Fiber Laser Oscillator for Cornell's ERL Project

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Abstract

Cornell's Energy Recovery Linac (ERL) will create an ultra-bright x-ray synchrotron source with very low beam emittance. In order to measure this emittance, a 50 MHz laser oscillator is needed. This paper describes the design, construction, and characteristics of the laser that was built to meet this need.

MODE-LOCKED LASERS

Lasers operate by pumping energy to a gain medium to create population inversion, where a large number of the electrons in the gain medium are at an elevated energy level. As these electrons fall back down to the ground state, they emit photons. As these emitted photons pass through the gain medium, they stimulate the emission of photons from the excited electrons around them. These stimulated photons travel in the same direction as the original photon and have the same wavelength. [1]

By constructing the path that the photons take such that they complete a circuit, or cavity, they pass through the gain medium multiple times. The gain medium amplifies the beam of light until an equilibrium is achieved and the gain is equivalent to the optical losses inherent to the cavity, thus resulting in Light Amplification by Stimulated Emission of Radiation, hence the name, "laser."

In basic lasers, these photons are travelling in different directions and move throughout the cavity at different times, resulting in a fluctuating output as the beams of light interfere with each other constructively and destructively. By adding a saturable absorber to the cavity, a single, intense pulse of light can be created from random noise.

A saturable absorber is an optical element that attenuates low intensity beams while transmitting high intensity beams with little loss, as shown by Figure 1. As noise travels throughout the optical cavity, low intensity beams in the noise are rapidly reduced while high intensity beams have much smaller losses. The gain medium will amplify the optical signals, compensating for the losses of the high intensity beams but failing to make up for the large losses incurred by the low intensity signals, with the net result being a single pulse with high peak power and short duration travelling through the cavity, as shown in Figure 2.When a laser exhibits this type of pulsed behavior, it is said to be "mode-locked," as the pulse is the result of a fixed phase relationship between modes of the laser, or the allowed wavelengths of light within the optical cavity.

Pulses that are less than a few tens of picoseconds in duration are said to be "ultrashort" pulses. Optical cavities can be fine tuned so that these pulses have durations as short as a few tens of femtoseconds. [2]

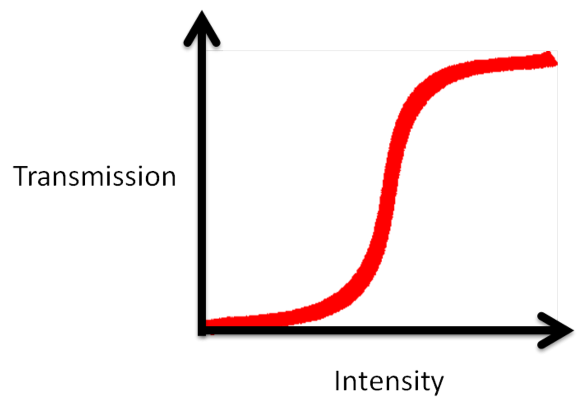

Figure 1: Simplified saturable absorber transmission characteristic.

Figure 2: The effect of a saturable absorber on optical signals.

ARTIFICIAL SATURABLE ABSORBERS

Optical fiber is a kerr-medium, meaning that when light propagates inside the fiber, it can experience some polarization-dependent phase shift. Low intensity in one polarization component will incur a large loss as they transit the fiber, while high intensity in other polarization components will experience smaller loss. If it is combined with half and quater waveplates as well as a polarizer, polarization dependent intensity moudlation can be achieved. It is very similar to the effect of a saturable absorber. This is usually called an artificial saturable absorber. This effect can be used to achieve mode locking in a fiber laser.

CHIRP

In addition to polarization change, optical fibers create chromatic dispersion. This results from the wavelength depenedence of the index of refraction in silica fiber. While the index is about 1.5 for all wavelengths, it is not perfectly uniform. Because the speed of light through a medium is dependent upon that medium's index of refraction, variation in the index across the optical bandwidth means that the highest wavelength photons present within the pulses will exit the fiber at a different time than those with the shortest wavelength, even if all photons entered the fiber at the exact same time. As a result, an ultrashort pulse can be spread out over a much larger period of time due to chromatic dispersion.

To compensate for chirp, double diffraction gratings are used. Light reflects off of diffraction grating at differing angles, depending on wavelength. Using this to disperse light in such a way that it counteracts the chromatic dispersion resulting from the optical fiber, "negative" dispersion can be introduced by the grating. Carefully selecting the distance between the grating can result in a net zero dispersion, where photons that travelled fastest through the optical fiber must travel the largest distance before being sent to a mirror, which reflects the light back through the grating pair and into a coherent beam. The end result of this process is that the photons will leave the grating pair with the same spacing they had before the pulse became chirped. [3]

SPECIFICATIONS

When the ERL project is completed, it will operate at 1.3 GHz. To perform emittancce measurement, the system must operate at the 26th sub-harmonic of this frequency, 50 MHz.

While there was no specified pulse duration, the minimum duration that could be experimentally achieved would be used. While typically emittance of bunches is measure by picosecond pulse lasers, Cornell already has an existing laser to meet this need. By building a laser with a pulse duration on the order of hundreds of femtoseconds, ultrafast events within the beam can be observed on the timescale upon which they occur. Additionally, the laser can be repurposed to measure any other event that operates on femtosecond time scales.

EXPERIMENTAL SETUP

The overall design of the laser is shown in Figure 3. The pump diode is that produces light centered at 976 nm. This light contains the energy that will be pumped into the gain medium to create population inversion. The WDM is a wavelength division multiplexer that is used to combine the light coming from the diode with the rest of the cavity.

The gain fiber is ytterbium-doped silica gain fiber. This is the gain medium used to create population inversion. Because the medium is fiber, rather than a crystal or semiconductor material, the laser is referred to as a "fiber laser."

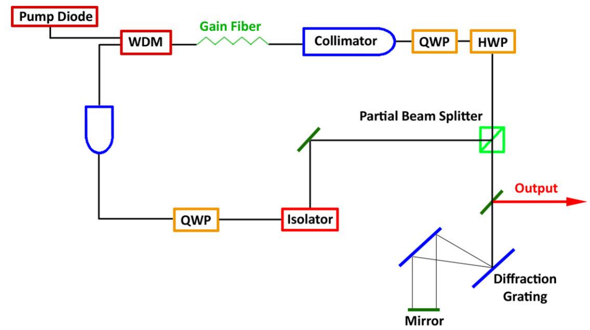

Figure 3: The placement of the various optical components described in the Experimental Setup section.

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Collimators are used to emit light from standard optical fiber into the cavity where the rest of the optical components are placed.

Quater waveplates (QWP) and the half waveplate (HWP) are used to change the polarization of light within the cavity. The polarization beam splitter transmits light horizontally polarized light while relecting the vertically polarized components. Light that remains inside the cavity is sent through a polarization-sensitive isolator, which is a device that allows light to travel in one direction but not the other. If light were allowed to travel in both directions through the cavity, opposing beams would interfere with one another, resulting in instability. These polarizers are used in tandem with the waveplates to create an artificial saturable absorber.

Light that does not remain in the optical cavity is sent to a pair of diffraction gratings. These gratings are used to dechirp the pulses coming from the laser.

MEASUREMENT TECHNIQUES

Because the pulses created by the laser are meant to be in the femtosecond range, the pulse cannot be directly measured. Even using the fastest photodiodes and oscilloscopes, resolution above a few hundred picoseconds cannot be achieved.

Figure 4 shows the pulse train as observed by a 300 MHz oscilloscope. The repetition rate can be deduced from this plot by measuring the time between pulses. The measured time of 19.84 ns corresponds to a frequency of 50.45 MHz. By taking the full width at half maximum (FWHM), a common means of measuring pulse width, this plot suggests a pulse width of 1.22 ns.

The true pulse width can be much more accurately estimated by measuring it indirectly, specifically by way of an autocorrelator. An autocorrelator is a special type of Michelson interferometer, where a beam of light is split into two paths. One of the paths reflects off a fixed mirror while the other reflects off a mirror with a variable distance.

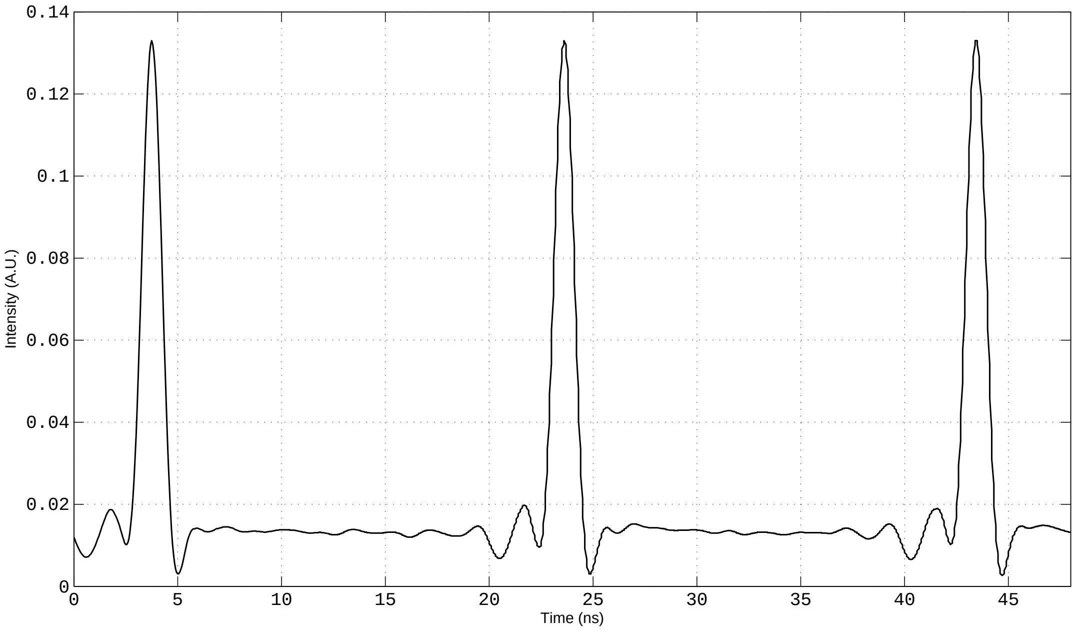

Figure 4: The pulse train as measured by an oscilloscope.

The two beams then travel collinearly into a nonlinear crystal. By sending a pulse through the autocorrelator, a slight variation in path length between the two beams results in a delay between the two pulses when they arrive at the nonlinear crystal.

The nonlinear crystal produces second harmonic generation (SHG). Higher intensity beams result in higher conversion to the second harmonic of the incident light. When the two pulses overlap perfectly, they have a very high intensity, resulting in a high rate of conversion to double frequency light. When one pulse is slightly delayed, this conversion rate will decrease, and when the pulses are not overlapping at all, there will be a very small conversion rate. The light that passes through the crystal is fed into a detector, wich can then be used to estimate pulse duration based on the power of the light that hits it. [4]

A Femtochrome FR 103-MN autocorrelator was used to measure pulse duration. It features a variable resolution so that it can be used to measure both intensity autocorrelations and interferometric autocorrelations. Both were used to estimate pusle duration of the existing laser.

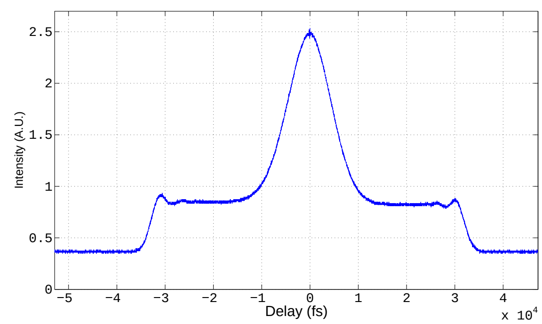

Figure 5: The chirped intensity autocorrelation. Assuming a near-Gaussian beam, this corresponds to a 5.3 ps pulse.

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RESULTS

The intensity autocorrelation of the chirped laser is shown in Figure 5. The peak is highest when the two pulses overlap completely and the detector registers the highest average power. As the delay between pulses becomes greater, the intensity of the light hitting the detector decreases, resulting the gradual drop of the peak. By taking the FWHM of this peak, information about the pulse duration can be extracted.

The chirped intensity autocorrelation pulse has a FWHM of approximately 8 ps which corresponds to a pulse duration of 5.3 ps if a Gaussian beam profile is assumed.

To reduce the pulse width, the laser output was sent through a diffraction grating pair for dechirping. A detail plot of the dechirped intensity autocorrelation is shown in Figure 6. The FWHM of this pulse is approximately 330 fs. Again, assuming a Gaussian beam profile, this number corresponds to a pulse duration fo 220 fs.

By increasing the resolution of the autocorrelator to .1fs, an interferometric autocorrelation is obtained. A plot of the interferometric autocorrelation is shown in Figure 7. From this measurement, we can see that the pulse duration is about 220 fs, which is in consistent with the intensity autocorrellation measurement.

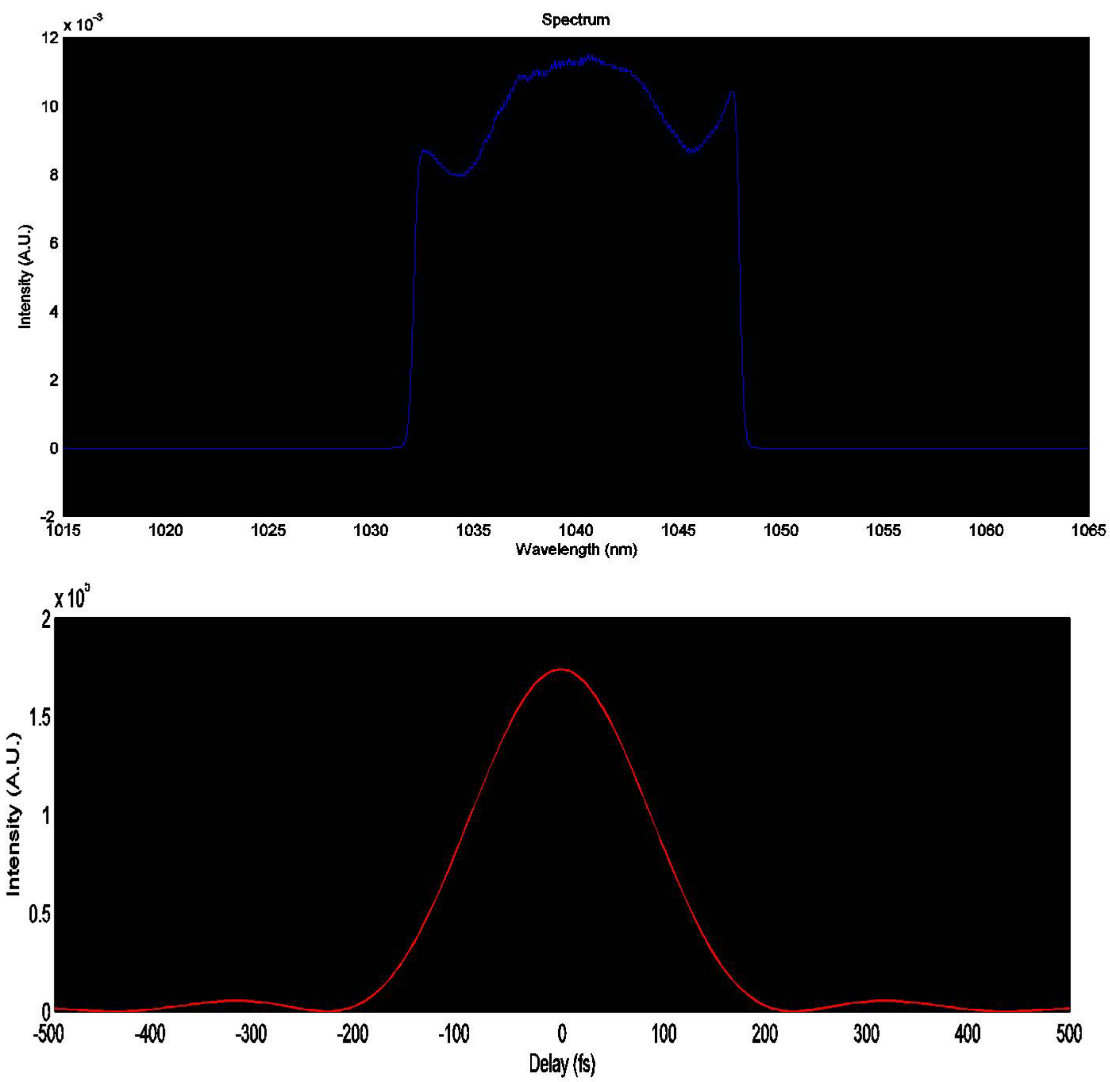

Figure 8: The spectrum of the laser and its Fourier transform.

One final means of estimating the pulse width can be performed by exploiting Fourier transforms, which relate function in the time domain with those in the frequency domain. By feeding the laser output into a spectrometer, Figure 8 was produced. The first plot in Figure 8 shows intensity versus wavelength of the laser. By applying a Fourier transform to this spectrum, a transform limited pulse duration can be found. The result of the Fourier transform on the spectrum data is shown in the second plot of Figure 8. From this simulation we find that the shortest pulse duration is about 200 fs. This indicates excellent agreement between the dechirping process and this theoretical prediction.

In addtion to providing information about the pulse, the spectrum measurements in Figure 9 show that the laser is centered around light of 1040 nm. While light within the bandwidth of the laser features high intensity, light outside is nearly 40 dB lower than the main signal. This is an important fact as is shows that there is no amplified spontaneous emission (ASE) ocurring within the laser. It also means that none of the original light from the pump diode is being sent around the cavity, as this light had a wavelength of 976 nm.

The peak power of the pulse can be estimated from the peak energy, which is itself given by the equation

$$E_{pulse} = \frac{P_{avg}}{f}$$

where E_{pulse} is the pulse energy, P_{avg} is the average power, and f is the frequency of pulses. Given that the chirped pulse was measured to have an average power of 203 mW that the pulse frequency is 50.5 MHz, the chirped pulse energy was calculated to be

$$\frac{203 * 10^{-3}}{50.5 * 10^{6}} = 4.02nJ$$

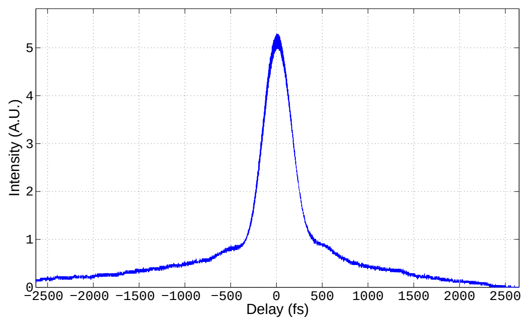

Figure 6: A detail view of the dechirped intensity autocorrelation. Assuming a Gaussian beam, this corresponds to a 220 fs pulse.

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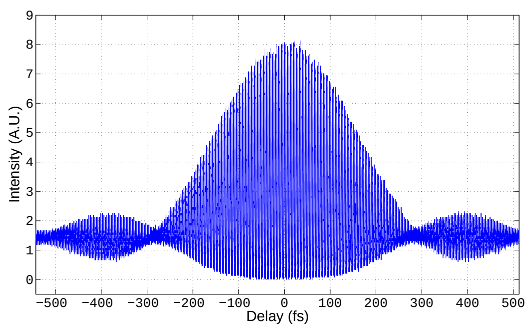

Figure 7: The dechirped interferometric autocorrelation. Assuming a Gaussian beam, this corresponds to a 220 fs pulse.

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The dechirped pulse suffered energy loss due to the diffraction grating, which only had about 25% efficiency. This large loss of energy can be attributed to the fact that one of the gratings was heavily scratched and worn. Average power of the dechirped signal was measured as 53.3 mW, meaning that the dechirped pulse energy was calculated to be

$$\frac{53.3 * 10^{-3}}{50.5 * 10^{6}} = 1.06nJ$$

Once the pulse energy is known, it is possible to estimate the peak power from the equation

$$P_{peak} = \frac{E_{pulse}}{\tau_{pulse}}$$

Where P_{peak} is peak power and τ_{pulse} is the pulse duration. For the chirped pulse, which had a duration of 5.3 ps, this becomes

$$\frac{4.02 * 10^{-9}}{5.33 * 10^{-15}} = 758.5W$$

The dechirped pulse, which had a pulse duration of 220 fs, had a peak power of

$$\frac{1.06 * 10^{-9}}{220 * 10^{-15}} = 4.82kW$$

It should be mentioned that there is a large loss associated with the grating. If one pair of highly efficienct grating could be used, the output peak power could be improved by three times.

FUTURE WORK

There are four major ways in which the existing laser can be improved upon. Firstly, mirrors in the cavity can be placed on translating mounts which allow them to be adjusted minutely without largely affecting alignment. This will make it easier for an operator to fine tune the cavity length to achieve precisely 50 MHz repetion rate rather than the current rate of 50.5 MHz.

Secondly, a diffraction grating pair can be added to the cavity itself to create zero net dispersion in the laser. This will decrease timing jitter and increase the laser's stability.

Thirdly, the birefringent filter can be changed to a thinner one, as this will change the spectrum and may result in a shorter pulse.

Laslty, the pump power may be increased and high efficiency grating can be used for the dechirping process to increase the output power of the laser.

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