Characterization of Ultrafast Fiber Lasers

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Ultrafast lasers have applications that span many disciplines from materials science to medicine. Traditionally, ultrafast lasers are assembled from a Ti:Sapphire (T:S) gain medium due to a fast pulse duration (5fs) and high output power. However, a large drawback to T:S is the cost and size. An ultrafast fiber laser (FL) can be developed for a lower cost and take up less space. Drawbacks to a FL is low power output and long pulse duration (20fs). A goal in FL development is to match the performance of a T:S laser. Characterizing performance of these lasers involves measurement of output power, repetition rate, and pulse duration. The assembly of the laser requires splicing optical fiber from a pump diode to fiber of several optical components. The laser is then mode-locked. Mode-locking is the process of generating an ultrashort pulse in the laser cavity by introducing a component called a saturable absorber. Mode-locking is crucial to producing an ultrafast laser. The mode-locked power is 58.5mW and the repetition rate is 45.5MHz, offering a pulse energy of 1.26nJ. The pulse duration is measured with a technique called second-harmonic intensity autocorrelation. Autocorrelation is necessary as the pulse is too fast for electronics to respond. The pulse duration is 97.4fs.

Keywords: Ultrafast, Fiber Laser, Mode-lock, Autocorrelation

I. INTRODUCTION

The development of the laser has paved the way for a plethora of technological and scientific advancements. It would seem that advancements in many fields follow advancements in laser technology. While there are many different types of lasers, this report will focus on ultrafast fiber lasers. Ultrafast fiber lasers get their name from their short pulse duration and the fact that they utilize fiber doped with a rare-earth metal as a gain medium.

One particular type and in fact the most common type of ultrafast fiber laser is the mode-locked fiber laser. Mode-locking is the process of establishing a fixed-phase relationship between longitudinal modes. Once these longitudinal modes are in a fixed-phase relationship, they can be manipulated such that they constructively interfere when they mix. This interference causes the laser light output to be a chain of pulses.

A laser is classified as ultrafast once its pulse duration is shorter than 100 picoseconds. Ultrafast lasers are useful because their short pulse duration helps to minimize thermal effects from the application of the laser. A simplistic way of viewing this is that ultrafast lasers can make the cleanest cuts. This paves the way for many applications in materials science and medicine.

Ultrafast lasers also have many other uses including spectroscopy, metrology, and imaging. Ultrafast lasers are typically bulky, complex structures requiring highly trained personnel for maintenance. Ultrafast fiber lasers offer a path towards compact, easy to use systems. With advances in ultrafast fiber lasers, it is important to be able to measure properties of the lasers and characterize them. Important properties of these lasers are average power, repetition rate, spectrum, and pulse duration. This paper focuses on the characterization of ultrafast fiber lasers.

The laser used for this project is a stretched pulse or dispersion managed laser. In 1996 the stretched pulse laser was patented by researchers at MIT[1] in an effort to produce a commercially and industrially viable ultrafast fiber laser. At the time of its development, the stretched pulse laser could produce a pulse energy of 110 pJ[1]. The spectral width of the mode-locked laser is 60 nm[1]. Since then, stretched pulse lasers have managed to achieve pulse energies of around 1nJ[2]. The width of mode-locked spectra can now be as large as 80 nm[2]. The stretched pulse laser is capable of having a pulse duration in the range of 50-100 fs[1]. The laser will have a repetition rate of 45 MHz[1]. So, when one measures these values on a stretched pulse laser this is what they might expect to find. One important aspect of this experiment is second harmonic intensity autocorrelation (Figure 1). This is a technique performed to measure the pulse duration of the mode-locked pulse. Second harmonic intensity autocorrelation is necessary because the pulse duration of an ultrafast laser is much faster than the response time of the electronics used to measure the pulse duration.

Assembly of the stretched pulse laser is accomplished by splicing a 976 nm pump diode, wavelength division multiplexer, and Yb gain fiber to the laser cavity (Figure 2). After the laser is properly assembled, it is mode-locked. The width of the mode-locked spectrum is 60nm. The average power is then measured. The average mode-locked power of this laser is 58.5 mW. The repetition rate is then determined, this laser's repetition rate is 45.5 MHz. This means that the pulse energy is 1.26 nJ. Finally, the laser is autocorrelated. The pulse duration of this laser is 97.4 fs. Thus, this stretched pulse laser has characteristics similar to the original stretched pulse design and the energy is similar to what more recent stretched pulse lasers output. One issue with the experiment is that there is a significant amount of noise in the autocorrelation signal and the signal is weak. Unfortunately, these issues could not be addressed at the time.

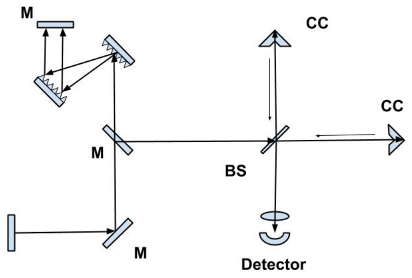

FIG. 1. Schematic for the autocorrelator

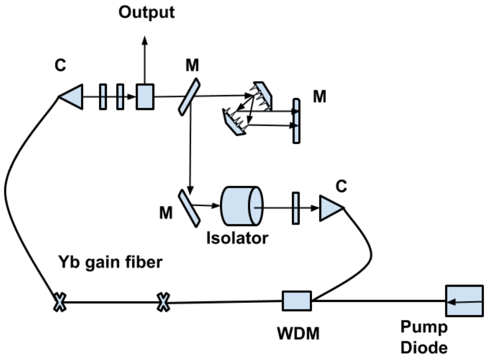

FIG. 2. Schematic for the stretched pulse fiber laser. WDM

C	Collimator
M	Mirror
WDM	Wavelength Division Multiplexer
BS	Beam Splitter
CC	Corner Cube (Mirror)

II. METHODOLOGY

Before the laser is to be characterized it must first be assembled. The majority of the laser cavity is already assembled and aligned. However, some components such as the wavelength division multiplexer (WDM), Yb gain fiber, and 976 nm pump diode have to be spliced into the cavity via a portable fusion splicer. A schematic of the stretched pulse laser is shown in figure 1. After each splice is made, the average power must be checked because mode-locking requires a certain threshold power output. Thus, power losses due to splicing must be minimized to achieve mode-locking. Once the components have been spliced into the cavity, the average power must be maximized by adjusting the three wave-plates in the laser cavity.

Once the power of the laser is maximized, the spectrum is measured with a spectrometer. If the power has been maximized, the spectrum will appear as a thin peak centered around 976 nm. This is a continuous wave (CW). Once it is confirmed that the output is a continuous wave, the wave-plates are adjusted until the spectrometer shows a mode-locked spectrum. There are many different longitudinal modes that can be occupied so the appearance of the mode-locked spectrum will vary. However, a mode-locked spectrum is very broad compared to the CW spectrum. A mode-locked spectrum will typically contain multiple peaks and it will also be an attractor. This means that as the cavity approaches the conditions for mode-locking, it will self mode-lock. One simply has to slowly rotate the wave-plates and they will see the spectrum abruptly shift to a broad mode-locked spectrum. Once mode-locking is achieved, the average power is measured again. In order to achieve autocorrelation of the laser pulse, the mode-locked power must be approximately 60 mW because the undergoes significant energy loss on its way to the autocorrelator. So, if the pulse has power that is significantly (10 mW) less than 60mW, autocorrelation cannot be achieved.

Before the laser is autocorrelated, the repetition rate of the mode-locked laser must be obtained. Measuring the repetition rate is a straight forward process. A photodetector is connected to an oscilloscope and the laser output is directed onto the photodetector. Determining the repetition rate is then as easy as reading the oscilloscope.

Autocorrelation is a very delicate process. The incident laser beam must be level throughout the autocorrelator. The two mirrors of the autocorrelator must be level with the beam such that the beam is incident on the center of the mirrors. The mirrors must be set to a specific distance based on the distance between the diffraction grating. The beam splitter must be adjusted so that the incident beam and split beams are level with the two mirrors. The photodetector must be adjusted to be level with the rest of the cavity. A 40x magnifying lens is placed in front of the photodetector. Once these components are set through much trial and error, the autocorrelation signal can be obtained. To determine the pulse duration from the autocorrelation, the signal must be normalized and evaluated via the full width, half max of the signal. This can be done because the pulse is a Gaussian pulse.

III. SECOND HARMONIC INTENSITY AUTOCORRELATION THEORY

As discussed earlier, the pulse duration is far faster than the response time of the detector. In order to measure the duration of an ultrafast pulse one must use something of comparable speed[3]. Rather than develop any new fancy detectors, it is possible to use the pulse itself to measure the duration. This is where second harmonic intensity autocorrelation comes into play.

Second harmonic generation, also referred to as frequency doubling, is a nonlinear optical process in which photons of identical frequency interact with a nonlinear medium. The interaction results in an effective combining of the two photons into a single photon with twice the frequency (and energy) of the incident photons. In general, the nonlinear medium is a nonlinear crystal such as β-Barium Borate. Second harmonic generation can also be accomplished via two photon absorption, which is the case for this experiment.

Two photon absorption is, as the name suggests, the absorption of two photons of either the same or different frequency[3]. The absorption leads to the excitation of an atom or molecule from one state to a state of higher energy. The energy difference between states is equal to the sum of the absorbed photon energies. This effect is a nonlinear process and is observed in some semiconductors. The absorption of two photons in a semiconductor allows for the absorption of light even if the photon energy is less than the band gap of the semiconductor. For this experiment, the semiconductor used to accomplish two photon absorption is Gallium Arsenide Phosphorus (GaAsP).

Intensity autocorrelation is a process in which the pulse of a laser is directed into a Michelson interferometer. In the case of intensity autocorrelation the interference is temporal rather than spatial. The interference is introduced as a time delay via a speaker with a corner cube attached to it (FIG 1). When the speaker is powered, the time delay is brought about as the speaker oscillates back and forth. To review, once the pulse of a laser enters the autocorrelator cavity, it is split by a polarizaing beam splitter, one of the beams is incident on a stationary corner cube and the other is incident on the oscillating corner cube. The split beams recombine and are directed onto the GaASP detector. When the split beams recombine they have an intensity governed by the following equation,

$$I_{signal}(t,\tau) = I(t)I(t-\tau) \tag{1}$$

Where I_{signal} represents the intensity of the combined beams, $I(t)$ represents the intensity of the beam from the stationary corner cube, $I(t-\tau)$ represents the intensity of the beam from the moving corner cube, and τ represents the delay introduced by the speaker. The autocorrelation signal can be described by the time integral of the intensity,

$$A(\tau) = \int_{-\infty}^{\infty} I(t)I(t-\tau)dt \tag{2}$$

where $A(\tau)$ is the energy per square metere of the pulse. It should be noted that much information is lost during autocorrelation in exchange for knowledge of the pulse duration. When an autocorrelation signal is obtained, the pulse duration is determined by normalizing the signal and calculating the full width half max of the signal. The pulse duration is the full width half max of the normalized signal.

IV. RESULTS

All of the data collected for this experiment is contained in Table 1. The average mode-locked power for the stretched pulse laser is 58.6 mW and the repetition rate is 45.5 MHz. From the repetition rate and the average power, the pulse energy can be determined. The pulse energy is the quotient of the power and the repetition rate. From the measured values, the energy is 1.2 nJ. After much effort, the pulse duration is determined to be 97.4 fs.

Mode-Locked Power	58.6 mW
Repetition Rate	45.5 MHz
Pulse Energy	1.2 nJ
Pulse Duration	97.4 fs

While from the pulse duration and the spectrum, one could deduce that this is an ultrafast fiber laser. The pulse duration of this laser is rather slow compared to other values reported in literature. Ultrafast fiber lasers can have pulse durations as low as 40 fs. At one point in time, 1.2 nJ was an upper limit for the pulse energy of a fiber laser. However, that limit has been pushed further by the ANDi laser and other subsequent fiber laser designs. The mode-locked power, going along with the energy, is rather low compared to similar fiber lasers. The repetition rate of this laser is similar to the repetition rate for other similar lasers.

The mode-locked spectrum of the laser (Figure 3) is quite broad. This is desired as a broad spectrum corresponds to an increased uncertainty in energy which corresponds to a decreased uncertainty in time according to the uncertainty principle. In other words, the broader the mode-locked spectrum, the shorter the pulse duration. The width of this spectrum is 71 nm. Similarly designed lasers can produce slightly broader spectra at around 80 nm[4].

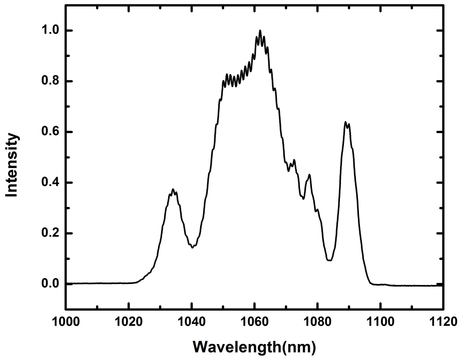

FIG. 3. Wavelength spectrum of stretched pulse laser

The autocorrelation signal (Figure 4) for the laser is weak and contains significant noise. However, the signal is good enough to obtain the pulse duration measurement. The primary issue with obtaining a "good" signal for the autocorrelation is that the laser is not providing enough power. By the time the beam reaches the autocorrelator detector, the power is 5 mW. All of the splicing is evaluated to be sure that light is not leaking out of the fibers. The autocorrelator is evaluated to ensure that the mirrors, beam splitter, and detector are properly aligned. The only issue that is not accounted for is a potential misalignment in the laser cavity. However, due to restrictions in the laboratory this issue could not be addressed.

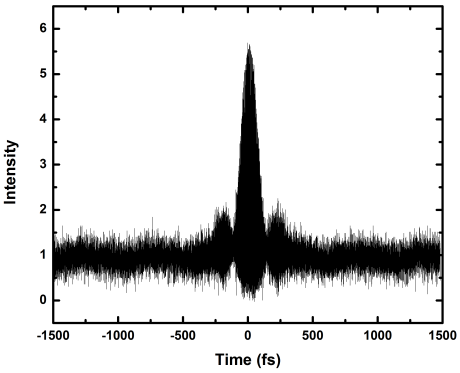

FIG. 4. Autocorrelation signal for stretched pulse laser

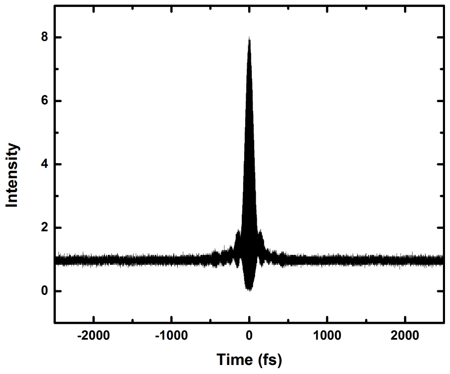

FIG. 5. An example of what a "clean" autocorrelation signal should look like

The data obtained for Figure 4 contains a significant amount of noise thus, it may not accurately portray a "normal" autocorrelation signal. The graph in Figure 5 provided by Dr. Andy Chong is an example of what an autocorrelation signal looks like given that the laser can offer enough power to overcome noise from light in the laboratory. The pulse duration for this signal is approximately 50 fs for comparison.

V. CONCLUSIONS

Ultrafast fiber lasers are becoming increasingly popular tools in science and industry due to their low cost, small size, and versatility. Due to the increasing popularity, it is important to be able to characterize these lasers and quickly evaluate their performance. Many tasks require lasers to operate in specific ranges of wavelength, have specific pulse energy, and specific pulse duration. Using the methods discussed in this paper, one can evaluate the efficacy of a laser for a given task. In the experiment performed. The performance of a stretched pulse laser with a 976 nm pump diode is evaluated.

The laser is first assembled by splicing the pump diode, an isolator, and a wavelength division multiplexor to the laser cavity. After assembly, the laser is mode-locked and the average output power of the mode-locked laser is measured. The average power for this stretched pulse laser is 58.6 mW. The repetition rate is measured after the power and is found to be 45.5 MHz. From the average power and repetition rate, the pulse energy is calculated. The pulse energy is 1.2 nJ. Finally, the laser signal is autocorrelated. The pulse duration of the stretched pulse laser is 97.4 fs. As discussed in the results section, the values obtained in this experiment are quite similar to those measured when the stretched pulse laser was first developed. So, while this laser may not be the most state of the art, it performs similarly to the first stretched pulse laser.

VI. REFERENCES

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