High-power diode laser technology XX: a retrospective on 20 years of progress

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ABSTRACT

The High-Power Diode Laser Technology conference was first presented at SPIE Photonics West in 2003. At that time high power laser diodes were just approaching 50-60% in efficiency, a couple of companies were developing systems based on these diodes, and fiber lasers were not yet an industrial product. Since then, laser diodes can exceed 70% electrical efficiency, power levels have grown from the 50-Watt bar level to today's heights of several hundred Watts. New wavelengths have been introduced and laser diode systems have increased in power from the couple of kWatts in 2003 to over 40 kWatts today. This technology area continues to expand with new applications, and new heights every year. We will review the hot topics of the time, technology, applications, and state-of-the art performance levels. What problems have been solved, and which remain today, twenty years later?

Keywords: high-power, diode laser, single-emitter, efficiency, reliability, brightness, cost, laser diode bar, direct diode system

1. INTRODUCTION

The first SPIE conference on high-power diode lasers was held in 2003, so 2022 marks the 20th session on this diverse and important topic. In the inaugural year, 19 papers were presented on a wide range of topics: semiconductor physics, reliability, micro assembly, optics and fiber coupling, cooling, and applications like welding, hardening, and cladding. Driven by the commercial success of industrial solid-state and fiber lasers, where high-power single emitter and bar diode lasers serve as the pump source, significant technical strides have been made over the last twenty years, and dramatic cost reduction has been realized in the industry. Over 50 technical papers on these subjects have been presented in the busier years, two new conferences have been split off (one on applications, and another on components), and the conference remains one of the most widely attended at Photonics West.

In this paper we make a brief review of some of the highlights we've seen over the years, and track the progress of key performance metrics. This is by no means a comprehensive review, but rather a collection of what the authors feel were important to our industry and of interest to this conference. We start with trends at the single emitter level, where major topics included reliability, power, efficiency, brightness, and cost. We then move to high-power diode bars, packaging, and systems.

2. SINGLE EMITTERS

2.1 Power and reliability

Exiting the telecom bubble and bust of the early-2000s, high-reliability GaAs-based laser diode technology was well established to serve demanding fiber-optic qualification standards. Several proprietary facet passivation methods were developed to mitigate catastrophic optic mirror damage, and a transition from soft solders like In and PbSn to the more robust AuSn hard solder was well underway. Reliable output power for a representative 100 micron wide facet aperture lasing in the 900nm wavelength band climbed from around 5W in 2003 to over 10W. Figure 1 shows this progression for one of the leaders in the field, Lumentum (formerly JDSU)[1].

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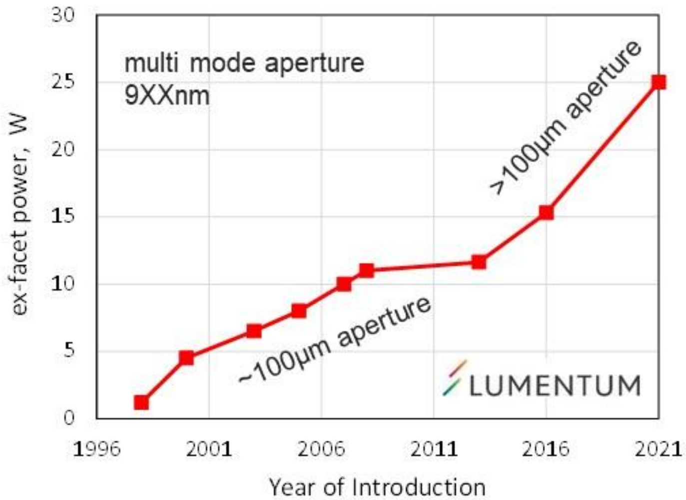

Figure 1. Progression of reliable optical power for multi-mode lasers in the 9XXnm wavelength band.

However, this rapid progress saturated at the 100-150mW/µm linear power density level (total optical power divided by laser aperture width) by ~2012, as the materials and technology hit some type of limit. And this limit appears to still be in place today for all manufacturers and facet passivation techniques. Interestingly, progress in narrow-stripe, single-mode lasers at 980nm has continued to increase through at least 2020, as shown in Fig. 2[1].

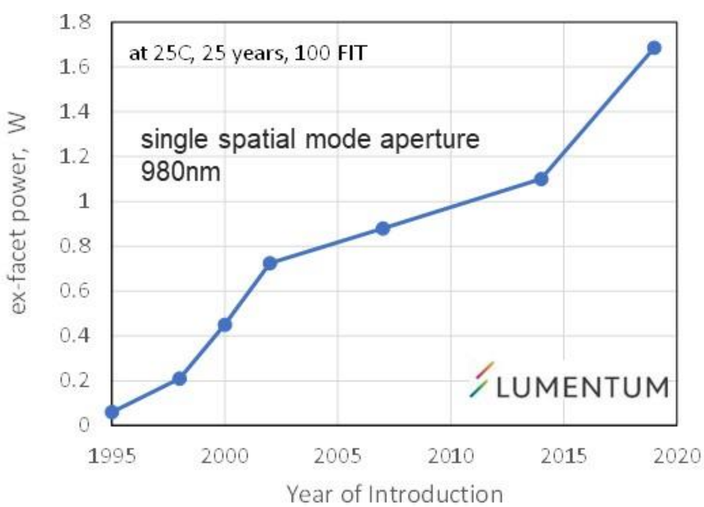

Figure 2. Progression of reliable power from single spatial mode 980nm wavelength lasers.

While linear power density for multi-mode lasers may have saturated, the total power per emitter has not. Wider apertures have been introduced, and power exceeding 25W from a single die are now commercially available and widely used. An example of this transition from TRUMPF[2] is shown in Fig. 3, and from Lumentum[1] in Fig. 1.

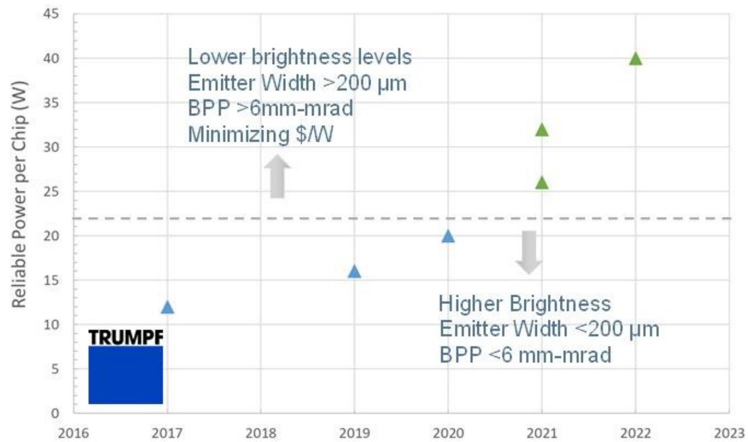

Figure 3. The reliable power from a single chip has increased over time, through increases in aperture width, and other parameters.

2.2 Efficiency

Improvements in electrical to optical power conversion efficiency can drive benefits in maximum power per chip, reliability, power consumption, and waste heat reduction. Such leverage was realized by the US Government Defense Advanced Research Projects Agency (DARPA) and inspired the Super High Efficiency Diode Sources project (SHEDS) in 2003. By 2005, the three funded participants plus an unfunded company had demonstrated ~73% peak efficiency, a dramatic improvement over the ~55% efficiency typical just several years earlier. Example power and efficiency versus current curves are shown in Fig. 4 from these four companies[3, 4, 5, 6]. The laser cavity lengths used for these record-breaking efficiencies ranged from 1-2mm, which limited their commercial usefulness due to relatively low power per emitter at peak efficiency. Today's more cost-effective designs have cavity length in the 4-5mm range, power in the 10-20W range, and operating efficiency in the 60-70% range.

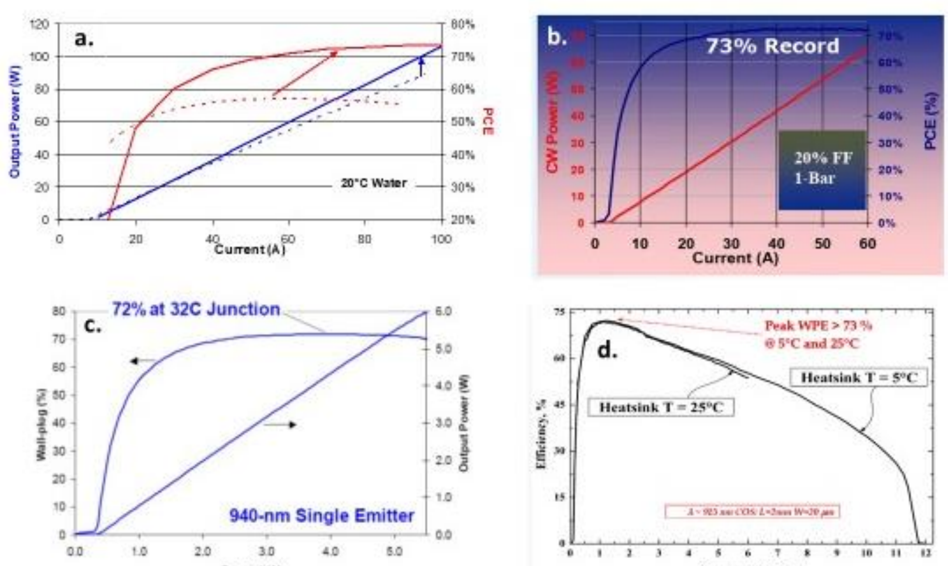

Figure 4. Power and efficiency results after the DARPA SHEDS project: a. JDSU[3], b. Alfalight[4], c. nLIGHT[5], d. IPG Photonics[6] (demonstrated with their internally funded efforts).

2.3 Brightness

The largest application for high-power single emitter diode lasers is fiber laser pumping. Fiber lasers have a limited etendue, the two-dimensional product of the near field and far field of the light, to couple into the pump core. Hence the “brightness” of the diode pumps, optical power divided by etendue, limits how much power can be injected into the fiber laser. As progress in the reliable linear power density saturated in ~2010, a renewed focus on brightness improvement started to address this problem.

High-power diode lasers are typically diffraction-limited in the fast-axis direction, perpendicular to the epitaxial layers, and so cannot be further improved. However, in the slow-axis direction, parallel to the lateral output aperture, many spatial optical modes are excited. As was the case in earlier improvement work with facet passivation and efficiency, proprietary techniques were developed to suppress higher-order lateral modes and increase the fundamental brightness of the chip. As the lateral brightness has increased, so has the power per module as described below.

Fiber laser pump diodes first need to mechanically packaged and coupled to optical fiber, and then spliced to the fiber laser pump core. The first high-volume commercial products paired one diode chip to one fiber. Example products are shown in Fig. 5. These ranged in power from 5 to 10W, from a fiber core diameter of ~105µm, and excitation NA of ~0.15. Much of the fundamental brightness of the laser diode was wasted with such packaging.

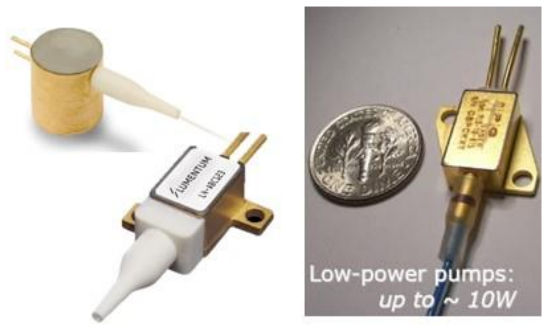

Figure 5. Product examples from JDSU, Lumentum, and IPG Photonics[6]. A single chip is coupled to a single fiber.

Etendue can be conveniently characterized for fiber-coupled sources as the beam parameter product (BPP), defined as the one-dimensional product of half fiber core diameter (i.e. core radius) times half divergence (i.e. numerical aperture, NA). A key performance metric for pump diodes is the “brightness” of the coupled light, defined as the optical power divided by the etendue. Using the BPP parameter, the brightness of a fiber coupled source may then be given as power / BPP^2, in Watts per (mm-mrad)^2. These single-chip modules had a good BPP value of 6~7mm-mrad, but poor brightness value of 0.1~0.2W/(mm-mrad)^2.

In our SPIE conference in 2006, IPG Photonics[6] introduced a 20W pump based on spatial combining of three chips into the same fiber BPP as one chip. In 2009 this concept was extended to six chips[6], See Fig. 6, with power reaching 60W. Chip production exceeded 100,000 units that year, and brightness levels exceeded 1W/(mm-mrad)^2.

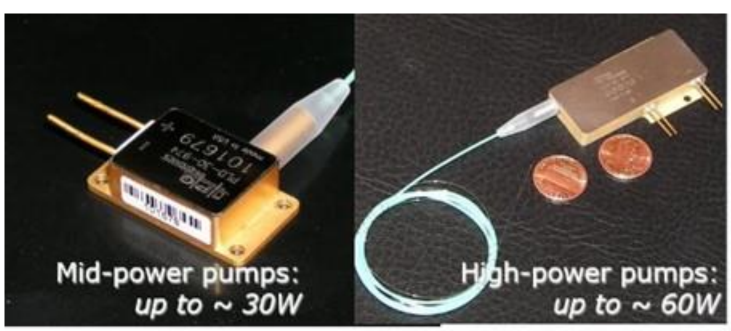

Figure 6. Product examples IPG Photonics[6]. Three to six chips are coupled to a single fiber with spatial combining.

In this timeframe, several other companies introduced larger emitter quantities, polarization combining, and eventually larger fiber cores to accommodate ever more emitters. A few examples from commercial datasheets are shown in Fig. 7. Figure 8 summarizes representative performance values for today's volume production, with ex-fiber power reaching 200-400W or more, and brightness values between 1.5~2.5W/(mm-mrad)^2.

Figure 7. Product examples from nLight, Lumentum, and Xinghan. Fourteen to 24 or more chips are coupled to a single fiber with spatial and polarization combining.

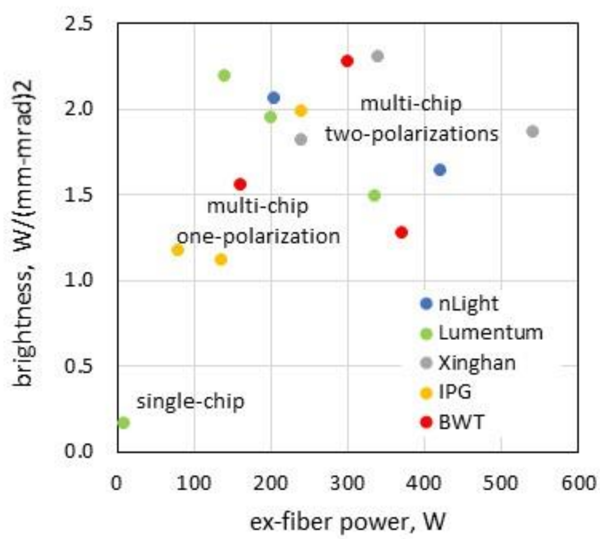

Figure 8. Brightness as a function of optical power for several commercial fiber-coupled laser diode packages from leading manufacturers.

2.4 Cost

In addition to the significant performance gains of high-power diode lasers over the last twenty years, there has been dramatic cost reduction. Driven by an expanding industrial market for fiber laser cutting and welding tools, 10s of millions of laser diode chips are manufactured per year for this market alone. The predominant GaAs wafer size in production in 2003 was 2-3 inch diameter. In 2022, most wafer fabs run 3-4 inch wafers, while at least two are running 6 inch. Larger wafers are necessary not only for cost reduction, but also to handle the sheer volume requirements of today's larger chips and much larger volumes. Laser cavity length, and resulting area per chip on the wafer, have increased from 1-2mm in 2003 to 4-5mm and longer in 2022.

The cost is being further driven down in terms of "dollars per watt" by increasing the laser aperture width, thus enabling higher reliable power, while keeping chip real estate the same as for smaller apertures. Following this trend are increasing fiber core diameters to allow efficient coupling of the wider emitters, and higher quantities of chips per package.

Looking back over thirty years, a steady progression in cost per performance has been realized for high-power laser diodes, similar to the trend seen with integrated circuits and characterized by Moore's Law, as analyzed by nLight[4] and shown in Fig. 9. In 2022, fiber-coupled pumps at 100-300 $/W/(mm-mrad)^2 are commercially available, at price points approaching $1/W.

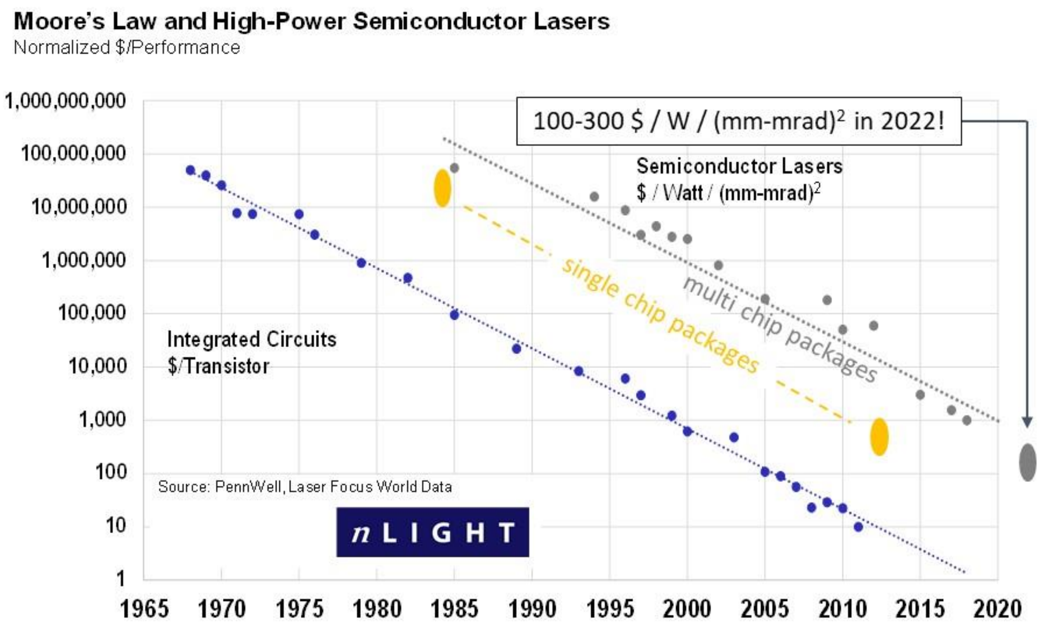

Figure 5. Moore's law for integrated circuits and high-power semiconductor lasers. The "cost per brightness" of fiber-coupled diode lasers has fallen at a similar rate to the well-known Moore's law. Multi-chip package trend from nLight[4], single-chip package trend and cost points from author.

3. HIGH POWER DIODE LASER BAR HISTORY

High power diode laser bars are now found in many products and applications including diode pumped disk lasers for industrial applications, fiber lasers and direct diode lasers. This does not include the recent breakthroughs in the defense sector where diode pumped lasers, whether slabs or fibers, use immense numbers of diode lasers to drive directed energy applications. So, what started this and how long did it take to reach this level of maturity? It all began in the early 1980's, 1 cm x 1cm substrates of GaAs were being used to grow epi-layers using Liquid Phase Epitaxy (LPE) or Molecular Organic Chemical Vapor Deposition (MOCVD) methods. McDonnell Douglas was an early researcher in this area, having written one of the first patents on diode pumped lasers, they were investing heavily in developing laser diodes.[7] In 1983 the predominate method was to grow diode lasers as a double heterostructure using LPE. The bars were typically operated only in a low duty cycle mode because of the high heat loads. A typical bar would produce 6.5Watts with a 5-6% duty cycle when mounted on a passive cooler.[8] Consequently, a more robust cooling method was needed to enable these bars to operate CW. At the time the best cooling method published was a paper by Tuckerman and Pease

Figure 6. Micro-channel cooler fabricated by soldering in 1985.

on silicon micro-channel coolers.[9] Their results were repeated in some early tests and a modification of using copper was implemented that proved to be even better at cooling these high heat load devices ~ 1,000W/cm^2.

The copper cooler was 1 mm thick, manufactured from OFC copper (Figure 6), the channels were milled in a 250µm thick copper plate, 150µm wide by 150µm deep on 400µm centers. A manifold was soldered over the channels and secured to a test fixture. The bar was a DH structure bar, with 60µm stripes on 180µm centers, and a cleave length of approximately 300µm. This record-breaking test resulted in nearly 5Watts CW from the bar.[10] While this was a significant advancement, it was still far short of the 20Watts CW needed for the application.

In 1986 a new epitaxial structure was being developed that demonstrated much higher power and efficiency due to a dramatic reduction in the intrinsic losses of the device. This structure was a Graded Index Separate Confinement Heterostructure Single Quantum Well (GRIN-SCH-SQW) and is the foundation of all laser diode designs today. The first devices fabricated using this heterostructure design immediately showed a dramatic improvement in power and efficiency from hundreds of milliwatts to Watts and from 25% to 53%. This breakthrough in design ushered in the rapid commercialization of this technology for industrial and military applications. During this same time manufacturing methods for micro-channel coolers were dramatically improved as well as their performance. The designs of these coolers benefited from chemical etching to define the internal structures and diffusion bonding to assemble the coolers. These advanced led to the rapid increase in output power for laser diode bars over time as shown in Figure 7. The efficiency of the bars was around 50% for many years until the DARPA SHEDS program in 2003 which invested in increasing the electrical efficiency of the laser diode bar.[11] This program made major improvements to the laser diode bar output power and efficiency, demonstrating laser bar powers in excess of 100 Watts and efficiency exceeding 73%.[12]

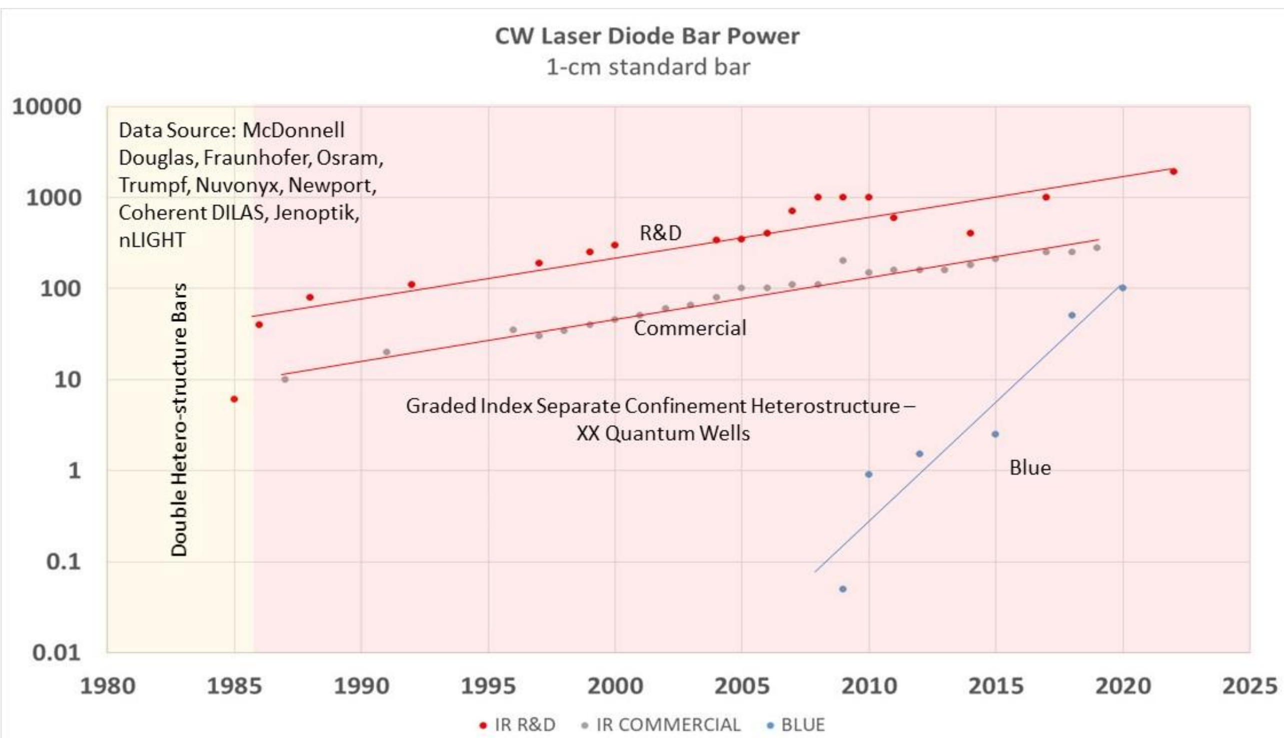

Figure 7. Growth of laser diode bar power since introduction of the GRIN-SCH-SQW technology.

High power infrared devices have slowed in their advance of output power. The main limitations are the management of the heat load and the management of the drive currents. Multiple methods of improving the cooling of the laser diodes bars have been demonstrated at the research level including sandwiching the laser diode bar between two micro-channel heat sinks. This has enabled power levels of 1 kW from a standard 1 cm bar to be achieved, but a commercial path has yet to be developed.

The development of blue laser diodes for blue ray disc readers and writers resulted in steady improvement of these devices as well. In 2012, a breakthrough in the output power of these devices was realized. At the 1.5 Watt per device level, it was not feasible to consider developing a 50Watt blue laser diode bar. OSRAM led this development and has rapidly scaled the output power of its laser diode bars from 45Watts to 100Watts.[13] This technology is rapidly finding applications in welding and 3d printing of materials that are highly reflective in the IR. As can be seen in Figure 7, the blue technology is rapidly approaching the performance of the IR, however, the blue laser technology has yet to break the 50% efficiency barrier like the IR laser diode bars did in 2006. Once higher efficiencies are achieved, higher power blue laser diode bars will be realized.

4. HIGH POWER DIODE LASER SYSTEMS

High power diode laser systems have dramatically improved in power and beam quality over time. This technology is now established as the best technology for brazing, cladding, heat treating, annealing and some welding. The first high power fiber coupled system introduced to the marketplace was a 100Watt fiber coupled unit built by McDonnell Douglas in 1993. That year the first article on how direct diode laser technology was going to one day compete with high power industrial lasers was featured in Industrial Laser Solutions. The article was met with much skepticism that direct diode lasers would ever challenge the status quo of lamp pumped lasers, diode pumped lasers and CO_2 lasers. Today, they have a clearly established place in the industrial marketplace due to their high-power capabilities, good beam quality and high reliability. The growth in direct diode laser system performance is shown in Figure 8 since 1991.

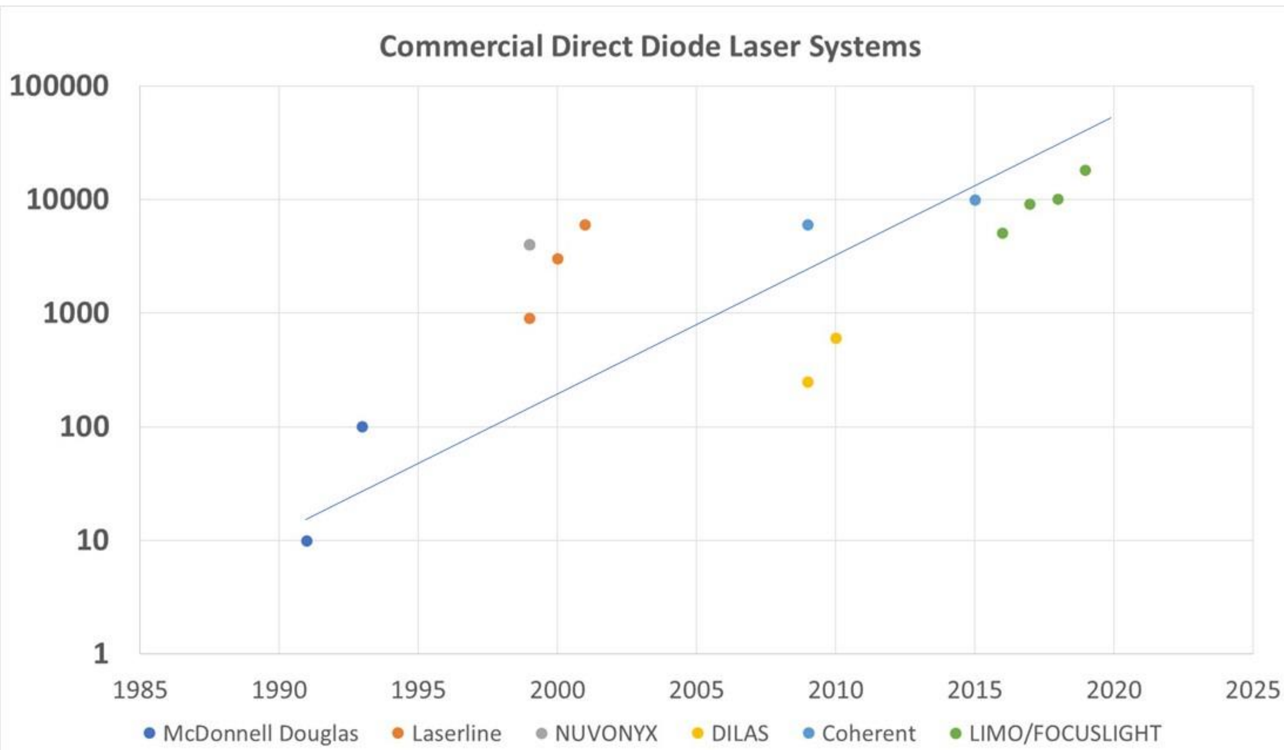

Figure 8. As the laser diode power has grown, so has the output power of direct diode laser systems.

Figure 8 is for direct diode laser systems, that do not include an optical fiber beam delivery system. The growth in power is a linear scaling of the beam quality of the systems as well, with the 18,000Watt systems built by Focuslight for annealing applications being a homogenous line focus versus a conventional spot focus. As the products undergoing the annealing process continue to expand, one can expect the power requirements of these systems to increase over time requiring larger and larger direct diode laser systems. Direct diode lasers have also found a niche in cladding large parts with low brightness laser diodes sources. These same sources have also found significant applications in heat treating applications where precise control of the hardening zone is required on modest to large industrial parts. Based on the high energy efficiency and good beam formation optics available today, the steady replacement of ovens or other inefficient processes by direct diode laser systems will continue to grow.

Diode lasers systems are unique in that the beam being created by these systems can be delivered either directly as shown in Figure 8, or through an optical fiber as shown in Figure 9. One supplier in particular stands out among the competition, and this is Laserline. They have been delivering high power fiber coupled diode laser systems with the highest power and performance and have outpaced all other competitors.

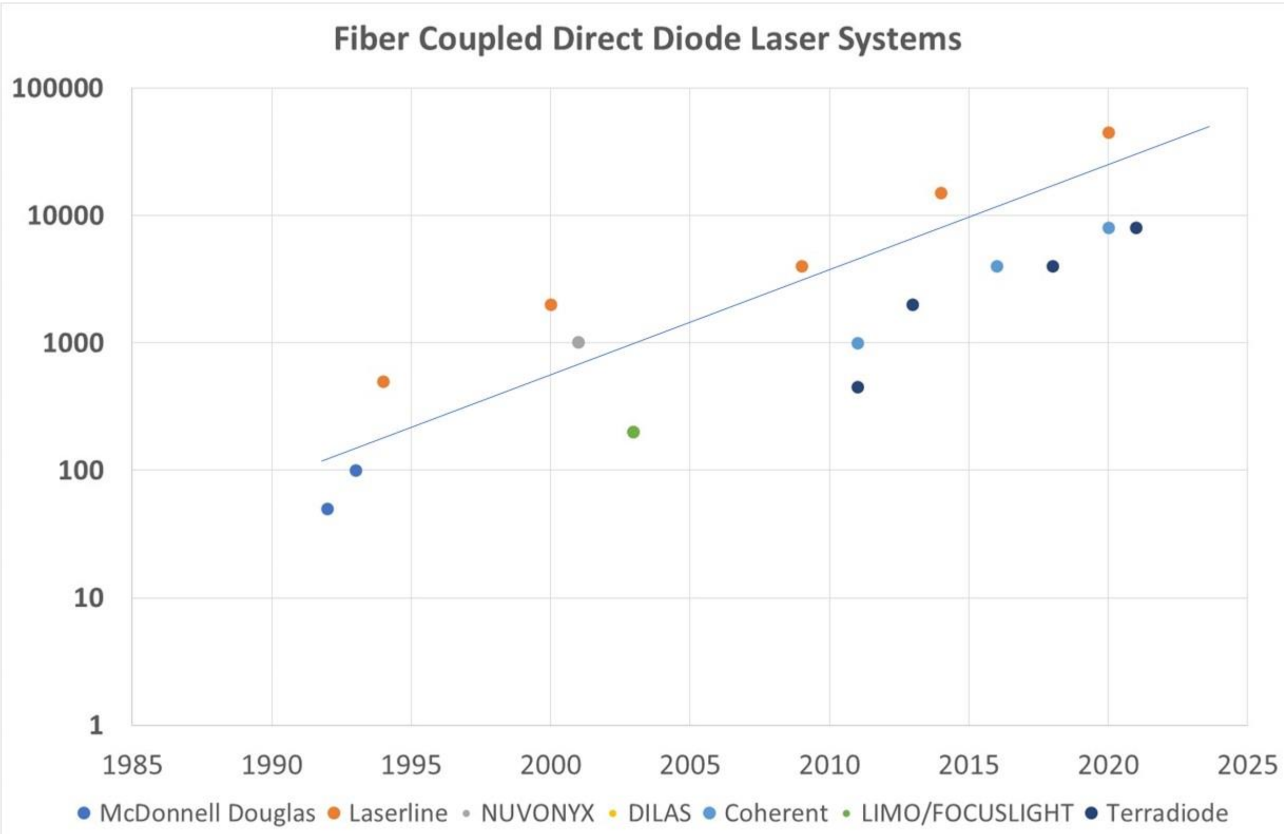

Figure 9. Fiber coupled diode laser systems continue to improve in power and brightness.

These lasers can be found performing brazing, welding, and deep penetration welding in many types of manufacturing plants. They have also been deployed for cladding and heat-treating applications. The record breaking 45kW systems introduced in 2020 are without a doubt a major accomplishment for this technology.

What does the future hold for fiber coupled diode laser systems? There is no doubt that the power levels will continue to move upward as applications demanding more and more power are uncovered. However, beam quality is another important factor and Panasonic/Terradiode is the current leader in delivering kW class systems with near fiber laser beam qualities. This company has been leading the industry in beam quality for a several years and the technology appears to be capable of scaling to even greater heights. This means that the higher efficiency direct diode laser and fiber coupled diode laser systems will continue to make inroads into the major industrial marketplace, replacing less efficient methods and laser models. The future for this technology is very promising and has fulfilled the prediction of 1993 by this author that one day, direct diode laser systems would be able to compete in applications such as welding and cutting. This is evident in Figure 10 where the performance of the fiber coupled diode laser systems now compete with other lasers in keyhole welding and metal cutting applications. The ultimate brightness applications of remote welding continue to be dominated by fiber lasers due to the higher brightness of these systems.

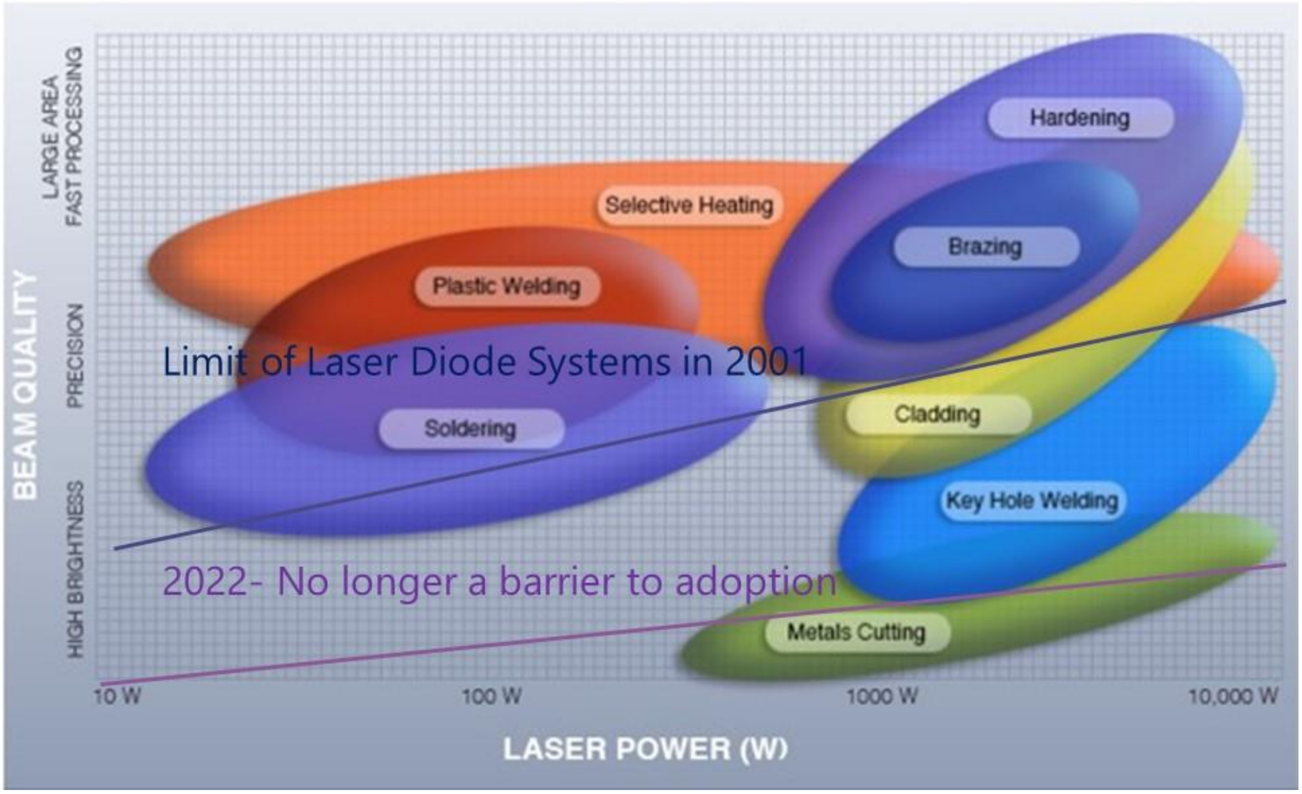

Figure 10. Fiber coupled diode laser systems have now achieved sufficient power and brightness to compete in keyhole welding applications as well as cutting applications.

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