# High-Power Fiber Lasers

## New Applications Are Being Enabled by Dramatic Advances in Design and Performance

High-power (multi-kW) fiber lasers are revolutionizing industrial materials processing markets by offering an unmatched combination of performance, reliability, and cost advantages. For example, in sheet metal cutting (the largest application, with more than $1B/year of laser sales), fiber lasers provide the highest cutting speed (especially for thin sheets, the dominant application), scalability to thick sheets (>1"), and the ability to process a wide range of metals with a single tool. Along with low power consumption and high reliability, these capabilities result in the lowest cost per part. Fiber lasers have thus been the fastest-growing segment of the laser market for the past decade.

As deployment of fiber lasers has increased, users have identified several shortcomings of existing designs:

- Their sensitivity to back reflections from the work piece causes frequent process interruptions, precludes processing certain metals or finishes, and can result in laser instability or damage.
- Their limited serviceability causes excessive downtime and service cost, and prevents system integrators from providing world-class customer service to the end-users.

Furthermore, several emerging applications would be enabled by more advanced performance, including higher beam quality and beam-shaping options, faster modulation rates and rise/fall times, and sophisticated waveform-generation capabilities.

The following sections cover:

- fundamental aspects of fiber-laser and component technologies that confer significant performance and reliability advantages,
- the design and performance of next generation fiber lasers that address the outstanding needs summarized above, and
- application examples that illustrate the capabilities of next-generation fiber lasers.

## Fiber Laser Basics

Figure 1 shows a schematic diagram of a generic laser system. All lasers are comprised of an optical gain medium housed in a cavity. A laser system may also include one or more amplification stages (additional gain media) that further increase the optical power. Key differences among laser designs include:

- the nature of the gain media,
- how the gain media are energized (pumped),
- the design of the cavity,
- the inclusion of components to control the spectral, spatial, and temporal characteristics of the output beam,
- the optical system employed to deliver the laser beam to the application, and
- the coupling among these components.

The choices made by the laser design-

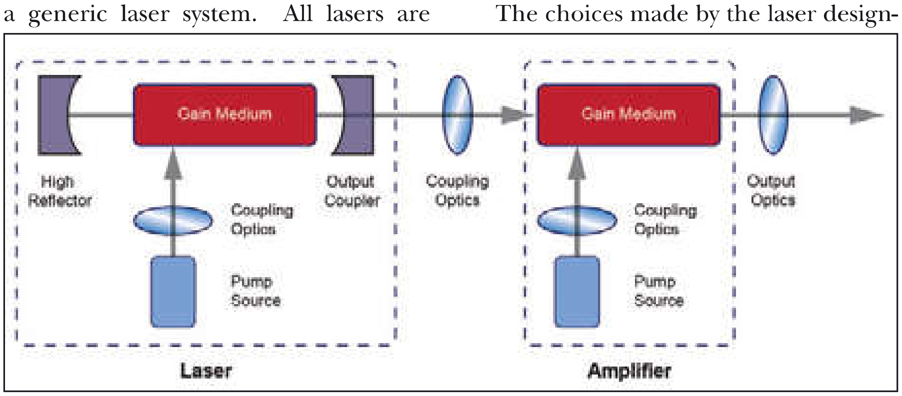



Figure 1. Schematic diagram showing the key components of a high-power laser system. The laser cavity is formed by the high reflector and output coupler mirrors. The number of amplification stages varies among laser designs (typically between 0 and 2). The various coupling and output optics may include multiple lenses and mirrors. In diode-pumped solid state lasers, the pump sources are based on semiconductor lasers, and the gain media are usually rare-earth-doped crystals or glasses.

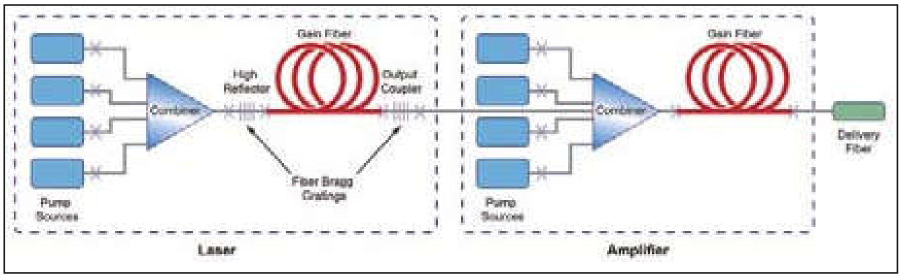
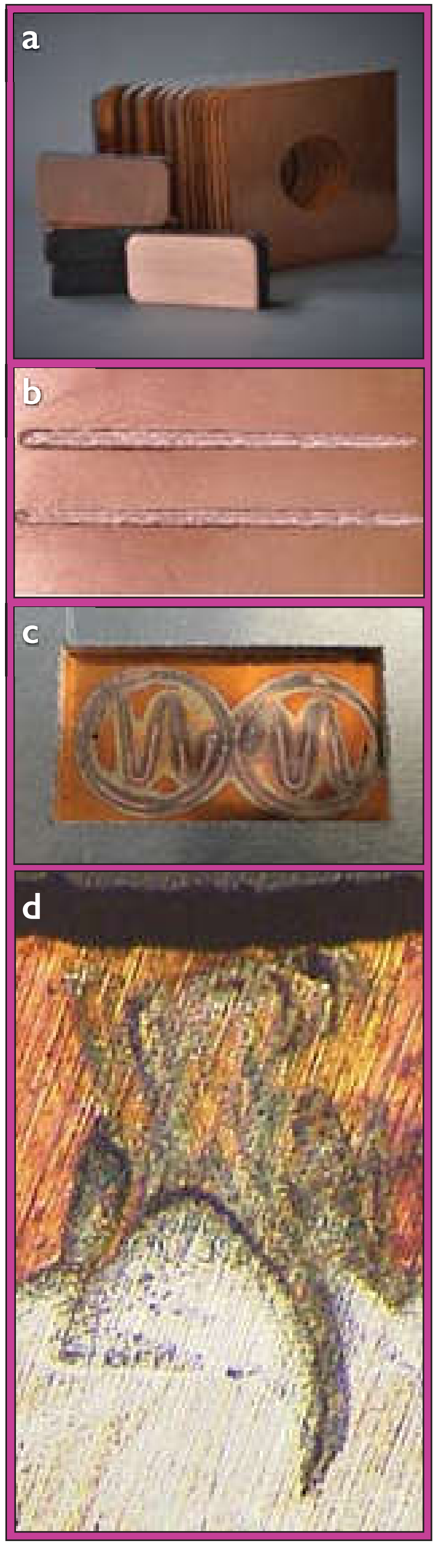



Figure 2. Schematic diagram showing the key components of a high-power fiber laser, illustrating the great simplification compared to the free-space design shown in Fig. 1. The laser cavity is formed by the high reflector and output coupler fiber Bragg gratings (in-fiber mirrors). The various coupling and output optics have all been replaced by passive fibers and fused-fiber components. Fiber-coupled semiconductor lasers are used as pumps, and the gain media are rare-earth-doped fibers. Splices are denoted "X".

er among these technologies determine all of the important laser characteristics, including performance (power, efficiency, beam quality, wavelength, polarization, stability, etc.) and practicality (cost, reliability, manufacturability, serviceability, etc.), which ultimately determine the suitability of the laser source for the intended applications.

Three key technologies have been especially important for the development of high-performance, high-reliability lasers for industrial applications:

1. **Diode laser pump sources:** Diode (semiconductor) lasers directly convert electrical energy to light with high efficiency (>50%). Continuous improvements, particularly during and after the telecommunications boom of the 1990s, have dramatically increased the power, efficiency, and reliability of diode lasers. Diode lasers are particularly well suited for pumping solid-state gain media because of their brightness and spectral characteristics. Diode lasers are manufactured in two formats: (a) single emitters, in which each semiconductor chip includes one light-producing region (emitter) that typically provides 10 – 20 W of power; and (b) diode bars, in which multiple emitters are included within one semiconductor structure. Single emitters were developed extensively for telecom (and the advances continue to this day); they provide the highest power, brightness, efficiency, modulation rate, and reliability (>1,000,000 hr. mean time to failure), in part because the emitters are thermally and electrically decoupled, and they can be efficiently coupled into an optical fiber.
2. **Solid-state gain media:** Solid-state gain media are generally more reliable and require less maintenance and consumables than gaseous or liquid gain media. Most solid-state gain media are composed of a rare-earth element, which provides optical gain, doped into a crystalline or glass host. The choice of the rare-earth dopant(s) and host material determines the absorbing (pumping) and emitting (lasing) wavelengths and the efficiency, which in turn determine the attainable power and beam quality. Yb-doped gain media are particularly well suited for high-power applications because they




Examples of material processing enabled by the back-reflection insensitivity and stability of nLIGHT alta™ fiber lasers. (a) Copper cutting samples. (b) Deep-penetration copper welds. Image provided by Laser Depth Dynamics. (c) Cap weld performed on a five-layer structure composed of a 250 μm copper foil on top of 4 layers of aluminum foil (100 – 250 μm). Image provided by Laser Mechanisms. (d) Cross-section of a weld between copper and aluminum, showing mixing of the materials within the weld joint.

are pumped at 910 – 980 nm, where diode lasers offer the highest power and efficiency, and lase in the wavelength range of 1030 – 1090 nm, where the small energy difference from the pump wavelength ("quantum defect") enables operation at high optical-to-optical (pump-to-lasing) efficiency and correspondingly low thermal load.

3. **Optical fibers:** An optical fiber is a strand of glass (typically silica-based) that guides light by total internal reflection, thereby eliminating the effects of diffraction. Confining a laser beam to a fiber enables low-loss transmission and delivery of optical power without the use of mirrors, lenses, or other free-space optics that are prone to misalignment, contamination, and damage and whose performance can be degraded by vibration, temperature variations, other environmental factors, and optical power changes. Passive optical fibers simply transmit light, whereas active optical fibers, in which the core is doped with a rare-earth element and pumped by a diode laser, provide gain. The fiber gain medium offers the highest optical-to-optical efficiency because of the long optical path length and excellent overlap of the lasing beam with the gain region. Furthermore, the high surface-area-to-volume ratio facilitates heat removal, making the fiber gain medium particularly well suited to power scaling. Finally, the mirrors required to form a laser cavity can be written into passive optical fiber (fiber Bragg gratings) and spliced to the gain fiber. As with pump diodes, advances in optical fibers have been driven by telecommunications applications and continue today.

Diode-pumped solid-state (DPSS) lasers combine the first two of these technologies. Fiber lasers combine all three technologies, enabling the highest performance, reliability, and practicality of any laser technology on the market. In particular, fiber lasers offer the following advantages:

- **Highest wall-plug efficiency:** For the reasons outlined above, fiber lasers provide the highest efficiency of any DPSS laser, typically achieving 30% and with the capability of 50%. In addition to reducing power consumption, high efficiency minimizes cooling requirements, further reducing power consumption, cost, and floor space required for the laser system.

- **Excellent beam quality:** The beam quality is determined by the wave-guiding properties of the fiber and is extraordinarily stable, even in the presence of environmental perturbations and changes in optical power level. With suitable designs, fiber lasers can provide single-mode (diffraction-limited) beam quality, although this feature is not typically used for multi-kW industrial applications. The high beam quality of fiber lasers enables:
  - improved processing speed and quality (e.g. for thin sheet metal cutting),
  - remote processing (where a small spot size must be maintained at a relatively large distance),
  - beam formatting (e.g. flat-top and line beams) for process optimization, and
  - a large process window (e.g. insensitivity to small misalignments or work piece variations).
- **High reliability:** A unique feature of fiber lasers is the ability to use fiber-based components and fusion splicing (melting together of the fibers) to completely eliminate free-space optics and their associated mounts and adjustments between the pump diodes and the process head. The optical beams are confined to a sealed, stable, alignment-free optical system that is impervious to vibration, contamination, power changes, etc. When pumped with single-emitter-based pumps with telecom-grade reliability, these fiber lasers have no consumables other than electricity and require no routine maintenance.
- **Fiber beam delivery:** Fiber delivery of the beam to the process head enables elimination of free-space optics and their accompanying mounts, beam tubes, and purge gas, and it ensures that the beam characteristics do not change with time or position on the work piece. Although other DPSS lasers can be fiber coupled, doing so employs high-power free-space optics with associated cost, complexity, optical loss, and the possibility for misalignment, contamination, and damage. In contrast, fiber lasers can be spliced directly to the delivery fiber, with no degradation of performance or reliability.

A fiber-based architecture enables all of the key components and functions of a laser system shown in Figure 1 to be incorporated into a fused, all-fiber assembly (Figure 2). The resultant combination of unmatched performance, reliability, and practicality thus derives from fundamental technological factors, as outlined above, and these sources are uniquely well suited for industrial applications, where cost, uptime, and processing quality are critical.

## Conclusions

As a result of their innate technological advantages and rapid advances in component technologies, fiber lasers offer unprecedented performance, reliability, and cost of ownership. Next generation fiber lasers are driving wider adoption in established applications and expansion into advanced and emerging applications. In particular, things like imperviousness to back-reflections, high power stability and tunability, rapid modulation capabilities, and unique serviceability are enabling uninterrupted processing of highly reflective metals and finishes, high-speed remote processing, and processing of CFRP and other novel materials, all with industry leading uptime and parts cost.

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