Application Note

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VCSELs for Sensing Applications

Product Line VCSELs

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1 Introduction

Vertical Cavity Surface Emitting Laser (VCSEL) arrays have emerged as an important technology for applications within the consumer, industrial, automotive, and medical industries. While laser-based sensing and imaging have been available for many years, the integration of VCSELs really expanded with the advent of face recognition integrated into mobile phones using a structured light approach. This market opportunity has created a second boom for VCSELs after their initial success in high bandwidth data communications. Since that time, VCSELs have been incorporated into an increasingly broad range of applications including wearables, medical, security, augmented/virtual reality, drones, logistics, robotics, industrial safety, passenger monitoring, gesture recognition, and automotive LiDAR.

AMS OSRAM has developed a family of VCSEL power arrays targeting many sensing applications. This application note introduces the relevant sensing markets, the benefits of the VCSEL technology, and the performance that has been demonstrated. This application note describes the key attributes that are relevant to performance requirements for illumination sources and the applicable laser design options available for high power VCSEL die for 3D sensing solutions.

2 Sensing Applications

2.1 Applicable Markets

High Power lasers have recently made significant inroads in the consumer market. They have found application as proximity and ranging sensors, face identification, and 3D cameras in cell phones. 3D cameras can also enable gesture recognition in gaming systems and situational awareness into augmented and virtual reality systems. Potential future consumer applications can include home automation involving biometric identification for security or gesture recognition for controlling appliances and electronics.

The benefits of 3D imaging and sensing are also recognized within the automotive market. The initial application of lasers in this market will be in the automobile interior, such as gesture recognition and driver monitoring. Exterior applications include 3D monitoring over shorter distance in advanced driver-assistance systems (ADAS) to detect the presence of pedestrians or bicyclists and avoid collisions in the field.

In the industrial market, VCSEL arrays play an important role in providing 3D vision for safety sensors, motion control, and robotic applications for factory and warehouse automation. Industrial applications also consist of IR illumination for night vision in security systems. Drones for surveillance or delivery applications benefit from 3D imaging and sensing, and 3D imaging can help build CAD models beneficial for construction.

Applications are also emerging in the medical market. Besides the numerous benefits previously mentioned, visible an IR 3D imaging provides complementary information to more traditional x-ray or MRI imaging methods by revealing differences in tissue oxygenation and high-resolution patient scanning systems. High power lasers can also be applied in low light laser therapy applications.

Consumer

- Emitters for 3D sensing
- Sensing illumination
- Display
- IR Flash
- UV-C disinfection

Automotive

- Lighting (exterior/interior)
- 3D LiDAR
- Display functional lighting
- Ambient lighting
- Projection
- Intelligent forward lighting
- Adaptive driving beam

Industrial

- Sensing illumination
- 3D
- Sign and signal lighting
- Material processing
- UV-C disinfection
- Horticulture
- Outdoor/indoor lighting
- Stage lighting & projection

Medical

- Sensing illumination
- Operating room lighting

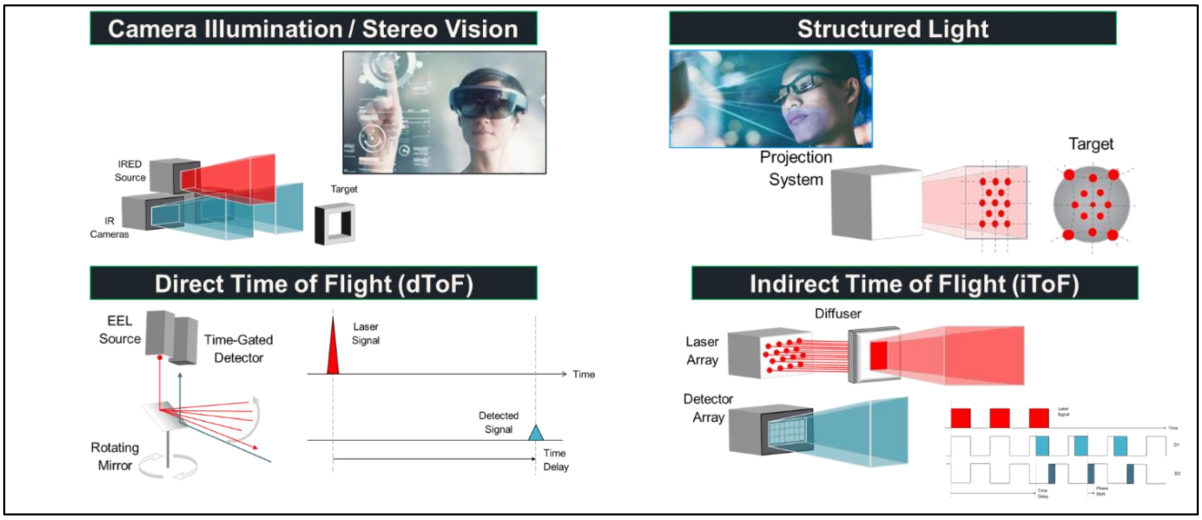
2.2 3D Sensing Methods

The characteristics of VCSELs have enabled the transformation of 3D sensing and imaging by providing a cost-effective optical source with unique characteristics. 3D sensing applications have driven most of the innovations in laser technology in recent years. The technical approaches to laser-based imaging have diversified to include stereo vision (SV), structured light (SL), Time of flight (ToF), and hybrid methods of these approaches.

Stereo vision (SV) involves the use of two cameras, with a known separation between them, that take images from two angles to reconstruct a 3D image. This includes the illumination for night vision cameras to enable constant uniform illumination over a wide angle. However, sensors can be based upon a variety of mechanisms combining the laser source with multiple cameras to capture multiple views for a complex algorithm and calculate 3D depth information that can be overlayed a final rendered image.

The structured light (SL) approach projects a known pattern of light that converts the observed depth distortions into information about the 3rd dimension of the illuminated object. In structured lighting, a pattern is imposed upon the light source (dots, lines, etc.), and then a high-resolution camera is used to detect distortion in the structure of the light to estimate object depth through trigonometry. This approach requires a more complex optical projection system to both improve 3D measurement resolution and reduce algorithm complexity.

Time of Flight (ToF) relies on measuring the temporal delay of a short laser pulse. In direct Time of Flight (dToF), a time gated camera measures the roundtrip flight time of a light pulse. dToF is ideal for long distances, but the distance resolution is limited to the pulse width and consistency of the laser electronics. A variation on this approach is the indirect Time of Flight (iToF) method, which modulates a pulse train and measures the intensity phase shift of the reflected light signal to estimate distance travelled. Special detectors measure the amount of measured power out of phase with the modulated signal. Multiple signals in iToF are collected and averaged to improve resolution in distance measurements, but its performance is typically limited to short-range applications.



2.3 Illumination Source Requirements

The requirements for the optical source depend upon the application and the sensing mechanism used. Each method uses VCSEL illumination over a wide range of operating conditions including peak optical power and pulse conditions. The focus on optimizing laser output power, efficiency, and beam divergence is essential in terms of VCSEL performance. While maximizing laser efficiency has always been a goal of VCSEL development, 3D sensing solutions are looking for many additional key features in an ideal illumination source. Some of the important requirements of the optical light source for these applications include the following:

- Optical Power: Sufficient power is required for illumination of the area of interest. The optical power can exceed > 100 W for long distance and wide Field of View (FoV) applications. For vehicular and transportation applications, laser solutions require > 1 kW of peak optical power for LIDAR in self-driving cars.
- Power Conversion Efficiency (PCE): A high efficiency in converting electrical to optical power is advantageous for product mobility. This is particularly true for consumer devices and autonomous vehicles, where battery lifetime is strongly dependent on environment sensing and illumination. In addition, the required thermal solutions to achieve the required illumination power result in reduced weight and product costs.
- Spectral Wavelength: For most human-interfacing applications, it is preferable that the illumination is in the infrared region, so it is unobtrusive to the human eye. On the other hand, low-cost silicon photodetectors or cameras cannot detect wavelengths in the long end of the spectrum. Therefore, the most desirable wavelength range is between 800nm and 1000nm. Lasers operating at 940nm are advantageous for outdoor applications, since water absorption in the atmosphere reduces solar radiation noise at this wavelength.
- Spectral Width and Stability: The spectral width of the array is important for use with filters for rejecting background radiation. The presence of background radiation, including sunlight, can degrade the signal-to-noise ratio of a sensor or camera. This can be compensated with a spectral filter on the detector or camera. More efficient notch filters can be implemented when an illumination source with a narrow and stable spectrum is used.
- Beam Divergence: A narrow, symmetric beam is ideal light collection and distribution when working with pattern projection with collimation optics or uniform illumination with diffuser optics.
- Packaging Solutions: The package provides the electrical and optical interface to the optical source. It may incorporate an optical element to control the beam profile and may generate a structured lighting pattern. Particularly for mobile devices, the overall packaging should be as compact as possible.

3 Semiconductor Optoelectronic Devices

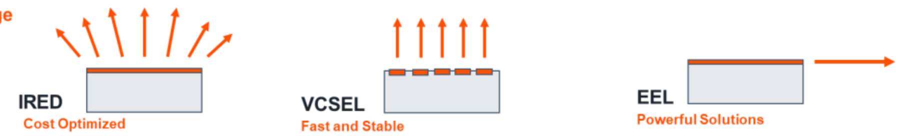
There are 3 main types of semiconductor-based NIR light sources, but the performance of each semiconductor optoelectronic device is different from one another due to their own design characteristics. They all begin with the growth of single crystal semiconductor layers on a gallium arsenide or indium phosphide substrate. Individual devices are then created by photolithographically patterning the wafer. Light Emitting Diodes (LEDs) emit light from the top surface of the wafer and can be tested at the wafer level. In contrast, lasers require a material that emits light and a cavity to provide feedback to achieve stimulated emission. The cavity for edge-emitting lasers (EELs) is formed by cleaving the wafer and polishing the end-faces. Due to the design, light is emitted from the cleaved edge of the chip, so the EELs cannot be tested before packaging.

The cavity for a VCSEL is built within the crystal by growing mirrors formed by alternating layers of two different refractive indices, creating a Distributed Bragg reflector (DBRs). With the light generating layers between two Bragg reflectors, a cavity is formed that produces stimulated emission that radiates from the surface of the wafer. Like LEDs, VCSELs can also be tested on the wafer. This reduces production costs by sorting nonfunctional die before packaging. Therefore, VCSELs combine the manufacturing advantages of LEDs with the performance advantages of EELs with the key benefits of improved beam quality and wavelength stability.

In addition, the vertically emitting nature of the VCSEL can take advantage of surface mount packaging that has been developed for LEDs. Packaging provides the electrical and optical interface to the VCSEL array, as well as mechanical protection.   VCSELs are frequently combined into modules that include optics and/or drivers to create the desired illumination profiles. Innovative methods in VCSEL design and integration can enable packaging to enhance both illumination source performance and footprint.

VCSEL Applications

The VCSEL Advantage



Power [CW]	~ 4 W – Scales with Area	~ 8 W – Scales with Area	~ 8 W – Point Source
Power [ns Pulsed]	N/A	~ 120 W – Larger Area	~ 120 W – Point Source
Power Density	Low	Mid	High
Beam quality	Lambertian / Very wide divergence	Symmetric / Low divergence	Asymmetric / Medium Divergence
Temperature shift	0.25 nm/K	0.07 nm/K	0.25 nm/K
Spectral width	20-30 nm	1-2 nm	3-8 nm
Speckle	Low	Low in an array	High
Switching time	ms	ns	ns
Packaging	Simple	Simple	Complex
Cost	Best	Good	Medium

4 VCSEL Performance Benefits

Power conversion efficiency (PCE) is the ratio of output optical power divided by the input electrical power used to drive the device. The PCE in VCSELs in the range of up to 60% can be achieved at wavelengths in the 800-1000nm range, which is typically better than the efficiency of most LEDs. When one considers the spectral width and beam divergence, the efficiency benefits become even more pronounced for complete illumination modules.

VCSEL geometry traditionally limits the amount of optical power a single VCSEL can provide at high efficiency. There is a limit to the maximum current density a single VCSEL can handle as well as how far current can be spread efficiently across larger diameter apertures. Thus, the maximum power that can be emitted from a single aperture is limited. For applications requiring more power, multiple VCSEL apertures are created on the chip that operate together in parallel. The ultimate solution for high power VCSELs to develop a larger VCSEL die with multiple apertures, each operating at peak efficiency to meet sensing illumination requirements.

Due to the circular design of VCSEL apertures, the optical beam from the VCSEL is circular with a much narrower emission angle compared to the other semiconductor optoelectronic technologies. The angular beam divergence of a VCSEL is typically 10-25 degrees full width half maximum (FWHM). The full beam from the VCSEL can be collected using optical elements including micro lens arrays (MLAs) for a focused beam profile, diffuser optics for a wide beam, or a diffractive optical element (DOE) for pattern generation. Additionally, the fact that the VCSEL apertures in an array are incoherent allows for the reduction in speckle as compared to a conventional high-power EEL. An important advantage of this solution is that the array of mutually incoherent lasers provides a low speckle illumination pattern while still maintaining narrow linewidth for notch filters.

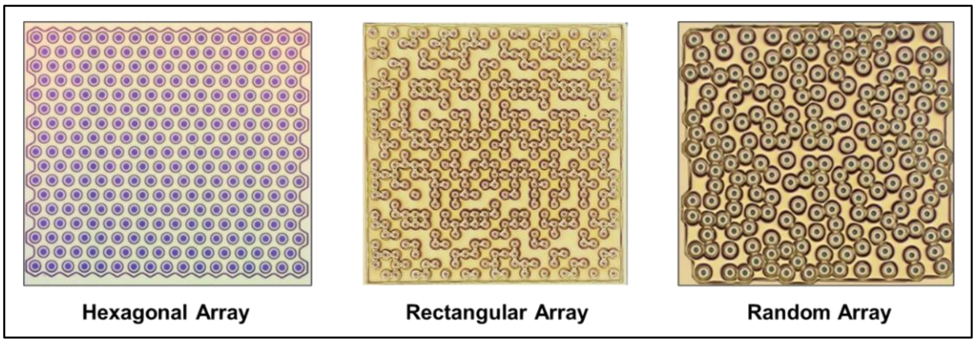
High-power VCSEL arrays are typically used in pulsed operation. In this mode a high peak power is produced that improves the signal to noise ratio, while the pulsed operation can be used to keep the average power within an eye safe regime. The output power of a VCSEL array is also limited by self-heating during operation, thus pulsed operation can often produce significantly higher peak output power. The increase of peak optical power can be achieved using narrower pulse widths and lower duty cycles. Like EELs, VCSELs can be driven with extremely short pulse widths < 10ns, typically over hundred times faster faster than what LEDs are capable due to slow rise times.

High power VCSELs have a spectral width of approximately 1nm. In comparison, an LED typically has a spectral linewidth of 20-50nm, resulting in the rejection of much of the light by a notch filter, and hence reducing the effective PCE of the LED. In addition, the wavelength shift is of the VCSEL is less sensitive to temperature, increasing only 0.06nm per 1 degree Celsius. This shift with temperature is 4X less than the wavelength shift in an LED or a Fabry-Perot EEL. This allows the use of filters with the photodetector or camera to reduce the noise associated with background solar radiation. VCSEL technology addresses the attributes required by 3D sensing and imaging, including power efficiency, the ability to combine a narrow spectral width with a low speckle illumination source, narrow beam divergence, and significant packaging flexibility.

5 VCSEL Design Solutions

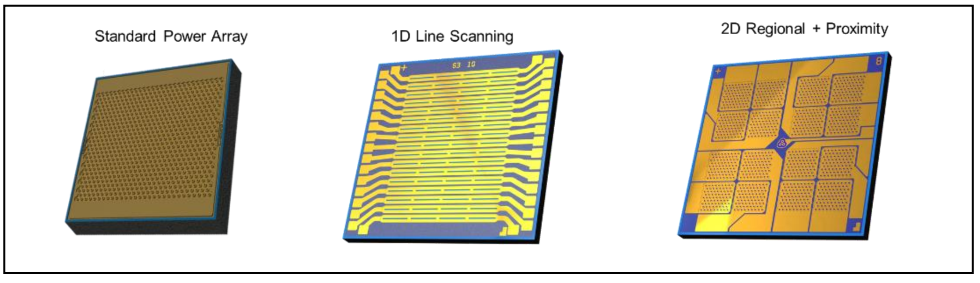
5.1 Advanced VCSEL Designs

With high power VCSEL products consisting of multiple laser emitters in a scalable 2D die, this framework enables improved flexibility in the design and application of VCSELs for 3D sensing applications. Utilizing projection optics, the emitter array can become a dot projection illumination source with photolithographic resolution for structured light applications. The structure of VCSEL emitters can be further compounded with the use of diffractive optical elements (DOEs) to create a complex structured pattern that improves 3D measurement resolution in sensing applications.



VCSEL die can be designed to improve illumination capabilities available to the laser integrator. One method to improve performance is in the utilization of segmented and addressable arrays. Traditional VCSEL die are binary light sources, and thus multiple laser illumination sources would require an appropriate quantity of individual laser die. Alternatively, the VCSEL die can be segmented and paired with appropriate optics to sequentially illuminate different segments in the field of view to compensate for the limited size of detector arrays and reduce glare from high reflectivity objects in detected regions.

Segmenting the VCSEL die into addressable units enables the VCSELs to make FOI adjustments to improve illumination and sensing control. If each segment can target a subunit in the FOI, each segment can be adjusted to control signal intensity, improve module efficiency, and reduce unwanted glare from the illumination target. VCSELs can also incorporate segments for different functionalities to combine multiple sensing features into a single package. As an example, both low and high power segments can be incorporated together on the same VCSEL die to combine proximity sensing and flood illumination respectively.

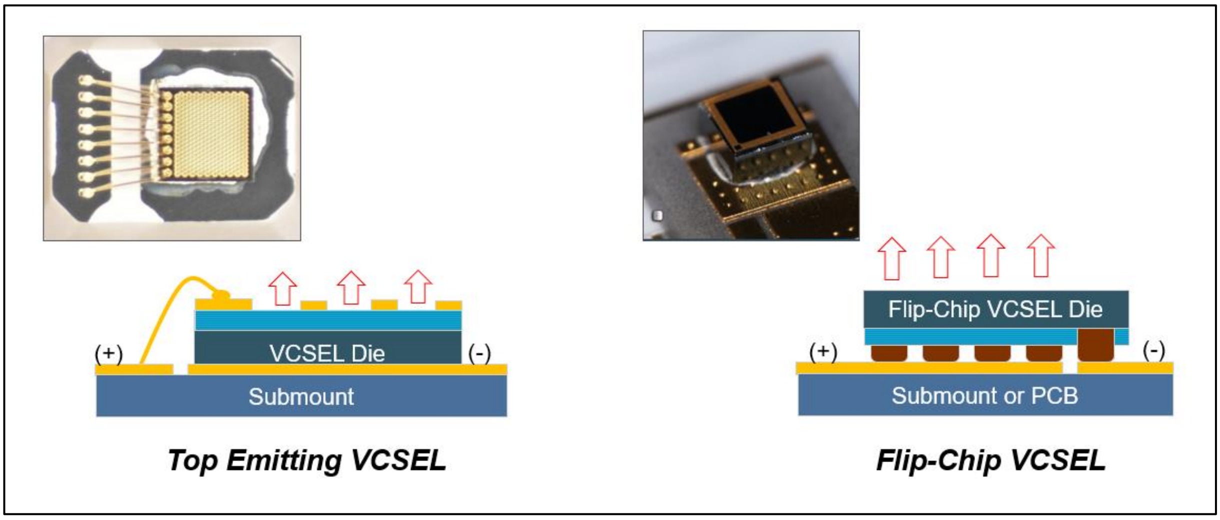


5.2 Flip Chip VCSELs

The next level of VCSEL integration is the development of flip-chip VCSELs that can be bump bonded onto a substrate. This design reduces the footprint compared to top emitting VCSELs that require additional space for wire bonding. Flip-chip VCSELs can be bonded in closer proximity to or directly on top of a laser driver chip to further reduce both package size and parasitic inductance.

The design incorporated both cathode and anode contacts with bump bonds on the original top surface of the wafer along with solder bumps for a subsequent solder reflow attachment to a submount. The VCSEL is designed to emit light down into the substrate side of the GaAs wafer, so the die is flipped to achieve upward-emission. Unless the substrate is removed from the wafer, the operating VCSEL wavelength must be longer than 900 nm to avoid excessive absorption from the GaAs substrate.

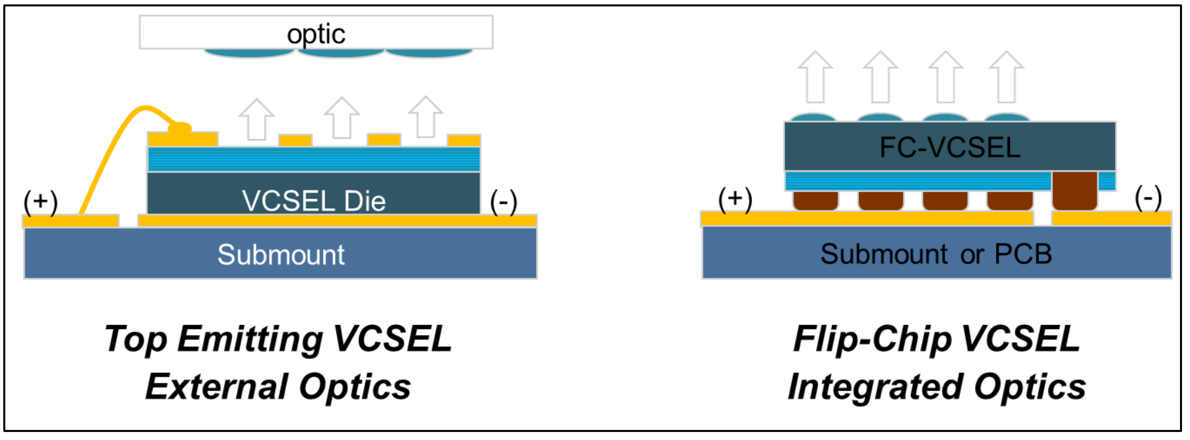
Flip-chip VCSELs exhibit improved power density due to their unique design. Traditional top emitting VCSELs are limited to 20 µm diameter apertures due to the difficulties in spreading current across the open aperture. In contrast, the apertures in flip-chip VCSELs can be fully metalized, significantly improving uniform current spreading across larger sized apertures, with minimal performance degradation in aperture diameters as large as 100 µm.



5.3 Wafer Integrated Optics

The development of an illumination module requires more than a high-performing VCSEL die. The light emitted from the VCSEL must be shaped into a profile that properly illuminates the target field of illumination. Future generations of VCSEL integration will continue to improve on the trends of improved FOIs, packaging miniaturization, and faster rise times.

The first generation of VCSEL SMD packaging involved the incorporation of beam shaping optics into the module. In next generation modules, optical components can be integrated into the top of flip-chip VCSELs to further reduce the module's size. A micro lens array (MLA) can be deposited onto flip-chip VCSELs with each lens aligned its corresponding aperture in a power array with reduced aperture pitch and increased alignment accuracy. Alternatively, diffuser and holographic patterns can be applied onto flip-chip VCSEL die to expand and shape the output beam for wide illumination and ensure the source is eye safe without requiring external optics. Both MLAs and diffuser patterns can be used to both control the optical beam width and angular direction, which can be applied to segmented VCSELs to improve segmented illumination in 3D sensing applications.



6 Summary

Optical sensing is becoming a key technology in a variety of markets. The multiple approaches, including structured lighting and time of flight, dictate performance requirements for the optical sources. Other requirements of optical 3D sensing, such as output beam profile and eye safety requirements, are essential in the illumination source. Semiconductor lasers meet these requirements, with VCSELs being particularly beneficial in applications requiring small size, high efficiency, and narrow spectrum.

The emergence of 3D sensing technology in the consumer, industrial and automotive markets, as well as increasing demand for applications requiring this technology has led to a second significant expansion of the market for VCSELs. The preferred performance characteristics of the devices for these applications is differentiated in many ways from previous requirements, which has driven innovation in VCSEL technology. The investment in VCSEL technology enable continued improvement in efficiency, peak powers and pulse rise time at multiple operating wavelengths. The VCSEL can also be designed for flexible and multi-functional laser illumination with the advent of die segmentation. Future requests to increase pulse performance and enable further miniaturization has led to the advent of flip-chip VCSEL technology. All of these known technological advances can be integrated in next generation VCSEL modules and are expected to be available for commercial applications in the next few years due to strong economic demand within the consumer, industrial, and automotive markets.

7 Revision Information

Changes from previous version to current revision v1	Page
Initial application note draft	

- Page and figure numbers for the previous version may differ from page and figure numbers in the current revision.
- Correction of typographical errors is not explicitly mentioned.

8 Legal Information

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