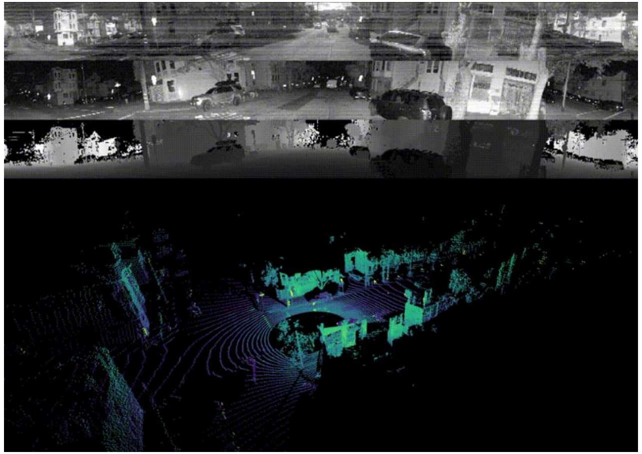
Silicon SPAD Arrays for Photon Counting

- Using avalanche photodiodes in Geiger mode or Single Photon Avalanche Diode (SPAD) detectors – silicon versions becoming hi-res low cost
- Amplifier noise is eliminated with very high effective gain (~10^6)
- Very sensitive to background light – narrow band filters and stable lasers required
- The high gain allows much lower laser power levels – eye safety at long range
- Applicable to both scanning and flash architectures



>250m Range LIDAR with 300k-pixel silicon SPAD array 940nm
Hirose et al, Sensors, 2018, 3642



Ouster scanning LIDAR with silicon SPAD array

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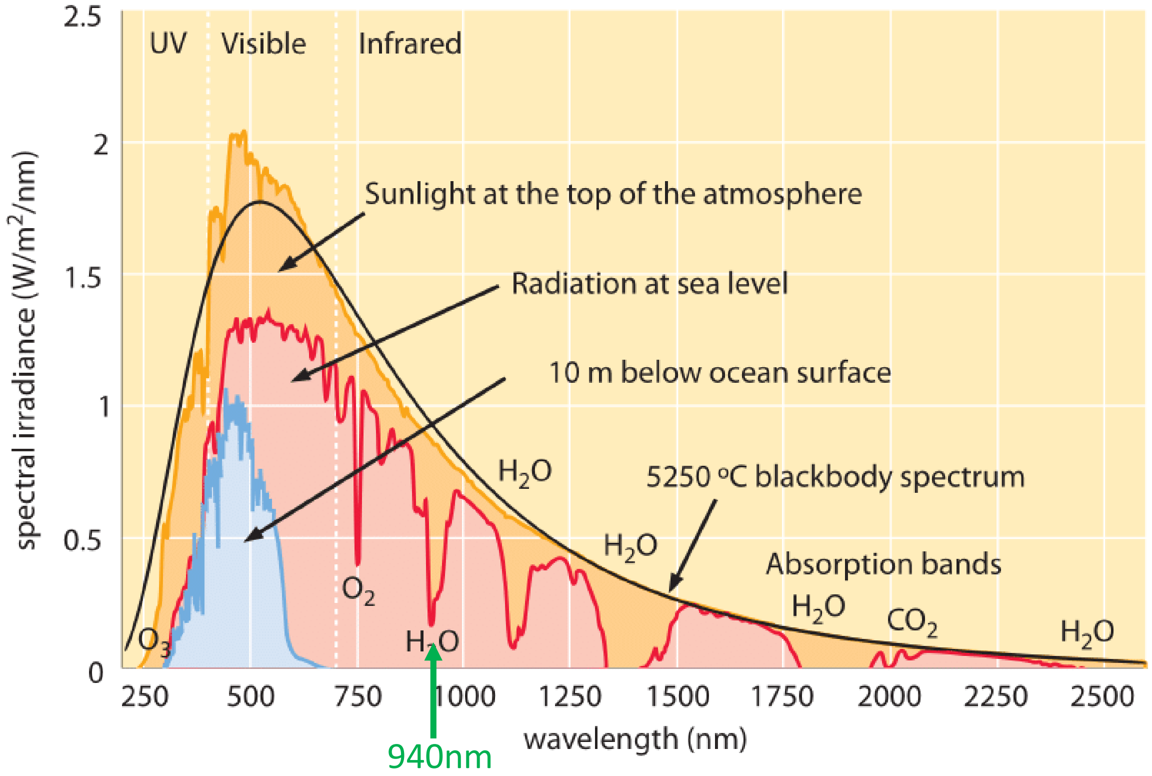
LIDAR Wavelength Choices



bionumbers.org (adapted from NREL data)

- 940nm optimum for silicon detector SNR in sunlight
- The optical bandpass filter has to be narrow
- The laser has to stay within filter bandpass
- LEDs and and most laser diodes – 0.3 nm/K, VCSELs and DFB lasers – 0.06 nm/K

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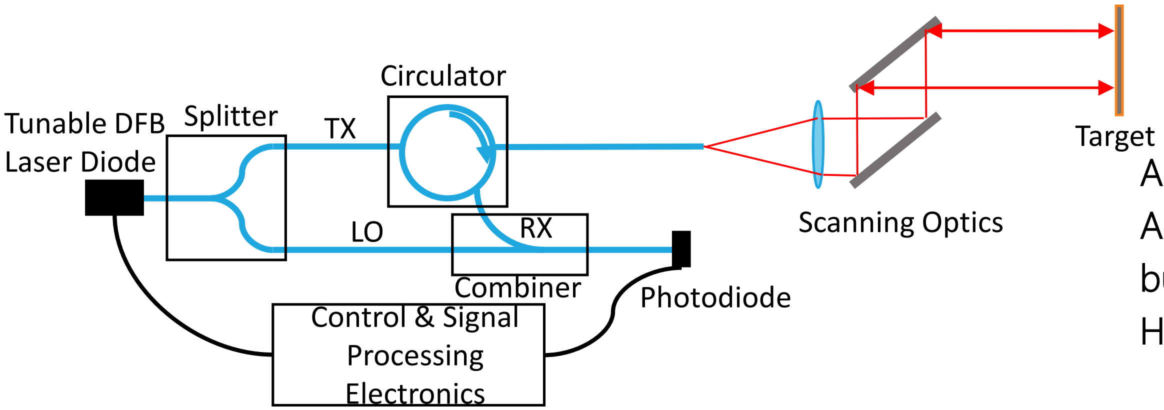
Coherent Detection



A simplified FMCW coherent LIDAR

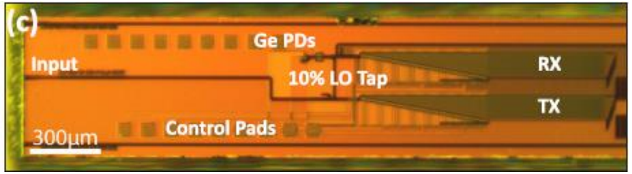
A very high performance LIDAR can be built with telecom fiber-optic components

How do you get the cost down?

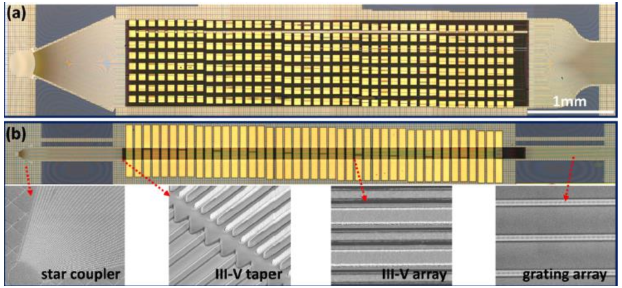
- Coherent detection LIDARs have phenomenal performance – high gain, low noise, high accuracy
- very low optical power required – eye safety limitations less of a problem
- Almost immune to background and crosstalk and can sense doppler shift for velocity
- Requires very narrow-line, tunable source – Coherence Length > 2R – linewidth kHz or low MHz – frequency modulated continuous wave (FMCW) - requires very linear "chirp"

Revolutionary Silicon Photonics Advances

- Extreme mechanical stability of monolithic integrated structures – ideal for complex optical paths like coherent detection & phased arrays
- Some processes are CMOS compatible processes in commercial foundries → full integration with electronics for control and interfacing
- Still need a high performance off-chip laser or integration of that laser on the silicon die
- Can they meet automotive environmental requirements?
- The silicon photonics die are not simple, inexpensive digital ICs – complex designs, large die, heterogeneous integration – yield? – cost?
- How soon can it be commercialized?



FMCW LIDAR on a Chip
Poulton Opt.Lett. **4091 (2017)**



240-channel OPA on a Chip
Xie Opt.Exp. **3642 (2019)**

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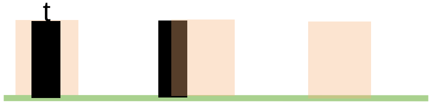
CMOS Time-of-Flight Cameras

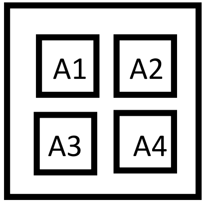
Indirect Pulse ToF
(fast-gated CMOS cameras with multiple global shutters)

$$z = \frac{Ct}{2} \frac{A1 - BG}{A1 + A2 - 2BG}$$

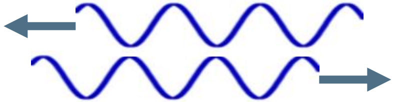


CMOS camera image sensors with fast global shutters

Indirect CW ToF
(synchronous detection in gated composite pixel CMOS cameras)



$$z = \frac{C}{2f} \frac{1}{2\pi} \arctan\frac{A1 - A3}{A0 - A2}$$



CMOS imaging sensors with multiple, time-gated sub-pixels

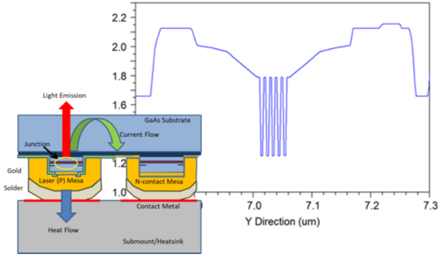
- Integrating detector arrays based on silicon CMOS imaging technology – low cost and scalable, but limited to shorter ranges (10-30m) – very high resolution cameras → megapixel

- Originally used only at 850nm, now extended NIR quantum efficiency improvements allow 940nm operation outdoors – can incorporate background subtraction as well

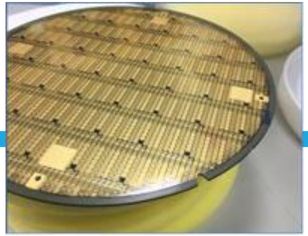
- **Can do monochrome or RGB visible, active NIR-illuminated imaging and NIR Time-of-Flight depth sensing in the same sensor!**

What Does TriLumina Do?

TriLumina VCSEL Array Designs

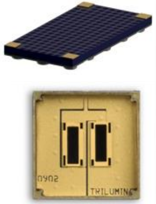


Design of EPI and VCSEL Array and Illumination Module

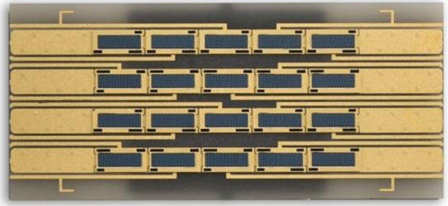


1000s Array/ 6” Wafer
Multiple 6” Fab Partners

TriLumina Illumination Modules



Low Cost VCSEL
Array for consumer



600 W Module for LIDAR

“Fabless” Startup Building Illumination Modules for LIDAR and 3D Sensing Systems Customers

Customers: 3D Sensing & LIDAR Systems
Integrated by Tier 1s and 2s

OEMs

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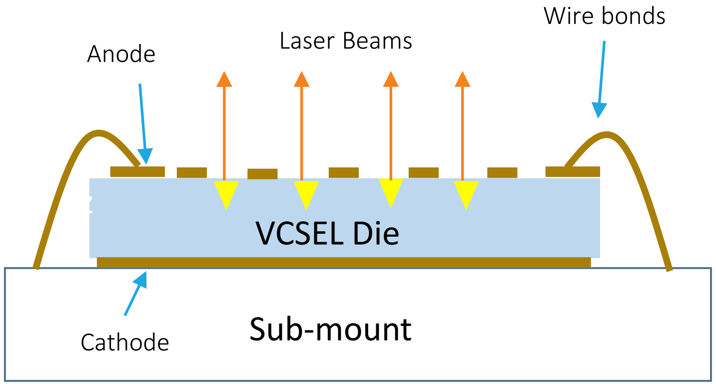
Conventional vs TriLumina VCSEL Technology

Conventional Top-Emitting VCSEL

- Bond Wires and Pads Required, More Inductance, Space

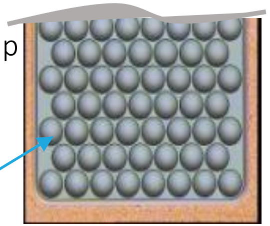


TriLumina Back-Emitting VCSEL*

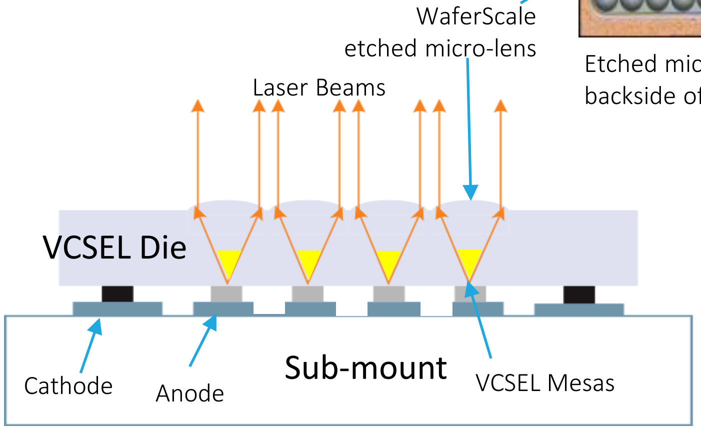
*65 Patents

With Integrated Micro-Optics

- Lasers, Micro optics, Electronic Beam Steering on a Chip
- No Bond Wires→Fast Rise Time, Short Pulses
- Junction Down Improves Thermal Management



Etched micro-lens on backside of chip



All Bump Bonds on Same Side of VCSEL Chip

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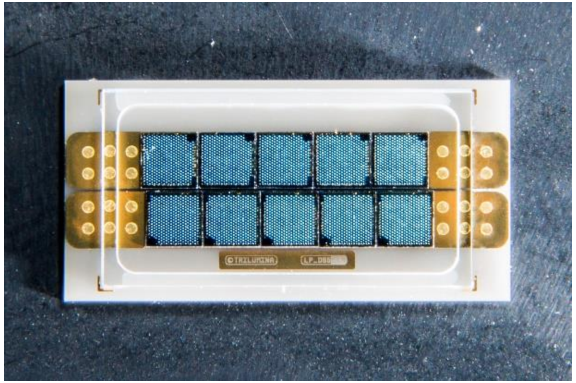
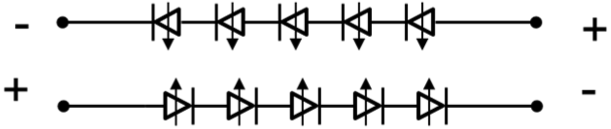
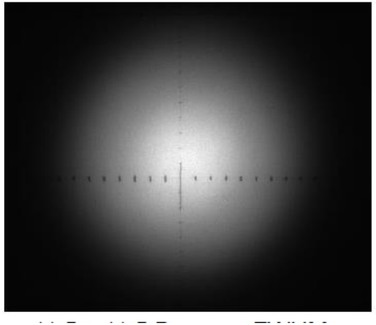
High Power Surface Mount Laser Arrays



~16mm X 8mm



- 300W in 10 ns pulses with 2X 100A driver circuits
- Repetition rate of 100 kHz, -40 to 125C
- Optimized for Flash LIDAR
- 940 nm, <15 degree FWHM divergence (round beam in Far Field)
- Series-connected combination for high slope efficiency
- Stable λ over temperature – 0.07nm/ ^{o}C



Incoherent array has almost speckle-free far-field

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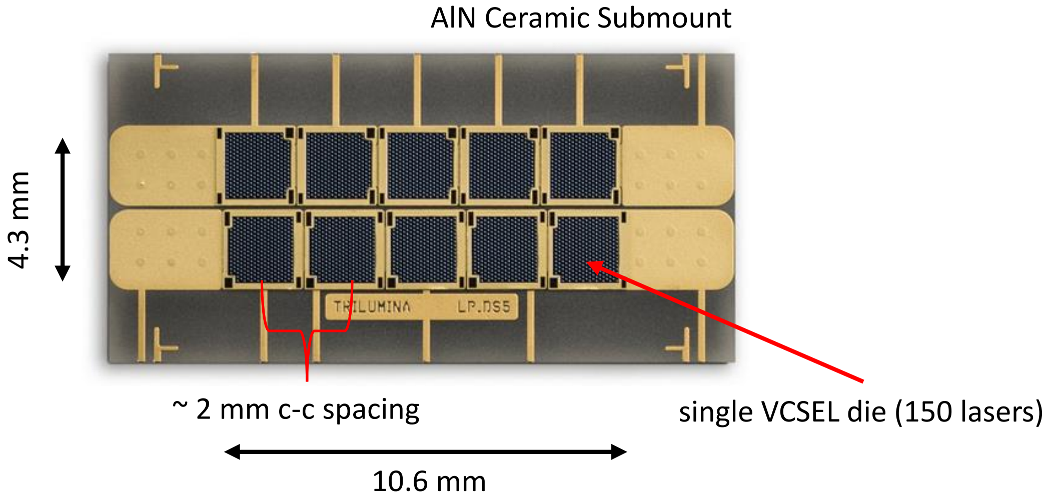
Engineering Eye Safety in the NIR

- The eye safety problem is getting sufficient power for long range while still being below the MPE at nearest (10cm) viewing distance.
- These are extended sources, at close viewing distances the optical power is limited by the angle of acceptance, γ in the IEC 60825-1 standard.



Sub-mount and VCSEL array with micro-lenses

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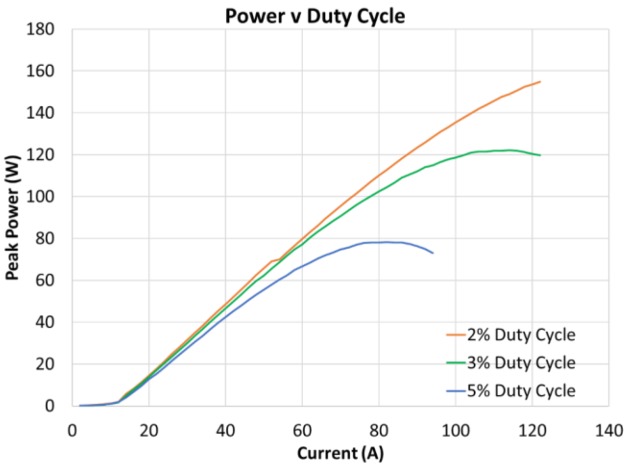
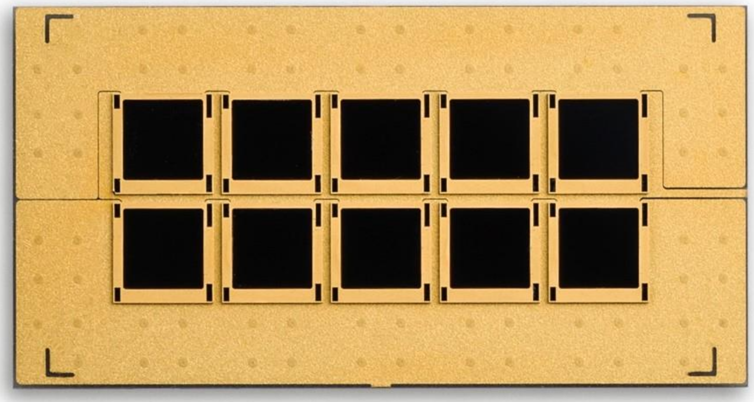
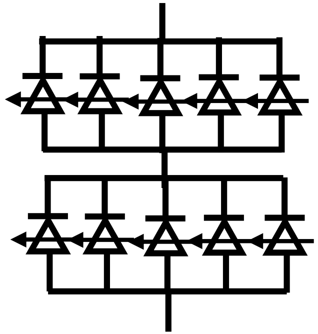
100W VCSEL Array for QCW Time-of-Flight Cameras

> 6,000 VCSELs in parallel-series combination for high power conversion efficiency in 1-5% duty cycle applications







A flexible, modular, scalable VCSEL array architecture

Conclusions

- High cost is the primary issue for success of automotive LIDAR
- Silicon-based detection technologies have the lowest cost
- Advanced detection approaches and innovative laser illumination designs are key to eye safe systems at silicon detection wavelengths
- It is likely that there will not be one winner. The industry likes multiple suppliers and solutions
- These high-performance sensors will find many other applications

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The End