Brightness and efficiency scaling of a 1 kW direct diode laser module emitting at 780 nm for additive manufacturing of aluminum

M. Hübner*[a], M. Wilkens[a], S. Arslan[a], L. Wittenbecher[a], J. Zender[a], B. Eppich[a], D. Martin[a], P. Della Casa[a], A. Ginolas[a], P. S. Basler[a], N. Lobo-Ploch[a], P. Crump[a]
M. Rozycki[b], A. Schultze[b],
U. Tradowsky[c], A. Knaub[c], H. Alder[c]

[a]Ferdinand-Braun-Institut (FBH), Gustav-Kirchhoff-Str. 4, 12489 Berlin, Germany
[b]SKDK GmbH, Staakener Str.16, 13581 Berlin, Germany
[c]Photon Laser Manufacturing GmbH, Staakener Str. 53-63, 13581 Berlin, Germany

ABSTRACT

A 1 kW continuous wave 780 nm diode laser process head for industrial additive manufacturing of aluminum is presented. This process head combines and focuses the beams of two stacks, each consisting of 24 sandwich-mounted wide-aperture diode lasers. Heat from the emitters is efficiently extracted via micro-channel-free water coolers soldered to the sides of the laser stacks. The compact and light-weight module (21 cm × 29 cm × 61 cm, 12.5 kg) can be mounted directly to a robotic arm, eliminating the need of a failure prone optical fiber and enabling long-stretch processing and operation in confined spaces. We present and compare the results of a brightness and efficiency improved module iteration. By optimizing the chip design for 1 kW operation, we were able to increase the efficiency from 33 % to almost 50 % and double the brightness to 2 kW / mm² by reducing the spot size from 1 mm² to 0.5 mm². We also demonstrate that we can transfer this performance to 793 nm stacks, allowing the module to be used directly as an efficient pump source for Tm-doped solid-state lasers or to scale it up with wavelength beam combining to a 2 kW process head. At the end, we show the results of the first successful AM trials with the first generation of our process head.

Keywords: high-power, diode-laser, additive manufacturing, 3D printing, micro-channel-free, bionic structure, light-weight, diode stack

1. INTRODUCTION

Additive manufacturing (AM), or 3D-printing, is a growing field across industries. It allows to create macroscopic objects from materials like wires, powders, liquids, or adhesives with minimal waste. A comprehensive review of different types of AM-techniques can be found in e.g. [1-3]. One successful technique to additive manufacturing of robust yet lightweight components is to form stabilizing support structures layer by layer on thin metal sheets using a wire that is melted by a laser. Laser manufacturing has been established in automotive and train production for 25 years, beginning with solid-state lasers (SSL) emitting several kilowatts at ~1050 nm [4]. These lasers offer long operational lifespans and high reliability. However, the emitted wavelength of typical SSL systems is poorly absorbed by many metals and the fiber optic cables required to transmit the light to the work piece limits the flexibility of the laser head and often fails [5]. These disadvantages of SSLs can be addressed using newer techniques like direct-diode lasers emitting at better absorbed wavelengths, e.g., 450 nm for copper or, like in our work, at 780 nm for aluminum. However, though challenges remain in compact system integration and beam quality [6-8].

In this work, we present the newest results of our 780 nm direct-diode laser process head for wire deposition of Al-alloys. By optimizing the built-in chip design, we were able to significantly increase the efficiency and brightness of our process head compared to previously shown results. This paper, therefore, is an update of our last year Photonics West 2025 contribution [9] and parts are repeated here for readers convenience. The first part of this paper will shortly recapture the design of our process head and introduce this new chip design. In the second part we will show the performance of the process head and compare both chip design iterations.

*Corresponding author: marko.huebner@fbh-berlin.de; phone +49 (0)30 6392 2716; www.fbh-berlin.de

With recently fabricated chips we could also realize a stack with a comparable performance but a slightly longer wavelength around 793 nm. This shifted wavelength could potentially be used for power scaling of our process head, via coarse wavelength combining, or for pumping of Tm:YAG SSL crystals. The results of this wavelength shifted stack will be presented in the third part of this paper. At the end of this paper, we will present some results of first additive manufacturing trials with our process head and subsequently give a conclusion.

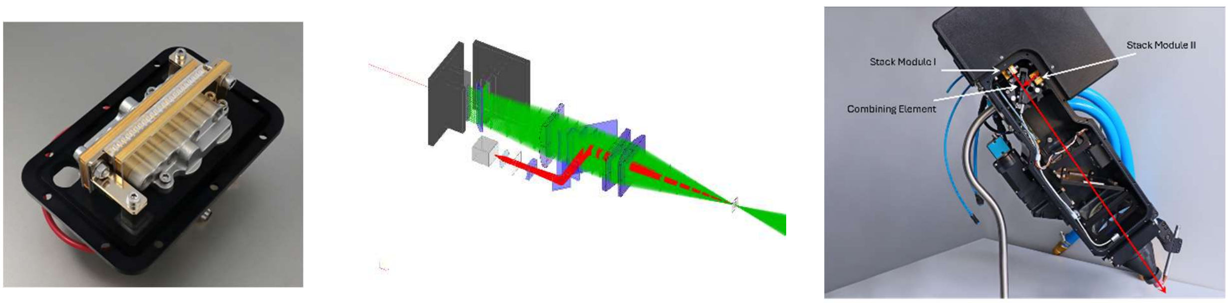
2. DESIGN AND FABRICATION OF THE DIRECT DIODE LASER PROCESS HEAD

The layout of the process head has already been described in [9], but for readers convenience, it will be briefly described again here, together with the new chip design.

First, GaAs-based wafers were grown by metalorganic vapor phase epitaxy and then fabricated into wide aperture broad area lasers. In a first development step, here named generation I, the chips were fabricated with a lateral aperture of 1200 µm and with a resonator length of 6 mm. The facets were cleaved, passivated and coated with dielectric layers achieving a front facet reflectivity $R_f = 0.8\%$ and a rear facet reflectivity $R_r = 98\%$. Subsequently, each chip was soldered between two heat sinks (“sandwich”) of thermal expansion-matched CuW, to form a single stack element [10-12]. Characterization and reliability tests of generation I chips showed potential for efficiency optimization and brightness enhancements by emitter size reduction. Hence, a second generation of chip devices has been developed, here named generation II, which was manufactured in exactly the same way like generation I but with a lateral aperture of 800 µm, a resonator length of 4 mm and a front facet reflectivity $R_\mathrm{f} = 4\%$ [13,14].

For both chip generations, stacks of 24 chip devices soldered vertically one over another were assembled and then soldered between two expansion-matched direct copper bonding (DCB) large-channel (micro-channel free) water coolers [10-12]. Thus, the generated heat can be efficiently dissipated over the entire length of the chips via the sides of the laser stacks. Subsequently, the stacks were assembled onto base plates which provide connections for cooling water, drive current and a readout for three PT100 temperature sensors for stack temperature monitoring. Finally, all emitters were individually vertically collimated by fast axis collimation (FAC) lenses, which were attached to the DCB coolers. Figure 1a) shows a photograph of a single stack module.

In the process head, the emitted beams of two of such high-power laser stacks were geometrically combined and then vertically and horizontally focused onto the work surface with just three lenses. Thus, an almost circular spot could be achieved in the focal plane with a working distance of 180 mm in front of the process head housing. The optical design of the process head was made with a simulation software [15] and is illustrated in figure 1b). The process head also includes a camera inside the housing for monitoring the focal plane, as well as a wire feeder attached to the housing. The first prototype, featuring a wire feeding system along with electrical and water-cooling connections, measures 21 x 29 x 61 cm³ and weighs 12.5 kg, making it a compact and lightweight system that could be easily mounted on a robotic arm. An image of the fully assembled process head is shown in figure 1c).



a) b) c)

Figure 1. a) Image of a fully assembled laser stack module. b) Optical layout for combining the output power from two high-power diode laser stacks and then directly imaging it onto the work surface. The two stack modules are the black elements in the left top corner while the path of the laser radiation and the camera path are depicted in green and red, respectively. Optical simulations done using a simulation software [15] c) Image of the fully assembled laser process head (top cover removed).

3. CHARACTERIZATION OF THE DIRECT DIODE LASER PROCESS HEAD

The laser process head was characterized for each chip generation with two laser stacks connected in series and powered by a constant current supply (Elektro-Automatik, EA-ELR 10000 3U). The cooling water was supplied by a lab chiller (Julabo) at 15 °C with a flow rate of approximately 3.5 l/min for each stack. Characterization measurements include total optical power, operating current and voltage, emission spectrum, and beam quality.

Optical Power, Voltage-Current Characteristics, and Conversion Efficiency

The voltage *U* and optical power P_{opt} were measured as a function of the stack current *I*. The optical power was measured, in a free space configuration after in-module collimation and focusing, with a calibrated high-accuracy laser power meter (Gentec HP-100A-3kW-HE-D0). The current was increased up to an optical output power of approx. 1 kW, with no indication of thermal roll-over. Figure 2 shows the results for the two chip generations. The laser threshold for generation II has been decreased from 10 A to 5 A compared to generation I and the slope efficiency has slightly been improved. Thus, the generation II module reaches 1 kW optical power already at 24 A compared to 35.7 A for the generation I stacks. The reduced chip size of generation II leads to an increased electrical resistance. However, the voltage at 1 kW has only been increased from 80 V to 85 V. Thus, the conversion efficiency at 1 kW has been significantly improved from approx. 33% for generation I to approx. 50% for generation II.

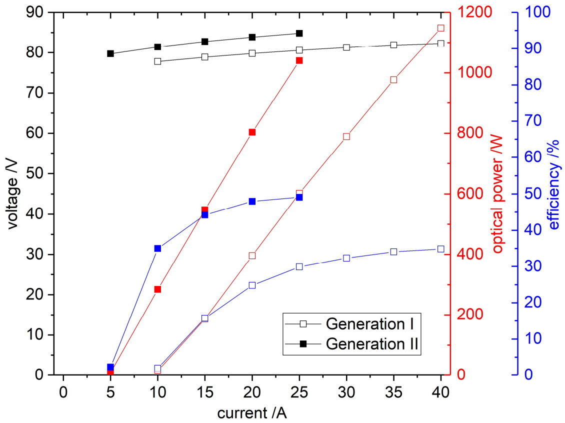
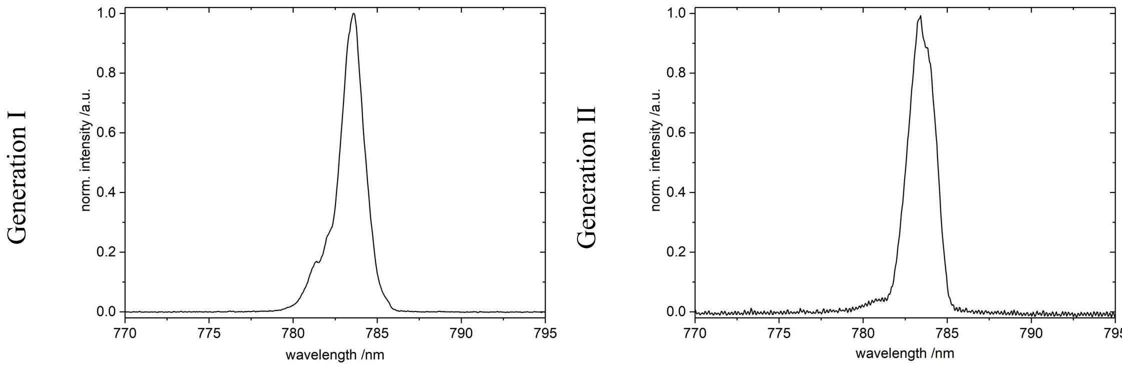


Figure 2. Voltage, optical power and conversion efficiency as a function of the drive current for the laser process head loaded with two generations of chip development. The measurements were done in CW operation.

Spectral characteristics

For the spectral characterization of the process head, the laser was focused into an integrating sphere which was connected, via a fiber, to a spectrometer (Ocean Optics HR4000). Figure 3 shows the normalized spectra of the process head loaded with two stack modules of each generation. Measurements were done in CW operation at 1 kW output power.



a) b)

Figure 3. Normalized emission spectra of the laser process head at 1 kW output power loaded with two stack modules. a) generation I at 35.7 A and b) generation II at 24 A.

The centroid wavelength λ_{cen} = 783.4 nm remains the same for the two chip generations while the spectral width $\Delta\lambda_{95\%}$ with 95% power content has been reduced from 4.4 nm for chip generation I to 3.9 nm for chip generation II.

The spectral measurements at different current levels were used to calculate the thermal impedance R_{th} which is a standard measure to understand and compare the thermal performance of such laser system. Due to the smaller size of generation II chips, the thermal resistance for the module was slightly higher with R_{th} = 39 mK/W compared to generation I devices with R_{th} = 32 mK/W.

Beam propagation ratio (M^2)

To assess the beam quality and to confirm the beam diameter in the focal plane, a caustic measurement was performed along the focal plane of the module, to determine the M^2 values in the horizontal and vertical directions. Therefore, a camera was moved along the propagation axis around the focal plane and intensity images were taken to determine the beam diameters vs. camera position. The measurements were conducted at 1 kW CW optical output power. These images were analyzed according to the ISO 11146 standard, but here employing 95% power content, to calculate beam diameter values in horizontal and vertical directions. Images were taken every 2 mm. The beam diameters were then fitted to the equation:

$$D(z) = D_0\sqrt{1 + ((z - z_0)/z_R)^2}$$

where D_0 is the beam waist diameter, z is the position along the propagation axis, z_0 is the beam waist position (set to 0 mm here), and z_R is the Rayleigh length. Figure 4 illustrates the calculated beam diameters alongside the fitted curves while Table 1 presents the fitted parameters for the process heads. Due to the narrower aperture of the generation II chips and the higher efficiency (less heat) the beam quality at 1 kW output power was improved in both axes and thus, the spot size in the focal plane could be reduced from approx. 1 mm² for generation I to approx. 0.5 mm² for generation II.

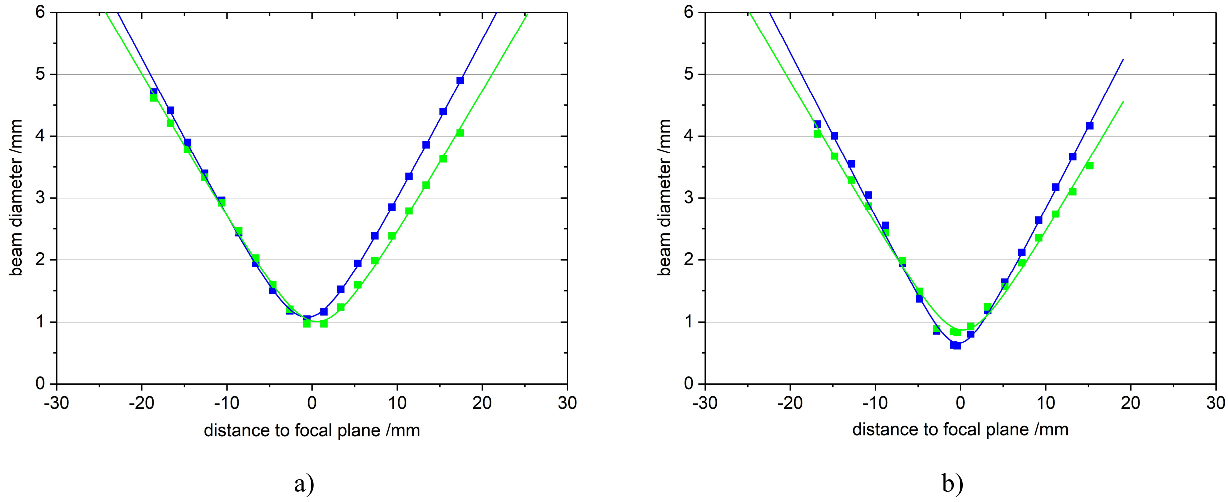


Figure 4. Measured beam diameter with 95% power content (symbols) and fit using Gaussian model (solid curve) for vertical (green) and horizontal (blue) beam for the laser process head. A 2D – intensity image was taken at each symbol position. a) generation I at 35.7 A and b) generation II at 24 A.

	Generation I			*Generation II*		
	D_0 / mm	z_R / mm	M^2	D_0 / mm	z_R / mm	M^2
horizontal	1.04	3.91	282	0.61	2.23	168
vertical	1.03	4.34	248	0.82	3.38	201

Table 1. Results of the parameters of fitting the Gauss model to the measured beam diameters for a 95% power content where D_0 is the beam waist diameter and z_R is the Rayleigh length for the horizontal and vertical beam dimension. The beam propagation ratio M^2 is given as well.

4. 793 NM WAVELENGTH SHIFTED STACK

In a recent process we slightly modified the quantum well structure in the epitaxial design in order to shift the emission wavelength to 793 nm. The manufactured wafers were then processed into laser chips as described in section 2, analogous to the generation II chips with a lateral width of 800 µm and a resonator length of 4 mm. Subsequently, a stack with 24 elements was assembled, identical to the previous stacks. Only the results from a single 793 nm stack are shown here. The characterization was carried out in the same way as for the results shown above. Measurements were taken at 600 W as reference power, and slightly different optics were used to generate a focal point, which only affects the beam waist diameter and not the beam quality. Figure 5 shows the optical power, voltage and efficiency vs. current curves of individual stacks with 780 nm (gen. I and gen. II) and 793 nm (similar to gen. II). As can be seen in the figure, the characteristic curves for both wavelengths are almost identical with the generation II design.

The spectral intensity distribution of the 793-nm stack is given in figure 6, measured with a CW current of 25 A (≈ 600 W) and with a cooling water temperature of 15°C. The spectral width with 95 % power content $\Delta\lambda_{95\%}$ = 4.2 nm is comparable to the 780-nm stacks. The center wavelength λ_{cen} = 796 nm at 600 W is slightly higher than anticipated, but can be tuned to 793 nm with a lower cooling water temperature and by adjustments in the epitaxial growth process.

The beam propagation ratio M^2 for individual stacks with 793 nm and 780 nm generation II devices at 600 W has been calculated from a caustic measurement (see above) and the measured beam diameters are given in figure 7 as a function of the position along the beam propagation direction. The determined beam quality for both stacks is almost identical with $M^2_x \approx 190$ and $M^2_y \approx 200$. All parameters are given in table 2.

Power, efficiency, spectral width and beam propagation ratio of the 780 nm and 793 nm stacks are very similar, therefore, the stacks in the process head should be easily interchangeable. Optical simulations showed, that a 1 mm optical fiber with NA = 0.15 can be placed in the focal plane of the process head with a coupling efficiency of 98%, allowing the process head to also function very well as pump source for Tm:YAG solid state lasers. The shifted wavelength also allows to design a process head with double the power and brightness by using a coarse wavelength beam combining schema.

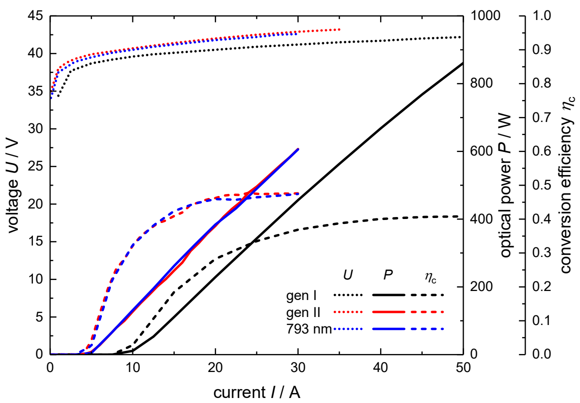


Figure 5. Voltage, optical power and conversion efficiency as a function of the CW drive current for 24 element laser stacks with chips of generation I and II, and 793 nm chips (gen II).

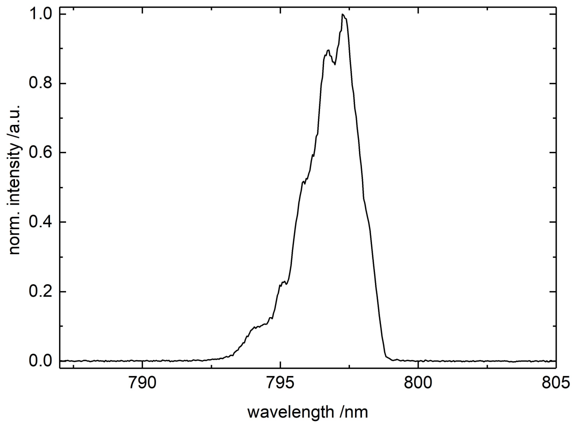


Figure 6. Normalized emission spectra of 793 nm stack at 25 A (CW).

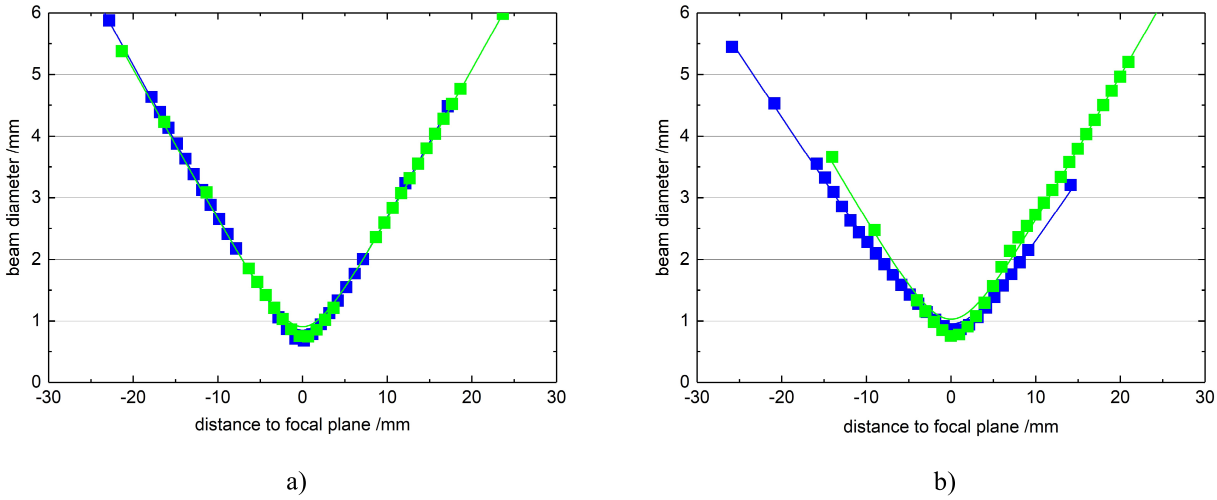


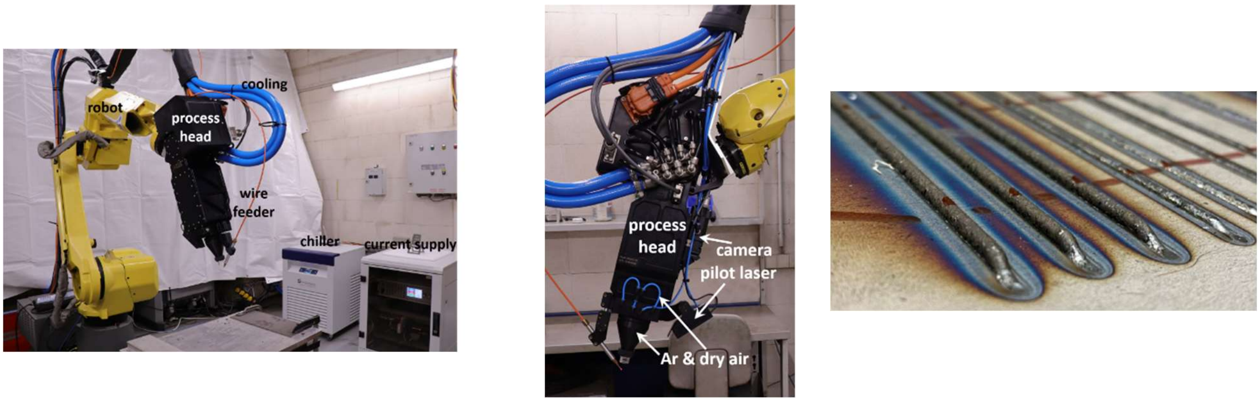
Figure 7. Measured beam diameter with 95% power content (symbols) and fit using Gaussian model (solid curve) for vertical (green) and horizontal (blue) for individual stack with a) 780 nm devices and b) 793 nm devices. A 2D intensity image was taken at each symbol position.

	780 nm stack module			*793 nm stack module*		
	D_0 / mm	z_R / mm	M^2	D_0 / mm	z_R / mm	M^2
horizontal	0.73	2.9	191	0.89	4.2	187
vertical	0.77	3.0	199	0.79	3.1	198

Table 2. Results of the parameters of fitting the Gauss model to the measured beam diameters for a 95% power content where D_0 is the beam waist diameter and z_R is the Rayleigh length for the horizontal and vertical beam dimension. The beam propagation ratio M^2 is given as well.

5. INSTALLATION OF THE LASER PROCESS HEAD FOR ADDITIVE MANUFACTURING TRIALS

To evaluate the 780 nm direct diode laser process head for laser-wire deposition of aluminum in AM systems, the system was installed on a robotic arm at Photon Laser Manufacturing GmbH, see figure 8a) and 8b). The setup includes an industrial wire feeder loaded with 1 mm metal wire, along with peripheral components such as a chiller, current supply, argon and dry air purging supplies, and a control computer. Automation of the AM process is managed by SKDK GmbH, enabling high throughput and cost efficiency. First 3D-printing attempts were successfully carried out with steel, which demonstrated that the process head is ready to use. In these trials up to 10 layers of steel wire were deposited on top of each other on a steel substrate, see figure 8c). First process trials with aluminum showed that the melt depth of the process head in an aluminum substrate was comparable to a classical 1030 nm SSL with twice the power (2 kW). A 1 mm aluminum wire could also be melted, but the achieved deposition was partially irregular. Problems with aluminum deposition are expected to be caused by aluminum oxide which reduces the power transfer into the wire / substrate. These problems with aluminum could be compensated by doubling the power of a future process head, as mentioned in the previous section.



a) b) c)

Figure 8. a) Direct diode laser process head mounted on a robotic arm at Photon Laser Manufacturing GmbH with the chiller, current supply and the industrial wire feeder. b) process head with camera housing and support for cooling water, high current cables and flashing dry air. c) first attempts of a printed 3D-support structure on steel.

6. CONCLUSIONS AND NEXT STEPS

In this paper, we have presented the latest results of our novel direct diode laser process head emitting around 780 nm, specifically designed for additive manufacturing (AM). The optimized wavelength significantly enhances aluminum absorption, making this system highly suitable for fabricating lightweight aluminum components. Its compact size of $21 \times 29 \times 61$ cm³ and weight of 12.5 kg allow direct attachment to a robotic arm, eliminating the need for optical fibers. With a new chip design, we were able to demonstrate a higher efficiency of almost 50% at 1 kW optical power in a reduced spot size of 0.5 mm², which means a doubling in brightness compared to our previous results. We also have shown, that we could reproduce these results at a shifted wavelength of 793 nm, which allows a usage of the module also as pump source for Tm:YAG lasers and opens up the possibility to design a process head with twice the power by using coarse wavelength beam combining.

This innovative laser system offers several unique advantages over state-of-the-art alternatives:

- Optimized wavelength: The 780 nm-800 nm emission targets aluminum's absorption peak, enabling efficient laser wire deposition of aluminum alloys.
- Compact design: The smaller form factor enhances spatial flexibility, facilitating the production of complex structures like topology-optimized stiffening components for mobility applications.
- Cost efficiency: The absence of external optical components or fiber optic cables reduces both initial and operational costs, making the technology more accessible for broader industrial use.

These features not only provide substantial benefits to the AM industry but also extend to other laser-based manufacturing technologies. Applications such as laser welding and brazing of aluminum alloys and steels can particularly benefit from the system's compact design, addressing challenges in geometrically constrained environments. This improved accessibility enables the fabrication of lighter structures, contributing to sustainability by reducing carbon emissions during product lifecycles.

In summary, the 780 nm direct diode laser process head combines efficiency, versatility, and sustainability, positioning it as a transformative tool for AM and beyond. Its innovative design is poised to expand the possibilities of lightweight construction, supporting industrial efforts to optimize performance and reduce environmental impact.

Furthermore, the laser module's stack technology can be adapted for pumping solid-state laser systems, with a broad emission range from approximately 620 nm to 1200 nm and the capability for quasi-continuous wave (QCW) operation. Delivering a CW power of 1 kW (up to 1.9 kW maximum) with a spectral linewidth of < 6 nm (95% power content), the system also holds promise for advanced pumping applications, e.g. Tm:YAG [12].
Therefore, one of the next steps will be the demonstration of its usability as 793 nm pump module.

Further next steps in development of the process head could be a doubling of the power by using coarse wavelength beam combining and reliability tests, which might also include the integration of a back-reflection protection in the optical module design.

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