Thulium-doped fiber lasers: the latest revolution in high-power fiber technology.

With output power levels now approaching the kW level, Tm-doped fiber lasers are beginning to emerge as the latest revolution in high-power fiber laser technology.[1] Operating at 1.9–2.1 µm, this technology falls into the 'eye-safer' category of lasers giving it potential advantages over 1 µm lasers for industrial and military directed energy applications. The greater potential for pulse scaling is also beginning to be realized with peak powers now approaching 100 kW without requiring excessively complicated fiber designs or sacrificing beam quality.[2]

Until recently, advances in fiber laser technology have primarily focused on Yb-doped fibers operating around 1 µm. The success of Yb-doped fiber technology is primarily owed to two main factors: the low quantum defect associated with this system and the abundance of high-brightness pump sources at 915–975 nm. This low quantum defect leads to 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 3 kW with near diffraction limited beam quality.[3]

Ytterbium sensitized erbium (Er:Yb) fibers operating at ~1.55 µm have been the traditional choice for eye-safer fiber laser applications. Progression of this 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 shown greater than 40% to date, and back conversion effects remain a hindrance for power scaling potential.[4] Figure 1 compares the progress of 1, 1.5 and 2 µm laser technology and shows that the power scaling of Tm-doped fiber lasers has rapidly gained momentum and now exceeds Er:Yb technology three-fold.[5]

The two main pump bands for Tm are at 0.8 and 1.6 µm. At first glance, one would presume that the lower quantum defect associated with pumping at ~1.6 µm should yield much higher conversion efficiency; however, owing to the cross-relaxation or 'two-for-one' phenomenon as shown if figure 2, similar efficiencies of 60~65% may be achieved when pumped at ~0.8 µm. High-power 1.6 µm laser diodes remain a relatively new technology, so 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, 0.8 µm diode technology is relatively mature due to the large market for pumping Tm- and Nd-doped crystals. The perception that pumping at ~0.8 µm causes rapid photo-degradation has recently been disproven. Latest generation fibers with optimized compositions show device lifetimes of several thousands of hours or more may be expected.[7]

Although power scaling of CW fiber lasers offers a simple benchmark to show improvements in the fiber technology, recent results on pulsed systems operating in the nanosecond regime also show performance levels beyond that available from 1.5 µm systems, including pulse energies approaching the millijoule level with near diffraction limited beam quality. As with the CW results, the available performance levels of these systems are limited only by the pump power rather than the fiber technology itself. This is in contrast to most of the recent work on 1 µm systems, where the primary limitation is most commonly non-linear effects within the fiber amplifier. The precise limitations of pulsed fiber lasers at 2 µm are the subject of some speculation at the moment and may well offer significant advantages over operating at the shorter wavelengths.

Despite the lack of optimized components at the 2 µm wavelength compared with 1.5 and 1 µm, several monolithic platforms are now becoming commercially available which utilize similar components to those that have been developed for shorter wavelengths, such as fiber Bragg gratings and couplers. We expect fiber-coupled isolators and a broader range of fiber coupled seed sources will also become more widely available as the customer base expands. High-brightness fiber-coupled pump diodes at 790–800 nm for pumping high power Tm-fiber lasers are becoming more readily available but still lag behind the 9xx-nm devices in power and are currently more expensive on a dollar-per-watt basis.

Much of the motivation for development of high-power 2 µm systems has been for applications which would benefit from operating at eye-safer wavelengths, where permissible free space transmission levels can be several order of magnitude greater than at 1 µm. 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 and range finding, or for conversion into the mid- and far-IR for countermeasures, remote sensing, and spectroscopy. Single-frequency systems at 2 µm 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 2 µm lasers.

As this technology rapidly matures, we see a broad range of potential applications 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.

References

[1] P. F. Moulton, “Power scaling of high-efficiency Tm-doped fiber lasers” paper 6873-15, Photonics West, San Jose, 19-24 January (2008)

[2] D.Creeden, P. A. Budni, P. A. Ketteridge, “High power nanosecond pulse amplification at 2-microns in thulium-doped fiber pumped at 795nm”, postdeadline paper, *Photonics West*, San Jose, 19-24 January (2008).

[3] V. Fomin, A. Mashkin, M. Abramov, A. Ferin, V. Gapontsev, "3 kW Yb fibre lasers with a single-mode output," in *International Symposium on High-Power Fiber Lasers and their Applications*, St. Petersburg (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” *Optics Express*, Vol. 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 Journal in Selected Topics in Quantum Electronics,* Vol 13, pp. 573-579 (2007)

[6] D. Gapontsev, N. Platonov, M. Meleshkevich, A. Drozhzhin & V. Sergeev, “415W Single-Mode CW Thulium fiber laser in all-fiber format” postdeadline paper CP2-3-THU, *CLEO Europe*, Munich (2007).

[7] G. Frith, B. Samson, A .Carter, D. Machewirth, J. Farroni and K. Tankala “Power scaling 790nm-pumped Tm-doped devices from 1.91 to 2.13µm” *Photonics West*, San Jose, 19-24 January, (2008).

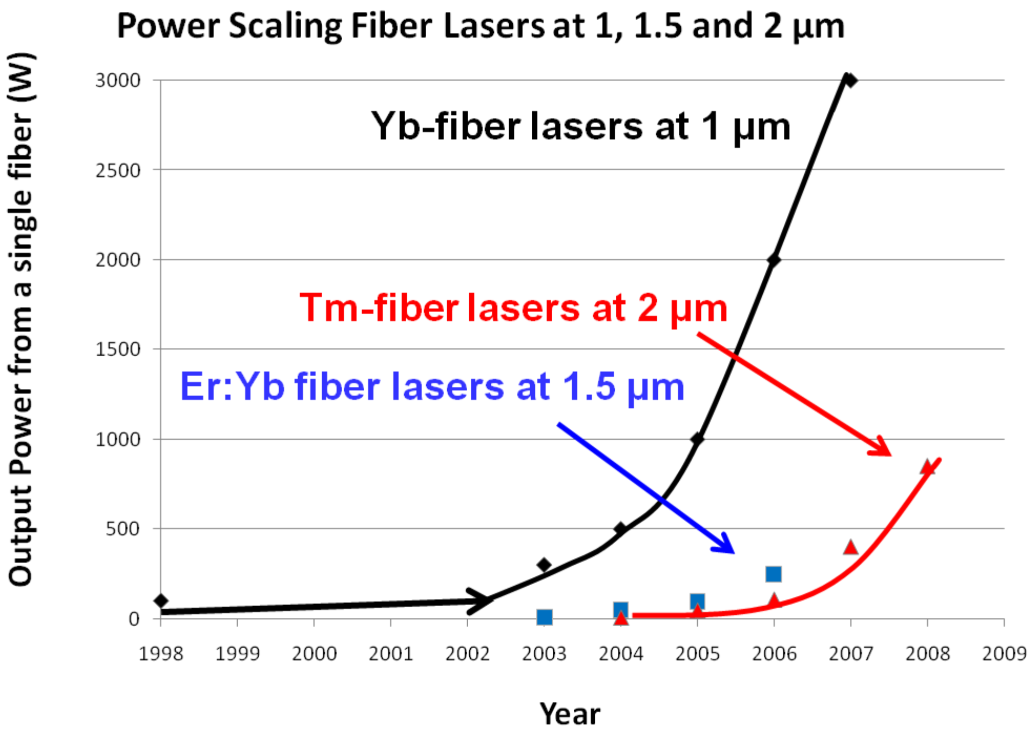

Figure 1: Comparison of power scaling from a single fiber laser at various wavelengths.

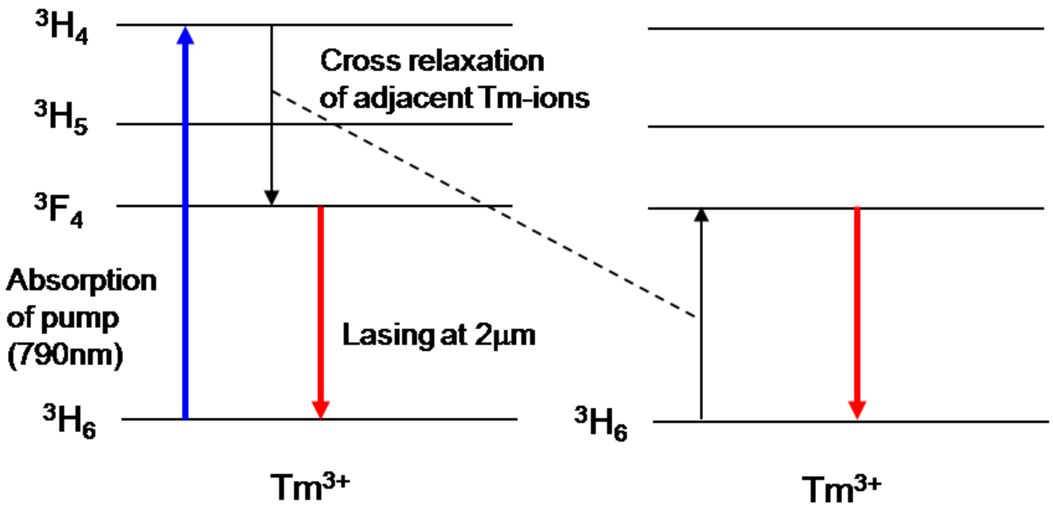

Figure 2: Cross relaxation of excited Tm-ions into the metastable level allows for pump (800 nm) to signal (2 µm) conversion efficiencies exceed 60%, despite the large quantum defect between the two wavelengths.