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WHITE PAPER

Infrared Illumination for Time-of-Flight Applications

Melexis TOF evaluation kit with LUXEON IR Domed Line emitters

The 3D capabilities of Time-of-Flight (TOF) cameras open up new opportunities for a number of applications. One of the challenges of TOF systems is due to the high modulation frequency operating condition, which means that all parts (camera, light sources, etc.) need to be high frequency capable; this might create the perception that TOF systems are rather expensive. This document focuses on Infrared (IR) illumination for TOF systems using Vertical Cavity Surface Emitting LASERs (VCSELs) and Light Emitting Diodes (LEDs) and shows that LEDs are a feasible and affordable option as IR illuminators.

Primary Applications for TOF Systems:

- In-Cabin Monitoring
- Air gesture recognition
- Object Classification
- Robot vision
- Surveillance & people counting

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Introduction

The operation principle of TOF systems is briefly described below. For a detailed description please check the Melexis TOF Basics Application Note.

In a TOF system, emitted light is modulated at very high frequencies (typically >10MHz), a duty cycle of 50%. The modulation frequency determines the distance range that the system can measure unambiguously. The emission occurs in bursts on the order of 250µs long; four such bursts are needed to acquire the distance information for each image frame. Typical frame rate is 25 to 60 depth Frames per Second (FPS).

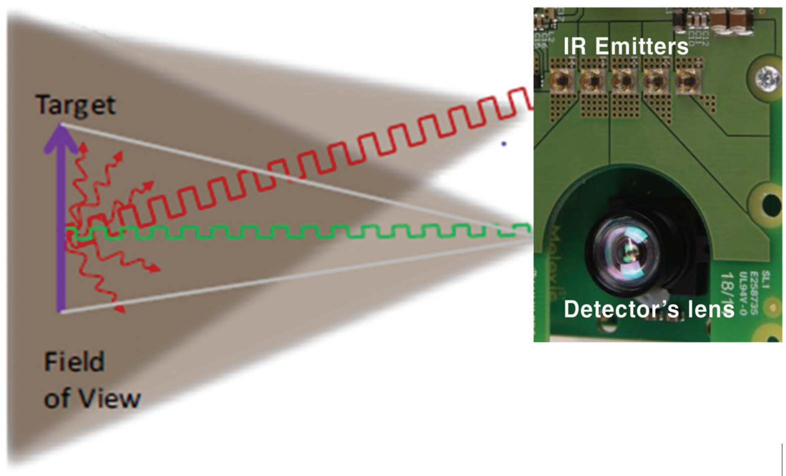

Figure 1. Schematics of a TOF system: modulated light (typically IR) is emitted towards the objects to be measured; the reflected signal has a delay proportional to the distance between the emitter and the object. By measuring this delay, it is possible to calculate the actual distance.

As in all optical systems, the amount of light available plays a critical role in overall performance, especially when ambient light is also present. Moreover, for some applications (e.g. automotive) the system must work in very demanding ambient conditions, like high temperatures, which limit the output and impact the properties of IR emitters.

When taking into account the factors mentioned above, it becomes clear that certain tradeoffs can be made in order to optimize the IR illumination for TOF applications. Some of the factors involved in these tradeoffs are maximum range, measurement accuracy, Field of View (FOV), cost, available space, etc. As outlined in this white paper, IR LEDs are a viable candidate for hitting the “sweet spot” of certain applications’ requirements.

This document is structured as follows:

- Section 1: TOF sensor’s specifications (the illumination requirements are directly driven by sensor’s performance)
- Section 2: Head-to-head comparison between typical IR VCSEL and LED emitters
- Section 3: Economics of LEDs and VCSELs (market penetration, costs)
- Section 4: Experimental measurement results; performance comparison of TOF system equipped with LEDs and VCSELs
- Section 5: Conclusions and recommendations

Section 1: Sensor specifications

Typical TOF sensor optical characteristics:

- Spectral responsivity (higher is better)
- Demodulation contrast (capacity to measure the phase shift of the incident light with regards to modulation signal; closer to one is better)
- Full well capacity per pixel (how many electrical charges a pixel can hold before being saturated; higher is better, as the increased dynamic range allows for better sun/ambient light rejection)

TABLE 1. KEY OPTICAL PARAMETERS OF MLX75024 QVGA AUTOMOTIVE-GRADE TOF SENSOR.

PARAMETER	850nm	940nm
External quantum efficiency	21%	13%
Well capacity (electrons)	>450 ke-	>450 ke-
Demodulation contrast 0-40 MHz	> 70%	>70%

Section 2: IR emitters for TOF – Head-to-Head Comparison

Background

As described in the previous section, IR illuminators for TOF systems need to operate in bursts, at high modulation frequencies and in demanding ambient conditions. This means that the optical output depends strongly on the emitter temperature and on the thermal management of the whole system. Therefore, the comparison will also include temperature-related parameters, like wavelength drift vs temperature.

Another important parameter is the operating wavelength. LEDs and VCSELs are both available at 850nm and 940nm; the next section will address some of the wavelength-related considerations of TOF systems.

Wavelength – 850nm vs 940nm

In principle, the accuracy of a TOF system does not depend on the wavelength (since the measurement is based on the speed of light, not the wavelength of the light). The efficiency and emitted flux of IR emitters are also similar at both wavelengths (though VCSELs become less efficient than LEDs at higher temperatures/currents), so the optical and electrical power budgets are not a strong discriminator either. However, in practice, the wavelength used can affect the overall performance in some applications, so the following issues should be carefully considered when choosing the wavelength:

- **Camera responsivity:** Typically the Quantum Efficiency (QE) of silicon-based detectors is 50% to 100% higher at 850nm than at 940nm; for the same amount of available light, this leads to lower noise at 850nm (at better precision), especially in low light conditions, as shown in Figure 6
- **Physiological factors:** Human eye sensitivity is very low in NIR, but 850nm light can still be seen, especially in dark conditions (this is especially true for LEDs, which have a broader emission spectrum extending towards shorter wavelengths). This can be uncomfortable and/or confusing; on the other hand, 940nm is completely invisible for humans, so it is a better choice in situations involving direct illumination of a person's face
- **Sun light (outdoor applications):** Solar irradiance at ground level can reach very high values; while its emission maximum is located in the visible range of the spectrum, it's still significant in near IR, however, due to atmospheric absorption, there is a dip in the 920nm to 960nm region, where the solar IR levels are less than half compared to 850nm (see Figure 2), thus, 940nm emitters might offer better system performance in this case
  - As a side note, due to their narrow emission band, in VCSEL-based systems it is possible to reject more sunlight by using a narrower optical filter

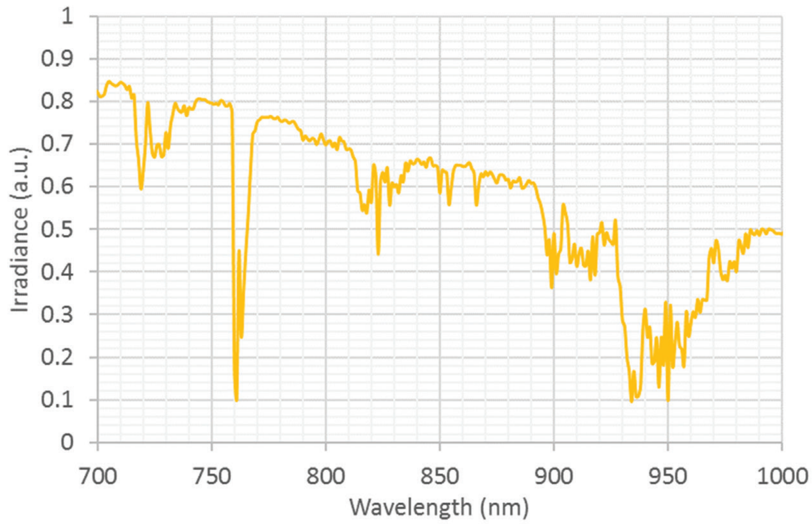

Figure 2. Typical solar spectral irradiance in NIR at ground level, showing a clear dip around 940nm.

VCSELs & LEDs – Head-to-Head Comparison

The table below summarizes the main parameters of interest for IR emitters at the two relevant wavelengths (850nm and 940nm) and gives typical values. The values listed here are typical values for LUXEON IR LEDs from Lumileds and commercially available VCSEL products.

Table 2. Parameters of interest for IR LED and VCSEL emitters at 850nm and 940nm. Unless otherwise specified, given values are valid for standard Lumileds qualification conditions – ambient temperature 25°C, forward current = 1A, 20ms monopulse.

	LED		VCSEL	
	850nm	**940nm**	**850nm**	**940nm**
Rise time[a] <ns>	12	9	< 1ns	<1ns
Fall time[a] <ns>	17	13	< 1ns	< 1ns
Max. operating frequency	< 40 MHz	< 40 MHz	>40 MHz	>40 MHz
Max. fwd current I_f <A>	1	1	1	1
Max. fwd current pulsed $I_{f,p}$ <A>	5	5	1.2	1.2
Typical. fwd voltage V_f <V>	3.2	2.9	1.7	1.9
Typical. optical flux <W>	1.350	1.450	0.770	0.660
Typical optical flux at max. $I_{f,p}$ (pulsed) <W>	5.6[b]	6.1[b]	0.880[c]	0.750[c]
dF/DT (temperature coefficient of output flux) <%/°C>	-0.24	-0.23	-0.38	-0.38
Peak wavelength (nm)	850	940	850	940
Spectral width – FWHM (nm)	35	50	0.8	0.8
dλ/dT (temperature coefficient of peak wavelength) <nm/°C>	0.26	0.29	0.07	0.07
Wall Plug Efficiency (WPE) <%>	38	44	30	29
Automotive qualification available	Yes	Yes	No	No
Eye safety	Intrinsically safe	Intrinsically safe	Class IV laser – additional safety measures needed	Class IV laser – additional safety measures needed

[a] Rise and fall times are measured at 10% – 90% of maximum
[b] Measured at I_f = 5A, pulse length 75μs, 7.5% duty cycle
[c] Measured at I_f = 1A, pulse length 100μs, 5% duty cycle

In general:

- VCSELs have lower rise/fall time and LASER-like characteristics (narrow emission band, directionality, coherence)
- LEDs output flux is less sensitive to temperature, this means that they have higher output at high temperatures, but also that they can be driven at higher currents (in both pulsed and continuous regimes) than VCSELs

Based on the overall characteristics of LEDs and VCSELs and the values listed in the table above, the following remarks can be made about their suitability for various applications:

Output flux:

- LEDs have a significantly higher output flux over a wider range of temperatures
- Due to their intrinsic directionality, VCSELs can emit comparable or higher intensities than LEDs in certain directions, despite the higher overall output of the LEDs
- However, for applications requiring larger FOVs and/or higher output flux, LEDs might be more suitable, since the output pattern of the LEDs has intrinsically a larger FOV
- The total flux has a direct influence on the system's precision, as shown in Figure 3; the plot below is valid for any light source (LED, VCSEL)

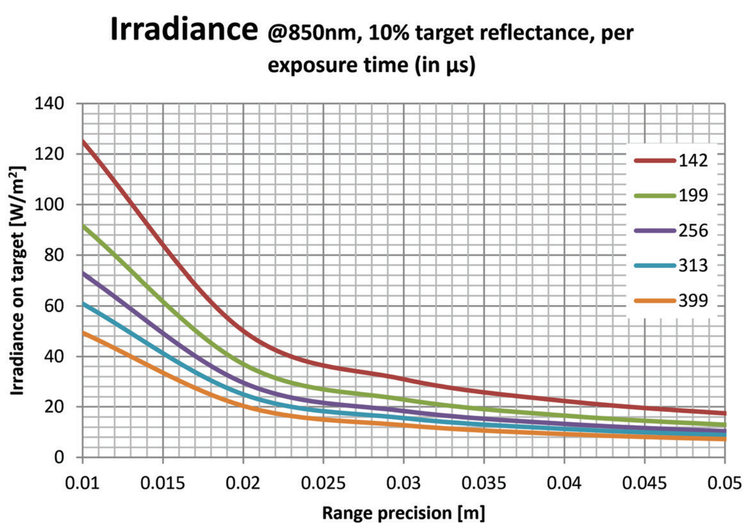

Figure 3. Irradiance on target required to reach a certain precision for Melexis EVK75024 TOF system, at different exposure times/ burst lengths. Note: Irradiance values shown here correspond to average irradiance within a burst.

Figure 3 shows how the required irradiance on the target reduces with higher exposure time.

VCSEL & laser emission – the fact that VCSELs are basically LASERs can have a significant impact on the implementation of certain applications:

- **Eye safety:** Unlike LEDs (which are inherently safe), for VCSELs, safety requirements are usually applicable; diffusers are typically used in order to make them safe for humans, which adds additional effort for design and qualification of the system, and also decreases its efficiency

Modulation frequency:

- VCSELs have faster rise/fall times, which makes them especially suitable for applications requiring very high switching frequencies
- Despite their longer response time, LEDs can reach frequencies in the 40MHz range, though the modulation shape might not be a clean "top hat"; deviations from the ideal waveform cause some nonlinearity errors, however, rise/fall time of LEDs output under fast (MHz range) modulation can be improved by using a customized current driver (voltage driver "boost"), as shown in Section 4 – see Figure 12 and Figure 13 for a comparison between an LED and VCSEL waveform, and the improvement in LED waveform shape due to the use of a boosted driver

- The range of a TOF system depends on the modulation frequency (for example a 20MHz frequency gives an unambiguous range of 7.5m); a lower frequency can be used to achieve a longer range; this makes LEDs an interesting candidate, since their modulation shape gets closer to the ideal “top hat” and their higher output flux means that it offers higher illumination levels of the target (which leads to better Signal to Noise Ratios (SNR)
- A higher modulation frequency leads to a better precision of the setup; in principle, the same precision can also be reached by averaging multiple frames and in such cases, LED illuminators could offer the same precision as VCSELs (even at a lower modulation frequency), as long as a lower frame rate is acceptable for that particular application

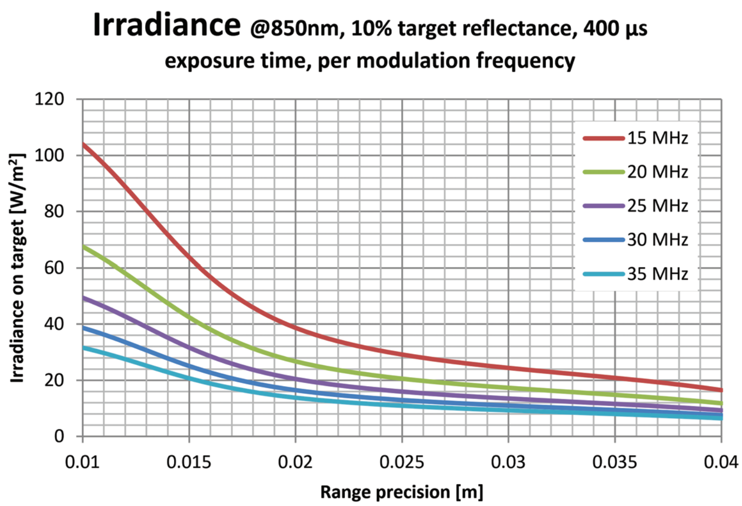

Figure 4. Irradiance on target required to reach a certain precision for different modulation frequencies lengths. Note: Irradiance values shown here correspond to average irradiance within a burst.

Figure 4 shows how the required irradiance on the target reduces with higher modulation frequency.

- For TOF applications, the integration time is an important parameter not only because it determines the amount of light collected by the camera, but also because the IR emitters need to be on during that time, which means that the emitter is actually driven at two frequencies:
  - A high frequency modulation on the order of 20MHz; this is so fast that the junction temperature cannot follow each modulation
  - A lower frequency modulation determined by the integration time (typically on the order of 200 to 500µs); at least four such “bursts” are needed to obtain a frame; a burst is long enough that thermal effects become significant, which can limit the modulation current (that is, the device is not in a purely pulsed mode anymore)
  - Therefore, in such situation it might be preferable to increase the driving current (thus increasing the peak flux) than to increase the pulse length, since over the length of a burst this would provide more photons; a shorter burst also helps with sunlight rejection (the amount of collected sunlight is proportional to the duration of the burst)

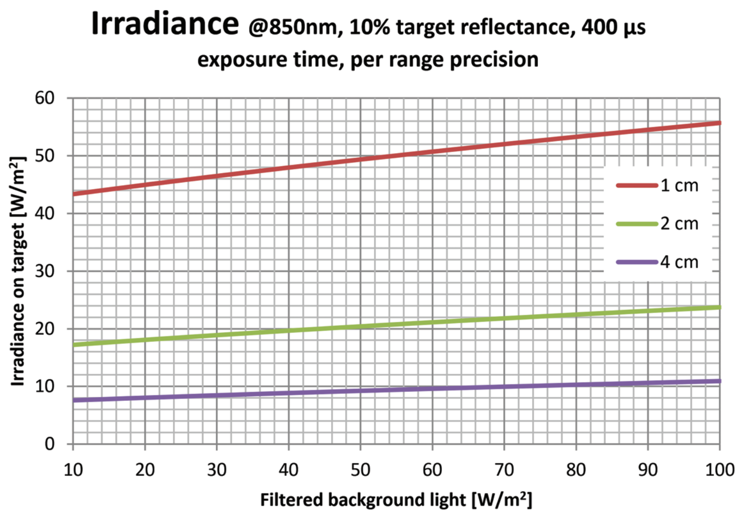

Figure 5. Irradiance on target required to reach different measurement precision values (1, 2 and 4cm respectively) as a function of filtered ambient background light levels. Note: Irradiance values shown here correspond to average irradiance within a burst.

Figure 5 shows how much irradiance is needed on a 10% reflectance target, to reach a given depth precision, versus the background light level on the target. Unfiltered full sunlight amounts to about 1,000 W/m2. Optical filtering around 850nm or 940nm is typically used to reduce that by 90-95%.

- The modulation depth (ratio between minimum and maximum luminous output over a high-frequency modulation period) does not affect the measured signal; that is, if the luminous signal has a DC component, it does not directly affect the performance of the system, however, a significant DC component will increase shot noise and decrease the dynamic range of the camera

Wavelength

- As explained in Section 2, the wavelength also affects measurement precision, mostly due to the fact that detector sensitivity is wavelength dependent; Figure 6 shows the irradiance required to reach the desired accuracy at 850nm and 940nm

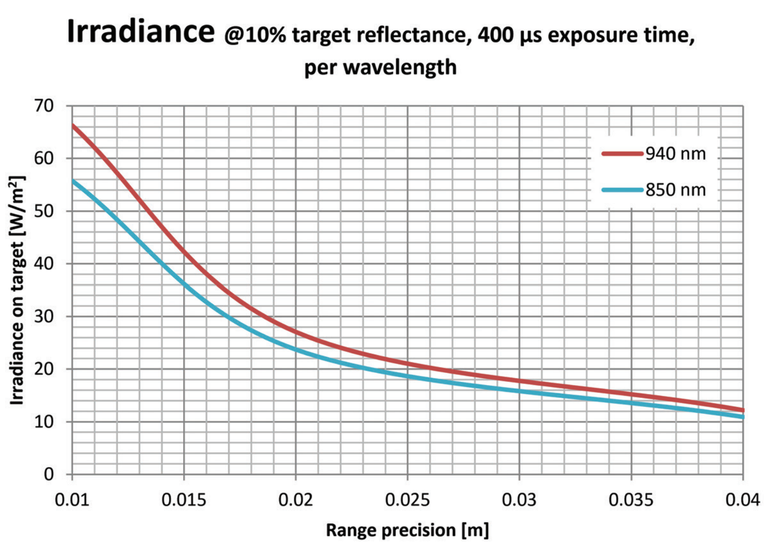

Figure 6. Irradiance on target required to reach a certain precision at 850nm and 940nm, at 100 klux ambient light condition. Note: Irradiance values shown here correspond to average irradiance within a burst.

Section 3: LED vs VCSEL Economics

The previous sections explained the trade-offs between using a VCSEL and an LED for TOF systems. The robustness of LEDs allows for higher power, higher temperature operation with the key consideration being modulation frequency. Eventually, the choice of using a VCSEL or an LED will come down to economics—the lowest cost system solution that can meet the application requirements will determine the choice.

The LED supply chain has a significant lead over VCSELs. Infrared LEDs have been manufactured in large quantities for a multitude of years, and the production capabilities have been honed in overtime to achieve good yields. On the other hand, VCSELs, specifically for sensing applications, are relatively new. Manufacturers are investing aggressively on improving yield and adding capacity, however, this will take a few years. These investments will materialize and allow for cost to reduce significantly over the next few years.

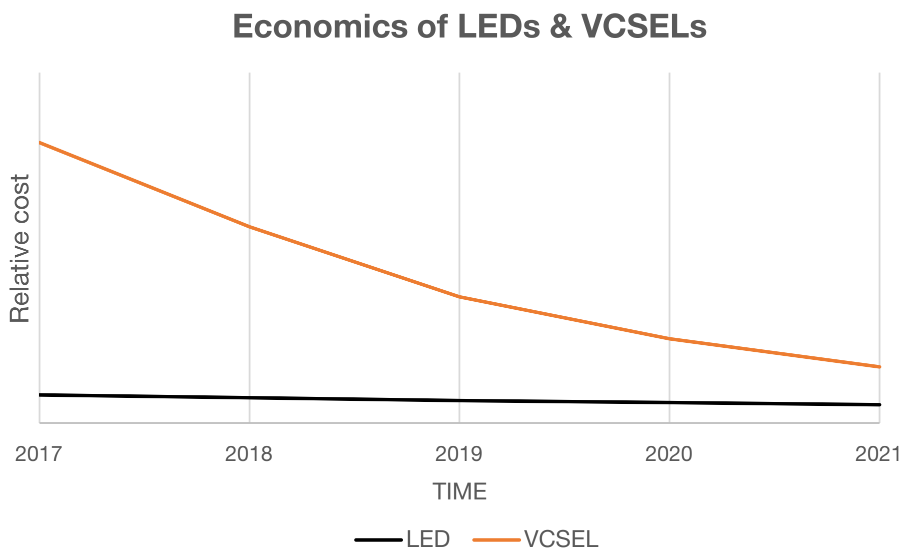

Figure 7. Expected relative price evolution of LEDs and VCSELs over time

In our estimate, in 2017, the relative cost when comparing a VCSEL to an LED of the same power output has been in the range of 10x, and it is expected to drop to 3x by 2021. The high 3x multiple in 2021 can be attributed to the magnitudes of difference in volumes shipped. Infrared LEDs have traditionally been used in industrial segments such as surveillance and machine vision which will continue, and as such, we expect the economy of scale will remain in favor of infrared LEDs.

Section 4: LED & VCSEL Illuminators for TOF – Measured Behavior

Data presented in this section was obtained with a customized Melexis TOF evaluation kit with the MLX75024 and MLX75123 chipset, fitted either with VCSELs (four emitters, 60° emission angle, wavelength 940nm) or with LUXEON IR Domed Line LEDs (five emitters, peak drive current 3.5A, 90° emission angle, wavelength 940nm, shown in Figure 1). For all measurements, ambient temperature was 22°C.

Average Irradiance (VCSEL vs LED)

The figure below shows measured emission spectra of a TOF evaluation 75024 kit when fitted with VCSELs and LEDs. In both cases, the modulation frequency was set at 20MHz, burst length at 250μs, and the sensor was placed at 0.5m from the emitter. Please note that the sensor measures the average irradiance over multiple frames.[1] Based on these measurements, the average irradiance within a burst was calculated and is shown in this section, so that the following plots are comparable with the plots presented in Section 2.

1 Spectrometer's integration time is set to 1 second, so it captures ~25 frames, corresponding to ~100 individual bursts.

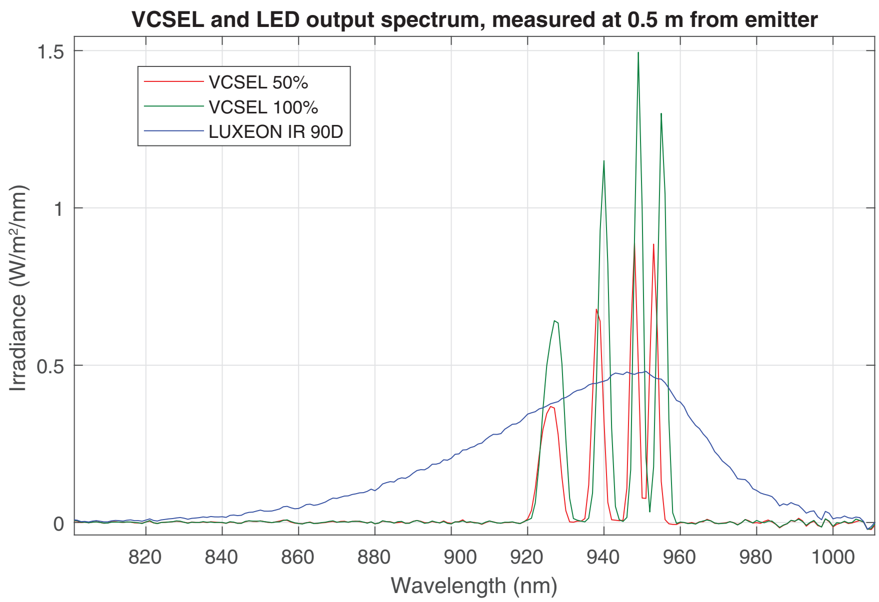

Figure 8. Measured spectra for VCSEL (driven at 50% and 100% of maximum current) and LED emitters (250µs burst length, 20MHz modulation frequency). Note: the spectrometer resolution (~2.5nm) is not good enough to resolve the VCSEL spectral width (< 1nm). The VCSEL shift in wavelength when increasing the drive current is due to temperature increase at higher current.

In this case, the LED emitters actually have a higher overall signal (integrated over the 820nm to 1000nm range); the figure below shows the measured irradiance for the two emitters. Note that the irradiance slightly decreases for longer bursts (due to higher temperatures reached by the device); however, keep in mind that the total amount of light collected by the detector actually increases, due to the longer burst/integration time.

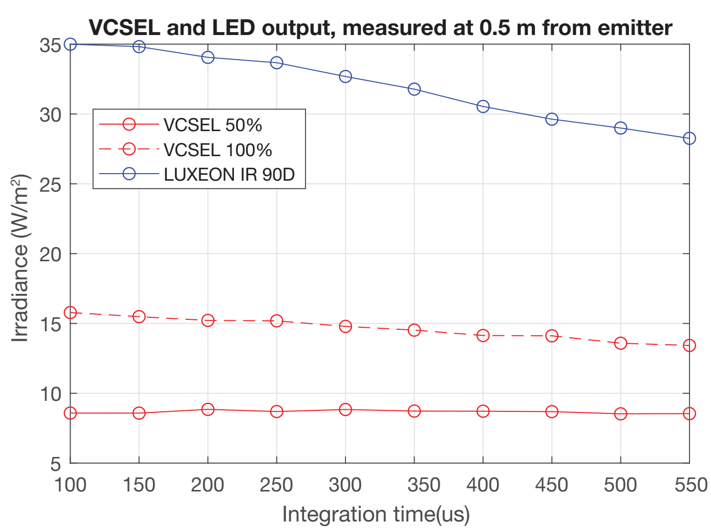

Figure 9. Average irradiance during a burst integrated over the 820nm to 1000nm range, measured for different burst lengths (modulation frequency 20MHz).

Since the VCSEL emission covers a narrower wavelength range, a band pass filter can be used to select only this range and reject everything else (like sunlight). In this case, the LED and VCSEL emitters have a similar irradiance in the wavelength range of interest (920nm to 960nm).

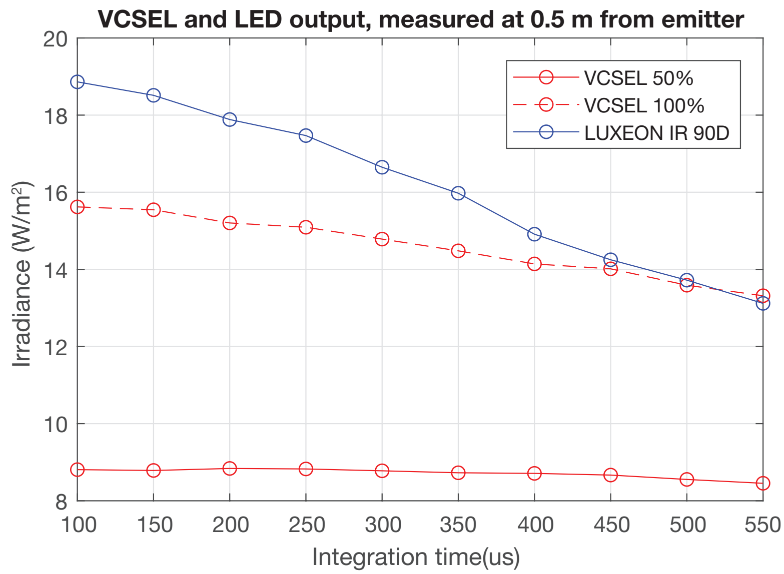

Figure 10. Average irradiance during a burst integrated over the 920nm to 960nm range, measured for different burst lengths (modulation frequency 20MHz).

For even narrower wavelength ranges, the VCSELs would have a clear advantage; however, when multiple VCSEL emitters are used, they'll have to be matched so that their wavelengths fit within the desired range. On the other hand, for application where a wide wavelength range can be used (e.g. indoor applications, which do not require sunlight rejection), LED emitters might be more suitable since their whole wavelength range could be used.

This is illustrated in Figure 11, where two 850nm illumination boards are compared, one fitted with LEDs, the other one with VCSELs. The LED provides a higher irradiance over the whole spectral range, but the VCSEL emits more light within the range of 845nm to 860nm. However, using such a narrow range is not practical, since it would mean that all VCSEL emitters would have to be matched to this range. Moreover, the VCSEL emission wavelength shifts with temperature; the filter used needs to be wide enough to accommodate this shift, and so even if only one VCSEL emitter is used, the wavelength range used still needs to be wider than the emission bandwidth.

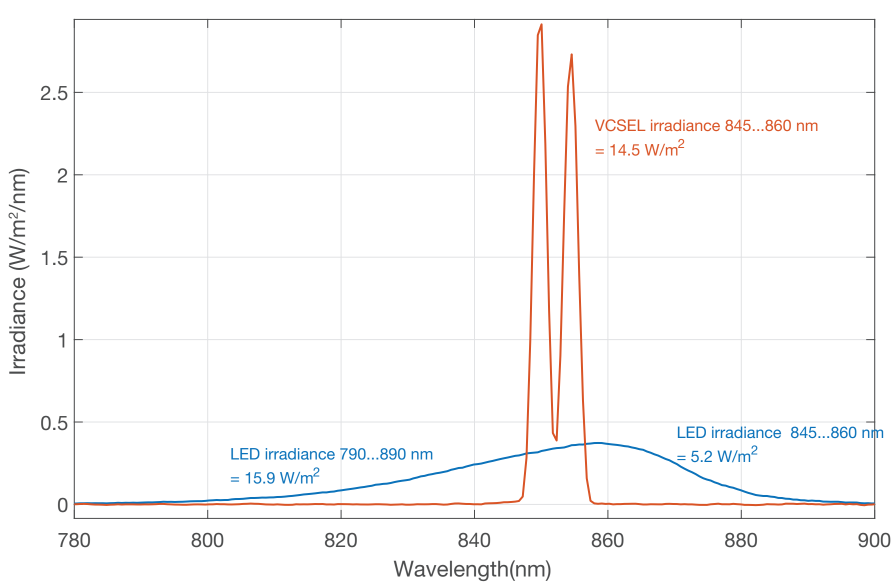

Figure 11. Irradiance of 860nm VCSEL and LED emitters (modulation frequency 20MHz, burst length 400µs), measured at a distance of 0.5m.

Pulsed regime (VCSEL vs LED)

As shown in Figures 12, 13 and 14, VCSEL emitters have shorter rise/fall times (Figure 12). However, it is possible to improve LEDs rise/fall times by using a voltage "boost" as shown in Figure 13. The rise time is decreased by a factor 2 and the pulse becomes more "top hat" like.

An additional benefit of the boost is that it improves the modulation amplitude, thus increasing the maximum modulation frequency at which the LED can be operated, for example, a boosted LED has no modulation drop at 20MHz compared to 12MHz, and only a 13% drop at 28MHz, compared with a 30% drop for a non-boosted LED (see Figure 14).

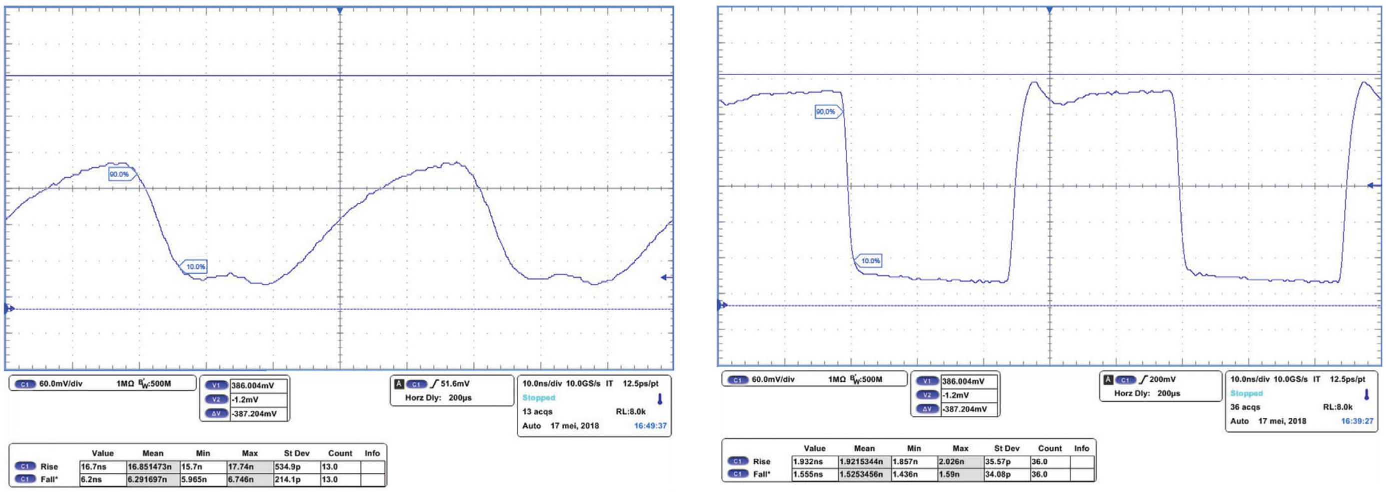

Figure 12. Pulsed behavior of a LUXEON L1I0 – 0940xxx emitter in a Melexis TOF evaluation kit (left) vs VCSEL (right). Modulation frequency 20MHz, integration time 400µs.

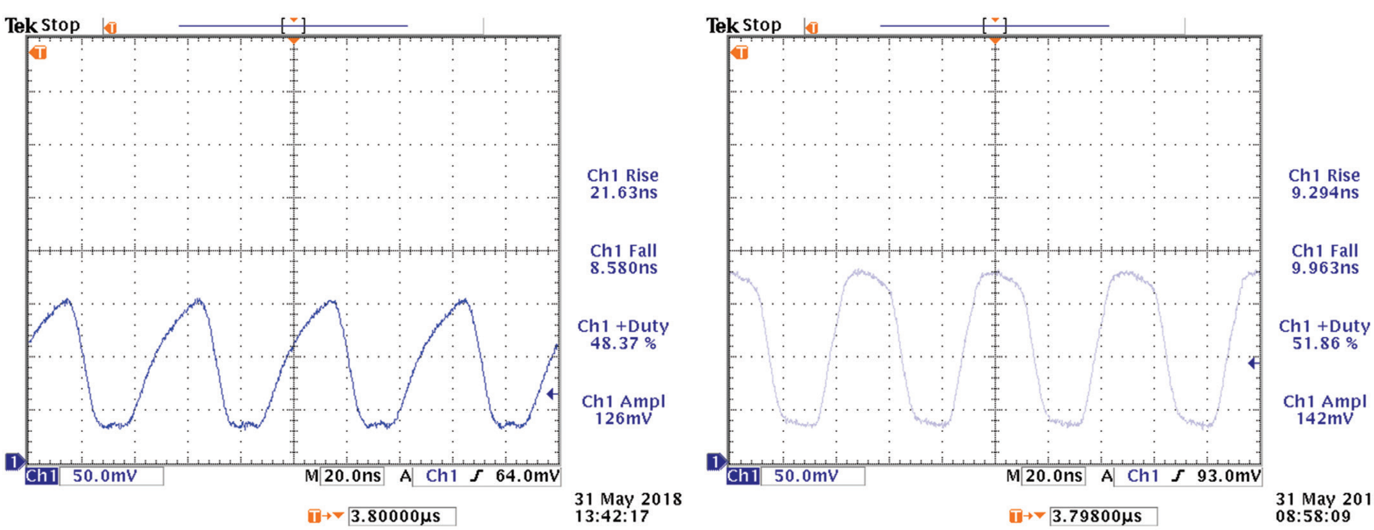

Figure 13. Pulsed behavior of a LUXEON L1I0 – 0940xxx emitter without (left) and with voltage booster circuit (right). Modulation frequency 20MHz, integration time 150µs, drive current = 3.5A.

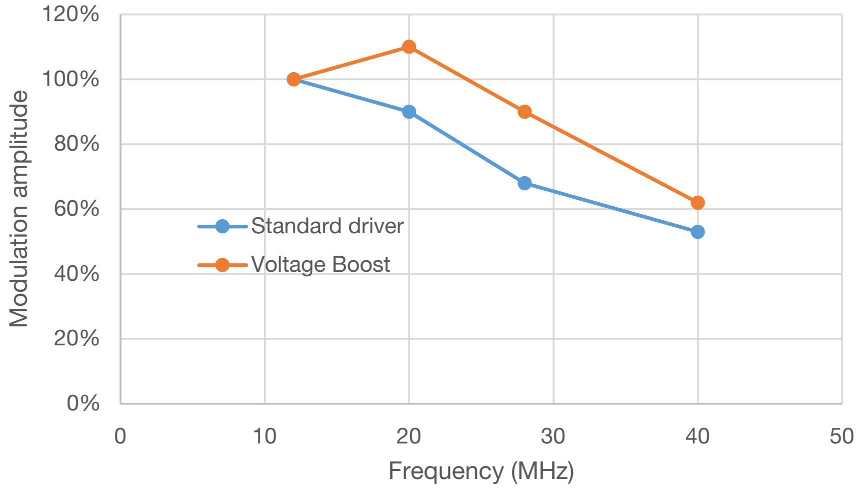

Figure 14. Modulation amplitude vs modulation frequency with and without voltage boost. The modulation amplitude at 12MHz is used as reference (integration time = 150μs, drive current = 3.5A).

System Performance – Distance Noise VCSEL vs LED

Ultimately, the end user cares about how precisely the system can measure distances. Having more light helps, but an equally important factor is the emitter's modulation frequency: measurement precision is proportional to the frequency, so faster modulation increases precision.

In this section, the performance of Melexis TOF systems equipped with VCSEL (850nm) and LED (940nm) illuminators is compared. The parameter used to judge the performance is "distance noise": the noise over 100 consecutive frames when the TOF system is measuring the distance to a static object, defined as the standard deviation of measured distance over 100 frames. The measurement is done at room temperature for different modulation frequencies and at different distances.

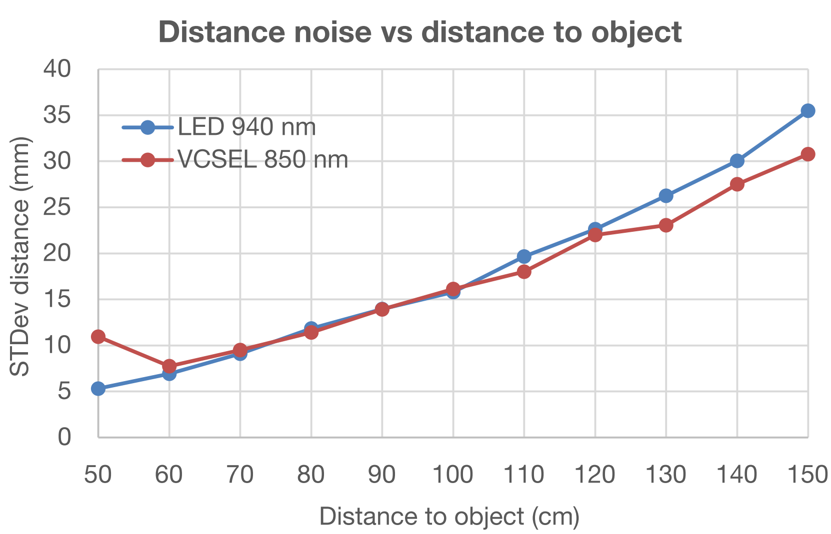

Figure 15. Distance noise measured for VCSEL and LED TOF system, at 12MHz modulation frequency, as a function of the distance to the object being measured

As shown in Figure 15, at a modulation frequency of 12MHz the two types of emitters provide equivalent precision (same noise level). At higher frequencies, the precision of the VCSEL system increases (see Figure 16).

For the LED emitter, increasing the frequency from 12MHz to 24MHz also leads to less noise and increased accuracy. However, for frequencies above 24MHz the noise level remains constant. This behavior is related to the higher rise/fall time of LED emitters and their lower ability (compared to VCSELs) to follow a fast modulation.

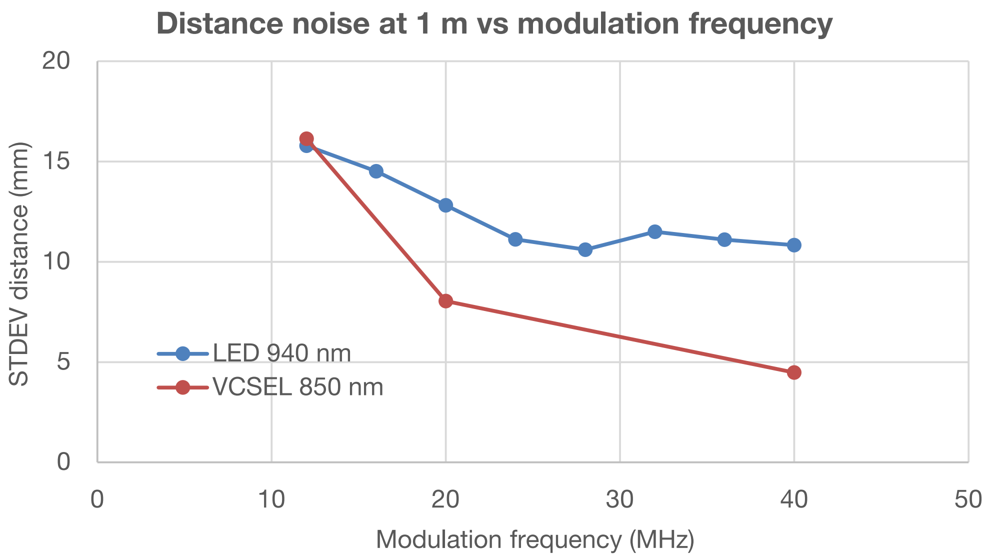

Figure 16. Distance noise measured for LED and VCSEL TOF systems for an object located at 1m distance, at different modulation frequencies.

Note that the distance noise can always be reduced by averaging multiple frames. Averaging over four frames would reduce the noise by up to a factor 2; for the LED illuminator modulated at 20MHz, this would mean a noise level of ~12mm at a distance of 1m cm, which is equivalent to the noise level provided by a VCSEL illuminator modulated at the same frequency (but without any averaging). Regardless of the emitter type used, LED or VCSEL, the noise can be reduced to arbitrarily low levels as long as a lower frame rate is acceptable.

Section 5: Conclusions LED & VCSEL – Application "Sweet Spot"

The diagram below summarizes, at a glance, the main characteristics of VCSELs and LEDs when used in TOF applications.

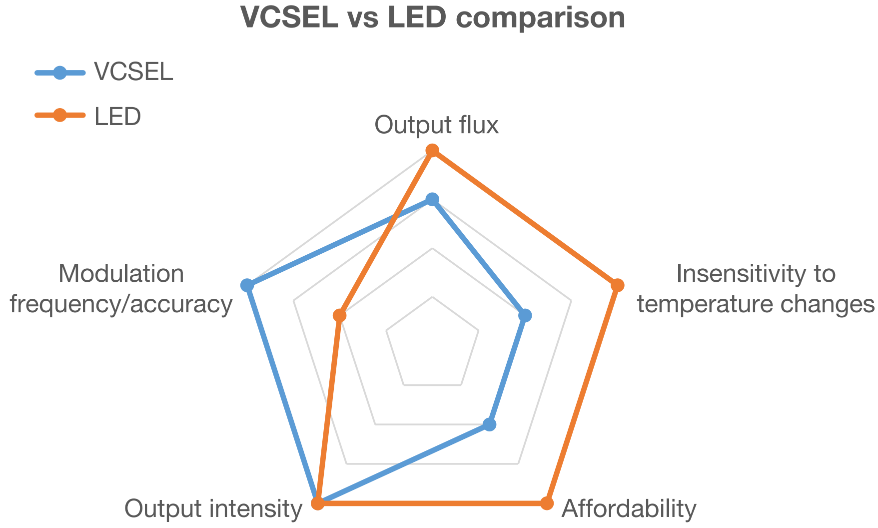

Figure 17. Qualitative comparison of IR VCSELs versus LEDs

The most suitable emitter depends on the precise specifications for each application; however, in general, here's a summary of how the two types of emitters fare, depending on application requirements:

- VCSELs:
  - High accuracy & frame rate
  - As good as possible rejection of ambient light
  - Narrower emission angles

- LEDs:
  - High total flux
  - Wider emission angles
  - Operating at high temperatures
  - Cost effectiveness

For more information on LUXEON IR LED emitters, visit https://www.lumileds.com/infrared-emitters

Melexis TOF sensor ICs and LUXEON IR LEDs can be obtained through selected distributors: https://www.lumileds.com/howtobuy

Melexis sales inquiries: https://www.melexis.com/en/contact

Melexis TOF systems & related info: https://www.melexis.com/en/search#q=TOF

About Lumileds

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To learn more about our lighting solutions, visit lumileds.com.