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ABSTRACT

Next-generation industrial fiber lasers enable challenging applications that cannot be addressed with legacy fiber lasers. Key features of next-generation fiber lasers include robust back-reflection protection, high power stability, wide power tunability, high-speed modulation and waveform generation, and facile field serviceability. These capabilities are enabled by high-performance components, particularly pump diodes and optical fibers, and by advanced fiber laser designs. We summarize the performance and reliability of nLIGHT diodes, fibers, and next-generation industrial fiber lasers at power levels of 500 W – 8 kW. We show back-reflection studies with up to 1 kW of back-reflected power, power-stability measurements in cw and modulated operation exhibiting sub-1% stability over a 5 – 100% power range, and high-speed modulation (100 kHz) and waveform generation with a bandwidth 20x higher than standard fiber lasers. We show results from representative applications, including cutting and welding of highly reflective metals (Cu and Al) for production of Li-ion battery modules and processing of carbon fiber reinforced polymers.

Keywords: fiber laser, high power, kW material processing, pump diodes, Yb-doped fiber, metal cutting, welding, CFRP

1. INTRODUCTION

Fiber lasers are revolutionizing industrial materials processing by offering improved part quality while simultaneously lower manufacturing costs.[1] As a result, fiber lasers are replacing both laser and non-laser technologies in existing applications, and they are enabling new applications that cannot be addressed by previous technologies. Despite this success, users have identified several shortcomings of existing fiber laser sources, including:

- excessive back-reflection sensitivity, which causes frequent process interruptions, precludes processing certain materials or finishes, and can result in laser instability or damage; and
- limited serviceability, which causes excessive downtime and prevents tool integrators (i.e., fiber laser customers) from providing the desired level of service and support to end users.

Furthermore, many emerging applications require more advanced fiber laser performance, including:

- higher beam quality and beam shaping,
- faster modulation rates and rise and fall times,
- sophisticated waveform-generation capabilities, and
- wide power tunability with high stability.

We have introduced a line of next-generation industrial fiber lasers designed to address these requirements without sacrificing the unique benefits that have made fiber lasers so successful to date.

nLIGHT has provided high-performance components to laser manufacturers for 18 years. Specifically, we supply single-emitter semiconductor chips, fiber-coupled pump diodes based on these chips, and passive and active optical fibers. We leveraged this vertical integration in the design of our fiber laser product line, which was first released in March, 2015 and now spans the power range from 500 W to 8 kW. In the following sections, we describe the performance and reliability of our component technologies before discussing our next-generation fiber lasers. We then show results of representative applications that illustrate the ability of nLIGHT fiber lasers to meet the challenging requirements identified above.

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2. FIBER LASER COMPONENTS

nLIGHT manufactures single-emitter semiconductor chips[2], fiber-coupled pump diodes[3], and optical fibers.[4] These critical components are employed in defense and aerospace systems and in industrial fiber lasers, direct diode lasers, and diode-pumped solid state lasers worldwide, providing extensive performance and reliability data; they are the foundation of the nLIGHT fiber laser platform. Our components have been designed to handle the high optical irradiances and heat loads required for power scaling without the onset of parasitic nonlinear effects, fiber photodarkening, thermal runaway, or other processes detrimental to performance and reliability at high power. As a result, nLIGHT fiber lasers have offered the industry's highest power available from a single gain stage since they were introduced (originally 3 kW, now 4 kW). They provide several other performance and reliability advantages, as described in Section 3.

2.1 Semiconductor lasers

The majority of industrial fiber lasers are pumped by single-emitter-based pump diodes at 9xx nm, which provide the highest reliability, efficiency, and brightness. nLIGHT introduced the first fiber-coupled, multi-single-emitter semiconductor lasers in 2005 (nLIGHT® Pearl™).[5] We introduced a new generation of these lasers in 2013 (nLIGHT® element®)[6-9] to address the needs of high-volume applications, including pumping of fiber lasers and diode-pumped solid state lasers, by providing high brightness and efficiency in a compact package. Element pump diodes have been widely adopted throughout the laser industry, and they are employed in all nLIGHT fiber lasers. Pearl and element lasers are available at wavelengths between 640 nm and 1550 nm (including wavelength-locked options), fiber core diameters of 105 – 400 μm, and power levels up to 220 W.[10]

Increases in pump brightness [i.e., power / (area x solid angle)] have driven many of the advances in fiber laser power and performance over the past decades. Figure 1 shows the 9xx nm power available from a standard 105 μm fiber with a beam numerical aperture (NA) of ~0.15 as a function of time. The pump brightness has increased approximately exponentially. This dramatic progress has resulted from innovations in chip design, facet passivation, beam formatting and fiber-coupling optics, burn-in and screening methods, and manufacturing technologies and processes. For the past several years, nLIGHT has provided the highest-brightness pumps in the industry, including the two highest-power pumps in Fig. 1 (165 W and 200 W elements). We anticipate that the trend of increasing pump brightness will continue, and we recently demonstrated 315 W at 915 nm from a 105 μm fiber.[11]

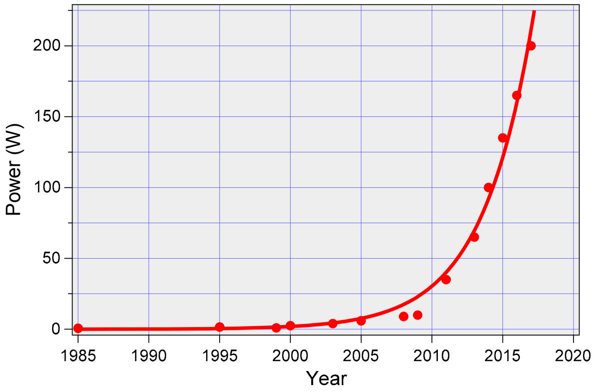


Figure 1. Power of 9xx nm fiber-coupled pump diodes with 105 mm fiber and ~0.15 beam NA vs. time from multiple manufacturers. The curve is an exponential fit to the data. The two highest-power data points correspond to nLIGHT element lasers.

Reliability is critical for industrial fiber lasers to minimize costly downtime and repair or maintenance costs. nLIGHT's chips have been extensively characterized in multi-cell life tests and achieve industry-leading reliability of >1,000,000 hr MTTF.[12] High-reliability chips are a necessary but not sufficient condition for production of high-reliability fiber-coupled pump diodes: Packaging and fiber-coupling of the chips can introduce new failure mechanisms, known as packaged-induced failure (PIF).[13] Unlike aging of semiconductor chips, accelerated testing is typically not applicable to PIF because the failure mechanism(s) lack accurate acceleration models. Extended life tests of packaged pumps are thus required to demonstrate reliability.

We have conducted numerous extended life tests of both Pearl and element lasers. Figure 2 shows a recent life test of eight e18 (200 W) elements, our highest-brightness pump diode. The elements were operated at an elevated package temperature of 40°C, corresponding to a chip acceleration factor of 31% with respect to the standard package temperature of 35°C.[9] The pumps started the life test at different times (different manufacturing batches) and were on test for between 2000 and 12,000 hr; a total of 144 chips were tested for a total of nearly 1,000,000 chip-hr. Key findings of this and previous life tests are:

- The only source of power degradation is failure of individual chips (the power steps evident in Fig. 2).
- No PIF is observed, i.e., the pump lifetime is determined by that of the high-reliability chips.

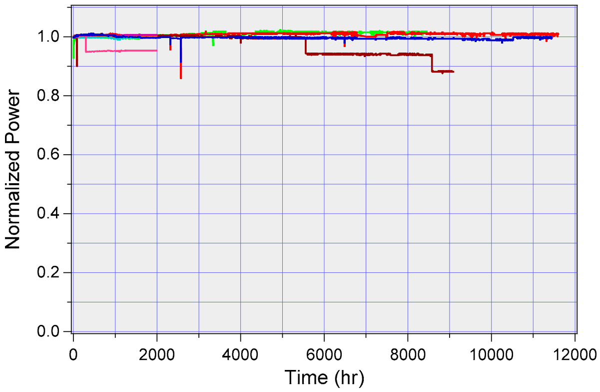


Figure 2. Life test of eight e18 element pump diodes (18 chips per package, 200 W, 105/125 fiber) operated at a package temperature of 40°C. The different test durations for the different pumps correspond to different start times. The three downward power steps correspond to three chip failures.

Lack of PIF is a notable benefit of nLIGHT pump diodes, ensuring long lifetime and graceful power degradation. A typical multi-kW fiber laser includes several hundred chips, so the occasional chip failure seen in Fig. 2 corresponds to a very gradual (sub-1%) system power degradation. Of course, the fiber laser can be recalibrated (diode current increased) to account for the gradual loss of pump power, further extending the service life of fiber lasers incorporating these pump diodes.

2.2 Fibers

A fiber laser includes many different types of fiber, including passive fibers, active (gain) fibers, single-mode and multimode fibers, photosensitive fibers (for writing fiber Bragg gratings), and glass-clad delivery fibers, as well as various fiber coatings to impart the desired optical and mechanical characteristics to the fibers. Of particular importance are the rare-earth-doped gain fibers, which convert the pump light to signal light and must operate with high efficiency, stability, and beam quality. Most industrial fiber lasers employ Yb-doped gain fibers that absorb 9xx nm pump light and lase in the 1060 – 1080 nm region. nLIGHT's Yb-doped fibers are manufactured using a proprietary process, Direct Nanoparticle Deposition (DND).[4] Most other fiber lasers employ Modified Chemical Vapor Deposition (MCVD). DND offers the advantages of:

1. high Yb concentration without photodarkening (a parasitic process that reduces the optical-to-optical efficiency), 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.

3. FIBER LASER PERFORMANCE

The advantages of nLIGHT fiber lasers can be classified into three categories with the following performance attributes:

1. Reliability
    a. Back-reflection isolation for processing reflective materials without restrictions.
    b. Stable output power over the full power range and including modulated operation.
    c. Reliable operation in harsh environment with minimal infrastructure requirements.
2. Programmability
    a. Wide power tunability.
    b. Fast modulation rate and response (rise / fall) times.
    c. Sophisticated waveform generation.
    d. High beam quality, configurable beam quality.
3. Serviceability
    a. Rapid field service.
    b. Serviceable by the system integrator.
    c. Serviceable in factory environments

In the following sections, we discuss attributes 1a, 1b, and 2a – c. The other attributes are discussed in Refs. 14 – 16.

3.1 Back-reflection isolation

Even for highly reflective materials, typical back-reflections are only a fraction of the laser output power because of work-piece surface irregularities, displacement of the back-reflecting surface from the beam waist, lack of precise alignment of the laser beam with the surface normal, and the limited collection angle of the process optics; furthermore, in many cases the back-reflection has a short duration (e.g., during piercing). Nonetheless, the design of legacy fiber lasers results in high sensitivity to back-reflections, resulting in laser instability or damage. Several mechanisms can cause damage from back-reflections; a common mechanism is deposition of optical power into polymer materials, which overheat and burn. Some fiber laser manufacturers suggest that users modify their beam alignment or cutting recipes to minimize back-reflections, but this approach is often inconvenient or impossible, can degrade performance (e.g., piercing speed), and offers only limited protection. Many fiber lasers employ software protection that disables the laser in the case of a back-reflection; this approach may protect the laser in some situations, but it precludes successful continuous material processing. Back-reflection sensitivity thus renders processing of reflective materials or surface finishes difficult or impossible.

All nLIGHT fiber lasers incorporate proprietary technologies to suppress back-reflections from the work piece, enabling uninterrupted processing of highly reflective materials. Back-reflected light that is coupled into the delivery fiber is stripped out and directed to a water-cooled beam dump where it is converted to heat without any interaction with polymers, thereby eliminating a primary damage mechanism. The design was validated by a high-stress life test, in which 100% of the output of a 1 kW fiber laser was back-reflected into the laser using a mirror. Typical back-reflection events have relatively short duration (e.g., metal piercing generates ms-scale back-reflections) and contain a fraction of the laser power, so the 100% cw test effectively corresponds to a highly accelerated condition. Despite this extreme level of back-reflection, the laser operated without any instability, damage, or shut-offs for 112 hr (Fig. 3). We know of no other laser that has been subjected to this level of back-reflection without damage.

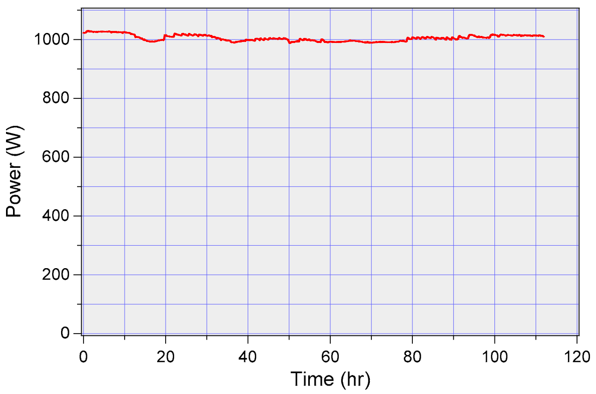


Figure 3. Back-reflection test showing the laser output power vs. time for a 1 kW fiber laser with 100% back-reflection into the feeding fiber. No laser interruptions, performance degradation, or damage were observed. The small power fluctuations result from changes in water temperature and beam sampling.

We further evaluated the performance of the isolation system in repetitive piercing tests (piercing is the portion of the cutting process that generates the highest back-reflection levels). In this test, we successfully performed 4900 consecutive pierces (a 70 x 70 array) in a 1/8” copper sheet with no interruptions, failed pierces, or laser damage. Numerous other real-world tests have demonstrated the efficacy of our back-reflection isolation system, and nLIGHT fiber lasers are routinely used to enable stable processing of highly reflective materials, including aluminum, brass, copper, silver, and gold.[17] Our effective back-reflection isolation also protects against process excursions, such as out-of-focus and loss-of-cut situations.

3.2 Power tunability and stability

nLIGHT fiber lasers are industry leaders in power stability, with a specification of ≤1% power variation (standard deviation / mean) over an 8 hr period. Furthermore, whereas the power stability specification of most lasers pertains only at full power, our specification pertains over the full power range of 5 – 100%. This excellent power stability specification ensures consistent processing performance and a wide process window, and it enables optimization for a variety of operations within a single tool.

Figure 4 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%). During any 8 hr subset of the data, the standard deviation was ~0.2%.

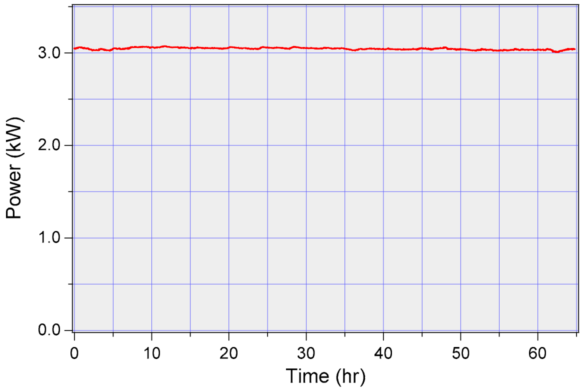


Figure 4. Continuous-wave stability test of a 3 kW fiber laser. The average power was 3.0 kW, and the standard deviation was 11 W (0.4%). In any 8 hr subset of the data, the standard deviation was ~0.2%.

Stability tests were also performed over a range of power levels and modulation settings that better represent real-world operating conditions:

- Figure 5 shows a stability test with the 3 kW fiber laser operating at 0.1 Hz modulation frequency 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%).

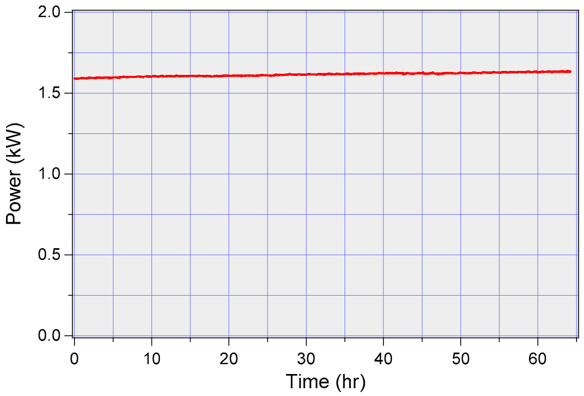


Figure 5. Modulated stability test (0.1 Hz, 50% duty cycle) of a 3 kW fiber laser. The average power is 1.6 kW, and the standard deviation is 12 W (0.7%).

- Figure 6 shows a stability test with a 700 W fiber laser operated at 37.1 W for nearly 9 hr. The standard deviation was 43 mW (0.12%).

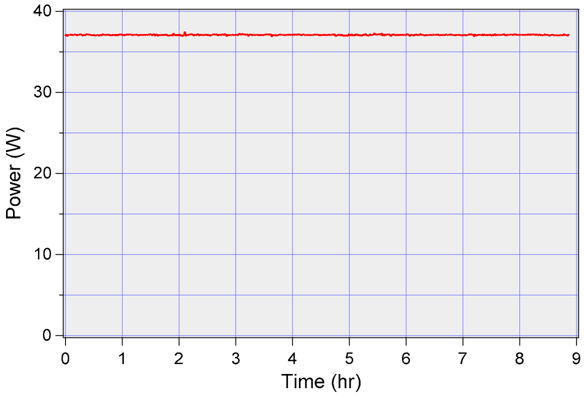


Figure 6.. Continuous-wave stability test of a 700 W fiber laser operated at ~5% power. The average power was 37.1 W, and the standard deviation was 43 mW (0.12%).

- Figure 7 shows a 28 hr power-cycling test of the 700 W laser. The laser was modulated with a 1 hr period and 90% duty cycle (54 min on / 6 min off). The left graph shows the full test, and the right graph shows an expanded view of 3 cycles. The standard deviation during the "on" portion of the cycles was 0.2%, including the small thermal overshoot after turn-on.

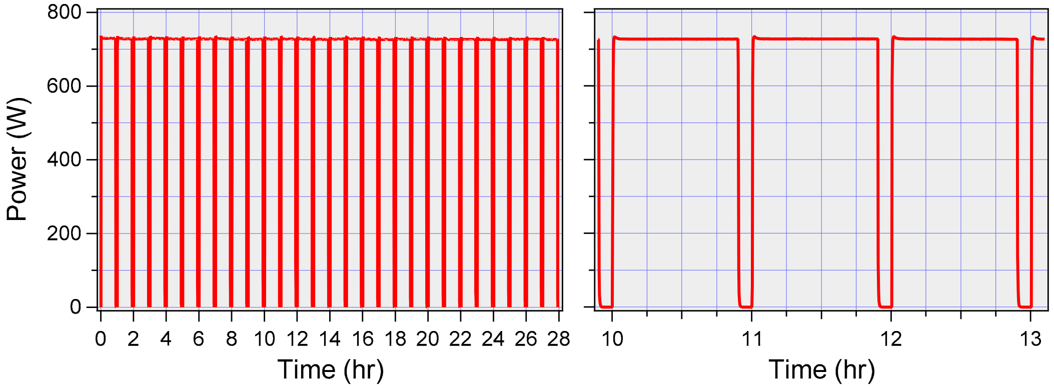


Figure 7. Modulated stability test (1 hr period, 90% duty cycle) of a 700 W fiber laser for 28 hr. The standard deviation during the "on" portion of the cycles was 0.2%. A small thermal overshoot is visible at the beginning of each "on" cycle and is included in the calculation of the standard deviation.

The above measurements, and similar tests performed on numerous nLIGHT fiber lasers, support our industry-leading power stability specification.

3.3 High-speed modulation and waveform generation

Most industrial multi-kW fiber lasers have a maximum modulation frequency of 5 – 10 kHz, with corresponding rise and fall times of 10's of µs. nLIGHT fiber lasers offer a maximum modulation frequency of 100 kHz, at least 10x faster. Figure 8 shows a 100 kHz waveform with a 50% duty cycle. The rise and fall times are ≤ 2 µs. The order-of-magnitude increase in modulation capabilities provided by nLIGHT fiber lasers enables more precise energy deposition and process control and optimization, and it enables rapid synchronization with external events or processes.

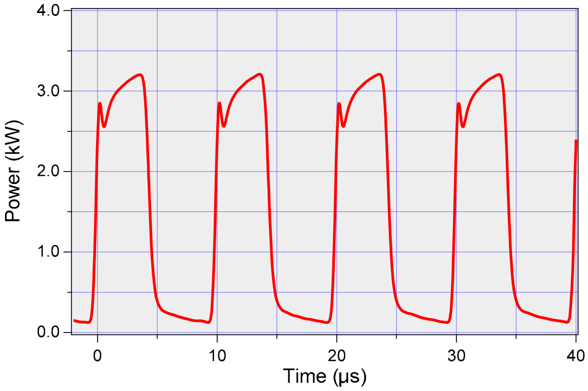


Figure 8. Optical waveform showing 100 kHz modulation (50% duty cycle) of a 3 kW fiber laser.

Users can employ the high-speed modulation capability of our fiber lasers to generate sophisticated waveforms that are unavailable from other industrial multi-kW lasers. For example, Fig. 9 shows a ~400 µs optical pulse with superimposed 10 kHz (left) and 20 kHz (right) modulation at 50% duty cycle. Figure 10 shows a saw-tooth waveform with superimposed 10 kHz modulation (left) and pulse packets with 500 µs duration and superimposed 12 kHz modulation (right). The waveforms shown in Figs. 9 and 10 were generated with the laser's hardware inputs (analog power control and digital gate), as described in the figure captions. We also provide a flexible waveform GUI to simplify generation of and synchronization with complex optical waveforms.

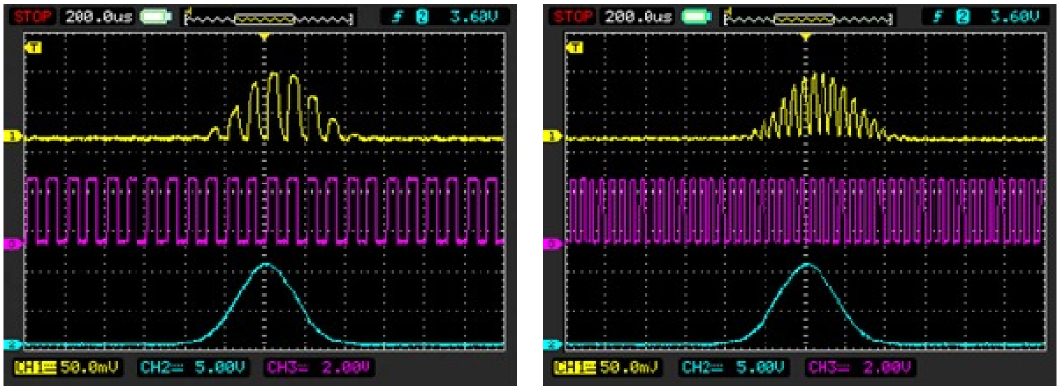


Figure 9. Oscilloscope traces showing optical waveform generation. The blue trace is the analog input voltage, which sets the laser power. The purple trace is the digital gate, which sets the modulation frequency and duty cycle. The yellow trace is the resultant optical waveform recorded with a photodiode.

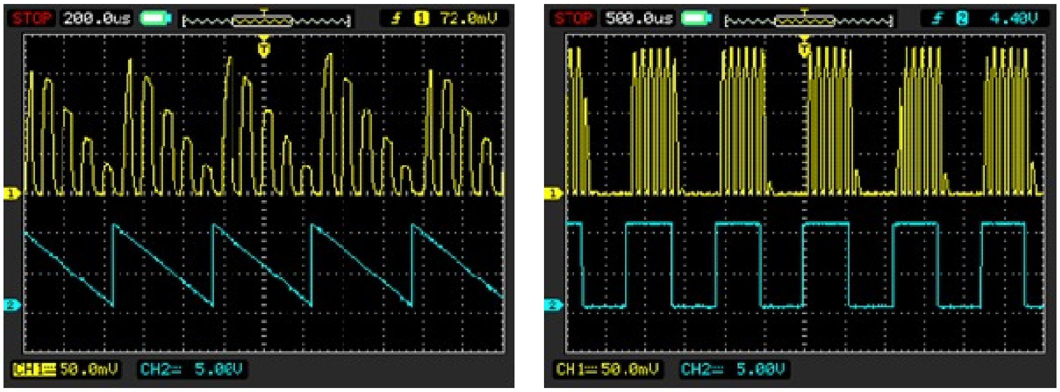


Figure 10. Oscilloscope traces showing optical waveform generation. The blue trace is the analog input voltage, which sets the laser power. For clarity, the digital gate waveform (similar to the purple traces in Fig. 9) are not shown. The yellow trace is the optical waveform recorded with a photodiode.

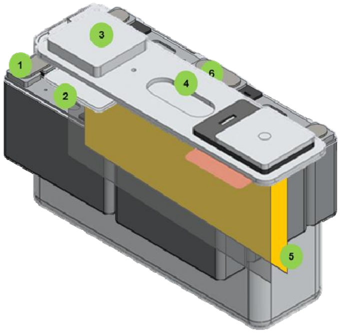
4. APPLICATION EXAMPLES

We present two applications that leverage the capabilities of nLIGHT fiber lasers described above:

1. Cutting and welding of reflective metals (Cu and Al) for Li-ion battery manufacturing, and
2. Processing of carbon fiber reinforced polymers (CFRP), which are increasingly used in the automotive and aerospace industries.

4.1 Li-ion battery demonstrator

The market for Li-ion batteries for electrical vehicles (EVs) is expected to grow from $2.5B at present to $14B in 2020, a 22% cumulative annual growth rate. The rapidly declining price of Li-ion batteries ($/kW-hr) is helping to drive widespread EV adoption. As summarized in Fig. 11, a number of critical manufacturing processes for Li-ion batteries entail processing of Cu and Al, including gas-assisted cutting, remote cutting, remote welding, and oscillation or stir welding. We partnered with Blackbird Robotics, Laser Mechanisms, Preco, and Precitec to demonstrate an entirely laser-based Li-ion battery manufacturing process flow.



	Process	Material
1	Foil sheet cutting	Cu, Al
2	Foil / Electrode stack weld	Cu-Cu, Cu-Al
3	Electrode joining	Cu-Al, Cu-Cu, Al-Al
4	Vent cap cut / weld	Al
5	Prismatic cell construction	Al-Al
6	Bus bar weld	Cu-Cu, Al-Al

Figure 11. Key processes associated with manufacturing of Li-ion batteries. A rendering of a battery cell is shown on the left, with numbers indicating the locations of the corresponding processes listed in the table.

Figure 12 shows collector tabs cut from 127 mm (0.005”) Cu and Al foils with our 4 kW fiber laser using a scanner-based (remote) cutting tool (Process 1 in Fig. 11). The cutting speeds were 4 m/min for Cu and 50 m/min for Al.

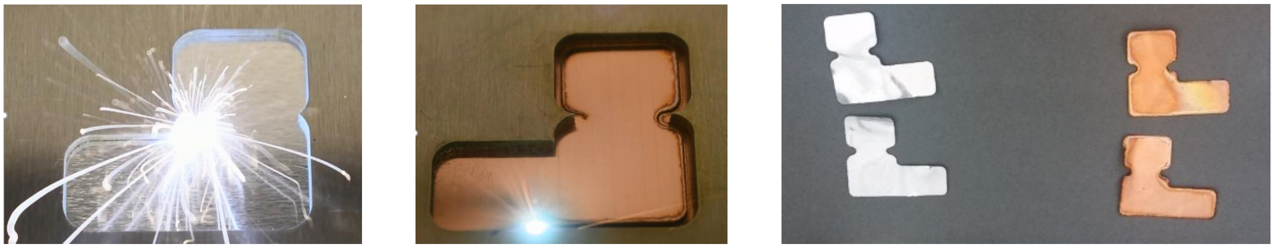


Figure 12. Collector tabs cut from Cu and Al foils. The first two images are frames from videos of the cutting process. The photograph on the right shows the finished parts.

Figure 13 shows remote welding of the collector tabs to the lid electrodes with our 2 kW fiber laser using a scanner-based (remote) cutting tool (Process 2 in Fig. 11). The welding speeds were 20 m/min for Cu and 45 m/min for Al.

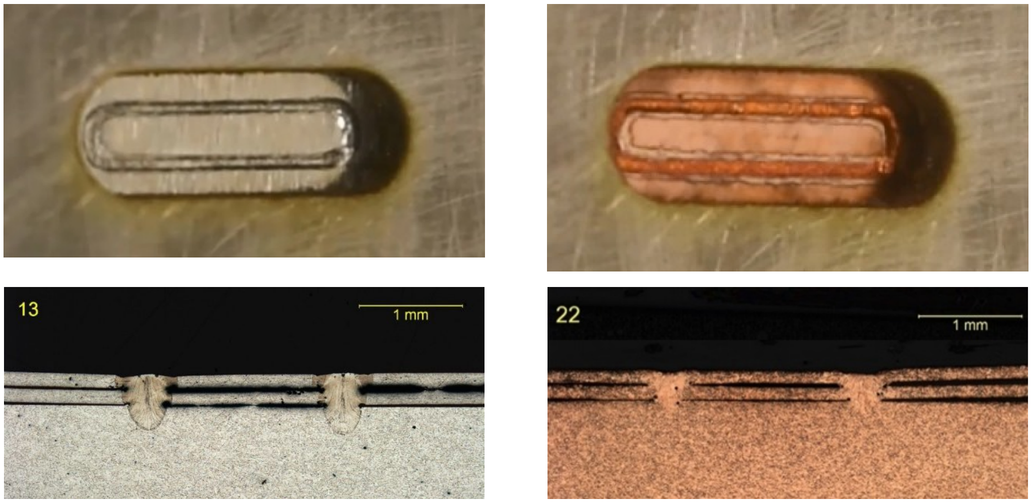


Figure 13. Photographs of stack-welded collector tabs showing top views (top images) and cross-sectional side views (bottom images).

nLIGHT fiber lasers were also employed for performing various Al welds (Process 5 in Fig. 11), including lid-to-case welding (Fig. 14) and structural welding of the individual cells into a module (Fig. 15).

Figure 14. Photographs of Al lid-to-case welding. The left image shows a frame from a video of the welding process, the top-right image shows a finished cell, and the bottom-right images shows a magnified view of the weld cross-section.

Figure 15. Photographs of the Li-ion cells assembled into a battery module.

In related work, remote cutting of coated Al foils was demonstrated using our 1.2 kW single-mode fiber laser (Fig. 16). The excellent beam quality of this single-mode source enables rapid single-pass cutting speeds with negligible effects on the electrode coating.

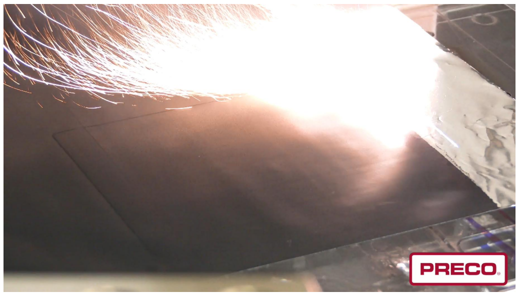


Figure 16. Photograph of remote cutting of coated Al foil using a 1.2 kW single-mode fiber laser.

This project convincingly demonstrates that fiber-laser-based processing will enable rapid scaling of Li-ion battery production with lower costs, increased flexibility, and more consistent quality.

4.2 CFRP processing

CFRP is used in the automotive, aerospace, and sporting goods industries because it offers high strength and light weight. CFRP has been adopted by multiple automobile manufacturers to help meet increasingly stringent fuel efficiency standards. Two critical CFRP processes are cutting and patching (or scarfing):

- Cutting entails fabricating 2-dimensional or 3-dimensional shapes in cured fiber + resin structures.
- Patching entails selectively removing material, usually without piercing the part, and preparing the surface to allow adhesion of the patch with new resin. This process is usually performed manually with a grinder, which is a slow and high-risk operation requiring skilled personnel.

Developing laser-based CFRP processes would provide higher speed, higher consistency, and lower costs.

Laser-based processing of CFRP is challenging because of the different material properties with the part: The carbon fibers have a high heat conductivity and high vaporization temperature, whereas the polymer matrix has low heat conductivity and a low melting or decomposition temperature. As a result, laser-processed CFRP parts can experience damage or a change in structural properties in the heat-affected zone (HAZ).

Laser Zentrum Hannover has demonstrated successful CFRP processing using our 3 kW fiber laser in a remote processing system based on a rapid scanner. For example, Fig. 17 (left) shows multi-pass cutting of a 2 mm CFRP sheet with minimal HAZ. The scan speed was 6 m/s, and 30 passes were used to perform the cut, resulting in a net cutting speed of 0.2 m/s for the full sheet thickness. Figure 17 (right) also shows a part prepared for patching in which material removal to different depths was demonstrated.

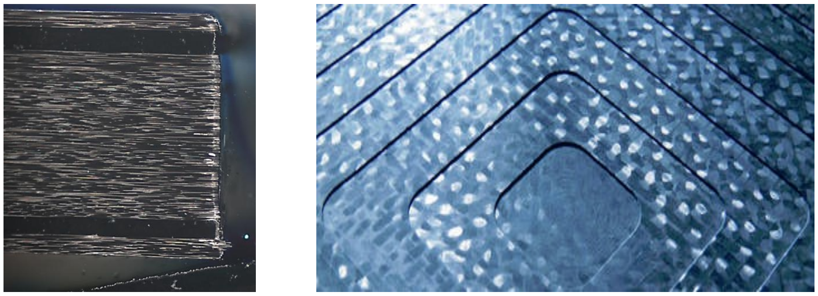


Figure 17. Photographs of CFRP parts processed with a 3 kW fiber laser: multi-pass cutting of a 2 mm sheet (left), and preparation of a part for patching (right) showing selective material removal.

5. CONCLUSIONS

nLIGHT has introduced a line of next-generation industrial fiber lasers that addresses key shortcomings of legacy lasers, enabling them to meet the demanding needs of both existing and emerging applications. We have shown how the unique design and high-performance components incorporated into these lasers provide levels of performance and reliability that were unattainable with legacy technologies. Advantages in reliability, programmability, and serviceability of nLIGHT fiber lasers were illustrated by industry-leading specifications for back-reflection protection, power tunability and stability, and high-speed modulation and waveform generation capabilities. We showed example applications of Li-ion battery production (cutting and welding of highly reflective materials) and CFRP processing. Rapid innovation in the critical component technologies and laser designs will continue to drive dramatic advances in fiber laser performance and reliability.

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