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ABSTRACT

Industrial lasers used for materials processing have become essential tools in a wide array of applications, including cutting, welding, drilling, cladding, marking, hardening, and additive manufacturing. The speed, quality, and process window are determined in part by the laser beam properties such as beam size, shape, and divergence. nLIGHT® has developed a new multi-kilowatt fiber laser, Corona™, that provides rapid tunability of the beam characteristics directly from the laser output fiber using a novel, all-fiber mechanism. Programmable beam shapes include flat top and donut beams with beam diameters from 100 µm to 390 µm and beam parameter products from 3 to 20 mm-mrad (M^2 values from 9 to 59). We describe the Corona fiber laser performance and show processing results and advantages of specific beam shapes for sheet-metal cutting, the largest industrial laser application.

Keywords: Variable beam, fiber laser, laser cutting, laser welding

1. INTRODUCTION

Lasers have become indispensable tools for materials processing, manufacturing, sensing, defense, and scientific applications. This success has been driven by laser performance improvements in several areas, including average and peak powers, wavelength coverage, temporal versatility (pulse duration and frequency, sophisticated waveforms), efficiency, power stability, long-term reliability, maintenance requirements, and operating costs. Fiber lasers have been particularly important in enabling several of these advances and now dominate many of the highest-volume industrial and microfabrication applications. In addition to their inherent efficiency and reliability, fiber lasers naturally enable fiber delivery to the process head, minimizing the burden of free-space optics in the laser and the machine tool.

In contrast to the other important laser properties, the beam spatial characteristics of conventional lasers remain relatively unoptimized and inflexible. Some applications require diffraction-limited beam quality (a near-Gaussian spatial profile with $M^2 \approx 1$), whereas others require lower beam quality and different beam shapes (near-field spatial profiles), divergence profiles, and propagation characteristics. Even within a given application, different beam properties may be required to optimize different process steps. Because the beam characteristics of most lasers are fixed, tool integrators and end users must either add components that provide beam tunability or accept limited tool capabilities and versatility. The former approach adds complexity and cost and/or degrades tool performance and reliability. The latter approach results in a limited job mix and can require the purchase of multiple tools. Development of a laser with tunable beam characteristics would address this longstanding need, enabling much more capable and versatile tools for a wide range of materials processing applications.

1.1 Applications of variable beams for metal processing

The laser beam shape influences heat deposition and temperature gradients in the workpiece. The non-uniform irradiance profile of Gaussian and other peaked beams can result in over- or under-processing of regions within the illuminated zone. A flat-top beam can mitigate this problem by delivering uniform irradiance. Annular beams and beams with a halo or pedestal surrounding the main beam are also known to improve processing quality in some applications.

In metal cutting, for example, a small beam with relatively high beam quality provides the highest speed for thin material, but the maximum thickness is limited by the resultant narrow kerf, which impedes ejection of the melt. A larger and more divergent beam (lower beam quality) allows cutting of thicker plate, with a corresponding speed penalty for thin sheet. A metal cutting tool with a small beam will thus be unable to cut thick plate, whereas a tool with a large beam

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will not be economical for cutting thin sheet. Furthermore, different beam shapes are optimum for different process steps. For instance, the piercing rate for thick metal can be increased significantly using a small beam, with the cutting speed or edge quality of the subsequent cut being optimized with a larger beam.

In welding, the beam irradiance profile determines weld penetration depth and width. High beam quality generates deep-penetration “keyhole” welds for the highest productivity on thick joints, whereas larger, lower-beam-quality spots generate shallow conduction welds for smooth esthetic joining of thin parts. An optimized beam shape can reduce spatter, porosity, and cracking and can provide improved stability and cosmetics.

In additive manufacturing with metal powders, different features sizes (width and height) and different materials require different beam characteristics to optimize the build rate and part quality. The optimum beam shape depends on the required spatial resolution and the heat-transfer rate within the workpiece.

1.2 Approaches for beam tunability

Most lasers provide fixed beam characteristics. The beam can be transformed to a different format by refractive, reflective, or diffractive optical systems. Approaches that provide some level of beam tunability include process heads with changeable optics, zoom lenses, switchable diffractive optical elements, deformable mirrors, beam combiners, and (for fiber-delivered lasers) fiber-to-fiber couplers and switches with motorized optics. These free-space optical approaches entail several drawbacks:

- Sensitivity to misalignment, contamination, and environmental conditions (temperature, vibration).
- Increased system cost and complexity.
- Optical loss.
- Thermal lensing in high-power applications, causing power-dependent changes in beam quality and focus position.
- In the case of manually changeable optics, loss of productivity and contamination risk.
- In the case of a zoom lens, increased size and weight of the process head.

To address the problems inherent to free space optics, fiber-based beam combination has been used to provide limited beam tunability. In these systems, the feeding fiber typically consists of a central core and a surrounding annular core, with different lasers launched into these two cores via a fused-fiber combiner. This approach has the advantage of eliminating free-space optics, at the cost of other drawbacks:

- Significant cost is incurred because the full laser power is unavailable in all but one of the beam settings, meaning that the end user is forced to purchase more laser power than is typically employed for their process.
- The division of power between the regions is “hardwired” when the laser is manufactured and cannot be changed to accommodate different processes or materials, limiting the versatility of the tool.
- The available beam shapes are limited. For example, this approach provides one annular beam size and shape. Obtaining different annular beams would require addition of a zoom lens or other optics, negating the primary benefit of the beam-combination technology.

Because available options providing beam tunability entail significant compromises in tool complexity, cost, performance, versatility, and reliability, most laser-based tools still employ a fixed beam, resulting in nonoptimal performance and/or a limited job mix. Some shops purchase multiple tools optimized for different tasks to address their range of processing needs.

1.3 All-fiber variable beam laser

nLIGHT recently released a new fiber laser, Corona™, that provides rapidly tunable beam quality at multikilowatt power levels. These fiber lasers employ a novel, all-fiber technology to deliver a wide range of beam shapes and sizes directly from the laser output fiber. Several Corona-enabled metal cutting tools have been introduced by leading tool integrators. Corona’s all-fiber mechanism includes the following components:

1. A feeding fiber that is segmented into multiple guiding regions. For example, the representative design shown in Figure 1 (left) uses a three-zone feeding fiber consisting of a central core with 100 µm diameter, an annular core with 200 µm outer diameter, and another annular core with 300 µm outer diameter. The beam shape is tuned by varying the partitioning of the laser power among these regions.
2. A length of the fiber that enables the beam to be shifted radially via application of a perturbation, resulting in tunable beam partitioning among the guiding regions, as shown in the beam propagation method (BPM) simulations in Figure 1 (right).
3. A perturbation mechanism to shift or adjust the beam. Several effective perturbation mechanisms have been identified, including microbending, macrobending, stretching, acousto and electro-optic perturbation, thermal variation, and others. Corona fiber lasers use a proprietary mechanism that has been shown to be both highly stable and reliable, as shown below.

The number and dimensions of the guiding regions and the beam partitioning among them can be optimized for different applications.

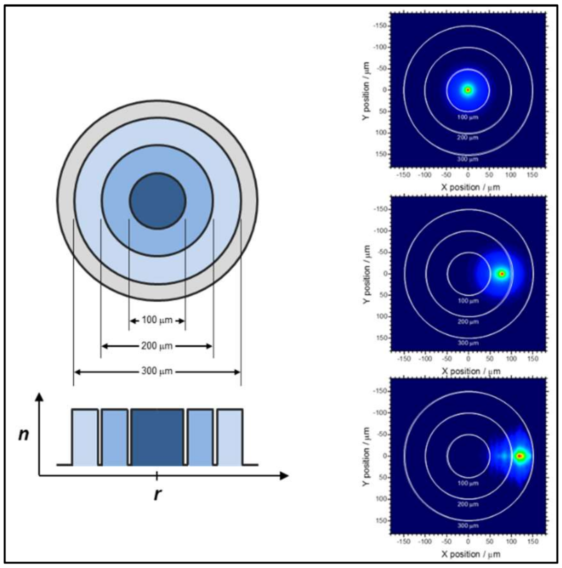


Figure 1. Shown at left is the fiber cross-section (top) and refractive index profile (bottom) for a feeding fiber with three guiding regions. Simulations (right) show the beam profile coupled into the guiding regions for different perturbation conditions. The beam homogenizes azimuthally within a guiding region as it propagates in the fiber.

The Corona mechanism can provide continuous tuning of the beam characteristics, with the full laser power available for each beam setting. It has been found that supplying a certain number of predefined beams (“Index” settings) is preferable to continuous tuning for process optimization and tool stability. Industrial lasers are frequently deployed in electrically noisy environments, in which analog control signals can be unstable on a variety of timescales. By providing fixed beam settings, the end user is ensured that their laser performance will be stable for years.

2. CORONA BEAM CHARACTERISTICS

2.1 Beam characteristics

Figure 2 shows typical beam settings used in sheet-metal cutting tools for Corona laser configurations with three guiding regions (left) and two guiding regions (right) at 4 kW and 12 kW, respectively. Beam parameters were characterized using a Dataray WinCamD-LCM beam profiler.

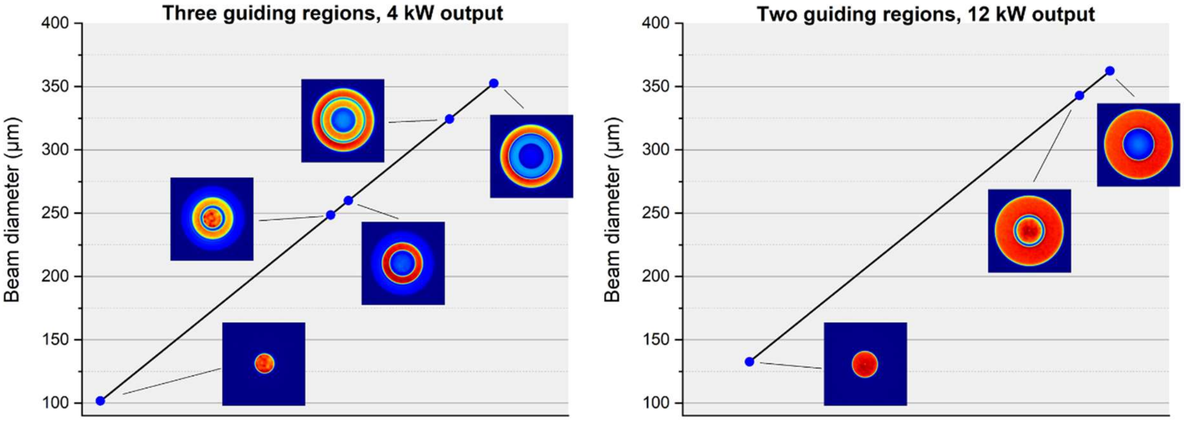


Figure 2. Typical Corona beam settings used in sheet-metal cutting tools for feeding fibers with three guiding regions (left) and two guiding regions (right). The second-moment beam diameters are given on the y-axis, and the images show near-field spatial profiles recorded at 4 kW for the three-region configuration and at 12 kW for the two-region configuration.

For the three-zone design, the five selected beam shapes correspond to a 100 µm flat-top (outside diameter), 200 µm flat-top, 200 µm donut, 300 µm thick-walled donut, and 300 µm thin-walled donut. The corresponding beam diameter and beam parameter product (BPP) values are listed in Table 1. The wide dynamic range in beam size and shape evident in Figure 2 is unattainable with any other practical technology.

Table 1. Second-moment beam diameters and BPP values for a typical three-zone Corona fiber laser recorded at 4 kW.

Beam description	Near field beam diameter (µm)	BPP (mm-mrad)
Small diameter, flat-top	101.7	2.9
Medium diameter, flat-top	248.5	13.5
Medium diameter, thin-walled donut	259.9	12.7
Large diameter, thick-walled donut	324.4	18.3
Large diameter, thin-walled donut	352.6	17.8

2.2 Switching time

The switching time was characterized with a high speed 900 Hz line-scan camera and shown to be less than 30 ms for the full range of beam size as shown in Figure 3. There is an initial internal communication delay of ~10 ms, followed by a switching time of another ~10 ms. The beam size is stable immediately following the switching event (i.e., no settling time is required). The laser maintains full-power operation while switching with no need for blanking.

Corona’s rapid tuning of the beam characteristics enables adjustments on-the-fly and optimization of the tool not just for different materials or thicknesses, but also for different process steps (for example, piercing vs. cutting, or straight cutting vs. cornering). In conventional fiber lasers, the power and modulation conditions can be varied to optimize the process, but the beam characteristics remain fixed. In Corona fiber lasers, the beam characteristics can be tuned, independently or simultaneously with the power and modulation conditions, to provide much greater versatility for process control and optimization.

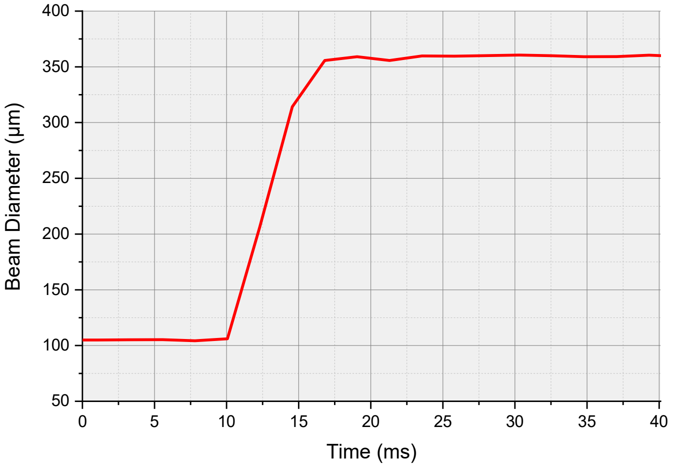


Figure 3. Near-field measurement of the second-moment beam diameter while switching between the smallest and largest beam settings for a 4 kW Corona fiber laser with a three-zone feeding fiber.

2.3 Reliability

Figure 4 shows the results of an accelerated life test, in which a Corona fiber laser was repetitively cycled through its six Index settings, with a 100 ms dwell at each setting. The test duration was 13.4 million Index changes, corresponding to >36-year operation for a tool with 1000 Index changes per day. The beam diameters for all Index settings remained stable to within ±3% (dominated by measurement uncertainty) throughout the test, with no drift or degradation. Corona fiber lasers thus maintain the stability and reproducibility of conventional fiber lasers with fixed beam characteristics.

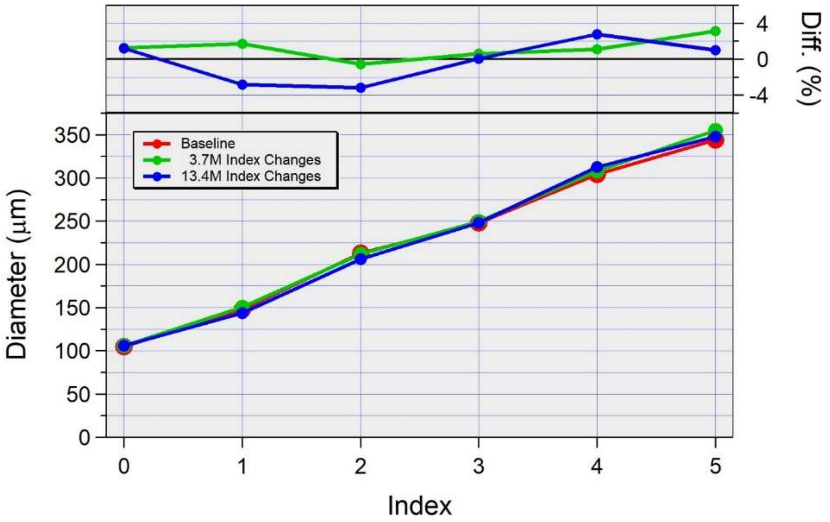


Figure 4. Results of accelerated life testing showing change to second-moment beam diameters after 3.7 million and 13.4 million Index transitions.

3. METAL CUTTING RESULTS

Cutting tests were performed at nLIGHT's applications laboratory in Vancouver, Washington, USA and the results have been validated and extended by leading tool integrators. For the cutting tests shown below, we used a 4 kW Corona laser with three guiding zones. A Cincinnati CL-900 laser cutting tool with a Laser Mechanisms FiberCUT® 2D processing head (100 mm focal length collimator, 150 mm focal length focusing lens, 0.14 NA) was used for the cutting tests. The following results were observed:

1. As expected, Index 0 provides cutting speed and edge quality similar to conventional fiber lasers with 100 μm feeding fibers. This setting is typically employed with thin sheet to maximize cutting speed.
2. For cutting of stainless steel and aluminum with N_2 assist gas, Index 1 and 2 can provide better edge quality with a small speed penalty. The edge quality can be even better than that provided by higher-power conventional fiber lasers. The versatility of Corona-enabled cutting tools allows the end user to optimize the part specifications and cost for the specific application and material.
3. For cutting mild steel (MS) with O_2 assist gas, Indexes 3 and 4 greatly increase the maximum thickness and process window at a given laser power. Furthermore, Corona provides significantly better edge quality than can be achieved with conventional fiber lasers (even at higher power levels), matching that of CO_2 lasers.

The third observation is particularly significant. Oxygen cutting of MS is the largest application for high-power lasers. Although fiber lasers now dominate this market, CO_2 lasers are still preferred for cutting thick plate (greater than ~10 mm) because they provide higher edge quality (reduced roughness and better straightness and perpendicularity). The maximum thickness addressed by fiber lasers has been increasing, largely by using higher laser power, but this approach increases up-front and operating costs, places significant demands on the cutting head, and still does not achieve the edge quality of CO_2 lasers. By providing CO_2-like edge quality for thick MS, Corona fiber lasers eliminate the last processing advantage of CO_2 lasers for metal cutting.

Figures 5 and 6 show a comparison of the cutting performance of 4 kW conventional and Corona fiber lasers for O_2 cutting of MS plate between 6.7 and 25.4 mm. The cutting speed is similar for both lasers, but the edge roughness is typically 2–3X lower for Corona, with a much lower dependence on thickness. This high edge quality reduces or eliminates the need for costly and time-consuming post-processing steps. Tool integrators have found that the edge quality and process window for 4 kW Corona fiber lasers are better than those for a 6 kW standard fiber laser. Furthermore, the maximum thickness that can be reliably cut (clean part drop) is 30% larger with the Corona fiber laser.

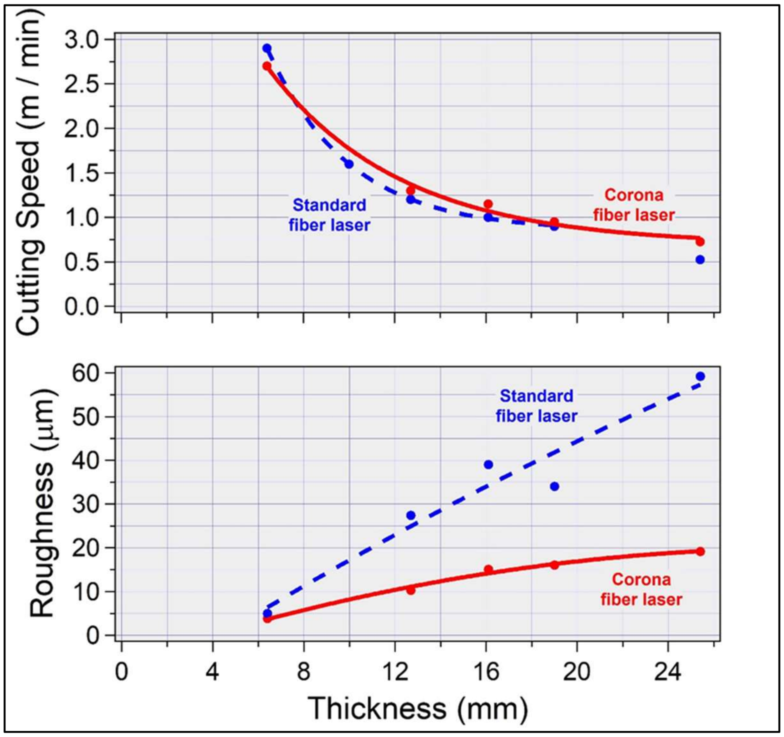


Figure 5. Cutting speed and cutting edge roughness are plotted against thickness of mild steel for a variety of material thicknesses with a standard fiber laser with 100 µm fiber output and a Corona variable beam laser at optimized beam Index settings.

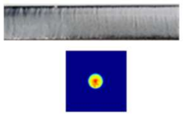
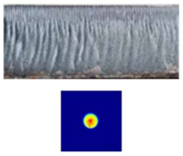
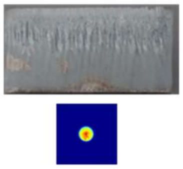
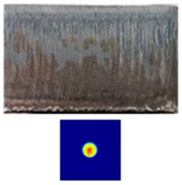
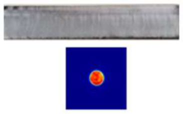
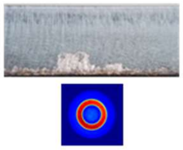
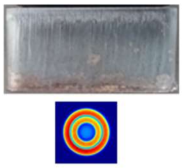
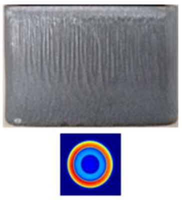
	6.7mm	12.7mm	19.0mm	25.4mm
Standard fiber laser				
Corona fiber laser				

Figure 6. Photos showing variation in edge quality of mild steel between a 4 kW standard fiber with 100 µm feeding fiber and a 4 kW Corona laser at optimized beam Index settings.

The above results have been verified and extended by several leading tool integrators, and Corona-enabled cutting tools are now available on the market.

4. CONCLUSION

The availability of a practical, all-fiber, highly reliable laser with rapidly tunable beam quality has opened a new dimension for materials processing and has already proven to be of significant value for metal cutting, the largest market for high-power lasers. The ability to precisely control and vary heat deposition into the workpiece in real time enables development of tools with much higher performance, productivity, and versatility for a wide variety of existing and emerging applications.

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