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Review Article

Yves Lutz and Martin Laurenzis*

Beam shaping of laser diode stacks for compact and efficient illumination devices at the French-German Research Institute of Saint-Louis

Abstract: Laser diode stacks are applied for the realization of compact and efficient laser illumination devices for active imaging (e.g., laser gated viewing). An efficient use of illumination power and sensor arrays has to adapt the laser illumination to the sensor's field of view (FOV) with a perfectly matched and homogeneous illumination field. In the past decades, ISL has studied different methods for beam shaping and homogenization of laser diode stacks. In this publication, the authors give a review of the development of different beam-shaping techniques for auto-stack, minibar stack in a specific configuration and standard laser diode stacks. The presented methods are based on the application of wedge-type waveguides, fast axis and slow axis collimation, and the rearrangement of the laser beams by polarization overlapping and virtual restacking. All presented methods have very high transmission efficiencies (>80%) and lead to a homogeneous illumination matched to the sensor's field of view.

Keywords: beam shaping; illumination; laser-gated viewing; laser diode stack.

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***Corresponding author: Martin Laurenzis,** French-German Research Institute of Saint-Louis (ISL), 5 Rue du General Cassagnou, 68301 Saint-Louis, France, e-mail: martin.laurenzis@isl.eu
Yves Lutz: French-German Research Institute of Saint-Louis (ISL), 5 Rue du General Cassagnou, 68301 Saint-Louis, France

1 Introduction

In the past decades, the French-German Research Institute of Saint-Louis (ISL) worked in the field of laser-gated viewing. This active imaging method is based on the synchronization of a pulsed laser illumination of a distant scene and a gated reception with a highly sensitive imaging sensor [1]. Laser-gated viewing is a prominent electro-optical sensor technology for long range day/night vision [1–3], target detection and identification [4–12], and the vision through obstacles (like rain, fog, smoke, etc.) [13, 14] as well as ranging [15–23]. At ISL, the research on this optronic concept focuses on three major aspects: the theoretical description and investigation of light propagation through the atmosphere and of the imaging process, the evaluation and improvement of key components and their integration in demonstration systems, and the investigation of the application of laser-gated viewing [24].

The two main components of a laser-gated viewing system are the imaging sensor unit and the laser illumination device. Both have to be optimized, aligned, and matched precisely to obtain a high-performance imaging system. Depending on the laser wavelength, different sensor technologies and laser sources can be applied. While solid-state laser sources have high brilliance with high energy per pulse and high laser beam quality, laser diodes have a high electrical-to-optical power conversion (around 50%). Further, laser diodes offer the opportunity to realize high-performing illumination devices, which have high energy efficiencies, low cooling demands, and comply with demanding volume constraints. Finally, the application of laser diodes is attracted by a good cost-benefit balance.

In the present publication, the authors want to focus on the aspects of laser diode stack beam shaping and collimation. These aspects are essential to realize high-efficiency laser-gated viewing system as well as high-quality illumination devices for other applications. Therefore, the authors give an overview of the methods used at ISL for high-power laser diode illumination devices.

2 Principle of laser diode illumination

The design of an illumination device based on laser diode stacks aims on the realization of a compact,

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cost-benefit-oriented, and efficient device, which enables high optical power on the target/scene and a homogeneous illumination field matched to the sensor's field of view (FOV). To realize these objectives, the laser light has to be transformed by beam shaping and homogenization optics and projected to the distant scenario in the far field, as illustrated in Figure 1. Different operational conditions load different demands and constraints to the design of these optical elements. The main fundamental characteristic of the laser source can be defined by, e.g., the volume constraints and targeted sensor's FOV. These parameters give direct constrains for the design of beam shaping and projection optics as well as the laser beam quality.

A measure of the laser beam quality is given by the beam parameter product BPP, i.e., the product of the minimal beam radius ω/2 and the half-angle divergence θ/2, as defined in equation 1 [25]. For instance, an aperture of the projection lens of 40 mm and a beam divergence of the illumination field of 1 mrad lead to a BPP of 10 mm·mrad. Typically, the beam of a laser diode stack is of poorer quality especially along the slow axis. For efficient projection of the laser light, the BPP has to be as low as possible. A high BPP of the laser beam would case losses during the projection with a limited aperture. For Gaussian laser beams, e.g., for solid-state laser sources, the beam quality is given by the so-called M^2 value, which is the BPP divided by diffraction limited BBP_0. Owing to the highly anisotropic divergence of laser diodes stacks, the M^2 value is not customarily used in this context.

$$\mathrm{BPP}=\frac{\omega}{2}\frac{\theta}{2} \tag{1}$$

A single laser diode for near-infrared applications, for instance, consists of a AlGaAs-GaAs hetero-structure emitting laser light at a wavelength of 808 nm with a resonator length of some 100 µm and an emission surface of around 1 µm (height) times ~10 µm (width) [26, 27]. Thus, the dimensions of the active area are comparable to the laser wavelength. Owing to diffraction of light at the exit facet, the emitted light has an elliptical divergence with a fast and a slow axis (FA and SA), as depicted in Figure 1. The full divergence angles θ_{FA} and θ_{SA} depend on the dimension of the exit facet and the laser wavelength λ and, typically, have values of θ_{FA}=40° (698 mrad) and θ_{SA}=10° (174.5 mrad), respectively.

Owing to critical optical damage limitations, a single semiconductor laser diode has relatively low peak-power. Higher power can be obtained by superposition of several single emitters. Typically, several (8–100) single emitters are realized on the same chip in a parallel alignment with a certain pitch. This emitter assembly is cut to a bar structure, and a stack of several bars can further increase the number of emitters leading to a two-dimensional (2D) emission facet. The size of this surface is determined by the number of diodes per bar times the intra-bar diode pitch and the number of bars times the inter-bar diode pitch. The density of emitters, electrical and optical losses, and the construction of the laser diode have impact on the thermal behavior of a laser diode stack. Typically, a laser diode stack is operated in a pulsed quasi-continuous-wave modus (QCW) with certain duty cycle (of, e.g., 2%) and a thermoelectric cooling.

An insufficient illumination field (far field projection) of a laser diode stack does not match the FOV of the sensor. Here, a significant part of the laser light is lost, or the sensor's FOV is only partly illuminated, respectively. If the illumination is optimized, the laser illumination is matched to the sensor's FOV. Here, laser light and sensor array can both be used very efficiently for active imaging. Further, the ISL beam-shaping methods lead to homogeneous illumination, which increases the optical resolution of active imaging system. This increase in illumination efficiency and homogeneity improves the system performance in means of higher ranges for DRI applications (detection, reconnaissance, and identification).

In contrast to solid-state laser illumination, laser diode stacks have multiple single emitters with low

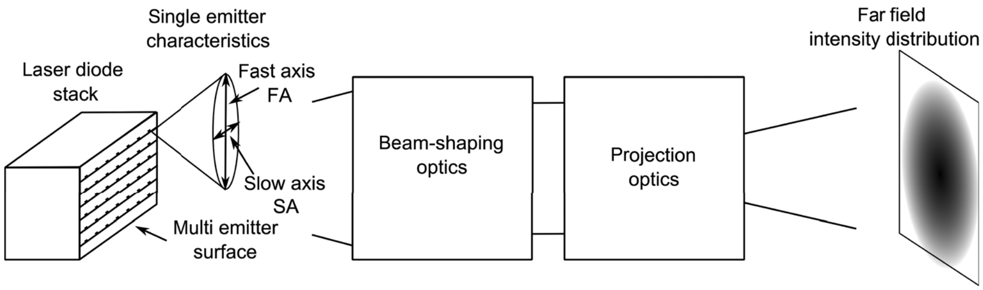

Figure 1 A beam shaping optics and a projection lens has to be applied for high efficient use of laser diodes for illumination.

coherence and high wavelength diversity. These characteristics reduce dramatically the illumination speckle [28]. Another advantage of laser diodes is the fact that the pulse length can be optimized for dedicated applications in a large range. For illumination issues, a pulse length of around 100 ns to several microseconds is sufficient. The application of laser diodes is limited by the maximum peak power and the duty cycle.

3 ISL methods for beam shaping and collimation of laser diode stacks

ISL has developed different illumination devices based on three types of laser diode stacks: (1) auto-stack laser diodes [29], (2) minibar laser diode stacks in a specific configuration [30], and (3) standard laser diode stacks [30, 31]. For these entire diode types, different beam-shaping methods were developed and tested for the application in laser illumination devices.

3.1 Auto-stack laser diodes

Auto-stack laser diodes have relative small emission surfaces with a huge number of emitters. Owing to electrical and optical losses and the small dimension, these diodes can only be driven with a very small duty cycle to remain underneath a critical heating of the active area even when thermoelectric cooling (TEC) elements are applied. Further, it is not possible to use microlenses for the collimation of the fast and slow axis divergence.

A typical emission surface has a size of around 2 mm (height) and 10 mm (width) with around 10 bars and each around 100 emitters. Thus, the diode pitch, i.e., the distance between two diodes is in the order of 100 μm and the bar pitch (bar-to-bar distance) has a typical value of around 200 μm. In Figure 2, an example image of an auto-stack emission surface is depicted. Here, the emission surface has a size of 9.5×1.5 mm² with 13 bars and a total number of 910 single emitters. Owing to the small dimensions and alignment errors, it is not possible to apply microlens arrays for slow axis and fast axis collimation (SAC+FAC). The beam parameter product of this type of laser diode stack is $\mathrm{BPP}_{\mathrm{SA}}$=414.5 mm·mrad and $\mathrm{BPP}_{\mathrm{FA}}$=261.8 mm·mrad.

Owing to the relative small dimensions of the emission surface, it is possible to couple the laser light directly into a waveguide. As depicted in Figure 2, a wedge-type waveguide with an entrance facet of 10×2 mm² can be used to collect the light from the emission surface and guide it to an exit facet by total internal reflection. Owing to high-quality antireflection coatings on the entrance and exit facet, the waveguide has a transmission efficiency of >80%. In the fast axis direction, the light is guided by multiple reflections at parallel surfaces. In the slow axis direction, the trapezoid cross section leads to an increase in the divergence angle and a reduction of the geometric aspect ratio. A perfect match of the exit facet dimensions (2.66×2 mm²) and the sensor's aspect ratio (4:3) can be obtained. Further, the internal reflections lead to a homogenization of the laser beam. The exit beam has a $\mathrm{BPP}_{\mathrm{SA}}$ of 435.2 mm·mrad and $\mathrm{BPP}_{\mathrm{FA}}$=349 mm·mrad with divergence angles of around 40° in both slow and fast axis direction. Thus, the subsequent projection optics must have a large aperture to collect as much light as possible. For a divergence angle of 40° a numerical aperture $NA=n \sin\theta/2$ of the projection lens of NA=0.34 can be estimated, which complies with a maximal f-number of 1.47. The projection of the exit facet leads to a very homogeneous illumination field.

The presented collimation technique was used in many demonstrator systems to illuminate the sensor's FOV with divergences of 20° to 1°. Here, very compact and robust illumination devices were set up. Owing to the simplicity of the setup, this method was successfully tested for ruggedized application in, e.g., artillery shells [32]. Owing to the small f-number, the projection lens increases in size and weight for smaller divergences. Therefore, alternative methods were studied to realize simple, compact, and high-performing beam shaping and collimation of laser diode stacks.

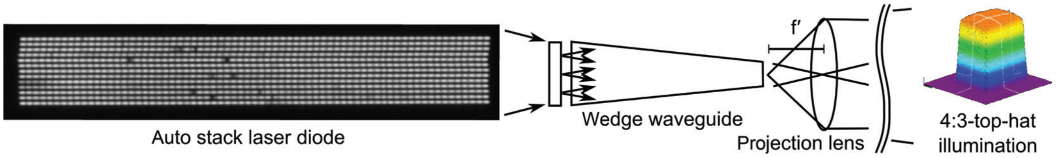

Figure 2 Beam shaping of an auto-stack laser diode by a wedge waveguide for homogeneous top-hat illumination profiles (ISL patented [28, 29]).

3.2 Minibar laser diode stack

Minibar laser diode stacks in a specific configuration were studied to have a *quasi in situ* adaption of the laser BPP to the illumination field. But, the applied laser diode stack represents a compromise between optimized beam quality and sufficient laser power. The applied laser diode stack consists of 15 minibars with a width of 1.5 mm. Each minibar has 10 emitters and an output peak power of 60 W/bar or 900 W, overall, with a duty cycle of 2%. The minibars are stacked with 1.2-mm spacing to enable the application of microlenses for fast axis collimation (FAC). Slow axis collimation is obtained by a single cylindrical lens. The beam quality can be determined with a $\mathrm{BPP}_{\mathrm{SA}}$ of 65.2 mm·mrad and $\mathrm{BPP}_{\mathrm{FA}}$ of 25.2 mm·mrad. This beam quality is good enough to couple the light with two cylindrical lenses into a homogenization waveguide with a cross section of 2 mm×1.5 mm and a length of 50 mm, as shown in Figure 3. For the projection of the exit facet, at least a lens with a numerical aperture of 0.06 or an f-number of 7.7 is needed. Good results were obtained with a projection lens of a focal length f′=573 mm and a diameter of 120 mm. To determine the transmission efficiency of the projection lens, a circular diaphragm was placed close to the output face of the projection lens, and the power was measured under variation of the diaphragm diameter. No power decrease was measured for diaphragm diameter >100 mm. This value gives the useful diameter of the projection lens.

As depicted in Figure 3, the divergence of the laser diode was too small to have multiple reflections inside the short homogenization waveguide. Significant inhomogeneities were observed in the far field illumination field. To reduce this effect, the impact of different holographic diffusers with diffusion angle from 0.5° to 5° was investigated. The diffusers were placed in front of the entrance facet, and the optical power as well as the homogeneity of the illumination was measured in the far field. In Table 1, the results of this measurement are summarized. Best results were achieved with a diffuser of 5°. Here, the illumination is perfectly homogeneous with an intensity fluctuation lower than 3% at a high overall transmission efficiency of 67.5% (laser source to target). The fluctuation in fast and slow axis direction is defined by the relation (2).

$$\triangle I_{\mathrm{FA}}=\frac{I_{max}-I_{min}}{I_{max}+I_{min}} \text{ and } \triangle I_{SA}=\frac{I_{max}-I_{min}}{I_{max}+I_{min}} \tag{2}$$

3.3 Laser diode stacks with fast and slow axis collimation

As a third option, ISL investigated the application of standard laser diode stacks with microlens arrays for fast axis (FAC) and slow axis collimation (SAC). Typically, the collimation has a very high quality. These types of laser diodes can be purchased from different distribution sources.

At ISL, the examined laser diode stack (LDS) consisted of an 8-bar stack with a width of 10 mm and a 1.6 mm spacing. The LDS had a peak power of 1000 W and could be driven with a duty cycle of 2%. After FAC and SAC, the laser beam had an emission surface of 10 mm×12.5 mm and a beam divergence of 4 mrad (FA) and 60 mrad (SA). Thus, the BPP was 12.5 mm·mrad (FA) and 150 mm·mrad (SA). For efficient coupling of the laser into a homogenization waveguide, these BPP values have to be equalized. To reach this aim, ISL pursued the strategy to reduce the geometrical dimension of the slow axis on two distinct ways: a polarization overlapping and a virtual geometrical restacking.

3.3.1 Polarization overlapping

The reduction of the slow axis BPP was realized by a reduction of the geometrical dimension by a restacking of emitters by polarization overlapping. As depicted in Figure 4,

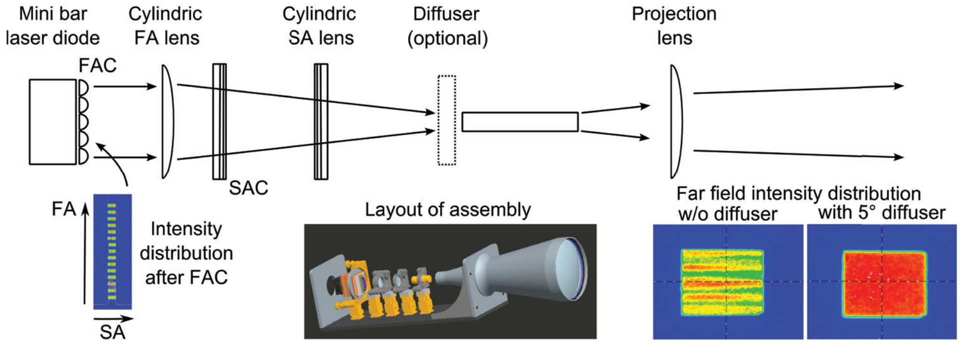

Figure 3 Layout of an illumination device based on minibar laser diode stack with fast axis collimation.

Table 1 Results for the application of different diffusers in the optical path.

Diffuser	Efficiency	ΔI_{FA}	ΔI_{SA}
no	75.8%	36%	12%
0.5°	68.7%	19%	12%
1°	68.7%	8%	10%
5°	67.5%	3%	2%

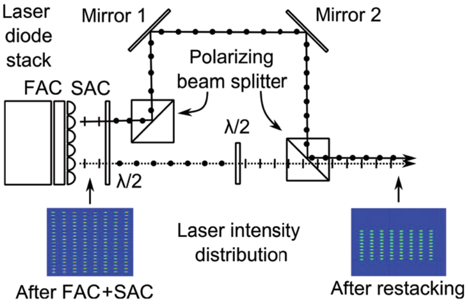

Figure 4 Rearrangement of laser emitter array by polarization overlapping.

after FAC and SAC by microlens arrays, the laser beam of the LDS consists of multiple single beams in an array arrangement. Half of this array is deflected by a polarization beam splitter and two mirrors on a second beam splitter to be aligned to the optical axis of the second half of the laser diode array. The polarization of the second half of the laser array is rotated by a λ/2 plate. This part of the laser beam is not deflected by the second polarization beam splitter. As a result, the two laser beam arrays are overlapped with perpendicular polarization leading to a reduction to the half of the origin emission surface. Thus, the BPP in the slow-axis dimension is reduced by a factor of 2: BPP_{SA}=75 mm·mrad, and the BPP_{FA} is still 12.5 mm·mrad. The transmission efficiency of this setup was above 90%.

3.3.2 Virtual restacking of emitters

An alternative approach is the virtual geometrical restacking of the emitter array. Here, ISL used three glass plates and a step mirror to separate and rearrange three areas of the emitter array. In a first step, the laser light is coupled into a stack of three glass plates. The shapes of these plates are designed to realize a deflection of three individual areas of the laser array in three directions by refraction at the entrance and the exit facets. After the glass plates, the three areas propagate parallel, but, with a certain offsets in the fast axis direction. As shown in Figure 5, a step mirror (mirrors 1–3) is used to align the beams in the slow axis direction. The transmission efficiency of both elements is above 90%. After passing these two elements, the emission surface has changed from 10 mm×12.5 mm to 3.3 mm×37.5 mm. With this method, a BPP of BPP_{SA}=50 mm·mrad and BPP_{FA}=37.5 mm·mrad was reached. These beam parameter products represent a very good quality for efficient coupling into a homogenization waveguide or, alternatively, for the coupling into an optical fiber.

4 Discussion and conclusion

ISL has investigated different methods for beam shaping and collimation of three different types of laser diode stacks. All methods lead to a homogenization of the laser beam profile with good ability for the coupling into a waveguide. A projection of the exit facet by a lens enables a homogeneous illumination in the far field with a perfect adaption to the sensor’s FOV. Both homogenization of the illumination and high transmission efficiencies enable the development of high-performance active imaging systems with an efficient use of laser light (low losses) and imaging sensor arrays (use of whole sensor, homogeneous illumination). The results for all beam-shaping methods are summarized in Table 2.

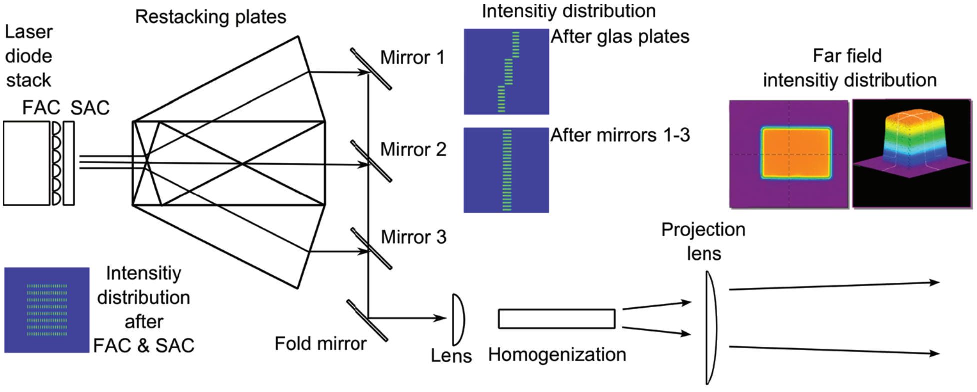

Figure 5 Rearrangement of laser emitter array by geometrical restacking.

Table 2 Summary of parameter of the discussed laser diode stack illumination devices.

Parameter	**Auto-stack LD**	**Mini-bar LDS+FAC**	**Restacking of LDS+FAC+SAC**	
			Polarization	**Geometrical**
Diode stack				
$n_{\text{emitters per bar}}$	70	10	20	20
n_{bars}	13	15	8	8
P_{peak} (W) pDC (%)]	1000 (0.2)	900 (2)	1000 (2)	1000 (2)
P_{mean} (W)	2	18	20	20
Width b_{SA} (mm)	9.5	1.5	10	10
Height a_{FA} (mm)	1.5	16.8	12.5	12.5
BPP_{SA} (mm·mrad)	414.5	65.25	150	150
BPP_{FA} (mm·mrad)	261.8	25.2	12.5	12.5
After beam shaping				
BPP_{SA} (mm·mrad)	435.2	65.25	75	50
BPP_{FA} (mm·mrad)	349	25.2	12.5	37.5
Efficiency (%)	>80	>80	90	>80
After projection				
Homogeneity	Very good	Very good (with 5°diff.)	tbd	Good
Efficiency (%)	>66	>67.5	tbd	>81
Divergence range	>1°×1.3°	≥0.15°×0.2°	tbd	≥0.15°×0.2°

Auto-stack laser diodes can easily be collimated by direct coupling into a wedge-type waveguide. The intensity distribution is homogenized and projected to the far field with a rectangular top hat profile, which perfectly matches to the aspect ratio of the sensor's FOV. The homogenization and reduction of the emission surface is achieved by an increase in the divergence angle along the slow axis. Therefore, the projection optics must have a great acceptation angle, which corresponds to a high numerical aperture or low f-number, respectively. For large FOV or small focal length, the projection optic has reasonable compact size. But for a small FOV, the size of a projection lens would exceed an acceptable dimension with the demand in increasing focal lengths.

The minibar laser diode stacks can be set up with microlens arrays for fast axis collimation and a simple cylindrical lens for slow axis collimation. These LDS have a good quasi *in situ* beam quality, which complies with the demands of focusing into a homogenization waveguide. For a very high degree of homogeneity of the intensity distribution in the illumination field, an additional diffuser should be placed in front of the entrance facet of the homogenization waveguide.

Standard laser diode stacks can be attached to microlens arrays for fast axis and slow axis collimation (FAC+SAC). This method reduces the fast axis divergence to a minimum; even the slow axis divergence is significantly reduced. But, due to the large emission surface, the BPP in the slow axis and the fast axis are very asymmetrical. To homogenize the BPP and, thus, increase the efficiency for the coupling of the laser beam into a waveguide, two different methods were studied to rearrange the geometrical distribution of the emitters. In a first approach, the emission surface was reduced to half by polarization overlapping. The second method used an assembly of glass plates and a step mirror for a virtual geometrical restacking. Both methods lead to a homogenization of the BBP in the slow and fast axis.

All in all, the results of the presented beam-shaping methods show different options for the development and system design of compact and efficient laser illumination devices based on different laser diode stacks.

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Yves Lutz received his MSc from the University of Franche Comté and his PhD from the University of Haute-Alsace (France) in the field of Laser Physics. He specializes in the field of development of laser sources and laser illumination devices. He is currently working on illumination sources for long-range active imaging applications.

Martin Laurenzis obtained his MSc in Physics from the University of Dortmund (Germany) and his PhD in Electrical Engineering and Information Technology from the University of Aachen (Germany). He is specialized in the area of night vision systems and active imaging with a particular interest in vision in poor weather conditions. He is currently developing new 3D techniques and new theoretical tools for performance evaluation of 3D active imaging systems.