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Megawatt – Class High Brightness Laser Diode Module

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A new megawatt class pump laser module operating at a wavelength of 888nm was developed for use in a high average power petawatt laser system. The pump laser module represents a combination of several innovations such as compact high power density laser diode arrays, monolithic micro lens array based beam collimation, and a scalable modular approach to achieve record level performance. A peak power of 940kW was achieved from the pump laser module in an emission area ~90cm^2 representing a power density of >10kW/cm^2. The pump laser module was operated at pulse repetition rates of 20Hz with a total energy of 329J/pulse. The performance of this module represents a threefold increase in peak output power and intensity compared to similar deployed systems. This is also the highest peak power laser diode pump module that has been deployed to date.

High energy laser systems are increasingly being deployed for scientific exploration and fusion research with potential applications in industrial, directed energy, and medical technologies. One of the key components in these systems is the sources that are used to pump the solid state gain media for amplification of main laser beams. Traditionally these large laser systems have used flash lamp as the pump source for the amplification stages. Increasing demand for higher repetition rate operation and reliability have made semiconductor laser diodes more attractive for these applications and the majority of the recent deployments of high energy laser systems have completely transitioned to semiconductor laser diode pumped amplifier stages [1]-[5].

This increase in laser system average output powers has driven a complimentary requirement for increasing average power requirements for the semiconductor laser pump sources. However, to meet increased output powers for the semiconductor laser diode pump sources several challenges need to be overcome. The main challenges are:

1) Increasing the brightness of the pump sources: The laser diode pump brightness needs to be increased to reduce the size of the pump to make it easier to couple the pump light into the gain media. Also this reduces the need for expensive optical systems that would otherwise be needed to couple the laser diode pump light into the gain media. The brightness of the pump source can be increased by increasing the output power of each laser diode bars in the pump source, decrease the pitch between the bars, and reducing gaps between sub-elements to increase the illumination area in the pump source.

2) Increasing the wall plug efficiency of laser diode pump source: The pump laser diode sources generate a significant amount of heat in a relatively small area posing a challenge for thermal management systems. In order to reduce the complexity and cost of thermal managements system that are used in high average power laser diode pump sources, the efficiency of the laser diodes need to be maximized.

3) Improved beam collimation technologies: Traditional collimation technologies use individual lenses for each laser bar in the laser diode pump source. While this technology works well for large bar to bar pitch arrays they are not cost effective or reliable for low bar to bar pitch arrays.

4) Reliability over wide operating temperatures: Due to the large operational conditions that are required for the laser diode pump sources they are required to maintain high reliability over temperatures in the range of -30°C to +45°C.

5) Performance uniformity: Due to the scale of the laser diode pump sources several hundred to several thousand individual laser bars are typically used to meet the power requirements. The spectral emission and output power performance of the laser diode bars must be uniform so as to not introduce undesired effects in the gain media.

6) Modularity and Scalability: Modularity allows for testing at a sub module level hence reducing the cost of integration. Modularity needs to be designed for easy scalability to meet the increasing demands of laser systems.

In addition to the main challenges, additional features such as field serviceability are important to maximize the operational time of the laser systems.

To meet the challenges described above, several technologies were developed and integrated into a megawatt class laser diode pump source. The following sections describe the performance of each of the technologies.

500W LASER DIODE BARS

The basic element of a high average power laser diode pump source is the laser diode bar. To increase the brightness and the total output power of the laser diode pump source the output power of the laser diode bar needs to be increased. The laser diode bars used here were based on a InGaAs/AlGaAs large optical cavity based structure that was grown an n+ GaAs substrate. The design of the active region of the laser diode bar was targeted for an operating wavelength of 888nm. C and Si dopants were used for the p-type and n-type dopants respectively. These dopants are known to have excellent long term stability in the epitaxial structure, reducing any diffusion induced reliability under high drive conditions. Careful optimization of the band structure and the dopant profiles was performed to minimize the internal cavity losses in the laser structure. The laser bars also used an Epitaxial Mirror On Facet (EMOF) technology to protect against catastrophic optical damage of the output facets of the laser diode bars.

In addition to the epitaxial structure optimization, physical optimization of the laser bar features, such as cavity length and fill factor, was performed to reach output powers of >500W at high wall plug efficiencies. The optimization yielded a laser diode bar with a cavity length of 3mm and a fill factor of ~75%.

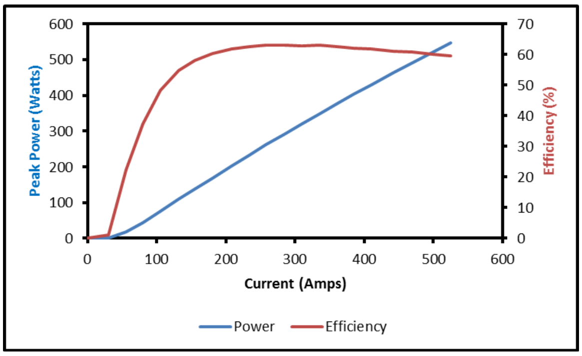

Figure 1 - Output power and efficiency characteristics of a 500W laser diode bar operating at 888nm. The bars were tested at 300µsec, 40Hz, 25°C

Figure 1 shows the output characteristics of the optimized laser diode bar. An output power of > 500W was achieved at a drive current of 500A. The operating efficiency at 500W was 60%. These values represent state of the art performance of laser diode bars at this wavelength.

COMPACT 40 BAR LASER DIODE ARRAY

The basic building block for the megawatt class laser diode pump source was a compact 40 bar laser diode array. Figure 2 shows a photograph of a typical compact laser diode array.

The compact 40 bar laser diode array is built with Lasertel's patented hard solder technology using expansion matched materials. This assembly technology has been proven to have reliable operation over a wide operating temperature and harsh vibration and shock environments. The bar to bar pitch in the compact laser diode array was minimized to 380µm. The design of the compact array allows for high packaging density by minimizing the dead areas around the laser diode bars. The overall dimensions of the compact 40 bar laser diode array were 11mm x 16.9mm.

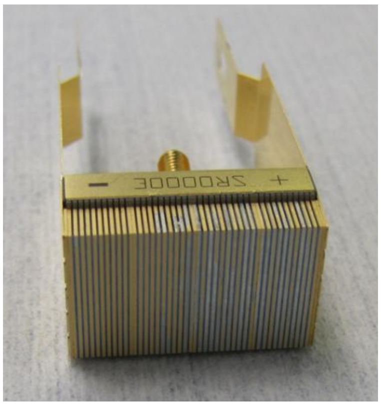

Figure 2- Compact 40 bar laser diode array. The array is a fully hard soldered assembly that uses patented processes

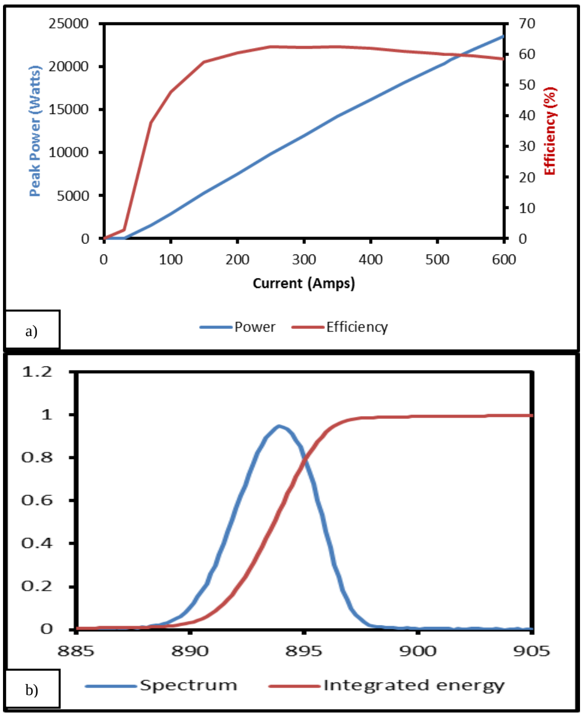

Figure 3 – a) Output power and efficiency characteristics of a compact 40 bar laser diode array. b) Integrated spectral output of a compact 40 bar array at 20kW. Measurements were made at 300µsec, 10hz, 20°C

Figure 3a shows the output power, efficiency and spectrum of the compact 40 bar laser diode array. An output power of 20kW was measured at 500A. The maximum output power was > 23kW. This represents a power density of > 11kW/cm^2 and is the highest power density array available in the market.

The integrated output spectrum of the compact 40 bar laser diode array, shown in Figure 3b, exhibits a single peak with a FWHM of 3.9nm. The narrow FWHM is indicative of the uniform performance of the laser diode bars and the lack of any significant thermal chirping across the array.

Figure 4 shows the energy per pulse as a function of pulse width for the compact 40 bar laser diode array. All measurements were performed at 10Hz and 20°C. A maximum pulse energy of 20J was measured at a pulse width of 1500µsec.

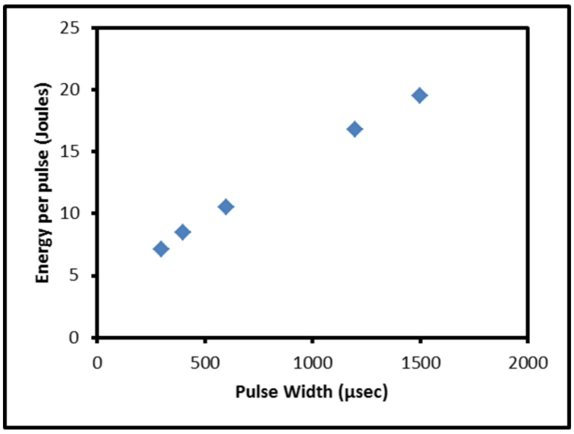

Figure 4 – Output energy per pulse as a function of pulse width for pulse width for a compact 40 bar laser diode array

The energy per pulse was limited by thermal capacity of the heatsinks. The next generation of compact array technology is expected to produce higher energies with further improvements to the thermal properties of the array heatsinks.

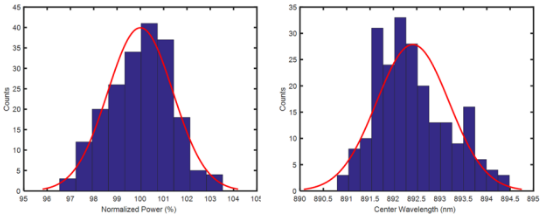

Figure 5 – Production performance statistics of over 200 compact 40 bar laser diode arrays

Figure 5 shows the distribution of the output power and center wavelength for over 200 compact 40 bar laser diode arrays. The production statistics indicate that the output power of the arrays was within ±2% and the center wavelength was within ±1.5nm. These tight distributions validate the excellent uniformity of the laser diode bars and the assembly process for the compact laser diode arrays.

ARRAY BEAM COLLIMATION

Traditional beam collimation technology that use individual lens elements to collimate each laser diode bar in an array suffer from a number of technological limitations that make it prohibitive to use in large scale pump laser diode sources. The main limitations are assembly cost – requires each bar to be aligned, footprint – requires a frame to hold the individual lenses in place, poor collimation performance – due to mismatch between lenses and array bar to bar pitch, and robustness – due to lack of rigidity to vibration and thermal environments.

To overcome these limitations a monolithic lens array was developed. This technology uses a scanning process to quickly locate the bar positions on a compact laser diode array and fabricates a custom optic on a glass substrate that is capable of collimating the output from all bars in the compact laser diode array in a single alignment step. A monolithic lens array is shown in Figure 6. A compact 40 bar array with the monolithic lens array attached is shown in Figure 7. As seen in Figure 7, the monolithic lens array attachment process did not require any increase in the compact laser diode array footprint.

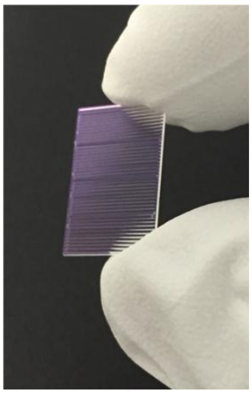

Figure 6 – A monolithic 40 bar lens array

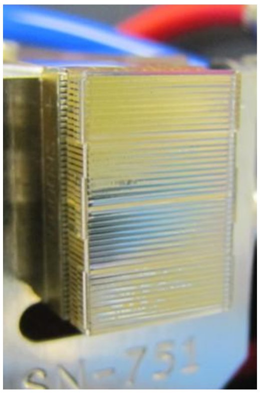

Figure 7- A compact 40 bar laser diode array with a monolithic lens attached

Figure 8 shows the beam cross section of a collimated compact 40 bar laser diode array using the monolithic lens array technology. The output beam had a divergence of 0.6 degrees at FWHM and a single lobe. The collimated beam performance showed high collimation quality and minimum bar to bar pointing errors. Further improvement to the manufacturing process for the lenses is expected to further improve the collimation performance.

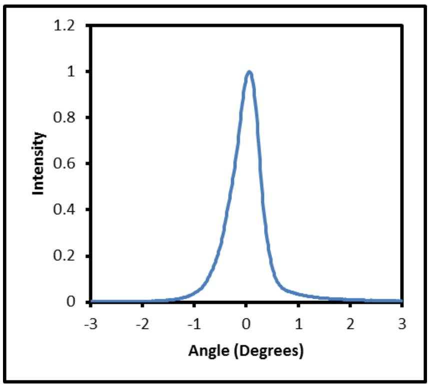

Figure 8 – Beam cross section of the collimated output of a compact 40 bar laser diode array using the monolithic lens array technology

Figure 9 shows the collimated beam performance of a compact 40 bar laser diode array using the monolithic lens technology through various environmental stress tests. The lack of any significant changes indicates the robustness of the monolithic lens array technology and validates the assembly process for the lenses.

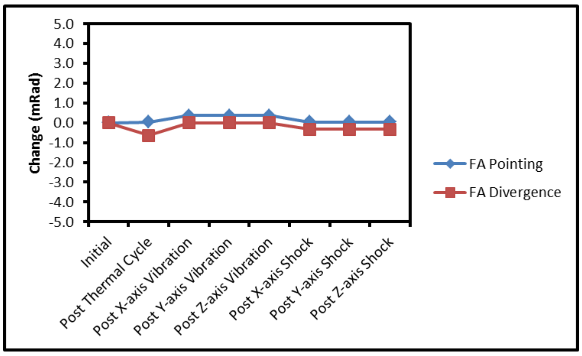

Figure 9 – Performance of beam characteristics of laser diode array collimated using the monolithic lens technology for various environmental stress tests

20KW COLLIMATED ARRAY RELIABILITY

The operational reliability of the collimated compact 40 bar laser diode arrays was tested on more than 5 arrays operating at >20kW. The testing results are shown in Figure 10. The total output power change in 120million shots was < 2%. The testing indicates that the laser diode array performance to be very stable with a median lifetime of > 2 billion shots.

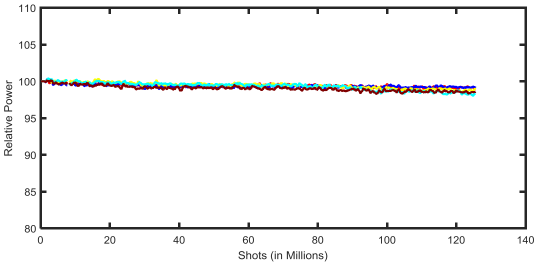

Figure 10 – Normalized output power of the compact 40 bar collimated arrays. The data is shown for 5 lens arrays that have been operated for ~ 120 million shots

MEGAWATT CLASS LASER DIODE PUMP MODULE

The megawatt class laser diode pump module was built using a 2 dimensional matrix layout of collimated compact 40 bar laser diode arrays. A 9x5 layout was used for the current embodiment of the laser diode pump module. The emission area of the module was 57mm x 156.4mm.

To introduce modularity to the assembly a submodule containing five (5) collimated compact 40 bar laser diode arrays was first assembled on a liquid cooled heat exchanged as shown in Figure 11. The liquid cooled heat exchanges were designed to be compatible with liquids that allowed operation down to -30°C. The rows of liquid cooled submodules were then integrated into a frame that also acted as a coolant distribution manifold. The laser diode array submodule assembly was then integrated into a housing with an AR coated output window assembly. The window was specifically designed to allow for a dry air purge so that no components inside the module, including the windows would have condensation during operation below dew point temperatures. Figure 12 shows a fully assembled megawatt class laser diode pump module. Each array in the module is individually addressable for enhanced flexibility in operation and optimization of the pump-gain media interaction.

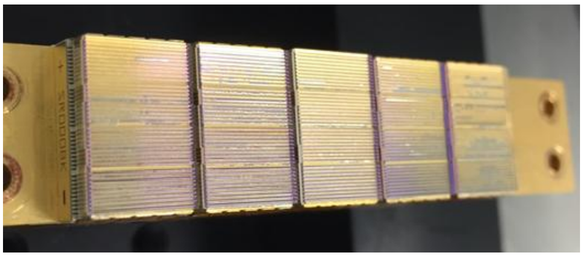

Figure 11 - A submodule assembly containing 5x collimated compact 40 bar laser diode arrays mounted to a liquid cooled heat exchanger. The assembly is build so it can be fully tested before integration into the next step

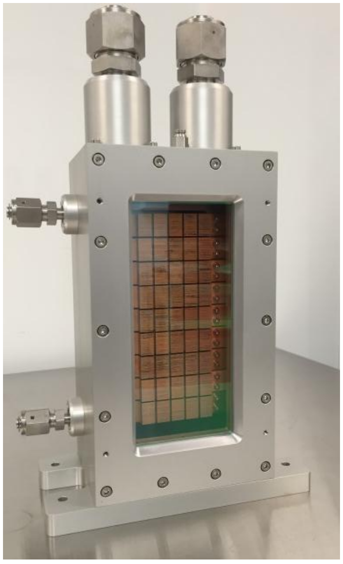

Figure 12 - Megawatt class pump laser module with a 9x5 matrix configuration of compact laser diode arrays

The output power characteristics of the megawatt class module under different pulse repetition frequencies is shown in Figure 13. A total output power of 940kW was obtained when each array in the module was driven with a drive current of 520A. There was no measurable output power difference when operated at 10Hz and 20Hz. The output power of 940kW represents a power density of >10kW/cm^2.

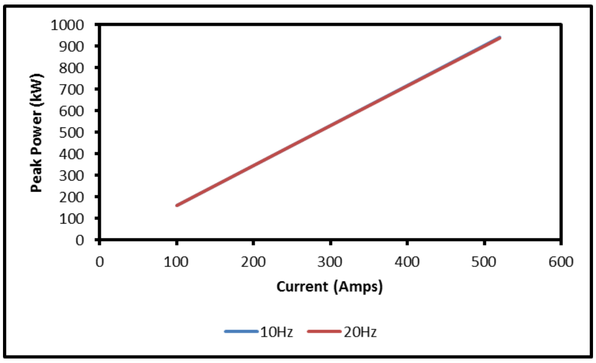

Figure 13 – Output power characteristics of the megawatt class laser diode pump module at different pulse repetition rates

The integrated spectral outputs of the laser diode module at different pulse repetition rates are shown in Figure 14. It should be noted that the coolant temperature was tuned to keep the center wavelength nominally the same. The integrated spectrum of the entire module had a FWHM of 4.2nm and showed a single peak distribution. This validates that the uniform performance measured on the individual arrays were maintained without any significant integration penalty. There was also no measureable difference in the spectral performance at the different pulse repetition rates indicating uniform thermal performance of the assembly.

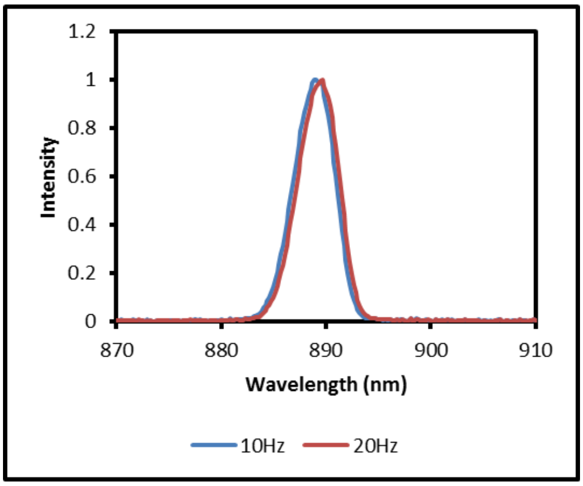

Figure 14 – Integrated spectral output of the megawatt class laser diode module at different pulse repetition rates. The temperature of the coolant was tuned to maintain constant centerwavelength

The collimation performance of the entire module was measured and the cross section of the output beam is shown in Figure 15. It should be noted that the output beam was intentionally defocused for the specific application that the modules were manufactured for. The output beam of the entire module was single lobed indicating that the relative pointing angles of the arrays were well maintained. The FW of the collimated beam measured at 1/e^2 was 4.5 degrees.

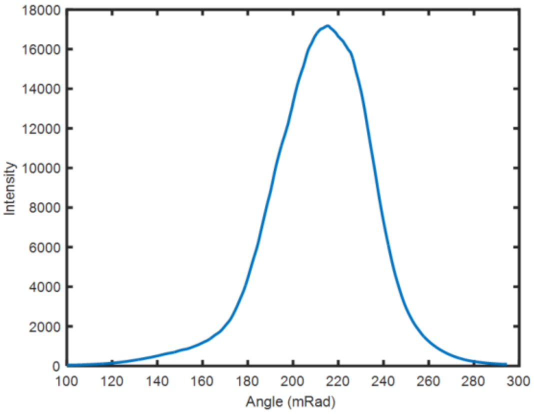

Figure 15 – Beam cross section of the output beam divergence of the megawatt class laser diode module. The output was intentionally defocused on the arrays to meet the requirements of the application

The illumination uniformity of the megawatt class module was measured at a distance of 40 cm from the output window of the array. The measured output is shown in Figure 16. The measured variation in illumination intensity was ±6%.

The good illumination uniformity generated directly from the module allows for the use of a simple optical element, such as a diffuser, and eliminates the need for expensive and lossy optical elements such as homogenizers to further improve the illumination uniformity at the gain media.

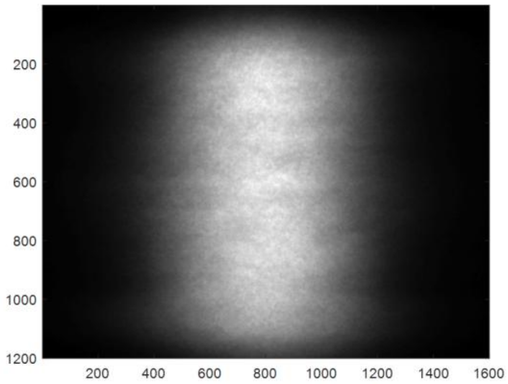

Figure 16 – Output uniformity of the megawatt class laser diode module measured at 40cm. No uniformity enhancing optical elements were used

SUMMARY

Several novel technologies were developed and integrated to produce megawatt class laser diode modules. Laser diode bars that produce >500W of peak output power with efficiencies of 60% were used as the key element in the building blocks for a scalable megawatt class pump module. The key building block for the megawatt class module was a compact 40 bar laser diode array that produced >20kW. A break through lensing technology was developed to collimate the output of the 40 bar laser diode arrays for better coupling into the gain media. Forty five (45) of the collimated compact 40 bar laser diode arrays were close packed in a 9x5 matrix arrangement to produce a peak output power of 940kW from the laser diode pump module. This represents a power density of 10kW/cm^2. The peak output power and the power density represent record breaking values with a 300% improvement over previously demonstrated modules.

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