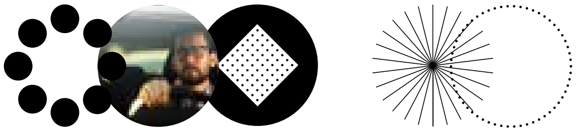
WHITE PAPER



# COMPARING VCSELS AND LEDS IN AUTOMOTIVE DRIVER AND OCCUPANCY MONITORING APPLICATIONS

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## Executive Summary

Today's driver monitoring systems (DMS) and occupant monitoring systems (OMS) rely on LED illuminators, but vertical-cavity surface-emitting laser (VCSEL) illuminators have many advantages. When integrated into the optical train of a typical time-of-flight (ToF) system, VCSELs can deliver more than twice the efficiency of LEDs. In addition, the spectral properties and modulation speed of VCSEL illuminators enable higher-performing and more-efficient monitoring systems for the next generation of vehicles.

After defining DMS/OMS illuminator requirements, this whitepaper compares LED and VCSEL illumination sources, examining user comfort, temperature stability, spectral performance, system efficiency, beam shaping, pulsing characteristic, speckle, and power stability versus temperature. Finally, we put it all together to see how LED- and VCSEL-based integrated systems stack up against each other.

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## Introduction

Increased autonomy requirements and new safety standards are spurring in-vehicle monitoring technology advancements. When it comes to autonomous driving (AD) vehicles rated Level 3 or under, drivers are still responsible for keeping their hands on the steering wheel and eyes on the road under certain conditions. In vehicles with Level 3–5 autonomy ratings, DMS and OMS, the latter of which monitors the entire cabin, are responsible for some advanced safety features not included in vehicles given a lower rating.

Since 2020, DMS have played a vital role in helping new cars achieve a five-star rating from Euro NCAP, an agency that tests and rates vehicles for safety. The European Union plans to mandate DMS for new models beginning in 2022, and other regions are expected to follow. Similarly, mandated OMS features, such as preventing drivers from locking the car if an infant is present, are imminent for North America and Europe (i.e., these features will be required on 2022 vehicles vying for a five-star rating from Euro NCAP). [1]

Today's driver monitoring systems rely on LED illuminator, but VCSEL illuminators have many advantages, enabling higher performing and more efficient monitoring systems for the next generation of vehicles. This white paper compares the two technologies in terms of DMS and OMS requirements.

## DMS and OMS Applications

Innovative technology is changing how people interact with vehicles. Areas of interest include in-cabin sensing and facial recognition. In-cabin sensing collects driver and occupancy data such as whether the driver is actively paying attention to the road or is distracted or drowsy and veering into another lane. In-cabin sensing also supports gesture recognition — for example, tilting the head left or right to turn the speaker volume up or down — for in-car navigation, communications, and infotainment systems.

Facial recognition, which has become commonplace with smartphones, is expected to become standard in vehicles over the next decade. With facial recognition technology, a driver can start the car while simultaneously signaling the vehicle to adjust seats, mirrors, and the steering wheel to the driver's preprogrammed preferences. The technology also monitors and differentiates between emotional states such as anger, relaxation, and anxiety and physical states such as drowsiness. This data can be used to avoid lane departures, which are common when drivers are upset or too relaxed, and correct steering accordingly (Table 1).

| DMS/OMS Capability | Benefit |
|---|---|
| User authentication (facial recognition) | Starts the car and customizes cabin environment. |
| Gaze and drowsiness monitoring | Warns when attention drifts. Can automatically adjust cabin conditions to alert driver via temperature, speaker volume, and lighting. |
| Child presence detection | Prevents the car from locking when infant or small child is present. |
| Cabin-gesture control | Controls environment with hand gestures and body orientation to avoid physical distractions. |
| Body orientation monitoring | Triggers airbag reaction to minimize damage to back and neck. |

Table 1: Some benefits of DMS/OMS capabilities include improved safety and convenience.

## Comparing In-Cabin Sensing and Facial Recognition Illumination Sources

U.S. and European transportation safety regulators are increasingly recommending or requiring DMS and OMS in vehicles, fueling the demand for next-generation 2D and 3D infrared cameras with high-performance infrared illuminators.

In-cabin sensing and facial recognition rely on 3D sensing, a technology that enables detection of body and object positions in three dimensions. Today, the in-cabin automotive market is dominated by infrared (IR) LED illumination sources. Contending technology that enables 3D sensing uses VCSELs with GaAs, the same technology mobile phones use for biometric unlock. [2]

A module currently available for automotive in-cabin applications is the 940 nm VCSEL flood illuminator with AEC-Q102 qualification. [3] These new VCSEL flood illuminator modules emit higher optical power with a narrower spectral width than infrared LEDs, as shown in Table 2, which lists important considerations when comparing LEDs to VCSELs for DMS and OMS applications.

| | High Power IR LED | High Power IR VCSEL Array |
|---|---|---|
| Low cost and manufacturability | ⊕⊕ | ⊕ |
| Ease of packaging | ⊕ | ⊕ |
| Output power | ⊖ | ⊕ |
| Reliability | ⊕ | ⊕ |
| Power conversion efficiency* | ⊕ | ⊕⊕ |
| Modulation speed | ⊖ | ⊕⊕ |
| Emission beam and optics integration | ⊖ | ⊕ |
| Spectral properties | ⊖ | ⊕⊕ |
| Speckle free | ⊕⊕ | ⊕ |

*Despite equal chip-level efficiencies, VCSEL-based optical systems are two to four times more efficient when integrated into a system.

Table 2: Comparison of IR LED and VCSEL array illumination sources.

In terms of **reliability** and **ease of packaging**, there are no relevant differences between the two technologies. Essentially the same infrastructure is used for packaging VCSELs and LEDs. While LEDs have a cost advantage today, it is not intrinsic. If manufactured in the same volumes, the price of LEDs and VCSELs would be comparable. More than 70% of the VCSEL market today is driven by consumer applications such as smartphones. As high-volume manufacturing continues to scale for the consumer market, emerging automotive VCSEL 3D technology is expected to go through a lower cost trajectory. However, if more than one LED chip is needed to achieve the required power in a Field of Illumination (FoI), the VCSEL might have the cost advantage overall.

At first glance, from a chip point of view, LEDs and VCSELs have a similar **power conversion efficiency (PCE)**. However, when integrated into a complete optical system, the VCSEL can be four times more efficient than the LED. VCSELs also have a strong advantage in terms of **emission beam and optics integration**. When it comes to **modulation speed**, VCSELs take the lead by a longshot. While LEDs are limited to less than 30 MHz maximum modulation frequency, the lasing of VCSELs makes extremely fast modulation practical, resulting in about 200 picosecond (ps) rise/fall times at speeds much greater than 30 MHz (in the hundreds of megahertz range). This is important because the faster the modulation speed, the better the 3D image depth resolution.

As incoherent light sources, LEDs are inherently **speckle free**, which can give LEDs an advantage in eye gaze–tracking applications, where speckle can create issues when identifying and tracking the iris. While VCSEL designs that minimize speckle are possible, the lasing nature of VCSELs means that they will be more prone to speckle.

## DMS and OMS Illuminator Requirements

To monitor a driver, DMS illuminators must be in close proximity to an unobstructed view of the person's face, such as in the dashboard, the center console, or the rearview mirror. DMS illuminators used for gaze monitoring or to detect drowsiness and distraction must be able to resolve the iris to determine which direction the driver is looking. An OMS illuminator, in contrast, would typically be mounted in the rearview mirror or somewhere in the interior car roof liner, such as in a central cabin light module. There, the OMS illuminator would require a very wide angle to flood the entire cabin, for monitoring the driver and the side passenger (and potentially back seat passengers) inside the vehicle.

The main technical requirements for DMS and OMS illuminators include the following:

- 2D and/or 3D imaging, e.g., with indirect ToF
- Power: 1–10 W, depending on range and sensor Field of View (FoV)
- Wavelength: 850 nm, 940 nm (nonvisible light preferred)
- High reliability, AEC-Q102 qualification
- Environmental operating temperatures of -20°C to 85°C
- Tailored FoI to application (FoV of the camera)
    - e.g., 60° x 45° (DMS), 110° x 85°(OMS), or even wider (>140°)
- Eye safety
- For gaze tracking: low speckle
- For 3D scan: high modulation frequency

## Criteria for Comparing LEDs and VCSELs

In addition to the previously stated illuminator requirements, it is important to consider several key factors when comparing LED and VCSEL illumination sources for use in in-cabin automotive DMS and OMS applications. This section covers factors such as user comfort, temperature stability, spectral performance, and system efficiency, as well as other important considerations such as beam shaping, pulsing characteristic, speckle, and power stability versus temperature.

### Cosmetic and User Comfort (Red Glow)

DMS and OMS devices must be aesthetically pleasing and seamlessly blend in with the vehicle's interior. Because the applications face the user, perception of the illumination light is also critical.

Similarly, automakers want to avoid a permanent red glow that might strain the eyes, irritate or distract drivers or contribute to fatigue and eye strain on long road trips. Ideally, the illuminators should be invisible to the driver and other occupants. Due to the sensitivity of the human eye, in the near-infrared reflectance (NIR) wavelength range, shorter wavelengths are more perceptible than longer wavelengths. Consequently, longer wavelengths, such as 940 nm, where most people have much less eye sensitivity, are preferred to avoid the disturbing red glow.

Furthermore, because LEDs have a large spectral width, even if the LED is emitting at 940 nm, there is much more spectral content in the shorter wavelength range towards the red, which tends to produce a residual glow that might be visible (Figure 1).

For user comfort, a VCSEL is the preferred illuminator because the red glow will always be less visible than with an LED illuminator.

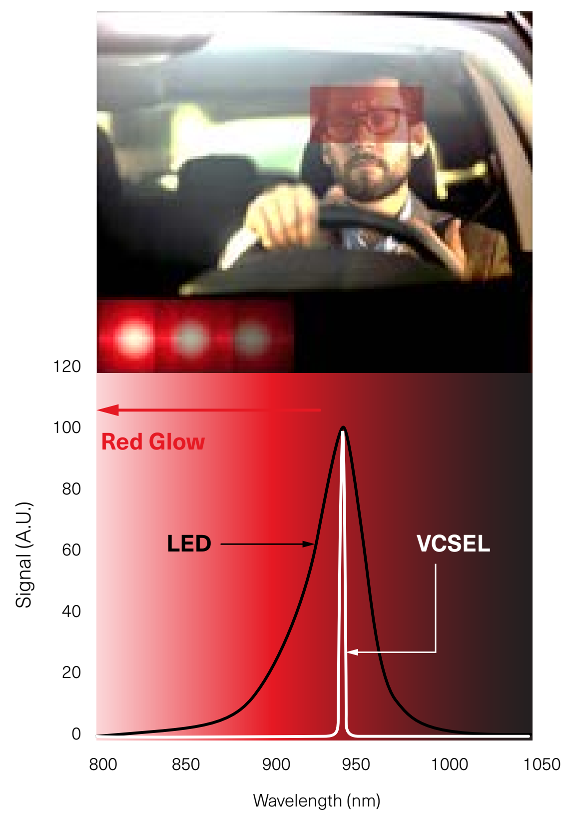



Figure 1: An LED emitting at 940 nm will always have more intense red glow than a VCSEL emitting at the same wavelength, due to the LED's larger spectral width reaching into the visible red spectrum.

## Temperature Stability and Spectral Performance

Comparing VCSELs and LEDs in Automotive Driver and Occupancy Monitoring Applications Temperature Stability and Spectral Performance Temperature ranges can swing widely inside any vehicle. As a result, environmental temperature requirements for DMS fandoms illuminators range from -20°C to 85°C (or even up to 105°C). When comparing LED- and VCSEL-based illuminators for in-cabin automotive applications, temperature stability and reliability are critical factors to consider. Figure 2 compares LED and VCSEL spectral performance at an emission wavelength of 940 nm at two temperatures, T0 andT0+70°C. The dotted blue and red lines show the spectral response of a 940 nm LED at 0°C and 70°C, respectively, and the solid blue and red lines show the VCSEL spectral response at 0°C and 70°C, respectively. Not only does the VCSEL have a narrower spectral width than the LED but the wavelength shift due to temperature is smaller (0.06 nm/°C for the VCSEL vs.0.3 nm/°C for the LED ) as well.

The Advantage of VCSELs over LED spectral Performance

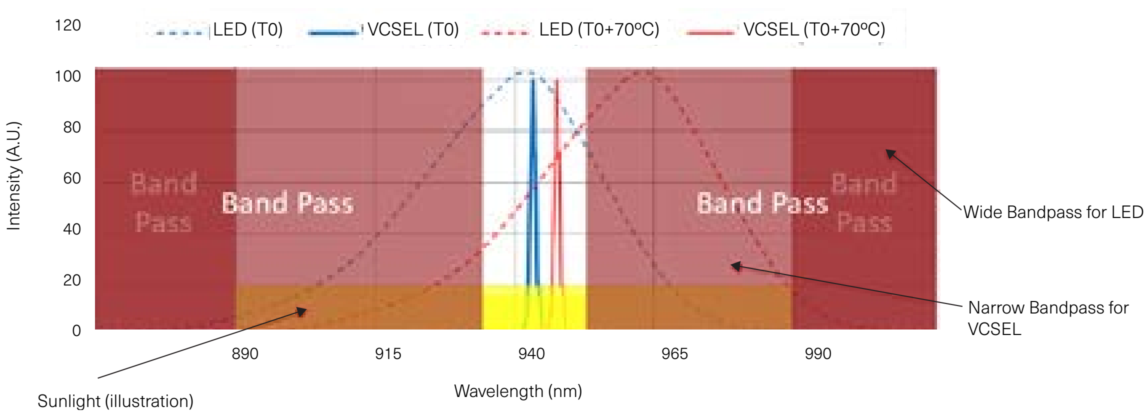



Figure 2: The narrower spectrum and low temperature shift of VCSELs allow a narrower rejection filter, which improves the signal-to-noise ratio (SNR) and reduces the power loss in the bandpass filter (BPF).

Note: the height of the peak is indicative only and is not representative of the comparison of power

The narrower spectrum of the VCSEL when compared to the LED is a significant advantage as in-cabin monitoring systems must be able to work even in bright sunlight. In addition, as Figure 3 shows, sunlight has minimal radiation at 940 nm — another reason why 940 nm is a good choice when compared to other common illumination wavelengths such as 850 nm and 905 nm.

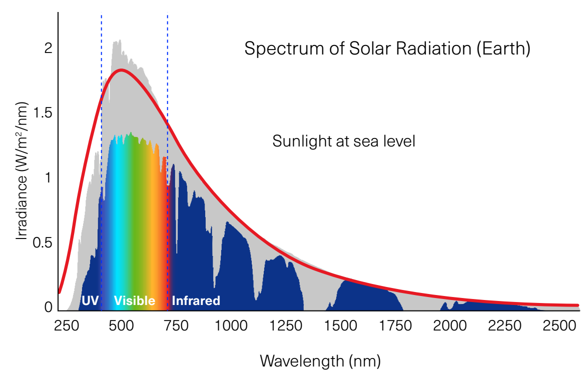



Figure 3: Solar irradiance reaching the Earth has low power content at 940 nm due to atmospheric absorption.

DMS and OMS often rely on bandpass filters (BPFs) to block un-wanted sunlight from reaching the sensor. Due to the wide spectral emission of LEDs at 940 nm and the large wavelength shift that they can experience in vehicles, LED illuminators must use a very wide BPF to avoid blocking illumination from the LED (see Figure 2 above). But this also allows more solar radiation to get through, reducing the signal-to-noise ratio (SNR) of the LED-based system. Consequently, to achieve the desired system sensitivity, LED illuminators have greater optical output power requirements than VCSELs to overcome the large amount of noise created by the sunlight, which contains no useful information.

Inversely, blocking ambient sunlight with a narrow BPF also blocks some of the light from the LED, which then degrades the system's efficiency and possibly the SNR if power is not high enough.

In contrast, a VCSEL's narrower spectrum and lower wavelength shift with temperature makes it possible to use a narrowband filter that blocks most of the sunlight, resulting in a much-improved SNR and lower power consumption compared to LEDs. For the same SNR, automakers can use VCSELs to reduce optical power requirements and save on component costs.

Figure 4 illustrates the relationship between LED power loss and BPF width. For example, the graph shows that a 54 nm BPF width results in an LED power loss of approximately 20%. With a VCSEL, that loss would be zero. However, that is just the amount of power that is cut by the filter. It does not include the extra power that would be required to improve the SNR when using an LED. For example, assume that 1 W incoming on the sensor is required for an application. If 20% of the power due to FoI is lost, only 0.8 W will reach the sensor. As a result, the raw power from the LED must be increased to 1.2 W to achieve 1 W at the sensor.

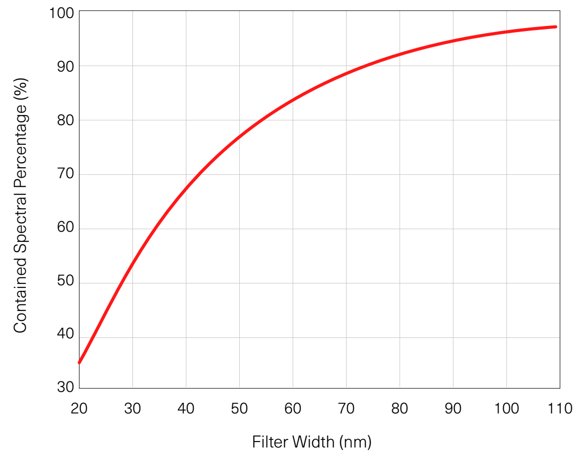



Figure 4: This illustration shows the amount of LED power going through an optical BPF as a function of filter width.

The SNR is critical to achieve accurate depth measurements and high-resolution imaging. Optical systems have a base level of noise that contains no depth information. The signal comes in on top of the noise. If it is too small, just a little above the noise, it is difficult to discriminate the signal, or depth information, from the noise. Overall, a VCSEL-based illuminator combined with a narrowband filter allows a lower cost, lower power consumption, high-performance in-cabin system.

**System Efficiency: Beam Shaping**

Another advantage of VCSELs over LEDs is beam shaping.

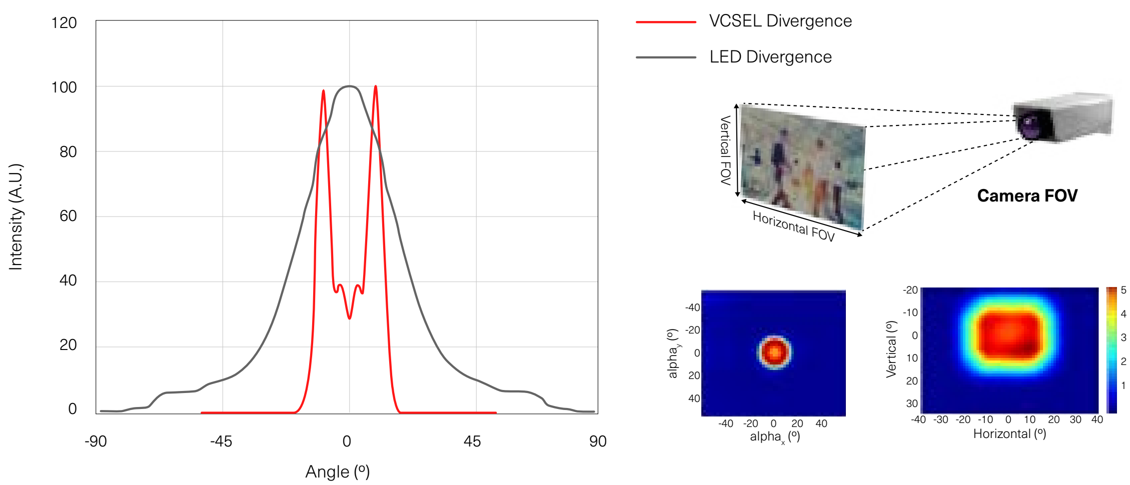



Figure 5: VCSELs have a lower divergence than LEDs, enabling smaller optics to be used with more efficient beam shaping to provide an improved FoI (Field of Illumination) match with the camera's FoV (Field of View).

Because the LED has a circular emission profile, either some of the camera sensor will not be illuminated or some of the illumination will be wasted. With a circle large enough to contain the entire camera sensor area, any light falling outside the sensor area is wasted. Thus, an LED requires more power to achieve an effective illumination on the sensor.

Precisely matching FoI with the FoV of the camera wastes no light. Consequently, using a VCSEL-based illuminator is preferred when compared to LEDs in terms of efficiency. With the VCSEL, the beam can be shaped to match the camera sensor exactly. The 2D plot in Figure 5 illustrates the steep rising and falling edges and the classic doughnut shape of VCSEL illumination divergence. This characteristic allows for beam shaping with a diffuser to produce a rectangular FoI shape that better matches the illumination source's FoI with the camera's FoV. With a VCSEL, the beam emission profile can be tailored to form almost any shape — emphasizing angles, for instance — to match demanding system requirements.

Radiant intensity (RI) comparison is another key factor to consider when comparing VCSELs and LEDs in terms of beam shaping and energy efficiency. Standard facial recognition systems use a camera with a 60˚ by 45˚ FoV. When using an LED illuminator with nominal 80˚ divergence, the transmission power in the 60˚ by 45˚ FoV is only about 37%. In contrast, a VCSEL illuminator with a diffuser designed for 60˚ by 45˚ FoV results in a radiant intensity (RI) transmission power of about 70%, or almost double that of an LED illuminator. Consequently, for the same amount of received power on the camera, the VCSEL uses about half the power of an LED (Figure 6a).

In the case of a wider angle 110˚ by 85˚ FoV system such as for OMS, an LED illuminator with a 130˚ divergence would have about 50% of the center RI at the corners and achieve a transmission power RI in the 110˚ by 85˚ FoV of 52%. In contrast, a VCSEL-based illuminator designed for a 110˚ by 85˚ FoV camera would have about 25% of the center RI at the corners and achieve a transmission power RI in the 110˚ by 85˚ FoV of 84%. The difference shown in Figure 6b is still significant.

Higher FoI angles are still feasible with a VCSEL to angles of 140˚ by 100˚ FoV with a 150˚ diagonal divergence LED and a VCSEL illuminator designed for 140˚ by 100˚. The RI for the LED is 67% while the RI for the VCSEL illuminator is 93%. These high-angle illuminators are especially compatible with OMS since they cast light over the entire cabin (Figure 7).

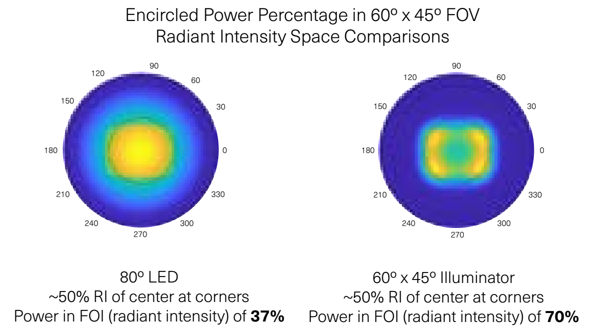



Figure 6a: For the same amount of received power on the camera, a VCSEL uses about half the power that an LED with 80˚ divergence in a 60˚ by 45˚ FoV would require.

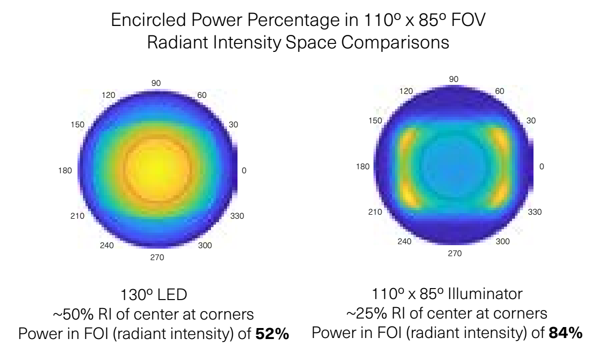



Figure 6b: For a 110˚ by 85˚ FoV system, an LED illuminator with a 130˚ divergence would have to achieve a 52% transmission power RI in a 110˚ by 85˚ FoV, while a VCSEL-based illuminator designed for a 110˚ by 85˚ FoV camera would need to achieve 84%.

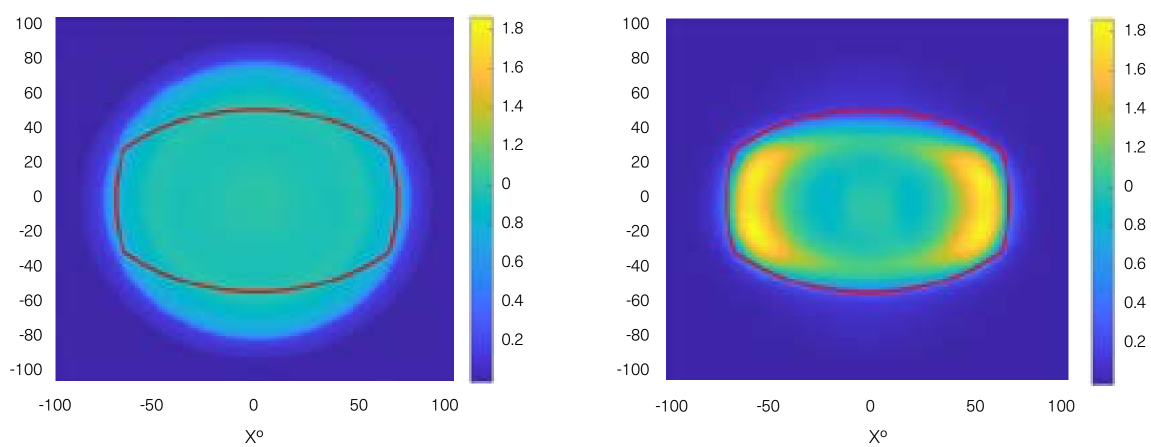



Figure 7: Radiant intensity for an LED (left) and VCSEL (right) mapped out to the 140˚ by 100˚ FoI (Field of Illumination) (red line).

## Pulsing Characteristic

Pulsing, or modulation speed, is another advantage of VCSELs over LEDs. VCSELs enable sharp rising and falling edges that can yield nanosecond pulse lengths (Figure 8) and enable high accuracy depth sensing, making them the preferred solution for 3D sensing applications.

VCSELs can generate < 50 ns pulses easily, while LEDs are limited to the >50 ns range.

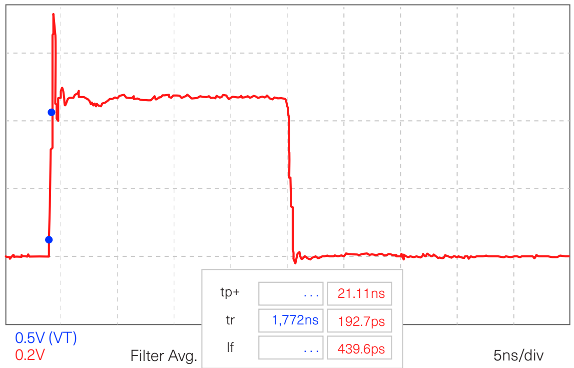



Figure 8: While modulation of LEDs is limited, the lasing of VCSELs makes extremely fast modulation practical, resulting in 200 ps rise/fall times at speeds greater than 30 MHz.

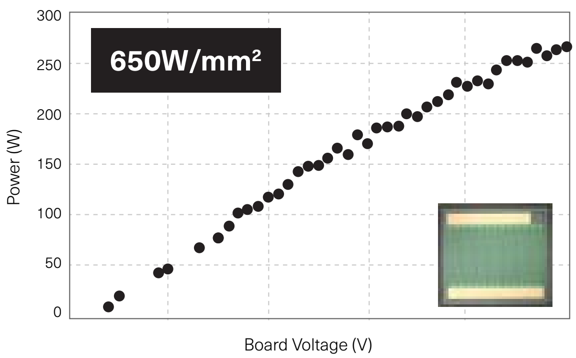


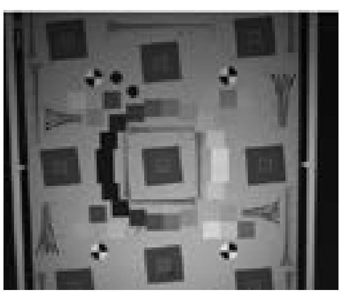

Figure 9: When a VCSEL operates in short pulse mode for dToF, the illuminator can achieve a peak power of > 250 W.

Furthermore, short pulse operation allows extremely high-peak power from VCSELs, extending the reach of depth sensing and enabling direct ToF (dToF) systems where the distance is extracted directly from the round trip time of the pulse, which imposes short and well defined optical pulses. For example, Figure 9 illustrates that a VCSEL designed for 3 W operation in an indirect ToF (iToF) system can emit more than 250 W with typical dToF pulses (3 ns pulse and 0.06% duty cycle).

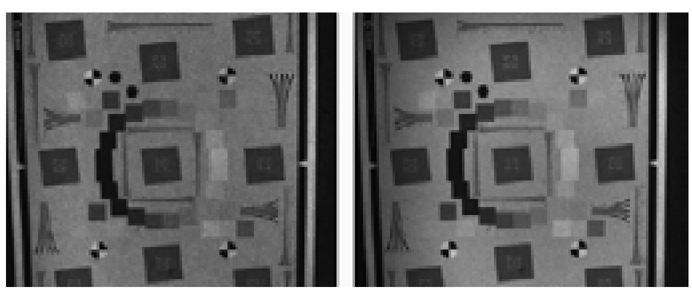
## Speckle

Since LEDs are incoherent light sources, they are not prone to speckle, giving them a clear advantage when speckle is a concern. In contrast, VCSELs, like all lasers, are coherent light-emitting sources, which are more prone to speckle. Figure 10 compares LED-illuminated and VCSEL-illuminated score-rated targets. The noise in the images created by the VCSEL speckle makes the image appear grainy in comparison to the LED illuminated image.

Speckle can cause problems for DMS using VCSEL illumination for iris identification and tracking applications because it makes it more difficult to get a clear picture of the iris due to shimmering, which tends to blur the image. While VCSEL designs that include an increased number of emitters can minimize speckle, laser illumination will always exhibit potential speckle.



LED Illumination



VCSEL Illumination

Figure 10: LEDs are inherently speckle free, giving them an advantage in gaze-tracking applications, where speckle can create issues identifying and tracking the iris.

### Power Stability Versus Temperature

Another factor to consider when comparing LEDs and VCSELs for in-cabin monitoring applications is power versus temperature. Figure 12 compares power versus base temperature by plotting normalized power versus base temperature at four different pulse lengths for a standard LED compared to Coherent's 940 nm VCSEL.
For shorter pulses, LEDs are comparable to VCSELs, but for longer pulses, LED power is more stable versus temperature than VCSELs. This is most likely because for the same base temperature, LEDs, which have a large emitting area, have lower junction temperatures. VCSELs are more advantageous when using short pulses, which is important in 3D depth systems.

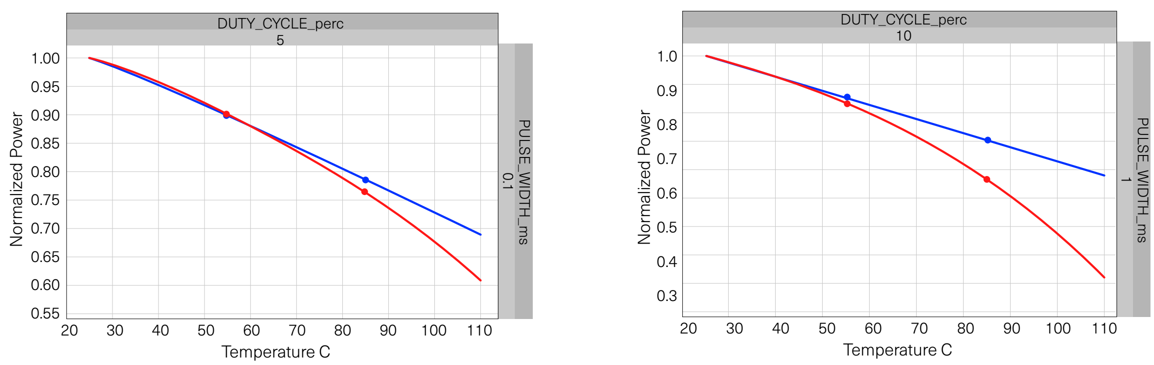



Figure 11: For shorter pulses, LEDs (blue) are only slightly more stable than VCSELs (red). The left graph illustrates 0.1 ms pulse width at 5% duty cycle and the right graph shows 1 ms pulse width at 10% duty cycle.

## Comparison of a Typical ToF System

When comparing LED- and VCSEL-based illuminators for automotive in-cabin monitoring, it is important not to just compare the bare chip performance but rather to analyze the entire integrated system. Figure 12 shows the following sequence of events, all of which occur in a standard ToF system:

- An electrical pulse is applied to the VCSEL or the LED, which triggers an optical beam to be emitted with a certain beam shape
- The emission passes through a diffuser designed to match the FoI with the camera FoV
- Light bounces off the target being imaged
- The data mixes with ambient sunlight (in outdoor or bright room daylight applications)
- A BPF cuts as much of the sunlight as possible to optimize the SNR
- The filtered light hits the ToF sensor
- The signal is decoded by software and transformed into a 3D point cloud

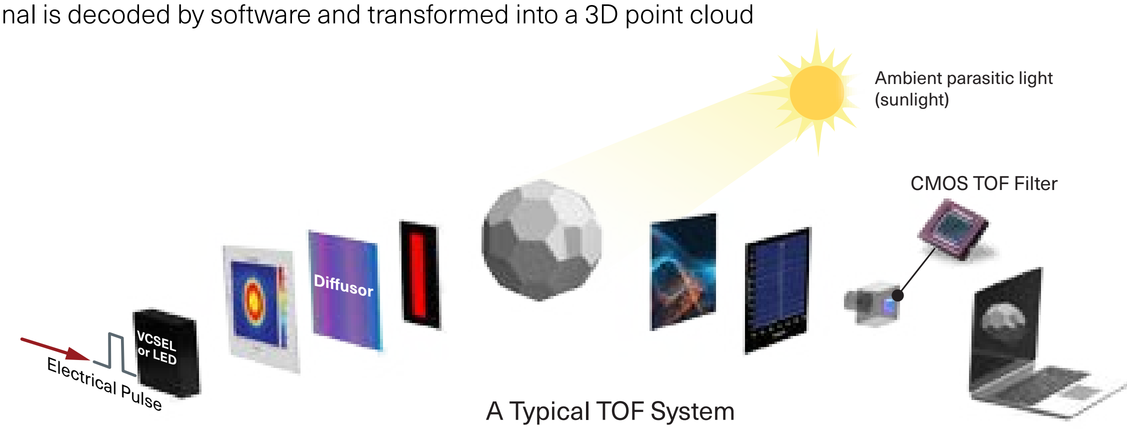



Figure 12: Optical train for a simple ToF architecture.

Table 3 compares the optical chain between an LED and a VCSEL, assuming a 60° by 45° FoV. An 80 nm BPF and equal bare chip efficiency of 45% for the LED and the VCSEL are assumed (note that with narrower BPF widths, VCSELs will exhibit an even greater advantage for total efficiency). The LED does not require a diffuser and so no light is lost.

With the VCSEL, about 10% of the light is lost through the diffuser. Due to its low divergence, well below the critical angle, VCSEL transmission through optical surface is 100%. As mentioned earlier, the energy in a 60° by 45° FoV is 37% of the light from the LED and 70% from the VCSEL. Reflection on the object is ignored in this analysis and assumed to be 100% for both.

| Loss Mechanism | Assumptions | LED | VCSEL |
|---|---|---|---|
| Efficiency of light source (hEO) | | 45% | 45% |
| Transmission through diffuser (habs) | | N/A | 90% |
| Critical angle loss through diffuser (hq) | n=1.5 | N/A | 100% |
| Energy in FoV | | **37%** | 70% |
| Reflection on object | Ignored here | 100% | 100% |
| Transmission through notch filter (Tfilt) | 80 nm filter (LED loses power when narrower) | **90%** | 100% |
| TOF sensor efficiency | Ignored here | 100% | 100% |
| Efficiency of electrical modulation | <30 MHz<br>>30 MHz | 100%<br>0% | 100%<br>100% |
| Total | <30 MHz<br>>30 MHz | **15%**<br>0% | 28.3%<br>28.3% |

Table 3: For the same starting illuminator efficiency, VCSEL-based systems show almost double the efficiency.

When considering the transmission through the notch filter, an 80 nm filter is considered wide, so the LED loses only 10% of its power, a percentage that would be a lot higher if the BPF were narrower. For modulation efficiency, two cases are considered. If speed is below 30 MHz, efficiency is 100% for both. If speed is greater than 30 MHz, it is zero for the LED. The difference in total efficiency for less than 30 MHz modulation is about a factor of two — 15% for the LED and 28% for the VCSEL.

## Conclusion

Starting from the same chip-level power conversion efficiency, when integrated into the optical train of a typical ToF system, VCSELs deliver twice the efficiency of LEDs. In addition to efficiency, VCSEL illuminators have many other advantages, including spectral properties and modulation speed. Connect with Coherent today for an application evaluation and let us show you how VCSEL illuminators can enable higher-performing and more-efficient DMS and OMS for the next generation of vehicles.

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