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## Introduction and Overview

Solid-state lasers have been demonstrated as attractive drivers for inertial confinement fusion on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) and at the Omega Facility at the Laboratory for Laser Energetics (LLE) in Rochester, NY. For power plant applications, these lasers must be pumped by semiconductor diode lasers to achieve the required laser system efficiency, repetition rate, and lifetime. Inertial fusion energy (IFE) power plants will require approximately 40-to-80 GW of peak pump power, and must operate efficiently and with high system availability for decades. These considerations lead to requirements on the efficiency, price, and production capacity of the semiconductor pump sources. This document provides a brief summary of these requirements, and how they can be met by a natural evolution of the current semiconductor laser industry.

The detailed technical requirements described in this document flow down from a laser amplifier design described elsewhere. [1] In brief, laser amplifiers comprising multiple Nd:glass gain slabs are face-pumped by two planar diode arrays, each delivering 30 to 40 MW of peak power at 872 nm during a ~200 μs quasi-CW (QCW) pulse with a repetition rate in the range of 10 to 20 Hz. The baseline design of the diode array employs a 2D mosaic of submodules to facilitate manufacturing. As a baseline, we envision that each submodule is an array of vertically stacked, 1 cm wide, edge-emitting diode bars, [e.g.; 2] an industry standard form factor. These stacks are mounted on a common backplane providing cooling and current drive. Stacks are conductively cooled to the backplane, to minimize both diode package cost and the number of fluid interconnects for improved reliability. While the baseline assessment in this document is based on edge-emitting devices, the amplifier design does not preclude future use of surface emitting diodes, [3,4] which may offer appreciable future cost reductions and increased reliability.

The high-level requirements on the semiconductor lasers involve reliability, price points on a price-per-Watt basis, and a set of technical requirements. The technical requirements for the amplifier design in Ref. [1] are discussed in detail below and are summarized in Table I. These values are still subject to changes as the overall laser system continues to be optimized. Since pump costs can be a significant fraction of the overall laser system cost, it is important to achieve sufficiently low price points for these components. At this time, our price target for tenth-of-a-kind IFE plant is $0.007/Watt for packaged devices. At this target level, the pumps account for approximately one third of the laser cost. The pump lasers should last for the life of the power plant, leading to a target component lifetime requirement of roughly 14 Gshots, corresponding to a 30 year plant life and 15 Hz repetition rate.

An attractive path forward involves pump operation at high output power levels, on a Watts-per-bar (Watts/chip) basis. This reduces the cost of pump power (price-per-Watt), since to first order the unit price does not increase with power/bar. The industry has seen a continual improvement in power output,[5] with current 1 cm-wide bars emitting up to 500 W QCW (quasi-continuous wave). Increased power/bar also facilitates achieving high irradiance in the array plane. On the other hand, increased power implies greater heat loads and (possibly) higher current drive, which will require increased attention to thermal management and parasitic series resistance. Diode chips containing multiple p-n junctions and quantum wells (also called nanostack structures) may provide an additional approach to reduce the peak current. [6]

**TABLE I. Diode Pump Subsystem Requirements and Operating Parameters**

| Item | Value | Comments |
|---|---|---|
| Array Size | 53 x 27 $cm^2$ | |
| Array Peak Power | 36 MW | |
| Diode wavelength range | 872 $\pm$ 6.6 nm | |
| Array Irradiance* | 20 $kW/cm^2$ | Without polarization multiplexing.* |
| Pulse width | 175 µs | Baseline value, may increase with laser optimization |
| Diode efficiency | 72% | Including fast-axis collimator |
| Repetition Rate | 15 Hz | Laser optimization may increase to 20 Hz |
| Duty cycle | <0.5% | |
| Diode fast axis divergence | 4 degrees FW $1/e^2$ | |
| Life time | ~14 Gshots | Target value; to 20% power reduction |

* The array irradiance is less than the irradiance required of the stack submodules, due to the space between stacks within an array. Required stack irradiance is estimated to be 25 $kW/cm^2$.

## Technical Requirements

The wavelength requirement for IFE pumps is determined by the absorption spectrum of the gain medium. The 872 nm Nd:glass absorption peak is close to the operating wavelength of commercial semiconductor lasers used for pumping (880~885 nm) and medical applications (870 nm).[7] These devices are produced using InGaAlAs or InGaAsP epitaxial layers on laser grade GaAs substrates, which are available in diameters up to four inches. Their wavelength can be tuned to 872 nm by small changes in the device epitaxy. [e.g.; 8,9] The required wavelength control ($\pm$6.6nm) is set by the amplifier configuration: the relatively long absorption path of the Ref. [1] design provides rather loose wavelength control requirements. Since wavelength tolerances of $\pm$3 nm can be routinely achieved, this requirement is not expected to impact production yields or costs.

High pump irradiance facilitates coupling pump light to the amplifier gain slabs, and enables a more compact beam line design. A diode pitch from 200 to 400 µm is required to achieve 20 $kW/cm^2$ in the array plane for diode powers from 500 to 1000 W/bar. As mentioned above, 500 W/bar QCW devices are already commercially available, and 1000 W/bar CW has been demonstrated in several research publications.[9,10] Stacks with bar pitch $\leq$ 200 µm have been described in the literature [2, 11] and are commercially available as products with pitches as low as 300 µm[12] using diode-on-submount technology and 150 μm pitch without submounts [11]. We therefore anticipate that this requirement can be met, although some development of stack packages optimized for IFE applications will likely be required (e.g. optimization of beam shaping optics allowing the required collimation at a low pitch). We anticipate that today's standard QCW package, which are typically based on CuW or BeO heat spreading submounts, may be replaced with alternative substrates that facilitate microlens alignment and attachment, and/or enable improved thermal management.

Pump efficiency requirements are primarily driven by the goal of optimizing overall laser efficiency. Our target efficiency for IFE application is 72%, which requires some improvement over current commercial devices in the 870~890 nm region. Current state-of-the-art devices have primarily been optimized for CW applications in the 808 and 940~980 nm wavelength bands, with research demonstrations of >70% wallplug efficiency at 808 nm and 940~980 nm.[13-15] These devices were optimized for CW, lower-power operation, rather than for high power, QCW operation. Under QCW conditions, efficiencies of 65% at 808 nm and at 300W peak power have already been demonstrated [16]. Some further development will be required to optimize device designs for higher efficiency operation in IFE applications. Back-of-the-envelope calculations suggest that our target efficiency can be achieved with epitaxial structures optimized for low series resistance, cavity absorption <0.7 $cm^{-1}$ (an experimentally demonstrated value [9]), and cavity lengths of 2~4 mm.[1] More sophisticated simulations, which include k·p calculations of gain and radiative recombination, carrier drift-diffusion transport, and quantum well capture/escape dynamics, also suggest that our efficiency targets are achievable at high output power. Simulation results are shown in Fig. 1.

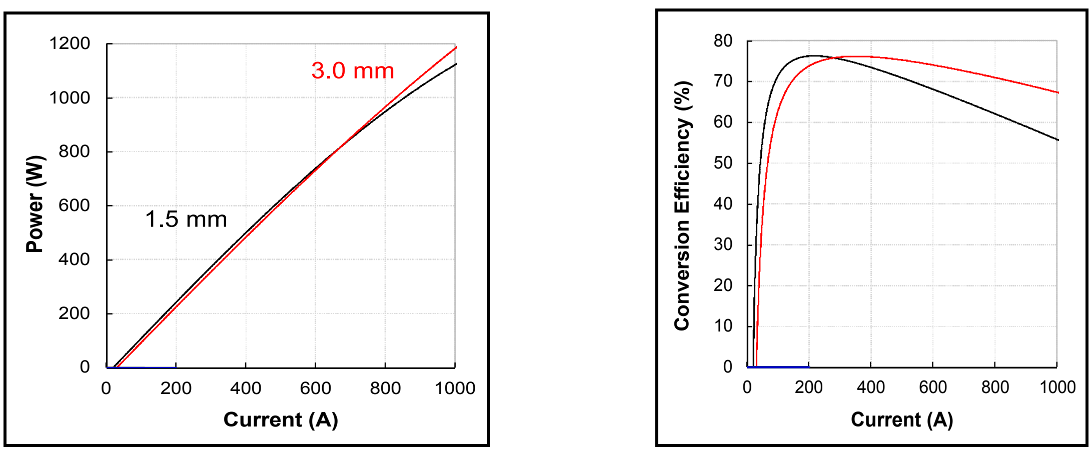


*Fig. 1: Simulated power-current and efficiency curves for an IFE-optimized semiconductor laser design. This particular design employs 80% fill factor and a 3 mm cavity length (red curve) to achieve efficiencies >70% at output powers above 500 W/bar. While simulations match experimental results obtained for other devices using the same epilayer design used in these simulations, the particular device geometry in the figure has not yet been tested experimentally. (Courtesy P. Leisher, nLight Corp.).*

## Device Lifetime/Failure Rate

Edge-emitting semiconductor lasers operating at ~300 W/bar on 25C heat sinks have demonstrated lifetimes >3 Gshots,[17] and are expected to exhibit 20 Gshot lifetimes.[18] These results suggest that our target device lifetime requirement is achievable. While operation at higher power might negatively impact device lifetime, we anticipate that this will be mitigated by improved device efficiency (lower heat load), short pulse width (<200 μs nominal) compared to usual 200 to 1000 μs width, and increased cavity length (reduced areal heat load in W/cm$^2$). Operation of IFE pumps with significantly colder heat sinks (~2 C coolant) is also planned,[1] to achieve improvements in both reliability[19] and efficiency, and will result in average junction temperatures below 27 C.[1] Based on considerations of this type, we anticipate that the IFE lifetime requirement can be achieved with edge-emitting devices. Further improvements in reliability should be achievable with devices that minimize optical intensity at absorptive free semiconductor surfaces (e.g.; edge-emitter facets) where optical damage can occur. Such enhancements can be achieved with edge emitters employing "nonabsorbing mirrors" created by material modifications near the emitting facet, and by surface-emitting devices, which emit over a broader area through nonabsorbing mirrors.

## Production Capacity

The state of the semiconductor laser industry is periodically documented in the trade press and other literature. [e.g.; 5,20,21] Based on reported annual consumption of epitaxial wafers for the entire laser diode market, and assuming a specific chip size and power (2 x 10 mm$^2$, 500W/bar), the epitaxy-limit on worldwide capacity for high-power semiconductor lasers is estimated to be roughly 80 GW/annum in 2009. This estimate assumes that all laser diode production is allocated to high-power devices, which is not the current situation. Since less than 10% of the diode laser market (by epiwafer areal consumption) involves high power devices, the production capacity relevant for IFE is significantly smaller at this time. Comparison to the 40~80 GW of peak pump power required for an IFE plant indicates that a substantial increase in production capacity will be required. Capacity increases can also be obtained by leveraging the capabilities of merchant epitaxy suppliers. Other industries that have reached the scale envisioned for IFE laser diodes have utilized these organizations for scaling production and producing epitaxial wafers in high volumes and low costs.

In addition to epitaxial wafer production, capacity will also be limited by the ability to package the semiconductor laser chips. Today's packaging technology and capacity have evolved to meet current market demands, and has yet to fully exploit all technologies available for higher volume production. These include the use of diode heat spreading submounts with mechanical fiducials and structures to facilitate precision alignments (e.g.; technologies analogous to the "silicon optical bench" technology used for low power fiber telecom components) and related technologies for hybrid packaging.[23] They also include the use of high-throughput automation, which can significantly increase packaging throughput for laser diodes, much as it does for silicon VLSI chips.[24,25] Finally, the use of surface-emitting semiconductor laser devices[3,4] may also enable increased packaging capacity, due to potential simplifications of the required packaging and testing.

To place the capacity increase required for IFE in perspective, it is worth considering recent increases in LED production. Prompted by market demands for display backlights, industry added over 100 MOCVD reactors to increase LED epitaxial growth in one year (some manufacturers placed orders for 100 MOCVD tools in one year). [22] In terms of high-power diode capacity, this quantity of production tools corresponds to ~100 GW of peak diode power production/year. While LED and high-power laser processes are not identical, this example clearly illustrates that capacity can be scaled given the appropriate market drivers. Therefore, we anticipate that capacity scaling to support IFE power production is feasible, given sufficient lead time. Due to the significant scale up required for IFE, several years will likely be required for this facilitization.

## Achievable Price Points

Any discussion of pump price points must consider the historical improvement in semiconductor laser prices over time, the increases in power/bar over time, and the dependence of pricing on both order volume and production rate. For example, the higher power possible for QCW pulsed operation in IFE applications results in lower pump costs (price/Watt) than is achievable for CW operation. Most significantly, the high volume of semiconductor lasers required for IFE will result in substantial price decreases on a price/Watt basis. As discussed above, one IFE plant will consume at least 100x more semiconductor lasers than are produced annually by any one company at the present time. Since current production infrastructure has been optimized to meet today's market volumes, today's price points are not representative of those achievable at IFE volumes. At higher volumes, we anticipate that semiconductor laser manufacturing will employ methods to both increase capacity and reduce cost that are similar to those used in high-volume silicon VLSI manufacturing. These include transitioning to larger diameter semiconductor wafers (current laser diode fabrication primarily uses 2 to 4 inch diameter wafers, in contrast to the 6 inch wafers used for GaAs electronic devices)[26] and increased use of automation for the handling, mounting, and stacking of individual laser chips,[24,25] the use of improved submount structures to facilitate chip mounting and microlens attachment,[23] as well as increased automation for the testing of final assemblies.

Five of us have independently performed studies to assess achievable semiconductor laser price points. These studies leveraged our internal expertise in the manufacture of edge emitting laser diodes, and employed production models that consider the relevant process steps, include both labor and capital costs. Each evaluation assumed a somewhat different build quantity, but all assumed a single, one-time build. Since each assessment was based on a different power per bar and on somewhat different stacked yields (due to the independent nature of these efforts), each assessment was normalized to a common power per bar (500 W) and stacked yield (80%) for comparison.[27] The normalized results range from $0.018 to $0.033/Watt, in rather close agreement given the variety of technology assumptions, production methods, and production rates assumed in the assessments.

Figure 2 summarizes these results. Since the assessments assumed a single build of one IFE plant, with diode production spanning multiple years, we have also extrapolated the results to the case of sustained production of multiple plants using the cost vs. production rate scaling established in [28]. These results are illustrated by the green curves in Fig. 2, for a range of scaling exponents.[29] They indicate that the target of 0.7 ¢/W target for $n^{th}$-of-a-kind IFE plants is achievable. Since these price points scale with the power per laser chip, additional price reductions should be achievable if the device power can be increased above the 500W/cm-bar value used in Fig. 2. This provides a motivation for continued development of higher power devices.

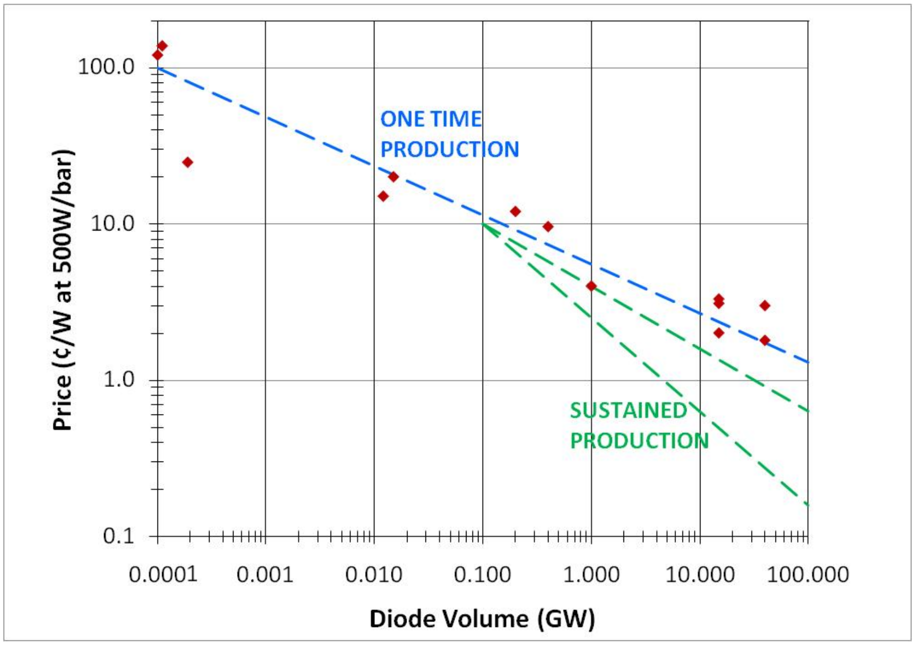


*Fig. 2: Summary of high-volume price assessments. Points represent study results for edge emitting diodes, assuming an output power of 500 W/bar. Prices will scale with the reciprocal of this power. The dashed blue line provides a guide for the eye to these results. The dashed green shows the range expected for sustained production based on the methods of [28], as described in the text.*

In addition to edge-emitter assessments, two of us have also evaluated the price points that could be achievable with surface emitter technology [3-4] These studies suggest that these technologies could further reduce the price/Watt of IFE pumps, by a factor of up to 1.4 to 3, providing motivation for continued development of this technology.

## Summary

A consideration of IFE semiconductor laser pump requirements shows that these requirements are achievable, from both a technical and cost perspective. Customizing existing technology for the IFE application will require some engineering, and there will be a lead time associated with this effort. Achieving the production capacity and price points required for IFE will require substantial changes and additions to current laser diode manufacturing infrastructure. While we anticipate that capacity and price targets will be achievable, several years will be required to build the facilities necessary to reach these goals.

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