Tuned in

by Dahv A.V. Kliner, senior director, industrial fiber lasers; Roger L. Farrow, senior fiber laser engineer; and Brian Victor, director of industrial lasers, nLight Inc.

Fiber laser breakthrough enables all-fiber tunable beam quality

From Lasik eye surgery and DVD players to the mouse on everyone's desk, lasers are a ubiquitous aspect of everyday life. They've risen to the point of being indispensable tools – for materials processing, manufacturing, sensing, defense and scientific applications. But their widespread success has not been by happenchance. It has been driven by a multitude of performance improvements over the past several years.

Those improvements can be found in a range of categories, including a laser's average and peak powers, wavelength coverage, temporal versatility (pulse duration and frequency, sophisticated waveforms), efficiency, power stability and long-term reliability. Lower maintenance requirements and operating costs have also contributed to the technology's proliferation.

Fiber's role

Fiber lasers, in particular, have dominated many of the highest volume industrial and micro-fabrication operations. Beyond 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 as well as the machine tool.

Although fiber lasers offer several beneficial properties, the beam spatial characteristics remain relatively unoptimized and inflexible.

The nLight Corona fiber lasers allow for rapid tuning of spot size and beam shape, optimizing performance across all metals and thicknesses.

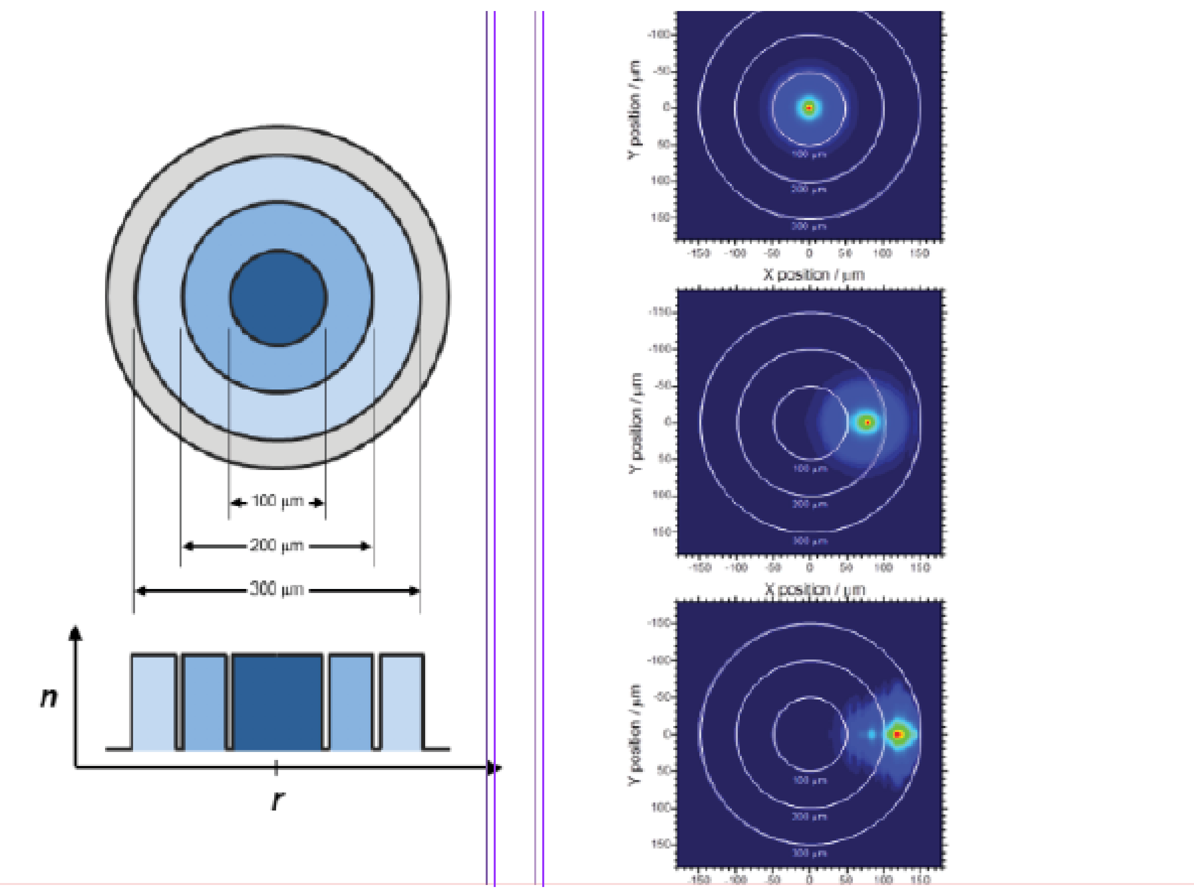


Figure 1. On the left, a fiber cross section (top) and refractive index profile (bottom) for a feeding fiber with three guiding regions. On the right, simulations showing the beam profile coupled into the guiding regions for different perturbation conditions. The beam homogenizes azimuthally as it propagates in the fiber.

Some applications require diffraction-limited beam quality while others require lower beam quality, different beam shapes, divergence profiles and propagation characteristics.

Put simply, in metal cutting, a small beam with relatively high beam quality provides the highest speed for processing thin material. But for thicker materials, the small kerf impedes ejection of the melt. A larger and more divergent beam (lower beam quality) allows cutting of thicker plate, but comes with a speed penalty for thin sheet.

A similar situation exists in laser welding where high beam quality generates deep-penetration keyhole welds on thick joints, and larger, →

The ability to tune the beam characteristics is a highly desirable capability, which could enable process optimization and tool versatility.

lower beam quality spots generate shallow conduction welds for smooth, aesthetic welds on thin parts. Beam shape also influences heat deposition and temperature gradients in the workpiece while also preventing over- or under-processing.

Most lasers provide fixed beam characteristics where the beam can only be transformed by a refractive, reflective or diffractive optical system. This means that laser-based tools with fixed beam systems can only address a limited range of processes or materials and thus suffer from compromised performance or a restricted job mix. For example, a sheet metal cutting tool with a small beam is unable to cut thick plate whereas a tool with a large beam is not economical for cutting thin sheet.

Knowing this, the ability to tune the beam characteristics is a highly desirable capability, which could enable process optimization and tool versatility. Various approaches have been developed that allow for some

level of beam tunability, including zoom lenses and switchable diffractive optical elements, such as deformable mirrors, beam combiners, and (for fiber-delivered lasers) fiber-to-fiber couplers and switches with motorized optics. These free-space optical approaches, however, have several drawbacks, including:

- Sensitivity to misalignment, contamination and environmental conditions, such as temperature or 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 a zoom lens, increased size and weight of the process head

To address the problems inherent to free-space optics, fiber-based beam combination technology 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. While this approach has the advantage of eliminating free-space optics, it does have 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" 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 the 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.

Beam breakthrough

To address the shortcomings of other available options, nLight Inc. developed its Corona fiber laser that provides rapidly tunable beam quality at multi-kilowatt power levels. The fiber laser employs a novel, all-fiber technology to deliver a range of beam shapes and sizes directly from the laser output fiber. In response, several Corona-enabled metal cutting tools have been introduced by leading tool integrators, achieving unprecedented levels of performance and versatility. Corona fiber lasers are currently available at 3 kW to 4 kW and have been demonstrated up to 14 kW.

The lasers include the following components:

- A feeding fiber that is segmented into multiple guiding regions.

For example, the representative design shown in Figure 1 employs a three-zone feeding fiber consisting of a central core with a 100-micron diameter, an annular core with a 200-micron outer diameter and another annular core with a 300-micron outer diameter. The beam shape is tuned by varying the partitioning of the laser power among these regions.

- A length of the fiber that enables the beam to be shifted radially via →

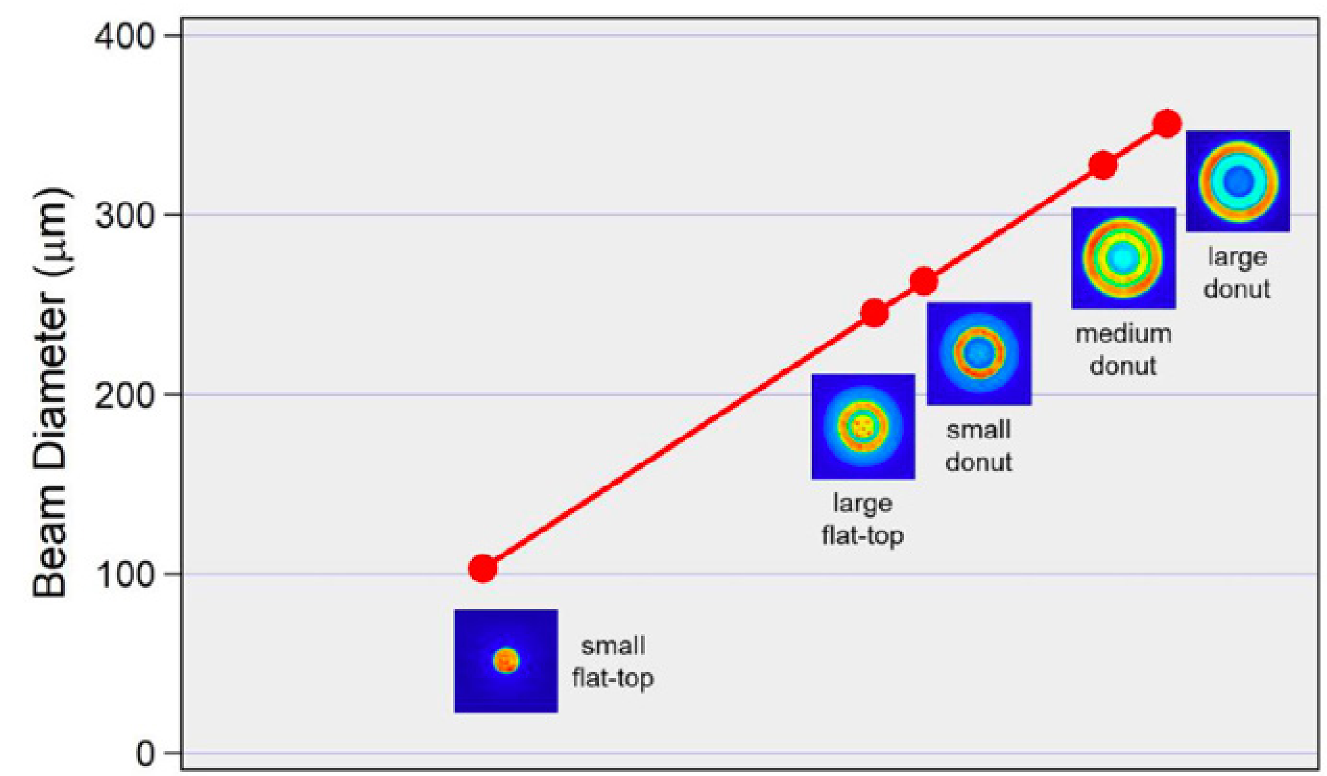


Figure 2. Typical Corona beam settings used in sheet metal cutting tools. The 2nd-moment beam diameters are given on the Y axis, and the images show near-field spatial profiles recorded at 4 kW.

application of a perturbation, resulting in tunable beam partitioning among the guiding regions, as shown in the simulations in Figure 1.

- A perturbation mechanism to shift or adjust the beam. The company has identified several effective perturbation mechanisms, including micro-bending, macro-bending, stretching, acousto- and electro-optic perturbation, thermal variation and others. Corona fiber lasers employ a proprietary mechanism that has been shown to be highly stable and reliable, which also can be seen in Figure 1.

The Corona mechanism provides continuous tuning of the beam's characteristics with the full laser power available for each beam setting. Supplying each product with a certain number of pre-defined beams (known as "index" settings) has been found to be preferable to continuous tuning for process optimization and tool stability.

Because industrial lasers are often found in electrically noisy environments, analog control signals can be unstable on a variety of timescales. By providing fixed beam settings, users can feel confident that their laser performance will be stable for years.

As seen in Figure 2, the typical Corona beam settings for use in sheet metal cutting tools are programmable between approximately 100 microns and 350 microns (2nd-moment definition). The five selected beam shapes correspond to a 100-micron flat-top (outside diameter), 200-micron flat-top, 200-micron donut, 300-micron thick-walled donut and 300-micron thin-walled donut. The wide dynamic range in beam size and shape evident in Figure 2 is unattainable with any other practical technology.

Additionally, the Corona switching time is less than 30 ms for the full range of beam sizes, and the laser maintains full-power operation while switching with no need for blanking. This rapid tuning of the beam characteristics enables on-the-fly adjustments and optimization of the tool not just for different materials →

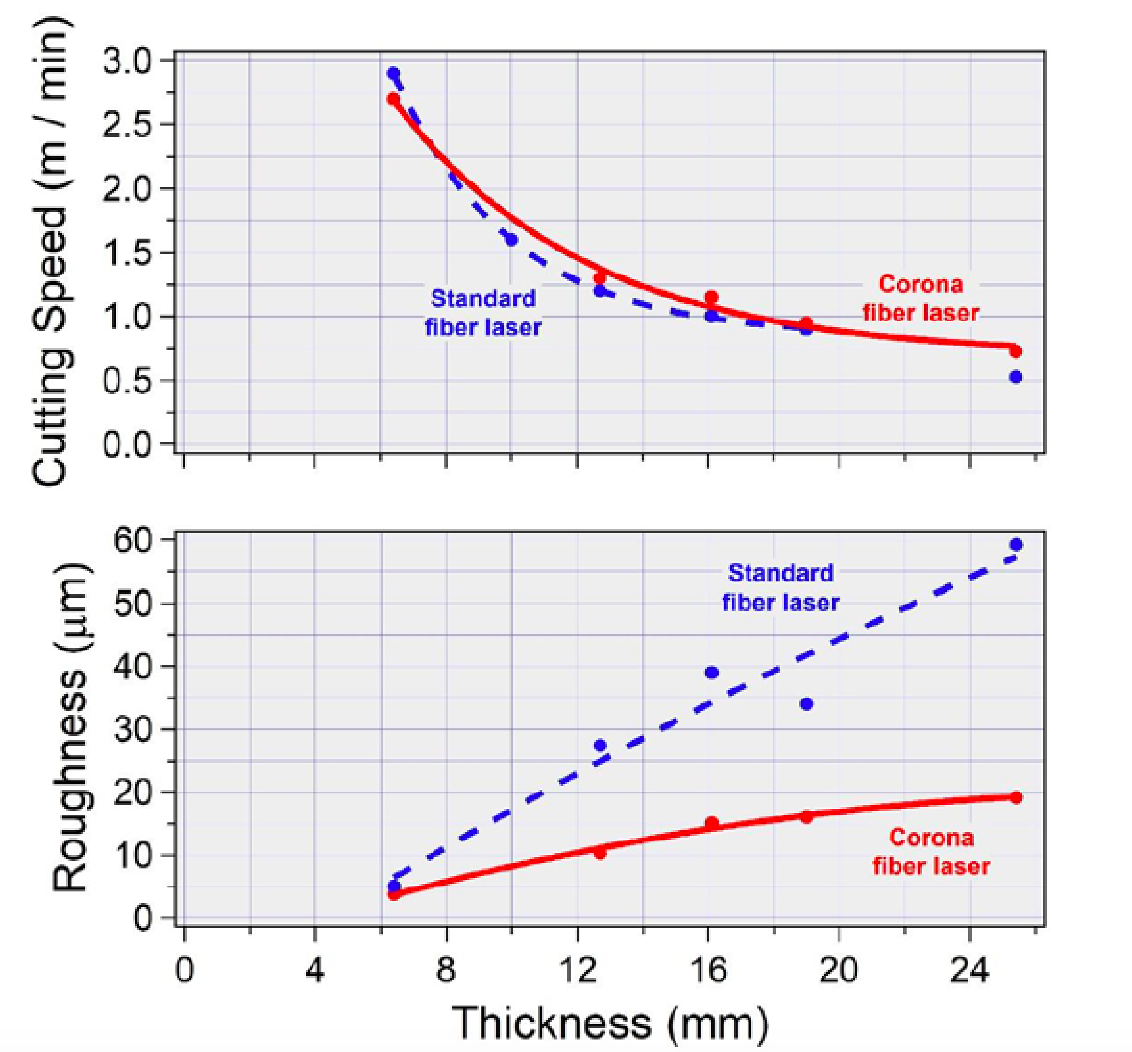
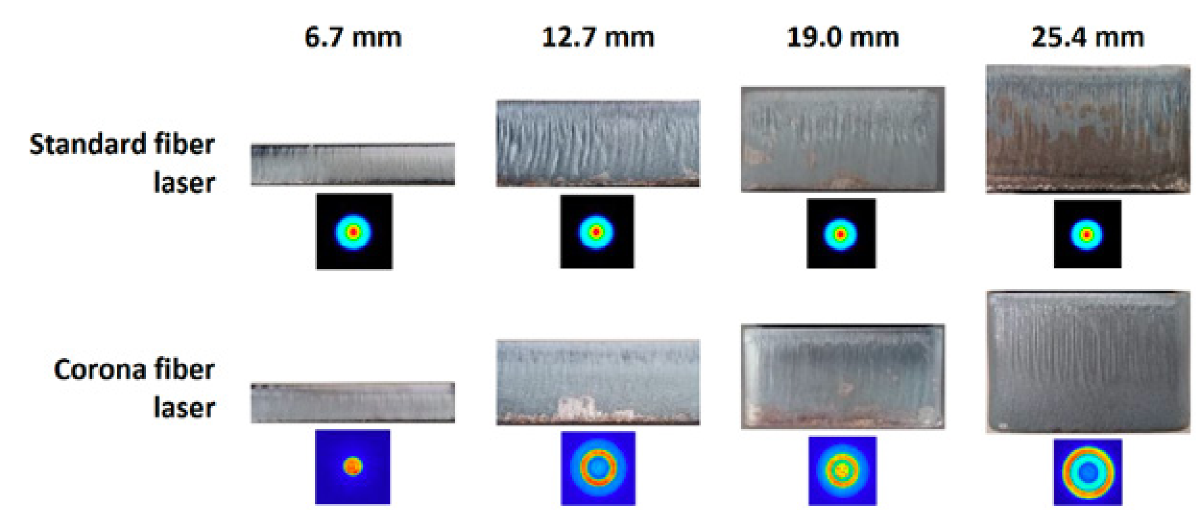


Figure 3. Cutting speed and measured edge roughness vs. thickness for oxygen cutting of mild steel. Images of the cut edges are shown in photos below along with the corresponding near-field beam profiles.



The Corona mechanism provides continuous tuning of the beam's characteristics with the full laser power available for each beam setting.

or thicknesses, but also for different process steps, such as piercing versus cutting or straight cutting versus cutting around corners.

As seen in an accelerated life test where the Corona fiber laser was repetitively cycled among its index settings with a 100-ms dwell at each setting, it maintains the exceptional stability and reliability of fiber lasers. The test duration was 13.4 million index changes, corresponding to a more than 36-year operation for a tool with 1,000 index changes per day. The beam diameters for all index settings remained stable to within ±3 percent (dominated by measurement uncertainty) throughout the test with no drift or degradation.

Cutting results

nLight's applications laboratory performed additional tests where the →

Table 1

Feature	Benefit	Zoom Lens	Switchable Beam-Shaping Optics	Motorized Fiber Coupler	Motorized Fiber Switch	Fiber Beam Combination	Corona
No free-space optics	Reliability	✗	✗	✗	✗	✓	✓
Compatible with standard fixed-optic process heads	Cost, Performance	✗	✗	✓	✓	✓	✓
Integrated into laser (no external devices or process fiber)	Cost, Reliability	✗	✗	✗	✗	✓	✓
Full power available for all beam shapes	Cost, Performance	✓	✓	✓	✓	✗	✓
Optimized power distributions (flat-tops, donuts, etc.)	Performance, Versatility	✗	✗	✓	✗	✗	✓
Fast switching on-the-fly	Performance, Versatility	✓	✗	✓	✗	✓	✓

Table 1. Desired features and benefits for an ideal laser source with tunable beam quality.

Corona fiber lasers were incorporated into laser cutters by several leading tool integrators with the following results:

- As expected, index 0 provides cutting speed and edge quality similar to conventional fiber lasers with 100-micron feeding fibers. This setting is typically employed with thin sheet to maximize cutting speed.
- For cutting of stainless steel and aluminum with nitrogen assist gas, index 1 and 2 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.
- For cutting mild steel with oxygen assist gas, index 3 and 4 greatly increase the maximum thickness and process window at a given laser power. Corona fiber laser provides significantly better edge quality than can be achieved with conventional fiber lasers (even at higher power levels), matching that of CO_2 lasers for metal cutting.

The third observation is particularly significant as oxygen cutting of mild steel is the largest application for high-power industrial lasers. Although fiber lasers now dominate this market, CO_2 lasers are still preferred for cutting thick plate (above approximately 10 mm) because they provide higher edge quality (reduced roughness, better straightness and perpendicularity).

The maximum thickness addressed by fiber lasers has been increasing, largely by using higher laser powers, but this approach increases upfront 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 and reducing the fiber laser power required to cut thick mild steel, Corona fiber lasers eliminate the last processing advantage of CO_2 lasers.

Figure 3 shows a comparison of the cutting performance of 4-kW conventional and Corona fiber lasers for oxygen cutting of mild steel plate between 6.4 mm and 25.4 mm. The cutting speed is the same for both lasers, but the edge roughness is →

nLight received the 2019 Prism Award for Industrial Lasers for its Corona fiber laser.

typically two to three times lower for the Corona fiber laser 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 a 4-kW Corona fiber laser 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 percent larger with Corona.

The desired features for an ideal laser source with tunable beam quality and corresponding scores for the available options are shown in Table 1. As seen, Corona fiber laser is unique in providing all of the features and benefits, resulting in performance with "no compromises" for the tool integrator and end user.

The availability of a practical, all-fiber, highly reliable laser with rapidly tunable beam quality has opened a new door 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 much higher performance and versatile tools for a wide variety of applications. The Corona fiber laser technology has wide generality, and future products will offer other power levels, beam sizes and beam shapes to target a growing list of laser applications.

nLight Inc. →