1550nm Triple Junction Laser Diode Outshines 905nm in Automotive LiDAR

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Introduction

LiDAR (Laser Imaging, Detection and Ranging) is one of the crucial systems to turn autonomous vehicles into reality in the future. It is expected to detect and recognize objects such as cars and pedestrians during day and night either on a city street or a high-speed freeway. The most stringent requirement for a successful LiDAR on a vehicle is its capability to successfully detect over 200 meters of range on a freeway at a typical driving speed of 75 mph. Only when a LiDAR can detect at such a long range under various weather conditions, the vehicle is then able to react and maneuver according to any potential obstacle without endangering other vehicles and people around (Fig.1).

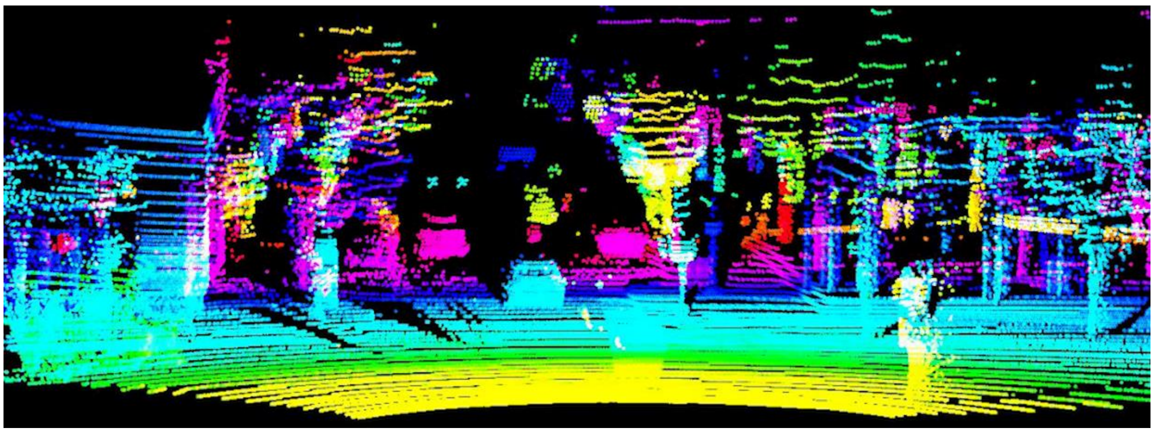

Fig.1 LiDAR point cloud

Unfortunately, most of the LiDAR systems available in the marketplace today require many laser emitters and a complex system design in order to detect targets over 200 meters, as a single laser emitter can hardly reach over 100 meters based on short wavelength lasers such as 905nm. In fact, the motivation behind the 905nm adoption has not been based on its performance, but rather on its commercial availability and lower cost. The major reason behind such a poor performance is its potential detrimental effect to human eyes based on the international eye safety standards IEC 60825-1 [1], limiting its allowable output energy. When increasing the 905nm laser energy in order to extend the LiDAR detection range, the unsafe photons can travel through human eye's lens and cornea, reach the retina and cause permanent damage.

On the contrary, it has been well noted to the LiDAR community that longer wavelengths such as 1550nm are the best choice for LiDAR light source, as they are in the range of eye safe spectrum >1300nm. Wavelengths above 1300nm are considered intrinsically eye-safe because light at these wavelengths are largely absorbed by the lens and cornea and dissipate harmlessly as heat without causing damage to the eye [1]. The reason few LiDARs based on 1550nm are under development or deployed is mainly due to the lack of high-power laser diodes at such long wavelength regime to deliver enough photons. Some LiDAR systems use fiber lasers at 1550nm to achieve long range performance, but they are commercially unfeasible due to high cost and complexity.

Here we demonstrate a newly developed high-power semiconductor laser diodes with triple junction at eye-safe 1550nm, shown in Fig.2. It can generate 50 times more photons per second and are capable of reaching 3 times longer the distance than their 905nm counterpart in one-to-one comparison. This breakthrough in 1550nm diode lasers allows the LiDAR industry to look beyond the 100-meters of 905nm with single emitter and opens up a whole array of long range detection applications.

Fig.2 1550nm triple junction laser diode and its near field image

The following analysis compares between 1550nm triple junction and 905nm on eye safety levels, amount of allowed photons, and photon budget over the detection range, target reflectivity, and atmospheric media. With receiver performance and assumed system parameters, the single-emitter LiDAR system is benchmarked based on signal-to-noise ratio SNR and probability of detection P_D showing that 1550nm easily outperforms 905nm over 200m.

Eye safe level of 905nm and 1550nm

In a LiDAR system using the TOF (Time of Flight) approach with a single emitter, collimated laser pulses are emitted out of the exit window, scanned across the targeted space within the field of view (FOV), and reflected by objects in front of the vehicle. The signal photons then are collected and converted into electrical signal via a receiver circuitry, and formed the point cloud data. The laser pulse energy allowed at the exit aperture is the first key parameter that can determine the available signal photons and the subsequent system performance.

According to the IEC 60825-1 eye safety standard for a Class 1 laser, the determination of the allowed photonic energy is based on parameters such as laser pulse width, repetition rate, aperture diameter, beam waist, collimated angle, etc. In our estimation, with a typical 905nm laser diode at 200μm aperture and capable of 90W peak optical power, the allowed maximal pulse energy is limited to 92 n-Joule over a 3 nsec pulse at 100 kHz repetition rate. This maximal energy is under the assumption that all photons enter into an 8mm-diameter pupil of a human eye. On the other hand, since 1550nm is intrinsically eye safe, in theory the allowed pulse energy can be as high as 29 μ–Joule over a 10 nsec pulse width at 400 kHz repetition rate, which is 300 times more than 905nm allowed.

In practice, the newly developed Triple Junction 1550nm laser diode with 350μm aperture capable of delivering 110W peak power over 10 nsec pulse width (Fig.3) would be able to generate an allowed energy of 1.1 μ–Joule, which is 12 times more than 905nm allowed. With four times more in the repetition rate and lower photonic energy, 1550nm pulses in a second would be able to generate 80 times more photons than 905nm.

Fig.3 LI data of the new Triple Junction 1550nm laser diode of 10 nsec pulse

Photon Budget by Distance, Target Reflectivity, and Atmospheric Loss

To assess the performance of a LiDAR system, we need to examine various parameters that impact the photon count prior to their collection by the receiver. Eq. (1) is used to calculate the overall signal photons along the light path out of a LiDAR with considerations of the distance R, target reflectivity ρ, atmospheric extinction coefficient γ, receiver aperture A, and receiver optical system efficiency η [2]

$$P_s(R) = P_o\, \rho\, \frac{A}{\pi R^2} \eta\, exp(-2\gamma R) \qquad \text{Eq.1}$$

It is noted that the signal gets drastically attenuated by the geometrical ratio of the receiver aperture to the flight distance squared. Signal photons also get absorbed, scattered, or reflected by the target surface, and the returned photons are collected by the photoreceiver aperture. The transmission ratio for the laser beam through the air is calculated by the term $exp(-2\gamma R)$ in Eq.1. The coefficient γ varies according to the wavelength of the radiation and meteorological visual range, which can be expressed by Eq.2 below [3]

$$\gamma(\lambda) \approx \frac{3.91}{R_v}\left(\frac{550}{\lambda}\right)^q \qquad \text{Eq.2}$$

where R_v is the visibility range and λ is the wavelength, q is calculated by $q = 0.585\ R_v^{1/3}$ when the visibility is less than 6 km, and 1.3 when over 6 km. We note that, by using this equation, the transmitted signal at 200m distance can be at high 98% when the visibility is over 20km, and that can be only 50% when the visibility is less than 2 km.

While investigating the photon budget as photon loss quickly built up due to the long range, low target reflectivity, and atmospheric media loss, a LiDAR may simply run out of useable photons. Table 1 exhibits the photon counts between 1550nm and 905nm after 200m distance, 10% target reflectivity, 20km of visibility, and an optical system with 85% transmission before the receiver. It is important to point out that 1550nm has 83 times more in available photons compared to 905nm, which is critical to turn a dark LiDAR over 200m range into a bright one with a Triple Junction 1550nm laser diode.

Table 1

before Receiver	Typical 905nm	1550nm Triple Junction
Photon count per sec	4.2×10^7	3.2×10^9
Relative photon count	1	83

Signal-to-Noise Ratio S/N and Probability of Detection P_D

To assess the LiDAR performance, we estimate the signal and noise of the overall system, and the detection probability is determined by the signal to noise ratio SNR. The signal current i_s is calculated from the photonic power P_s by

$$i_s = P_s \cdot R_o \cdot M \qquad \text{Eq.3}$$

where R_o is unity gain responsivity [A/W] and M is the avalanche gain of APD used in our study. Typically a Si APD is used for 905nm LiDAR and InGaAs APD for 1550nm. The noise calculation includes the dark current of APD, shot noise, and thermal noise, which can be expressed by Eq.4 below [4]

$$i_n = \sqrt{\{2q\ [I_D + (P_s + P_B)M^2F] + I_t\}BW} \qquad \text{Eq.4}$$

where I_D is the dark current, P_s is the signal photon flux onto the APD, P_B is the solar irradiance background noise, F is the excess noise factor, I_t is the thermal (Johnson) noise calculated by $4k_BT/R_{eq}$, and BW is the system bandwidth.

As the returned signal photons get collected by the receiver aperture, the solar background noise also needs to be considered in the shot noise calculation. The total solar background power incident on the APD can be estimated by Eq.5, assuming the worse scenario when the angle between the target surface normal and the line joining the target and receiver center is zero [4]

$$P_B = \frac{\pi E_\lambda \rho\ \beta_R D_R \Delta_\lambda \eta\ \exp(-\gamma R)}{16} \qquad \text{Eq.5}$$

where E_λ is the solar spectral irradiance [W$\cdot m^{-2} \cdot nm^{-1}$], β_R is the receiver field of view, D_R is the receiver aperture diameter, and Δ_λ is the receiver bandpass filter range. With 20nm for Δ_λ of 905nm and 40nm for Δ_λ of 1550nm, we estimate that 1550nm has less solar noise than 905nm by approximately 78%. It is also noted that 1350nm has the lowest solar irradiance noise where E_λ is merely 0.0045, versus 0.9 for 905nm and 0.2 for 1550nm, which results in a negligible solar background noise shown in Fig.4.[5] The extremely low solar background noise at 1350nm should be explored for potential LiDAR designs.

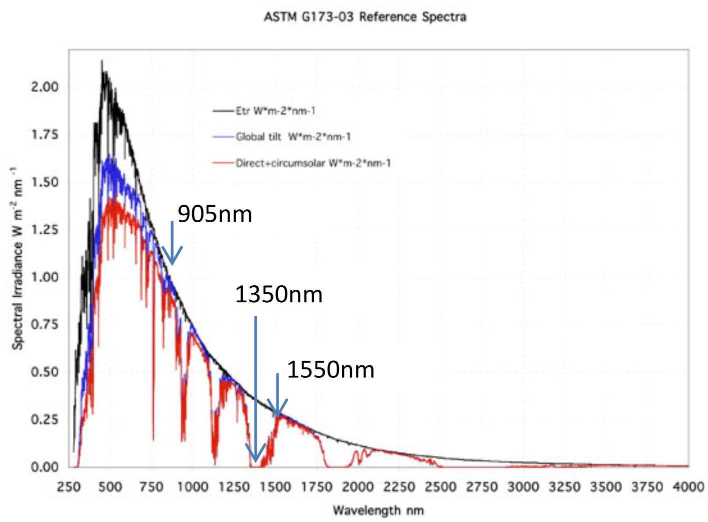

Fig.4 Solar irradiance spectrum

For comparison, we adopt known specifications of Si APDs (for 905 nm systems) and InGaAs APDs (for 1550 nm systems), a 50mm receiver aperture, typical avalanche gain of 100 for Si and 30 for InGaAs APD, excess noise factor of 5 and 10 for Si and InGaAs APD respectively. With the assumed system parameters 80% of the receiver optical efficiency, 20MHz of system bandwidth, and 10Mohms of equivalent resistance, we obtain the signal-to-noise ratio

$$SNR = \frac{i_s^2}{i_n^2} \quad \text{Eq.6}$$

Similar to RADAR, the probability of detection P_D for LiDAR is approximated by Eq.7 with a complementary error function for a target [6]

$$P_D \approx 0.5 \times erfc\left(\sqrt{-\ln P_{fa}} - \sqrt{SNR + 0.5}\right) \quad \text{Eq.7}$$

where P_{fa} is the probability of false alarm. We note that a thorough investigation between different LiDAR designs require more rigorous numerical simulation as targets can be fluctuated by changing directions with the four Swerling models.[7] In our benchmark, a typical 1% for the probability of false alarm is assumed.

Fig.5 below shows the benchmark results of LiDAR with 1550nm Triple Junction laser diode vs. 905nm under various conditions of distance, target reflectivity, and visibility. In general, 1550nm LiDAR has a much superior performance to 905nm. At 100m distance, 905nm needs a high target reflectivity in order to achieve a decent SNR and probability of detection. By comparison, 1550nm LiDAR performs at 100% detection probability. A single-emitter 905nm LiDAR with poor SNR is unable to detect any object beyond 100m, while 1550nm outperforms by 60 times in SNR and 24 times in detection probability at 200m. At 250m range, a single 1550nm can function nicely in both clear sky and low visibility conditions. Given the safety level required for automotive LiDAR, the 1550nm performance may enable fully autonomous LiDAR implementation with confidence.

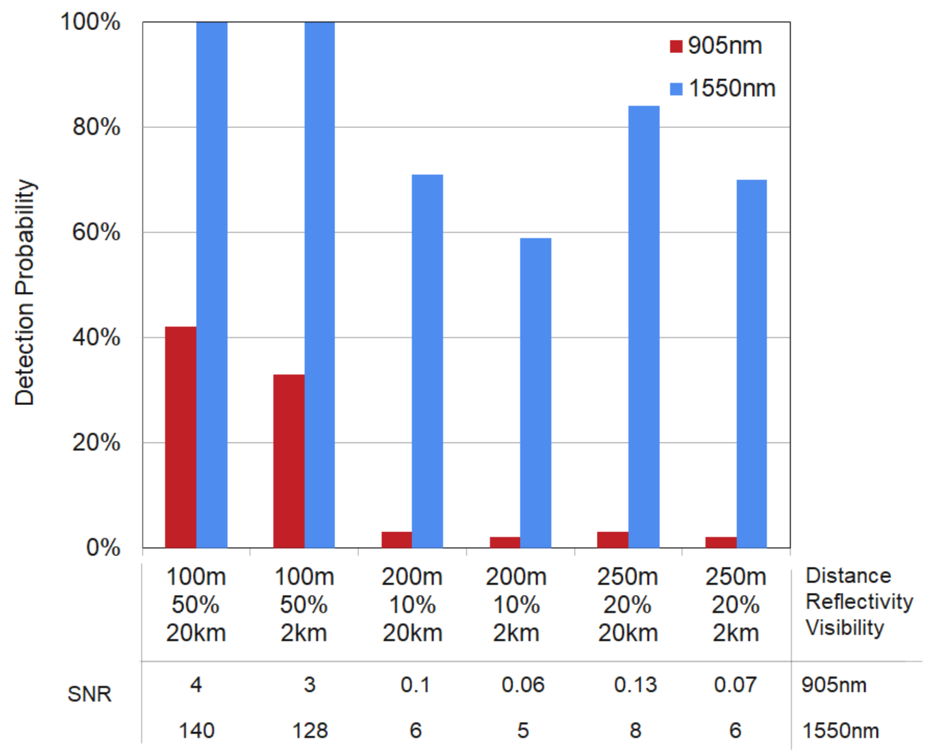

Fig.5 SNR and Detection Probability of 1550nm Triple Junction vs. 905nm in single-emitter LiDAR

In this benchmark we assume the beam diameter of the laser emitter matches with the size of a dilated pupil. In practice, 905nm LiDAR designs often add many more emitters and enlarge the beam diameters significantly in order to meet the safety standards, achieve a better SNR and farther distance. Such approach for 905nm complicates the overall LiDAR design, adds significant costs and deteriorates the image resolution of the target. By comparison, LiDAR systems with a 1550nm Triple Junction laser diode can deliver longer range with lower complexity for autonomous vehicles.

Conclusion

The benchmark results show that the eye safety requirement drastically limits the usefulness and increases the complexity of 905nm in LiDAR application. With a single emitter it cannot detect objects over 100m distance, which completely undermines the ultimate goals of a reliable LiDAR system for autonomous vehicles in all conditions. On the other hand, the new Triple Junction 1550nm laser diode is eye safe and able to deliver the best LiDAR performance for autonomous vehicle at long range. The 1550nm Triple Junction provides a practical path forward for autonomous vehicles and the automotive industry with a simpler LiDAR system without sacrificing detection resolutions. 1350nm laser diodes with higher efficiencies and higher optical power may be an even better choice for LiDAR when considering a significantly lower solar noise.

Authors

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