10.1117/2.1200807.1152

Developments in thulium-doped fiber lasers offer higher powers

Scott Christensen, Gavin Frith, and Bryce Samson

Advanced light sources with optical efficiencies approaching 65% and kilowatt output powers have practical potential in areas ranging from defense to medicine.

Thulium (Tm)-doped fiber lasers, which operate at 1.9–2.1μm, are emerging as the latest revolution in high-power fiber laser technology.[1] Although no laser is completely safe for for human eyes, this technology falls into the 'eye-safer' category, promising advantages over 1μm lasers for industrial and military directed-energy applications. The potential for scaling up the power in pulses is beginning to be realized, with peak powers now approaching 100kW without requiring excessively complicated fiber designs or sacrificing beam quality.[2]

Until recently, most advances in fiber laser technology focused on ytterbium (Yb)-doped fibers operating around 1μm. Two factors account for much of the success of these lasers. First, the materials can be very efficient because the transfer of energy between atomic energy levels can be very efficient (in other words, this materials system has a low quantum defect). Second, there are many high-brightness pump sources at 915–975nm. These factors allow high-efficiency operation and low thermal loading of the fiber. As a result, Yb-doped fiber lasers have now been scaled in power to above 3kW with near-diffraction-limited beam quality.[3]

Ytterbium-sensitized erbium (Er:Yb) fibers operating at ∼1.55μm have been the traditional choice for eye-safer fiber laser applications. Progression of the technology has been aided by the abundance of fiber components and test instruments at this wavelength, which were primarily developed for the telecommunications industry. Although the quantum defect for such a system indicates that efficiencies approaching 60% should be possible, very few demonstrations have topped 40%, and power scaling is hindered by an effect called back conversion.[4] Figure 1 compares the progress of Yb-doped lasers at 1μm, Er:Yb-doped fibers at 1.5μm, and 2μm Tm-doped fiber laser technology. It shows that the power scaling of Tm-doped lasers has rapidly gained momentum and now exceeds Er:Yb technology.[5]

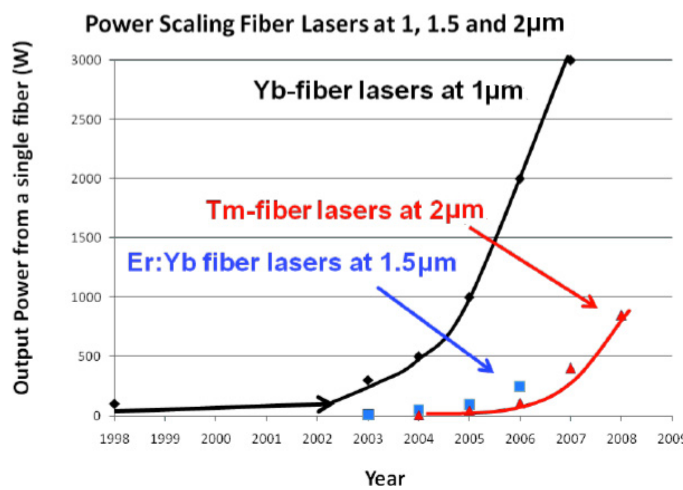

Figure 1. Comparison of power scaling from a single-fiber laser at various wavelengths. In the past 5 years, power output from ytterbium (Yb)-doped fiber lasers has increased dramatically. Improvements for thulium (Tm)-doped fiber are more recent. Er: Erbium.

The two main pump bands for Tm are at 0.8 and 1.6μm. Because high-power 1.6μm laser diodes are still relatively new, pumping at this wavelength is usually implemented using Er:Yb fiber lasers.[6] The overall optical efficiency of the system is therefore reduced by the efficiency of the Er:Yb laser. In contrast, 0.8μm diode technology is relatively mature due to the large market for pumping Tm- and neodymium-doped crystals. At first glance, one would presume that the lower quantum defect associated with pumping at ∼1.6μm should yield much higher conversion efficiency than pumping at 0.8μm. However, owing to the cross-relaxation or 'two-for-one' phenomenon, as shown in Figure 2, pumping at ∼0.8μm yields similar efficiencies of 60–65%. Also, the perception that pumping at ∼0.8μm causes rapid photodegradation was recently disproven. The latest generation

Continued on next page

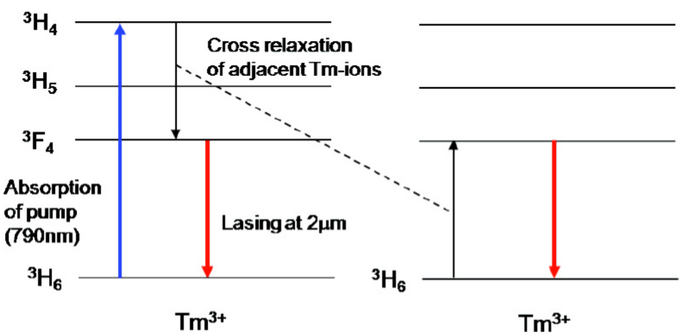

Figure 2. *Cross-relaxation of excited Tm ions into the metastable level allows for pump (800nm) to signal (2μm) conversion efficiencies to exceed 60%, despite the large quantum defect between the two wavelengths.* $^3H_4$, $^3H_5$, $^3F_4$, *and* $^3H_6$ *represent energy levels.*

of fibers with optimized compositions shows device lifetimes of several thousands of hours or more may be expected.[7]

Power scaling of continuous-wave (CW) fiber lasers offers a simple benchmark that shows improvements in fiber technology. Recent results on pulsed Tm-doped fiber lasers operating in the nanosecond regime also show performance beyond that available from 1.5μm systems, including pulse energies approaching a millijoule with near-diffraction-limited beam quality. As with the CW results, the performance of these systems is limited by the pump power rather than by the fiber itself. This is in contrast to most of the recent work on 1μm systems, where the primary limitation is commonly nonlinear effects within the fiber amplifier. The precise limitations of pulsed fiber lasers at 2μm are the subject of some speculation at the moment.

Despite the lack of optimized components at the 2μm wavelength compared with 1.5 and 1μm, several monolithic platforms are now commercially available, which use components similar to those developed for shorter wavelengths, such as fiber Bragg gratings and couplers. We expect that fiber-coupled isolators and a broader range of fiber-coupled seed sources will also become more widely available as more people use these lasers. High-brightness fiber-coupled pump diodes at 790–800nm—which can pump high-power Tm-fiber lasers—are becoming more readily available. They still lag behind the diodes emitting in the 900–1000nm range in both power and dollar-per-watt cost.

Much of the motivation to develop high-power 2μm systems is for applications that benefit from operating at eye-safer wavelengths. One benefit is that at 2μm, the permissible power transmission in free space can be several orders of magnitude greater than at 1μm. Military deployment of laser weapons systems could certainly find wider acceptance if the systems operated at eye-safer wavelengths. Pulsed laser systems may be used either for direct applications such as LIDAR (light detection and ranging) and range finding, or for conversion into the mid- and far-IR for military countermeasures, remote sensing, and spectroscopy. Single-frequency systems at 2μm are of interest for wind shear and turbulence mapping as well as coherent detection. In the medical market, Tm-doped fiber lasers present a potential alternative to current-generation CW solid-state 2μm lasers.

As this technology rapidly matures, we see a broad range of uses beginning to emerge. Although their efficiency will never rival that of Yb-doped fibers, for eye-safer and pulsed applications Tm-doped fibers appear to hold several key advantages over competing technologies. They may well represent a significant revolution in fiber laser technology.

Author Information

Scott Christensen, Gavin Frith, and Bryce Samson
Nufern
East Granby, CT
http://www.nufern.com

References

1. G. Rines, K. Wall, E. Slobodtchikov, and P. Moulton, *Efficient, high-power, Tm-doped silica fiber laser*, **Solid State Diode Laser Technol. Rev.**, p. 229, 2008.
2. D. Creeden, P. A. Budni, and P. A. Ketteridge, *60 W of average output power from a pulsed thulium-doped fiber amplifier operating at 2 microns*, **Solid State Diode Laser Technol. Rev.**, p. 190, 2008.
3. V. Fomin, A. Mashkin, M. Abramov, A. Ferin, and V. Gapontsev, *3 kW Yb fibre lasers with a single-mode output*, **Int'l Symp. High-Power Fiber Lasers Appl.**, 2006.
4. D. Y. Shen, J. K. Sahu, and W. A. Clarkson, *Highly efficient Er,Yb-doped fiber laser with 188W free-running and >100W tunable output power*, **Opt. Express 13**, pp. 4916–4921, 2005.
5. Y. Jeong, S. Yoo, C. A. Codemard, J. Nilsson, J. K. Sahu, D. N. Payne, R. Horley, P. W. Turner, L. M. B. Hickey, A. Harker, M. Lovelady, and A. Piper, *Erbium:ytterbium co-doped large-core fiber laser with 297W continuous-wave output power*, **IEEE J. Selected Topics Quantum Electron. 13**, pp. 573–579, 2007. doi:10.1109/JSTQE.2007.897178
6. D. Gapontsev, N. Platonov, M. Meleshkevich, A. Drozhzhin, and V. Sergeev, *415W single-mode CW thulium fiber laser in all-fiber format*, **CLEO Europe**, 2007. Post-deadline paper CP2-3-THU
7. G. Frith, B. Samson, A. Carter, J. Farroni, K. Farley, and K. Tankala, *Efficient and reliable 790nm-pumped Tm lasers from 1.91 to 2.13μm*, **Solid State Diode Laser Technol. Rev.**, p. 200, 2008.