FEATURE

The FIBER Advantage

Careful engineering and innovative configurations yield practical, high-performance fiber lasers.

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Fiber lasers offer a competitive alternative to traditional lasers due to their superior performance, compactness, ease-of-use, and low running costs. The capability to generate kilowatts of optical power and deliver it in a spot less than 10 µm in diameter makes fiber lasers suitable for cutting, welding, micro-machining, materials processing, marking, and printing, and enables the development of new applications.

As with any type of laser, a fiber laser requires a pump source, a gain medium, and optical feedback to produce lasing action. At Southampton Photonics Inc. (SPI; Southampton, U.K.), we've developed a technology platform in which a singlemode laser fiber (the gain medium) and multimode pump-carrying fibers are held in optical contact with each other in a single unit (see figure 1). To manufacture the platform, we mount the three individual preforms side-by-side, draw them into three fiber strands simultaneously, and coat them together immediately as a group.

Fiber Bragg gratings (FBGs) spliced to the laser fiber form a resonator, while fiber-pigtailed, broad-area diode lasers spliced to the pump fibers provide the pump sources. This configuration is a novel example of a class of double-clad fibers that enables cladding pumping: coupling the pump radiation into the fiber cladding. The multiple pump fibers provide several inputs, greatly increasing the level of pump power that can be coupled into the laser fiber.

Theory to Practice

The broad-area diode pump lasers can be in the form of single-diode emitters, bars of diode lasers, or stacks of diode-laser bars. Single emitters can couple more than 5 W of optical power into a multimode fiber using a fiber lens; the technology benefits from the high-reliability designs and volume production techniques developed for telecom applications. Diode-laser bars and stacks can be coupled into the fiber via free-space optics and are available with output powers exceeding 50 W and several hundred watts, respectively.

We use single-emitter diode-laser pump sources with multimode fiber combiners for high-reliability and low-cost assembly. To achieve low-loss coupling, conserving brightness from the pump diode laser pigtails through to the pump-fiber cladding, we focus on the design of the cladding diameter and the numerical aperture (NA) of the spliced fibers. Once coupled into the pump fibers, the pump radiation transfers gradually to the laser fiber by evanescentfield coupling, resulting in distributed side pumping of the fiber laser with no "hot-spots."

The core of the laser fiber provides the active medium that absorbs the pump radiation and provides optical gain. The dopants of the laser-fiber core include rare-earth elements such as neodymium (Nd), ytterbium (Yb), or erbium (Er). Er, commonly found in fiber amplifiers for telecom applications, features absorption bands at 980 and 1480 nm and provides output power in the telecom C-band (1520 to 1570 nm) and L-band (1560 to 1610 nm).

Yb is commonly used for industrial fiber lasers, since the 1090-nm output wavelength is close to the 1064-nm wavelength of traditional Nd-doped yttrium aluminum garnet lasers. The proximity of the signal band to the two strong absorption bands in Yb-doped alumino-silicate glass at 915 and 976 nm results in optical-to-optical conversion efficiencies of greater than 80%. We use the broader 915-nm pump band. This relaxes the specification on pump-laser output wavelength, eliminating the need to precisely manage the pump-laser temperature, significantly reducing the weight, cooling requirements, power consumption, and size of the resultant fiber laser.

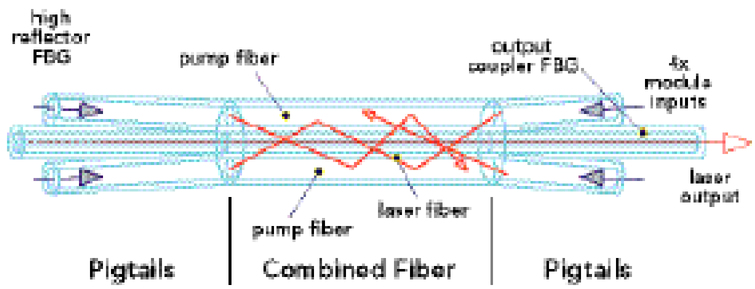

Figure 1 Our typical fiber design consists of a pair of high-numerical-aperture, multimode pump fibers in optical contact with a singlemode laser fiber, although more pump fibers can be used. The pump power passes to the cladding of the laser fiber by evanescent coupling; fiber Bragg gratings (FBGs) act as cavity mirrors.

The singlemode core of the laser fiber also provides the waveguide for the laser radiation, and is principally responsible for the high beam quality of fiber lasers. The core properties are designed to avoid non-linear effects such as stimulated Raman scattering (SRS), which can cause the output power at the signal wavelength to saturate, while maintaining singlemode guidance for low-loss splicing to a singlemode passive pigtail fiber for beam delivery. The high surface-to-volume ratio of the fiber permits effective cooling, thus avoiding thermal degradation of the core guiding properties and hence the beam quality.

Singlemode FBGs spliced onto the laser pigtails act as cavity mirrors. A high reflector (>99.9%) and a lower reflectivity output coupler ensure the directionality of the laser and define the wavelength in the region of 1090 nm with better than 1-nm accuracy by virtue of their designed-in wavelength-dependent properties. The output coupler reflectivity is optimized for maximum laser output efficiency and temporal stability.

The approach described above yields practical, high-performance laser systems. We have produced a 100-W continuous-wave/modulated (CW/M) industrial fiber laser with a near-diffraction-limited beam quality factor ($M^2 < 1.05$) and a power stability of better than ±0.5% rms over a full 12-hour production shift (see figure 2). Careful fiber design to control the saturation power allows the system to internally modulate the output at up to 50 kHz with a controllable leading-edge pulse of 700 W to 1 kW and a rise time of about 1 µs; alternatively, the output can be controlled with a slower (~150 µs) rise-time without the initial pulse.

Future power scaling of fiber laser products can be readily achieved in a number of ways. The first way is to increase the number of pump sources feeding each of the fiber combiners. The second is to provide more pump inputs to the laser fiber by either concatenating more than one fiber spool by splicing together their laser fibers or including more than two pump fibers in the initial draw of the multifiber unit. The third method is to spatially combine the outputs from several fiber lasers.

We have just released a 200W CW/M industrial fiber laser, and kilowatt-class systems will follow. In the laboratory, we have produced 1.4 kW of output with $M^2 = 1.4$.

Taking the Pulse

Pulsed fiber lasers are increasingly becoming the laser of choice for applications such as micromachining, drilling, and marking. To achieve sufficiently fast throughput, applications such as marking demand peak powers in the 5- to 10-kW range, at repetition rates on the order of 100 kHz. Conventional single-stage Q-switched lasers, although very efficient in storing energy, suffer from variable average power and substantially diminishing peak power as the repetition rate increases. At repetition rates in excess of 10 to 20 kHz, the peak power can drop below the process (e.g. marking) threshold; this limitation constrains speed and throughput. Fiber lasers offer an alternative.

In a master-oscillator-power-amplifier (MOPA) configuration, a pulsed fiber laser can operate with more control over the pulse characteristics and peak power performance than comparative solid-state systems. The MOPA configuration comprises a fiber-pigtailed, directly modulated 1080-nm diode seed laser; a two-stage, all-fiber amplifier based on the technology described above; and a beam-delivery fiber up to 5-m long. These are spliced to each other via interstage

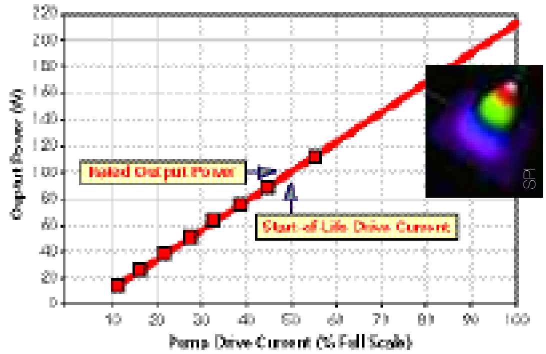

Figure 2 A 100-W-rated industrial fiber laser actually produces output powers of 140 W or more while producing a high-quality beam (inset).

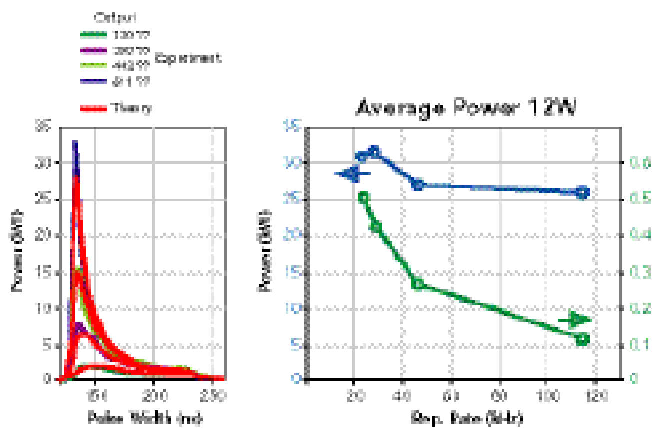

Figure 3 A pulsed fiber laser based on a master-oscillator-power-amplifier (MOPA) configuration achieves pulse powers as high as 33 kW in the lab (left). Note: The peak power for a commercially available version of this fiber laser remains relatively steady as repetition rate increases (right).

optical isolators, to protect the system from amplified back-reflections.

The pulses tend to narrow and sharpen as they pass through the fiber amplifiers. These pulse-sharpening effects place stringent design constraints on the fiber to minimize SRS. Laboratory systems have achieved pulse energies of up to 0.6 mJ (better than 30 kW peak power; see figure 3). Our commercial system achieves pulse energies of 0.5 mJ and peak powers in excess of 5 kW, while limiting SRS to less than –20 dB; hence >99% of the emission is at the required wavelength.

If we consider system performance as a function of repetition rate, for an average power in excess of 12 W, the pulse energy and duration vary but the process-critical peak power remains almost constant at about 5 kW for repetition rates from 10 to 400 kHz. To the best of our knowledge, this is the first time that such performance has been reported for a pulsed fiber laser. In a marking system, for example, such a system could improve throughput by a factor of 20.

Stand and Deliver

High power without sufficient beam quality can be useless for many applications. The beam quality achieved by fiber lasers as a result of the singlemode gain and delivery fibers offers distinct advantages. Fiber lasers offer longer focal length (working distance) and greater depth of focus (work-piece positioning tolerance) than competing technologies. For a fixed focal length and focus spot size, the beam diameter as delivered directly from the laser can be smaller. This allows the use of cheaper, lighter process optics that are easier to maneuver about the work-piece. Alternatively, the system can achieve a smaller focal-spot diameter, making it possible to process materials in much finer detail than with other lasers.

The use of fiber throughout the system not only ensures high beam quality, but avoids pointing-stability errors that occur with thermal warm up and in shipping traditional lasers based on rods and disks. Pointing instability leads directly to processing errors and output power reduction when coupling to beam-delivery fibers, and, significantly, provides a practical limit to beam quality for systems coupling a free-space beam to a delivery fiber.

We have focused on industrial systems, but scientific, aerospace, and medical opportunities will open up for fiber lasers as output powers grow. We think that a 10-kW CW single-fiber laser may be possible. Realizing such a system would require improved pump-source brightness and the development of very-low-NA fiber designs. Thermal management of the fiber could also be an issue, though it is unlikely to present a major challenge. At high CW powers, the delivery fiber becomes a concern. One approach is to use more sophisticated designs like holey fibers.

In the case of pulsed lasers, however, increasing pulse energy increases peak powers, which can introduce unacceptably high levels of SRS. Reducing SRS requires larger-mode-area fiber, which in turn may compromise beam quality, so the effort presents an interesting engineering challenge. Laser history has shown that technology eventually surmounts such challenges, however, so in the future we expect fiber lasers to be used in an even wider range of application areas. **oe**

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