Perspectives on the performance scaling of high-power diode laser pumps for use in Inertial Fusion Energy Systems

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ABSTRACT

Diode lasers with substantially reduced cost and increased performance over the current state-of-the-art are needed for Inertial Fusion Energy (IFE) systems, and research efforts are summarized here. We focus on 1-cm diode laser bars based on grating-stabilized coupled-multi-junction designs, that have potential to deliver multi-kilowatt output powers, for massively reduced cost in €/W. We address three areas needed for this technology to find IFE implementation: facet passivation, monolithic grating technology and beam forming. Improved passivation allows ~ 885 nm single emitters with 200 µm stripe width that use single junction designs to operate at 40 W for > 2 GShots without failure, consistent with operation at 1.5 kW per junction in bar format. Improvements in monolithic grating-stabilization allow single-junction bars to deliver 800 W output power (250 µs 10 Hz) at 883 nm within 0.7 nm spectral width (FWHM). Ray-tracing calculation shows that the beam generated by a stack of coupled-multi-junction diode lasers could be homogenized using a simple optical system. However, improved diode laser technology must operate with high reliability, for example in near-term use within prototype IFE beamlines. A first estimate of the diode-level requirements and the efforts needed to confirm sufficient reliability is presented. We show that a "500-FIT" limit may be a suitable criterium, and potentially testable in around a year. We then conclude with a brief look forward, discussing the potential for Photonic Crystal Surface Emitting Laser (PCSEL) technology to find IFE application, as a further example of a grating-stabilized coupled-multi-junction device.

Keywords: diode lasers, high-power diodes, inertial fusion energy

1. INTRODUCTION

The performance status and emerging requirements for diode laser pumps for future application in inertial fusion energy (IFE) systems were recently reviewed in [1]. In short, for the realization of economic power generation via IFE, substantial cost reductions (around 20× in terms of €/W or $/W) in the diode pumps are needed, and performance scaling (power, fabrication yield, efficiency, reliability) of these critical components will play a significant role in making such scaling possible. We present some recent progress in applied research at the FBH towards achieving these goals. As noted in [1,2,3], current estimates show that at current costs of 0.1 $/W, for commercial per-bar powers of around $P_{\mathrm{opt}} = 500$ W, diodes would account for a prohibitive share of greater than 90% of the capital cost of an IFE power plant. If diode laser purchase costs could be reduced to around 0.01 $/W, this would reduce to below 50% share. If reliable per-bar power in coming years can be scaled to first kilowatts then to the multi-kilowatt level, this would a great contributor to the needed cost reduction [3], as would efforts to improve fabrication yield [4] and to implement sufficient production scaling [3].

Again, as recently summarized [1], multiple diode laser epitaxial structures can be grown on top of each other, linked via tunnel junctions, and this has long been used for edge-emitting lasers for generating high energies in short pulses, for use in long-reach LIDAR. In more recent work at the FBH, coupled multi-junction edge-emitting devices have been introduced, where several active regions are integrated in a single shared waveguide, that lases in one optical mode. Such coupled multi-junction approaches also allow gratings to be introduced to the structure, so that the spectrum is stabilized and narrowed, potentially eliminating yield losses due to wavelength targeting, and bringing benefits to the pumping scheme (e.g. access to narrow spectral lines). Both conventional and coupled multijunction approaches have demonstrated peak $P_{\mathrm{opt}} = 400$ W [5,6] from single emitters with stripe width $W = 200$ µm, at pulse widths in the $\tau = 1 \ldots 10$ ns range, equivalent to a (current-heating-free) per-bar peak $P_{\mathrm{opt}} \sim 14$ kW. In recent studies, 1-cm wide laser bars that use conventional de-coupled double junction designs that emit with a centroid wavelength around $\lambda_c = 870 \ldots 880$ nm have

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been demonstrated that operate with P_{opt} = 1800 W under fusion-relevant conditions with high current heating levels (τ ~ 250 µs, f ~ 10 Hz), with conversion efficiency η_E close to that of reference single junction bars [7]. Although coupled multi-junction bars that that operate with P_{opt} = 2200 W have long been demonstrated [8], realizing these with suitably high efficiency for use under fusion-relevant conditions requires extensive re-design efforts (ongoing), and progress will be presented elsewhere.

A successful multi-kilowatt implementation of grating-stabilized coupled-multi-junction diode lasers for ultra-low-costs will require not just an efficient epitaxial layer design and low-loss grating technology, but also progress in many other steps too, and the requirements for a high yield, robust III-V process technology suitable for reliable operation at high P_{opt} are summarized schematically in Fig. 1 [4]. Efforts to ensure high fabrication yield of these complex structures via the implementation of AI-assisted rapid defect identification and advanced epi and process metrology techniques are reviewed elsewhere [4,9,10]. The use of AI techniques is well-motivated, based on demonstrated rapid over tenfold cost reduction and volume scaling achieved using a similar approach in the fabrication of micro-optics for diode laser collimation [11]. Here, we instead summarize progress in two key enabling technologies, namely high-power facet passivation and the implementation of monolithic gratings in high power bars, focusing in both cases on diode lasers around λ_c= 870…890 nm. After the summary of progress in technology, we next present two plausibility estimates of readiness for fusion application, beginning with a discussion of the likely impact of the structured far field of a multi-junction device on the beam uniformity of a stack of bars, where we show that a uniform homogenized and highly intense beam can be created, suitable for application in pumping. Finally, a first level reliability calculation is given, which shows both that single emitters with a FIT score of around 500[2] could be sufficiently reliable for use in a beam line demonstrator, and that a (relatively) compact aging study test could be sufficient to confirm consistency with this requirement. The effort needed to realize high performance diode laser coolers [12,13] and quasi-continuous-wave current drivers suitable for multi-kilowatt bar operation is also dealt with elsewhere [14,15].

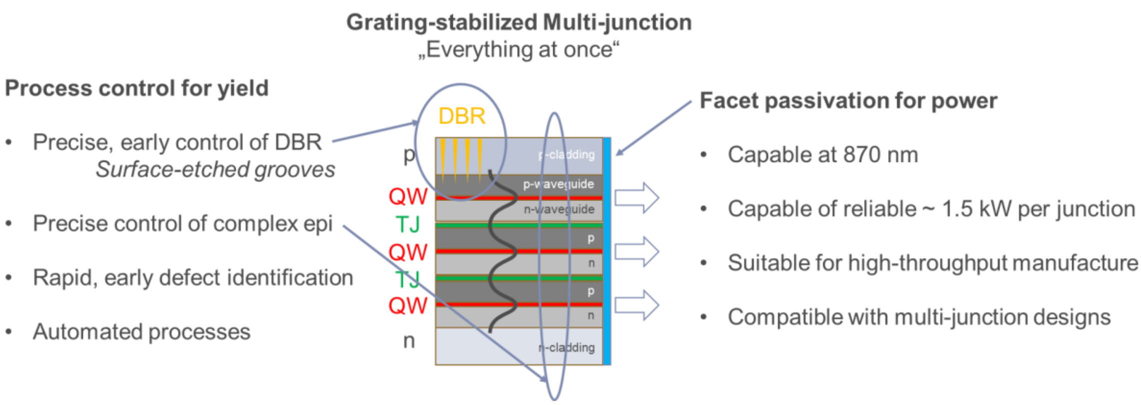

Figure 1. A schematic cross-section of a coupled multi-junction diode laser design, noting critical needs to ensure sufficient process control (yield) and robustness (power-capability).

2. FACET PASSIVATION

A fast and economic assessment of the reliability of kW-laser bars is essential to assess readiness of new technologies for application in future fusion power plants. The initial assessment of the reliability of single emitters rather than bars under operational or accelerated operation conditions is practical, because it reduces the requirement for the current drivers (typically currents in excess of 1 kA are required for kW-bars and not widely available) and reduces the power consumption. The later also reduces the required cooling power and hence costs of the tests. With this in mind, we choose to study single emitters with W = 200 µm, a cavity length L_c = 4 mm and a λ_c ~ 880 nm mounted on a conducting cooled package (CCP). A kW-laser bar would typically contain 35…38 of such emitters, depending on emitter spacing. The laser facets of these single emitters were cleaved in air and then passivated with ZnSe after hydrogen cleaning under a high vacuum. This is a volume-scalable passivation method that can readily be applied to thick multi-junction epitaxial layer

[2] Here FIT is defined as being the average of the hazard failure rate multiplied by 10^9 hours, so that a diode laser technology that is characterized by 500 FIT would result in 500 fails occurring within 10^9 device-hours.

designs and therefore is of special interest for inertial driven fusion [1]. As noted in Fig. 1, we define a facet robustness goal of $P_{opt} \geq 1.5$ kW per junction. For reference, single emitter reliability testing of ZnSe passivation is consistent with a peak per-bar $P_{opt} \sim 3$ kW at λ_c = 9xx nm [16], allowing single junction bars to be tested failure-free to P_{opt} = 1.9 kW [17].

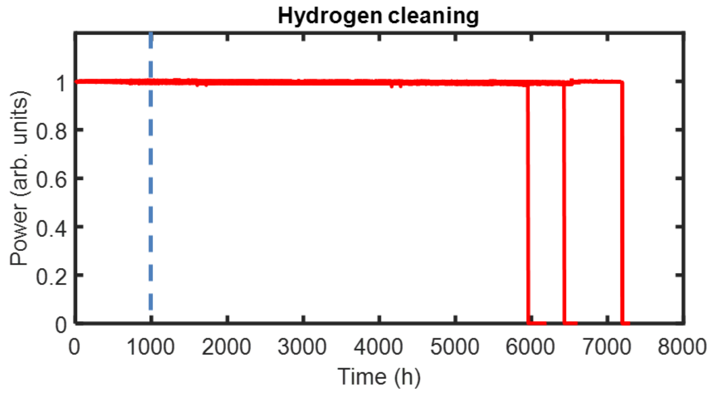

Fig. 2. CW lifetime measurements of 200 µm wide single emitters with a cavity length of 4 mm. The operation current of 20 A and temperature setpoint of 25°C result in an output power of 17 W at a wavelength of 892 nm. The max on time during operation in a fusion power plant, see text, is indicated by the dashed blue line.

Since kW-laser bars are operated in QCW mode, they are off most of the time. In fact, the total time that they emit light is around 1000 hours, for an example IFE-operating life of 12 GShots at τ = 250 µs. A quick plausibility assessment of the laser stability can thus be obtained by operating lasers in continuous wave (CW) mode for 1000 hours or more. Even though the output power is reduced under CW operation, it is important to stress that similar thermal conditions can be realized. We therefore started with testing the facet stability under CW operation using a current of 20 A and a temperature of 25 °C, resulting in an output power of 17 W. Under these conditions the wavelength increased from λ_c = 880 nm (directly above threshold) to λ_c = 892 nm at 20A, a thermal induced wavelength shift of 12 nm, corresponding to an average active region temperature $T_{AZ} \sim 62$ °C at the used heatsink temperature of T_{HS} = 15 °C, slightly above that of the laser material in a QCW stack operating at P_{opt} = 1 kW per bar [12]. CW lifetime measurements under these conditions, Fig. 2, show that laser facets obtained by hydrogen cleaning can sustain these thermal conditions for more than 5500 hours, corresponding to five times the required QCW on-time. This is a strong indication that these laser diodes meet the thermal stability requirements for QCW operation during an operational lifetime of 12 Gshots.

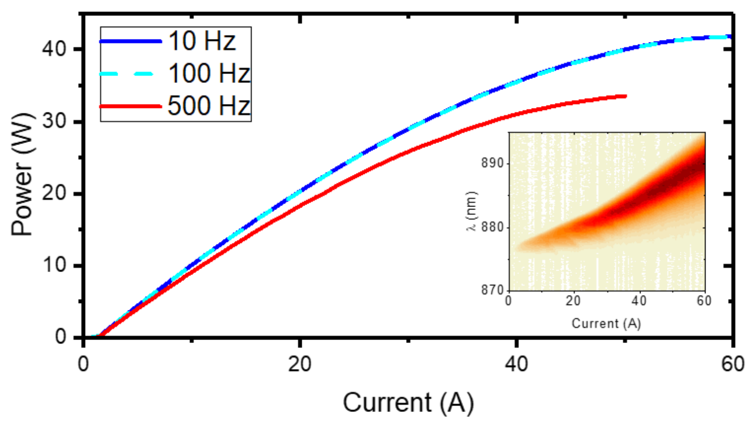

Fig. 3. QCW-measurements of optical power as a function of current for an 880 nm single emitter at T_{HS} = 15 °C using 250 µs pulses. The inset shows the spectral map (spatially integrated intensity plotted as a linearly-scaled false color map, as a function of wavelength and current) taken at 100 Hz.

As a next step, more realistic aging conditions need to be chosen, i.e. QCW operation, to test for the presence of pulse-driven failure modes and to stress the device facets to higher powers. Therefore, QCW measurements of a single emitter were performed using 250 µs pulses and a temperature setpoint of T_{HS} = 15 °C, see Fig. 2. At a current of I = 50 A an output power of P_{opt} = 40 W was reached for a repetition rate in the range of 10…100 Hz. Under the assumption that a bar contains 38 emitters, the output power of 40 Watt is equivalent to a power level of a 1.5 kW bar. From the spectral map we see that a wavelength shift of 12 nm occurs (λ_c = 876 → 888 nm), for an average T_{AZ} similar to CW operation mentioned above. For a higher repetition rate of 500 Hz a reduction of the output power was observed and a 40 W output power could no longer be realized. Therefore, an aging test with 5 diodes at 100 Hz was performed, see Fig. 3. This corresponds to a 10 times faster aging rate compared to the envisioned operation conditions. During the lifetime tests we observed two failures before 1500 hours. These occurred at the rear facet and their origin remains unclear. However, such early failures were not observed during additional lifetime tests (15 diodes in total, to date to 3500 hours, without failure), suggesting that it is not a typical failure and can be prevented by effective screening. The other three diodes are still functional after more than 6500 hours of operation. This timeframe corresponds to more than 2 GShot, estimated to be sufficient for a fusion beamline demonstrator. This is thus a strong indication that diode laser bars operating at λ_c ~ 880 nm with a power of around a kW per junction are realistic for such applications.

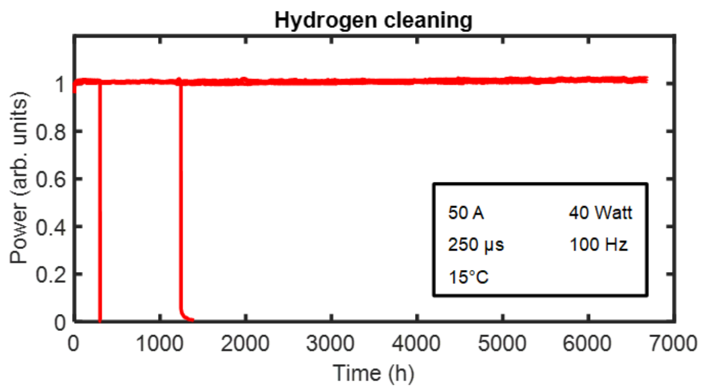

Fig. 4. lifetime test of 5 single emitters with an aperture of 200 µm, cavity length of 4 mm and wavelength of 888 nm under the operation conditions indicated in the inset.

However, in order to reach the 12 Gshot that are required for a fusion plant the lifetime test would have to run for a couple of years, even at f = 100 Hz, limiting how quickly promising new device technologies can be assessed. In order to overcome this limitation, we investigated single emitters with W = 200 µm and L = 4 mm that use an improved epitaxial structure that enables operation at a higher conversion efficiency (less heat). QCW measurements using repetition rates of 100 Hz and 500 Hz of such an emitter are shown in Fig. 5. It is easily observed that the output levels are higher compared to the measurements presented in Fig. 2. Importantly, 40 W output can be realized using a 500 Hz repetition rate and a current of 47 A. Using these parameters lifetime tests of single emitters with output powers equivalent to that of a 1.5 kW bar that reach 12 Gshot become feasible within a single year. This represents a useful time frame for performing fast assessments of the facet stability of single emitters and finally laser bars, and will be used in future work, to assess further improved passivation technology.

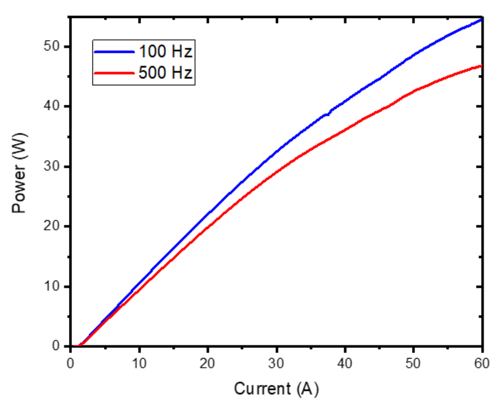

Fig. 5. QCW measured optical output power as a function of bias current for an λ_c = 880 nm single emitter (W = 200 µm, L_c = 4 mm) at heatsink temperature of T_{HS} = 15°C using 250 µs pulses. The use of an improved epitaxial structure with increased conversion efficiency allows higher output powers to be sustained to higher frequencies.

3. IMPLEMENTING MONOLITHIC GRATINGS IN HIGH POWER 883 NM BARS

In an update to [18], using the same epitaxial layer design and process technology, diode laser bars that emit around $\lambda = 885$ nm with monolithically integrated DBR gratings at the rear facet were fabricated with higher fill factor (23 × 200 µm → 35 × 195 µm), shorter total resonator length (L_c: 5 → 4 mm) and shorter DBR length (L_{DBR}: 1 mm → 500 µm), so that they are better suited for application in QCW stacks. After facet passivation and facet coating, bars were mounted on high-current-capable CCP assemblies and tested under QCW conditions ($\tau = 250$ µs, $f = 10$ Hz), with results shown in Fig. 6. The larger fill factor of the bars (pumped area is increased 1.3×) reduces the electrical resistance and increases the threshold current, with less rollover observed, due to the improved thermal resistance (anticipated here to be around 0.02 K/W). Scaling pump area in this way is a long-established method for shifting peak efficiency towards higher P_{opt} [14,19]. Improved performance is observed, with increased η_E (800 W): 44 → 50%, slightly lower than the best reported results, that were obtained at $\lambda_c \sim 970$ nm, where $\eta_E \sim 55\%$. The DBR ensures wavelength locking with λ(800 W) = 883 nm, where spectral width is $\Delta\lambda_{95\%}$(800 W) = 1.4 nm and $\Delta\lambda_{FWHM}$(800 W) = 0.7 nm, at 95% power and full-width-half-maximum levels, respectively. The overall device design is selected as a current best compromise between performance and fabrication yield, with further development needed to scale efficiency and power per junction (ongoing), based on lessons from [19], for example by using extreme triple asymmetric vertical layer designs and by increasing the emitter count per bar further.

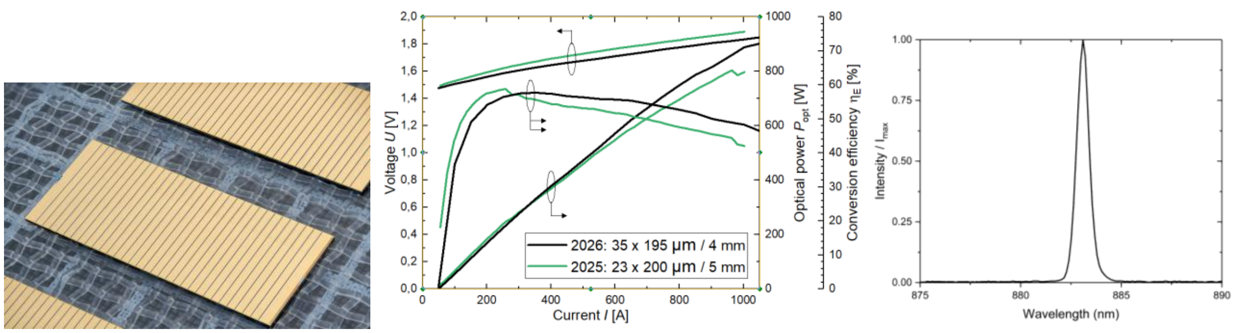

Fig. 6. (Left) Photograph of exemplary DBR-stabilized bars (Image © FBH / Schurian). (Center) Measured QCW optical output power ($\tau = 250$ µs, $f = 10$ Hz), voltage and conversion efficiency as a function of bias current for an $\lambda_c = 883$ nm diode laser bar (35×195 µm on 259 µm pitch, $L_c = 4$ mm, $L_{DBR} = 500$ µm) at heatsink temperature of 25°C. (Right) Measured spatially-integrated intensity as a function of wavelength at $P_{opt} = 800$ W for the bar with $L = 4$ mm ($\tau = 250$ µs, $f = 10$ Hz).

4. RAY-TRACING ASSESSMENT OF STACK OF MULTI-JUNCTION LASERS

Multi-junction coupled waveguide diode lasers operate with a broad, multi-peaked vertical near- and far field, arising from the need to have intensity maxima in the active regions and intensity nodes in the tunnel junctions. The structured beam is a risk element for pump applications, as intensity non-uniformity in the solid-state crystals can excite parasitic modes, that are (at best) loss elements, or (at worst) lead to system damage or even failure. Therefore, an early assessment of the likelihood of being able to realize a properly uniform beam is helpful, to confirm that the power and cost benefit of multi-junction approaches can find application. Here, we take the known (calculated) vertical beam characteristics of an exemplary triple-junction design from the FBH, and show an estimate of how its expected beam profile would impact the beam from an exemplary high-density stack, here assuming a 31-bar variant taken from [12] with 850 µm vertical pitch.

Specifically, a ray tracing simulation was performed to estimate the far field of the stack mounted with FAC lenses. All calculations were performed using BeamXpertDESIGNER [20]. For this simulation, a top-hat-shaped lateral near field with a width of 195 µm and pitch of 259 µm (following the bar design in Fig. 6) and a Gaussian-shaped lateral far field with a divergence angle of 12 degrees (95% power content) were assumed for each emitter, using far field angles from [17] for a single junction 1-cm laser bar at $\lambda_c = 940$ nm operating at $P_{opt} = 1.5$ kW. In the vertical direction, the calculated near and far field of the multi-junction structure were taken into account. Fig. 7 shows the resulting calculated far field. The lateral and vertical divergence angles (95% power inclusion) are approximately 7 mrad and 210 mrad, respectively, with slightly broader residual vertical divergence than the ca. 5 mrad achieved experimentally in [12] for a conventional single-junction design.

To examine the possibility of beam homogenization, a homogenization system consisting of two customized microlens arrays and a far-field lens (see Fig. 8) was also simulated using ray tracing. In Fig. 9, the profile of the resulting 1-cm^2 homogenized beam is presented at an exemplary imaging plane. This shows that a top-hat profile can be generated in this simple "proof of principle" case, despite the structured (non-Gaussian) vertical near-field and far-field distributions of the multi-junction emitters.

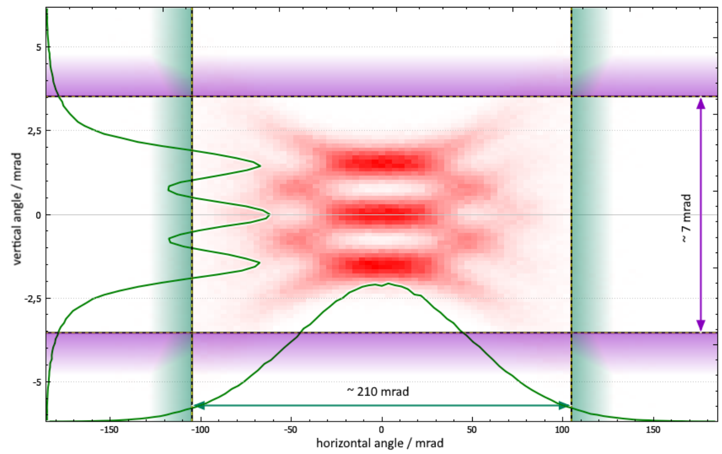

Fig. 7. Ray tracing simulation of a predicted far field of a 31-bar stack with fast axis collimation lenses and 850 µm vertical spacing between bars, where each bar makes use of an exemplary (unpublished) FBH coupled-waveguide triple-active region design and the bar layout used in Fig. 6 (not to scale).

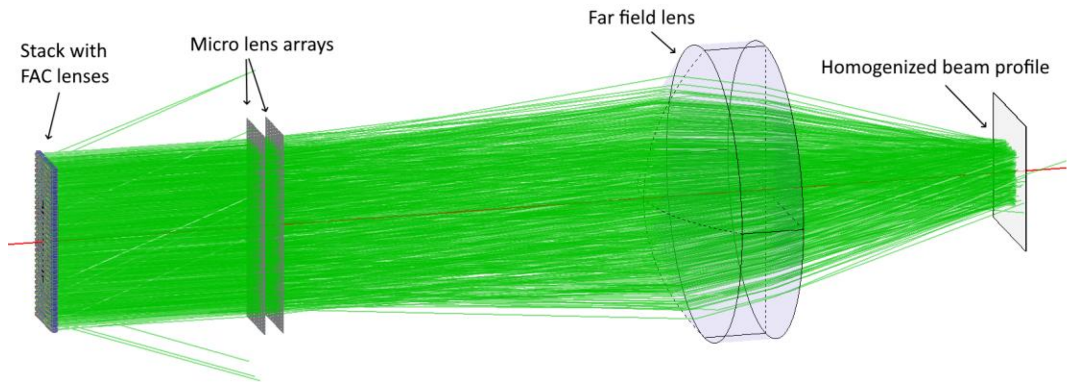

Fig. 8. Ray tracing calculation of an exemplary homogenization system consisting of two customized microlens arrays and a far-field lens.

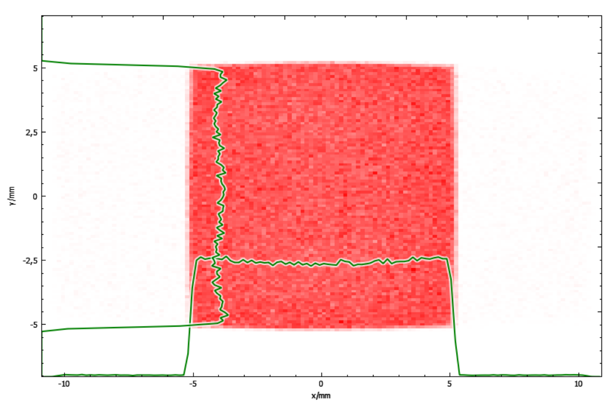

Fig. 9. Ray tracing simulation of the generation of a homogenized square top-hat beam profile at the image plane in Fig. 8.

If we assume that 1.5 kW per 3-junction bar at $\lambda_c \sim 870\ldots885$ nm is achievable in such a stack configuration, we can calculate both an anticipated brightness and also a delivered power density at the imaging plane in Fig. 9. The power per stack would be around $P_{stack} = 46$ kW (31×1.5 kW), delivered from a near field of size $D_x \times D_y \approx 0.9$ cm × 2.7 cm, within a far-field angle of $\theta_x \times \theta_y \approx 210$ mrad x 7 mrad. The resulting brightness B would be: $B = P_{stack} \div (D_x \times D_y \times \theta_x \times \theta_y) = 13\times10^6$ W/cm^{2}sr, and the power density at the image plane would be c. 46 kW/cm^2, that is around 2.5× larger than the target in [1] of 18 kW/cm^2, i.e. consistent with significant cost savings.

5. ESTIMATING AND CONFIRMING NEEDED LASER DIODE RELIABILITY LEVEL

In the current period where new technologies for the IFE industry are rapidly developing, an equally rapid assessment procedure is needed to decide if these promising approaches are suitable for near-term use in demonstration efforts that require significant capital investment, such as in prototype beam lines. A similar process was followed informally in the fiber laser business, with early reliability assessments confirming readiness of emerging high power broad area lasers for industrial application based on small sample sizes [21], followed later by extended qualification programs to fully determine the reliability of devices from a given supplier, suitable for robust deployment in very large systems [22]. One goal of the Star Fire diode laser working group [23] is to help define and agree suitable standards for such efforts in the IFE context, to help suppliers assess system readiness in their development efforts and to protect users as they define and purchase pumps for demonstrations at scale. We present here one example calculation for orientation, that gives a first estimate of needed diode-level reliability and an economic method to assess if it is achieved.

Lifetime prediction for laser stacks based on aging experiments of single emitters is rather challenging, since the distribution of heat, power and stress among single emitters is non-uniform and emitter failures are not independent, since each failure can locally enhance the thermal stress, and crystal defects may propagate towards neighboring emitters. We further note that even very well-developed industrial diode laser and assembly technology can present very different lifetime expectations for CW [24] and QCW application [25]. Nevertheless, for developing improved high-power laser stacks it can be useful to estimate the outcome of aging experiments based on simple assumptions. In such extrapolations, we effectively assume that all other failure points in the pump assemblies (solder, lenses, coolers, beam shaping etc.) have far higher reliability than the diode lasers, which is only the case in highly developed technology.

In the following, we use the concept of scale-accelerated failure-time for aging over a limited time (10,000 h) in order to estimate the reliability of an example pulsed high power laser stack of 50 diode laser bars following [12]. We make these estimates in this first step as a best-case analysis for material operating at $\lambda_c = 940$ nm, that is the most reliable and most published device configuration, where most information is available on aging behavior. Specifically, in this section we assume the diode laser bars to be operating at $P_{opt} = 1000$ W at $\lambda = 940$ nm, using the bar layout followed in [17], i.e. containing 20 emitters. Stacks are assumed to operate with a total peak power of $P_{stack} = 50$ kW at $f = 15$ Hz, $\tau = 0.5$ ms pulse width and to have up to $r = 20\%$ power drop allowed over 20 years. We apply a typical diode laser stress function that is dependent on power P_{opt} and temperature T_{AZ} in the active zone, including frequency dependence by an arbitrary exponential function, and use this for scaling of the time to failure (t_F) as [26,27]:

$$t_F \propto f^{-m} P_{Opt}^{-n} \exp \frac{E_A}{kT_{AZ}} \quad (1)$$

with derating exponents m and n for frequency and power, respectively, and thermal activation energy E_A. Note, that for $m = 1$ the number of shots until failure $s_F = t_F f$ would be independent of frequency, as usually assumed. Here, we include a frequency dependence to allow for the influence of thermomechanical stress, which we set to be proportional to the frequency on log-scale, for simplicity.

Recalling the standard Telcordia GR-468-CORE as normative reference for laser diodes, the failure distribution can be modeled by log-normal for wear-out and exponential for "random failures" [26,27]. Taking both distributions into account in a simple and consistent manner, the hazard failure rates add up resulting in multiplication of their complementary distributions for the reliability $R(t)$ as function of operational time t, where failure events occur at scale-accelerated failure time $t = t_F$:

$$R(t) = \exp[-\lambda t]\, \Phi_{norm}\left[\frac{\mu - \ln(t)}{\sigma}\right] \quad (2)$$

Provided that the life time of laser diodes is scale-accelerated by stress as (1) and distributed as (2), the parameters *m*, *n*, E_A for acceleration factors and λ, *μ* and *σ* for the distribution factors can be estimated experimentally, for example by lot-wise accelerated life testing.

In the following, we use representative numbers for acceleration factors and reliability distribution parameters, each time assuming to be known within reasonable confidence limits for diode lasers, that are consistent with a stack lifetime of around 10…20-years. First, we show the predicted results of a four cell (four lot) emulated reliability study, that could be used as a plausibility test, to assess if a given diode laser technology is broadly consistent with the assumed parameters. Next, we use the same parameters and plot the predicted stack lifetime, showing the 10-20% lifetime. The operating parameters for the simulated life tests of four lots as listed in table 1.a), assumed to be applied to a total of 26 half-bars, each with10 emitters. The chosen values of the acceleration and distribution parameters are indicated in table b). The chosen failure rate $\lambda = 5\times10^{-7}$/h can also be presented as "FIT" value of 500, i.e. the diode material is broadly characterized as operating at an expected rate of 500 fails per 10^9 hours before wear-out, where FIT values are a typical performance metric for communication lasers [27].

Table 1.a) Test lots for simulations of 26 half-bars with each 10 emitters

Lot	Half-bars	P/W	f/Hz	T_{AZ}/°C
1	10	50	15	100
2	6	75	60	42
3	5	75	75	42
4	5	80	90	42

1.b) Parameters, simulated MLE results with 10% and 90% upper confidence limits at test time = 10,000 h

Param.	Choice	10% Limit	MLE	90% Limit	Units
μ	12.9	12.3	13.1	14.2	ln(h)
n	4	0.04	3.0	6.7	
E_A	0.5	0.13	0.34	0.55	eV
σ	0.5	0.47	0.55	0.66	
λ	5×10^{-7}	1.97×10^{-7}	6.6×10^{-7}	16×10^{-7}	1/h
m	1.5	1.15	1.87	2.48	

Random number ("Monte Carlo") simulations were performed for a test time of 10,000 h with 500 samplings, each evaluated using maximum-likelihood estimate (MLE). The MLE values of the parameters and their 10% and 90% (upper) confidence limits are listed in tab. 1.b. In any case, the confidence intervals cover the initial parameters of choice. The result is displayed in Fig. 10a) for single emitters and – assuming independent failures – for a stack of 50 bars, each containing 20 emitters (for total emitter count in the stack of $N = 1000$) with $r = 10\%$, 15% or 20% of single emitter failures per stack allowed (Binomial distribution) in Fig. 10b). The red lines indicate the MLE values, the 500 dots are non-parametric (Kaplan-Meier) estimates, each dot representing one failure. The grey areas are 99% confidence bands in case of single emitters and 80% bootstrap confidence bands in case of stacks. A comparable four lot test of real devices would then be sufficient to confirm consistency of a given diode population with the assumed aging parameters (i.e. would be a plausibility-demonstration of consistency with 500 FIT for random failures and a median time $t_m = e^{\mu} = 4\times10^5$ h [45 years] for wear-out).

The results further demonstrate that for $r = 20\%$ allowed failures, the reliability exceeds 99% for over 20 years at MLE and 10 years at 90% (one-sided) confidence for a nominal 50 bar stack, on the best-case assumption that its reliability is limited only by the diode laser characteristics - see Fig 10(b).

We can further estimate the impact of such a reliability level on a nominal Yb:YAG-based beamline demonstrator, that is pumped with a total power of 70 MW, supplied by an assembly of 1400 stacks, each themselves providing 50 kW output power. In such a case, again assuming $r = 20\%$, we estimate that around 57 stacks would fail per year of operation, corresponding to 4% of the total pump power, sufficient to enable the use of an emerging diode laser technology in a near-term beam line demonstrator.

For future work, aging experiments based on accelerated lot testing and failure mode analysis shall improve the significance of the prognoses aimed at closing the gap between simple assumptions and physical effects, such as generation and propagation of material defects, on the failure modes. Studies that confirmed that a chosen diode laser configuration functions with a < 500 FIT reliability level would be likely needed for this to find application in IFE, even at the prototype level. Parallel efforts to demonstrate that the chosen stack assembly approach does not introduce any more rapid failure modes would also be needed, for example via rapid and highly accelerated step stress testing, e.g. at over-bias and to very high repetition rates > 100 Hz.

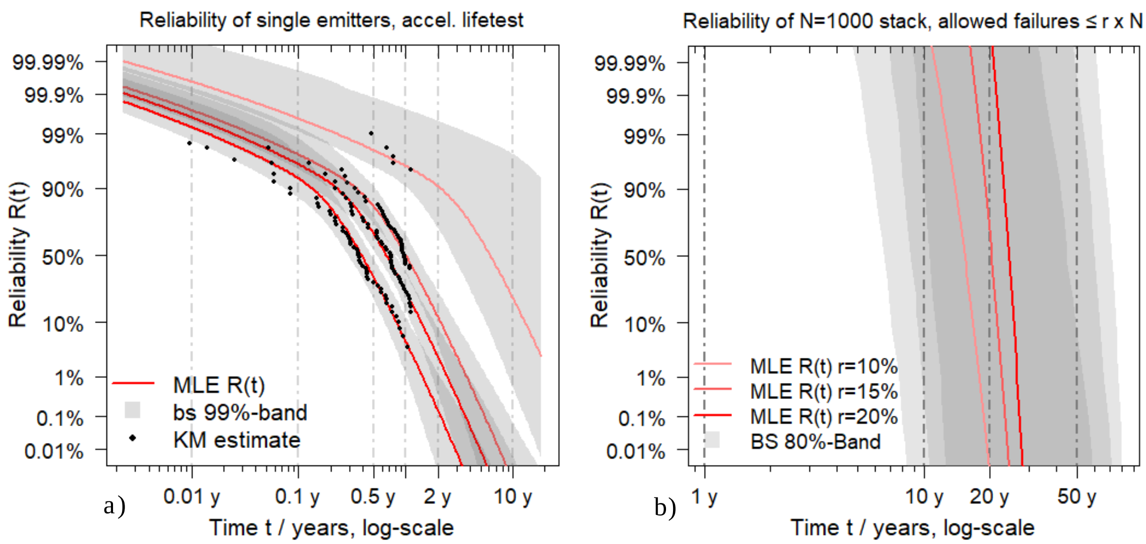

Fig. 10. Simulated reliability of (a) single emitters and (b) stacks of 50 bars each 20 emitters (total device number N = 1000) as a function of operation time, with estimated single emitter failure distribution shown for a test time of 10,000 hours.

6. ALTERNATIVE APPROACHES

In a final note, on the longer term, there are alternative diode laser approaches that offer a compelling path forward, for example the photonic crystal surface emitting laser, or PCSEL. In these devices, light is emitted vertically, but the resonator is formed in-plane, due to optical feedback from a monolithically integrated photonic crystal, PC, layer [28]. The PC is designed to ensure that the device is held in a (nearly) single optical mode with Gaussian profile, so that light is emitted from the substrate in a narrow spectral line with a very narrow far field.

First, we emphasize their advantages. In such devices, there is no need for passivated facets or for collimation lenses, eliminating two of the most critical failure points in the system. Further, mounting and cooling are planar, potentially dramatically simplifying packaging efforts, for lower cost. In addition, the similarities with LED processing would offer a path to very high volume, low-cost fabrication. Finally, in the most recent research, a single coupled-multi-junction PCSEL operated in short-pulse (ns-class) mode delivered peak power up to P_{opt} = 1800 W at λ_c ~ 940 nm from a 3 mm aperture [29]. If such PCSELs could be fabricated in arrays with (say) 80% fill factor, then a (peak) power density sufficient for application in IFE would be delivered, albeit within far shorter pulse widths than needed for IFE. However, PCSELs have also disadvantages. Their peak conversion efficiency is currently (best case) in the 20…30% range, they are extremely challenging to fabricate [20], with the highest performance devices making use of a complex regrown buried air-hole technology, and to date only the pioneering research group of Professor Noda in Kyoto has reported such high powers.

As a complement to many studies world-wide, the FBH is developing an alternative approach, based on a fully-semiconductor-based (no air holes) technology and a so-called “stretched-isosceles-triangle” PC design, that has (predicted, but as yet unproven [31-33]) potential to scale to the efficiencies and powers needed for fusion application. Both a schematic depiction of the device design approach and a photograph of an early proof-of-principle PCSEL device are shown in Fig. 11, and experimental results will be reported later in 2026.

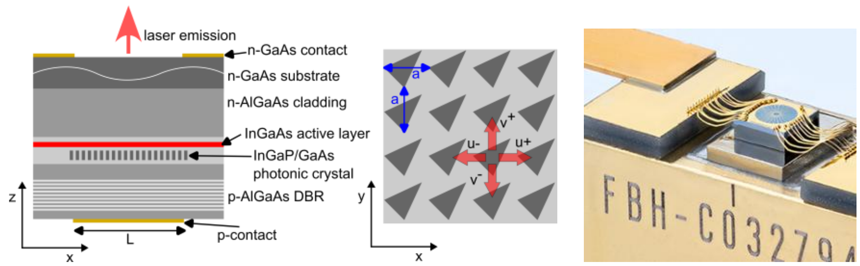

Fig. 11. A schematic depiction of the device layout used in the FBH all-semiconductor approach for realizing PCSELs [31-33], showing a vertical cross-section of the entire device with contact diameter, *L* (left) and an overview of the PC layout, with PC period *a*. (Right): Photograph of a prototype FBH PCSEL mounted junction side down on c-mount for testing, showing the structured n-side metallization (© FBH / Schurian). Experimental results will be reported later in 2026.

7. CONCLUSIONS

An overview was presented on efforts in research to scale diode laser performance, as an enabling tool for inertial fusion energy systems, following on from the general review presented in [1]. We focused on research efforts towards enabling future massive cost reduction of the diode laser technology via large-scale increase in their optical output power. Diode laser bars based on monolithically grating stabilized coupled-multi-junction technology are a highly promising approach, and established at around λ_c = 905 nm for short-pulse LIDAR application. An overview of efforts to date to enable such designs to find use in IFE systems as pumps with λ_c ~ 880 nm was given, focusing on the enabling technology. Experimental studies showed strong progress in facet passivation (single emitter test data shown consistent with > 2 GShot operation at 1.5 kW per junction) and monolithic gratings (1-cm diode laser bar test data with 800 W output power in a 0.7 nm spectrum, using a single junction design). Ray-tracing calculation further indicated that the structured beam of a coupled-multi-junction stack could be homogenized using a simple optical system, so that they could find application in pumping. Further, a first calculated estimate was presented of the reliability level needed (ca. 500 FIT) for a promising diode laser technology to find application in a prototype IFE beam line demonstrator, as was an estimate of the size of aging study required to confirm consistency with this requirement (ca. 260 emitters for one year). Finally, we noted briefly the promise of PCSELs as a technology solution for IFE, if their performance limitations could be overcome.

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REFERENCES

[1] Crump, P., Fenwick, W., Elattar, M., Tamer, I., Häusler, K., Nelson, M., Boschker, J. E., Knigge, A., and Deri, R. J., "Diode laser pumps for future inertial fusion energy systems: status and perspectives," Optics Express 33(22), 46456-46470 (2025). https://doi.org/10.1364/OE.575048

[2] Nelson, M. K., Galbraith, J. D., Deri, R. J., Fenwick, W. E. and Tamer, I. F., "Lifetime requirements for semiconductor lasers in inertial fusion energy systems," Proc. SPIE Conference 13888 (Optical Technologies for Inertial Fusion Energy II) San Francisco USA, paper 13888-4 (2026).

[3] McDougall, S. D., Boucke, K., D'Souza, M., Thiagarajan, P., Walker, R., Gruber, L., Deri, R. J., Fenwick, W. E., and Tamer, I. F.., "Semiconductor laser costs for inertial fusion energy applications," Proc. SPIE Conference 13888 (Optical Technologies for Inertial Fusion Energy II) San Francisco USA, paper 13888-3 (2026).

[4] Crump, P., Della Casa, P., Unger, R-S., Martin, D., Maaßdorf, A., Haberland, K., Binetti, M., Lörchner-Gerdaus, C., Rupapara, H., Boschker, J., Glaab, J., Zink, C., Einfeldt, S., Knigge, A., and Weyers, M., "Diode Laser Technology for Inertial Fusion Energy: Techniques for Scaling Yield and Power", Proc. IEEE Phot. Conf. (IPC 2025), Singapore, Singapore, paper TuB1.3 (2025). https://doi.org/10.1109/IPC65510.2025.11282061

[5] Ammouri, N., Christopher, H., Maaßdorf, A., Fricke, J., Ginolas, A., Liero, A., Wenzel, H., Knigge, A., and Tränkle, G., "420 W pulse power from a 905 nm distributed bragg reflector laser with multiple active regions and tunnel junctions," Phys. Scr., 100(7), pp. 075514 (2025). https://doi.org/10.1088/1402-4896/adde8e

[6] Müller, M., Lauer, C., Swietlik, T., Fuchs, L., Tangring, I., Furitsch, M., Roth, M., Kors, A., Schmid-Pillmeier, M., Eigenmann, F., Hein, S., and Behringer, M., "Advances in infrared high-power lasers," Proc. SPIE Conference 13876 (High-Power Diode Laser Technology XXIV) San Francisco USA, Paper 13876-6 (2026).

[7] Neukum, J., Fenwick, W. E., Liu, G., Pope, D. L., Xu, Z., Boisselle, M. C., Zhang, Q., Gilmore, L. V., Guo, B., Tamer, I., Lei, S., Deri, R. J., Zhang, Y., Zeitschel, A., Carriere, J., Kissel, H., Köhler, Venohr, R., and Weiss, E., "Efficiency and spectral behavior of > 1 kW/bar multi-junction semiconductor lasers," Proc. SPIE Conference 13888 (Optical Technologies for Inertial Fusion Energy II) San Francisco USA, paper 13888-2 (2026).

[8] Knigge, A., Ammouri, N., Christopher, H., Glaab, J., Liero, A., Fricke, J., and Wenzel, H., "2 kW Pulse Power from Internal Wavelength Stabilized Diode Laser Bar for LiDAR Applications," 28th Int. Semi. Laser Conf. (ISLC 2022), Matsue, Japan, paper TuB-02 (2022).

[9] Zink, C., Ekterai, M., Martin, D., Clemens, W., Maennel, M., Mundinger, K., Richter, L., Crump, P. and Knigge, A., "Deep learning based visual inspection of facets and p-sides for efficient quality control of diode lasers", Proc. of SPIE. 12403, 124030E (2023). https://doi.org/10.1117/12.2648691

[10] Maaßdorf, A., Zettler, J. K., Brendel, M., et al., "Efficient Front-End Manufacturing of High-Quality VCSEL – Enabled by In-Situ and Ex-Situ Optical Metrology During Epi Growth and Processing," Int. Conf. Compound Semicond. Manufacturing Technology (CS ManTech), New Orleans, Louisiana, USA, paper 10A.3 (2025).

[11] Liu, V. X, "Scaling of Pumping Sources for High-Power Diode-Pumped Solid-State Lasers: From Technology to Mass Production", Proc. IEEE Phot. Conf. (IPC 2025), Singapore, Singapore (2025)

[12] Barnowski, T., Vekathe, T., Atwater, K., Gong, T., Zanghi, E., Razavi, R., and McDougall, S., "Advances in manufacturing of high peak energy diode laser stacks," Proc. of SPIE 13452, 1345201 (2025) https://doi.org/10.1117/12.3053696

[13] Strohmaier, S. G., Erbert, G., Rataj, T., Meissner-Schenk, A. H., Loyo-Maldonado, V., Carstens, C., Zimer, H., Schmidt, B., Kaul, T., Karow, M. M., Wilkens, M. and Crump, P., "Forward development of kW-class power diode laser bars," Proc. of SPIE 10514, 1051409 (2018). https://doi.org/10.1117/12.2290382

[14] Crump, P., Frevert, C., Hösler, H., Bugge, F., Knigge, S., Pittroff, W., Erbert, G., and Tränkle, G., "Cryogenic ultra-high power infra-red diode laser bars," Proc. of SPIE 9002, 90021I (2014). http://dx.doi.org/10.1117/12.2041279

[15] Fulkerson, E. S., Telford, S., Deri, R. J., Bayramian, A., Lanning, R., Koh, E., Charron, K., and Haefner, C., "Pulsed power system for the HAPLS Diode Pumped Laser System," 2015 IEEE Pulsed Power Conference (PPC), Austin, TX, USA, pp. 1-6 (2015). https://doi.org/10.1109/PPC.2015.7296854

[16] Boschker, J. E., Spengler, U., Ressel, P., Schmidbauer, M., Mogilatenko, A., and Knigge, A., "Stability of ZnSe-Passivated Laser Facets Cleaved in Air and in Ultra-High Vacuum," IEEE Photonics J. 14(3), Art no. 1531606 (2022). https://doi.org/10.1109/JPHOT.2022.3176675

[17] Miah, Md. J., Boni, A., Arslan, S., Martin, D., Della Casa, P., and Crump, P., "Optimizing Vertical and Lateral Waveguides of kW-Class Laser Bars for Higher Peak Power, Efficiency and Lateral Beam Quality," IEEE Photonics J. 14(3), art. 1525505 (2022). https://doi.org/10.1109/JPHOT.2022.3165399

[18] Elattar, M., Wenzel, H., Fricke, J., Della Casa, P., Kreutzmann, S., Knigge, A., Pietrzak, A., Jiang, C.-L., Liu, X., Amtout, A., McDougall, S.D., and Crump, P., "Monolithic DBR broad-area diode lasers with high conversion efficiency in the 87x–88xnm wavelength range," Proc of SPIE 13345, 1334507 (2025). https://doi.org/10.1117/12.3045200

[19] Crump, P., Boni, A., Elattar, M., Khamari, S.K., Marko, I.P., Sweeney, S.J., Arslan, S., King, B., Miah, Md. J., Martin, D., Knigge, A., Della Casa, P., and Tränkle, G., "Power and Efficiency Scaling of GaAs-Based Edge-Emitting High-Power Diode Lasers," IEEE J. Sel. Top. Quantum Electron. 31(2), art. 1502512 (2025). https://doi.org/10.1109/JSTQE.2024.3484669

[20] https://www.beamxpert.com/en (last accessed 10 Feb. 2026)

[21] Pendse, D. R., Chin, A. K., Bull, D., and Maider, K., "Reliability assurance of broad-area high-power multimode laser diodes for telecommunications equipment", Proc. SPIE 4285, pp. 1-13 (2001); https://doi.org/10.1117/12.426873

[22] Zucker, E., Zou, D., Zavala, L., Yu, H., Yalamanchili, P., Xu, L., Xu, H., Venables, D., Skidmore, J., Rossin, V., Raju, R., Peters, M., Liao, K-H., Lee, K-W., Kharlamov, B., Hsieh, A., Gurram, R., Guo, J., Guerin, N., Gregg, J., Duesterberg, R., Du, J., Demir, A., Cheng, P. and Cheng J., "Advancements in laser diode chip and packaging technologies for application in kW-class fiber laser pumping," Proc. of SPIE 8965, 896507 (2014). https://doi.org/10.1117/12.2038268

[23] StarFire Hub, Diode Technology Working Group https://www.fbh-berlin.de/en/media-center/press-releases/fbh-joins-ife-starfire-hub-to-advance-inertial-fusion-energy (last accessed 10 Feb, 2026).

[24] Hülsewede, R., Schulze, H., Sebastian, J., Schröder, D., Meusel, K., and Hennig, P., "High Reliable – High Power AlGaAs/GaAs 808 nm Diode Laser Bars," Proc. of SPIE 6456, 645607 (2007). https://doi.org/10.1117/12.705119
[25] Deichsel, E., Schröder, D., Meusel, J., Hülsewede, R., Sebastian, J., Ludwig, S., and Hennig, P. "High Reliable qcw Laser Bars and Stacks," Proc. SPIE 6876, 68760K (2008). https://doi.org/10.1117/12.761476
[26] W. Q. Meeker and L. A. Escobar, *Statistical Methods for Reliability Data*, (John Wiley & Sons, 1998)
[27] Telcordia GR–468–CORE "Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment" (1998)
[28] Noda, S., Inoue, T., Yoshida, M., Gelleta, J., Zoysa, M. D., and Ishizaki, K., "High-power and high-beam-quality photonic-crystal surface-emitting lasers: a tutorial," Adv. Opt. Photon. 15, pp. 977–1032 (2023). https://doi.org/10.1364/AOP.502863
[29] Katsuno, S., Yoshida, M., Inoue, T., Zoysa, M. D., Hatsuda, R., Ishizaki, K., and Noda, S., "Design and experimental demonstration of photonic-crystal lasers with multijunction active layers," Appl. Phys. Express 17, 122004 (2024). https://doi.org/10.35848/1882-0786/ad9430
[30] King, B., Wenzel, H., Radziunas, M., Kuhn, E., and Crump, P., "omparison of Design Tolerance for High-Power PCSELs," PCSEL Workshop, 10-12 Nov., Aston, UK, paper 42 (2025). https://www.pcsel.org/abstracts (last accessed 10 Feb, 2026).
[31] King, B., Wenzel, H., Kuhn, E., Radziunas, M., and Crump, P., "Design of very-large area photonic crystal surface emitting lasers with an all-semiconductor photonic crystal," Optics Express 32(25), pp. 44 945–44 957 (2024). https://doi.org/10.1364/OE.537452
[32] Radziunas, M., Wenzel, H., King, B., Crump, P., and Kuhn, E., "Dynamical simulations of single-mode lasing in large-area all-semiconductor pcsels," Opt. Letters 50(6), pp. 1953–1956 (2025). https://doi.org/10.1364/OL.553405
[33] Poojitha, S., Della Casa, P., Brox, O., Fricke, J., Unger, R-S., Rentner, D., King, B., Crump, P., Weyers, M., Knigge, A., and Tränkle, G., "Process Development to Realize All-Semiconductor InGaP-GaAs based Photonic-Crystal Surface Emitting Lasers," Micro. Nano. Eng. 30, 100354 (2026). https://doi.org/10.1016/j.mne.2026.100354