Increased Output and Efficiency of Fiber Lasers

An evolution in fiber design and glass composition has spawned a renewed and rapidly growing interest in fiber laser technology.

by Adrian Carter, Nufern

Fiber lasers are, in many respects, a mature technology with commercially available systems delivering multi-kilowatt, near-diffraction-limited pulsed and CW outputs. They are used in a myriad of applications, from high-power industrial materials processing such as cutting and welding, tactical weapons and sensing devices, to marking, printing and surgery, with an estimated total annual market value approaching $1 billion. However, this superficial observation masks an ongoing evolution in the fundamental design of the active gain material — the fiber itself. In fact, for most of its 50-year history, complications inherent to fiber design have rendered the substance a significantly inferior technology compared with its solid-state and gas laser alternatives. These complications have severely restricted its application.

Increased power

The classical design of small-core, single-mode, single-clad step-index fibers meant that the achievable output power from a fiber laser was limited to the milliwatt domain by the need to launch excitation energy directly into the core of the fiber. In 1988, the advent of double-cladding fiber designs made it possible to target only the geometrically larger inner-cladding region and to use the fiber laser device as an effective method of brightness conversion. At this point, the limitation to power scaling became the availability of high-brightness pump radiation, rather than the fiber itself. Development culminated in 1999 with the demonstration of the world's first single-mode fiber laser exhibiting a continuous-wave output power in excess of 100 W. However, it was soon recognized that conventional small-core, high-numerical-aperture fiber designs are not appropriate for applications requiring further scaling of

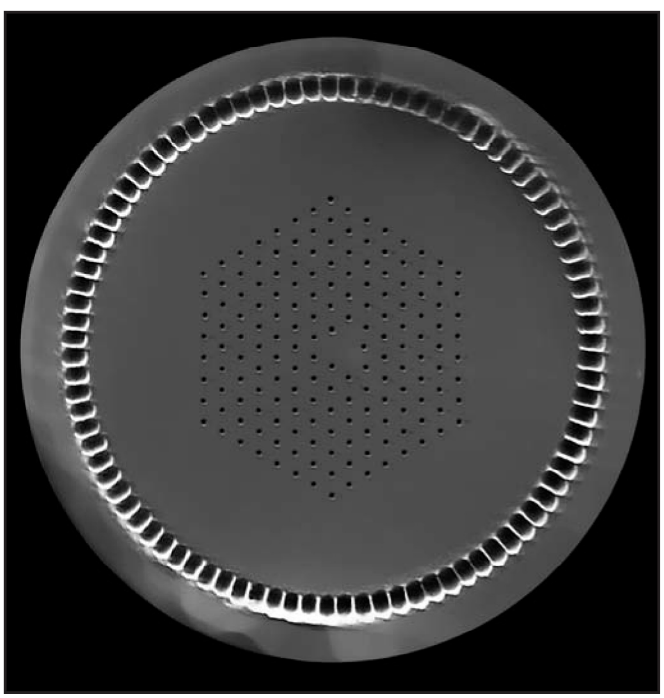

Figure 1. *Through the incorporation of a microstructured arrangement of low-index material in the fiber core, numerical apertures as low as 0.02 are possible in all-glass air-clad photonic crystal fibers.*

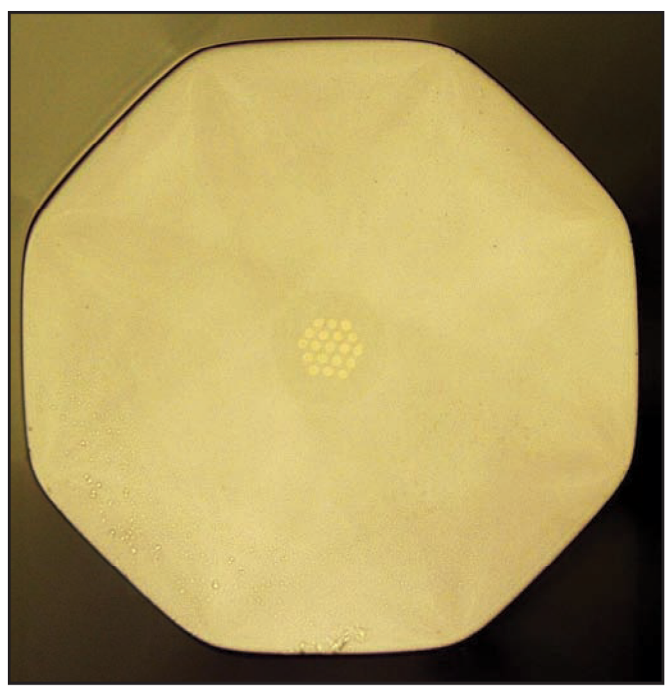

Figure 2. *Octagonal-clad 19-core optical fibers have been investigated as a means for power scaling through phase matching in a single fiber.*

the output power. More specifically, it was found that the maximum achievable output power in such fibers is restricted by a fundamental susceptibility to optical nonlinearities, including stimulated Raman scattering, stimulated Brillouin scattering and self-phase modulation.

Overcoming the limitations imposed by these parasitic nonlinear processes required the development of fibers with relatively large, low-numerical-aperture cores and high lanthanide ion dopant concentrations. However, these high concentrations may impose a deleterious effect on long-term reliability because of an increased likelihood of induced optical losses — more commonly referred to as photodarkening. These so-called large-mode-area fibers are directly responsible for the recent explosion in demonstrated diffraction-limited beam-quality output powers. However, despite these significant advancements, fiber lasers are still limited to output powers of only a few kilowatts CW and pulse powers of around 1 to 2 mJ.

The output power achievable from a fiber laser is determined principally by how much pump power can be coupled into the fiber cladding and by the size of the fiber core. However, there is an upper limit to the core diameter, beyond which diffraction-limited beam quality is difficult to maintain. More specifically, for a step-index fiber with a core numerical aperture of around 0.06, this limit is around 25 μm. However, it is not possible to reduce the numerical aperture further because the fibers begin to exhibit extremely high bend sensitivity.

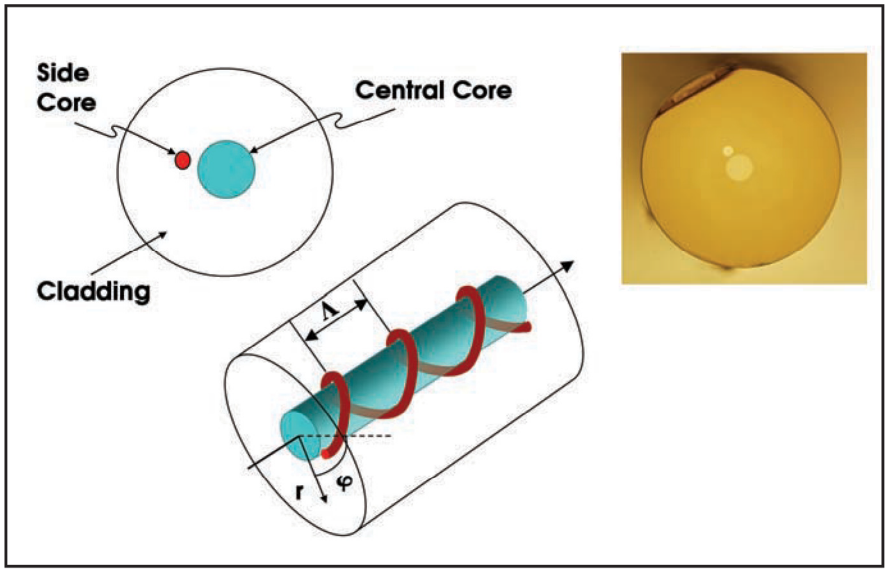

Figure 3. *In a chirally coupled core fiber, the large central core is orbited by a passive satellite, which acts to decouple higher-order modes from the core.*

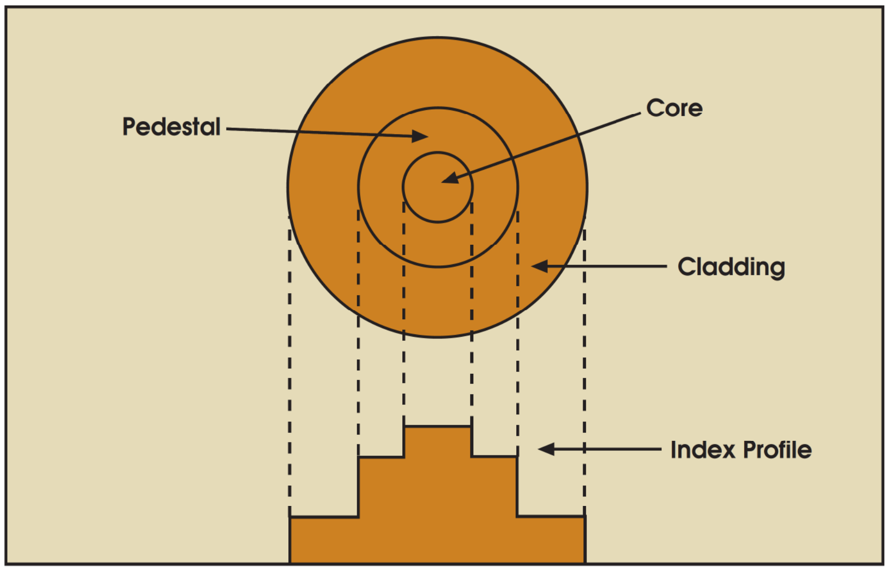

Figure 4. *By incorporating an appropriate pedestal design, the core of an optical fiber, which otherwise may have been highly multimoded, now may have its effective index reduced so as to be large-mode area.*

Avoiding fiber bend

One potential solution to this limitation is to avoid bending of the fiber altogether. This is the approach used in photonic crystal fibers wherein, by incorporating a microstructured arrangement of low-index material in the fiber core, numerical apertures as low as 0.02 are possible. Such fibers commonly use very large cladding diameters (up to around 1 mm) and an air cladding, rather than the more conventional polymer technologies (Figure 1). They have been investigated extensively for use in high-power pulsed amplifiers, as the air cladding allows a higher pump numerical aperture (typically around 0.60) and, consequently, shorter devices with increased nonlinear thresholds. However, difficulties in handling and packaging these fibers have meant that their success has been restricted primarily to laboratory-based demonstrations.

Coherent beam combining within a single fiber with multiple closely spaced cores (Figure 2) has been demonstrated, though it has not successfully scaled to high power. Output power scaling by combining coherent or spectral beams also may be applied to an array of fiber lasers with narrow spectral linewidth. For directed energy applications, each of the lasers in this array ideally would be single-frequency CW and have output powers on the order of 1 kW. For such applications, stimulated Brillouin scattering is the key obstacle. Significant effort is being focused on the optimal compositional design profiles of the core and cladding features of conventional large-mode-area fibers so as to be optically guiding but acoustically antiguiding. Similarly, fibers with unique refractive index profiles — such as large flat-mode fibers — have been demonstrated, but without yielding significant benefit. Much theoretical analysis has been published on the potential advantages of using higher-order guided modes, in so-called higher-order-mode fibers, though very little has been demonstrated, and such fibers remain commercially unavailable, presumably because of the inherent complications associated with their manufacture.

Chiral coupling

The chirally coupled core fiber design enables large cores with effectively single-mode performance, independent of excitation conditions and external perturbations (such as bending or fiber splicing) (Figure 3). Chirally coupled core geometry exploits the difference in modal symmetries for achieving highly selective mode suppression and, therefore, should provide single-mode cores with a diameter up to around 100 μm which, in theory, will permit an increase in output power of at least an order of magnitude beyond that of conventional large-mode-area fiber.

The most recent addition to this list of novel fiber designs is an all-glass leakage channel fiber, similar in principle to photonic crystal fiber, although with a reduced number of larger low-index material features. Single-mode operation has been demonstrated in a passive version of this fiber type with a core diameter as large as 170 μm. It is claimed that active versions of this design will extend the reach of practical ultrafast fiber amplifiers to milliJoule pulse energies and up to 10 kW in a continuous-wave amplifier.

While the focus here has been limited almost exclusively to ytterbium-doped fibers with a lasing wavelength at around 1 μm, significant advances also have been reported recently in the output power and, most importantly, in the efficiency of thulium-doped fiber lasers operating at around the eyesafe wavelength of 2 μm. Through careful optimization of glass composition and incorporation of a pedestal feature that reduces the effective index of the core and allows it to mimic large-mode-area operation, fiber lasers with output powers exceeding 300 W CW and with slope efficiencies around 60 percent have been demonstrated (Figure 4). Despite the geometric space requirements of the pedestal region, it is even possible to make these fibers in a polarization-maintaining format as is necessary for the construction of linearly polarized lasers.

Further power scaling in fiber lasers will involve overcoming the limitations imposed by the optical nonlinearities of the host material by modifying the guiding structure in such a way as to further reduce the optical power density without sacrificing output beam quality. As such, a number of novel fiber designs have recently been proposed and developed recently with the goal of increasing the area of the mode. Demonstrating that these sophisticated fiber designs are both robust and manufacturable remains an ongoing endeavor. ☐

Meet the author

Adrian Carter is chief technical officer at Nufern in East Granby, Conn.; e-mail: acarter@nufern.com.

Running head: Optical Fiber