11 kW direct diode laser system with homogenized 55 x 20 mm² Top-Hat intensity distribution

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ABSTRACT

In comparison with other laser systems diode lasers are characterized by a unique overall efficiency, a small footprint and high reliability. However, one major drawback of direct diode laser systems is the inhomogeneous intensity distribution in the far field. Furthermore the output power of current commercially available systems is limited to about 6 kW.

We report on a diode laser system with 11 kW output power at a single wavelength of 940 nm aiming for customer specific large area treatment. To the best of our knowledge this is the highest output power reported so far for a direct diode laser system. In addition to the high output power the intensity distribution of the laser beam is homogenized in both axes leading to a 55 x 20 mm² Top-Hat intensity profile at a working distance of 400 mm. Homogeneity of the intensity distribution is better than 90%. The intensity in the focal plane is 1 kW/cm².

We will present a detailed characterization of the laser system, including measurements of power, power stability and intensity distribution of the homogenized laser beam. In addition we will compare the experimental data with the results of non-sequential raytracing simulations.

Keywords: High power diode laser, homogenization, beam shaping, direct diode, incoherent coupling

1. INTRODUCTION

Beam homogenization techniques are well-established for laser systems based on excimer lasers. Typical applications are production of micromechanical structures and mask projection systems for lithography[1]. Recently an increasing demand for laser systems with a homogenized beam profile is observable. This includes systems with homogenization in one direction providing a line focus and systems that are homogenized in both axes leading to a rectangular or even square focus. These inquiries appear from different fields of applications like LCD-panel technology, printing industry, general illumination tasks, plastic welding, thermoplastic tape placement technology and other surface applications like hardening or thermal annealing. In addition for many of these applications it is not essential that the wavelength of the laser beam has to be in the ultraviolet spectral range. Therefore diode lasers with wavelengths in the infrared spectral range are an attractive alternative for such laser systems. In contrast to excimer lasers diode laser systems offer a lot of advantages, like a high wall-plug efficiency, high reliability, long lifetime, low maintenance, relatively low investment costs and a small footprint.

In general high power diode laser systems have become well-established laser sources for a number of different applications with output powers up to several kilowatt[2]. The only drawback of direct diode laser systems is the inhomogeneous intensity distribution, which is a consequence of the basic setup of such a diode laser system. The basic element of a direct diode laser system is a diode laser bar, which consists of a number of single emitters. Further power scaling is typically accomplished by combining a large number of individual diode laser bars. Therefore a direct diode laser systems consists of a very large number of single emitters. If no additional beam shaping and homogenizing optics is used power fluctuations from emitter to emitter and other inhomogeneities are transferred directly to the work piece. However if such diode laser systems are combined with homogenization optics these problems can be solved leading to a very attractive homogenized laser device.

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2. BASIC CONCEPTS OF BEAM HOMOGENIZATION

The basic goal of beam homogenization is to transform an arbitrary intensity distribution into a homogeneous intensity distribution that should be independent from fluctuations and inhomogeneities of the original laser beam. Optical parameters that define such a homogenization module are the homogeneity (mostly defined as peak to valley value), the shape of the intensity profile which can be Top-Hat or Gaussian, the edge-steepness and the dimension of the homogenized intensity distribution, which can be a homogenized line profile or a complete two-dimensional homogenized area. In addition, the total output power and the wavelength are important parameters for such a module.
With regard to the mechanical setup the module should have a small footprint and consist of a small number of components. Furthermore it should be cost-effective and easy to align.
Homogenization of a laser beam can be achieved by a number of basic concepts. One approach for transformation of a Gaussian beam to a Top-Hat beam is to rearrange parts of the laser beam by means of aspherical lenses[3]. However the design of the aspherical lenses is very sensitive to the parameters of the incident beam. Therefore slight changes or fluctuations of the incident beam will lead to a significant deterioration of the resulting Top-Hat profile.
Another very simple approach is homogenization by simple beam overlapping of several single laser sources placed next to each other. However this method has a number of disadvantages as described in Sect. 2.1. More sophisticated solutions are homogenization by waveguides and microoptical arrays which are described in Sect. 2.2 and 2.3., respectively.

2.1 Homogenization by simple beam overlapping

As indicated above a very simple approach of beam homogenization is to arrange a number of diode laser bars next to each other in the slow-axis direction. Fig. 1 shows the basic principle of such an arrangement for eight diode bars. The slow-axis divergence of the laser bars causes a beam overlap between adjacent diode bars. This overlap increases with propagation of the beam leading to a homogenization of the overall beam. As a matter of course the degree of homogenization strongly depends on the distance to the diode module.

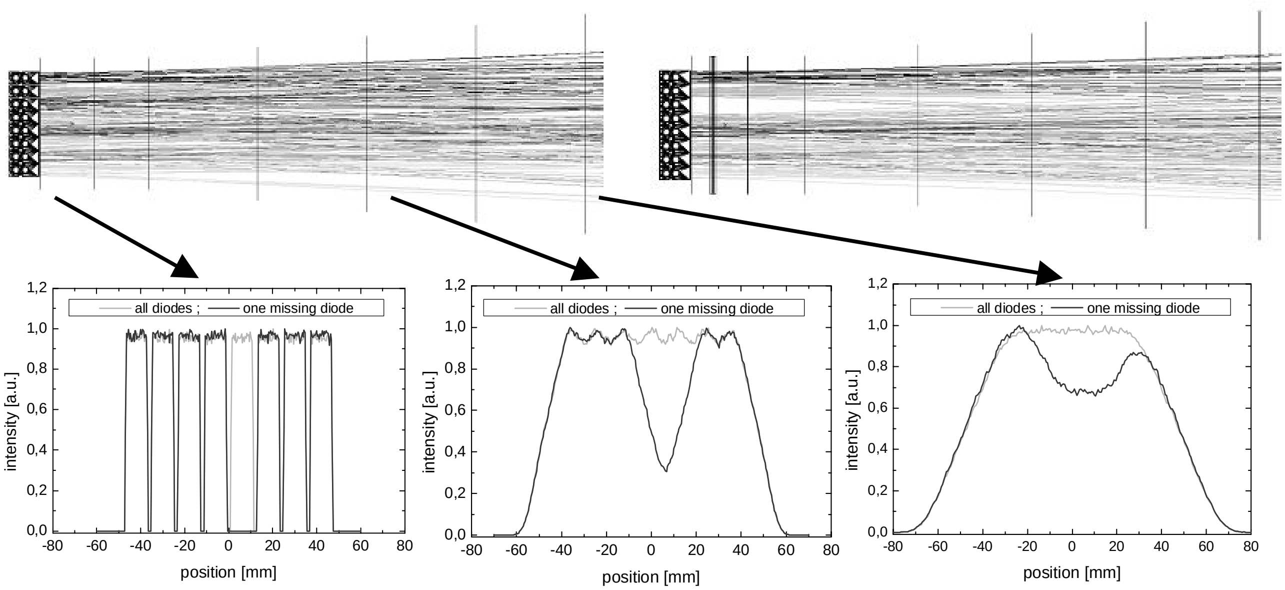


Fig. 1: Simple approach for beam homogenization by arranging diode laser bars next to each over. The diagrams below show the simulated intensity distribution for three different distances to the source. The simulation also shows the effect of one missing diode on the overall intensity distribution.

The effect of homogenization is indicated in the results of the simulation in Fig. 1. One major drawback of this homogenization method is the sensitivity to intensity fluctuations of the diode bars. Differences in output power per bar, unequal degradation of individual bars or even a complete failure of one bar will have a significantly effect on the homogeneity. The effect of a complete failure on the intensity distribution is also shown in Fig. 1. A further disadvantage is the flattening of the edge area of the intensity distribution with increasing distance. For large distances this intensity distribution approaches the far-field angular distribution of the diode bar in slow-axis direction. However, despite these drawbacks the results of this approach are sufficient for a lot of applications. Due to the large lifetime of diode laser bars the effects of degradation or even failure are negligible for many practical applications.

2.2 Homogenization by means of a waveguide

To overcome the drawbacks of the homogenization methods mentioned above more sophisticated approaches have to be applied. One method is homogenization by means of an optical waveguide. Typically a waveguide is a rectangular glass volume with polished parallel side walls. The entrance and exit surfaces of the glass volume are also polished. Fig. 2 shows the basic principle of this homogenization method. The light of a diode laser source is focused into an optical waveguide. Inside the waveguide the light is guided by total internal reflection leading to a segmentation and mixing of the intensity distribution at the end of the waveguide. Finally the exit surface is imaged onto the work piece. The result of the homogenization depends on the number of reflections inside the waveguide, which is defined by the aspect ratio of the waveguide, the divergence of the incident beam and the refractive index of the waveguide. A detailed analysis of homogenization by means of an optical waveguides can be found in Ref. 4.

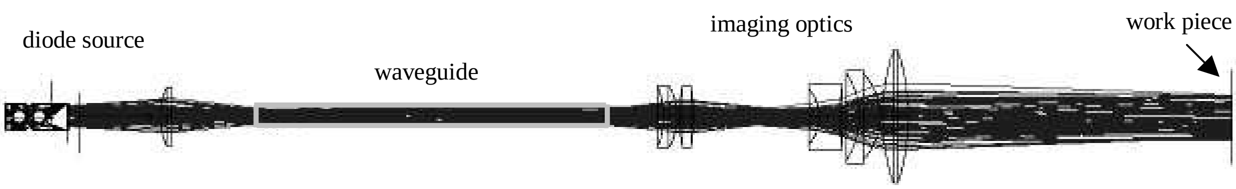


Fig. 2: Homogenization of a diode laser by means of an optical waveguide.

2.3 Homogenization by microoptical arrays

An alternative approach for homogenization is performed with microoptical lens arrays. The basic setup for a homogenization system based on microoptical lens arrays is shown in Fig. 3. The light of a diode laser source is incident on a microoptical lens array, that cuts the beam into a number of individual beams (beamlets). The function of the field lens is to overlap all beamlets on the work piece leading to a homogenized intensity distribution. A detailed description of the basic functionality of a microoptic homogenizer is shown in Fig. 4. In comparison with the waveguide approach homogenization by means of microoptical lens arrays is more flexible and requires a reduced number of optical components. As a consequence the overall size of such a system can be significantly smaller. This is clarified by the comparison of the basic homogenization setups in Fig. 2 and Fig. 3.

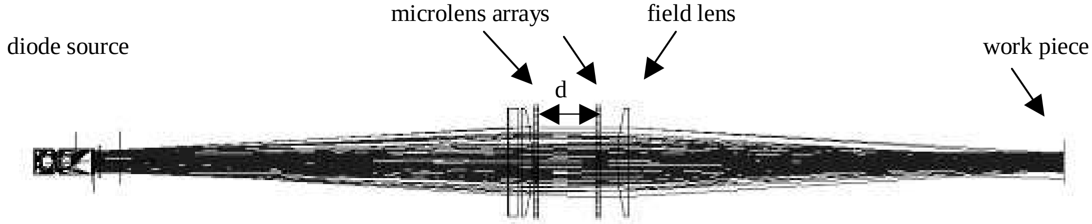


Fig. 3: Homogenization of a diode laser by means of microoptical lens arrays.

Fig. 4 shows the basic principle of beam homogenization with microoptical lens arrays. An inhomogeneous beam with beam width d is incident on a microoptical lens array. The lens array is characterized by the distance between two adjacent lens segments (pitch p) and the focal length f_{MA} of an individual lens segment. The shape of the lens segments is depending on the application. Mostly cylindrical lens segments are used, but spherical or hexagonal shapes are also possible. Depending on the beam size d and the pitch p the incident beam is divided into a number of beamlets. Subsequently these beamlets are overlapped in the focal plane of a field lens with focal length f_f. Homogenization in one direction is achieved with a setup as shown in Fig. 4. If homogenization is required in both axes a microlens array with spherical lenses can be applied. However, for different aspect ratios of the homogenized spot two microlens arrays with crossed cylindrical lenses have to be used.

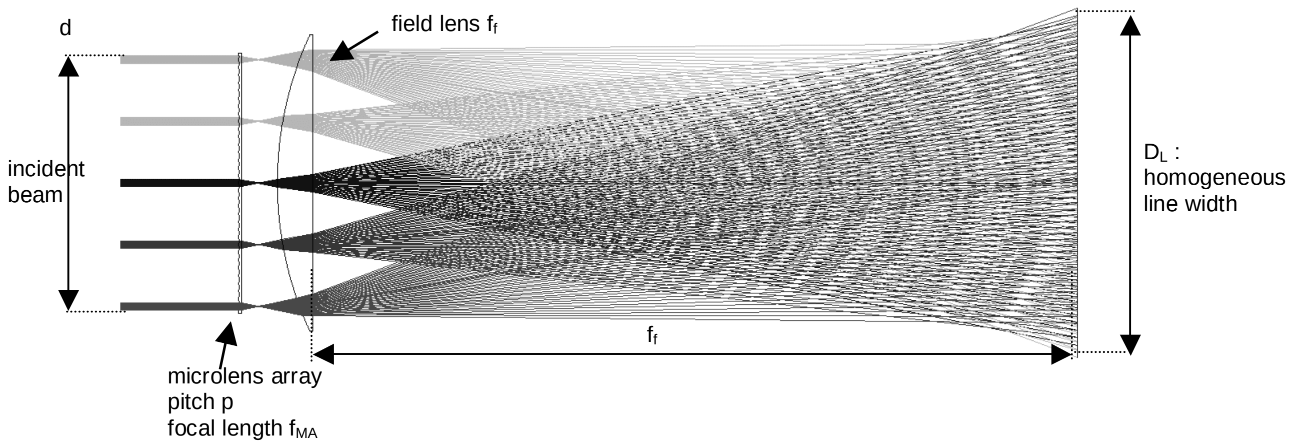


Fig. 4: Principle of beam homogenization by means of microoptical lens arrays.

The basic setup in Fig. 4 shows the principle of a non-imaging microlens array. One drawback of this simple setup is that an incident beam with a sufficient beam quality is required for good results with regard to homogeneity and edge steepness.

An important parameter which defines the edge steepness is the ratio between the divergence of the incident beam θ_0 and the divergence θ_{MA} which is generated by the microlens array. The divergence θ_{MA} is calculated by the parameters of the microlens array and is identical to the numerical aperture of the array. The formula for the numerical aperture of the microlens array is given by Equ. 1:

$$\theta_{MA} \approx \arctan\left(\frac{p}{2 \cdot f_{MA}}\right) \approx NA_{MA} \tag{1}$$

A good edge steepness is realized if the divergence of the incident beam is much smaller than the numerical aperture of the lens array. In addition good homogeneity demands for a large number of beamlets to be overlapped in the focal plane of the field lens. Therefore, for a given pitch of the microlens array a large aperture of the incident beam is required. In combination an incident beam with a large aperture and low divergence, i.e. a beam with a good beam quality is desirable for a non-imaging microlens array. The beam size D_L of the homogenized beam is calculated from the parameters of the homogenization setup :

$$D_L \approx 2 \cdot f_f \cdot \tan(\theta_{MA}) = \frac{p \cdot f_f}{f_{MA}} \tag{2}$$

Another drawback of using non-imaging microlens arrays is that diffraction effects might disturb the homogenized intensity distribution. This effect is described in more detail in Sect. 3.2. To overcome these disadvantages of non-imaging microlens arrays a combination of two microlens arrays has to be used. The basic setup for such a system is shown in Fig. 3. Usually two identical microlens arrays with the same focal length are used. The distance *d* between the microlens arrays equals the focal length of the second array. Under these assumptions the size of the homogenized spot can also be calculated by Equ. (2). As well as for the non-imaging setup the first microlens array divides the beam into several beamlets. Afterwards the combination of the second array and the field lens produces an image of each beamlet, which are overlapped on the workpiece. Therefore, such a setup is called an imaging microlens array.
In comparison with non-imaging setups homogenizers based on imaging microlens arrays offer the advantages of better homogeneity and edge steepness. Furthermore the demand on beam quality of the incident beam is not so critical and diffraction effects can be neglected. Another important advantage is the possibility to adapt the size of the homogenized beam by changing the distance *d* between the two microoptical lens arrays. However this can only be done for a small parameter range and at the cost of the edge steepness. However, a setup based on imaging microlens arrays is more complicated because the two microlens arrays have to be aligned carefully. Furthermore such a setup is more expensive.
Typical efficiencies for homogenizers based on microoptical lens arrays are above 95% for both non-imaging and imaging microlens arrays.

3. LAYOUT AND DESIGN OF THE LASER SYSTEM

Although the laser system was designed for a specific application we attached great importance to a modular approach for the complete system to allow for customization with regard to different output power levels and beam profiles.

3.1 Target specifications for the laser system

The laser system was designed for a specific application, which demanded for the following target specifications :

- Beam size : 50 x 18 mm^2 (plateau region)
- Output power : 10 kW
- Wavelength : 940 ± 10 nm
- Working distance : > 300 mm
- Homogeneity : better 5% (peak to valley value)
- Edge steepness for y-direction : ≈ 5 % of the beam width
- Edge steepness for x-direction : ≈ 15 – 20 % of the beam width
- Modularity with regard to customization of spot size

3.2 Optical design and simulation results

As described in Sect. 2.3. homogenization with microoptical arrays has a lot of advantages compared with e.g. homogenization by a waveguide. We decided to use microoptical arrays for homogenization mainly because of overall size and modularity reasons. The homogenization system is described by four main parameters that are the size and the divergence of the original laser beam, the numerical aperture of the microoptical arrays and the focal length of the field lens. In order to match the target specifications for the spot these four parameters have to be designed carefully.

The first design approach is to roughly calculate the required parameters defined in Sect. 3.1. by using Equ. (1) and (2).
After defining the basic parameters for the microoptical arrays and the field lens the design is verified by means of a non-sequential raytracing calculation with ZEMAX™. The simulation yields the spot size, the edge steepness and the homogeneity of the intensity distribution in the focal plane. However, with regard to homogeneity, the results of the simulation have to be checked carefully, because the degree of homogeneity strongly depends on the number of rays used in the non-sequential Monte-Carlo simulation. Therefore, it is always necessary to control the results of the simulation with experimental results to learn how to interpret the simulation results.

To check the performance of the homogenization unit it is always recommendable to model the source with realistic data. Therefore the laser source should be modelled with specific irregularities like smile or power variation from diode to diode. If the homogenization module is well-designed such irregularities of the source should have no noticeable impact on the homogeneity of the final intensity distribution in the focal plane.
The result of the simulation is shown in Fig 5. The simulated intensity distributions are in good agreement with the estimated spot sizes. Taking into account only the plateau region the spot size is approximately 50 x 18 mm^2. The spot size increases up to 60 x 24 mm^2 for an enclosed power value of >98%. The simulation also confirms that the edges of the intensity profile in x-direction are not as steep as in y-direction. The edge steepness can be adjusted by the ratio of divergence of the incident beam and the numerical aperture of the microoptical array if non-imaging microlens arrays are used. For imaging microoptical arrays the edge steepness can be influenced by a slight misalignment of the distance between the two microoptical arrays.

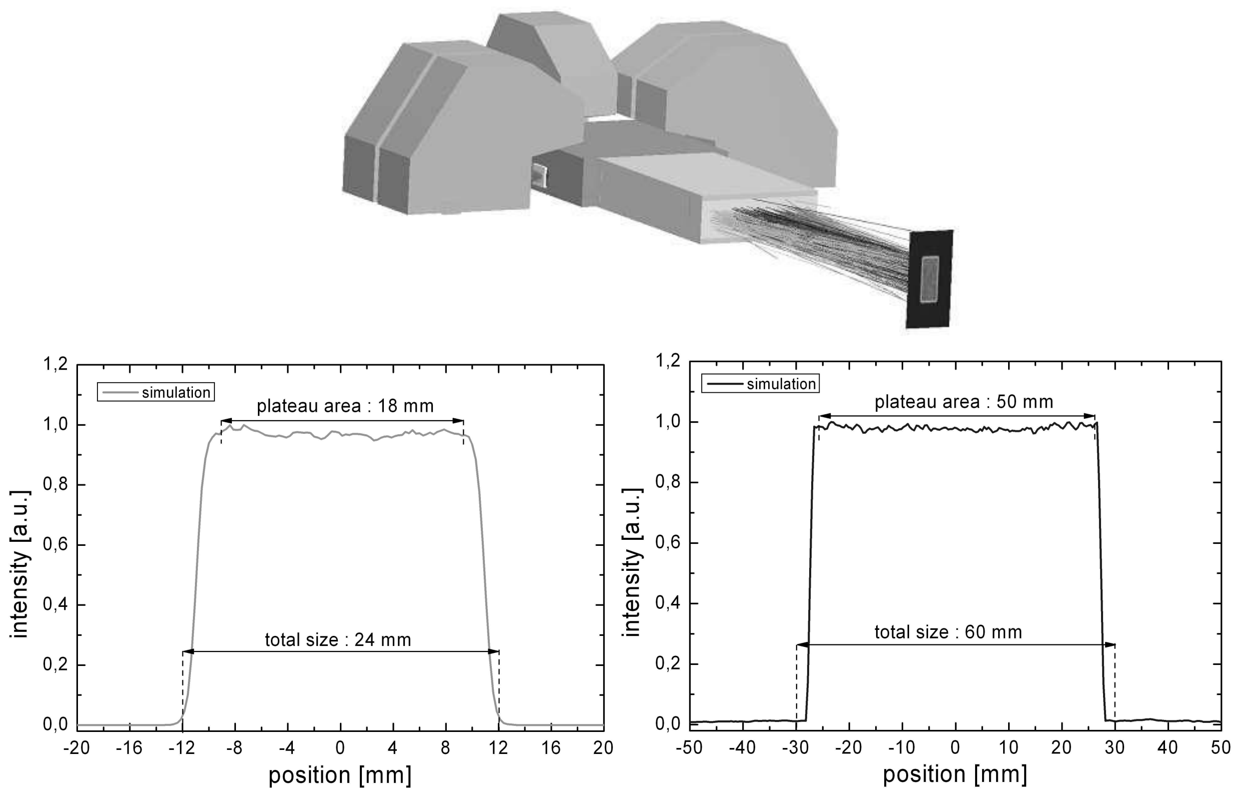


Fig. 5: Optical design model of the laser system (top) and results of the raytracing simulation (bottom). A cross-section of the simulated intensity distribution is shown for the x-direction (bottom left) and the y-direction (bottom right), respectively.

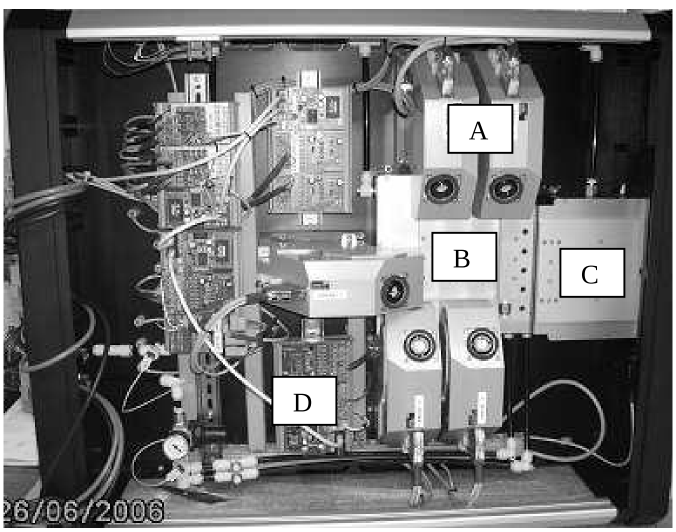
Furthermore, another important issue has to be considered. As non-sequential raytracing is based on pure geometrical optics, it does not account for diffraction effects. However, a microoptical array is a periodic arrangement of single lenses that as a whole can work as a grating. A very useful parameter that gives an estimation if diffraction effects have to be considered is the so called Fresnel-Number[5] that is defined in Equ. (3):

$$F \approx \frac{p \cdot D_L}{4 \cdot \lambda \cdot f_f} = \frac{p^2}{4 \cdot \lambda \cdot f_{MA}} \tag{3}$$

In Equ. (3) the parameters of the microlens array are the pitch p and the focal length f_{MA} of a lens element. Further parameters are the size of the homogenized spot D_L,, the wavelength λ and the focal length f_f of the field lens. To achieve good homogeneity the Fresnel-Number should be as high as possible. If non-imaging microlens arrays are used diffraction effects are observable for Fresnel-Numbers below approximately 10. Therefore, the Fresnel-Number should be well above 10 to get a homogeneous intensity distribution that is not modulated by diffraction effects. If the Fresnel-Number is near or below 10 and a very homogeneous intensity distribution is required imaging microlens array have to be used.

3.3 Components of the laser system

The complete laser system consists of three main units. The key component is the laser head, which provides the optical power and the beam shaping optics. The dimensions of the laser head are 1000 x 800 x 500 mm^3 with a weight of 100 kg. The other two main components are a cooling unit and a power supply with an integrated control unit.
Fig. 6 shows a picture of the internal setup of the laser head, which is composed of three main submodules. The first submodule includes 5 diode laser units each providing about 2.4 kW of laser power at a wavelength of 940 nm. The second submodule is an optical component consisting of several mirrors and lenses. The goal of this module is to combine the diode laser modules geometrically into one single beam and to adjust size and divergence of the laser beam for the subsequent homogenization module. Homogenization of the intensity distribution is realized by a combination of different cylindrical microlens arrays, which are included in the third submodule. A picture of the homogenization module is shown in Fig. 6. Furthermore the laser head contains the water distributor for the diode laser modules and the control units which provide the communication interface between the sensor data and the central control unit.
This modular approach allows the customization of the total output power as well as the customization of intensity profile and focus dimensions. The total output power can be varied from several watts up to 11 kW. The customization of the homogenization optics allows homogenization in one or two directions resulting in line, rectangular or even square illumination profiles.



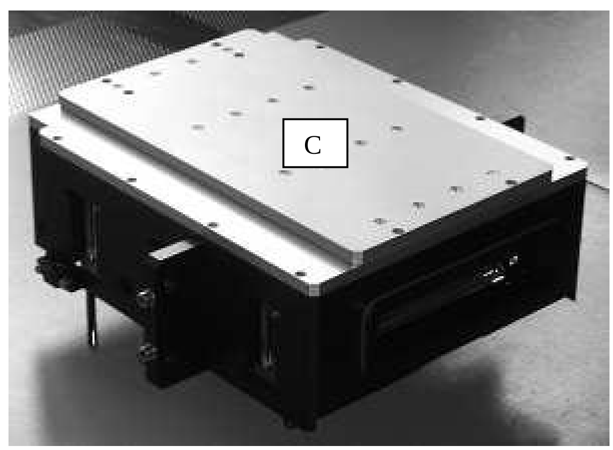


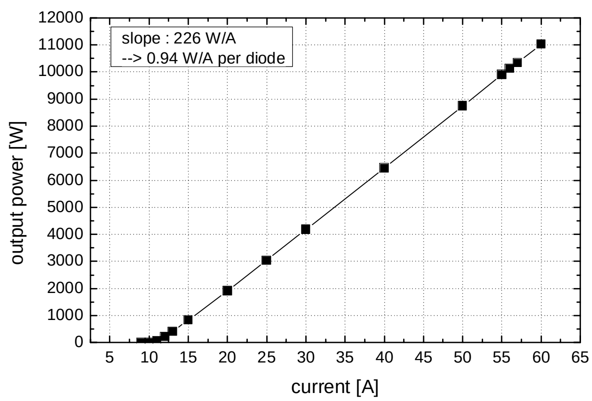
Fig. 6: Photo of the internal setup of the laser head (left) and the modular homogenization unit (right). The photo of the laser head shows the 5 diode laser units (A), the beam combination module (B) and the homogenization unit (C). Furthermore the electronics for the control unit is apparent (D).

4. CHARACTERIZATION OF THE LASER SYSTEM

The system was characterized in detail with regard to output power, power stability and beam quality. The main focus of the investigations was on the characterization of the homogenized intensity profile with respect to homogeneity and dimensions of the spot size. Furthermore the experimental results were compared to the results of the simulation based on non-sequential raytracing calculations.

4.1 Output power and stability

The left diagram in Fig. 7 shows the total output power of the laser system as a function of operating current. The maximum output power was 11024 W at a current of 60 A. The power vs. current curve shows a linear performance up to the maximum current of 60 A with a corresponding constant slope of 226 W/A. These power measurements were performed with a power meter from PRIMES GmbH (Power Monitor)[6].



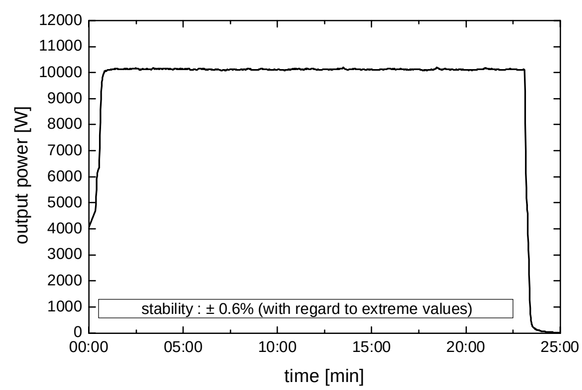


Fig. 7: Output power as a function of operating current (left) and measurement of power stability (right) at an operating current of 56 A, which corresponds to an output power of about 10 kW.

The mechanical and thermal layout of the laser system is designed for a typical operating modus of 15 minutes cycles at an output power of 10 kW. The right diagram in Fig. 7 shows a typical measurement of the power stability for a duration of 20 minutes and an output power of 10100 W. The corresponding current was 56 A. Taking into account the minimum and maximum power value during the measurement period the stability was as good as ± 0.6% (peak to valley value). The standard deviation yielded a value of ± 0.1 %. As a matter of course the laser system can also be operated with longer cycles or even in pure continuous wave mode. However, depending on the operation mode some minor changes on the mechanical and thermal design of the laser system will be necessary.

4.2 Beam Profile

The intensity distribution of the laser beam in the focal plane was investigated by different approaches.
The first method used an infrared conversion screen that converts infrared radiation into the visible spectral range. This screen was also used for alignment purposes. As a matter of course the laser has to be operated with a very low duty cycle (e.g. 20 µs pulses with a repetition rate of 50 Hz) to prevent damaging the sensor card. Fig. 8 shows a photo of the intensity profile on the conversion screen (left) in comparison with the result of the simulation (right). The scale is identical for both pictures. The aperture of the conversion screen was too small to visualize the whole spot size. Therefore two conversion screens where placed next to each other to cover the whole intensity profile. As a result of the combination a black line is apparent at the transition of the two screens. The comparison shows a good agreement between the simulation and the experimental result with regard to spot size and intensity distribution.

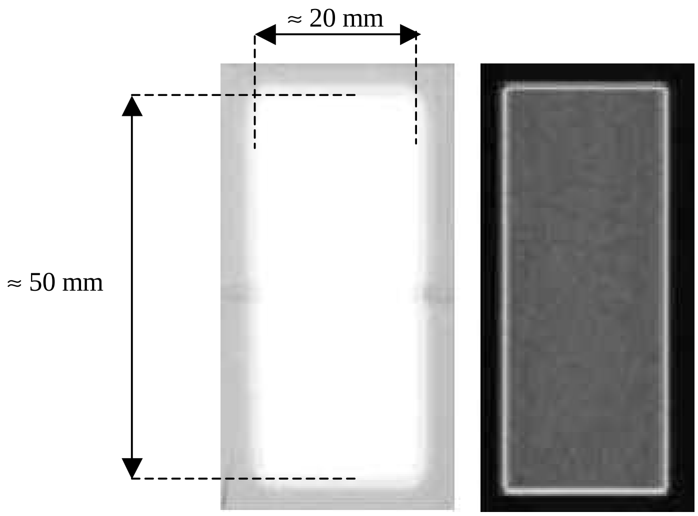


Fig. 8: Visualization of the intensity distribution in the focal plane. The photo on the left side shows the intensity distribution on the conversion screen in comparison with the result of the simulation (right). The black line in the middle of the conversion screen is a result of the combination of two different sensor cards (cf. text).

The next approach for visualization of the intensity distribution was illumination of a plastic panel. The result can be seen in Fig. 9. It is evident that this test also can not be performed at full operating power. Therefore the laser was operated near threshold. The exact parameters were 80 W (11 A) with an exposure time of 1 s (left part of Fig. 9) and 150 W (11.5 A) with an exposure time of 1.5 s (right part of Fig. 9), respectively. The result of the illumination shows the well-defined rectangular spot profile with sharp edges and a homogeneous Top-Hat intensity distribution. Furthermore the result is consistent with the intensity distribution measured with the conversion screen. The black tail down to the right of Fig. 9 was caused by the exhausting of the smoke.

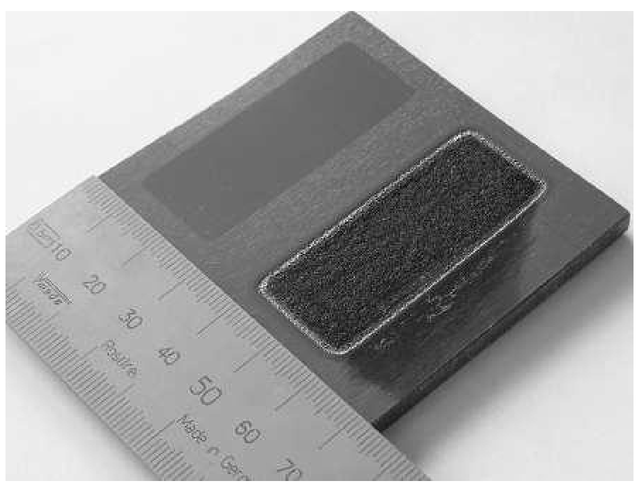
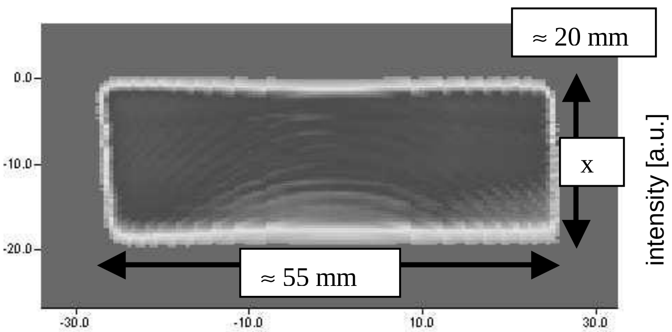


Fig. 9: Visualization of the intensity distribution in the focal plane. The photo shows the result of an illumination of a plastic panel at two different power levels and exposure times. The detailed parameters were 80 W with an exposure time of 1 s (left part) and 150 W with an exposure time of 1.5 s (right part). The black tail down right was caused by the exhausting of the smoke.

One main disadvantage of the methods named above is that they can not be performed at full operating power. Therefore another measurement was done at full operating power with a beam measurement device from PRIMES GmbH (Beam Monitor BM100)[5]. The principle of this device is to fade out a small part of the laser beam by scanning the beam with a rotating mirror. The measurement was performed with the entire operating power of 11126 W (60 A).

The result of this measurement can be seen in Fig. 10. The left part of Fig. 10 shows the two dimensional intensity distribution in the focal plane and the right part is a horizontal section of the 2D-profile.



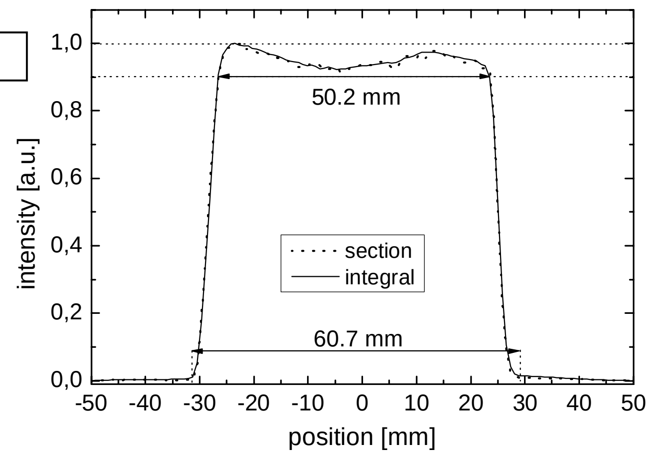


Fig. 10: Visualization of the intensity distribution in the focal plane by measuring at full operating power of 11126 W with PRIMES Beam monitor BM100[5]. The photo on the left side shows the two dimensional intensity distribution. The right part shows a horizontal section of the two dimensional intensity profile (dotted line) as well as an integrated intensity profile (solid line). The integrated profile is calculated by integrating the two-dimensional intensity distribution along the x-axis.

Fig. 10 indicates a ring structure in the two dimensional intensity profile. This is a consequence of the measurement principle based on a rotating sensor. Even though a radius correction is implemented in the measuring device the circular scanning path is still visible. As a consequence the horizontal section in the right part of Fig. 10 shows a slight modulation of the intensity profile. It is important to notice that this modulation is an artificial effect which is caused by the measurement. This is also confirmed by the fact that the modulation is identical for the horizontal section and the integrated intensity profile as can be seen in the right part of Fig. 10.
The measured homogeneity including the modulation by the measurement system is better than ± 5 % in the plateau region (peak to valley value). Recalculating the homogeneity without the modulation yields a value of better than ± 2.5 %. The two dimensional intensity profile in Fig. 10 yields a spot size of approximately 55 x 20 mm^2 (enclosed power value > 95%). This value is in good agreement with the results of the simulation (cf. Fig. 5). Taking into account the total power of 11024 W at an operating current of 60 A the resulting power density is 10 MW/m^2 (1 kW/cm^2). However, it should be mentioned that the system was optimized for a specific spot size and not with regard to maximum power density.

4.3 Realization of a line focus

As mentioned in Sect. 3.3. the whole system is characterized by a modular concept. This is also true for the internal setup of the homogenization unit, that consists of two submodules for homogenization of the x- and the y-direction. By simply removing the submodule for the x-direction the rectangular spot is transformed into a line focus with a sharp-edged Top-Hat profile in the y-direction. The profile in the x-direction is characterized by a Gaussian intensity distribution, which has its origin in the typical Gaussian profile in the far-field of the fast-axis direction The dimension of the line focus is 55 x 3 mm^2. It should be remarked that no additional alignment is necessary when the submodule for the homogenization of the x-direction is removed.
Fig. 11 shows a measurement of the intensity profile of the line focus. Fig. 12 shows the two dimensional intensity profile and a 3D-diagram of the line focus. The corresponding power densities are 67 MW/cm^2 (6.7 kW/cm^2). The power density with regard to the line is 200 W/mm.

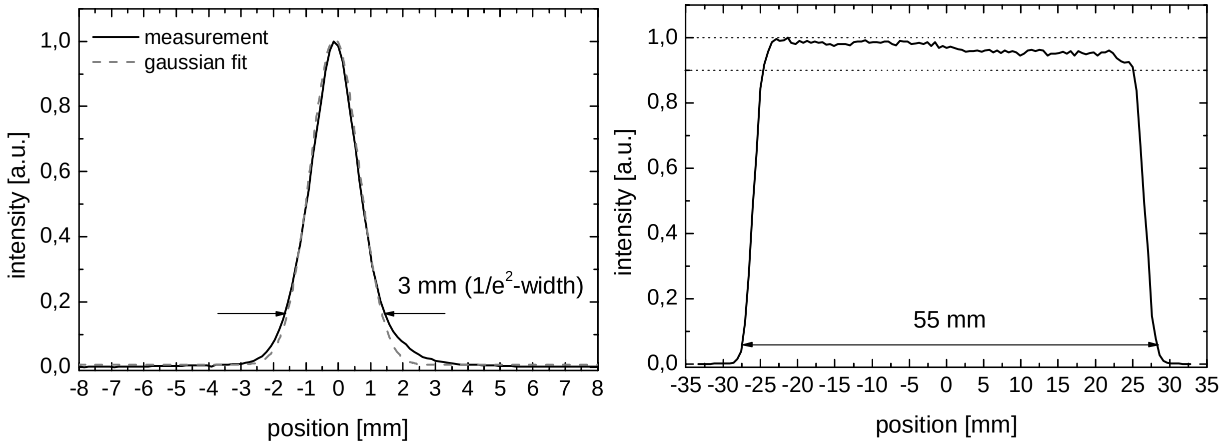


Fig. 11: Intensity profile of the line focus in x-direction (left) and y- direction (right).

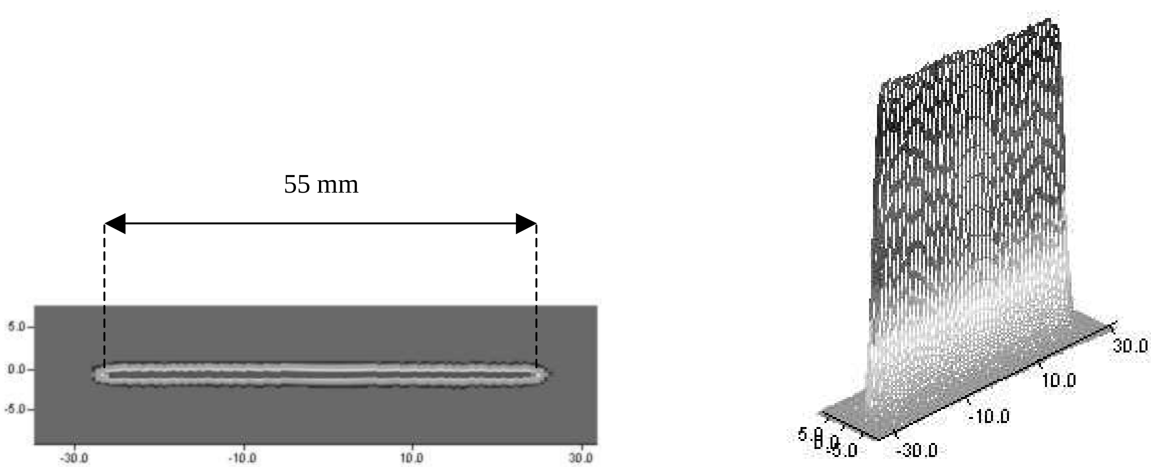


Fig. 12: Two dimensional intensity profile (left) and 3D-diagram of the line focus (right).

5. SUMMARY AND CONCLUSION

In conclusion, we have developed a modular concept for a flexible multi-kW laser system with optional beam shaping optics. As an example we realized a diode laser system with 11 kW output power at a single wavelength of 940 nm for customer specific large area treatment. In addition to the high output power the intensity distribution of the laser beam was homogenized in both axes leading to a 55 x 20 mm² Top-Hat intensity profile at a working distance of 400 mm. Homogeneity of the intensity distribution was better than 90%. The intensity in the focal plane was 1 kW/cm².

The modular approach allows the customization of the total output power as well as the customization of intensity profile and focus dimensions. The total output power can be varied from several Watts up to more than 11 kW. The customization of the homogenization optics allows homogenization in one or two directions resulting in line, rectangular or quadratic illumination profiles. The potential parameter range for the spot sizes extends from dimensions below 1 mm up to several hundreds of mm for each dimension. The standard wavelength range extends from 800 nm to 1000 nm. However, as there are no special requirements on the laser diodes non-standard wavelengths like 1470 nm can also be applied. We believe that in future the realized parameter range will be extended by further applications that will benefit from the advantages of high power diode laser systems with homogenized intensity distributions.

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