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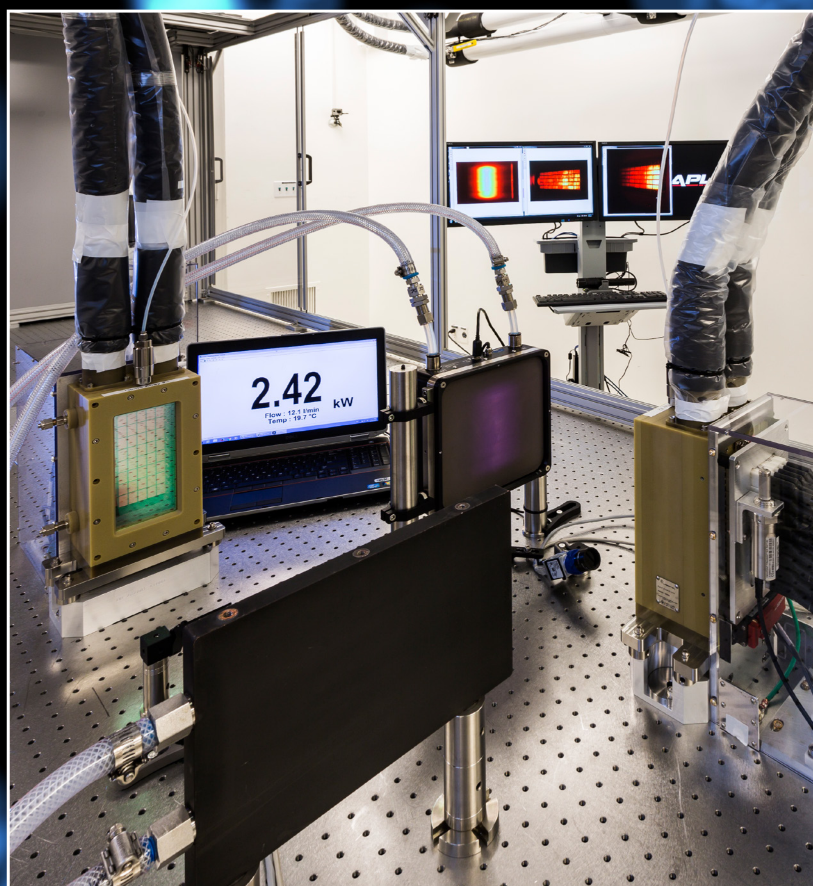
High-Power Intelligent Laser Diode System (HILADS)



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High-Power Intelligent Laser Diode System (HILADS)

VIDEO LINKS:
http://youtu.be/UALMN4iSF3k

1. General Entry Information

A. Product brand name and name of submitting organization(s)

High-Power Intelligent Laser Diode System (HILADS)

Submitting Organizations:

Lawrence Livermore National Laboratory
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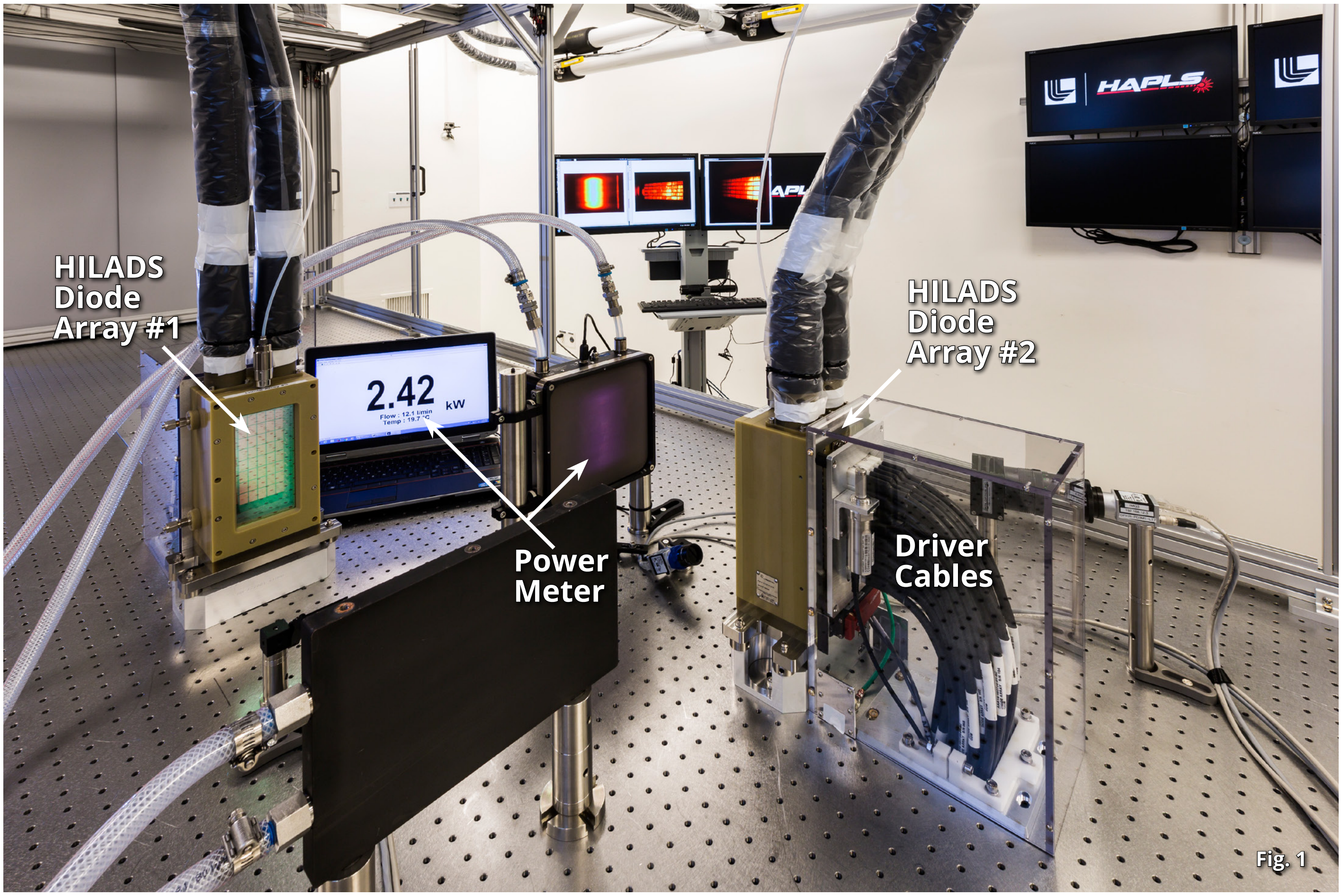
B. Short description of the product (MAXIMUM 100 WORDS)

The High-power Intelligent Laser Diode System (HILADS) is an *extremely intense*, pulsed diode laser source with *integrated drive electronics and controls functionality*. HILADS employs advances in laser diodes and electrical drivers to achieve two-to-three-fold improvements in peak output power and intensity over existing technology, in a 10 times more compact form factor that can scale to even larger arrays and power levels. The largest deployment to date produces 0.8 megawatts of peak optical power at 20 Hertz repetition rate. Integrated compact current drivers provide fast risetime (5 μs) pulses above 1 kA/channel, relieving customers from the challenge of providing high-current pulses. By integrating compact, high current (kA/channel) drivers, HILADS relieves customers from the engineering challenges of providing electronic drivers.



C. One photo, preferably in the Entry Form

Fig. 1. Two HILADS systems operating simultaneously at 10 Hz repetition rate and 800 kilowatts (kW) peak power each, in the High Repetition Rate Advanced Petawatt Laser System laboratory at LLNL. The 885 nm emission beam appears as a violet spot in the center of the photo, and the power meter readout shows the 2.4 kW average output power of a single HILADS system.

D. Price in U.S. dollars

HILADS is a modular system that can be configured to support a wide range of optical power outputs, from less than 100 to 900 kW of diode output power. The integrated system price (including diode array and power conditioning) depends on the specific configuration and order quantities; it can be as low as $1.15 per Watt of peak output power.

2. PRODUCT DESCRIPTION (MAXIMUM 300 WORDS)

A. What does the product or technology do? Describe the principal applications of this product.

Pulsed laser diode arrays are essential for pumping high energy solid-state lasers at frequencies above 5 Hz, for materials processing (e.g. laser peening), defense applications, and scientific exploration. The European Extreme Light Infrastructure initiative will use high energy diode pumped lasers to explore light-material interaction physics, with anticipated spinoffs to industrial and medical technologies. Key diode array attributes for this application are high output power, at least 10 Hz frequency, and high brightness for efficient transport to the main laser amplifier. HILADS is a modular, integrated laser diode pumping system that produces a high power beam of intense optical pulses from an external direct current supply input. It internally generates high-current electrical pulses to drive laser diode stacks that emit optical pulses, and provides a unified controls/management interface including user-programmable pulse shaping and real-time response to external faults for machine and personnel safety.

B. How does the product operate? Describe the materials, composition, construction, theories or mechanism of action.

HILADS comprises a high-density diode array and electronic driver/controller subsystem. A two-dimensional diode stack array is mounted on a backplane that provides cooling and mechanical alignment. Each stack contains 40 edge-emitting diode chips hard soldered between expansion-matched metal spacers to minimize stress-related fatigue. Monolithic microlens arrays collimate each stack's output in the fast axis to maximize brightness.

HILADS is modular, with a dedicated current driver for each stack (one "channel"). Any channel can be populated (or not) to optimize price/power. Channel waveforms can be individually adjusted to optimize array uniformity. HILADS has demonstrated 0.8 MW peak power at 20 Hz with 40 channels populated and supports 0.9 MW with all 45 channels populated.

Current drivers are housed in a common chassis providing power distribution and controls. An embedded, real-time computer provides control and safety interlock functions. A free-space optical communications backplane delivers control signals with immunity to electromagnetic interference generated by the high switching currents (23 kA/chassis).

3. PRODUCT COMPARISON

A. Product Comparison Table.

Table I below compares HILADS to existing, 100 kW-class diode array systems and technologies. The competition is described by both the best and typical values, and it is important to note that the best values do not correspond to the same competitive system. For example, the highest intensity competitor (4 kW/cm²) produces only 0.2 kW average power, while the next highest competitive intensity is below 2 kW/cm². Since almost all of the competition does not incorporate integrated electronic drive capability, Table I includes stand-alone current drivers as well. This comparison is restricted to drivers with sufficient voltage compliance to drive the high-chip-count diode stacks essential for high intensity arrays.

Table 1 shows that HILADS provides *three times more peak* optical output power, *twice as high* an optical intensity and average power, and a *ten times smaller* driver form factor (cm³/peak kW) than the competition. HILADS compares favorably to the competition in all other metrics as well.

Parameter	Units	HILADS	Product Competition	
			Best of Class	Typical
Overall Performance				
Peak optical power	kW/Array	**900**	270	160
Average optical power	kW/Array	**5.4**	2.6	1.1
Peak optical intensity	kW/cm²	**10.2**	4.0	1.7
Repetition rate	Hz	**20**	10	10
Fast-axis collimation		**Yes**	Yes	Yes
Areal scalability[1]		**Yes**	Yes	No-Yes
Anticipated reliability[2]	Mshots	**2,000**		200-2,000
Technology				
Diode pitch	mm	**0.38**	0.8	1.2
Fast axis divergence at <1 mm pitch	degrees FWHM	**2**	5	>5
Operating current[3]	A/channel	**520**	400	300
Available current[4]	A/channel	**1,100**	600	350
Optical rise/fall time[5]	microsec	**5**	3	10
Available electric pulse power	kW/channel	**110**	105	46
Current driver size[6]	cm³/channel	**2,540**	6,270	9,000-17,000
Driver size/peak power ratio[7]	cm³/kW	**23**	314	700

Table 1. Product Comparison Table notes

[1] "Areal Scalability" refers to the ability of the diode array architecture to expand gracefully in both dimensions. Arrays limited to only two rows (or columns) of stacks to provide space for interconnection cannot scale in area.

[2] Reliability is defined as the number of pulses before an optical power loss of 20%, at constant current drive.

[3] Operating currents shown for HILADS and GOLD are the currents corresponding to the output power and reliability in the table. HILADS has been operated up to 600 A in short-term tests, and other diode stacks have been operated above 1,200 A with the HILADS drivers.

[4] Available current drive is reported at a compliance voltage of 100 V.

[5] Rise times for HILADS and GOLD are measured results, including the effect of up to 12 feet of cabling between pulsers and array. Values quoted for other systems are at zero cable length.

[6] Current driver size includes the volume of the required (external) DC power supply.

[7] Driver size/peak power ratio normalized the channel volume by the peak pulse power available per channel.

B. Describe how your product improves upon competitive products or technologies. Describe limitations of your product.

Scaling the energy of diode array pulses is essential for developing the high-energy and high-power laser systems desired for greater industrial throughput, pushing the bounds of scientific exploration, and eventually for driving the ignition reactions needed for inertial fusion energy production. Since the usable diode pulsewidth is limited by the energy storage lifetime of the main laser (e.g. ~300 μs for neodymium-doped media), such scaling requires diode pumps that not only emit more optical power in each pulse, but also provide that power in a format that can readily be coupled to the main laser gain medium. This means that the diode intensity (W/cm^2) at the emission plane must be maximized and the diodes must be collimated to minimize their divergence. While the combined effect of intensity and divergence determine the overall brightness, which enables efficient coupling to the gain medium, the intensity is particularly critical to the practical manufacturing constraints and costs of the required coupling optics. HILADS improves upon competitive products by providing significantly more optical power at significantly higher intensity in a system with substantially smaller footprint and a higher degree of integration. This enables the creation of more energetic laser systems.

High energy laser systems for scientific exploration are typically deployed in clean room environments to minimize damage to the laser optics due to interaction of the highly energetic laser beam with rogue particles. Space is at a premium in these laboratories, and reduced pump system volume translates to reduced facility capital and operating costs. By providing a smaller footprint relative to competitive products, the HILADS electronics subsystem enables customers to achieve these cost advantages.

The relationship between our technological innovations and this enhanced performance is best understood in the context of the system design tradeoffs and relationships between the diode components and their drivers. The following series of interrelated technological challenges must be addressed to scale diode array power and intensity:

1. Increasing output power per laser diode chip, which in turn requires

    - Current drivers capable of greater output drive, while maintaining fast rise times and providing the capability to drive cables with little pulse over/undershoot, to avoid reverse-bias diode damage and conserve valuable space on optical tables by remote location of the electronics.

    - Increased chip reliability at higher drive levels

2. Maintaining a high chip count per diode stack, to avoid intensity loss due to mechanical gaps between stacks. This in turn requires:

   - Stress-free assembly design and processes for the fabrication of the diode stacks.

   - Current drivers with sufficient voltage compliance to drive the stacks at high current.

3. Minimizing the space between semiconductor chips ("bar pitch"), which requires microlensing techniques that can effectively collimate light from multiple closely-packed chips in the fast-axis. This is a challenge because the bar pitch places limits on the lens focal length, resulting in tighter alignment tolerances to maintain chip-to-chip pointing tolerances and excess divergence due to transverse bowing or "smile" of the individual chips.

4. Implementing a fully 2-D array architecture (row and column counts unrestricted by feedthrough requirements) while minimizing the space between diode stacks to enable future power scaling without intensity compromises. This requires:

   - Tight mechanical integration to accommodate electrical feedthroughs to stacks in the center of the array without electrical breakdown associated with tight packing.

   - Effective thermal management to maintain diode reliability and array output uniformity based on efficient diode chips and careful thermo-mechanical design.

This list shows that diode pump scaling requires innovations in both diode lasers and current drivers and illustrates the close interrelationship between these two subsystems. This section describes these innovations, which are covered by three granted and five pending patents.

HILADS was designed as an integrated system to facilitate its overall optimization and to free customers from the challenges associated with integrating the two subsystems. The overall system consists of the diode array module (Fig. 2 a) and the driver subsystem (Fig. 2 b). The drivers and diode array can be connected by cables greater than 10 meters long (Fig. 1 shows the array end of these cables on the right), which facilitates placement of the electronics to conserve space on congested laser tables.

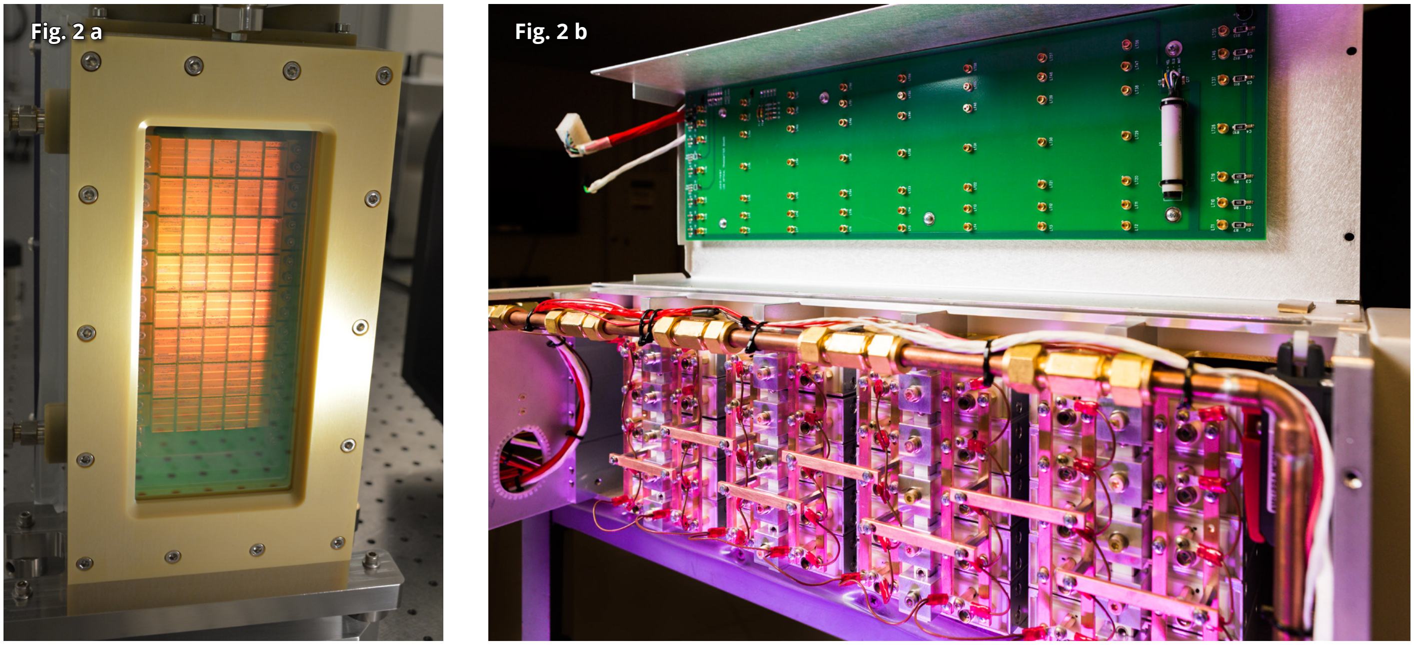


Fig. 2. (a) HILADS diode array populated in an 8x5 channel configuration (bottom row of stacks not populated). As a scale reference, holes on the optical table are spaced 25 mm apart.

(b) HILADS drivers in their chassis, with cover lifted to show optical backplane.

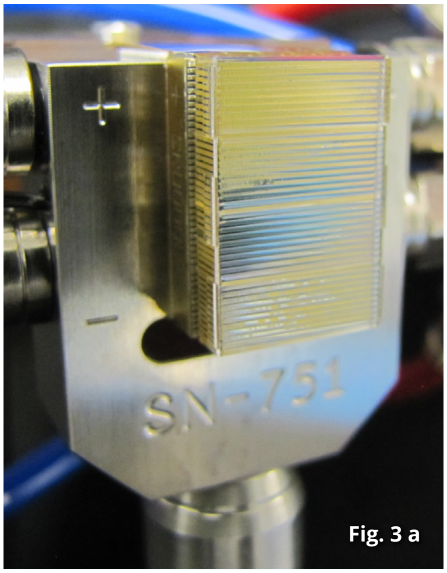
Key innovations that enable the two to three times increase in peak optical intensity in HILADS are twofold: a) stress-free monolithic assembly of high chip count HILADS diode stacks with high chip power, and b) collimation of the diode chip output in the fast axis using a custom single-optic monolithic microlens array. Significant increases in the peak array optical intensity require raising achievable power levels for each chip in the diode stacks, increasing the number of chips in each stack, decreasing the pitch between the laser diode chips, and decreasing the area around the laser diode chips. To produce laser diode stacks with the required operational reliability (in the range of billions of pulses), all these requirements must be met while maintaining minimum stress levels on the laser diode chip. As an ensemble these requirements pose a significant challenge to the design and assembly of laser diode stacks. This has significantly limited the ability to integrate more than 10 to 25 laser diode chips, depending on chip geometry and operating power levels, in a single diode stack assembly. While laser diode chips with output powers of greater than 500W have been demonstrated, they are not readily available in a high chip count laser diode stack assembly with low chip to chip pitch (less than 800μm).

Innovations in the design and assembly processes were developed to fabricate the HILADS laser diode stack to overcome the limitations discussed above. The HILADS diode stack is a fully soldered monolithic assembly that consists of laser diode chips, thermally conductive spacers to transport heat to the heat sink, electrically insulating high thermal conductivity ceramics, and terminals for connecting to a driver. A fully soldered monolithic assembly process is needed to ensure reliable operation of the stacks in real use environments. Each stack assembly uses 40 laser diode chips capable of producing greater than 500 W of peak output power. The pitch between the chips was reduced to a value of 380μm. The composition of the composite metals that are used for the spacers and the heat sink were carefully selected to provide the mechanical and thermal properties needed to minimize the mechanical stresses in the assembly and meet the heat dissipation requirements. The terminals needed to inject current into the stacks are manufactured with special insulation technology and routed to minimize footprint. The result of this development is a stack that produces greater than 20 kW of peak output power in a footprint of 11 x 17 mm^2. This foot print allows for assembly of 2-dimensional array of laser diode stacks to achieve megawatt class pump modules while maintaining high optical intensities.

The second area of innovation in the HILADS diode stack is the technology used for the collimation of the fast axis of laser output from the laser diode stacks. Traditional techniques to achieve good collimation use a longer lens focal length, which requires a larger laser chip to chip pitch, typically greater than 800 μm, which significantly degrades the peak optical intensity of the stack. Reducing the stack pitch with these methods produce poor collimation, typically >5 degrees full width at half maximum (FWHM), due to defocusing and beam pointing errors caused by positional mismatch between the lenses and the laser emitters in each laser diode chip. Furthermore, traditional collimation employs individual lenses for each laser chip, resulting in a more costly and labor intensive assembly process.

The key collimation innovation that enables increased HILADS intensity is the development of a custom, single optic monolithic microlens array technology (Fig. 3 a). This technology uses a custom process to rapidly map the position of every laser emitter on every laser chip in the 40-chip laser diode stack to sub-micrometer precision. This information is used to fabricate a custom single optic that contains a monolithic array of microlenses covering an entire laser diode stack. By matching each laser emitter position with the corresponding microlens position, this technology enables fast axis divergence values as low as 0.3 degrees FWHM. The HILADS modules demonstrated to date use a deliberately defocused fast axis (2 degrees FWHM) to facilitate homogenization of the pump diode light by the optics that couple it to the main laser (Fig. 3 b). In addition to the excellent collimation, the single optic monolithic microlens array optic only requires one alignment step, thus significantly reducing the labor cost of collimating the laser output beam.

These diode technology innovations enable HILADS to operate at record levels of optical output intensity, significantly improving its usefulness in pumping solid-state lasers. HILADS is the first high-power (Megawatt class) diode array operating at 500 W/bar chip powers and at a chip pitch below 800 μm.



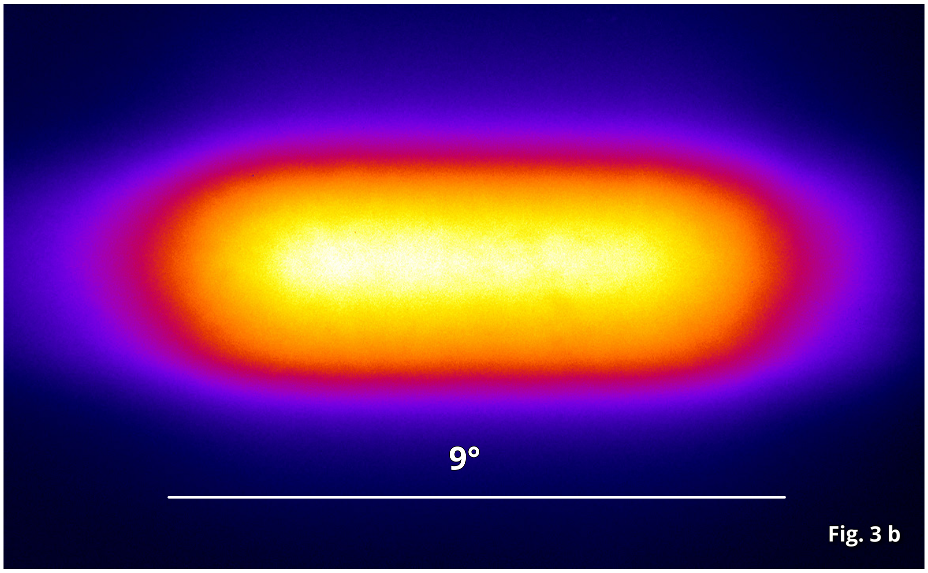


Fig. 3. (a) Microlens array on a HILADS diode stack, mounted in a test fixture.

(b) Far-field image of the output from an entire HILADS array module during 800 kW, 10 Hz operation. The far-field dimensions are 9.0 x 2.2 degrees FWHM.

Key innovations in the high-current driver are the use of arbitrary-waveform, high-peak-power drivers, and a system engineering approach enabling significant size and complexity reduction of the driver subsystem. Each current driver (Fig. 4 a) uses power MOSFETs to vary the current output to its diode stack. By incorporating an arbitrary waveform generator in each driver, current waveforms can be independently shaped in each channel (with microsecond resolution) to improve the waveform for risetime, reliability, linearity, and channel-to-channel uniformity. Maintaining a short risetime (relative to overall pulse durations >200 μs) is important because pulse energy in the rising and falling edges of the pulses is lost; it does not contribute to the final energy of the main laser output. Excessively rapid current transitions create positive and negative voltage spikes at the diode load due to cable inductance, reducing diode lifetime. The ability to shape the current waveform allows the current transitions to be optimized for sharp (5 μs) transitions without spiking, even while driving substantial lengths of cable (Fig. 4 b). HILADS incorporates enough intelligence in each driver to store waveform information locally, so that triggering each current pulse requires limited information transmission from the system to each pulser. The arbitrary waveform generator functionality also enables users to compensate thermally-induced output droop during long pulses, and to minimize stack-to-stack nonuniformities to homogenize the HILADS output across the entire diode array. Stack-to-stack production variations in electro-optic efficiency can result in power nonuniformity across the array aperture, which can be compensated by tuning the current amplitude of each channel. Similarly, production variations in stack center wavelength can be compensated by adding low current pedestals to the primary current pulse to thermally tune individual stack wavelengths.

The compact size of the HILADS electronics was achieved by careful partitioning of functions between individual drivers and the HILADS chassis/controller. While the tight control loops needed for rapid control of current waveforms are implemented in the drivers, other control and diagnostic functions are provided at the chassis level, minimizing the required space and presenting a unified system interface to the user. All 45 HILADS channels are controlled via a single ethernet port for low speed controls, an external trigger pulse port for high-speed, low-jitter synchronization with the main laser, a safety-rated, relay contact closure for interlock response, and two additional connectors to accept diagnostic data related to maintaining diode functions, such as coolant flows and temperatures. This approach miminizes the space required for supervisory hardware and external connections. The space needed for internal wiring was reduced by employing a free-space optical communications 'backplane' to deliver control information from the HILADS controller to the pulsers. This resulted in a greater than twofold overall volume reduction relative to competing products and provides a platform that is inherently scalable to much higher power levels. The electronics chassis can be located below an optical table because of its compact size (44 x 65 x 18.4 cm^3), and because it generates no thermal air currents that can degrade laser operations. All residual driver heat is rejected to cooling water rather than ambient air, which prevents thermal currents and improves reliability by eliminating the failure-prone components needed for forced air cooling.

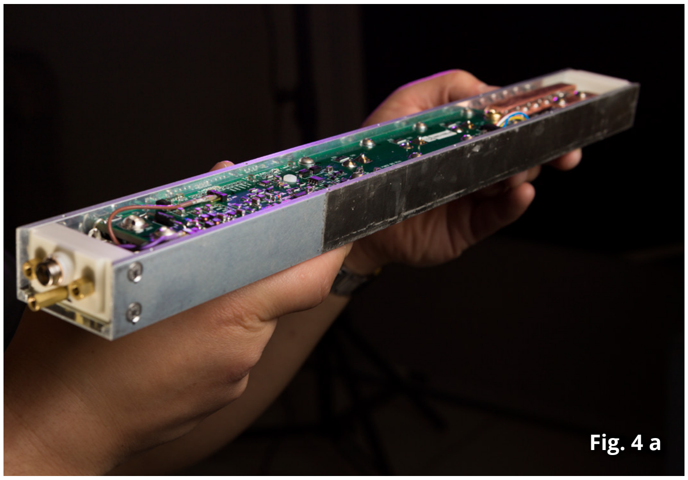


Fig. 4 a

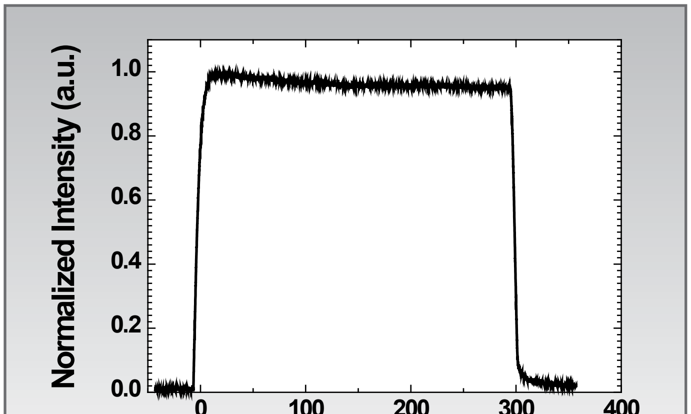


Fig. 4 b

Fig. 4. (a) the HILADS current driver module, capable of greater than 100 kW pulses at over 1 kA. The module length is only 41.3 cm.

(b) HILADS optical output waveform of an entire 800 kW array operating at 800 kW peak power, 10 Hz, and 300 μs pulsewidth with two meters of driver-to-stack cabling.

The features and advantages of HILADS have been demonstrated in its first deployment. Four HILADS systems have been delivered to Lawrence Livermore National Laboratory and are deployed for pumping the High-repetition-rate Advanced Petawatt Laser System (HAPLS). This laser system is going into one of the most prestigious laser installations in Europe, the Extreme Light Infrastructure in the Czech Republic.”. This laser requires the high power, high intensity, and compact footprint of HILADS to produce a train of 1 Petawatt optical pulses (30 J, 30 fs) at 10 Hz. Each of these HILADS units contains 40 channels and provides 800 kW of peak pump power. The existing hardware can provide 900 kW by fully populating all channels, and the architecture will scale to even greater powers without compromising intensity by adding additional slots for diode stacks and current drivers to the diode array housing and electronics chassis. The delivered HILADS units have demonstrated operation up to 20 Hz repetition rate at full peak power and are optimized to pump neodymium-doped gain medium with an 8 nm absorption band at 885 nm. The HILADS spectrum is not restricted to these values; other values can be selected by changing the bandgap of the diode laser materials during production. Fig. 5 a shows the spectrum of an 800 kW HILADS system, which delivers more than 97% of its energy within the target absorption band. The overall system is extremely stable, with power variation below ±0.4% standard deviation (Fig. 5 b). Extensive testing of the diode stacks used in these systems under accelerated conditions, suggests that the system lifetime will exceed 1,000 million pulses (Mshots). Testing under nominal use conditions is now underway, and preliminary results suggest that the lifetime will exceed 2,000 Mshots.

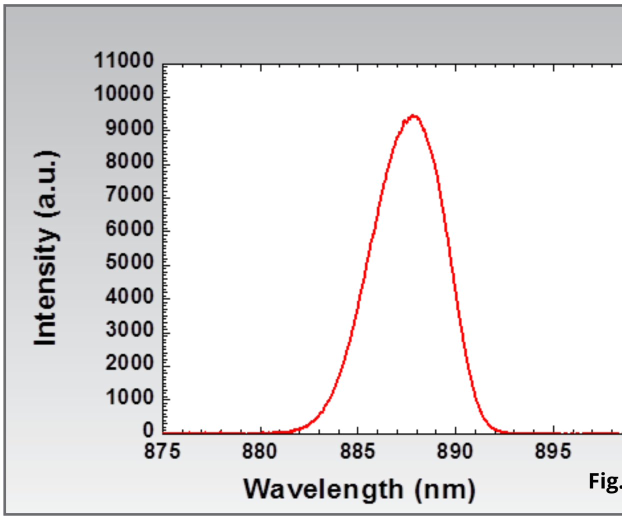


Fig. 5 a

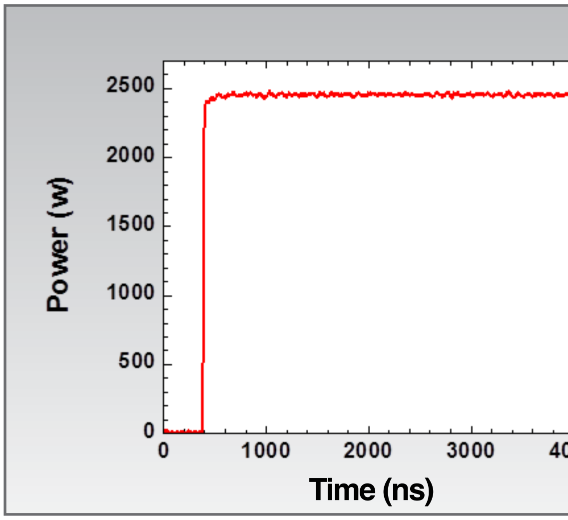


Fig. 5 b

Fig. 5. (a) Optical output spectrum of an entire HILADS operating at 800 kW peak power, 10 Hz, and 300 μs pulsewidth. Over 95% of the power is contained within a 7.14 nm band.

(b) HILADS average power stability over a one hour run duration, under the same operating conditions as (a). The power is extremely stable, varying only ±0.34% (standard deviation).

HILADS has two primary limitations. First, it is only suitable for “quasi-CW” diode pumping with pulsewidths in the range of 100 μs to several milliseconds; it is not designed to support continuous “CW” operation. Second, HILADS is designed to support large laser systems that require diode pumps with array outputs of approximately 100 kW and above; it is not the optimal solution for significantly smaller laser diode systems.

4. SUMMARY

HILADS is an integrated optical pump system that produces extremely intense, pulsed diode laser light from a direct current electrical source. “It provides three times more output power at twice the intensity of its competion, and is more than ten times more compact. Furthermore, the HILADS architecture can scale to even greater output power without compromising intensity or brightness. These performance levels are the result of innovations in both diode laser and electrical driver technologies.

HILADS enables production of the next generation of diode-pumped lasers for operation at repetition rates of 10 Hz and above. These systems have applications in materials processing, defense, and scientific exploration. Ultimately, we envision that similar lasers will be used to drive the capsule implosions required for inertial fusion energy and thus provide a carbon-free, low-risk source of electricity. Four HILADS units are currently in operation, providing 3.2 MW total optical power to the HAPLS laser. This laser is a source of 1 petawatt optical pulses to be delivered for the L-3 beamline of the European Extreme Light Infrastructure project in the Czech Republic.

5. CONTACT INFORMATION

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6. AFFIRMATION

By submitting this entry to R&D Magazine you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product. You affirm that you have read the instructions and entry notes and agree to the rules specified in those sections.

For more information, please call 973-920-7032 or email rdeditors@advantagemedia.com

APPENDIX A: ADDITIONAL CONTRIBUTORS

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