White Paper

Efficient Beam Shaping for LiDAR

西安炬光科技股份有限公司
Focuslight Technologies Inc.

中国
陕西省 西安市
高新区丈八六路 56 号

56 Zhangba 6th Road,
High-Tech Zone,
Xi'an,
Shaanxi 710077,
China

Tel +86 29 8188 9945 电话
Fax +86 29 8177 5810 传真
Email sales@focuslight.com 邮箱

1 Background

The goal of the next generation of advanced high-resolution LiDAR products is to provide compact solutions that can reliably and affordably recognize objects at long distances and wide angles while being safe for other road users and pedestrians. Moreover, reducing unused photons in upcoming autonomous vehicles will be essential to avoid uncontrolled photonic noise and non-visible contamination with laser lights on streets and throughout cities. Such noise could affect other technologies, equipment, and the eyes of both people and animals. In this article, we discuss the critical factors that influence the control of LiDAR photons with the latest beam shaping innovations and how to achieve control while maintaining high quality for volume production. We start by considering the requirements for laser sources, such as high-power and good signal-to-noise ratio for long range. These influence the need for damage threshold and homogeneity distribution for all optical components. Wide angles and eye-safety can be addressed by glass optics with high refractive indices in combination with intelligent ROE and DOE beam shaping approaches, reducing zero-order or hot spots. Keeping these parameters stable under different environmental influences, i.e., wide range of temperatures, is the key to a safe and reliable product for the automotive industry and beyond.

2 Requirements / Challenges

The use of LiDAR technology for distance measurements is an accurate and reliable technology. The transfer from speed or topology measurement to continuously monitoring and analyzing the dynamically moving environment from the perspective of driving cars and other transportation vehicles introduce a wide range of challenges for laser sources and optics. Due to a wide range of addressable driving profiles, speed and traffic dependent distance and area measurement of in front or around the cars can be addressed by combining different types of laser sources and optics with pulsed laser power from a few Watts to Kilowatts level. Laser safety and safe detection of other road users with millisecond detection and analysis is a challenge for optics, electronics, and networks as well.

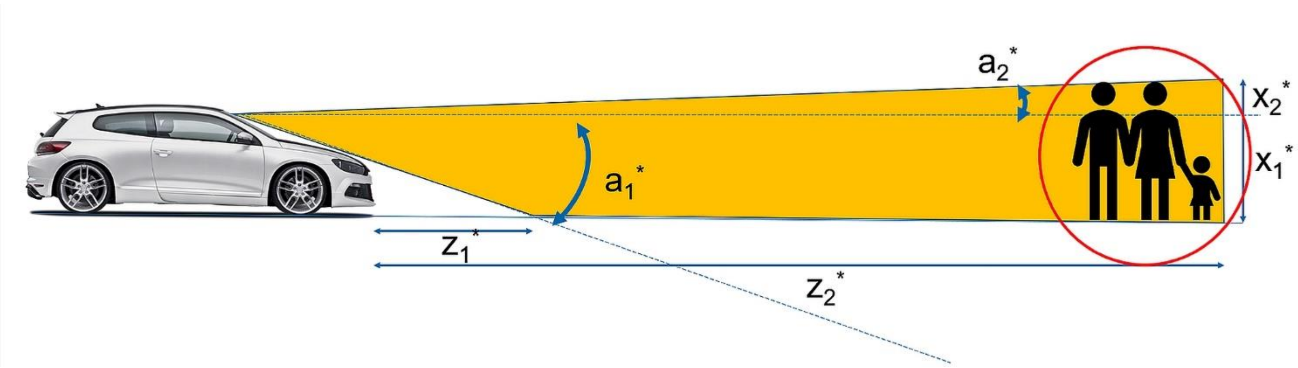
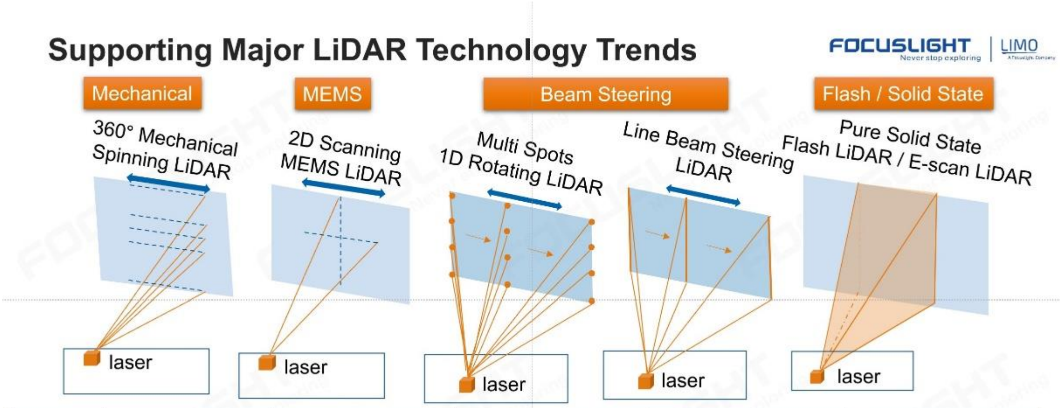


Figure 1: Vertical cross-section of a short and mid-range LiDAR illumination profile

To generate a high-resolution photo-like distance mapping around the car requires very defined angular resolution of the laser source and the detector, independent of the technological choice between (multi) spot-, (segmented) line- or field-illumination approach for the emitter side of the LiDAR system.



	Type #1	Type #2	Type #3	Type #4	Type #5
Lasers	905nm EEL	905nm EEL 1550nm fiber laser	905nm EEL	905nm EEL, VCSEL 1550nm EEL	850-940nm VCSEL 1064nm DPSS
Scanners	Mechanical spin	MEMS	Rotating Mirror	Rotating Mirror / MEMS	Electronic scanning
Focuslight Offering	Optics Assembling	Optics Assembling	Optics Assembling	Optics Transmitters Assembling	Optics Transmitters Assembling

Figure 2: Examples of LiDAR illumination technologies (Focuslight Automotive BU)

Today, a wide range of diode and solid-state laser sources are available that can be used in LiDAR applications. Since every laser source has a specific beam profile and beam quality, the related optics needed to bring the light into the right direction with a very defined angular resolution requires a very flexible and accurate design of both optics and corresponding production technology, so that it can address all kind of beam collimation, shaping and splitting functions, precisely matching the emitter with the required illumination profile at the target. The latest developed Focuslight LiDAR optics, included in our most recent optical systems, was selected to not only to bring the laser photons into the right direction with the right beam profile, but also to minimize the photons outside the detector's field of view – the observable area of the corresponding detector or receiver unit.

The aspiration is the combination of a cost-effective high-power laser source, such as a VCSEL or (stacked) diode laser, with tailored micro-optics that precisely shape the beam to the application with minimum loss, reliable over the car's lifetime, and producible in high volume. The major competing approaches are (multi) spot-, (segmented) line- and field/flash-illumination, but they all have in common that the quality of their specifically designed micro-optics decides about the system's performance. Every photon that is lost outside the detectable area will either directly decrease the LiDAR's range or decrease the sensitivity via a reduced signal-to-noise ratio. Therefore, beam shaping optics are needed that transform the laser source into a high-resolution measurement and detection system. In addition, the reliable, long lifetime operation of the LiDAR system without degradation of range, resolution and speed is essential to select the right balance of performance, cost, and reliability.

The current and coming LiDAR applications and related quantities are very attractive and motivating for all kind of optics manufacturer and contract manufacturer to offer products and capabilities to this new fast-growing market. The use of LiDAR for safety related applications has some challenges for all optics that will limit the choice of applicable optics. Since a LiDAR system for a car needs a 360° view around the vehicle, but a far smaller angle in vertical direction, the aspect ratio will be huge, even if the horizontal view will be separated into several LiDAR systems. Thus, designs based on conventional optics with a rotational symmetry will ultimately face strong challenges with respect to distortions or homogeneity, leading to a natural advantage of anamorphic beam shaping for rectangular illuminations, using cylinder-array based design.

For the collimation and beam shaping of diode lasers, Focuslight uses glass based acylindrical lenses and lens arrays that have high order spherical shapes to maximize the optical functionality per surface and to minimize the number of optics needed for the shaping of the laser light. In addition, these optics are products of a room temperature process with complementary polishing, which yield glass optics with an outstandingly low scattering and low diffraction loss performance. Unlike molding approaches, the cold processing avoids any heating & cooling steps, so that stress inside the glass is completely prevented. Thermal imaging, bi-refringence or thermally induced fractures are therefore eliminated. Similar like the wafer-level production technology of diode laser optics for industrial laser, Focuslight uses the same 25 years proven technology to produce collimation and beam shaping optics for anamorphic designs of high-resolution LiDAR laser sources, made of glass with polished surface quality, including AR coatings and automatic separation and cleaning technologies that can handle millions of lenses per month, today.

3 Methodology

The steps needed to design an optical system for LiDAR applications cover several tasks and milestones that are needed to achieve an application specific optimized optical system design. In addition to the description of the technical analysis and design process, we have selected some examples to get a better understanding about the steps needed to come to the best possible design and performance.

3.1 Selection of object illumination parameters

Depending on the kind of vehicle, the illumination parameters must fit to the operation modes like

- slow speed + higher resolution + larger field of view
- faster speed + smaller resolution + larger distance of detection + smaller field of view

In addition, the quality of the illumination can be defined and selected with the following parameters that become more and more relevant because of the accuracy of detection needed for the safety level given by the local country specific regulation for the performance of such devices.

- resolution and contrast, discrete points or homogeneous line or field profile
- intensity per measurement point
- number of qualified points or line length or field size (equivalent to the angle of incident)

The parameters that are needed and the related performance that is possible with a commercial product implement some challenges that can be solved using a flexible and precise beam shaping technology described in the following chapters.

3.2 Laser source

Due to a large variety of available and suitable diode and solid-state based laser sources, each type of laser has a specific light emission characteristic that needs an individually designed and produced optical system to transform these characteristics into the application specific beam shape, which is the basis to illuminate and detect a specific area and range of distances. In each case, pulsed operation with short pulse width is required, with suitable wavelength and highest power for maximum range, limited by power density eye safety requirements.

3.3 LiDAR Optics

Given a certain laser source, one of the fixed input parameters for the LiDAR optics is the laser's beam parameter product. It defines the next steps in optics choice, including effective focal length and achievable divergence, influencing distance and resolution for the application. In some cases, it could be more efficient to define first the brightness and beam parameter product of the illuminated area and in a second step select the compatible laser and the beam shaping optics in between.

First priority has the use and the conservation of the maximum brightness of the laser beam parameter. This brightness level can be used to select a first aspheric or acylindrical lens that collimates the laser source with the residual divergence needed in the LiDAR concept. For diode laser sources, Focuslight typically uses a single plano-convex acylindrical lens with an effective focal length in the range of a few millimeters to collimate the beam within a few milliradian divergence and a defined beam diameter to fit into the scanner aperture that moves the beam over the target area. For maximum efficiency, the lenses should be designed with aspheric parameters of higher order, which are available for design in all standard optical simulation tools.

Surface description of aspheric or acylindrical lenses: $z = \frac{c_v \cdot p^2}{1+\sqrt{1-c_v^2(1+k)p^2}} + \sum_{i=1}^{\infty} AS_i \, p^i$

The commonly used equation is advantageous to reduce spherical aberrations, and especially beneficial if used for a combination of several acylindrical lens arrays with different surfaces shapes to bring the light into the right shape and direction. The use of different oriented cylindrical lenses and lens arrays helps to achieve the right aspect ratio of lateral and horizontal areas of illumination with homogeneous intensity distribution, which is especially beneficial in LiDAR system designs. The following picture shows some combination of cylindrical beam shaping arrays that can be utilized to generate an intensity distribution that matches the field of view and the field of illumination.

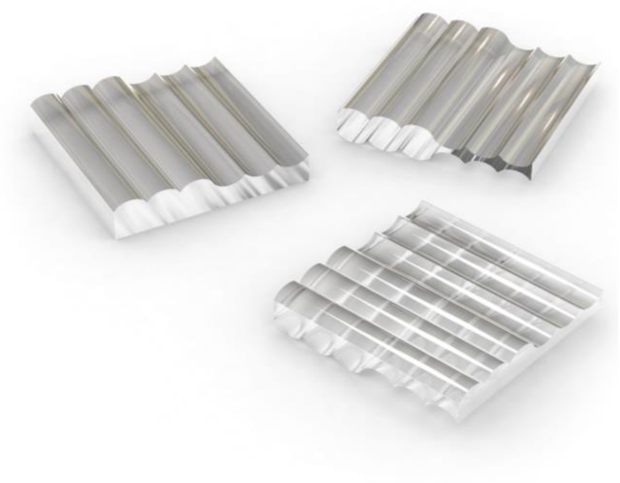


Figure 3: Examples of anamorphic beam shaping configuration

To minimize the loss of light that is based on diffraction or scattering, the design should be simulated with wave propagation methods, which help to see all unused and uncontrolled photons. The Focuslight optics are designed and simulated with various commercial and specifically customized tools to achieve the best possible and brightness saving lens design. Due to the use of wafer level production technology, all optical components for collimation, shaping and beam mixing are produced in a non-sequential production process and are tested on the wafer before being cut into individual components.

The combination of application specific selected glasses and high-order aspheric surface designs enables a compromise-free shaping and propagation of the light through the optical system with fully defined and controlled laser beam geometries and intensity profiles. In addition, the complementary polishing process of all optical surfaces inside the beam path maximizes the level of usable light in the illumination of the targets in the environment of the vehicle, by minimizing the creation of stray light. With the right choice of high-quality glass, the smooth precision optics surface is far less susceptible to harsh environmental conditions over the product's lifetime than their polymer-based counterparts, keeping the optical functionality and performance of beam shaping components on a high-quality level.

Figure 4: Various fast axis collimation lenses with focal length from 0,16mm to 7,7mm for diode laser

To be able to select and focus during the design phase on the most relevant technical parameter, the following key performance indicators of LiDAR optics can be selected for high performing system designs:

1) Transmission efficiency
    a. All optical surfaces combine the polished precision optics surface quality with AR-coatings optimized for the characteristics of the laser and the application.
    b. All photons that pass the optics will be used in the application and enable optimized optical signal quality and amplitude to achieve a clear separation from the signal of the environment.
2) Laser light collection efficiency
    a. The optical designs with acylindrical optical surfaces combined with selected optical glass can collect all the emitted laser light up to highest numerical apertures with a single optical component (fast axis collimation lens).
    b. Every selected laser source with its specific emission characteristic can be collimated and shaped with the above described acylindrical free-form surface design.
    c. Using optics dimensions from sub millimeter to several millimeters enable maximum optical functionality with the smallest formfactor.
3) Application specific adapted angular spectrum
    a. The field of illumination can be scaled up to 160° full angle with a single optical component.
    b. The lateral 360° field of illumination can be done with only 3 devices.
    c. The separate selected illumination angle in horizontal and vertical direction of the vehicle can be selected according to the dimensions, the speed, and the typical operation modes within buildings, on streets with high density of people and other vehicles and on highways.
4) Application specific angular resolution
    a. Selection of sufficient number of detectable points in a defined angular spectrum.
    b. Laser or optics defined number of total detectable points.

c. Combination of specific field of illumination and angular resolution.

d. High resolution detection for highest safety and maximum personal data securing with a quasi-camera mode without seeing and saving personal data.

5) Adapted intensity level and variation

a. Homogeneous area illumination, or

b. Intensity optimized structured illumination

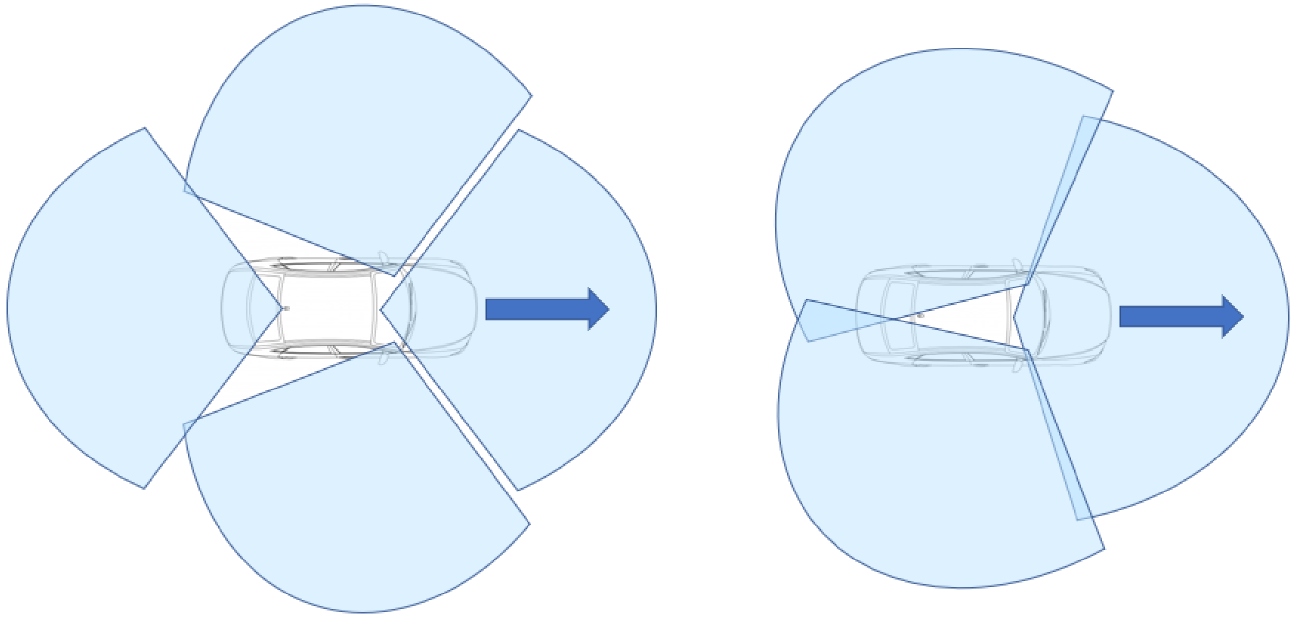


Figure 5: Examples of large angle LiDAR illumination schemes

All these performance indicators can be addressed and solved with diffraction limited optical beam shaping of light while keeping the diffraction loss on the lowest level. Avoiding stochastically diffraction losses is beneficial since they cannot be systematically reconstructed and processed in the laser illumination and corresponding detection in LiDAR architectures. Keeping the transmitted light fully usable in the LiDAR application, improves not only the safety and related signal detection level, but also optimizes the energy efficiency of the devices, which increases the related system lifetime. With the improved signal-to-noise ratio and the homogeneous illumination, the hot spots will be reduced, diminishing both interferential detection errors and laser induced eye flare. This enables an increased number of operating devices in the streets as a basis for an accident-free transportation.

Beside of collimation and homogenization features of optics, also splitting of beams with good contrast and angular separation between the channels becomes more and more important. Therefore, the optimization of beam profiles should be done with logarithmic intensity plots to understand in an early stage of the design that the selected optical components will be optimized within 30dB signal-to-noise ratio that can be measured during installation with high dynamic CMOS cameras. The following graphs shows the intensity distribution of a beam splitter with linear and logarithmic intensity distribution, that give much more information about the real contrast between the channels in a real environment.

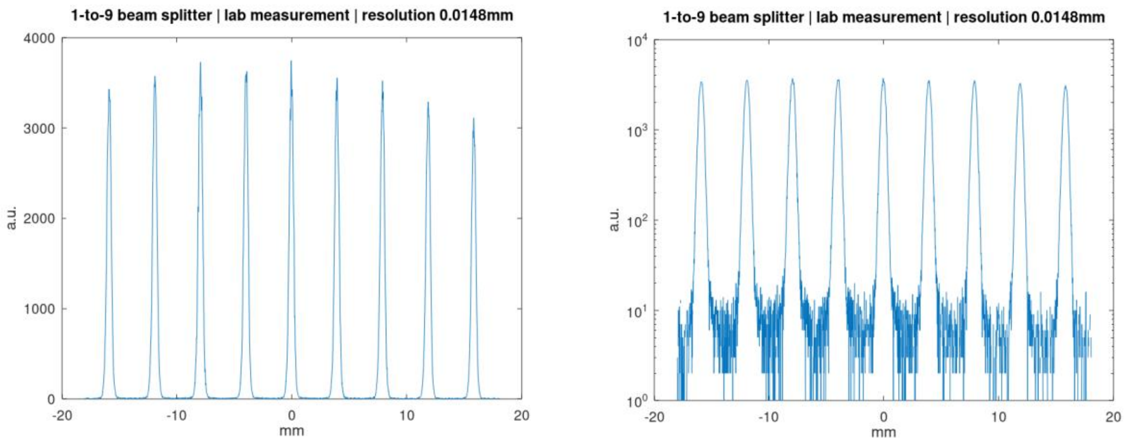


Figure 6: Comparison of linear and logarithmic design and analysis multi-channel structured light

Due to the increasing resolution in optical system simulation, related computer power and the possibility of using wave propagation methods to simulate even complex optical beam shaping system without simplification and low-resolution raytracing estimations, the design of optical systems and the selection of multi-functional beam shaping optics will be used to improve continuously the LiDAR performance and the intelligent interaction of vehicles with their environment. The new options to design and produce precision laser illumination units with accurate beam profiles and high-definition resolution will increase the functionality of LiDAR systems. Funneling and optimizing the different approaches into standardized sub-systems, they may evolve into new building blocks for intelligent networks, combining position and communication features for a safe transportation around the globe.

4 Examples and solutions

The following examples show some optical standard configuration used in LiDAR applications and some new configurations of next generation LiDAR products and infrastructure. All examples follow the Focuslight key performance strategy to bring the photons into the directions and areas where they can be used to avoid photonic noise and save the environment for maximum safe application and environmental integration.

4.1 FAC 3000, FAC 7700

New Fast Axis Collimator for high peak power pulsed diode laser arrays.

- HD LiDAR with up to 0.1° resolution possible

- Single element design for simplified optical system designs
- Acylindrical surface optimized for 10µm nano-stack diode laser arrays
- >99% transmission of the diode laser power
- Wafer level production and 100% performance tests for safety relevant applications
- Standard FACs for 4- and 8-channel nano-stacks with 3.3 mm and 7.7 mm available

4.2 Diffuser

New wide-angle diffuser for up to 160°FWHM illumination with a single light source.

- For all LiDAR laser sources
- Single element design for simplified optical system designs
- Wafer level production and 100% performance tests for safety relevant application
- Diffusers from 0° to 160° in Top Hat, Cos^{-2}, Cos^{-X} or individual design available
- Stable performance in a wide temperature range without degradation

4.3 What's next: Beam Splitter

Beam splitter with low diffraction loss splitting the laser beam into several discrete beamlets with similar power and intensity and up to 30dB contrast (simulation and design for customer specific laser sources on request). Glass or Fused Silica based products will become available for LiDAR and other applications using pulsed laser sources with high peak power.

- Excellent signal-to-noise ratio
- Single element design for simplified optical system designs
- Combination with diffuser approach possible to achieve wide angles
- Applicable for LiDAR, ranging & sensing or even materials processing

5 Conclusion

The design and integration of high performing LiDAR technology in transportation vehicles opens a new level of safety and active position control in current and coming autonomous transportation. The efficient use of laser photons with application optimized resolution and wide angles of illumination and detection increases the flexibility in the integration of this technology into current and next generation of car bodies and other transportation devices. The use of beam shaping optics with accurate control of intensity and angular distribution will enable new functions and performance levels with LiDAR technology to bring the individual transportation and mobility to the next level of safety and reliability.

Contact Info

Focuslight Technologies Inc.

Tel: +1 973 714 1850 (Americas)
+49 170 7759 695 (EMEA)
+86 29 8956 0050 (Asia)

Email: sales@focuslight.com

Website: https://www.focuslight.com

About Focuslight

Founded in 2007 and headquartered in Xi'an, China, Focuslight Technologies Inc. is a fast-growing company that develops and manufactures high power diode lasers (photon generation), laser optics (photon control), and photonic modules and systems (application solutions) used in advanced manufacturing, health, research, automotive, and information technology applications. In 2017, Focuslight acquired LIMO, one of the leading manufacturers of micro optics and beam shaping solutions, and a pioneer in groundbreaking photonics production technologies. Focuslight has over 400 patents worldwide and is ISO 14001, ISO 45001, ISO 9001:2015, and IATF 16949 certified. Additional information can be found at www.focuslight.com.