Fiber laser has all-fiber tunable beam quality

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A newly developed fiber laser provides real-time tunability of beam characteristics directly from the laser output fiber using an all-fiber mechanism.

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 above 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.

Why tunable beam quality is needed

For example, in metal cutting (the largest industrial application), a small beam with relatively high beam quality provides the highest speed for thin material, but the maximum thickness is limited by the resultant small 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. In welding, 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 welds on thin parts. Furthermore, the specific beam shape influences heat deposition and temperature gradients in the workpiece. Unlike a Gaussian beam, a flat-top beam can prevent over- or under-processing by delivering uniform irradiance, and annular or donut-shaped beams are known to improve the processing quality in some applications.

Most lasers provide fixed beam characteristics. The beam can be transformed to a different format by refractive, reflective, or diffractive optical systems. Laser-based tools with fixed-beam systems can address only a limited range of processes or materials and thus suffer from compromised performance or a restricted job mix. For example, a metal-cutting tool with a small beam will be unable to

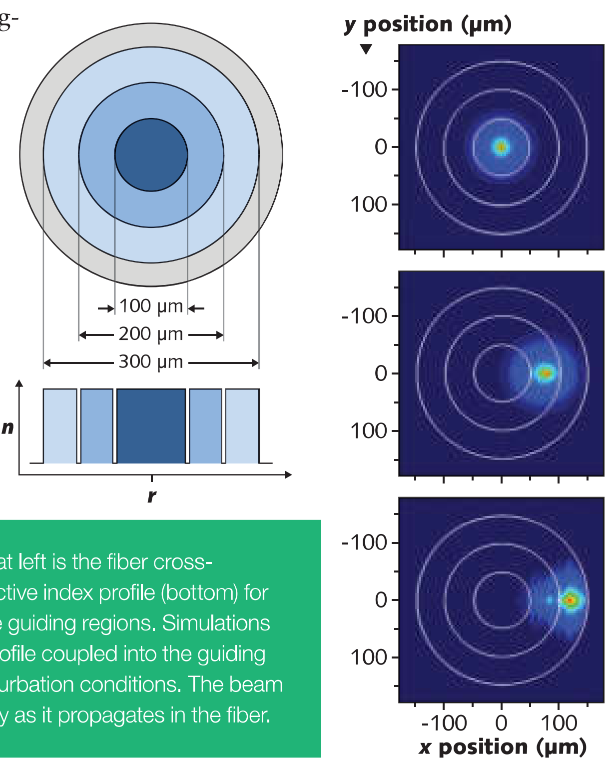

FIGURE 1. Shown at left is the fiber cross-section (top) and refractive index profile (bottom) for a feeding fiber with three guiding regions. Simulations (right) show the beam profile coupled into the guiding regions for different perturbation conditions. The beam homogenizes azimuthally as it propagates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

cut thick plate, whereas a tool with a large beam will not be economical for cutting thin sheet.

Tunability of the beam characteristics would be highly desirable to enable process optimization and tool versatility. Various approaches have been developed that provide some level of beam tunability, including 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 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.

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- 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 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.

All-fiber tunable beam quality

nLIGHT recently released a new fiber laser, called the 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 fiber lasers are currently available with output powers of 3 to 4 kW and have been demonstrated to 14 kW.

Corona fiber lasers provide tunable beam quality via an all-fiber mechanism that 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 simulations in Figure 1 (right).

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	✔	✘	✔	✘	✔	✔

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.

This 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 each product with a certain number of predefined beams (known as "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.

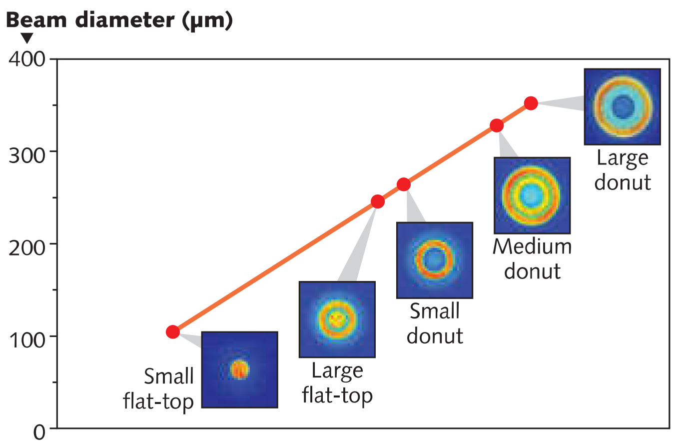

FIGURE 2. These are some typical Corona beam settings used in sheet-metal cutting tools. The second-moment beam diameters are given on the *y*-axis, and the images show near-field spatial profiles recorded at 4 kW.

Figure 2 shows the typical Corona beam settings for use in sheet-metal cutting tools. The beam diameter is programmable between about 100 μm and about 350 μm (second-moment definition). 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 wide dynamic range in beam size and shape evident in Figure 2 is unattainable with any other practical technology.

The switching time is less than 30 ms for the full range of beam size, and the laser maintains full-power operation while switching, with no need for blanking. This 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).

Corona maintains the exceptional stability and reliability of fiber lasers. An accelerated life test was performed, in which a Corona fiber laser was repetitively cycled among its 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.

Metal cutting results

Corona fiber lasers have been tested in nLIGHT's Applications Laboratory and also have been incorporated into sheet-metal cutting tools by several leading tool integrators worldwide, with the following results:

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.
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. 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 industrial lasers. Although fiber lasers now dominate this market, CO_2 lasers are still preferred for cutting thick plate (above around 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 and reducing the fiber laser power required to cut thick MS, Corona fiber lasers eliminate the last processing advantage of CO_2 lasers for metal cutting.

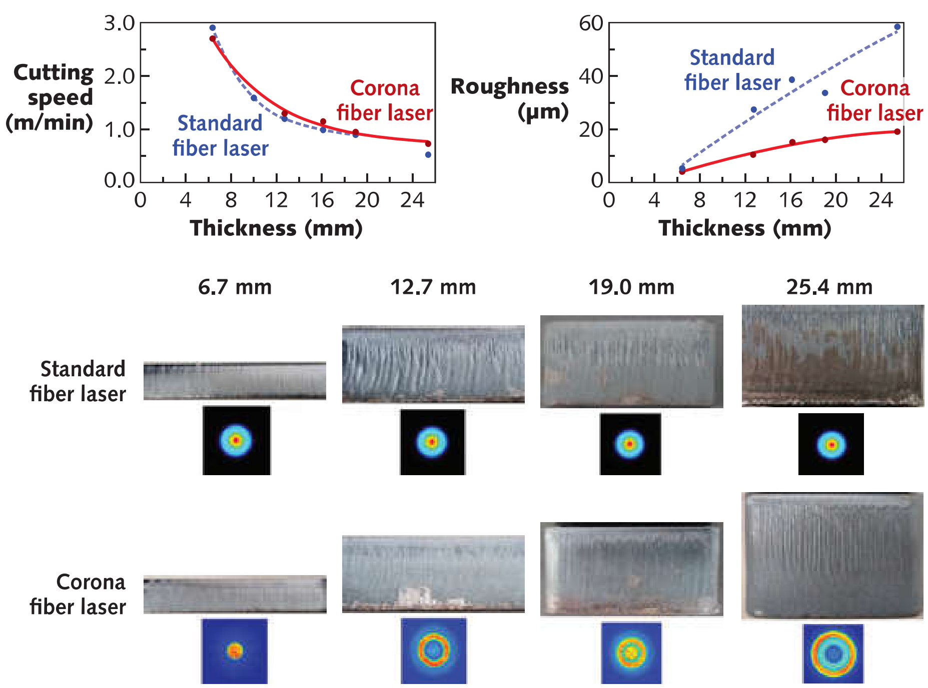

FIGURE 3. Cutting speed and measured edge roughness are plotted vs. thickness for oxygen cutting of mild steel (top). Images of the cut edges are shown in photos below the graphs, along with the corresponding near-field beam profiles.

Figure 3 shows a comparison of the cutting performance of 4 kW conventional and Corona fiber lasers for O_2 cutting of MS plate between 6.4 and 25.4 mm. The cutting speed is the same 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 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.

The table lists the desired features for an ideal laser source with tunable beam quality and scores the available options. 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 much higher-performance and versatile tools for a wide variety of applications.

ACKNOWLEDGEMENTS

nLIGHT is a registered trademark of nLIGHT, and Corona is a trademark of nLIGHT.

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