New Developments in High Power Eye-Safe LMA Fibers

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ABSTRACT

In this paper we present advances made in the development and fabrication of highly efficient, large-mode area fibers for eye-safe wavelengths (1.55 μm, 2.0 μm). LMA Er/Yb co-doped and Tm doped fibers have been successfully fabricated, with 25 μm core and 250 to 300 μm clad diameters, that are suitable for nanosecond pulsed amplification in LIDAR applications as well as high power CW amplification. Manufacturing challenges for these novel fibers are discussed. Measured and modeled data, for both types of fibers, are presented. The development of non-PM and PM-LMA fibers for eye-safe applications is expected to spur rapid progress in power scaling at these wavelengths, similar to that witnessed by the industry at 1.06 μm.

Key Words: Eye-safe, Large Mode Area, Er-Yb co-doped, Tm doped, High Power, Fiber Lasers and Amplifiers

INTRODUCTION

The advent of double clad fiber technology has facilitated the evolution of high power lasers and amplifiers . These high power devices have numerous military, industrial, medical and scientific applications. Fiber lasers and amplifiers are being used in these markets for materials processing, optical sensing, range finding, laser weapons and free space communications.

Recent development in large-mode area (LMA) fibers [1-3] has lead to demonstrations of kiloWatt level outputs in CW lasers and MegaWatt level peak powers in pulsed amplifiers (with sub-nanosecond pulses). However, development of LMA fibers has largely been restricted to ytterbium based fibers for use at around 1.06 μm, due to the relative ease of manufacturing LMA Yb^{3+} doped fibers and the low quantum defect (hence high efficiencies (~ 80%), associated with this laser system). The ability to achieve relatively high concentrations of Yb with relatively low levels of matrix modifying co-dopants lends itself to fabricating low numerical aperture (NA), large core fibers. The low NA core supports a few modes and the higher order modes can be easily discriminated against by preferential seeding [4] or bending [5] to achieve diffraction limited operation. In spite of the numerous advantages, a significant drawback of the Yb based systems is the relatively high sensitivity of the human eye to wavelengths in the 1.0 μm region.

The retinal absorption of radiation in the 1.5 μm and 2 μm wavelength regions is substantially lower than that at 1.0 μm. High power lasers and amplifiers operating in these wavelength bands are therefore of interest in both military and commercial applications. In military applications these wavelengths are of interest because they minimize collateral damage. Similarly, "eye-safe" lasers are welcome in commercial application as they greatly reduce the challenges associated with laser safety. In addition to eye-safety, the 2.0 μm lasers may find applications as pump source for Ho-lasers or non-linear conversion to longer wavelengths. Although there has been significant interest in eye-safe lasers, progress in developing high power CW and pulsed lasers at these wavelengths has been limited by the availability of LMA Er:Yb and Tm doped fibers. This limitation is primarily caused by the minimal effort dedicated towards development of these LMA fibers for eye-safe wavelengths, due to the difficult processing of low core-NA optical fibers containing these rare-earth dopants.

Despite the lack of LMA fibers, important work has been conducted in developing high power Er:Yb lasers using multimode fibers. Koroshetz et. al. [6] demonstrated a 40 W, 10 Gb/s amplifier for free space communication and Shen et. al. [7] reported 188 W of CW output with an M^2 of 1.9 using a 30 um, 0.22 NA Er:Yb codoped fiber. In addition, Yusim et. al. [8] have been able to take a 20 μm core Er:Yb fiber, which supports 30 modes, and achieve 100 W output with a near diffraction limited beam by employing single mode fiber based components in the cavity and making careful splices between the SM fibers and the MM active fiber. Although a high power diffraction limited output was achieved, such methods are cumbersome and emphasize the need for LMA fibers. Similarly, noteworthy work has been conducted in developing highly efficient Tm doped fibers [9, 10] by exploiting the two-for-one cross relaxation process between Tm ions and output powers as high as 85 W have been demonstrated albeit with a multimode output [10].

In this paper, we discuss the challenges associated with fabricating LMA Er:Yb and Tm doped fibers. We report the development and performance of LMA Er:Yb co-doped fiber (25/300 um, core/clad dimensions) and Tm doped fiber (25/250 um). Such fiber will be useful in applications requiring good beam quality, high power CW amplifiers and nanosecond amplification for applications such as eye-safe LIDAR.

FIBER DESIGN CONSIDERATIONS

Unlike Yb doped fibers, the compositional requirements for Er:Yb and Tm doped fibers make fabrication of LMA fibers particularly challenging. The compositional requirements for these fibers are individually discussed below:

Er:Yb Co-doped Fibers: It is well known that sensitizing Er^{3+} doped fibers with Yb^{3+} enhances pump absorption and hence increases the efficiency at the Er^{3+} lasing wavelength. Er^{3+} has a very narrow absorption peak, and cannot be incorporated into silica glass at very high concentrations without clustering. Sensitization is accomplished by taking advantage of the broad absorption band and the high cross-section of Yb^{3+} compared to Er^{3+} [11]. Yb^{3+} ions can be incorporated into silica glass at a much higher concentration than Er^{3+} ions without clustering, with the result that Er:Yb co-doped fibers have a very broad absorption band, and it is possible to obtain a peak absorption which is more than two orders of magnitude greater than conventional Er^{3+} doped fibers [12].

For efficient energy transfer from the Yb^{3+} to Er^{3+} 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, and the Raman spectrum has a peak at 1330 cm^{-1}, as compared to 1190 cm^{-1} for pure silica [13]. This helps in rapid depopulation of the $^4I_{11/2}$ band of Er^{3+} ions, limiting the back-transfer of energy from Er^{3+} to Yb^{3+} ions (Figure 1a). Thus, efficient Er:Yb fibers contain phosphorus in the core. The phosphorus co-doping also aids in minimizing the clustering of the RE ions. A substantially high level of phosphorus is needed to achieve both of the aforementioned goals. However, phosphorus also increases the refractive index of the base glass, resulting in relatively high core NAs of around 0.17-0.20 or greater. Thus, the difficulty in producing an LMA fiber, which requires a low NA, becomes apparent.

Tm doped Fibers: Tm^{3+} doped fibers have a number of potential pump bands. However, pumping at 793 nm is preferred due to the availability of high power semiconductor diodes in the 800 nm spectral region. In conventional, Tm^{3+} doped fibers the maximum conversion efficiency of a 793 nm pumped laser is about 40%. However, compositionally engineered Tm^{3+} doped silica fibers can achieve substantially higher efficiencies (approaching 80%).

Important energy transfer processes relevant to the performance of Tm^{3+} doped silica fibers have been identified [14] and corroborated by others [10, 15]. Figure 1b shows the relevant cross relaxation and up-conversion in Tm^{3+} doped silica fibers. Two cross relaxation processes, namely $^3H_4$, $^3H_6 \rightarrow {}^3F_4$, $^3F_4$ and $^3H_4$, $^3H_6 \rightarrow {}^3H_5$, $^3F_4$, have been identified with the $^3H_4$, $^3H_6 \rightarrow {}^3F_4$, $^3F_4$ being very efficient in Tm doped silica due to the large degree of spectral overlap between the $^3H_4$, $\rightarrow {}^3F_4$ emission spectra and the $^3H_6 \rightarrow {}^3F_4$ absorption spectra. This cross relaxation process results in generation of two signal photons for every pump (793 nm) photon. This cross relaxation process can be promoted by using high Tm^{3+} concentrations. However, 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 using very high Al:Tm concentrations and thereby preventing clustering of the Tm^{3+} ions.

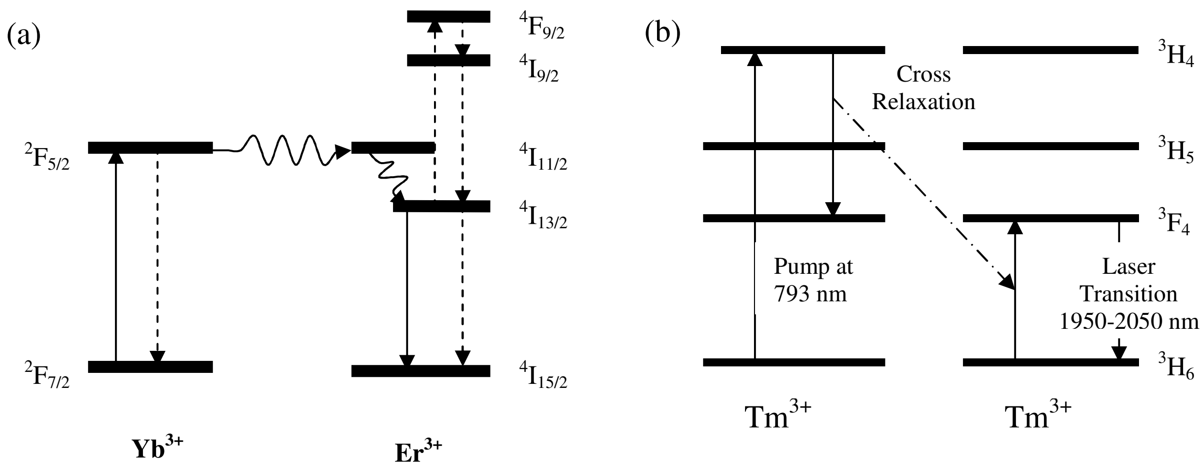
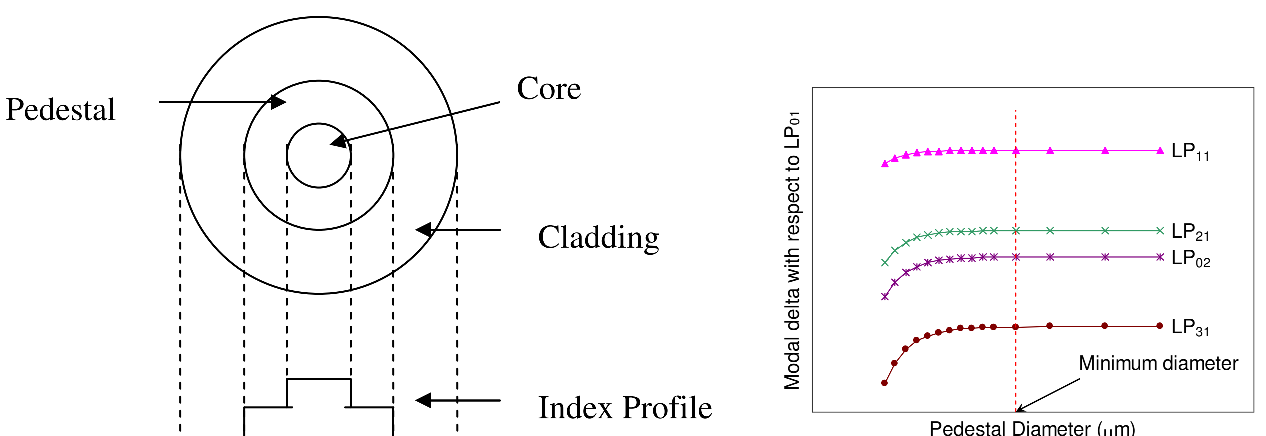


Figure 1: Energy transfer processes in (a) Er:Yb and (b) Tm doped fibers

Thus, high Tm^{3+} as well as high Al^{3+} concentrations are needed to achieve > 100% quantum efficiencies in Tm^{3+} doped fibers. In fact careful compositional engineering can yield power conversion efficiencies similar to Yb^{3+} doped fibers making such fibers very desirable for eye-safe laser system. The high Tm^{3+} and Al^{3+} concentration, needed for highly efficient fibers, 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^{3+} fiber limits the ability to make the low NA desired for fabrication of large mode area fibers. A typical NA would be in the range 0.18-0.24.

Large Mode Area Fiber Design: In a typical step index fiber the NA of the core is defined by the index of the core and that of the cladding surrounding it. However, if an appropriate pedestal is designed, the core can have an effective index as defined by the index of the core and that of the pedestal as shown in Figure 2. A specific pedestal index with respect to silica is chosen for Er:Yb doped fiber and Tm doped fiber to get a effective core NA of ≤ 0.10.



(a) (b)

Figure 2: (a) Schematic diagram of LMA fiber using a pedestal design, (b) Determination of minimum pedestal diameter

An appropriate pedestal size is chosen based on computer simulations, such that further increasing the pedestal diameter has no significant effect on the core modes, particularly the fundamental mode. At this diameter, the pedestal behaves as a “true” cladding to the core, rather than an extended core feature. If the pedestal is made any smaller, the mode field diameter of the core fundamental mode starts decreasing, and core light may be coupled to the pedestal modes. At the same time, the pedestal should not be made much larger than needed, due to increased manufacturing cost, as well as the possibility of trapping pump light in the helical modes in the pedestal.

EXPERIMENTAL RESULTS

Er:Yb Co-doped Fibers: Er:Yb doped single mode DC fibers were made with appropriate core composition to ensure that the Yb:Er ratio and host glass composition was appropriate to provide good slope efficiency. The index of the core relative to a pure silica cladding was measured and a suitable pedestal index was chosen to achieve an effective core NA of 0.1. In addition, the pedestal diameter was chosen to ensure that the mode field diameter of the fundamental mode was dictated by the index difference between the core and the pedestal only and not influenced significantly by the cladding. A fiber with a 25 µm core with a pedestal was fabricated such that the NA of the core was 0.1. The pedestal preform was made by the MCVD process and the rare-earths were incorporated in the core via solution doping. The fiber was drawn to a 300 µm diameter cladding and an NA of 0.46. Figure 3 shows the absorption and a slope efficiency ~30% for the 25/300 pedestal fiber.

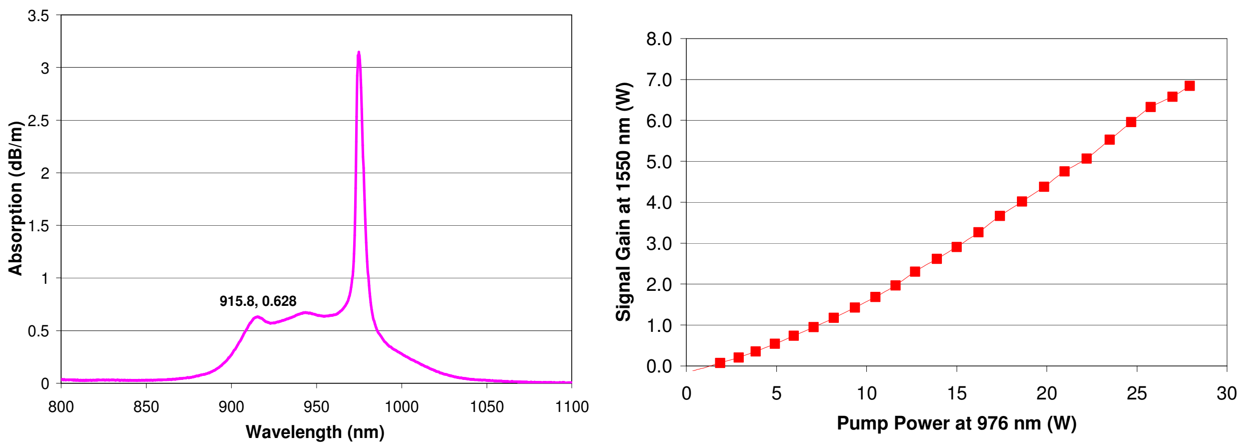


Figure 3: Absorption spectra and slope efficiency for the LMA-EYDF-25/300

The key benefit of the pedestal fiber design is clearly the lower number of modes supported by the doped core of the fiber, and we would expect this fiber to be easier to excite and maintain the fundamental mode than a similar diameter high NA (~0.17) core. The V-number of a 25 µm core fiber at an NA of 0.17 is 8.616, while at an NA of 0.10, it is 5.067. Figure 4 shows that incorporation of the pedestal is expected to reduce of the core modes from 11 to 4, making it possible to achieve near diffraction-limited beam quality. Importantly, both exciting the fundamental mode (at the expense of higher order modes) and maintaining the power within this mode through the appropriate fiber length should be significantly easier in the few-mode fiber rather than then highly multi-mode fiber, because of less mode coupling. More detail calculations including the effect of the pedestal on the modal parameters is summarized in table 1, where we estimate the first six modes of the core/pedestal design have significant overlap with doped core and will experience the highest gain.

Experimentally good beam quality from the pedestal fiber concept this has been verified in a seeded amplifier configuration taking care to excite the fundamental mode of the doped core [4] using standard mode matching techniques, where the pedestal fiber was easier to maintain good beam quality than high NA 18µm core fiber. Single mode beam profiles and an example M^2 measurement are shown in Figure 5 in fiber length compatible with making efficient amplifiers. Although good beam quality has been demonstrated in lab based experiments with high NA large core fibers [8], developing components and designing systems to guarantee a beam quality specification would be very challenging. We believe the adoption of a pedestal fiber design will make the challenges associated with delivering good quality at eyesafe 1.5µm and 2µm wavelengths manageable in future systems.

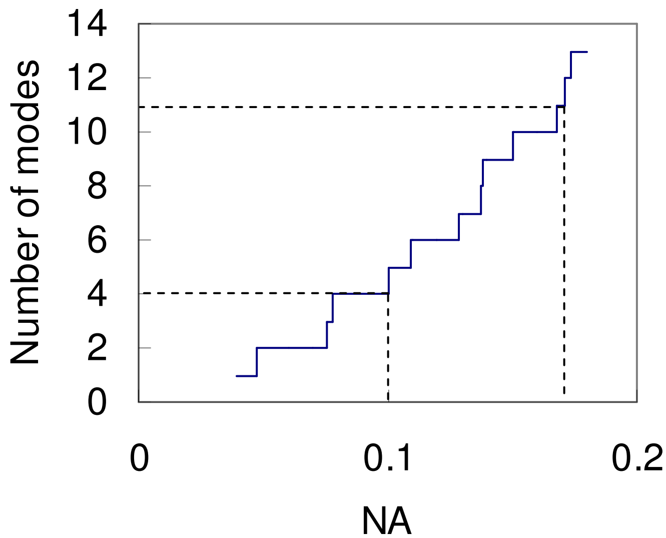


Figure 4: The influence of NA on the number of modes in a 25 μm core fiber

Table 1: Modal parameters for the six critical modes of for 25/300 pedestal fiber

Mode	**Aeff (μm2)**	**Confinement (%)**
LP01	336	99. 72
LP02	308	95.82
LP11	474	99.04
LP12	479	90.17
LP21	515	97.47
LP31	578	93.4

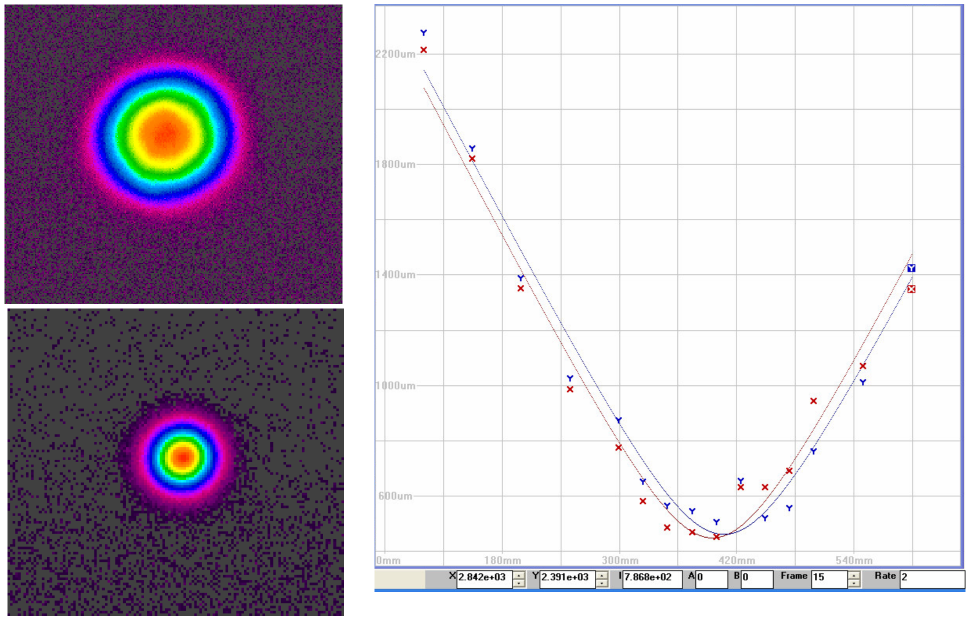


Figure 5: Near field and far field beam profile from LMA-EYDF-25/300 fiber under seeded amplifier conditions along with M^2 measurement.

Tm doped Fibers: Compositional development of Tm doped fiber was conducted to optimize the Tm concentration and Al concentration in the fiber to promote the two-for-one cross relaxation process. A 25 µm core(multimode) Tm doped fiber with a 250µm cladding was fabricated first to verify the performance of the fiber. Figure 6 shows the efficiency of the compositionally engineered multimode Tm fiber (NA~0.22). A slope efficiency of 53% (>130% quantum efficiency) confirms the two for one cross relaxation process in the fiber. Additional compositional work was subsequently conducted and a SE as high as 68% (170% quantum efficiency) was achieved.

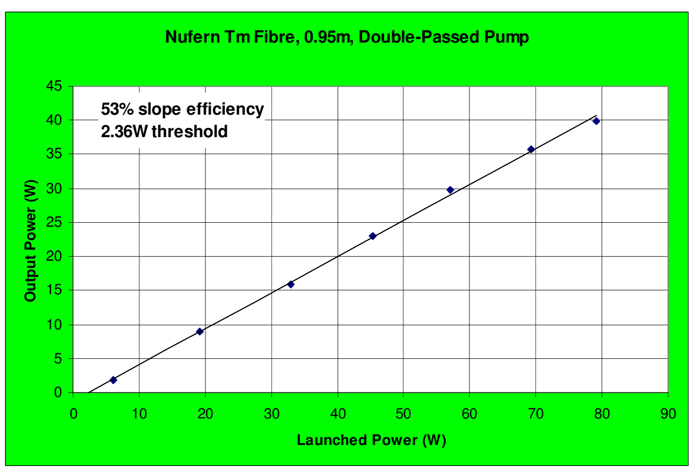


Figure 6: Slope Efficiency of Tm doped fiber (Data Courtesy: G. Frith, DSTO, Australia)

An LMA Tm doped fiber was fabricated with a 25 µm core and a pedestal of index appropriate to achieving an effective core NA of 0.1 NA using the same fabrication process as for the Er:Yb fiber.. Figure 7 is an index profile of the LMA Tm doped fiber (LMA-TDF-25/250) showing the refractive indices of the core and the pedestal relative to the cladding.

The absorption of the fiber at 790 nm was measured to be ~4.5dB/m and the absorption spectrum is shown in Figure 8. The fiber was evaluated at DSTO, Australia for beam quality and an $M^2$of < 1.3 was reported [16].

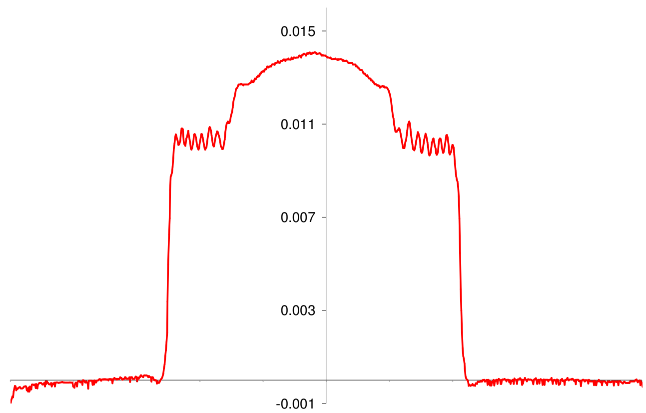


Figure 7: Fiber refractive index profile of large mode area Tm-doped fiber

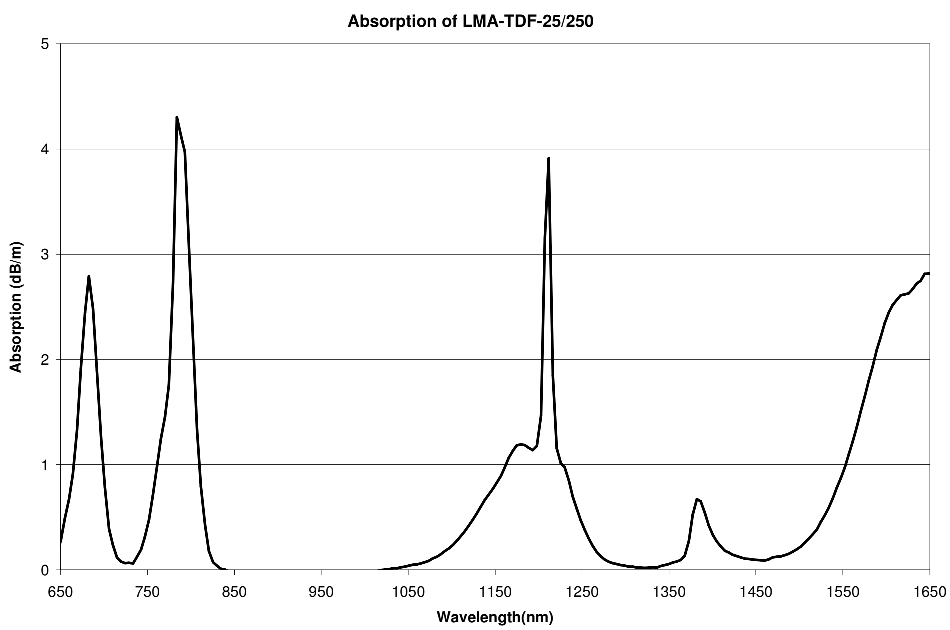


Figure 8: Cladding absorption for LMA-TDF-25/250

CONCLUSIONS

Much as LMA Yb fibres led to the development of kilowatt level lasers at around 1.06 µm, the evolution of LMA Er:Yb and LMA Tm doped fibres can be expected to spur the development of high power lasers and amplifiers in the eye-safe regions of 1.55 µm and 2.0 µm respectively.

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