Highly efficient, Large Mode Area (LMA) fibers for use in high power eye-safe wavelength lasing applications

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Summary
Through the incorporation of a unique raised inner-cladding, which facilitates the use of conventional LMA mode selection techniques, we have extended the availability of fibers suitable for high power lasing applications to the eye-safe region.

The recent development of large-mode area (LMA) Yb-doped double clad fibers and high brightness diodes has lead to demonstrations of kilowatt level CW outputs and megawatt level peak powers in sub-nanosecond pulsed amplifiers. Such output powers have been achieved with near diffraction-limited output beam quality, because the low 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, due to the inherent difficulties associated with manufacturing fibers containing relatively high lanthanide ion dopant concentrations whilst maintaining a low core NA, the development of LMA fibers has until recently been restricted to Yb fibers for use at around 1.0μm.

In spite of its numerous advantages, a significant drawback of the Yb-based system is the relatively high sensitivity of the human eye to wavelengths in the 1.0μm region. Consequently for a variety of military and commercial applications, such as ranging, pollution monitoring, clear-air turbulence analysis and free-space communications, operating in the "eye-safe" 1.5-2.0μm range is preferred. Furthermore there are a number of medical and sensing applications that specifically require lasing output in this wavelength range.

It is well known that sensitizing Er doped fibers with Yb enhances pump absorption and hence increases the efficiency at the Er lasing wavelength. Sensitization is accomplished by taking advantage of the broad absorption band and the high cross-section of Yb compared to Er.[3] Furthermore, for efficient energy transfer from the Yb to Er ion, the Raman shift of the base glass is increased by doping it with phosphorus. The presence of P=O bonds increases the phonon energy of the glass host, facilitating rapid depopulation of the $^4I_{11/2}$ band of Er ions, thereby limiting the back-transfer of energy (Figure 1a). Thus, efficient Er:Yb fibers require substantially high levels of Er, Yb and phosphorus; each of which markedly increase the refractive index of the base glass, resulting in relatively high core NAs of around 0.17-0.20 or greater.

Current commercially available fiber lasers operating at around 2μm are based on Tm-doped fibers resonantly pumped at ~1.6μm by an Er:Yb fiber laser, which is in turn diode pumped at ~960nm. Consequently the optical-to-optical efficiencies of such devices are typically less than 30%. However recent advances in the compositional engineered of Tm^{3+} doped silica fibers have led to the development of fibers with substantially higher efficiencies, approaching 65%.[4] These fibers owe their improved efficiencies to a cross relaxation processes, namely $^3H_4$, $^3H_6 \rightarrow {}^3F_4$, $^3F_4$ (Figure 1b), which results in the generation of two signal photons for every pump (793 nm) photon but which necessitates the presence of high Tm concentrations. Meanwhile, energy transfer up-conversion processes, namely $^3F_4$, $^3F_4 \rightarrow {}^3H_5$, $^3H_6$ and $^3F_4$, $^3F_4 \rightarrow {}^3H_4$, $^3H_6$, have to be kept in check to prevent quenching of the $^3F_4$ energy multiplet. This can be minimized by preventing clustering of the Tm ions with very high Al:Tm concentration ratios. So it is that the high Tm and Al concentrations, required for highly efficient operation, substantially increase the refractive index of the core compared to pure silica.

Hence, as in the case of Er:Yb co-doped fibers, the compositional requirements for an efficient Tm fiber limits the ability to make the low NA desired for fabrication of LMA fibers. To solve this problem it was recognized that through the incorporation of an appropriately sized pedestal index feature around the core (Figure 2) it is possible to reduce the effective core NA.[5] The key benefit of the pedestal fiber design is clearly the reduced number of modes supported by the doped core of the fiber. Figure 3 shows that incorporation of the pedestal reduces of the number of core modes in a 25micron core fiber from 11 to 4, making it possible to achieve near diffraction-limited beam quality.

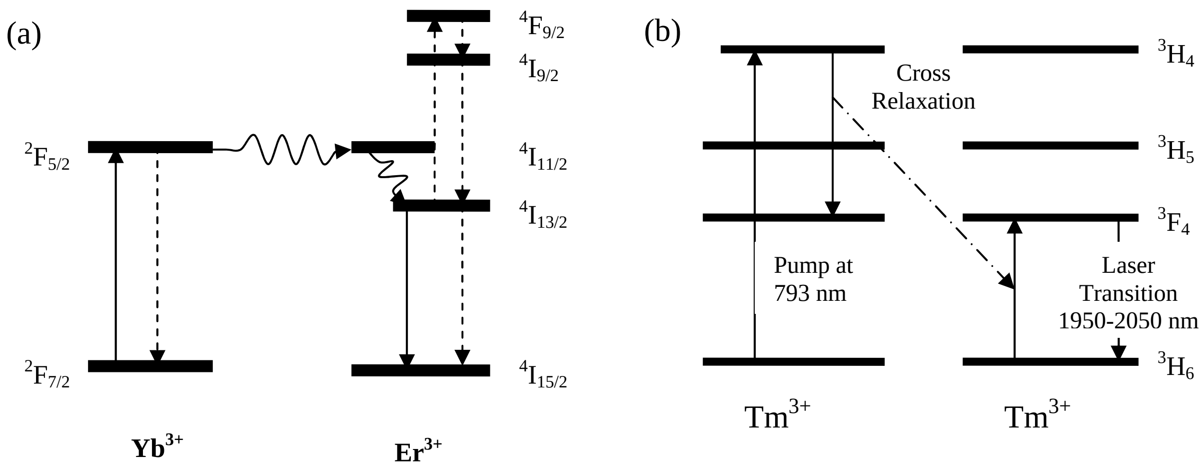

Figure 1: Energy transfer processes in (a) Er:Yb and (b) Tm doped fibers

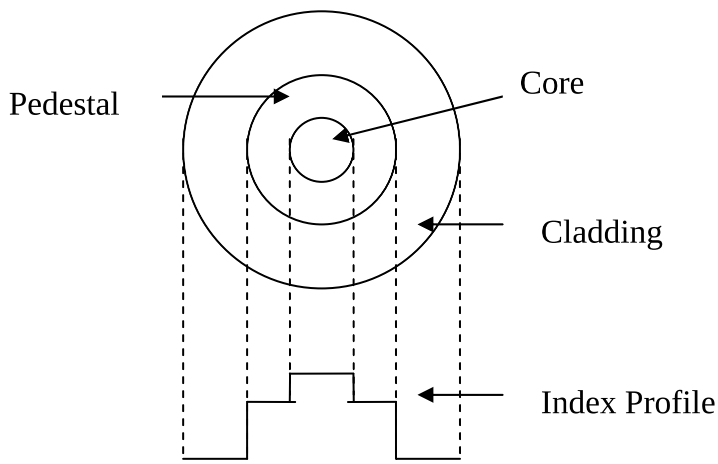

Figure 2: Schematic diagram of LMA fiber using a pedestal design

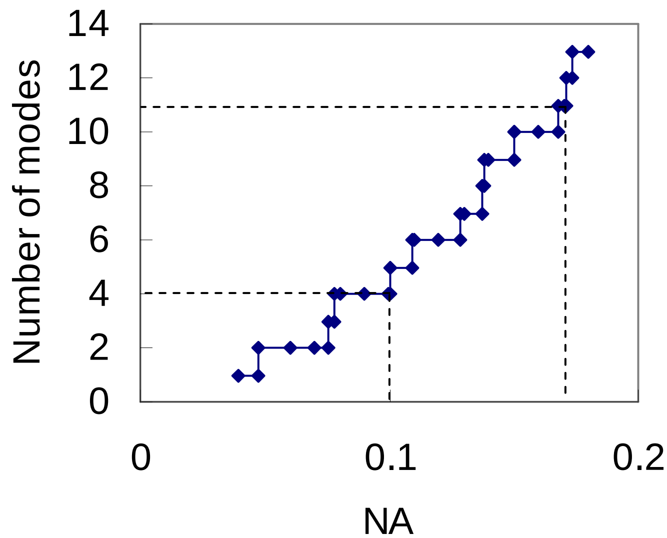

Figure 3: The influence of NA on the number of modes in a 25 μm core fiber

A number of large core diameter (typically around 25μm) LMA Tm and Er/Yb doped fibers with a pedestal of index appropriate to achieving an effective core NA of 0.1 have been manufactured and commercialized.[6] Recent published results have demonstrated the suitability of these large core fibers for scaling to high output powers but whilst maintaining near diffraction-limited beam qualities.[7-10] It is therefore anticipated that just as LMA Yb fibers led to the development of kilowatt level lasers at around 1.0μm so to the evolution of LMA Er:Yb and LMA Tm doped fibers can be expected to spur the development of high power lasers and amplifiers in the eye-safe regions of 1.5μm and 2.0μm respectively.

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