TUTORIAL

Fiber Laser Technology Reels in High Power Results

ILLUSTRATION BY WARREN GEBERT

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By using bending loss to suppress higher-order modes in multimode fiber, researchers have achieved high power output from fiber lasers.

Single-mode, rare-earth-doped fiber lasers and amplifiers are widely used in telecommunications and other applications requiring compact, rugged optical sources with high beam quality. Fiber sources provide high electrical-to-optical efficiency (up to 39% for Yb-doped fiber amplifiers), small-signal gains as high as 10^5, and low-threshold operation. The devices can achieve diffraction-limited beam quality ($M^2 = 1$) that is defined by the refractive-index profile of the fiber and is thus insensitive to thermal or mechanical fluctuations or optical power level. The glass host broadens the optical transitions in the rare-earth ion dopants, yielding continuous tunability; moreover, the variety of possible rare-earth dopants such as Yb, Er, and Tm yields broad wavelength coverage in the near-IR spectral region. Fiber lasers can be diode pumped and further offer low heat dissipation and facile heat removal (high surface-area-to-volume ratio) and room-temperature operation. They also require no consumables other than electrical power.

Until recently, fiber sources had been limited to relatively low output powers, preventing their use in a number of important applications that demand high average power, peak power, and/or pulse energy. Recent advances, however, have enabled dramatic power scaling of continuous-wave (CW) and pulsed fiber sources, bringing the benefits of this technology to a wide range of applications previously dominated by other laser systems: materials processing, lidar, and nonlinear frequency conversion, for example. These developments have led to a surge of interest in fiber-based laser systems for both industrial and military use.

Power Limitations

An idealized step-index fiber has uniform refractive indices in both the core (n_{core}) and the cladding (n_{clad}). Such a fiber will guide only the fundamental mode LP_{01} if the normalized frequency (V) is ≤ 2.4, where $V = \pi\, d_{core}\, NA_{core} / \lambda$, d_{core} is the core diameter, λ is the wavelength, and the numerical aperture NA_{core} is given by $\sqrt{n_{core}^2 - n_{clad}^2}$. Typical singlemode fibers operating in the near-IR spectral region have d_{core} values of 6 to 8 µm and NA values of about 0.15.

High-power fiber sources incorporate double-clad fiber (see figure 1), in which the rare-earth-doped core is surrounded by a much larger and higher-NA inner cladding. Light from high-power multimode pump diodes can be launched efficiently into the inner cladding, but the pump light is absorbed only in the core, retaining the benefits of a singlemode gain region.

A fundamental limitation on power scaling of fiber sources is imposed by properties of the fiber itself: low energy storage (relevant for pulsed fiber sources) and the onset of nonlinear processes in the fiber (relevant for both CW and pulsed sources). Amplified spontaneous emission (ASE), which limits the maximum population inversion, determines the energy-storage capacity of a fiber. The most important nonlinear processes that limit the output power and energy are stimulated Brillouin scattering, stimulated Raman scattering, and self-phase modulation; their relative importance is determined by the pulse duration, spectral linewidth, and fiber length.

The simplest way to overcome both limiting factors is to increase d_{core}, which results in a smaller fraction of spontaneous emission being captured by the core in the fundamental mode and a larger LP_{01} mode-field diameter (MFD); the threshold power for nonlinear processes scales as MFD^2. In addition, the pump absorption coefficient increases quadratically with d_{core} for a given inner-cladding size, allowing the use of shorter fiber lengths and proportionally raising the threshold power for nonlinear processes.

Maintaining a singlemode core while increasing d_{core} requires a corresponding decrease in NA_{core}. Singlemode fibers with NA_{core} below about 0.06 have unacceptably high bending sensitivity, however, imposing an effective upper limit to the value of d_{core}.

Beyond the Singlemode Limit

Lifting the constraint of $V \leq 2.4$—that is, use of multimode fiber—permits power scaling well beyond the singlemode limit. For many important applications, however, the poor beam quality generally associated with multimode fiber is unacceptable. Several research groups have suppressed the propagation of transverse modes other than LP_{01} in multimode fiber by suitably designing the fiber index and dopant profiles, introducing special cavity configurations, tapering the fiber ends, or carefully adjusting the launch conditions of a seed beam.

In 2000, we demonstrated that bend loss in coiled fiber can act as a form of distributed spatial filtering and suppress all but the fundamental mode of a highly multimode (large d_{core}) fiber amplifier, yielding singlemode, diffraction-limited operation. This technique exploits the fact that LP_{01} is the least sensitive to bend loss and that, for all modes, the bend-loss attenuation coefficient (in dB/m) depends exponentially on the radius of curvature. Thus, by strategically choosing the spool diameter, one can introduce very high loss for all higher-order modes but negligible loss for LP_{01}.

This approach is easy and inexpensive to implement, does not increase system complexity or part count, is compatible with compact amplifier packaging, and does not involve obstructing the fiber ends or the use of complex fiber designs. It can be used in conjunction with other methods for suppressing higher-order modes. In the case of externally seeded fiber amplifiers, the technique does not require matching the seed beam quality or the alignment to LP_{01}; in fact, it is even applicable to construction of diffraction-limited ASE (unseeded) sources.

A key distinction exists between bend-loss-induced mode filtering and conventional spatial filtering. The latter method involves discarding higher-order modes by focusing an optical beam through a small aperture. This process results in improved beam quality but with a consequent loss of power and efficiency, and possibly increased power fluctuations. In contrast, the mode-filtering technique suppresses propagation of higher-order modes along the entire length of the fiber amplifier. These modes do not build up significant intensity, leaving the energy in the gain medium to be extracted in LP_{01}. The net effect is that the amplifier slope efficiency is unaffected, and singlemode operation is obtained without compromising any other performance characteristics. Of course, as the mode-filtering technique nears its ultimate limit, there will be a tradeoff between beam quality and LP_{01} loss, but this limit has not yet been reached, even for fibers with values of V in excess of 10 (more than 50 guided modes).

The above combination of advantages makes bend-loss-induced mode filtering uniquely well suited to construction of high-power CW and pulsed

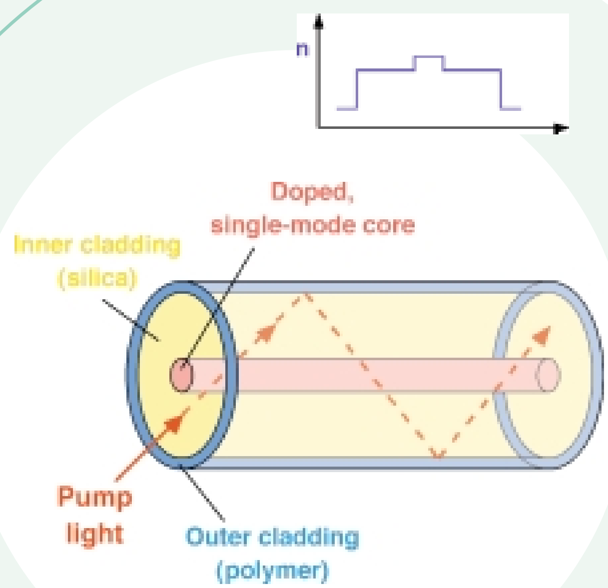

Figure 1 Double-clad fiber consists of a rare-earth-doped core surrounded by a much larger and higher-NA inner cladding.

fiber sources. We first demonstrated this method using a Yb-doped double-clad fiber with d_{core} = 25 µm and $NA_{core} \approx 0.10$ ($V = 7.4$ at λ = 1064 nm).[1] The fiber was pumped at 975 nm and seeded with a narrow-linewidth neodymium-doped yttrium aluminum garnet (Nd:YAG) laser. The system was tested with and without coiling (see figure 2). The dramatic improvement in beam quality provided by mode filtering is evident: The uncoiled amplifier supported about 30 modes ($V^2/2$ for a step-index fiber), while the coiled amplifier operated stably on LP_{01} with no measurable decrease in slope efficiency; M^2 measurements confirmed singlemode operation. Even when operated as an ASE source, the system generated a beam with an M^2 of 1.09±0.09; this test is particularly stringent because spontaneous emission uniformly excites all modes of the fiber.

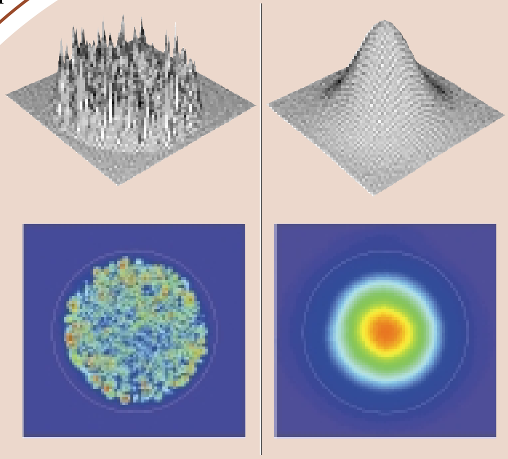

Figure 2 Near-field spatial profile of the output from a multimode fiber amplifier with d_{core} = 25 µm (mode-field diameter of 20 µm) when the fiber was uncoiled (left) and coiled for mode filtering (right) show the advantages of the technique; the circles in the bottom panels indicate the fiber core.

In a separate experiment, we seeded the mode-filtered amplifier with the output of a passively Q-switched Nd:YAG microchip laser that provided transform-limited, 0.8-ns pulses at 8 kHz. The amplifier produced diffraction-limited output pulses with an energy of 255 µJ and peak power of 305 kW (2.2 W average power).[2] This source was frequency doubled, tripled, quadrupled, and quintupled to produce light in the visible and UV spectral regions (532 nm to 213 nm). The high peak power and beam quality of the mode-filtered amplifier provided very high nonlinear conversion efficiencies—52% for 1064 to 532 nm, and 50% for 532 to 266 nm.[3]

The mode-filtering technique has enabled record-setting power levels for both CW and pulsed diffraction-limited fiber sources. Andreas Liem and colleagues at the Friedrich-Schiller Universität (Jena, Germany) seeded a Yb-doped double-clad fiber (d_{core} = 28 µm, NA_{core} = 0.06) with a single-longitudinal-mode Nd:YAG laser with 2 to 3 kHz linewidth and generated over 100 W of output power. The beam exhibited an M^2 value of 1.1 and no measurable degradation of the linewidth or noise characteristics by nonlinear processes in the fiber.[4] More recently, the group demonstrated a mode-filtered, Nd/Yb-co-doped fiber laser (d_{core} = 24.5 µm, NA_{core} = 0.086) operating in CW mode and produced 500 W of output at about 1100 nm, with a slope efficiency of 72%.[5] Finally, a Yb-doped double-clad fiber (d_{core} = 30 µm, NA_{core} = 0.06) seeded with 70- to 300-ns pulses from a Q-switched Nd:YAG thin-disk laser produced 4 mJ pulses at a repetition rate of 3 kHz (12 W average power) and 2 mJ at a repetition rate of 50 kHz (100 W average power); M^2 was measured to be 1.1 for a fiber bend radius of less than 5 cm.[6]

These impressive results do not represent the ultimate limit of the mode-filtering technique, and further power scaling is likely in the near future.

Designing Fiber

Although the mode-filtering technique can be applied to any fiber to provide suppression of higher-order modes relative to LP_{01}, only properly designed fiber can fully exploit the benefits of this (or any other) mode-discrimination approach. As in the case of singlemode fiber, minimizing NA_{core} while maximizing the concentration of the rare-earth dopant provides optimal stored energy and power-handling capability. A low NA_{core} value also ensures that the required radius of curvature for mode filtering will not be so small as to diminish the fiber's long-term reliability.

Ideally, the refractive index and rare-earth-dopant distributions should not exhibit the effects of burn-out, a phenomenon that occurs when the tube that will become the preform is heated and collapsed to form a solid rod. During this process, some of the dopants (notably Ge, P, and sometimes the rare-earth species) are volatilized, resulting in a drop in the refractive index and the rare-earth-dopant distributions near the center of the preform. These donut-shaped distributions overlap poorly with the LP_{01} mode-field distribution and are well matched to the intensity profile of the first higher-order mode (LP_{11}). In singlemode fiber, the effects of burn-out are not of great importance; in multimode fiber, however, this built-in mode discrimination must be overcome to achieve the desired LP_{01} operation. Bend-loss-induced mode-filtering can counteract such mode discrimination, but burn-out significantly undermines the ability to scale d_{core} while maintaining diffraction-limited beam quality.

The mode-filtering technique would be ineffective if the coiled fiber exhibited rapid transverse-mode scrambling between LP_{01} and higher-order modes. In practice, this problem is not observed for high-quality double-clad fiber manufactured using modified chemical vapor deposition, as demonstrated by the lack of degradation of slope efficiency upon coiling.

Many applications for fiber sources need stable linear polarization, which requires the use of polarization-maintaining (PM) fiber.[7] Moreover, use of PM fiber is not detrimental for any application because such fiber can be used to construct both polarized and unpolarized sources.[8] The mode-filtering technique can be applied to PM fiber.

From the time double-clad fiber was first reported in 1988 through the telecom boom of the mid-1990s, the supply of multimode double-clad fiber appropriate for mode filtering has been limited and of variable quality. Moreover, very few fiber manufacturers have the requisite combination of capabilities to produce high-quality, rare-earth-doped double-clad fiber for high-power operation. Recently, however, the availability of double-clad fiber has increased as industrial and military applications of fiber sources have expanded, driven largely by power scaling. Multimode double-clad fiber is now becoming available with standardized, reproducible specifications that are well matched to the needs of mode filtering and power scaling (see ***oe**magazine*, August 2003, p. 53). This development promises to allow high-power fiber sources to enter markets currently dominated by other laser types; moreover, the uniquely practical advantages of high-power, diffraction-limited fiber lasers and amplifiers will enable a variety of new applications. **oe**

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