TECHNICAL NOTE

An Explanation of LiDAR Components and Their Functions in a LiDAR Sensor for ADAS and Autonomous Vehicles

An Overview

This Technical Note aims to explain the various components of a LiDAR sensor, working fundamentals and their functions within the LiDAR sensor. The document starts with an explanation of the processes that take place in a LiDAR and how distance and object velocity are calculated using time and distance and the Doppler shift formula respectively. It then details the various subsystems in a LiDAR with an emphasis on LiDARs for autonomous vehicles. The focus of this Technical Note is time-of-flight (ToF) LiDARs, and continuous-wave LiDARs have been referenced where applicable.

How Does a LiDAR Work?

A time-of-flight LiDAR works by emitting pulses from a light source and calculating the time it takes for these pulses to return. A continuous-wave LiDAR works by emitting a continuous flux of photons, varying either the frequency or the phase of the light in a known fashion, and using the difference between the emitted light and returned light to measure distance. Velocity measurement for the object is calculated by measuring the Doppler shift from the received signal.

- **Distance to object (in a time-of-flight LiDAR) calculation:**

  $R = c * (\Delta t/2)$

  - R = Object distance (m)

    Note: *The maximum distance a LiDAR can detect an object is the LiDAR range.*

- c = Speed of light (m/s)
- Δt = Time of flight (s)

  ***Note:** Time of flight is the time it takes for the laser pulse to return to the sensor and the time it takes for the pulse to reach the object.*

- **Doppler shift equation:**

$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_0}$$

  - v = Velocity of the object (m/s)
  - c = Speed of light (m/s)
  - $\Delta\lambda$ = Change in wavelength (m)
  - λ_0 = Reference wavelength (m)

Time-of-flight LiDAR consists of a transmitter unit, receiver unit, optics and beam steering unit as well as a processing unit. These subsystems combine to enable the LiDAR to create a point cloud of its environment, which is then used by the perception system in an autonomous vehicle to detect, classify and track objects. The LiDAR operation is described below and has been simplified to enable readers of all levels to understand the functioning:

1. Laser driver fires the laser beam.
2. Timing clock is started.
3. Beam passes through the transmitter optical system.
4. Beam is reflected by the object.
5. Reflected beam passes through the receiver optical system.
6. Reflected beam is incident on photodetectors and converted to electrical signal.
7. Timing clock is stopped.
8. Analog-to-digital converters (ADC) convert photodetector analog current signal to a digital voltage signal.
9. Digitized waveform is processed to form a point cloud.

An Overview of Transmission Subsystems in LiDARs

Time-of-flight LiDARs for advanced driver assistance systems (ADAS) and autonomous vehicles typically use lasers emitting short pulses of light and most commonly operate at 905 nm and 1550 nm wavelengths. ADAS and autonomous vehicle requirements for high range mean that laser power needs to be maximized. However, laser power is limited by maximum permissible exposure limits for eye safety as per IEC 60825-1 standards. A by-product of high-energy pulses (of the order of nanoseconds) is heat generation. Heat in the laser creates multiple complications for LiDARs, such as:

- Reduced power output
- Change in emitted wavelength
- Electromagnetic interference causing noise
- Reduced signal-to-noise ratio
- Increased complexity in signal processing

Lasers can be characterized by their mode of operation (pulsed lasers or continuous-wave lasers) and also by the medium used to generate the laser beam. The main types of lasers are:

- **Gas lasers:** Electric current is sent through a gaseous medium to create the laser beam and utilizes population inversion (more atoms are in an excited state than unexcited) for laser action.
- **Solid-state lasers:** Use solid materials such as ceramics, crystals or glasses doped with rare-earth elements (Nd, Cr, Er) for optical gain laser beam. These lasers are popular in LiDARs.
- **Fiber lasers:** Use optical fibers made of silica glass mixed with a rare-earth element as their gain medium.
- **Liquid (or dye) lasers:** Use an organic dye in liquid form as their gain medium and are also known as tunable lasers since their wavelength can be controlled while in operation.
- **Semiconductor lasers:** Use an alloy of aluminum and gallium arsenide as p-n junction material which allows the laser to achieve resonance and the gain required for laser action. Semiconductor lasers can be further sub-categorized into edge-emitting lasers (EEL) and vertical-cavity surface-emitting lasers (VCSEL) depending on laser beam emission direction.

The second critical component within the transmission subsystem is the laser diode driver board on which the laser is attached. The driver board is responsible for charging the capacitors and firing this accumulated charge to the laser to create the pulse, all timed with a central synchronization unit. LeddarTech's LeddarEngine™ is a system-on-chip component that synchronizes this firing and performs signal acquisition and pre-processing. The laser diode driver board controls current to the diode, which often acts as the energy source and controls the pulse duration.

LeddarTech, through its Leddar™ Ecosystem and LiDAR XLRator™ platform, has partnered with industry-leading component providers to provide expertise in emitter technology and preferred access to components for LiDARs. The LiDAR XLRator is a LiDAR development platform based on the LeddarEngine (timing synchronization and signal acquisition and processing unit) for LiDAR developers, Tier-1 manufacturers and system integrators. The following section details the second subsystem in a LiDAR, the receiver subsystem.

An Overview of Receiver Subsystem in LiDARs

Receiver subsystems primarily consist of the detector and the related optics. Detectors convert light energy (photons) into electrical current. This current is used by readout subsystem for signal processing and point cloud formation.

Detector technologies used in LiDARs for advanced driver assistance systems (ADAS) and autonomous vehicles are avalanche photodiodes (APDs), single-photon avalanche diodes (SPADs) and silicon photomultipliers (SiPM).

While a SPAD detects photons individually, a SiPM is connected in parallel to SPADs and detects the total number of photons detected by all SPADs. Due to increased sensitivity, SPADs are a popular choice for photon detection. The higher the photon detector sensitivity, the higher the signal-to-noise ratio and the LiDAR range. A detector's sensitivity to photon detection combined with accurate timing electronics determines the distance accuracy to an object.

Avalanche photodiodes (APDs) can be operated in linear mode or Geiger mode. In the linear mode, the APD is a four-layer device that operates in reverse bias, below its breakdown voltage. Its outermost layers are heavily doped and are less resistive. When a photon is incident on the device, it causes the generation of an electron and hole pair in the middle intrinsic layer of the APD. Electrons generated in the intrinsic layer of the APD experience high electric field and acceleration that cause these free electrons to collide with atoms in the p layer, thereby generating more electron and hole pairs. This process continues, resulting in a multiplication of electrons (and holes) being generated. This is called impact ionization–when one electron collides with an atom and causes the generation of more electrons. Impact ionization is an example of the detector intrinsic gain mechanism.

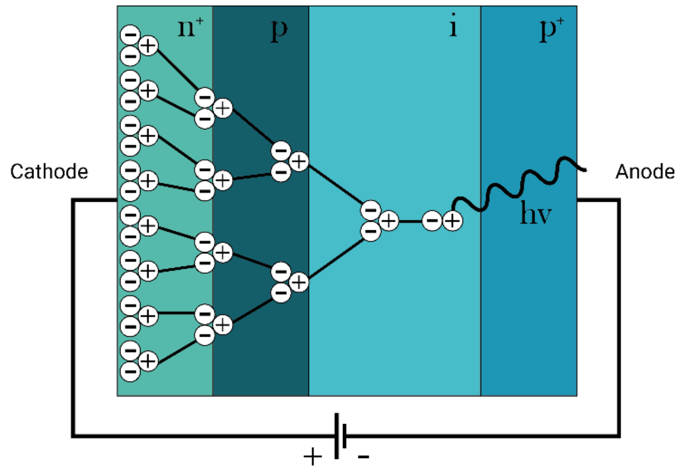

Figure 1 – Impact ionization process

Single-photon avalanche diodes (SPADs) are APDs working in Geiger mode. They operate above the breakdown voltage and are sensitive to single photons that, when incident on the device, trigger a self-sustaining avalanche and rise in current. The self-sustaining avalanche is quenched by lowering the electric field across the junction to below breakdown voltage. SPADs have a downtime during its operation when it is unable to detect an incident photon. This occurs when the electric field must be re-applied across the diode to return it to its original state.

LeddarTech, through its Leddar Ecosystem and LiDAR XLRator platform, has partnered with industry-leading component providers to provide expertise in receiver technology and preferred access to components for LiDARs. The LiDAR XLRator is a LiDAR development platform based on the LeddarEngine (timing synchronization and signal acquisition and processing unit) for LiDAR developers, Tier-1 manufacturers and system integrators. The following section details the third subsystem in a LiDAR, the processing subsystem, of which LeddarEngine is a critical component.

An Overview of the Processing Subsystem in a LiDAR

Data received from the detector is processed to develop 2D images, 3D point clouds, object velocity or other information. The readout subsystem in a LiDAR for ADAS and autonomous driving typically includes a CPU, system on chip (SoC) and field-programmable gate array (FPGA). The FPGA may or may not be needed depending on the application and usually executes time-sensitive acquisition tasks.

Together, these components are responsible for:

- Signal processing
- Noise filtering
- Waveform acquisition
- Digital sampling
- Developing point cloud
- Time-of-flight calculation
- Doppler shift calculation

Figure 2 – LeddarEngine timing synchronization and signal acquisition and processing unit

Some challenges within the processing subsystem relate to sampling rate limitations (affecting LiDAR resolution), signal crosstalk, saturation and noise. The CPU/SoC executes algorithms to address these challenges. Another challenge that processing subsystems face is the computational power requirements; large amounts of data must be processed to develop an accurate point cloud of the environment. LeddarTech's LeddarEngine is an SoC with signal acquisition and processing functionalities. Comprised of the LeddarCore™ SoC and LeddarSP™ signal processing, the LeddarEngine supports multiple LiDAR architectures and integrates proprietary signal acquisition and processing algorithms that address challenges of:

- Signal crosstalk
- Saturation
- Noise
- Sampling rate limitations

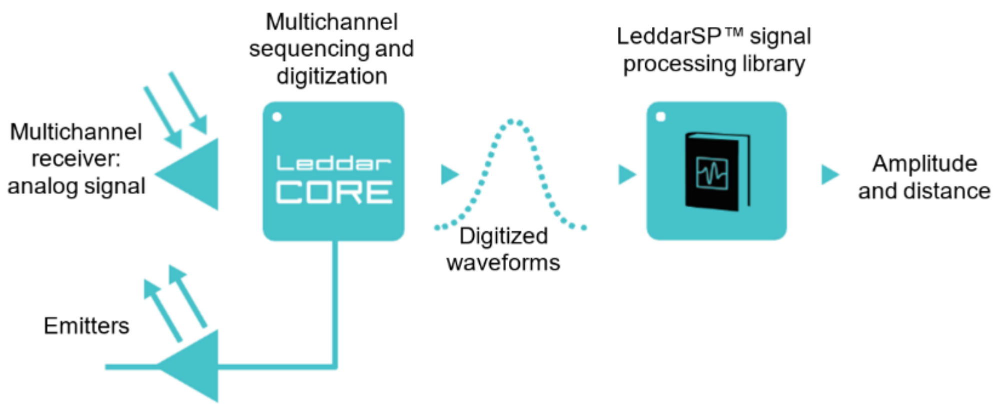

Figure 3 – Signal acquisition and processing process flow diagram

These proprietary algorithms and techniques of LeddarEngine enable automotive-grade distance accuracy and precision. These are as low as 5 cm and 1 cm respectively for ranges up to 300 m. Specifications of LeddarEngine are available at LeddarEngine Specs and Performance Video.

An Overview of Beam Steering and Optical Units

Time-of-flight LiDARs, except flash LiDARs, emit laser pulses across the LiDAR's field of view at various angles. This laser beam redirection to a specific angle is called beam steering. Traditionally, beam steering has been achieved through an electro-mechanical system fitted on the emitter unit, while micro-electromechanical system (MEMS) mirrors have gained popularity recently. When current flows through a conductor placed in a magnetic field, the conductor experiences a force acting upon it. MEMS mirrors utilize this phenomenon to electronically control mirror actuation and achieve beam steering.

However, LiDARs for ADAS and autonomous vehicles must be solid-state, i.e., they must not have any moving parts. The preferred method to achieve beam steering is through liquid crystals and light polarization. While there are multiple ways of achieving a change in the direction of the light using liquid crystals and polarized light, such as through twisted nematic crystals, LeddarTech achieves this by using two liquid crystal-based components to accomplish two different tasks. The first is a layer of dynamically controllable liquid crystal cells that control the direction of circular polarization. The second component is a layer of passive liquid crystals, where the orientation of the liquid crystal molecules is fixed in a pattern. This is exemplified in Figure 4 below.

Passing through the first layer, light is circularly polarized and is deflected to one angle or its opposite angle, depending on that direction of polarization. The second liquid crystal, also referred to as a polarization grating, performs this deflection. To change the direction of circular polarization, liquid crystal molecules are oriented according to the desired direction at any given moment by applying an electric voltage across the cell.

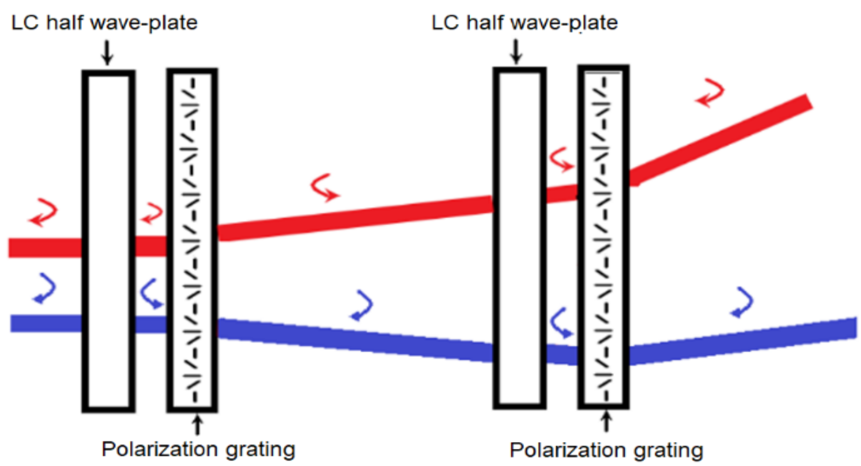

Figure 4 – Two layers of liquid crystals used for beam steering

Beam steering enhances LiDAR performance by segmenting the field of view into smaller sections and redirecting the emitter LiDAR and/or receiver detector towards that section. LeddarTech's beam steering solution, called LeddarSteer™, actively manages the temperature in the beam steering unit through a heat control loop. Additional benefits of digital beam steering are:

- Enhanced signal-to-noise ratio and LiDAR range
- Reduced size, cost and complexity of the LiDAR components
- Smaller optical system required in the LiDAR
- Solid-state technology with no moving parts, for higher MTBF (mean time between failures)
- Extended FoV elevation and azimuth; up to 120° per axis

Ecosystem Partnerships: Adding Significant Value in LiDAR Development

Developing automotive-grade LiDAR sensing solutions for ADAS and autonomous driving is a complex, resource-intensive undertaking that requires combining a variety of technical expertise. With this reality in mind, LeddarTech has developed the Leddar Ecosystem by bringing together a select group of world-class partners, LiDAR component suppliers and collaborators to support and accelerate the development efforts of Tier 1s, Tier 2s and LiDAR manufacturers. Figure 5 presents an overview of its participants.

Figure 5 – Leddar Ecosystem partners

Videos, pictures and Spec Sheet on digital beam steering and more insights on its role in developing autonomous solutions are available at leddartech.com/solutions/leddarsteer-digital-beam-steering/.

LeddarTech®
CANADA – USA – AUSTRIA – FRANCE – GERMANY – ITALY – ISRAEL – HONG KONG – CHINA

Head Office
4535, boulevard Wilfrid-Hamel, Suite 240
Québec (Québec) G1P 2J7, Canada
leddartech.com

Phone: + 1-418-653-9000
Toll-free: 1-855-865-9900