Solid State Automotive LiDAR: Physics Principles, Design Challenges, and New Developments

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- Light Sources & Beam Steering
- Solid State (Flash) LiDAR
LiDAR Concepts
Basic Layout of Time of Flight LiDAR

Measure the time of flight $\Delta t$

Distance $d = \Delta t \cdot c/2$
FMCW LiDAR: Heterodyne Mixing

Legend:

- $f_{LO}$ – Local oscillator frequency
- $f_{PO}$ – Power oscillator frequency of transmitted light
- $f_a$ – Frequency of returned light; $\Delta f$ due to distance and Doppler’s effect
- $f_{offset}$ – Offset frequency added by the frequency shifter, ~10 – 100 MHz

These are instantaneous values.
Example of Frequency Modulation: Double Linear Ramp

T ~ 10’s μs – 1 ms, B ~ 100’s MHz – 10’s GHz
Frequency Shift in FMCW LiDAR

\[ d = \frac{c(f_{B1} + f_{B2})T}{8B} \]
\[ v_r = \frac{c(f_{B2} - f_{B1})}{4f_0} \]
\[ \delta d = \frac{c}{2B} \]
\[ \delta v_r = \frac{c}{f_0T} \]
Heterodyne Optical Mixing

\[ |E_{tot}|^2 = |E_a + E_{LO}|^2 = |A_a \cos(2\pi f_a t + \varphi_a) + A_{LO} \cos(2\pi f_{LO} + \varphi_{LO})|^2 \]

\[ |E_{tot}|^2 = |E_a|^2 + |E_{LO}|^2 + A_a A_{LO} \cos[2\pi(f_a - f_{LO})t + (\varphi_a - \varphi_{LO})] \]

\[ P_{\text{sig}} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos[2\pi(f_a - f_{LO})t + (\varphi_a - \varphi_{LO})] \]

\[ i_{\text{sig}} = \eta \frac{P_{\text{sig}}}{hf} = i_a + i_{LO} + 2\sqrt{i_a i_{LO}} \cos[2\pi(f_a - f_{LO})t + (\varphi_a - \varphi_{LO})] \]

**amplification!** measure this

\[ \Delta f = (f_a - f_{LO}) - f_{\text{offset}} \]

\[ \Delta f \text{ gives } d \text{ and } v_r \]
## Comparison Between ToF & FMCW Concepts

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<th>Pros</th>
<th>FMCW</th>
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<td>Easy optical layout</td>
<td>Optical amplification of the returned signal</td>
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<td>Easy distance calculation</td>
<td>Photon shot noise detection possible</td>
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<td>Any wavelength of light can be used</td>
<td>Immunity to background and interference</td>
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<td>Large detection bandwidth → increased noise</td>
<td>Gives both distance and radial velocity of the target</td>
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<td>Weak returned signal</td>
<td>Complex optical layout</td>
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<td>Susceptible to background and interference</td>
<td>Expensive tunable laser with a long coherence length needed</td>
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| Cons                                                                 |                                                              |
|----------------------------------------------------------------------|                                                              |
| Susceptible to background and interference                           | Complex distance and velocity calculation                     |

- **ToF**
  - Easy optical layout
  - Easy distance calculation
  - Any wavelength of light can be used
  - Large detection bandwidth → increased noise
  - Weak returned signal
  - Susceptible to background and interference

- **FMCW**
  - Optical amplification of the returned signal
  - Photon shot noise detection possible
  - Immunity to background and interference
  - Gives both distance and radial velocity of the target
  - Complex optical layout
  - Expensive tunable laser with a long coherence length needed
  - Complex distance and velocity calculation
Light Sources & Beam Steering
## Light Sources

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<th>FMCW</th>
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<td><strong>Short-duration pulses:</strong> ~ few ns</td>
<td><strong>Tunable output frequency</strong></td>
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<td><strong>High peak power:</strong> ~ 100 W</td>
<td><strong>Coherence length</strong> $L &gt; 2d_{max}$</td>
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<td><strong>Repetition period:</strong> ~ ms - μs</td>
<td><strong>Stable phase</strong></td>
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Wavelength: NIR, e.g., 905 nm, 1550 nm

some light source offerings by Hamamatsu
905 or 1550?

Solar background at 905 nm is higher than at 1550 nm

\[ P_B @ 905 \text{ nm} > P_B @ 1550 \text{ nm} \]
905 or 1550?

H$_2$O absorption @ 1550 nm > (100 × ) @ 905 nm

Reference: “Comparison of 905 nm and 1550 nm semiconductor laser rangefinders’ performance deterioration due to adverse environmental conditions,” Wojtanowski et al. 2014
905 or 1550?

905 nm

+ Better transmission in atmosphere
+ Silicon-based photodetector

1550 nm

+ Best eye safety
+ Lower background
+ Coherence length $L \propto \frac{\lambda^2}{B}$
- Requires IR (non-silicon) photodetectors
Mechanical Beam Steering: Rotating Platform

Each laser is matched with its own detector

Horizontal sweep

Vertical sweep

Scan direction
Rotating Galvo mirrors are another example of a *mechanical* beam steering.
Beam Steering: Optical Phase Array

Amplitude and phase of the light emitted by each pixel (emitter) can be controlled electronically.

Optical phased array is an example of a *solid state* or "no moving parts" beam steering.
OPA Emitter and Receiver

- emitted beam
- detected beam
- Light feed for emission
- Local oscillator light for optical amplification
- Control unit
- Current output
LiDAR Based on OPA Emitter and Receiver

First prototype of a FMCW LiDAR that uses optical phased arrays for beam steering and light detection.

The figure is from “Coherent solid-state LIDAR with silicon photonic optical phased arrays” by Poulton et al. 2017

Fig. 3. (a) Schematic of the solid-state LIDAR system with transmitting and receiving optical phased arrays. (b) Chiplet containing LIDAR system on top of a dime. (c) Optical micrograph of the device. (d) Packaged system with epoxied fiber.
Beam Steering: Flash and Structured Light

- Wider the angle, smaller the surface brightness
- For a Gaussian beam, the surface brightness is not uniform
- Lateral resolution limited by the 2D sensor

- Beams have the same intensity
- Lateral resolution limited by the angular separation between the beams

Laser and pulse expander

Divergent pulse of light

Array of lasers such as VCSELs
Solid State (Flash) LiDAR
The emission FOV, $\theta_e$, should be matched with the detection FOV, $\theta_d$. 
Focal Plane Distance Measurement

A single “pixel” in the 2D detector determines distance to a single element of the scene.
Distance Resolution

\[ \delta d = \frac{c}{2B} \]  

(distance resolution)

\[ B \sim \frac{1}{T} \quad T \text{ – pulse duration} \]

For \( T = 5 \text{ ns} \), \( \delta d \approx 0.75 \text{ m} \rightarrow B \approx 200 \text{ MHz} \)

Better distance resolution requires pulses of even shorter duration. The limitation is in the laser technology (parasitic inductance).
Distance Uncertainty

\[ \sigma_d \sim \frac{(\delta d)^2}{S/N} = \frac{c^2}{4B^2 S/N} \] (distance uncertainty)

1. The larger the \( \frac{S}{N} \), the smaller the uncertainty, all else being the same
2. Photodetector and electronic time jitters also contribute to the uncertainty.
Photon Budget: Single Photodetector

\[ P(d) = P_0 \rho \frac{A_0}{\pi d^2} \eta_0 e^{-2\gamma d} \]

Assumptions:
- Lambertian reflection
- Laser spot smaller than the target
- Normal incidence
- \( \gamma \) is constant

- \( P(d) \) – Peak power received
- \( P_0 \) – Peak power transmitted
- \( \rho \) – Target reflectivity
- \( A_0 \) – Aperture area of the receiver
- \( \eta_0 \) – Receiving optics transmission
- \( \gamma \) – Atmospheric extinction coefficient
Photon Budget: Single Photodetector

\[ P(d) = P_0 \rho \frac{A_0}{\pi d^2} \eta_0 e^{-2\gamma d} \]

Example: \( P_0 = 100 \) W, \( \rho = 0.1 \), \( A_0 = 3.14 \times 10^{-4} \) m², \( \eta_0 = 0.5 \), \( \gamma = 0.5 \) km⁻¹

for \( d = 100 \) m, \( P = 45 \) nW

1. Atmospheric extinction \( \gamma \) depends on weather conditions and wavelength. Its value can range from about \( 4 \) km⁻¹ to about \( 0.1 \) km⁻¹ at 905 nm.

2. For a square 5-ns pulse (\( \lambda = 905 \) nm), the number of emitted photons is \( \sim 2.3 \times 10^{12} \) and the number of received is \( \sim 1 \times 10^3 \).

Reference: “Comparison of 905 nm and 1550 nm semiconductor laser rangefinders’ performance deterioration due to adverse environmental conditions,” Wojtanowski et al. 2014
Photon Budget: Flash

There is a tradeoff between spatial resolution and $\frac{S}{N}$.
Photon Budget: Flash

\[
P(d) = P_0 \rho \frac{\theta_p^2}{\Theta^2} \frac{A_0}{\pi d^2} \eta_0 e^{-2d\gamma} \quad \text{(received peak power per pixel)}
\]

\(\theta_p\) – angular subtense (field of view) of a pixel

\(\Theta\) – angular field of view of the pulse projector (pulse divergence)

Note that \(\theta_p \ll \Theta\), so if the pulse peak power is the same, the amount of light received by a single pixel is proportional to \(\frac{\theta_p^2}{\Theta^2}\) for a given distance \(d\).

Photodetection (Single Element)

- Active area of the photodetector, focal length of the lens, and placement of the optical bandpass filter determine the photodetector’s field of view.
- Avalanche photodiode or silicon photomultiplier are commonly used photodetectors.
Noise in Transimpedance Amplifier

\[ C_T = C_t + C_f + C_{op} + C_s \quad \text{(total capacitance)} \]

\[ i_T = \sqrt{i_n^2 + i_j^2 + i_d^2 + i_{ph}^2} \]

\[ v_n = e_n \left[ \left(1 + \frac{R_F}{R}\right)^2 + \frac{4\pi^2}{3} (\Delta f)^2 C_T^2 R_f^2 \right]^{1/2} + R_f i_T^2 + 4kT R_f \]

All else being equal, noise increases with terminal capacitance of the photodetector.
Bandwidth and Stability of Transimpedance Amplifier

\[ v_{\text{out}} = I \frac{-R_f}{1 + \frac{1}{A_{ol}}} \]

\[ \beta(j\omega) = \frac{1}{1 + j\omega R_F C_i} \]

\[ \frac{1}{\beta(j\omega)} = 1 + j\omega R_F C_i \]

where \( C_i = C_j + C_{op} \)

\( A_{ol} \) – Open loop gain of TIA

Gain peaking and oscillations occur around this frequency

\[ f_{GBWP} \] – Unity gain bandwidth of the op-amp

Simplified equivalent circuit of a photodetector connected to an uncompensated TIA
Bandwidth and Stability of Transimpedance Amplifier

Simplified equivalent circuit of a compensated photodiode connected to an uncompensated TIA

\[
\beta(j\omega) = \frac{1 + j\omega R_F C_F}{1 + j\omega R_F (C_i + C_F)}
\]

\[
f_F = \frac{1}{2\pi R_F (C_i + C_F)}
\]

\[
f_i = \frac{1}{2\pi R_F C_F}
\]

\[
C_F = \frac{1}{4\pi R_F f_{GBWP}} \left( 1 + \sqrt{1 + 8\pi R_F C_i f_{GBWP}} \right)
\]

(Optimal value of the compensating capacitor)
Importance of Noise and Bandwidth

High bandwidth → higher noise but high fidelity

Low bandwidth → lower noise and lower fidelity
Importance of Excess Noise (F)

Fixed trigger level gives different round-trip-times, $\Delta t_1 \neq \Delta t_2$ ✗

Constant-fraction trigger gives the same round-trip-times, $\Delta t_1 = \Delta t_2$ ✓
Takeaway

Analog photodetection in ToF LiDAR, especially in flash LiDAR, is very challenging.

Is there anything else we can do?

What about a statistical measurement using SPAD?
Single-Photon Avalanche Photodiode (SPAD)

$$R_Q \gg R_l$$

**Quench resistor**

**Load resistor**

$I_{SPAD}$

$V_{BIAS} / R_Q$

$V_{BD}$

$V_{BIAS}$

$V_{SPAD}$

$R_Q$ must be large enough to ensure quenching
Measuring Distance with a Single SPAD

\[ \Delta t = \frac{2d}{c} \]
Multiple pulse illumination provides distance information to the target. The information comes from a histogram of trigger times.
SPAD Arrays

Photodetector array

Micro-bumps

ASIC

(application-specific integrated circuit)
Detection Techniques with a SPAD Array

Time gating:

Only the events in the pre-defined time window are counted. The choice of the time window depends on the expected knowledge of the target distance.
Detection Techniques with a SPAD Array

Temporal and spatial correlation:

Event not counted: temporal correlation but **no spatial correlation**.
Detection Techniques with a SPAD Array

Temporal and spatial correlation:

Event not counted: spatial correlation but no temporal correlation.
Detection Techniques with a SPAD Array

Temporal and spatial correlation:

Event counted: spatial correlation but no temporal correlation.
SPAD Pixel for Correlated Detection
SPAD Pixel for Correlated Detection

- Signal photon
- Background photon

Pulse coincidence detection
1. This technique can be used both in a scanning and flash LiDAR.
2. In a scanning LiDAR, an OPA array is well-suited for beam steering.
3. The greatest advantage is a reduced sensitivity to the background light.
4. Additional advantages: less affected by gain variations, sensitivity in IR (using non-silicon structures), compatible with CMOS-based ASICs.
5. Challenges: SPAD arrays can exhibit crosstalk and high dark count rates.
Hamamatsu Assists LiDAR Companies

- Photodetectors (Silicon or InGaAs, PIN, APD, SiPM, SPAD and more) for all LiDAR concepts
- Light sources (PLDs or VCSELs) for selected LiDAR concepts
- Custom integrated optical assemblies, from front-end electronics to complete ASICs
- Support automotive grade qualifications (AEC, ISO and more)
- Full customization of photodetectors, light sources, and optical assemblies

Because of our wide offering of optical components, Hamamatsu is unbiased when recommending the correct detector and/or light source to each unique LiDAR concept (customer) in the market.
Photodetectors for LiDARS (850 nm – 940 nm)

Si PIN photodiode
High Photosensitivity; Internal Gain = 1

Si APD
High Photosensitivity; Internal Gain ~ 100

SPPC (or SPAD)
Low Photosensitivity; Internal Gain ~ 10^5 to 10^6

MPPC (or SiPM)
Low Photosensitivity; Internal Gain ~ 10^5 to 10^6
Photodetectors for LiDARS (1550 nm)

**InGaAs PIN PD**
- High Photosensitivity;
- Internal Gain – 1

**InGaAs APD**
- High Photosensitivity;
- Internal Gain ~10-20
Closing Remarks

1. Two distinct LiDAR systems, ToF and FMCW, are actively researched
2. Each system presents a unique set of engineering challenges
3. Beam steering and photodetection are the two most outstanding challenges
4. Flash LiDAR together with a SPAD-based statistical detection is a new avenue of research
Thank you

Thank you for listening

Contact information:
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