# nLIGHT alta™: A Versatile, Next-Generation Fiber Laser Platform for kW Materials Processing

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We describe an innovative fiber laser platform that addresses the needs of current and emerging kW materials processing applications. Most multi-kW fiber laser systems employ an architecture based on combining the outputs of multiple, lower-power fiber lasers, resulting in significant shortcomings in cost, performance, serviceability, upgradeability, and amenability to technological advances. We introduce a novel kW fiber laser architecture that solves these problems by housing the pump diodes and drivers in standalone Pump Modules and the gain fibers in a configurable Gain Module that can generate >4 kW of output power. This platform provides industry-leading performance, including high efficiency, tailorable beam quality (BPP $\geq$ 1.1 mm-mrad), and high-speed modulation (up to 100 kHz), resulting in superior processing for a wide range of materials. The laser design incorporates a robust, integrated back-reflection isolator, enabling uninterrupted processing of highly reflective materials without laser damage or destabilization. These lasers have been successfully deployed in challenging factory environments worldwide, demonstrating unmatched performance, reliability, and uptime. They have been used for high-quality cutting and welding of mild steel, boron steel, stainless steel, aluminium, brass, and copper and have also been employed in emerging applications, including additive manufacturing and surface texturing and engraving.

**Keywords:** fiber laser, high power, continuous wave, modulated, kW materials processing, metal cutting, welding, additive manufacturing

## 1. Introduction

Fiber lasers have revolutionized kW materials processing because of their unique combination of practical and performance advantages [1]. High-power fiber lasers are displacing other laser and, more importantly, non-laser technologies in the >$100B worldwide machine tool market, and they are enabling new applications that cannot be addressed with previous technologies. Despite this progress, fiber laser users have identified several shortcomings of current products, including:

1. feedback sensitivity, which causes frequent process interruptions, precludes processing certain metals or finishes, and can result in laser instability or damage;
2. limited serviceability, which causes excessive downtime and prevents system integrators from providing the required level of customer service; and
3. lack of upgradeability, which limits product offerings and the rate of technology adoption.

In addition, emerging applications require more advanced performance, including better beam quality, higher modulations rates, more rapid optical rise and fall times, and sophisticated beam-shaping and waveform-generation capabilities.

We have developed a next-generation fiber laser platform (nLIGHT alta™) to address the above needs. This platform, currently available with output powers up to 4 kW, offers simultaneously the industry's best beam quality, fastest modulation frequency, shortest optical rise/fall times, greatest immunity to back reflection, and highest reliability and environmental robustness for deployment in harsh factory environments. Furthermore, we employ a novel architecture that enables rapid field service and field upgradeability, even in dirty environments, and that facilitates continued technological innovation.

Section 2 describes the architectures of legacy fiber lasers and of our next-generation fiber laser, discusses the key components, and summarizes the benefits of the next-generation architecture for serviceability and upgradeability. Section 3 provides an overview of the fiber laser performance. Section 4 shows application examples, including some that leverage the new fiber laser capabilities.

## 2. Fiber laser design and components

### 2.1 Architectures

Figure 1 shows the architecture employed in previous multi-kW industrial fiber lasers. These systems consist of multiple lower-power fiber laser building blocks whose outputs are combined using a fused-fiber combiner. The fiber laser building blocks are typically single-mode or slightly multimode. Their power has been increasing with time, thereby requiring fewer fiber laser modules to reach a given total power. This evolution is beneficial for reducing system cost (lower redundancy of expensive components and subsystems) and improving beam quality. Current fiber laser building blocks typically have a power of 0.5 – 2 kW.

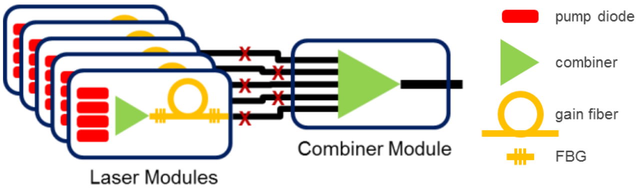


**Figure 1.** Schematic diagram showing the architecture of legacy multi-kW industrial fiber laser systems. A legend of the components is given on the right (FBG = fiber Bragg grating). The red X's denote splices between modules. Note that this figure is representational, and the details of the module designs vary among systems.

Characteristics of the legacy design are as follows:

1. Significant redundancy exists in expensive optical, electrical, and mechanical components, which drives cost (hence the evolution described above).
2. The laser modules have limited serviceability, particularly in dirty environments, which negatively impacts the timeliness and cost of service and restricts control of service activities to the laser manufacturer.
3. Field replacement of fiber laser modules requires sophisticated equipment and highly trained personnel, again driving the speed and cost of service or upgrades.
4. The design is poorly suited to accommodate advances in pump diode technology. The semiconductor-based pumps are the fastest-evolving technology within the fiber laser, enabling continuous improvements in cost, power, brightness, and efficiency. In the conventional architecture shown in Fig. 1, the pump diodes are closely coupled mechanically, thermally, and electrically with the rest of the fiber laser module, resulting in significant design ripple if the pumps or their constituent chips are upgraded. This coupling limits the innovation cycle and the design options.

We note that the legacy architecture evolved from limitations of the constituent components and manufacturing processes. Multiple groups have been addressing these limitations, enabling the power scaling of fiber laser modules described above, but the basic architecture shown in Fig. 1 has not been rethought until now.

Figure 2 shows the nLIGHT alta™ architecture. The pump diodes are housed in standalone Pump Modules, and the Yb-doped gain fibers are housed in a separate Gain Module. Each Pump Module contains up to 14 element™ pump diodes (Section 2.2.1), two fused-fiber combiners, diode drivers, and sensors and other electronics required for system monitoring. Each Pump Module provides up to 1.9 kW of output pump power, depending on which pump diodes are incorporated into the module, and the system includes up to three Pump Modules. The Gain Module includes all fiber laser oscillator and amplifier stages, sensors and associated electronics, and a proprietary back reflection isolator that prevents feedback from the work piece or other sources from damaging any of the components in the Pump or Gain Modules (see Section 2.2.3). More than 4 kW of fiber laser output power is available from each Gain Module.

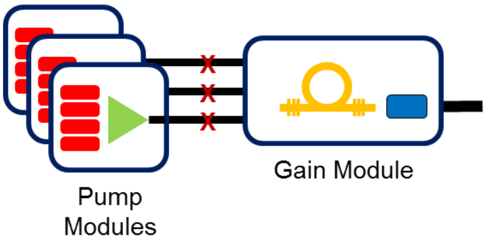


**Figure 2.** Schematic diagram showing the architecture of the nLIGHT alta™ industrial fiber laser. The components are defined as in Fig. 1. The blue rectangle in the Gain Module represents the back-reflection isolator. As in Fig. 1, the figure is representational and indicates the function of the modules rather than their design details.

Key features of the nLIGHT alta™ architecture are:

1. The design eliminates undesirable redundancy of complex or expensive optical, electrical, and mechanical components.
2. The Pump or Gain Modules are field replaceable via a simple splicing procedure, which minimizes the equipment and personnel/training requirements. This advantage over the conventional architecture derives from the nature of the required splices: The splices shown in Fig. 1 are between fibers transmitting the high-brightness signal beam, with core diameters of ~10 μm; the alignment and cleave-angle tolerances are thus very tight, and the high optical irradiance (~1 GW/cm$^2$) results in high sensitivity to contamination or imperfections. The splices shown in Fig. 2 are between fibers transmitting the low-brightness pump beam, with core diameters >100 μm (300 μm in the case of nLIGHT alta™); the alignment and cleave-angle tolerances are correspondingly larger, and the optical irradiance is ~3 orders of magnitude lower.
3. The system power can be increased in the field by adding or replacing Pump Modules, offering a graceful and cost-effective upgrade path.
4. The design is well suited to accommodate advances in pump diode technology because the pumps are mechanically, thermally, and electrically isolated from the fiber laser gain stages. New Pump Modules can be developed and incorporated in the fac-

5. tory or the field with no design ripple to the rest of the system as long as the output fiber is compatible with the input fibers to the Gain Module.
6. The Pump Module can serve as a building block for direct diode systems, thereby driving higher volume of common components and subsystems.

### 2.2 Components

The nLIGHT alta™ architecture leverages our high-performance components. Specifically, nLIGHT is a vertically integrated manufacturer of single-emitter semiconductor chips [2], fiber-coupled pump diodes [3], and active and passive fibers [4]. These critical components have been employed in defense and aerospace systems and in industrial fiber lasers, direct diode lasers, and diode-pumped solid state lasers worldwide for 15 years, providing extensive performance and reliability data; they are the foundation of the nLIGHT alta™ platform. nLIGHT components have been designed to handle the high optical irradiances and heat loads required for power scaling, enabling the architecture shown in Fig. 2. We have thus been able to scale the power and brightness of the Pump and Gain Modules to provide >4 kW output power (Section 3) without the onset of parasitic nonlinear effects, fiber photodarkening, thermal runaway, or other processes detrimental to performance and reliability at high power.

*2.2.1. Pump diodes*

The majority of industrial fiber lasers are pumped by single-emitter-based pumps at 9xx nm. These pumps provide the highest reliability, efficiency, and brightness. nLIGHT has developed proprietary designs and processes for chip fabrication, facet passivation, and burn-in. nLIGHT's chips have been extensively characterized in multi-cell life tests and achieve industry-leading reliability of >1,000,000 hr MTTF [5].

nLIGHT introduced the first fiber-coupled, multi-single-emitter-based pump sources in 2005 (Pearl™) [6], and we introduced a new generation of these pumps in 2013 (element™) [7] to address the needs of high-volume applications, including pumping of fiber lasers and diode-pumped solid state lasers. Element™ pumps offer the highest powers and brightnesses, and they are employed in all nLIGHT alta™ fiber lasers.

*2.2.2. Fibers*

nLIGHT's Yb-doped gain fibers are manufactured using a proprietary process, Direct Nanoparticle Deposition (DND) [4]. Most other fiber lasers employ Modified Chemical Vapor Deposition (MCVD) and solution doping to introduce the rare-earth elements. DND offers the advantages of:

1. high Yb concentration without photodarkening, which minimizes the required fiber length and thus increases the efficiency and the threshold for nonlinear processes;
2. precise control of the dopant radial distribution, which ensures high beam quality, exceptional batch-to-batch uniformity (consistent performance), and excellent splicing characteristics; and
3. wide flexibility in core and cladding parameters, enabling innovative fiber designs.

nLIGHT also manufactures the passive fibers employed in our fiber lasers.

*2.2.3. Back-reflection isolator*

A key component developed for the nLIGHT alta™ platform is a proprietary back-reflection isolator (Fig. 2), which enables uninterrupted processing of highly reflective materials. Typical back reflections are only a fraction of the laser power because of work-piece surface irregularities, lack of precise alignment with the surface normal, and the limited collection angle of the process optics; nonetheless, processing of reflective materials is difficult or impossible with legacy fiber lasers. We have life tested our back-reflection isolator for >3300 hr (Fig. 3). This life test was performed with 536 W launched into the isolator (the maximum available at the time the test was started). Stable attenuation of the back reflection by >98% was achieved with no degradation. Note that metal piercing, which generates a relatively large back reflection, typically lasts <1 ms, so the life test shown in Fig. 3 represents a very stringent test. Most importantly, no nLIGHT alta™ users have experienced laser instability or damage when processing highly reflective materials (Section 4), validating the design of the back-reflection isolator and demonstrating that nLIGHT alta™ is immune to back reflections in real-world applications. It is important to note that the nLIGHT alta™ back-reflection isolator provides hardware protection to enable uninterrupted processing of highly reflective materials. In contrast, many legacy fiber lasers employ software protection that disables the laser in the case of a back reflection; this approach may protect the laser, but it precludes successful material processing.

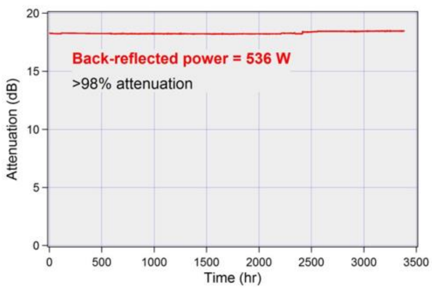


**Figure 3.** Life test of the back-reflection isolator, showing stable, >98% attenuation of back-reflected light for >3300 hr.

*2.2.4. Sensors*

The nLIGHT alta™ fiber laser includes built-in photodiodes with real-time analog outputs for process monitoring. These signals can be used for process optimization and control (e.g., pierce detection) or for tool calibration (e.g., beam position and focus). Figure 4 shows examples of the signal from laser light back-reflected from the work piece when piercing stainless steel, aluminum, and copper sheet metal.

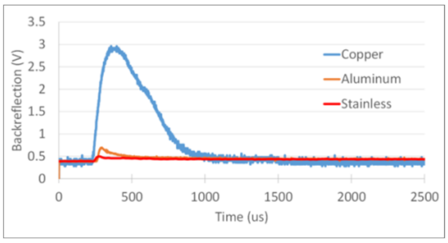


**Figure 4.** Back-reflection photodiode signals recorded when piercing stainless steel, aluminum, and copper.

### 3. nLIGHT alta™ performance

#### 3.1 Power

Figure 5 shows the output power vs. control voltage (used to set the pump diode current) for the 3 kW and 4 kW fiber lasers. The lasers are calibrated to provide the specified output power at a control voltage of 10 V, and both systems include significant overhead in the power.

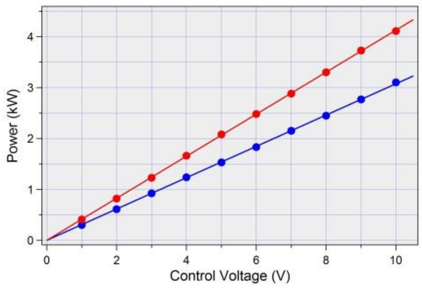


**Figure 5.** Output power vs. control voltage (used to set the pump diode current) for 3 kW (blue) and 4 kW (red) nLIGHT alta™ fiber lasers.

Following the introduction of the 3 kW fiber laser, we developed a new generation of semiconductor chips that operate at higher current and provide higher power. These chips enabled scaling of the power of each element™ pump diode from 110 W to 150 W (Fig. 6 top) and thus the Pump Module power from 1.5 kW to 1.9 kW (Fig. 6 bottom). As a result, the fiber laser output power was scaled from 3 kW to 4 kW (Fig. 5). Note that the only difference between the 3 kW and 4 kW fiber lasers shown in Fig. 5 is that the latter employed the new generation of higher-power chips, which enabled the Gain Module output power to be correspondingly increased with no design ripple to other components or subsystems. This result validates one of the key advantages of the nLIGHT alta™ architecture (Section 2.1), namely the ability to leverage rapid advances in semiconductor-based pump diodes. Further power scaling will be enabled by continued increases in the power and brightness of the element™ pumps.

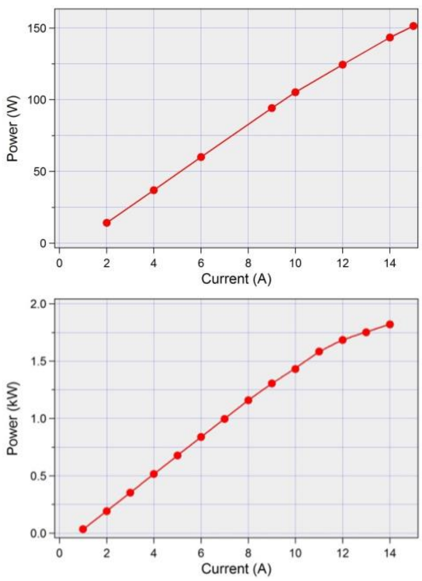


**Figure 6.** Output power vs. current for an element™ pump diode with our newest generation of high-power chip (top) and for a Pump Module incorporating these pumps (bottom). The curvature at the highest currents represents thermal rollover, and the fiber laser output power is calibrated to be linear with control voltage (Fig. 5).

#### 3.2 Power stability

Figure 7 shows a 65-hr stability test of a 3 kW fiber laser. The average power was 3.0 kW, and the standard deviation was 11 W (0.4%). The nLIGHT alta™ fiber laser thus exhibits excellent stability. Similar performance is observed over the entire operating power range (5 – 100% of full power).

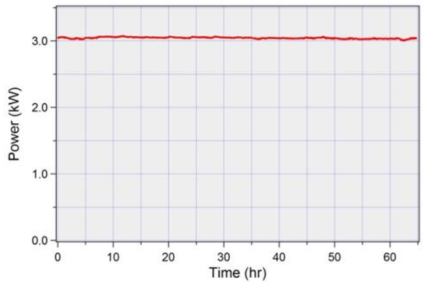


**Figure 7.** Continuous-wave stability test of a 3 kW fiber laser. The average power is 3.0 kW, and the standard deviation is 11 W (0.4%).

Figure 8 shows a stability test that better represents real-world operating conditions. The fiber laser was modulated at 0.1 Hz and 50% duty cycle (5 s on / 5 s off) for 64 hr, corresponding to > 23,000 cycles. The average power was 1.6 kW, and the standard deviation was 12 W (0.7%).

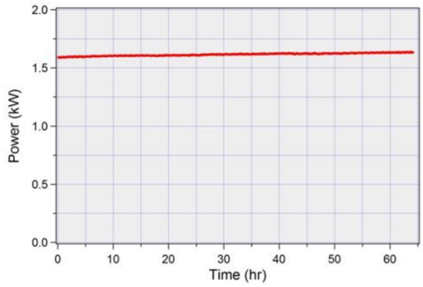


**Figure 8.** Modulated stability test (0.1 Hz, 50% duty cycle) of a 3 kW fiber laser. The average power is 1.6 kW, and the standard deviation is 12 W (0.7%).

#### 3.3 Beam quality

The nLIGHT alta™ fiber laser is offered with various feeding fiber core diameters, which provide different BPP values. The smallest available core diameter (lowest BPP) is 40 μm. Figure 9 shows a BPP measurement of a 3 kW fiber laser with this fiber, including beam images at various points along the caustic. The measured BPP value of 1.1 mm-mrad is the lowest (best beam quality) of any industrial fiber laser at this power level. Such high beam quality is very useful for providing the smallest spot size at the work piece (fastest cutting of thin metals and finest features) and/or for providing the longest depth of focus (largest process window). In addition, high beam quality greatly simplifies the optical setup for applications requiring beam shaping.

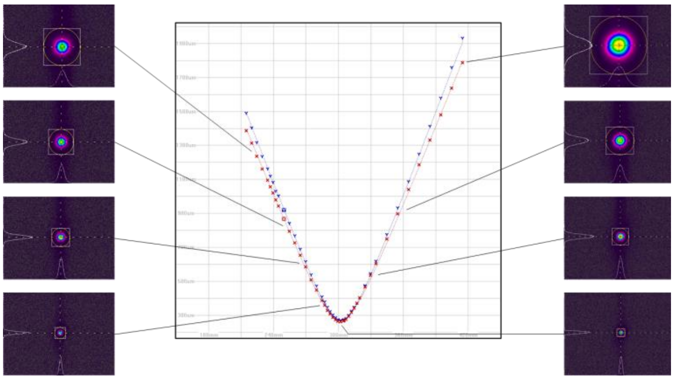

**Figure 9.** BPP measurement (beam size vs. position through the focus) of a 3 kW fiber laser with a 40 µm feeding fiber, including beam images at various points along the caustic. The measured BPP value is 1.1 mm-mrad.

Many applications do not require high beam quality (e.g., cutting of thick sheet metal). nLIGHT alta™ is thus offered with conventional feeding fiber core diameters (typically 50 – 300 µm), resulting in standard BPP values. For example, Fig. 10 shows a BPP measurement with a 100 µm feeding fiber, providing a BPP value of 2.4 mm-mrad, which is comparable to other industrial fiber lasers.

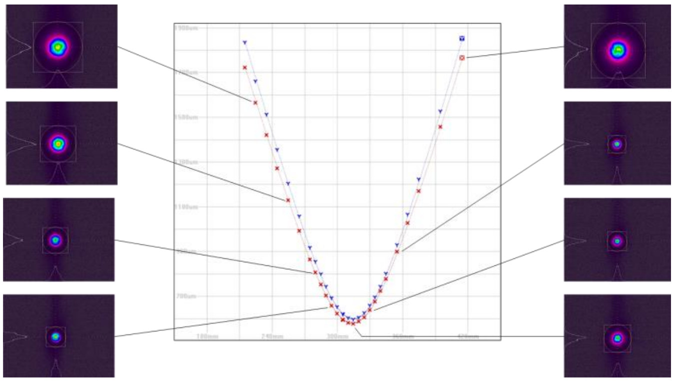

**Figure 10.** BPP measurement of a 3 kW fiber laser with a 100 µm feeding fiber, including beam images at various points along the caustic. The measured BPP value is 2.4 mm-mrad.

The beam images shown in Figs. 9 and 10 demonstrate a unique feature of the nLIGHT alta™ fiber laser: The beam shape (intensity distribution) is similar at all points along the caustic; lobes and other non-uniformities are not observed. This clean beam propagation, resulting from the design of the Gain Module, is advantageous for achieving high process uniformity and reproducibility for a given fiber laser and from unit to unit.

### 3.4 Modulation

Industrial multi-kW fiber lasers typically have a maximum modulation frequency of 5 – 10 kHz, with corresponding rise and fall times of 10's of µs. nLIGHT alta™ fiber lasers offer a maximum modulation frequency of 100 kHz, at least 10x faster. Figure 11 shows a 100 kHz waveform with a 50% duty cycle. The rise and fall times are ≤ 2 µs.

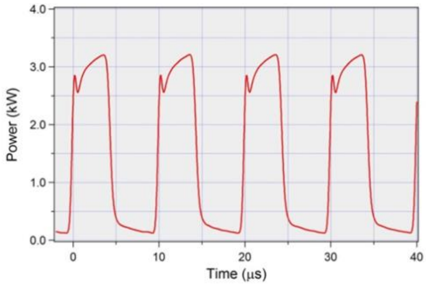


**Figure 11.** Optical waveform showing 100 kHz modulation (50% duty cycle) of a 3 kW fiber laser.

The order-of-magnitude increase in modulation capabilities provided by nLIGHT alta™ fiber lasers enables more precise energy deposition and process control and optimization. Users can employ this capability to generate sophisticated waveforms that are unavailable from other industrial multi-kW fiber lasers. For example, Fig. 12 shows a ~400 µs optical pulse with superimposed 10 kHz (top) and 20 kHz (bottom) modulation at 50% duty cycle. Figure 13 shows a saw-tooth waveform with superimposed 10 kHz modulation (top) and pulse packets with 500 µs duration and superimposed 12 kHz modulation (bottom).

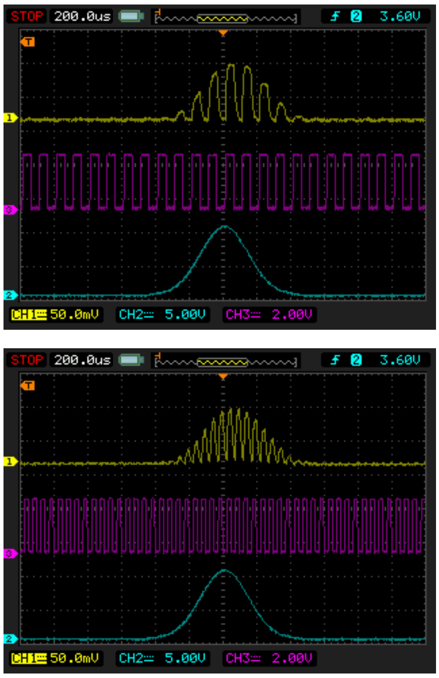


**Figure 12.** Oscilloscope traces showing optical waveform generation. The blue trace is the analog input voltage, which sets the laser power. The purple trace is the digital gate, which sets the modulation frequency and duty cycle. The yellow trace is the resultant optical waveform recorded with a photodiode.

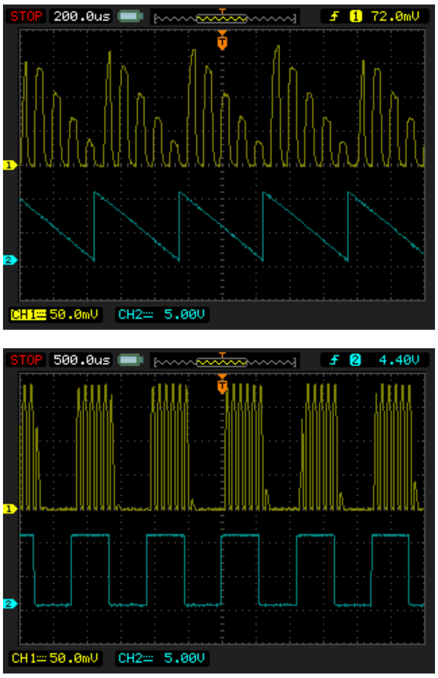

**Figure 13.** Oscilloscope traces showing optical waveform generation. The blue trace is the analog input voltage, which sets the laser power. The yellow trace is the resultant optical waveform recorded with a photodiode. For clarity, the digital gate (i.e., the purple trace in Fig. 12) is not shown.

### 3.5 Spectrum

Figure 14 shows the optical spectrum of a 3 kW fiber laser with a feeding fiber with a 40 µm core diameter and 20 m length. The fiber laser output is centered at 1081 nm and has a FWHM of 3.8 nm. The spectrum is very clean, with stimulated Raman scattering (~1140 nm) nearly 40 dB below the peak signal power (Fig. 14 inset). Other multi-kW industrial fiber lasers have significantly more out-of-band emission. The low out-of-band emission of nLIGHT alta™ fiber lasers, resulting from the fiber design in the Gain Module, simplifies the beam delivery optics and coatings and the optical safety requirements.

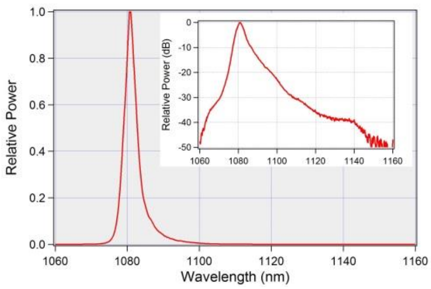


**Figure 14.** Optical spectrum of a 3 kW fiber laser (feeding fiber has a 40 µm core diameter and 20 m length). The inset shows the spectrum on a logarithmic scale.

## 4. Application examples

nLIGHT alta™ fiber lasers have been deployed in challenging factory environments worldwide and have exhibited high reliability and uptime. They have successfully processed a wide range of materials, including those that cannot be processed using legacy fiber lasers. This section presents some application examples provided by tool integrators and end users.

Sheet metal cutting is the largest market for kW fiber lasers. nLIGHT alta™ fiber lasers have enabled uninterrupted cutting of mild steel, boron steel, stainless steel (including mirror stainless steel), aluminum, brass, copper, hard copper, silver, and gold. Many of these materials are particularly challenging because of the high back reflection during piercing (e.g., copper, silver, and gold), yet no cases of fiber laser instability or failure have been observed. The maximum thicknesses cut to date using the 3 kW fiber laser are 20 mm for mild steel, 12 mm for stainless steel, aluminum, and brass, and 10 mm for copper. The cutting speed and quality are equal to or better than that achieved with legacy fiber lasers, and further process optimization is increasing the maximum thickness, the cutting speed, and the edge quality. nLIGHT alta™ fiber lasers have been integrated into both 2D and 3D cutting tools. Figure 15 shows some representative cutting samples.

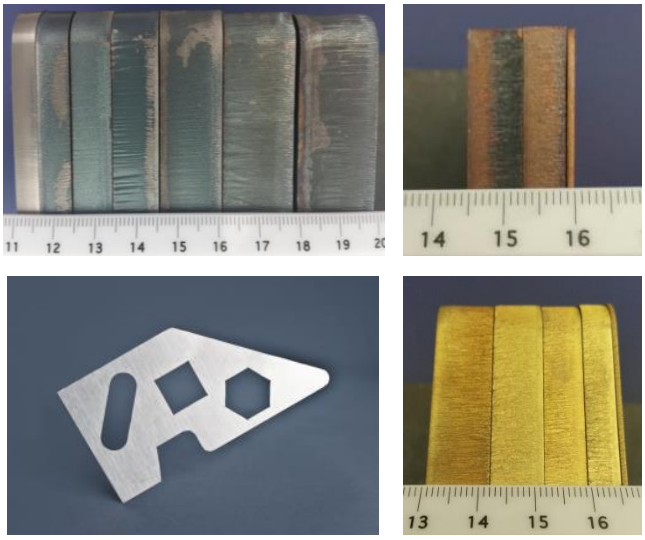

**Figure 15.** Cutting samples. Clockwise from top left: Mild steel, copper, brass, and stainless steel.

nLIGHT alta™ fiber lasers have also been used for welding of mild steel, stainless steel, aluminum, brass, and copper. Welding generally produces higher or more sustained back reflections than cutting, yet again no laser instability or damage has been observed, even for welding at normal incidence. Figure 16 shows examples of copper welding, a particularly challenging application that has resulted in significant damage to legacy fiber lasers; nLIGHT alta™ fiber lasers experienced no process interruptions, demonstrating the efficacy of the back reflection isolator (Section 2.2.3). Figure 17 shows cross sections of brass welds performed with the nLIGHT alta™ fiber laser (top) and with a legacy fiber laser (bottom); the superior weld quality achieved with the nLIGHT alta™ fiber laser is evident.

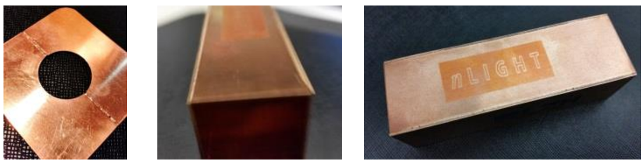

**Figure 16.** Examples of copper welding. The two photographs on the right are different views of the same part; this sample was provide by Laser Zentrum Hannover. The photograph on the right also shows surface texturing (the nLIGHT logo).

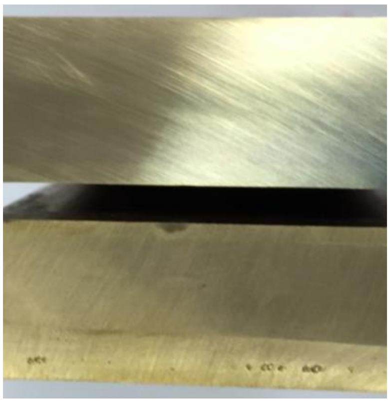

**Figure 17.** Polished cross section of brass welds performed with the nLIGHT alta™ 3 kW fiber laser (top) and with a legacy 3 kW fiber laser (bottom) showing the superior weld quality achieved with the nLIGHT alta™ fiber laser.

Finally, nLIGHT alta™ fiber lasers are being deployed in emerging applications that take advantage of its unique capabilities (high beam quality, rapid modulation and waveform generation), including fine processing, additive manufacturing, surface texturing, and processing of carbon fiber reinforced plastic (CFRP). The right photograph in Fig. 16 shows surface texturing of copper, and Fig. 18 shows an example of surface texturing and engraving of aluminum.

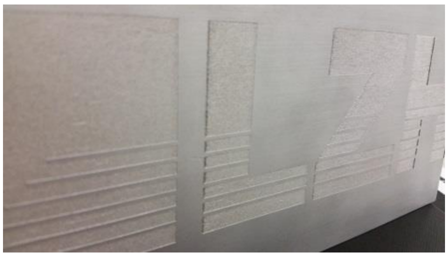

**Figure 18.** Example of aluminum surface texturing and engraving. This sample was provided by Laser Zentrum Hannover.

## 5. Conclusions

We have described the design and performance of the nLIGHT alta™ multi-kW industrial fiber laser. This system employs a unique architecture and provides industry-leading performance, resulting in significant advantages for processing a wide range of materials. Key features of nLIGHT alta™ fiber lasers include:

1. A novel approach to modularity that eliminates unnecessary redundancy of complex and expensive components, greatly simplifies field service, provides a cost-effective upgrade path (by simply scaling the pump power), and enables leveraging of the rapid innovation cycle of semiconductor-based pump diodes.
2. A robust back-reflection isolator that enables uninterrupted processing of highly reflective materials.
3. Vertical integration in high-performance, high-reliability components that have been extensively tested in industrial fiber lasers, diode-pumped solid state lasers, and direct diode lasers for > 10 years.
4. The best beam quality, highest modulation frequency, and fastest rise and fall times for an industrial multi-kW fiber laser.
5. Sensors for real-time process monitoring and control.

nLIGHT alta™ fiber lasers are currently available at output powers up to 4 kW. They have been deployed in challenging factory environments worldwide and have demonstrated unmatched performance, reliability, and uptime when processing a wide range of materials.

## References


[1] M. O'Connor and B. Shiner, "High-Power Fiber Lasers for Industry and Defense," in *High-Power Laser Handbook*, H. Injeyan and G.D. Goodno eds. (McGraw-Hill, New York, 2011), Ch. 18.

[2] L. Bao *et al*., "Reliability of High Power/Brightness Diode Lasers Emitting from 790 nm to 980 nm," in Proc. SPIE Vol. 8605 (Bellingham, WA, 2013), Paper 860523.

[3] M.D. Hemenway *et al*., "High-brightness, fiber-coupled pump modules in fiber laser applications," in Proc. SPIE Vol. 8961 (Bellingham, WA, 2014), Paper 8961-66.

[4] J.J. Koponen *et al*., "Progress in direct nanoparticle deposition for the development of the next generation fiber lasers," Opt. Eng. 50(11), 111605 (2011).

[5] L. Bao *et al*., "High Reliability and High Performance of 9xx-nm Single Emitter Laser Diodes," in Proc. SPIE Vol. 7918 (Bellingham, WA, 2011), Paper 7918-05.

[6] S.R. Karlsen *et al*., "100-W, 105-mm, 0.15NA Fiber Coupled Laser Diode Module," in Proc. SPIE Vol. 7198 (Bellingham, WA, 2009), Paper 7198-29; A. Brown *et al*., "Progress in commercial wavelength-stabilized high-brightness diode sources suitable for pumping Yb-doped fiber lasers," in Proc. SPIE Vol. 8039 (Bellingham, WA, 2011), Paper 8039-22.

[7] K. Price *et al*., "High brightness fiber coupled pump modules optimized for optical efficiency and power," in Proc. SPIE Vol. 8605 (Bellingham, WA, 2013), Paper 86050N.