High-Power Large-Mode Area Optical Fibers for Fiber Lasers and Amplifiers

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Abstract: Much of the recent improvement in high power fiber laser performance has been obtained by increasing the mode field area of the core guiding region beyond that found in standard telecom fiber designs. This simple scaling concept has delivered highly efficient kWatt level fiber lasers and amplifiers operating at 1μm, based on Yb-doping and more recently the extension to 2μm using highly efficient Tm-doped fibers.

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Introduction

Much of the recent progress in pushing cladding pumped high power lasers and amplifiers into the kWatt regime has been achieved in waveguides remarkably similar to the fiber designs commonplace in telecom systems and erbium doped amplifiers. One of the most successful levers used to increase the power and overcome non-linear limitations has been to increase the fiber core diameter to around 20 to 30μm. In this case the NA of the fiber is lowered (typically between 0.06 and 0.1) to reduce the mode content of the fiber core and one of several techniques adopted to maintain the single mode beam quality from the laser/amplifier, either based on preferential mode excitation [1] or higher order mode filtering [2]. Because of the relatively short fiber lengths involved (typically between several meters and several 10's meters) the ability of these so called *Large Mode Area* (LMA) fibers to maintain single mode beam quality over the active device length and even throughout chains of components such as couplers [3] and isolators has proved acceptable for many of the applications adopting high power fiber laser technology.

Results and Discussion

One of the problems often encountered when manufacturing fibers with low NA cores is the restriction placed on the glass composition and the reduced control of refractive index variation, uniformity and centre dip. Other issues to be addressed with the optimal composition are the rare earth solubility which may lead to clustering phenomena along with lifetime quenching [4] and photodarkening in the fiber [5]. This latter point is critical for reliable high power operation of the fiber laser over the 10-20,000hr lifetime (Figure 1) required in industrial laser applications. Furthermore, recent modeling of mode propagation in coiled LMA fibers [6] has shown that a regular step index between the core and cladding is not necessarily optimal for further scaling of mode size and this may place further demands on the control of refractive index profile for future LMA designs.

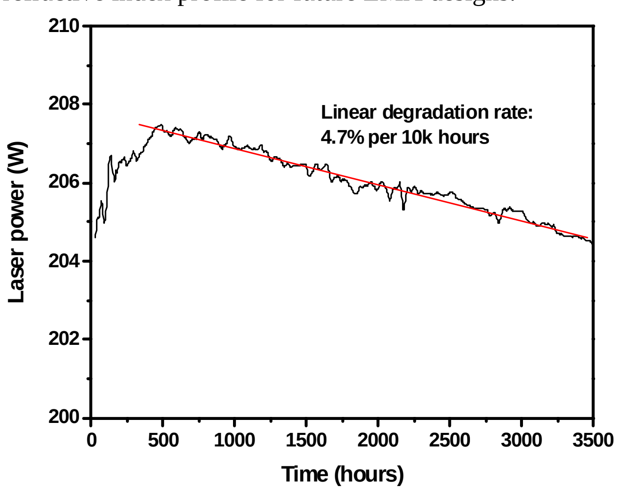

Figure 1*: Example of a high power single mode fiber laser based on Yb-doped LMA fiber operating at 200W without significant degradation over the lifetime of the laser, (typically >10,000hrs). The data is obtained from a free running laser in constant current mode.*

In addition to this, many of the more optimal rare earth doped glass compositions are not compatible with a low NA between the doped core and a pure silica cladding. These include cores highly doped with phosphorus for efficient Er:Yb fiber amplifiers at operating at 1.5µm [7] and Tm-doped fibers with very high dopant concentrations which are required to promote cross relaxation between excited Tm-ions. In this case the adoption of a raised pedestal layer around the rare earth doped core can reduce the effective NA of the core to around 0.1 and allow LMA designs with core diameters of around 25µm, whilst maintaining single mode beam characteristics throughout the device length [7].

Finally many high power applications require control of the output polarization of the single mode beam from the amplifier. The adoption of telecom-type panda fiber technology has proven the most valuable of all the PM fiber technologies in the high power laser/amplifier domain. As an example of the high power performance of this technology, we show in Figure 2 power levels approaching the kWatt from a PM-LMA fiber amplifier based on a 33µm core diameter (signal waveguide) and 440µm clad diameter (pump waveguide) fiber, delivering ~85% slope efficiency from 976nm (pump) to 1064nm (signal). Good PER and beam quality were obtained from this amplifier [8]. Clearly the incorporation of the panda stress elements into the cladding pumped fiber design does not affect the efficiency of the fiber or its ability to handle kWatt level pump power. Furthermore, the availability of key components and the optimization of splicing technology has allowed the building of monolithic (all-fiber) PM amplifiers at this kWatt level [8].

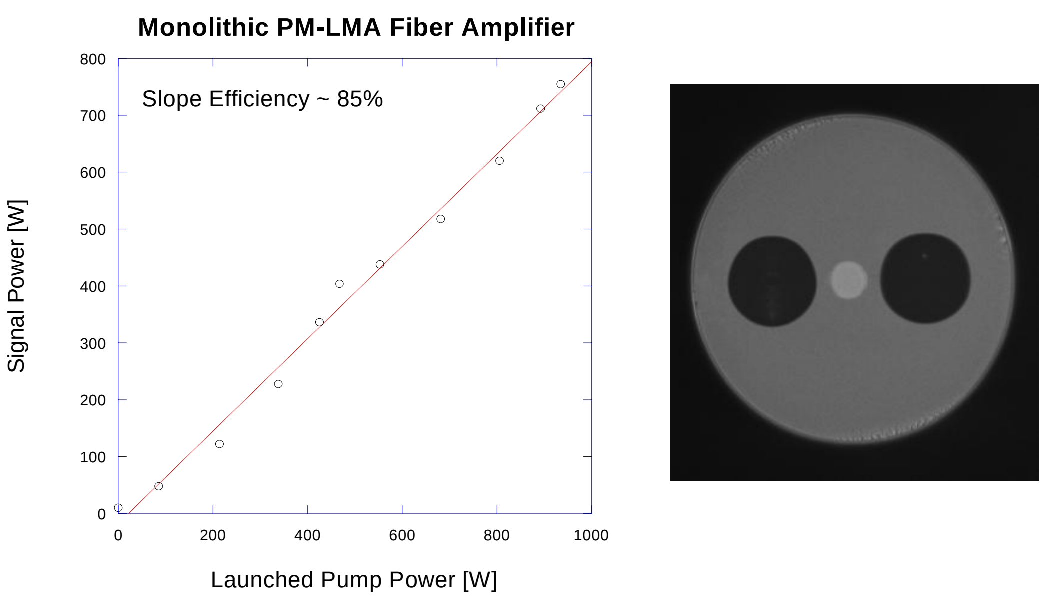

Figure 2: *750W from a PM-LMA fiber amplifier based on Yb-doped 33/440 fiber 5.5m long and pumped at 976nm with ~900W. The PM-LMA fiber is based on PANDA style stress rod technology as shown in the photograph.*

One of the benefits of Yb-doped fiber laser technology is the very high pump to signal conversion efficiency which results from the small quantum defect between pump and signal combined with the extremely efficient lasing process in an optimized Yb-doped fiber. Applications involving the current solid state laser technology operating at 1064nm, based on Nd-YAG or disc laser technology, correspond well with the lasing wavelength of most Yb-doped fiber lasers. However applications where eye-safe operating wavelengths (>1.4µm) are important usually involve either erbium or thulium doped fibers. State-of-the-art Tm-doped fibers [9] can be efficiently pumped at 790nm and utilize the cross relaxation of excited state Tm-ions in a 2:1 process that increases the slope efficiency from ~40% to >65% in the case of an optimized fiber (Figure 3). Despite the problems of characterizing fibers at this wavelength, optimized fibers and components for 2µm are now becoming available including couplers, isolators and fiber Bragg gratings, allowing the design and manufacturing of monolithic lasers and amplifiers at this wavelength.

Furthermore, the availability of suitable high power diode pumps is not a major problem for Tm-doped fiber lasers given the availability of 0.8µm pumps for Nd-YAG lasers.

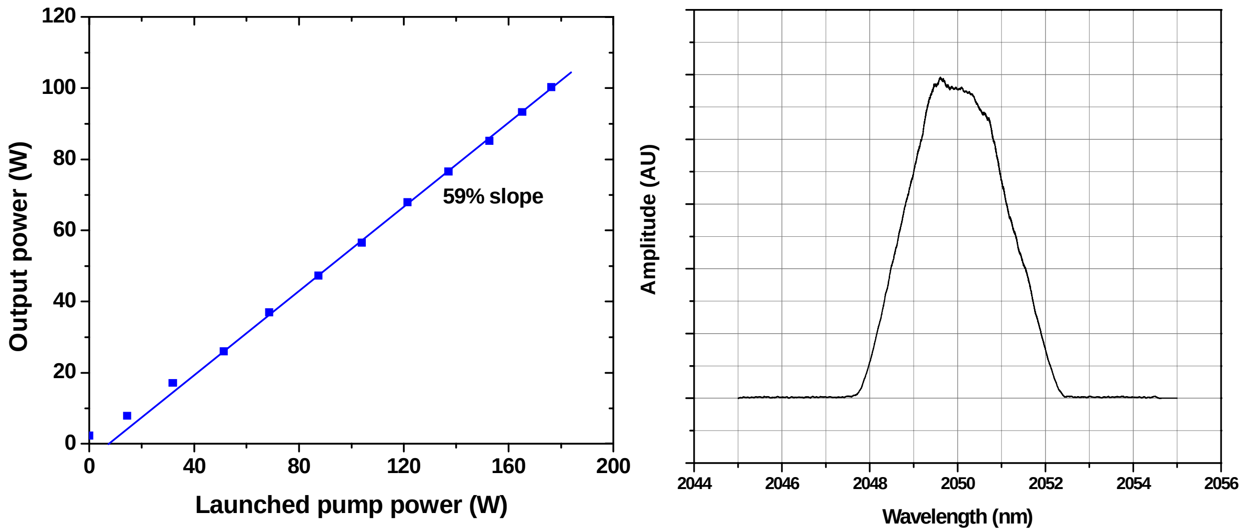

Figure 3: *Tm-doped fiber lasers and amplifiers operating around 2µm and pumped at 790nm now produce output powers >100W and include grating based monolithic devices that operate with >60% slope efficiency when the fiber is optmized for cross relaxtion between Tm-ions.*

Conclusions

Despite the many new innovations in fiber design for high power lasers and amplifiers, much can still be achieved through simple scaling of the mode field and careful optimization of the core composition. The application of LMA fiber technology to the kWatt regime at 1µm has been on-going for several years and the recent extension of this to panda-style PM fibers has recently received much attention [8]. In addition, much of the science pertaining to photodarkening effects in Yb-doped LMA fibers is now understood and LMA fibers operating at elevated power levels are now commercially available for use in highly demanding industrial laser applications. More recently the extension of LMA fiber technology to eyesafe wavelengths and in particular highly efficient Tm-doped fibers has seen the development of a new operating window for high power fiber lasers at 2µm.

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