Optical fibers for high-power eye-safe lasing applications

Adrian Carter

A new type of inner cladding allows the fabrication of large-mode-area laser fibers with low numerical aperture and near-diffraction-limited beam quality.

Fiber lasers have recently undergone rapid development, making them attractive candidates for many high power applications in material processing, medicine, spectroscopy, and military countermeasures. Over the past few years, most of the research effort has been directed towards achieving high continuous wave (CW) output powers. The recent development of large-mode-area (LMA) Yb-doped double-clad fibers and high brightness diodes with kilowatt-level CW outputs and megawatt-level peak powers in sub-nanosecond pulsed amplifiers accordingly represents a key advance. Of significant interest is that these output powers have been achieved with near diffraction-limited output beam quality. This is because the low numerical aperture (NA) core supports only a few modes and the higher order modes can be easily discriminated against by preferential seeding\(^1\) and/or bending.\(^2\) However, the development of LMA fibers has until recently been restricted to Yb fibers for use in the 1.0\(\mu\)m region. This is due to the inherent difficulties associated with manufacturing fibers containing relatively high lanthanide-dopant concentrations while maintaining a low core NA.

In spite of their numerous advantages, a significant drawback of Yb-based fibers is the relatively high sensitivity of the human eye to wavelengths in their 1.0\(\mu\)m operating range. Hence the interest for developing fibers in the ‘eye-safe’ 1.5–2.0\(\mu\)m range has increased significantly. Energy transfer processes in (a) Er:Yb- and (b) Tm-doped fibers.

\[\text{Er}^{3+}, \text{Tm}^{3+}\] Furthermore, energy transfer from Yb\(^{3+}\) to Er\(^{3+}\) can also be enhanced by doping the glass host with phosphorus, which increases its Raman shift. This is due to the presence of P=O bonds that increase the phonon energy of the host, facilitating the rapid depopulation of the \(4I_{11/2}\) energy level of Er\(^{3+}\), thereby limiting energy back-transfer to the \(2F_{5/2}\) level of Yb\(^{3+}\). Thus, efficient Er:Yb fibers require substantially high concentrations of Yb\(^{3+}\), Er\(^{3+}\), and P, each of which markedly increases the refractive index of the base glass, resulting in relatively high core NAs (0.17–0.20 or greater).

Commercially-available fiber lasers operating in the 2\(\mu\)m region are currently based on Tm-doped fibers resonantly pumped at \(\sim 1.6\mu\)m by an Er:Yb fiber laser, which is in turn diode-pumped at \(\sim 960\)nm. The optical-to-optical efficiencies of such devices are typically less than 30%. However, recent advances in the compositional engineering of Tm\(^{3+}\)-doped silica fibers have led to substantially higher efficiencies, approaching 65%.\(^4\) These improved efficiencies require high Tm concentrations and result from the cross-relaxation processes illustrated in Figure 1(b) that involve the \(3H_{4}, 3F_{4}\) and \(3H_{6}\) levels and enhance the \(3H_{6} \rightarrow 3F_{4}\) lasing emission by allowing every pump photon (793nm) to generate two signal photons. In this scheme, up-conversion processes, such as \(3F_{4} \rightarrow 3H_{5}\) and \(3F_{4} \rightarrow 3H_{4}\), have to be minimized to prevent the depopulation of the \(3F_{4}\) energy level. This can be achieved by preventing clustering of the Tm ions with very high Al:Tm concentration ratios.

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The requirement for these high concentrations however, substantially increases the refractive index of the core compared to pure silica and limits the ability to achieve the low NA required for the fabrication of Tm-LMA fibers, as is the case for Er:Yb co-doped fibers.

The problem can be addressed by incorporating an appropriately sized pedestal index feature around the core (see Figure 2), which makes it possible to reduce the effective core NA. The key benefit of this design is clearly the reduced number of core modes, as illustrated in Figure 3 showing that pedestal incorporation reduces the number of modes in a 25µm core fiber from 11 to 4, making it possible to achieve near-diffraction-limited beam quality.

Using this approach, a number of large-core-diameter (typically around 25µm) LMA Tm- and Er:Yb-doped fibers with an effective core NA of 0.1 have been manufactured and commercialized. Recent results have also demonstrated the suitability of these large core fibers for scaling to high output powers while maintaining near diffraction-limited beam qualities. It is therefore anticipated that, just as LMA Yb fibers led to the development of kilowatt lasers operating at ~1.0µm, the availability of LMA Er:Yb- and Tm-doped fibers will also spur the development of high power lasers and amplifiers in the eye-safe 1.5µm and 2.0µm regions.

Author Information

Adrian Carter
Nufern
East Granby, CT

Adrian Carter is the founder of Nufern, where he is presently chief technology officer. He received his BS and PhD in physical and theoretical chemistry from the University of Sydney, Australia, and was previously an assistant professor at the Laboratory for Lightwave Technology at Brown University.

References