Efficient and reliable 790nm-pumped Tm lasers from 1.91 to 2.13µm

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Lasers at ~1.9µm

1908nm is a key wavelength used as a low quantum defect pump source for Ho:YAG lasers [1]. The long storage time of Ho:YAG enables the generation of high energy pulses at 2.1µm. Possible direct applications of pulsed Ho:YAG lasers include ranging and LIDAR, but more significantly, it is well suited for nonlinear frequency conversion into the mid and far-IR, key for DIRCM and remote sensing.

Most high power demonstrations of 790nm-pumped Tm lasers have to date been at wavelengths exceeding 2.04µm [2,3,4] where reabsorption effects are relatively mild. For cladding-pumped Tm-doped fibers operating below about 1.95µm, signal reabsorption losses are a significant design concern. For core-pumped systems, reabsorption is less significant however schemes such as cascaded pumping (Er:Yb pumped Tm) cannot achieve the same quantum efficiencies as pumping at 790nm due to the absence of the cross-relaxation process [5].

Key to obtaining high efficiency in cladding pumped Tm-doped fibers at shorter wavelengths therefore involves minimizing the number of active ions present within the optical path. This is generally achieved through the use of large core-to-clad ratios; however, whilst employing as large a core-to-clad ratio as possible is beneficial to reducing reabsorption losses, practical considerations such as thermal management, mode control (beam quality) and operating threshold place an upper limit on suitable core size.

Taking into consideration a desired output power level of 50~100W and the brightness of economically available pump sources, we designed a fiber with a pump cladding size of 250µm and a fundamental mode field diameter of around 22µm at 1.9µm. To aid cross-relaxation, relatively high concentrations of Tm^{3+} and Al^{3+} were incorporated [6]. A raised refractive index 'pedestal' was deposited around the core to lower its effective NA, so as to maintain near diffraction limited beam quality [7]. The measured pump absorption for the fiber was ~6dB/m @ 792nm.

A master-oscillator/power-amplifier (MOPA) architecture, as shown in Figure 1 was used to evaluate the efficiency of the aforementioned large mode area high-concentration fiber. The MO was based upon a simple end-pumped Fabry-Perot cavity in single-mode fiber. It was capable of delivering up to 10W at ~1908nm with <0.5nm FWHM as shown in Figure 3. Light from the MO was launched into a passive fiber that was mode-matched to the active fiber of the main power amplifier stage. To maintain the seed beam quality, this passive fiber was coiled to remove any higher order modes which were subsequently removed from the cladding before reaching the amplifier stage.

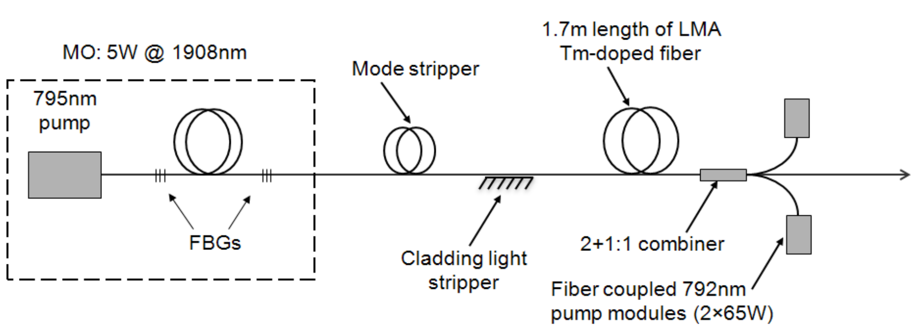

Figure 1. Schematic diagram of 1908nm MOPA.

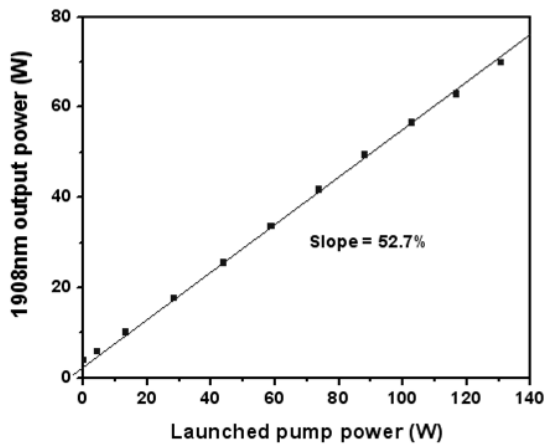

Figure 2. Slope efficiency for amplifier stage

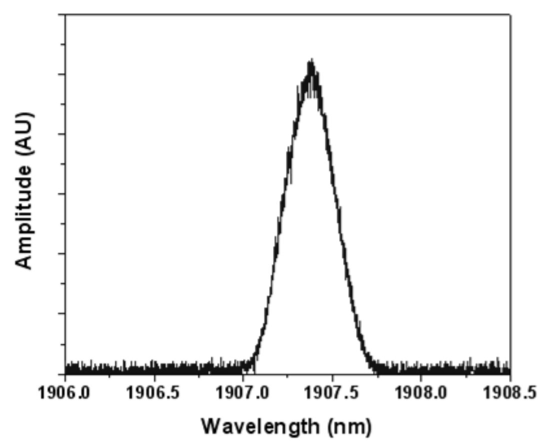

Figure 3. 1908nm seed laser output spectrum

Through experimentation, the best efficiency and stability was observed when counter-pumping 1.7m (~10dB pump absorption) of active fiber. The output from two 792nm pump diodes, each delivering up to ~65W into 200/220 0.22NA fiber, were coupled into the amplifier using a 2+1:1 pump/signal multiplexer.

Considering the relatively high absorption of the fiber, careful attention to thermal management was essential for maintaining reliability and efficiency. The effect of optical efficiency with respect to fiber temperature for 790nm-pumped Tm fibers has been shown in the past [8]. A 90mm diameter mandrel with a helically cut 'U-shape' channel ensured highly effective heat removal and provided sufficient mode control to ensure excellent beam quality.

The slope efficiency for the amplifier is shown in Figure 2. Whilst some deviation from linearity was observed, by altering diode temperature it was determined that this was due to diode wavelength variation rather than thermal roll-off. For this fiber, the peak absorption was measured to be 788nm, hence the pump diodes tended to move off the absorption peak at higher powers and temperatures. During experiments where the amplifier was co-pumped, we were able to determine that the pump absorption decreased from 9dB at threshold to only 6dB at full power. The measured slope efficiency was therefore somewhat artificially low.

Lasers beyond 2.1µm

Within the range of 2.1 and 2.2µm lies a broad atmospheric transmission window. Opportunities for the detection of many air pollutants including CH_4, N_2O and NH_3 also exist within this range. Tm-doped lasers present excellent candidates for generation of light in this region. Operation of a Tm-doped silica laser up to 2188nm was recently reported, thus demonstrating ability of Tm-doped lasers to span this longer wavelength window [9].

In that experiment, wavelength tuning was implemented using bulk optics in a Littrow configuration and as such, efficiency was limited by coupling and absorption losses associated with the bulk-optic components. To better demonstrate the intrinsic efficiency of the fiber we constructed a monolithic Fabry Perot fiber cavity as shown in Figure 4. The active fiber used had ~11µm mode field diameter at 2.13µm, 130µm octagonal shaped inner cladding. Fiber Bragg gratings written into a mode-matched photosensitive fiber were spliced to the active fiber and had nominal reflectivities of >99% for the high reflector and 15% for the output coupler. The laser cavity was end-pumped using a 50W 795nm pump source through a taper to convert output from the 200/220 0.22NA diode delivery fiber to the 130µm 0.46NA double-clad laser fiber.

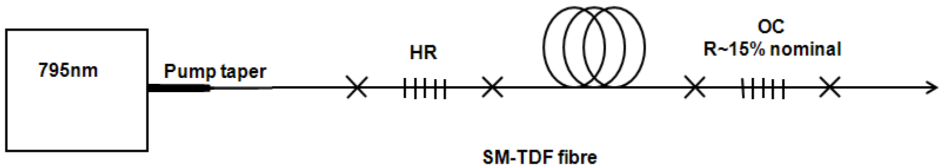

Figure 4. Schematic for testing Tm-doped fiber at 2125nm.

Despite the higher background loss of the silica host and the lower emission cross section of Tm^{3+} at these longer wavelengths, we demonstrated up to 20W at 2125nm with 41% slope efficiency as shown in Figures 5 and 6. Above 20W it became difficult to suppress emission at shorter wavelengths. With further optimization of the fiber and cavity finesse, we believe that higher efficiency powers should be achievable. It should be noted that this result from a singly-doped fiber are commensurate with recent demonstrations of Ho:Tm co-doped fibers [10].

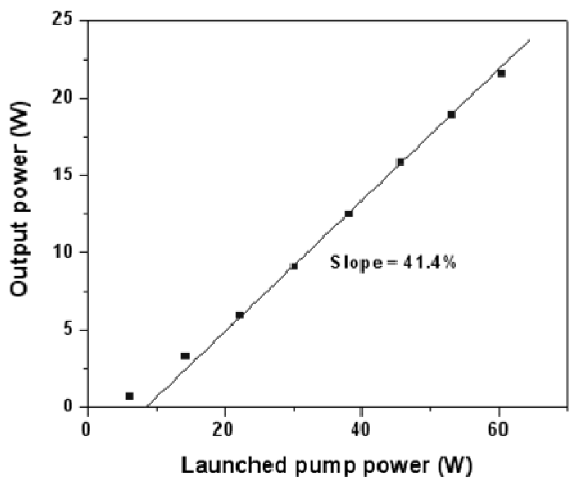

Figure 5. Slope efficiency for 2125nm laser

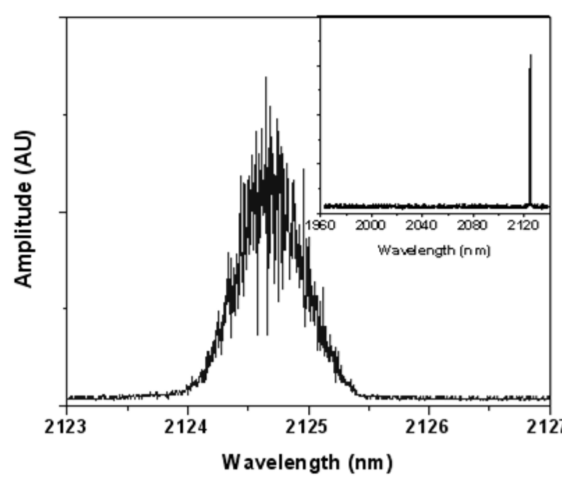

Figure 6. Laser output spectrum

Device reliability

Until recently, perception that 790nm-pumped Tm lasers at ~2µm rapidly degrade has largely remained uncontested. Whilst photodegradation of Tm^{3+}-doped silica fibers exposed to visible light has been documented in the past [11,12,13], fibers designed for efficient operation at 2µm generate very little visible or UV light. Maximization of the cross-relaxation process results in inhibition of energy transfer upconversion - the mechanism responsible for short wavelength light generation.

To demonstrate the reliability of latest generation fibers, we constructed a 1950nm laser cavity pumped at 792nm which was run for over 500 hours. To accelerate the degradation, we purposely chose a fiber with a high core/clad ratio and a low cavity finesse to give comparatively high inversion.

From the test, the extrapolated time for 10% device degradation was shown to be of the order of 2000 hours as shown in Figure 7. It should be noted that this figure does not separate degradation of cavity components or the bar-based diode pump source from the intrinsic fiber loss. We believe that by now applying lessons learnt from Yb-doped fiber development, additional improvements may be made to fiber compositions and designs to further decrease degradation.

We have also included 25 hours of data from a 100W laser operating at 2.05µm in Figure 8. Although this test was not performed for as long as the other test, we can show that even at high powers, high reliability operation is still observed. After initial settling, there was no observable degradation of this laser.

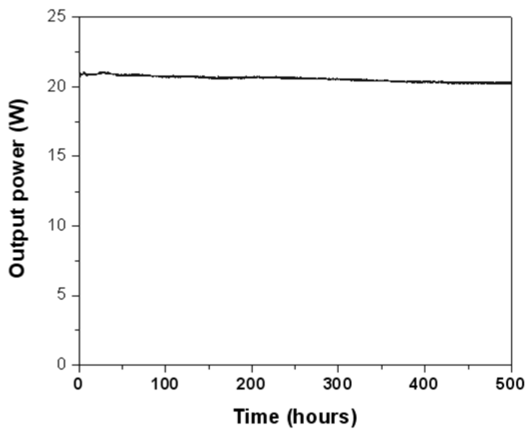

Figure 7. 500 hour laser test of LMA-TDF-23/250 operating at 1950nm

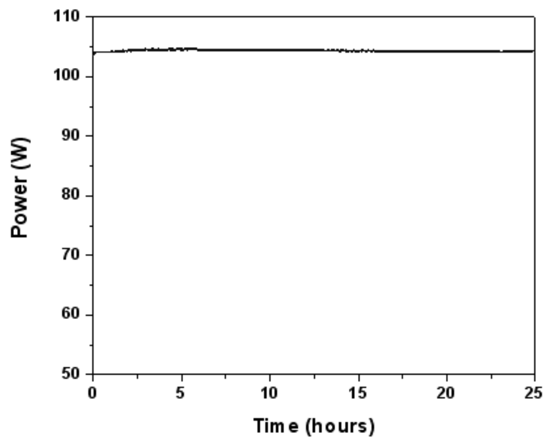

Figure 8. 25 hour test of LMA-TDF-25/400 operating at 2050nm

High brightness pump sources

Until now, the demand for laser diodes near 0.8µm has mainly been for pumping of Nd-doped crystals. Often these applications do not require the brightness that pumping a fiber laser demands so although the material has become relatively mature, high brightness fiber-coupled sources are not as abundant as the 9xx-nm diodes used for pumping Yb-doped fibers.

As the demand increases for high-brightness fiber-coupled 790nm diodes, we expect that many more sources will become available. As an example of what can be achieved we have included some data for a fiber-coupled 792nm diode currently being developed for us by DILAS Inc. in Tucson AZ. This diode is capable of delivering >20W into 100µm 0.22NA fiber with >40% electrical-to-optical efficiency as shown in Figure 9.

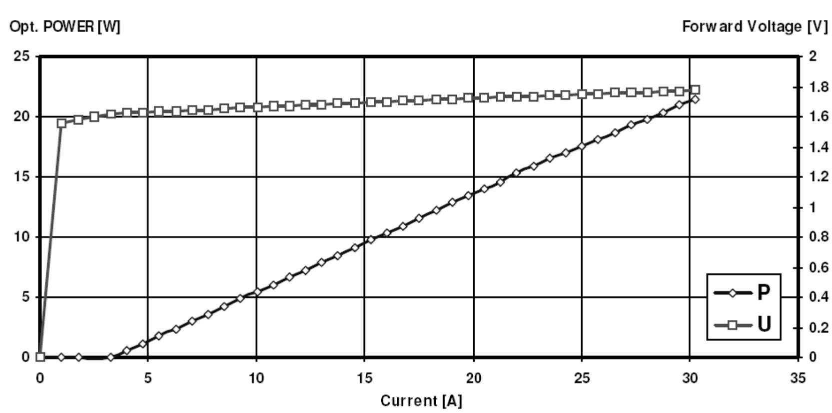

Figure 9. LIV curve for fiber-coupled 792nm diode bar delivering >20W with $\eta_{e\text{-}o}$ > 40%

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