High Power Thulium Fiber Lasers

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Abstract. Recent years have seen a phenomenal rise in the capabilities of high power fibers lasers. 10 kW is now achievable in single-mode fiber and the race is on to break the 100 kW mark. This has been enabled with the development of high power 976 nm pump diodes, ideally matched for efficiently exciting the ~1030 – 1080 nm transition in Yb-doped silica fibers. In the shadow of this remarkable development we are now witnessing a similar growth pattern for a sister to this laser, the 2 μm thulium fiber laser. This laser possesses rather unique characteristics. Pumped by 790 nm diodes, the excitation scheme uses a cross-relaxation process that results in two-for-one photon generation with slope efficiencies approaching 70%. Powers approaching the kW level are now achievable. This talk summarizes the development of this unique laser source in the MIR, and speculates on its future applications in the medical, manufacturing and defense arenas. In particular we describe new experiments where we exploit the broad >200 nm spectral bandwidth, and the advantages this laser brings to operating in the pulsed regime. We characterize the capabilities of conventional gratings, fiber Bragg gratings, volume Bragg gratings and guided mode resonant filters to lock the linewidth to as small as 50 pm, within the range from ~1950 nm to ~2150 nm. This spectral region covers many sharp atmospheric absorption lines in the atmosphere. We describe the first long range (1 km) atmospheric transmission tests with a tunable high power (200 W) thulium fiber laser. The capability to lock a number of these lasers to specific wavelengths each with <100 pm linewidths opens the option of spectrally combining many lasers within the overall spectral bandwidth. We examine the benefits of this approach to reaching 100 kW power levels. In the pulse regime we describe the generation of nanosecond, picosecond and femtosecond pulses in oscillator and MOPA configurations.

Keywords: fiber lasers; laser operation, continuous; laser radiation, propagation (atmospheric optics)
PACS: 42.55.Wd, 42.60.Pk, 42.68.-w

INTRODUCTION

The development of efficient, high power, high brightness laser systems has rapidly accelerated through the combination of advances in laser diode performance and improvements in rare earth doped optical fibers. In this symbiotic relationship, the active fiber is fundamentally a brightness converter. Over the past ten years, single-mode output from a single ytterbium fiber laser has increased from a few hundred watts to the current record 10 kW level[1]. Although it remains several years behind Yb:fiber, the development of thulium doped fiber is following a similarly rapid

CP1278, *International Symposium on High Power Laser Ablation 2010,* edited by C. R. Phipps

increase in output power. We will review many important advances in the development of high power Tm:fiber lasers and discuss paths for future progress. We will also discuss the unique applications that are enabled by the broad laser emission band of Tm:fiber from ~1850 – 2100 nm well within the "eye-safe" regime.

BACKGROUND

The development of compact, high-power, high-efficiency, and high-brightness Yb:fiber and Yb:thin disk lasers has lead to many advances in materials processing applications such as laser cutting and remote welding. However, the 1 μm output wavelength is generally not appropriate for high power laser applications requiring long distance propagation through free-space due to the possibility of accidental blindness from scattered or reflected laser radiation. The risk of permanent blindness is significantly reduced for 2 μm light, because this radiation is strongly absorbed by the cornea and therefore cannot reach the lens or retina to cause damage[2].

There are also large spectral regions of high optical transmission corresponding to laser emission band of Tm:fiber, which are appropriate for efficient high power multi-km propagation. We have begun experimental confirmation of MODerate resolution atmospheric TRANsmission (MODTRAN) code simulations at the Innovative Science and Technology Experimentation Facility (ISTEF) laser range on Cape Canaveral Air Force Station, Florida, and some initial data is shown in Figure 1[3]. The bands centered at ~2040 nm and ~2100 nm, respectively, are particularly promising for applications requiring multi-kilometer propagation through the atmosphere.

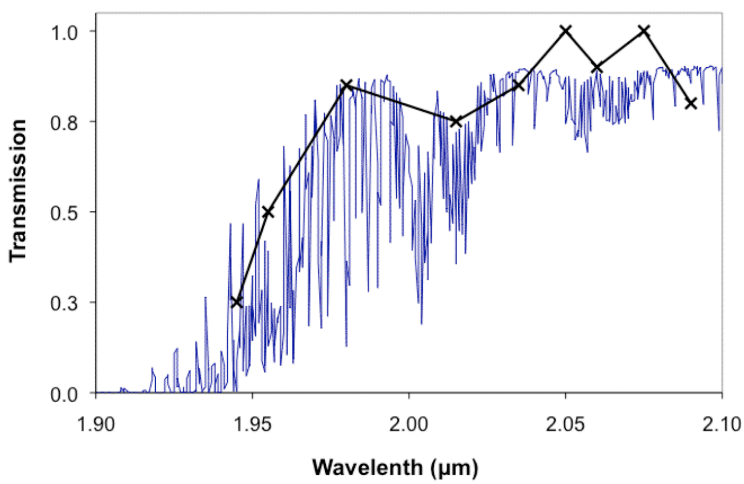

FIGURE 1. Experimental measurements of relative atmospheric transmission of the fiber laser beam at 1 km downrange is shown along with the MODTRAN simulation[3].

As demonstrated with Yb:fiber lasers, high efficiency and high power fiber lasers require appropriate diode laser pumps. Unlike ytterbium, it is not currently possible to directly diode-pump thulium with a low quantum defect. Fortunately, it is well known that it is possible to excite two laser photons at ~2 μm in thulium via one pump photon at 790 nm via cross-relaxation[4]. By properly optimizing the fiber composition for high concentration thulium doping (>2 wt%), it has been possible to achieve the same 2-for-1 cross-relaxation process in Tm:fiber[5,6] and thereby achieve slope efficiencies >65% despite the 39% quantum defect. It has also been necessary to develop appropriate large mode area (LMA) double clad fiber structures. These requirements place severe constraints upon fiber manufacturing process to achieve optimal dopant levels[7] while avoiding problems such as photodarkening[8], and to precisely control the refractive index levels and uniformity necessary for LMA cores with numerical apertures (NA) ≤0.10. It is necessary to co-dope with aluminum in order to obtain sufficiently high thulium concentrations for efficient cross-relaxation while avoiding clustering of the thulium ions; however, this would result in a core NA of ~0.20[9] which is far too large to enable single-mode propagation in LMA fibers. Fortunately, it has been possible to develop thulium doped silica fibers utilizing a "raised pedestal" design[9] in which a larger pedestal region surrounds the core area with elevated refractive index relative to the undoped cladding. As such, it is possible to achieve thulium dopant concentrations as high as 4 wt% in silica fiber with a core NA ~0.10[9,10].

ADVANTAGES OF LASER ACTION AT 2 μm

In addition to enabling new laser applications by providing an efficient, high-power laser source at ~2 μm, operation at this longer wavelength is itself an important advantage when it comes to high peak power generation in fiber lasers. As shown in Eq. 1 (where d is the fiber core diameter and λ is the propagation wavelength), for a fixed NA the core diameter is proportional to the signal wavelength.

$$V = \pi * NA * \frac{d}{\lambda} \tag{1}$$

Thus, it is possible to maintain the ~0.10 core NA required for single-mode propagation in a step-index fiber with twice the fiber core diameter at 2 μm than is possible at 1 μm. This is particularly important, since laser nonlinear processes and optical damage ultimately limit performance.

Furthermore, the thresholds for nonlinear phenomenon most common in fiber lasers (i.e. stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self-phase modulation (SPM), and self-focusing) also scale with the laser wavelength. For example, the current record CW power for the generation of narrow linewidth light in a single mode fiber at 1 μm is 400 W[11] as limited by SBS. However, as the amount of backscattered power is proportional to 1/λ[12], it has been possible to achieve 600 W single-frequency, single-mode output from a LMA Tm:fiber[13]. Similarly, the onset of SRS is the primary limitation in the amplification of high peak power nanosecond laser pulses. To date, the highest peak power that has been achieved at 1 μm in a bendable fiber is 800 kW in a Yb-doped photonic crystal fiber (PCF) as limited by SRS[14]. The ultimate limit to amplification in fiber at 1 μm is self-focusing. The critical power for self-focusing is ~4.5 MW at 1 μm, and this level of performance has been achieved using a Yb-doped PCF fiber rod with 100 μm core diameter[12].

However this critical power is proportional to λ^2, which increases this limit to ~18 MW at 2 μm. To date, such high peak powers have not been realized in Tm:fiber but this demonstrates the potential scalability, particularly for pulsed lasers.

Coupled with the reduced influence of nonlinearities, Tm:fiber is very attractive for the generation and amplification of ultrashort laser pulses. The extremely broad laser emission bandwidth should be capable of producing pulse energies >1 mJ with <100 fs pulse duration using conventional chirped pulse amplification techniques. To date there have been several demonstrations of modelocked Tm:fiber lasers as described in 15 and 16 and the references therein. The highest peak power yet produced in Tm:fiber is 230 kW with 108 fs pulse duration[17], however this amplifier utilized a relatively complicated seed source consisting of a modelocked Er:fiber laser which was Raman shifted to 1980 nm for amplification.

LASER PERFORMANCE MILESTONES

In addition to the achievements already mentioned, it is important to catalogue several recent performance milestones as these indicate the accelerating developments in Tm:fiber lasers. As recently presented at Photonics West 2010, Tm:fiber output has exceeded the 1 kW power level[18]. In addition to proving the potential of high average power Tm:fiber oscillators, this work highlights that significant effort remains in the development of fiber optical components in the 2 μm range. However, high power is generally not useful without spectral and/or temporal control of the output.

To investigate the tuning range of Tm:fiber and long range atmospheric propagation, we have constructed a tunable Tm:fiber master oscillator power amplifier (MOPA) system, producing >200 W, with <200 pm linewidth from 1927-2097 nm[4]. To our knowledge, this has the widest tuning range with high average power yet demonstrated using Tm:fiber. As shown in Figure 1, this system has provided experimental confirmation of atmospheric transmission variations in the 2 μm regime.

There have been several demonstrations of high power (>100 W) monolithic Tm:fiber systems utilizing fiber Bragg gratings (FBGs) for wavelength stabilization[19,20]. We are also actively investigating other techniques for spectral control. We have utilized a volume Bragg grating (VBG) as a highly reflective feedback element in an oscillator consisting of a LMA 25 μm core, 400 μm cladding Tm silica fiber. As shown in Figure 2, it was possible to generate 159 W with <1.5 nm linewidth and 54% slope efficiency with only a small loss in efficiency relative to using a highly reflective (HR) mirror[21]. We have also implemented the VBG for tunability in a Tm:fiber oscillator, producing up to 48 W from 1947 – 2052.5 nm[21].

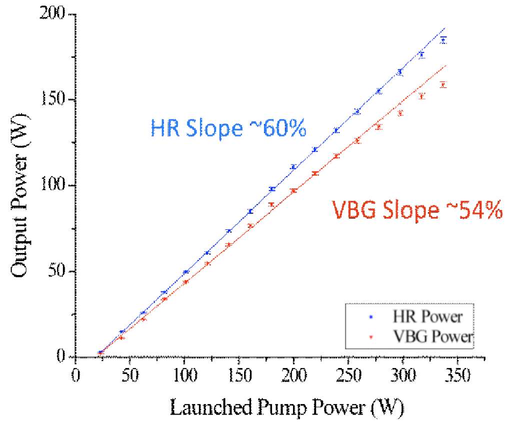

FIGURE 2. Slope efficiency of a Tm:fiber oscillator using a VBG and HR as intracavity feedback elements[21].

Another novel technology that we have investigated is the use of guided-mode resonant filters (GMRFs). These devices consist of a sub-wavelength grating combined with a confinement waveguide layer on a single substrate, and are capable of providing very high reflectivity with narrow resonant linewidth[22]. The maximum GMRF reflectivity is currently limited to ~50% in the 2 μm regime[23]. Further optimization of fabrication techniques and parameters should enable GMRF reflectivities to reach 99% as has been demonstrated at 1.5 μm[24], and will significantly improve Tm:fiber laser performance. Despite the relatively low reflectivity, >10 W output with <500 pm linewidth has been produced in a GMRF stabilized oscillator and generation of >150 W has been achieved by using a power amplifier seeded by a GMRF stabilized oscillator[23].

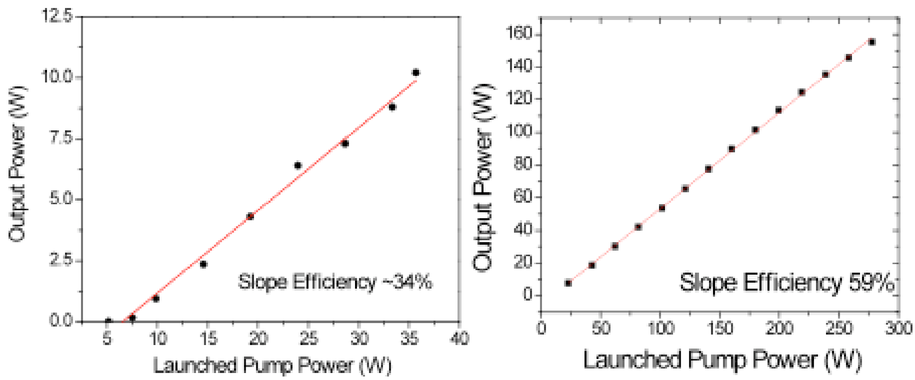

FIGURE 3. Slope efficiency of a GMRF stabilized oscillator is shown on the left along with the slope efficiency of a power amplifier seeded with a GMRF stabilized oscillator[23].

The ability to precisely control the wavelength and exploit the broad emission band of thulium also makes it extremely attractive for power scaling via beam combination techniques. An early demonstration of this was reported in reference 25. More recently, we have made use of GMRFs for spectral beam combination (SBC)[26]. Although the combined power was a modest 49 W, the ability to generate three separate wavelength channels with <50 pm linewidth spanning a 40 nm wavelength band[26] demonstrates the potential to densely pack a large number of independent channels within the thulium bandwidth.

Within the pulsed regime, there have been several recent developments in Tm:fiber. To date the highest peak power is 25.4 kW, with 350 μJ and 13 ns at 50 kHz[27]. The ability to achieve such high peak power with high repetition rate at 2 μm wavelength opens up many opportunities for high average power generation in the 3-5 μm regime via Tm:fiber pumped optical parametric oscillators (OPOs)[28]. However, this laser system utilized a gain-switch Er:fiber system to pump the Tm:fiber in order to generated the <20 ns pulses. More recently, there has been rapid development of less complicated laser systems using intracavity q-switching of Tm:fiber. A low repetition rate (5 Hz) Tm:fiber laser with pulse energies >500 μJ with narrow linewidth have been developed for probing atmospheric water vapor by differential absorption LIDAR (DIAL)[29]. A high repetition rate system has also been demonstrated, producing 300 μJ pulses with 41 ns pulse duration and >30 W average power[30].

Our research group has demonstrated a q-switched oscillator using three different feedback elements: an HR mirror, a gold-coated reflection grating, and a VBG[31]. Following upon this work, we have recently scaled the pulse energy to nearly 500 μJ at 20 kHz repetition rate with sub-100 ns pulse duration and sub-nanometer linewidth at 2005 nm. Figure 4 shows the pulse energy vs. pulse duration in this case. It is noteworthy that this performance was achieved using a 25/400 LMA Tm:fiber, and no facet damage was observed despite the laser fluence of ~30 J/cm^2.

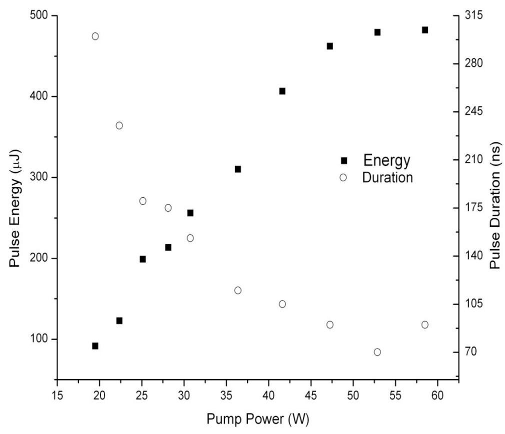

FIGURE 4. Pulse duration and pulse energy vs. pump power for a q-switched Tm:fiber laser.

As mentioned earlier, Tm:fiber is particularly promising as a source for ultrashort laser pulses. The broadest spectral bandwidth (35 nm FWHM), shortest pulse duration (173 fs), and highest pulse energy (4.3 nJ) produced from a Tm:fiber ultrashort pulse oscillator are described in reference 16. However, there is considerable opportunity for improvement since the 35 nm spectral width is only a small fraction of the bandwidth available in Tm:fiber. The primary challenge will be to develop techniques for dispersion control at 2 μm, since methods used for dispersion compensation in the 1 and 1.5 μm regimes are not appropriate.

To date, there has been relatively little in the development of amplified ultrashort pulse Tm:fiber laser systems. As mentioned previously, the first demonstration of femtosecond amplification in Tm:fiber utilized a Raman shifted Er:fiber seed source[17]. Notably, a peak power of 230 kW was achieved without the use of chirped pulse amplification without any signs of pulse degradation due to nonlinear effects. We have recently demonstrated the only amplified 2 μm ultrashort pulse system with a modelocked Tm:fiber oscillator[32]. The Tm:fiber oscillator is modelocked using a saturable absorber similar to that described in reference 33, formed by single-walled carbon nanotubes deposited onto the fiber core by an optically driven deposition process[34]. The oscillator is a ring cavity producing 32 pJ energy pulses with 5 ps duration at 46 MHz and ~1 nm FWHM at 1920 nm. These pulses were directly injected in a LMA Tm:fiber, and amplified to 0.6 W and 13 nJ pulse energy. This performance was primarily limited by the poor, ~25%, coupling efficiency and poor optical isolation between the oscillator and amplifier. Thus, modest improvements in the system design and components should enable to generation of ultrashort pulse with energies exceed 1 μJ.

CONCLUSIONS

Tm:fiber lasers are following a similar path of rapid development established by Yb:fiber. Further improvements will take advantage of the established benefits of fiber lasers, such as high efficiency, robust laser architecture, and high power with nearly diffraction limited mode quality. However, Tm:fiber has several unique advantages over Yb which promise to greatly increase the range of applications utilizing fiber lasers. Tm:fiber particularly offers great promise to revolutionize pulsed fiber lasers in the nanosecond and ultrashort pulse regimes.

ACKNOWLEDGMENTS

The authors would like to acknowledge support and funding from the JTO MRI (contract # W91NF-05-1-0517) and the State of Florida.

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