LiDAR for Autonomous Vehicles:

The Principles, Market and Trends

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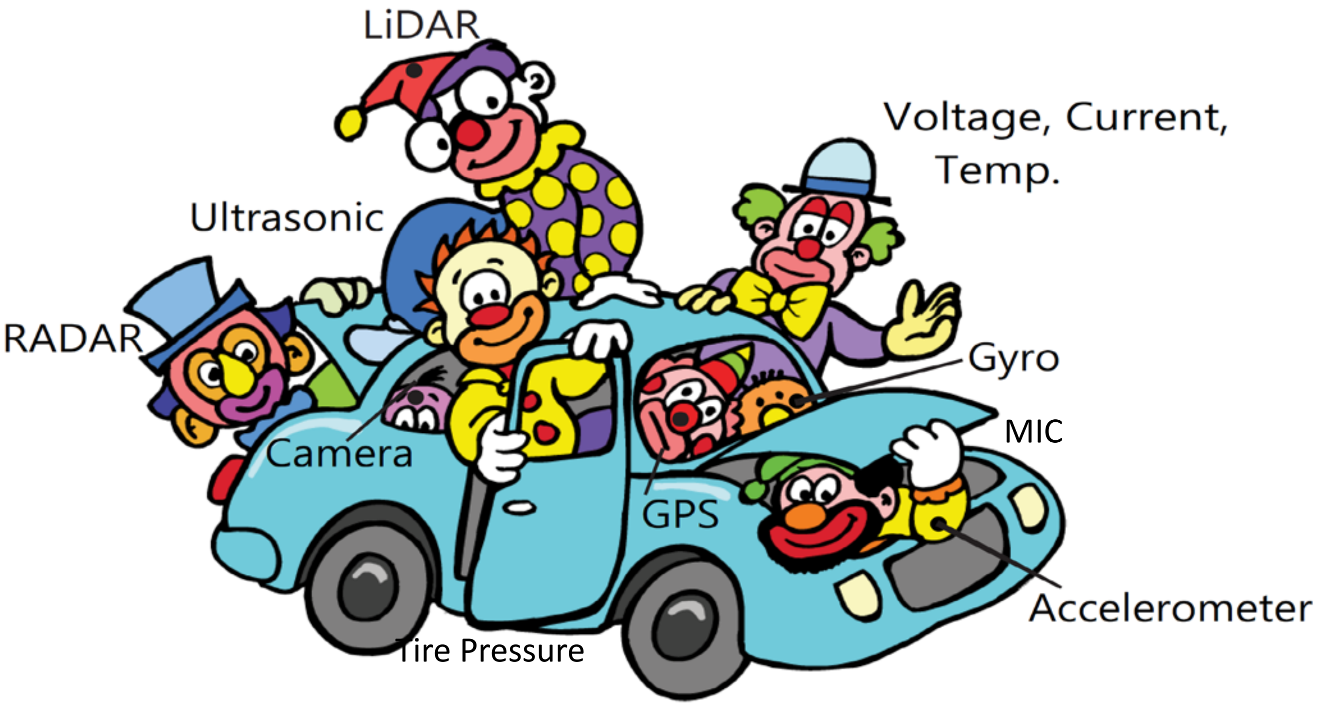
LLR RR Apollo 11

Source: wikipedia

Agenda

- Need for Autonomous Vehicle
- LiDAR Introduction
- Block Diagram
- Optical Components
- ToF, FMCW, Flash LiDARS
- Market & Trends
- Test Challenges
- What is next?

Car Full of Sensors



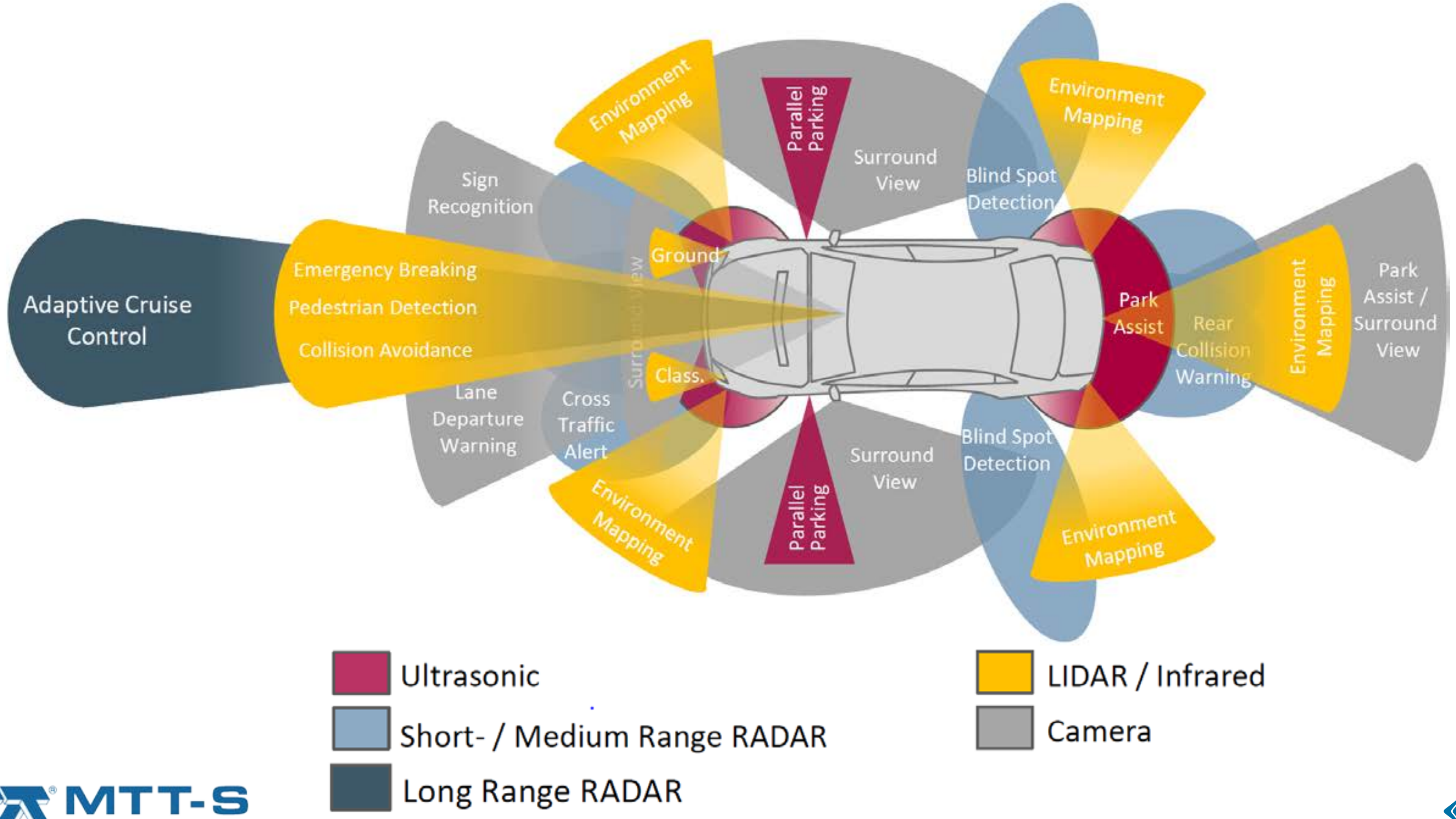
A modern car has about 100 to 200 sensors.   ADAS related sensors are soon expected to be 20-30 per car.

Need for Autonomous Vehicles

- **Reduced Number of Accidents and fatalities**
- Reliable, safe and timely movement of people and goods
- Reduced Traffic Congestion
- Reduced CO2 Emissions
- Lower Fuel Consumption
- Last Mile Services.
- Reduced Travel Time and Transportation Costs.
- More Effective and Affordable Taxis
- Reduced need for Parkings
- More Efficient use of Vehicles

Source: ITSDigest.com Feb 2018

ADAS Sensors



Automotive Sensors Comparison

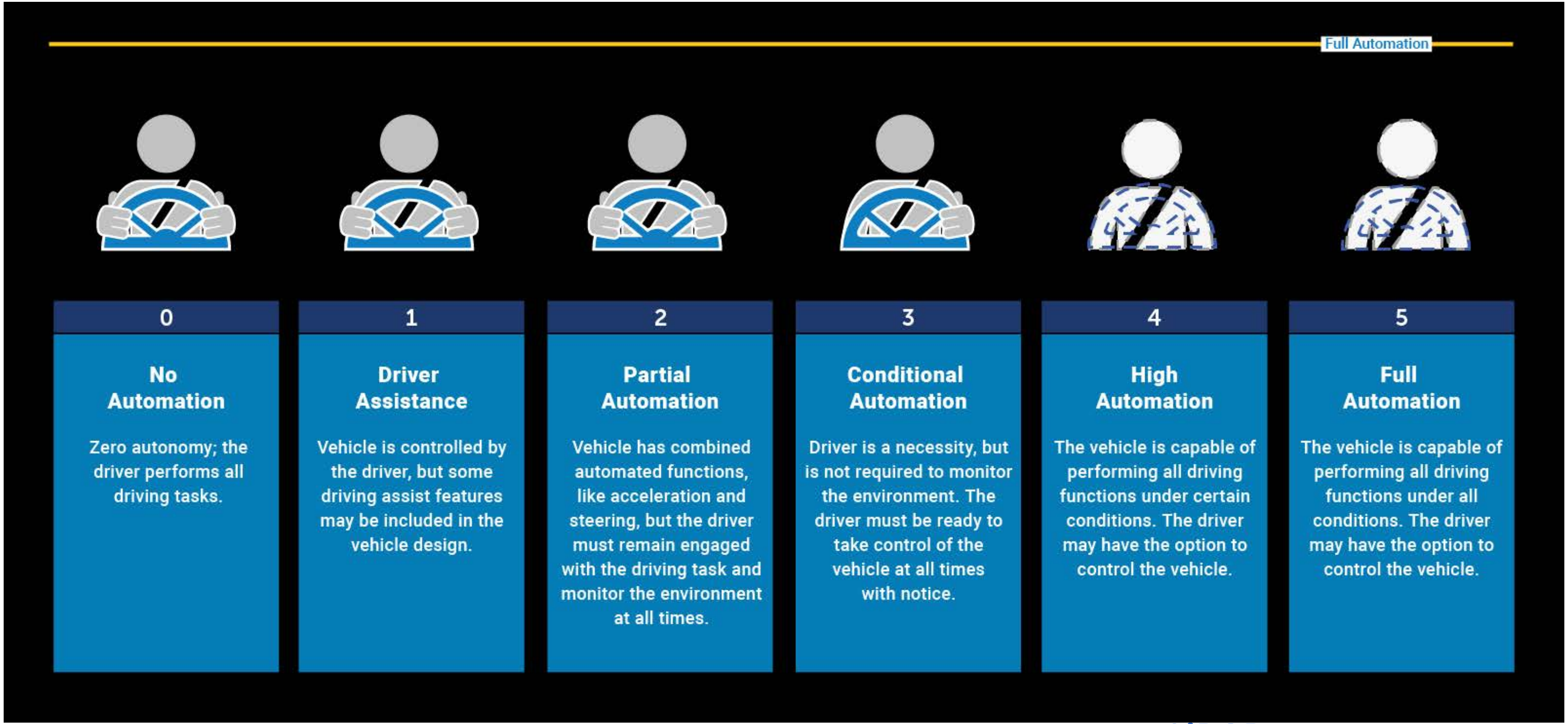
Feature	Solid State LiDAR	Radar*	Camera
Sensing Dimension	3D	1D	2D
Range (in m)	200 m	250 m	100 m
Field of View	V.Good	good	good
Accuracy (cm)	V.Good	Poor	Poor
Effective in Adverse Weather	Good	Very Good	Poor
Pitch Dark	Very Good	Very Good	Medium
Bright Sunlight	Good	Very Good	Good
Read Color & Signs	Poor	Poor	Very Good
Principal Application	Pedestrian Protection	Obstacle detection & Cruise Control	Sign reading, texture analysis
ASP	$1,000	$100	$150


LiDAR – Quanergy S3


mmW Radar - Continental


Camera- Jabil

Levels of Self Driving Cars (SAE)



LiDAR

What is LiDAR?
Light Detection and Ranging

- LiDAR is an optical device which can be used to measure distance, angle, velocity and reflectivity of a target.
- Uses Laser pulses or frequency ramps in the infrared region of 850 to 1550 nm (352.7 to 193.4 THz)
- Functions like RADAR; uses light instead of RF (77 to 81 GHz)
- It can generate very high-definition point cloud images with object classification.
- Applications for SDC level 3+ due to its high resolution

Ouster

Waymo

Quanergy

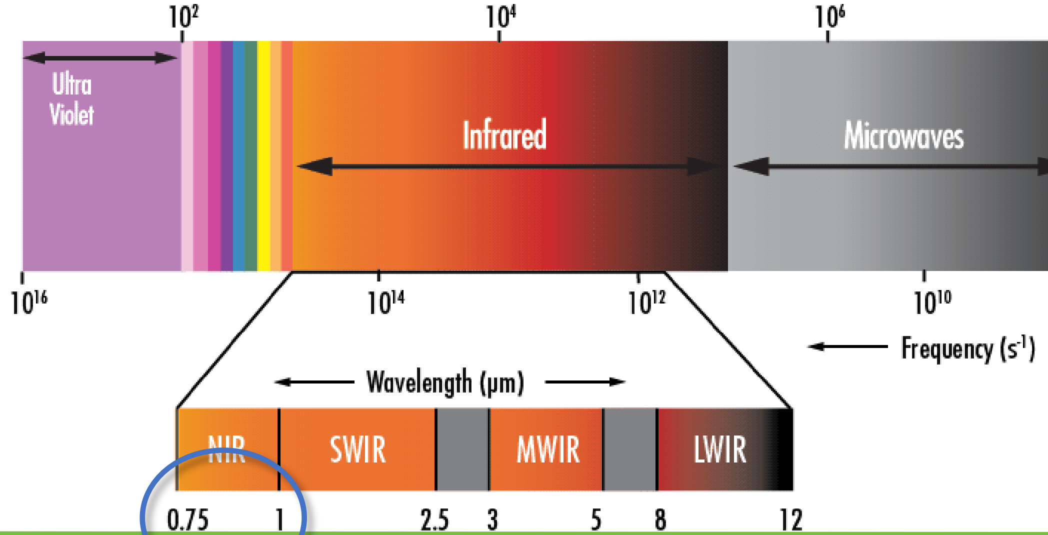
Velodyne

LiDAR History

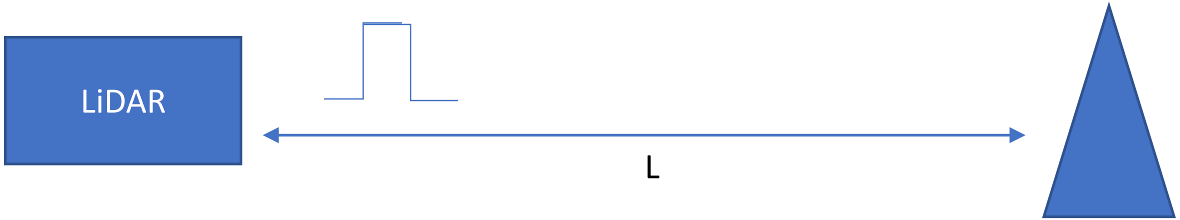
- Laser Invented 1960
- Distance to moon measured accurately using LiDAR in 1970. 239,228.3 miles. Return time: 2.58 secs
- Low loss fiber and solid-state laser developed in about 1970 gave a major boost to optical and photonics world.
- LiDAR has been used in large number of applications since.
- First Commercial Airborne LiDAR system 1995
- Technology has recently driven cost to enable use in Automotive Apps.
- First commercial car with LiDAR: 2018 Audi 8
- More than $1 billion in corporate and private investment has gone into some 50 LiDAR startups over the past three years

SPECTRUM VIEW

Visible	400 nm–700 nm	790 THz – 430 THz	3.3 eV – 1.7 eV
Infrared	700 nm – 1 mm	430 THz – 300 GHz	1.7 eV – 1.24 meV
Microwave & mmW	1 mm – 1 meter	300 GHz – 300 MHz	1.24 meV – 1.24 µeV



LiDAR Principles



LiDAR Equation: $P_R = P_T \frac{\sigma_s}{4\pi} \left(\frac{A_{Tx/Rx}}{\lambda L^2} \right)^2$

For spot < target: $\sigma_s = \rho * \frac{\lambda^2 L^2}{A_{Tx}}$

$P_R = P_T \frac{\rho A_{Rx}}{4\pi L^2}$

σ_s= scattering cross section

ρ = target reflectivity

Assuming ρ = 10%, L= 200 m, P_T = 100 mW and A_{Rx} = 1 cm^2

P_R = 2 pW = -117 dBm

Using Energy of a photon E = $h * c/\lambda$

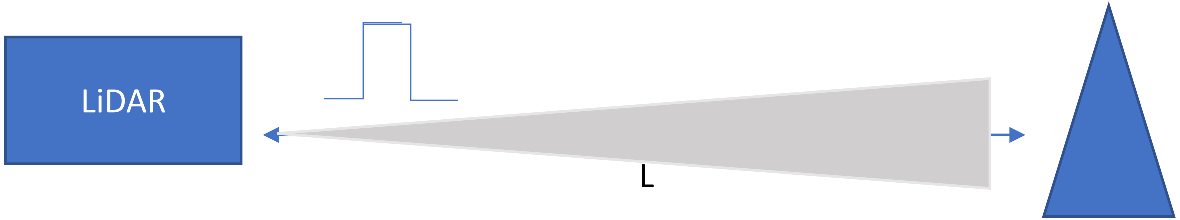
P_R ~ 15 photons/µsec

Where h is the Planck Constant 6.6261 x 10^{-34} J*s
c is the speed of light (299 792 458 m/s
λ is the wavelength of the photon (1550 nm)

MTT-S MHz to THz Community

IEEE

LiDAR Principles



Beam Spreading Radar vs LiDAR

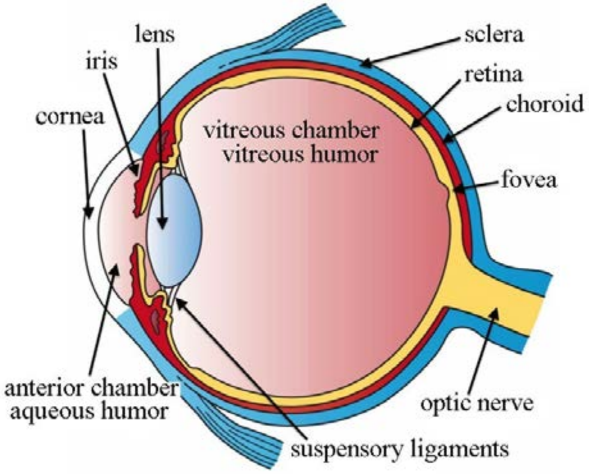
Beam Divergence θ = $\frac{\lambda}{D}$

Radar 79 GHz λ ~ 4 mm D= 10 cm θ = 0.04 rad or 4 meters at 100 m

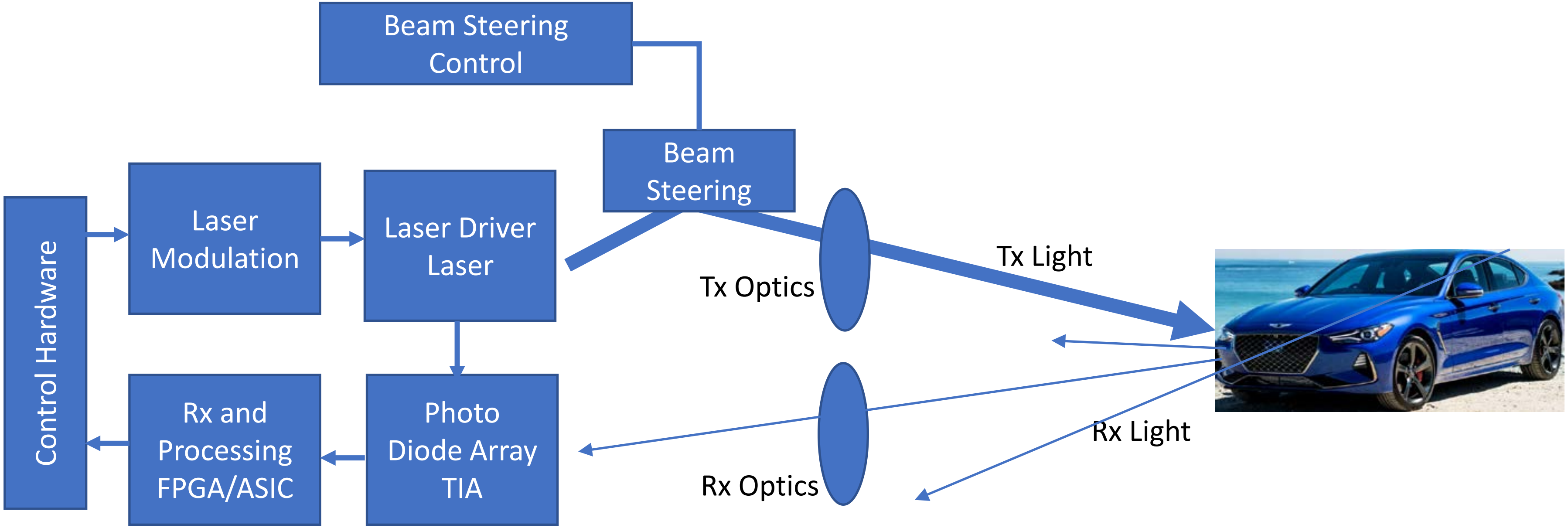
LiDAR 200 THz λ ~ 1.5 μm D= 1.5 mm θ = 0.001 rad or 10 cm at 100 m

LiDAR Eye Safety Concerns

- 905 nm safety concerns
  - The lens and vitreous fluid in the eye will transmit 905 nm to the retina.
  - There are strict limits as to how much laser power can be generated.
  - Average power/Peak power
- Longer wavelengths are less dangerous
  - The lens and vitreous fluid in the eye will absorb 1550 nm, blocking it from reaching the retina
  - 10-40x higher eye safety optical power limit at 1550nm compared to 905nm
- Longer wavelengths require special optics.
  - Many types of “transparent” glass, plastics also absorb IR.
  - Careful choice of materials are required for 1550 nm.



LiDAR Basic Block



Technologies for Automotive LiDAR

SOURCE

- NIR
- SWIR
- Laser Diode GaAs
- Laser Diode InP
- FMCW Laser
- VCSEL

BEAM OPTICS

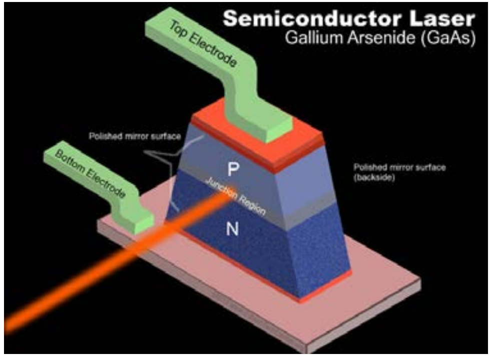
- Scanning
- Flash
- Mechanical
- Nanosecond Pulse Laser
- MEMS
- OPA

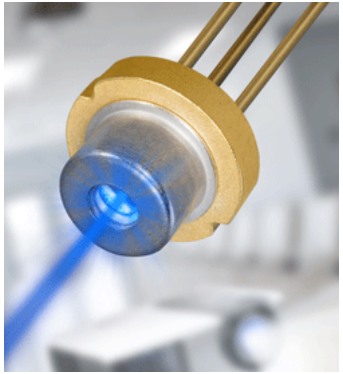
DETECTOR

NIR	SWIR
SiPM	
SPAD	SPAD
APD	APD
PIN Photodiode	PIN Photodiode

Lasers

- A device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.
- **semiconductor lasers** are laser diodes, which are pumped with an electrical current in a region where an n-doped and a p-doped **semiconductor** material meet.
- Diode lasers have two classes: EEL(Edge Emitting Laser) and VCSEL (Vertical Cavity Surface Emitting Laser).





Different Types of Laser Diodes

- **FP**

  A Fabry-Perot Cavity is the standard cavity with two highly reflecting mirrors bouncing the Light back and forth, forming a standing wave. This is an Edge Emitting laser with elliptical beam.
  It has narrow bandwidth of about 1 nm.

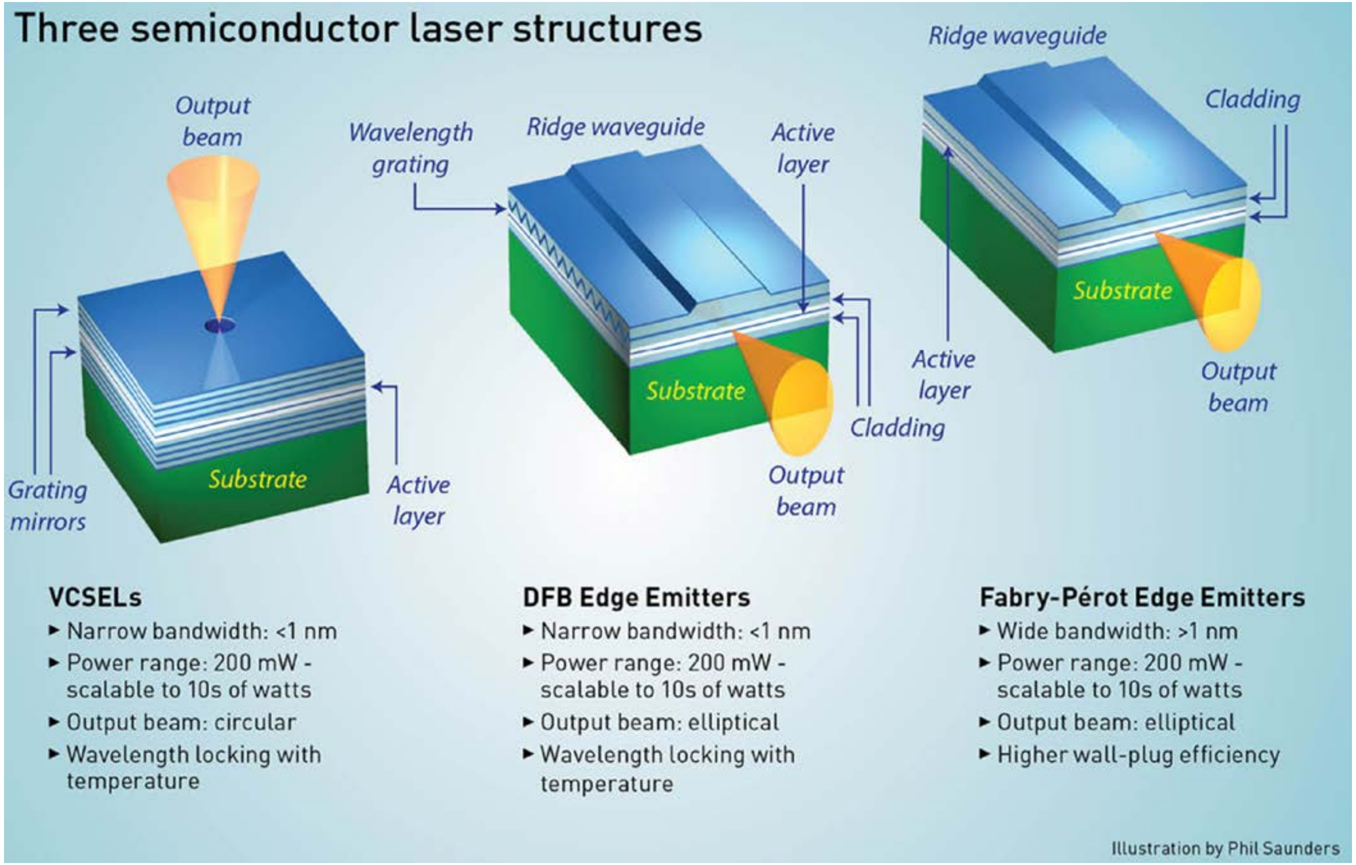
- **DFB** (Distributed Feed Back)

  the active region of this device contains a periodically structured element that builds a one-dimensional interference grating (Bragg scattering) providing desired optical feedback for the laser. This is an Edge Emitting laser with elliptical beam

- **VCSEL**

  consists of two distributed Bragg reflector (DBR) mirrors parallel to the wafer surface. Typically function between 650 and 1300 nm based on gallium arsenide (GaAs) wafers with DBRs formed from GaAs and Aluminum gallium arsenide. Beam is circular vertical to the junction.

Semiconductor Laser Types



Source: OSA – Optics and Photonics News February 2019

Photo Detectors for LiDAR

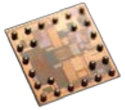
- PIN Photo Diode

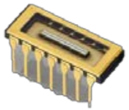
  -A reverse biased photodiode causes absorbing photon to generate current. Gain μ= 1
- Avalanche photodiode (**APD**)

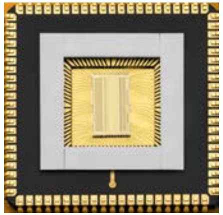
  -Uses reverse voltage to multiply photo current through avalanche effect. Si based APDs function to about 1100nm. InGaAs APDs are used to 1700nm. μ <100
- Single-Photon Avalanche Diode (**SPAD**)

  -APD designed to operate above the breakdown voltage (Geiger-mode) $\mu < 10^6$. Limited to digital one-bit operation. CMOS technology allows integration.
- Silicon Photomultiplier **(SiPM)**

  -Integrates SPAD pairs with resistor in a dense array thus providing magnitude of an instantaneous photon flux.

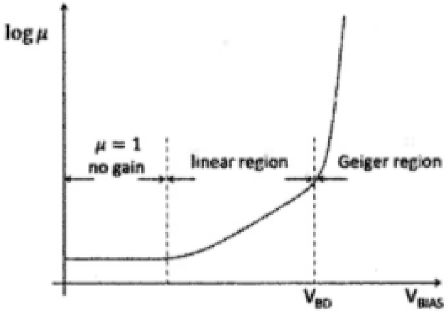






SPAD ARRAY

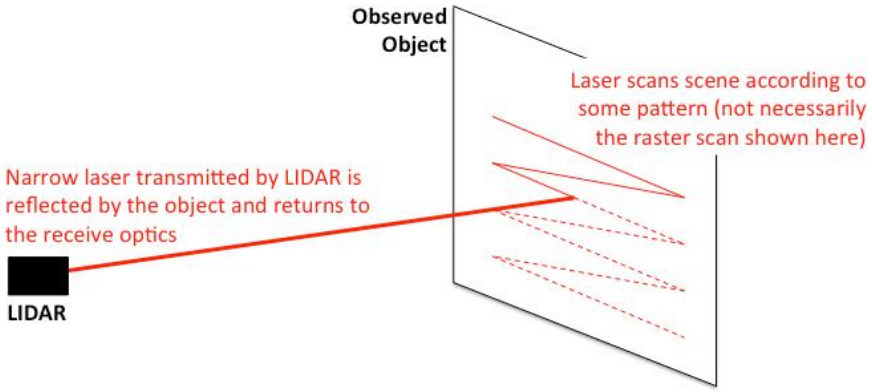
Linear and Geiger (digital) Modes



Log of gain vs reverse bias for a PN junction

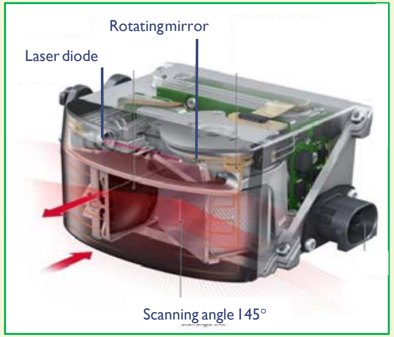
Distinguishing Features for LiDARS

- Distance Measurement
  - Time of Flight
  - AMCW
  - FMCW
- Laser Wavelength
  - 850 nm
  - 905 nm
  - 1550 nm
- Beam Steering Technology
  - Spinning LiDAR
  - Mechanical Scanning
  - Optical Phased Array LiDAR
  - Flash LiDAR



MECHANICAL SCANNING AUTOMOTIVE LiDAR

Mechanical LiDAR for ADAS



In 2017, Audi released the A8 with Level 3 autonomy thanks to the Scala LiDAR from Valeo. The A8 is capable of traffic jam assist. It is the only LiDAR available for consumer cars.

Active players:

Valeo

In collaboration with:

ibeo

Audi

Mechanical LiDAR for Robotic cars

Robotic cars are equipped with multi-channels LiDAR in which multiple lasers and photodetectors are rotating 360°. These LiDAR are bulky and cannot blend in consumer cars.

Active players:

Velodyne

Valeo

robosense

Micro-motion LiDAR

CEPTON

Other mechanical LiDAR

LUMINAR

1550 nm

Source: Yole 2018

LiDAR Technologies Referred to as "Solid State"

OPA

- Continuous beam steered by optical phase modulator
- Superior form factor as laser is integrated on an OPA chip
- Dynamically adjustable scan rate, resolution and zoom
- Higher data collection rate with multi-beam scanning

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Flash

- Similar to a digital camera, illuminates the environment with a single laser pulse
- Vulnerable to vibration effect that can distort the image
- High energy consumption due to laser power requirements
- Tradeoff arises between: (i) long range but expensive, or (ii) low cost but short range

AEYE, Benewake, LeddarTech (MASTERING LIDAR SENSOR TECHNOLOGY)

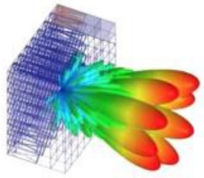
MEMS

- Moves laser by cascading tilt angles of multiple tiny mirrors
- Mirror alignment susceptible to shock and vibration, requiring frequent recalibration
- Fixed scan rate and resolution; blind spot due to minimum range
- Expensive laser and MEMS packaging

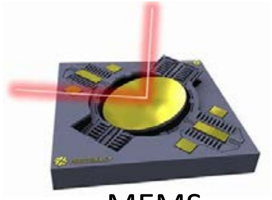
CEPTON, LUMINAR, INNOVIZ TECHNOLOGIES, Velodyne Lidar, Pioneer

Comparing Scanners

	Mechanical Scanners	MEMS Scanners	OPAs	Flash
Working principle	Galvos, rotating mirrors or prisms	MEMS micromirror	Phased array of antennas	Pulsed flood illumination
Main advantage	360 deg FOV in horizontal	Compact and lightweight	Full Solid State	Fast frame rate
Main disadvantage	Moving elements, bulky	Laser power management, linearity	Coupling to signal	Limited range/Blindable



OPA

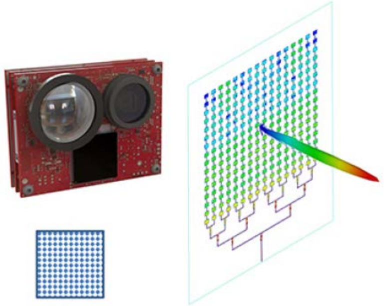


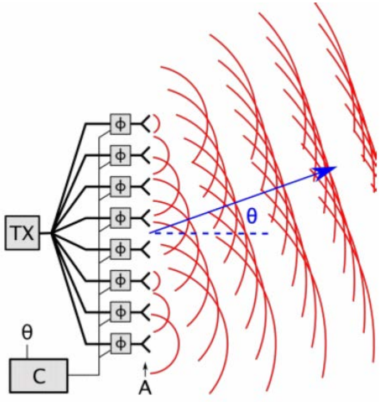
MEMS

Mechanical

OPA LiDAR

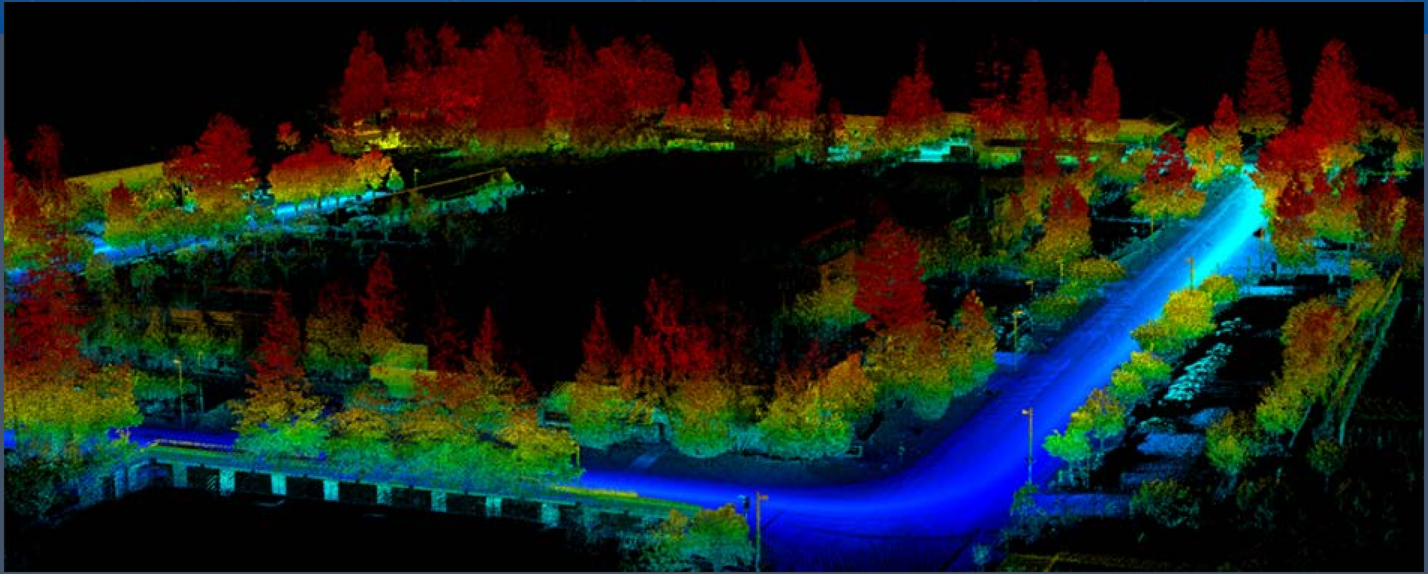
- Diffraction limited performance
- High efficiency
- Non-mechanical 2-dimensional beam steering
- Used in lens-free LiDAR and free-space communication
- Can be used for emitting and receiving
- High performance using low-loss on-chip waveguides, phase shifters, and optical antennas
- Scalable to centimeter-scale apertures
- Integrated with on-chip detectors and CMOS electronics





Transmitter optical phased array

Industry Leading Performance: High Density, Accurate Point Cloud



- **Denser Point cloud and better resolution than competitive solutions**
  - 1.3M point per second, 2X the point cloud density of competitors
  - Centimeter-level range accuracy
  - Very low noise
- **Up to 200m range (80% reflectivity)**

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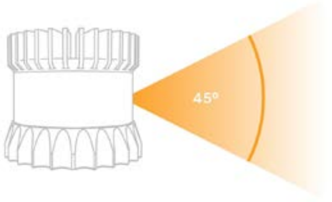
Flash LiDAR

- Laser Beam is not scanned. Scene is illuminated at once by a diffused laser source.
- Array of photodetectors is needed to form an image like a camera
- Limited FoV and Range
- No moving parts
- Lower assembly cost
- Potentially higher frame rates & better spatial resolution
- Multi beam Flash is showing great promise.
  120 meters range for 128 Channel. 2.6M PPS (Ouster)
  However there are challenges ahead.



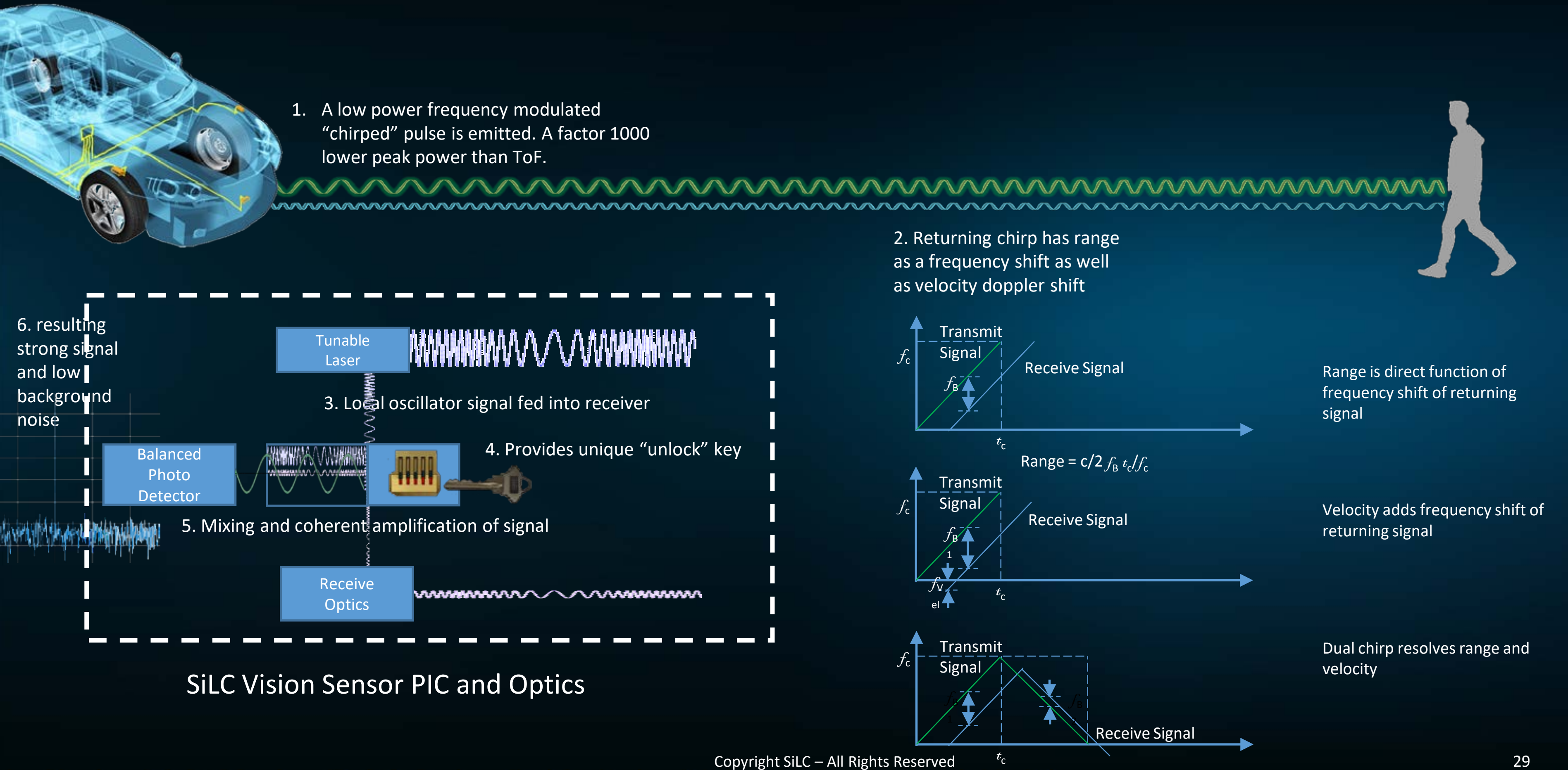
Flash Players include: ARGO, sense photonics, Continental, Leddartech, Xenomatix, Luminar, Ouster, TriLumina….

Distinguishing Features of FMCW LIDAR

- It can reach larger distances than most current pulsed designs. More than 300 meters range has been reported.
- Eye safe lasers are generally used (1550nm).
- Measures velocity instantaneously unlike pulsed LiDAR. (150m/s with 0.2 m/s resolution)
- Requires lower power lasers & lower power consumption.
- Higher dynamic range
- High precision of range and velocity measurement
- Interference resistant from sunlight as well as from other Lidars.
- Potentially lower cost thanks to PIC technology advances

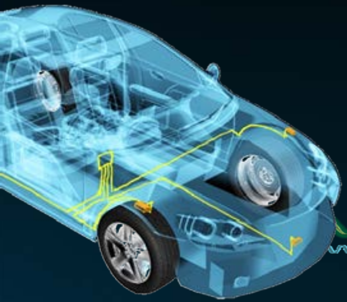
FMCW (Principle of Operation)

SiLC

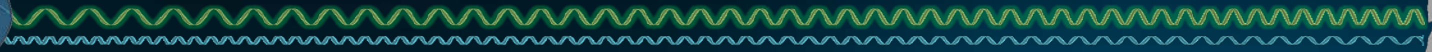


FMCW

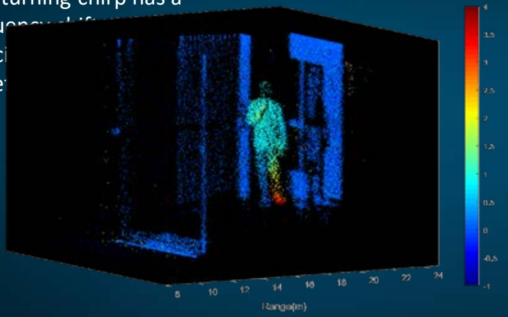
SiLC

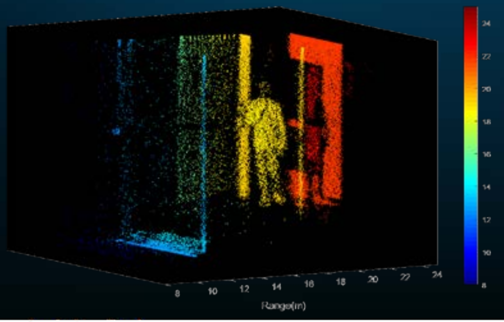


1. A low power frequency modulated “chirped” pulse is emitted. A factor 1000 lower peak power than ToF.

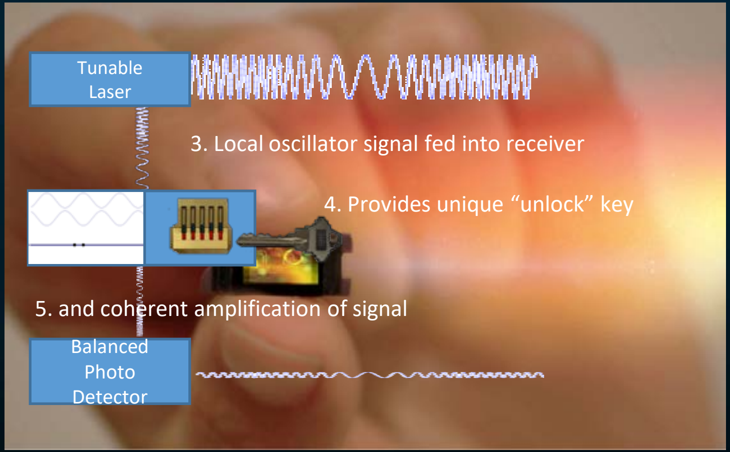


2. Returning chirp has a
frequ
veloci
wave



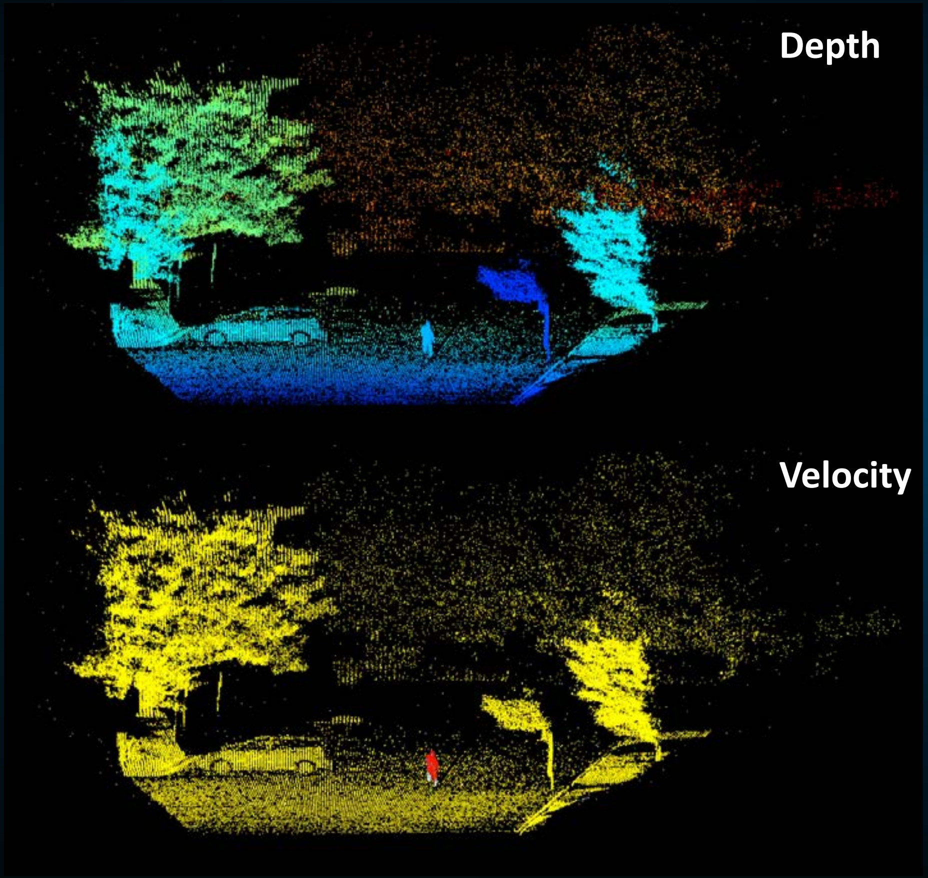


6. resulting strong signal and low background noise



Benefits of SiLC Vision Solutions

- Completely eye safe even for long range
- Accurate Instantaneous velocity
- Ultra high depth precision
- Immunity to multi-user and background interference
- Integration: Low cost, size, power etc



ToF vs FMCW

Feature	ToF (NIR)	ToF (SWIR)	FMCW (SWIR)
Position Accuracy	Good	Good	Excellent
Velocity Data	Inferred	Inferred	Direct
Velocity Accuracy	NA	NA	v.good
Laser Cost	Low	high	High
Photo Detector Cost	Low (Si)	Medium (GaAs)	Traditional: High Integrated: Low
Eye Safety Challenge	High	Medium	low
Interference Rejection	Low	Moderate	Very High
Technology Readiness	High	High	Low to moderate
Single Chip Tx/Rx	Unlikely	Unlikely	Possible

FMCW is low-power, ultra-long range, software-defined, better interference rejection, direct doppler & highly accurate

MTT-S
MHz to THz Community

IEEE

Market Update

Industrial Markets Being Transformed by LiDAR

Mapping

State of the art solution for 3D aerial and terrestrial mapping

Security

- Infrastructure monitoring
- Intrusion detection
- Access control
- Perimeter security
- Border security

Industrial

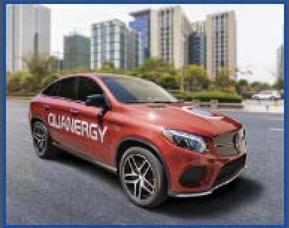
- Robotics
- Port Automation
- Warehouse Automation
- Measurement

Smart Cities & Spaces

- Retail
- Airports
- Enterprises
- Intersections
- Public Venues
- Gov. Agencies

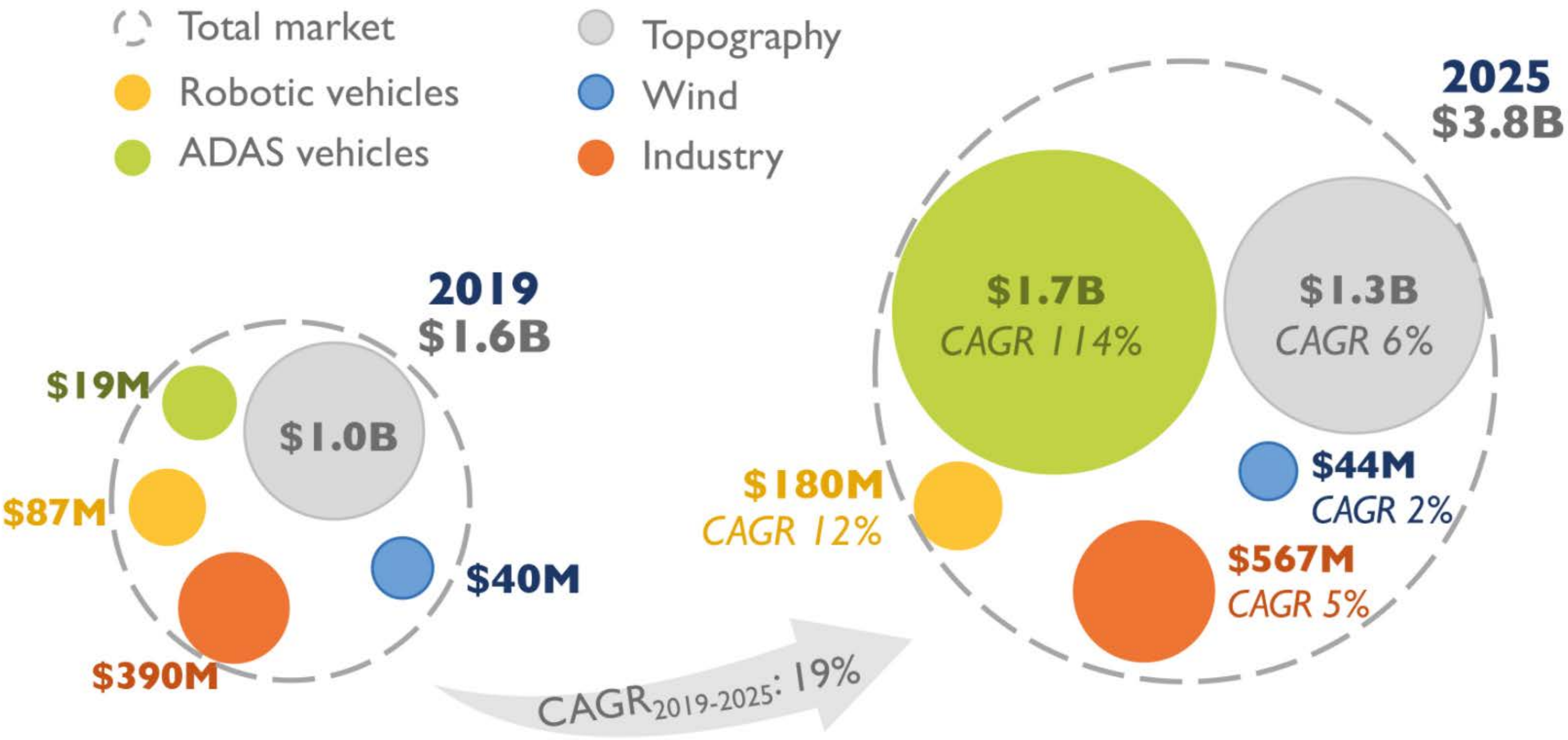
Transportation

- ADAS
- Robo-Taxi
- Autonomous Valet Parking
- Autonomous Driving



QUANERGY

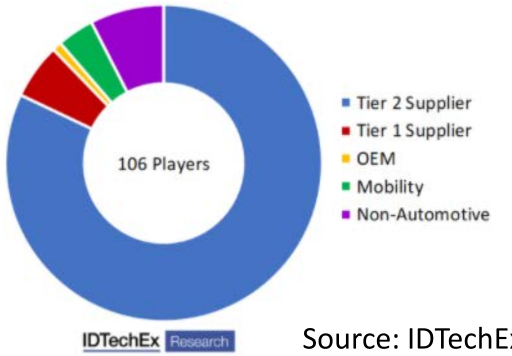
LiDAR Market by Applications (2019-2025)

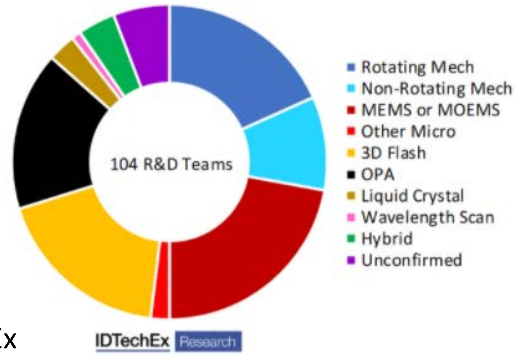


Source: LiDAR for Automotive and Industrial Applications Report, Yole Developpement 2020

Market Factors

- High investment >$2B
- 107 players
- New players FMCW
- COVID-19 Impact





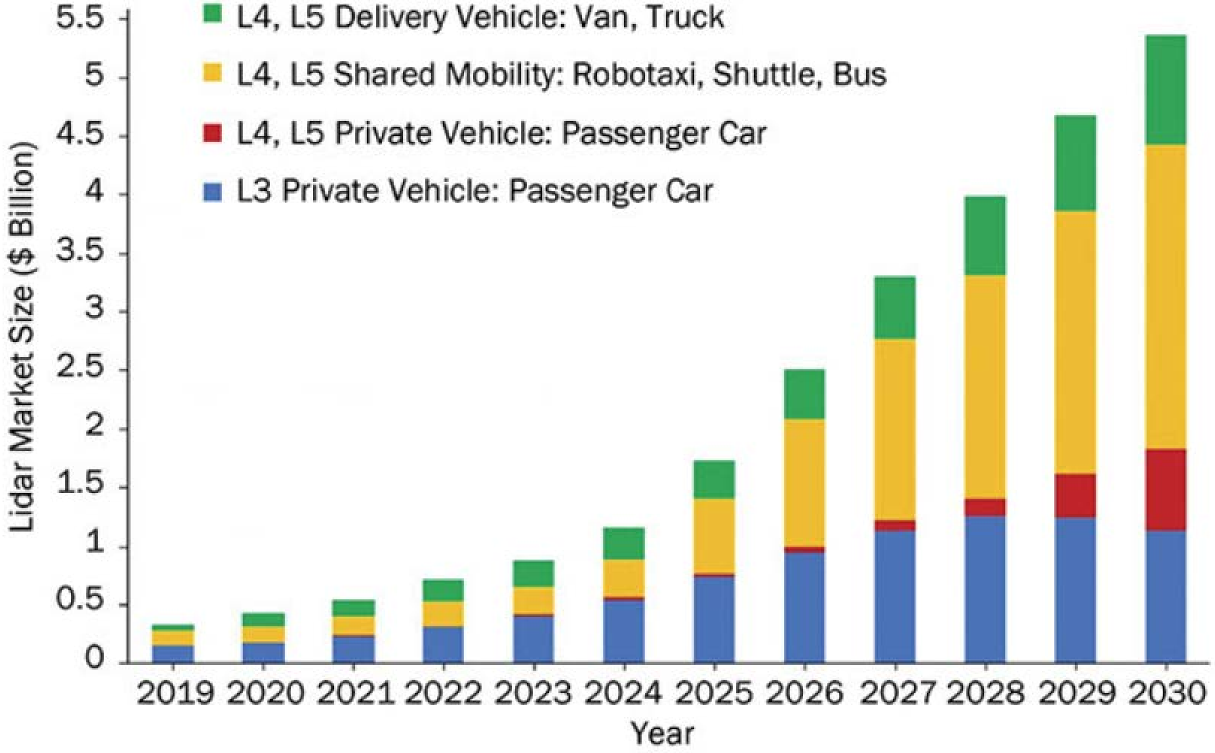
Source: IDTechEx

Active Players

Non-Exhaustive Lists

R&D Players

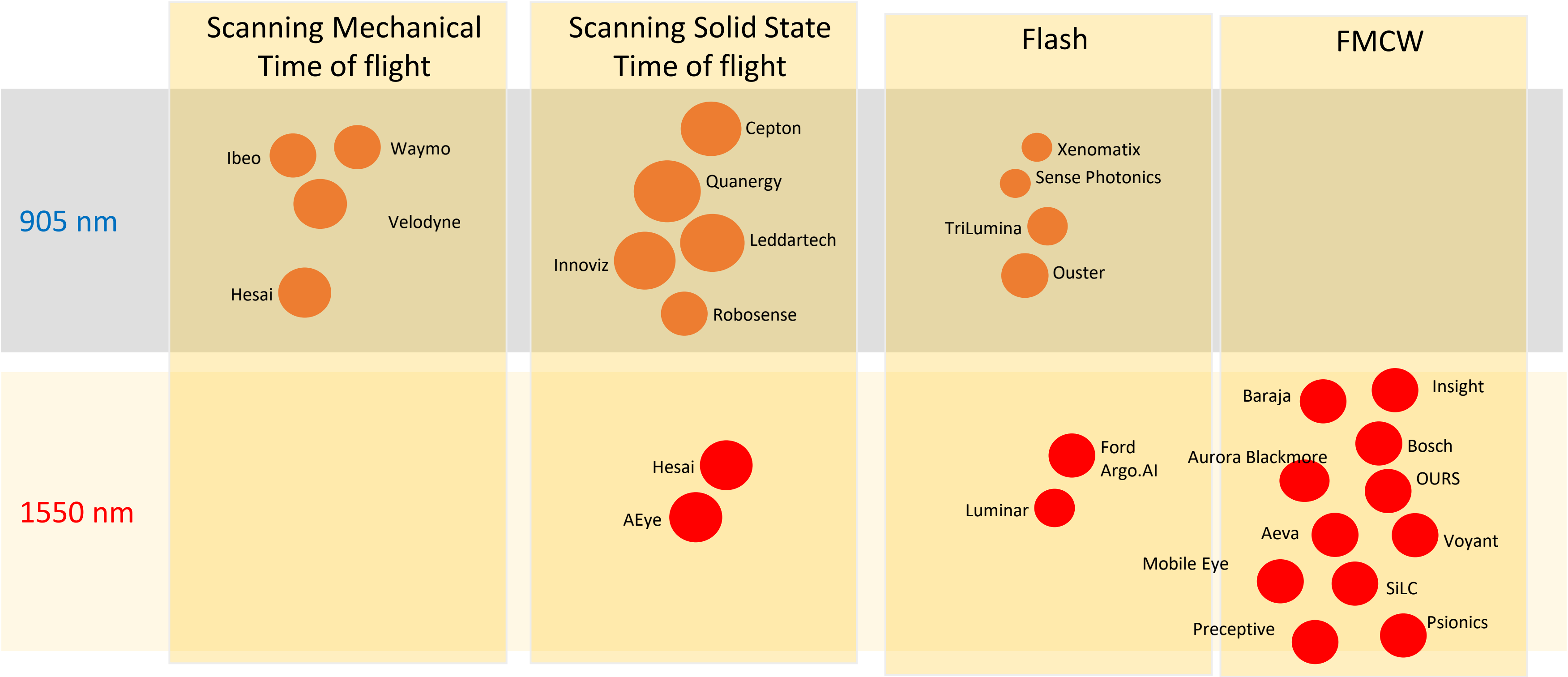
LiDAR Market Growth



Source: photonics.com courtesy ID TechEx

LiDAR Map: Companies, Technology, Wavelength

Non-exhaustive list



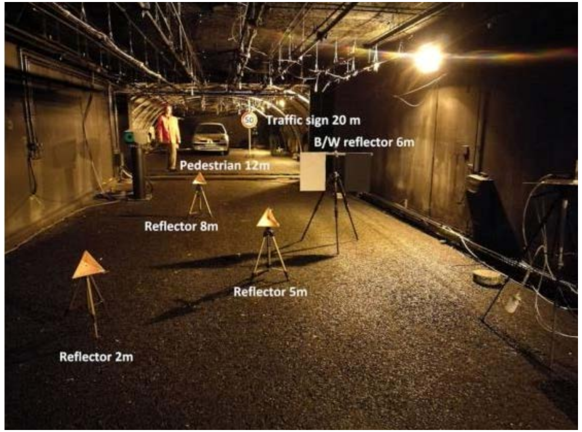
More than 100 companies are currently working on automotive LiDAR **E&OE**

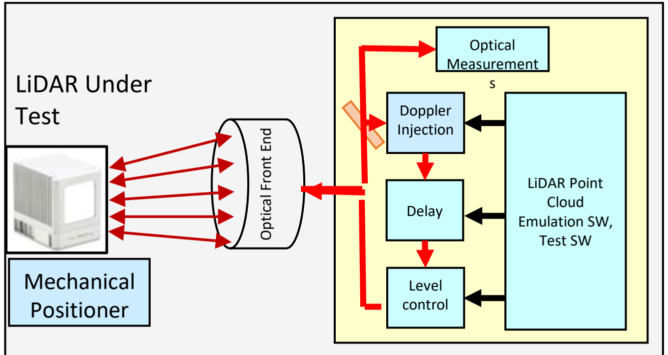
Source: Reuters, Yole Research, Inetrnet

LiDAR Target Emulation and Measurements

Challenges

- Current test systems are manual, using physical retro reflector targets causing inaccuracies & repeatability issues.
- These are not scalable and require a large physical space.
- While current LiDAR are largely ToF-based, many new LiDAR technologies are being develop. Flexible instrumentation solutions are needed to cover the multiple emerging configurations and modulation
- Creation of point cloud scenarios necessary to emulate real-word scenarios





LiDAR test system concept

Trends

- FMCW LiDAR is becoming more popular thanks to advances in PIC
- VCSEL/SPAD combinations picking up speed but major challenges lie ahead
- ADAS applications are expected to continue to be a minor use of LiDARS over the next five years
- Non-linear scanning protocols are being experimented
- Sensor fusion is getting more attention both from design as well as test perspective
- Trucks and public transports are likely to be the first ones adopting autonomy and using LiDARS
- Level 4 & 5 Autonomous vehicles are expected to have LiDARS in one form or another.

Challenges & What Next

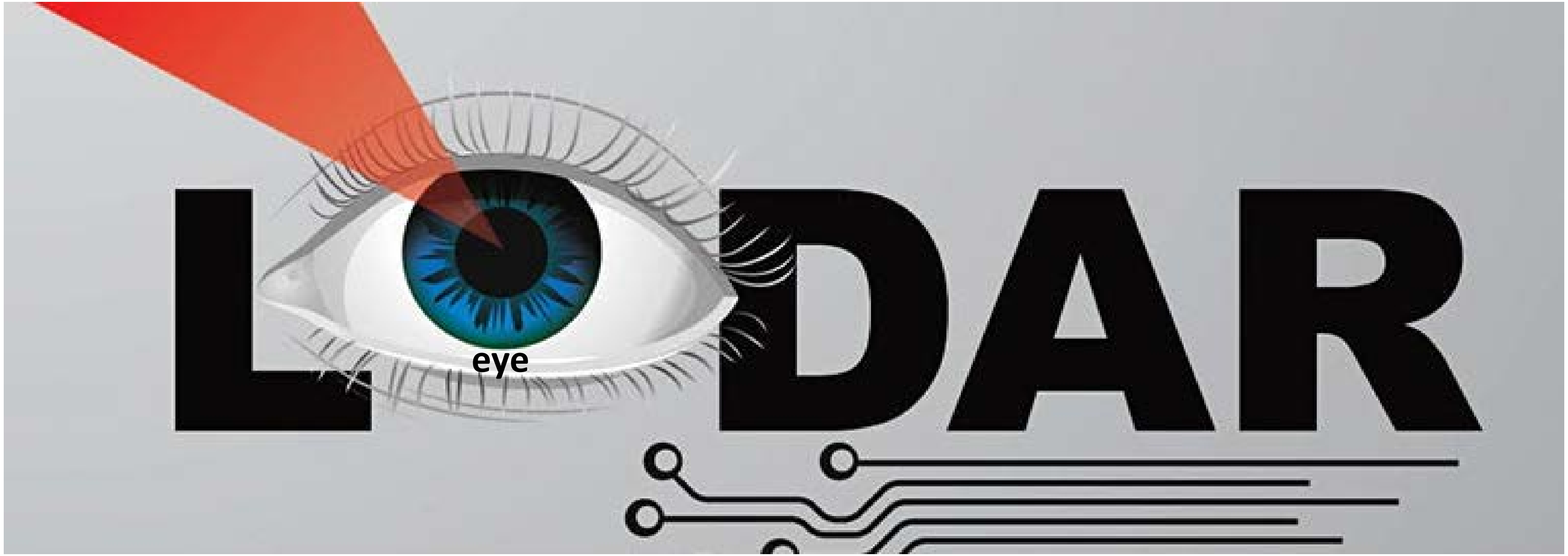
- Consolidation of vendors
- How many types of LiDAR will make to the end: FMCW, ToF, Flash?
- Standards
- Integration efforts need to speedup. LoC, Programmable PIC, AI…
- How far can VCSEL/SPAD Multi beam Flash can go?
- Scalable Test/Emulation systems will be needed
- Chip-scale FMCW lidar is emerging as a promising technique for long-range, high-resolution performance at industry cost targets
- Cost needs to be below $250 in volume for broad adoption for ADAS.

Latest Application of LiDAR: iPhone 12

- LiDAR functionality in iPad Pro earlier this year
- A chip LiDAR was just announced in iPhone 12 Pro
- Uses VCSEL/SPAD may be around 850 nm
- Impressive Applications:
  - Delivers stunning depth-sensing capabilities, supporting new photo and video apps.
  - improved augmented reality
  - the ability to scan and measure rooms, humans...
  - Race for iPhone Apps using LiDAR is on:
    - Matterport, Sitescape, Occipital....

Source: spar3d.com

Q & A



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