Amplification of Picosecond Pulses Generated in a Carbon Nanotube Modelocked Thulium Fiber Laser

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Abstract: Generation of 5 ps, 32 pJ pulses from a carbon nanotube modelocked thulium fiber oscillator and their amplification to 0.6 W average power, 2.6 kW peak power, 13 nJ pulses by an LMA thulium fiber amplifier is discussed.

OCIS codes: (140.3510) Lasers, fiber; (140.7090) Ultrafast Lasers;

1. Introduction

Interest in high power thulium fiber lasers has been steadily growing in the past few years for a variety of reasons. They have a potential for high operating efficiency in the eye safe regime and can operate at wavelengths within a useful window where absorption minima for atmospheric propagation exist. Within its bandwidth there are also regions where absorption maxima in organic and non-organic materials make them useful for applications that require higher laser absorption, such as medical and materials processing applications. The majority of thulium fiber laser research has focused on CW lasers with high average powers, spectrally controlled lasers and lasers in the nanosecond regime.

Ultrashort pulses (USPs) in the picosecond and femtosecond regime are of use in materials processing, LIBS, atmospheric sensing and medical applications. Such pulses generated in the thulium wavelength region from 1.8 to 2.1 µm will open new applications and enhance existing ones. In addition, there are inherent advantages to the use of thulium as a gain medium in the USP regime. Thulium's large spectral bandwidth enables the generation and amplification of potentially very short duration USPs. Its longer wavelength enables easier scaling of mode field diameter with less of an impact on beam quality, which increases the peak powers achievable before the onset of nonlinear and damage limitations. USP generation based on thulium fiber has been achieved in several cases using a variety of methods and has reached pulse durations from the picosecond range down to 100's of femtoseconds [1-5]. However to date such pulses have achieved low pulse energies, and most relevant applications call for pulses at least 100's of nJ to µJ energies. Since most oscillators are not capable of such powers, thulium fiber amplifiers must be employed to boost pulse energies into the useful power regime. However use of such amplification techniques of USPs at 2 µm wavelengths has only been reported once [6], and that system used a Raman shifted modelocked Er fiber laser based seed, rather than a direct thulium based oscillator. This paper will discuss the generation and subsequent amplification of picosecond level pulses in a directly modelocked thulium fiber laser system.

2. Single Walled Carbon Nanotube Picosecond Oscillator

An "all-fiber" modelocked thulium ring laser (Fig. 1) is based on an ~15 cm length of PM single mode, 10 µm core, ~4 wt% thulium doped fiber spliced to a PM WDM which is used to couple up to 1.5 W of 1550 nm pump power from a simple FBG based Er:Yb fiber laser into the thulium doped fiber core. The other end of the thulium doped fiber is spliced to a FC/APC connectorized SMF-28 pigtail which is part of the single walled carbon nanotube (SWCNT) saturable absorber. The saturable absorber (SA) is fabricated using the optically driven deposition technique, discussed in [7], by dipping a clean FC/APC connector into a dispersed solution of ~1.5 nm mean diameter SWCNTs with ~10 mW optical power exiting the core. This causes preferential deposition of tubes on the core, and after absorption of ~50% of the 2 µm light used for deposition is achieved, the connector is screwed to a second FC/APC connector in a mating sleeve to form the transmissive SA. The opposite end of the SA is spliced to a 90/10 tap coupler for output coupling, the 90% port of which is spliced to the appropriate port of the WDM to complete the ring.

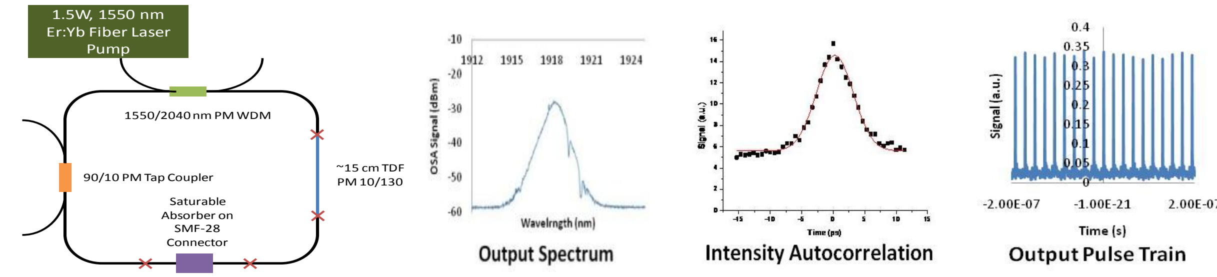

Fig. 1: Schematic of the SWCNT modelocked laser and performance data in the modelocked regime with ~1.5 mW of output power

As pump power is increased, the laser moves from brief CW regime to a self-starting modelocked regime. However, the laser usually starts in a multi-pulsing regime and the power must be backed down from initial onset of modelocking to achieve stable, ~46 MHz (corresponding to the ~4.3m cavity length) single pulse operation. Modelocking is typically achieved at ~240 mW pump power, while laser threshold is ~190 mW. When stable operation is achieved, the laser emits ~1.5 mW per output port because the ring resonator operates bidirectionally due to the lack of an appropriate intracavity optical isolator. The spectrum is centered at ~1918 nm with a FWHM of ~1 nm in agreement with a ~5 ps pulse duration as determined from an intensity autocorrelation (Fig. 1). It should be noted that due to the mismatch between the non-PM SMF-28 and the PM fiber used in the rest of the laser, the laser is quite sensitive to environmental perturbation including temperature variations and strong mechanical perturbations and this is likely the reason for the slight pulse to pulse instability seen in the output pulse train (Fig. 1: output pulse train). This instability is being remedied by implementation of a tapered saturable absorber similar to that used in [1], based on PM fiber, thus making the laser an all spliced, all-PM ring. We are also investigating techniques for intracavity dispersion compensation to further reduce pulse durations, using WDMs and taps designed for broader bandwidth at the laser wavelength (current WDM and tap are designed for ~2040 nm so outcoupling percentages are likely not correct). We also intend to increase the output coupling and force unidirectional operation to increase the average power. Shorter cavity length will also help stabilize operation, as with the larger material dispersion in silica at thulium wavelengths, excessive cavity length can destroy the formation of clean pulses. Increase in output power is critical to enhance overall system performance.

3. Picosecond Pulse Amplification

The output fiber from the tap port of the modelocked oscillator used as the seed for amplification is spliced to an FC/APC connectorized SMF-28 pigtail which is mounted in front of an 11 mm AR coated glass aspheric lens. It is then launched through a 4 mm diameter optical isolator designed for 2050 nm and is coupled into a second connectorized SMF-28 pigtail by a matching 11 mm asphere (Fig. 2). This process can be avoided in tthe future, as commercially available fiber coupled isolators in the 2 µm regime are becoming available.

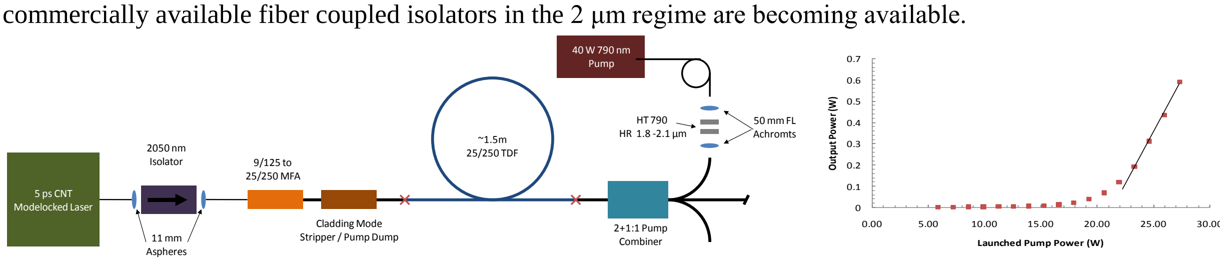

Fig. 2: Schematic of the amplifier system and plot of output power vs launched pump power

The SMF-28 is spliced to a mode field adaptor matching to a section of LMA, passive 0.1NA, 25 µm core, 250 µm clad fiber. The total transmission of the seed up to this point is ~25% due to the losses associated with the unpolarized seed beam in the polarizing isolator (~50%), absorption and reflection losses in the lenses (12% total for two lenses) and from free space fiber tips (~5% total) and isolator (~20% due to AR coating not at the required wavelength) and losses in the MFA (~15%). A cladding mode and residual pump stripper is included before the passive LMA fiber is spliced to a ~1.5 m section of 25 µm, 0.1NA, core, 250 µm, 0.46NA clad thulium doped fiber. The doped fiber is wrapped on a water cooled ~6 cm diameter mandrel at 14 C. The fiber is counter-pumped by a 40W, 100 µm fiber coupled, 790 nm laser diode through a 2+1:1 pump combiner. The counter pumping scheme is not ideal for the extremely small seed power; however, it was used to minimize backwards ASE which tends to destabilize the modelocking despite the optical isolator. The pump light was not spliced to the pump combiner, but rather was launched free space into one of its input ports with >80% efficiency in order to allow the insertion of dichroic mirrors to protect the pump diode from any leaked amplified signal. This will be avoided in the future through the use of a laser diode with integral dichroic filters, enabling direct splicing and thus a truly "all-fiber" system. The output end of the amplifier (the feed-through port of the pump combiner) was cleaved at a ~10° angle to suppress parasitic lasing and feedback.

For a seed power of 1.5 mW (32 pJ energy) from the master oscillator, it is estimated that 25% (~0.4 mW or ~9 pJ) was coupled into the amplifier. Pumping the amplifier with up to 27 W power achieved a maximum average power of ~0.6 W (13 nJ) at the full repetition rate of the modelocked laser before feedback into the oscillator became a problem. This feedback is either from amplifier ASE or back-propagating amplified signal leaking through the relatively poor (<15 dB isolation at ~1918 nm) isolator, since it is actually intended for use at 2050 nm. Fig. 2 shows the exponential growth of the output from the amplifier, as expected in this regime of operation far below saturation. Amplifier performance with the seed laser operating in the pulsed regime is similar to that for the seed in the CW regime at similar input power levels. The corresponding 10% slope efficiency with respect to launched pump power when growth begins to become linear is also low due to a combination of operation well below saturation power and a large amount of leaked pump power through the only ~1.5 m fiber, which has an estimated 5-7 dB absorption. Power could not be measured directly due to the use of a pump dump to strip leaked pump power. No signs of nonlinear effects, ASE or parasitic lasing were observed in the output spectrum of the amplifier up to the operating power level where feedback-induced instability occurred. Beam quality was not directly measured, but it is expected to be quite high owing to the ~6 cm coiling diameter of the active fiber, and the relatively low NA of the LMA amplifier fiber.

3. Discussion and Conclusions

There is significant room for improvement of the performance of the amplifier and oscillator. The oscillator improvements will come from optimization of cavity parameters to produce higher seed powers which will enable better saturation of the amplifier. Cavity optimization should also help to reduce pulse durations, thus increasing peak output power. If output power from the seed cannot be significantly increased, the use of pre-amplification in single mode fiber will also be required. With higher seed powers, the efficiency of the amplifier should improve dramatically, potentially approaching twice the quantum defect limit for thulium as a result of well known cross relaxation processes. Use of a more appropriate optical isolator (or multiple isolators) as well as improvements in the operating stability of the oscillator by removing the non-PM fiber should allow significantly higher average powers to be achieved. There is also an interest in achieving higher pulse energies without needing to scale to extremely high average power. This can be achieved by use of a pulse down-counter, perhaps to MHz or 100's of kHz repetition rates in order to achieve μJ level pulses from the system. Testing of the amplifier in this regime (once sufficient seed power is available) will reveal the point at which the onset of any nonlinear limitations which may occur, Results of such testing will perhaps reveal the higher potential pulse energies that thulium fiber laser should be capable of as a result of the inherent benefits of longer operating wavelength. The current system can easily be configured to a fully "all-fiber" laser that could be readily packaged with very small footprint.

In conclusion, a SWCNT SA based modelocked thulium fiber laser putting out 5 ps pulses at 46 MHz with ~1.5 mW average power at 1918 nm is demonstrated. The pulses are amplified to ~0.6 W average power, limited by instability associated with feedback. The ~13 nJ pulses generated reach peak powers of 2.6 kW. To the author's knowledge, this represents the first report of the thulium fiber based amplification of picosecond pulses generated directly from a modelocked thulium fiber oscillator.

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