

Characterizing ultrashort laser pulses:

Construction of GRENOUILLE

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Abstract

Characterizing ultrashort laser pulses involves splitting the pulse to be measured into two halves and overlapping them on a second harmonic crystal in a process called Frequency-Resolved Optical Gating (FROG). GRENOUILLE is a simplified optical setup that uses properties of FROG to measure pulses. A GRENOUILLE setup was constructed and tested on pulses from a Ti:Sapphire pulsed laser. The simplified optical system was built on a breadboard to allow easy transportation around the lab. Several Labview programs were written to convert image data into a format that pulse-retrieval software can use. Using GRENOUILLE and the software, FROG traces were retrieved from the laser with errors between 0.004 and 0.005, which are acceptable errors for pulse measurements.

Introduction

The production of ultrashort laser pulses, those with durations on the order of femtoseconds, has been feasible for a few decades now. The more difficult task proves to be characterizing the pulses, or quantitatively measuring pulse durations. The issue arises because in order to measure the duration of an event, an even shorter event must be used. Since no shorter event than ultrashort laser pulses can be created, the pulses are difficult to measure. The only way to characterize the pulses is to use the pulse to measure itself. This involves overlapping a pulse with itself both spatially and temporally on a second-harmonic-generation (SHG) crystal. Second-harmonic-generation is a nonlinear optical process in which two photons of frequency ω combine to produce a photon of frequency 2ω . By observing the resulting signal, information about the pulses' duration can be obtained.

Early on in ultrashort-pulse measurement, a technique termed autocorrelation overlapped pulses by splitting them with a beamsplitter and then refocusing the two resulting beams on an SHG crystal. The second-harmonic signal is then read by a detector that measures its intensity. This intensity autocorrelation is only a rough measure of the pulse since many different pulses can have the same autocorrelation, yielding many ambiguities. In addition to these ambiguities, obtaining the intensity autocorrelation of a pulse is difficult experimentally, because splitting and recombining the pulses involves several extremely sensitive alignment degrees of freedom.

In the 1990s, Dr. Rick Trebino and Dr. Daniel Kane invented a way to eliminate the ambiguities in the autocorrelation measurements. By obtaining information about the spectrum of the second-harmonic signal, thus working in the time-frequency domain,

they were able to turn the pulse-retrieval problem into a two-dimensional problem instead of the one dimensional autocorrelation problem. Counter-intuitively, the pulse-retrieval problem is easier, since mathematically, each second-harmonic signal in the time-frequency domain is unique. Thus, each signal corresponds to a single pulse structure. Trebino called this technique Frequency-Resolved Optical Gating, or FROG [1]. Optically, FROG uses an intensity-autocorrelation measurement as had been done previously, but in addition, FROG uses a spectrometer to simultaneously spectrally resolve the signal. While FROG was a major breakthrough in pulse measurement, the implementation in the lab was still difficult, as three sensitive alignment degrees of freedom still existed.

Ten years later, Trebino and others at Georgia Tech modified the FROG setup in such a way as to eliminate the sensitive alignments that were inherent in FROG. He did this by replacing the FROG beamsplitter with a Fresnel biprism, an optical device that automatically splits and overlaps pulses on the SHG crystal. This simpler optical setup, named GRENOUILLE (Grating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields; the acronym is French for “frog”) is much easier to build in the lab [2]. The goal of my summer project was to build GRENOUILLE for Dr. Reitze’s ultrafast physics lab at the University of Florida.

The work done to build GRENOUILLE fell into two categories: optical setup and information processing. The optical setup consisted of aligning three cylindrical lenses, a Fresnel biprism, a telescoping lens stage, an SHG crystal, and a CCD camera. The information processing interfaced the CCD camera with an external computer, using the CCD software to obtain images of the beams and writing data to a log that could be fed

into FROG software that uses numeric methods to extract the pulse characterization.

GRENOUILLE also had to be calibrated so that the time per pixel and wavelength per pixel values were known for the CCD camera. With these steps completed,

GRENOUILLE is ready to be tested on an amplified ultrashort laser pulse system.

Theory

As stated earlier, in GRENOUILLE, a Fresnel biprism splits an input pulse into two and overlaps the halves on a nonlinear crystal. The crystal then produces the light's second harmonic, converting two photons of frequency ω to one photon of frequency 2ω . For pulses composed of wavelengths around 800 nm, blue light of wavelength 400 nm is produced. A CCD camera behind the crystal then measures the Fourier transform of the signal field:

$$I_{Frog}(\omega, \tau) = \left| \int_{-\infty}^{\infty} E(t)E(t-\tau) \exp(-i\omega t) dt \right|^2, \quad (1)$$

where $E(t)$ one half of the initial pulse and $E(t-\tau)$ is the other half of the pulse, delayed with respect to the first half by some time τ . Since the detector cannot respond to such short pulses, it detects the time integral of the signal. Now, let

$E_{sig}(t, \tau) = E(t)E(t-\tau)$. Suppose that the Fourier transform of $E_{sig}(t, \tau)$ with respect to τ is a new quantity $\tilde{E}_{sig}(t, \Omega)$. Then,

$$E_{sig}(t, \tau) = \int_{-\infty}^{\infty} \tilde{E}_{sig}(t, \Omega) \exp(-i\Omega \tau) d\Omega. \quad (2)$$

Substituting this quantity into Eq. 1 gives:

$$I_{Frog}(\omega, t) = \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{E}_{sig}(t, \Omega) \exp(-i\omega t - i\Omega \tau) dt d\Omega \right|^2. \quad (3)$$

This substitution seems to complicate what quantity the CCD image captures, but in fact, this step is necessary in order to measure the pulses. The problem with measuring just the intensity autocorrelation or spectrum of the pulse is that neither of those quantities can uniquely determine the pulse shape. Phase information cannot be extracted from those traces. In fact, the *1D phase-retrieval problem* is a classic unsolvable problem; thus, $E(t)$ cannot be determined uniquely in the one-dimensional case [3,4]. However, the *2D phase-retrieval problem* is a solvable problem [5]. There exist a few ambiguities in retrieving the phase information in the 2D case, but these are mostly trivial. For a more in-depth discussion of the mathematics of GRENOUILLE, see Dr. Trebino's book on the subject [6].

Now, knowing that the 2D phase retrieval is unique, $\tilde{E}_{sig}(t, \Omega)$ can be determined uniquely from the trace $I_{Frog}(\omega, t)$. This is useful, because GRENOUILLE can be calibrated to retrieve $E(t)$ from $\tilde{E}_{sig}(t, \Omega)$. Taking the inverse Fourier transform of $\tilde{E}_{sig}(t, \Omega)$ yields $E_{sig}(t, \tau)$. Remembering that $E_{sig}(t, \tau) = E(t)E(t - \tau)$, consider the beam geometry of GRENOUILLE (Fig. 1).

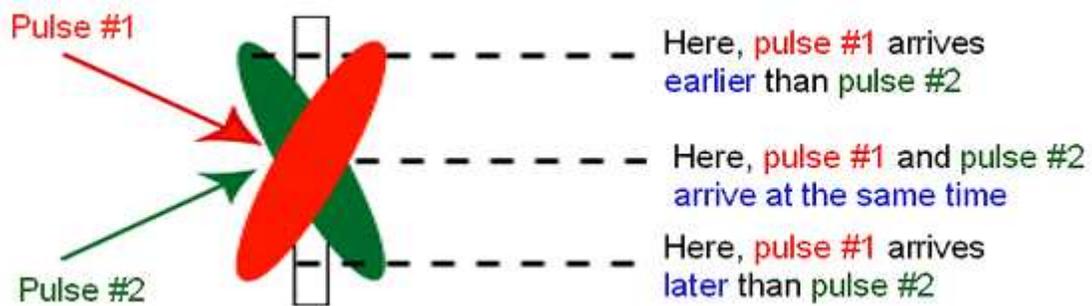


Fig. 1: Beam geometry at SHG crystal in GRENOUILLE. Source: Reference [2].

The two beams from the Fresnel biprism reach the crystal at different times depending on the position of the crystal. Thus, $\tau = \tau(x)$. If GRENOUILLE is calibrated such that

$\tau = \tau(x) = t$, then $E_{sig}(t, \tau) = E_{sig}(t, t) = E(t)E(t-t) = E(t)E(0)$. So, from the initial trace $I_{Frog}(\omega, t)$, the quantity $E(t)E(0)$ can be derived uniquely. While interpreting the meaning of $E(t)E(0)$ is somewhat complicated, the quantity is enough to determine $E(t)$, which is the goal of pulse characterization.

To perform the actual computations needed to find $E(t)$, Dr. Trebino's company has written software to perform the 2D phase retrieval through an iterative process well-known in the image-processing fields. By inputting the wavelength per pixel and time per pixel for the axes, the image data itself, and the wavelength of the first pixel, one can characterize laser pulses from GRENOUILLE.

Experimental Procedure

A Ti:Sapphire oscillator already built in Dr. Reitze's lab was used to produce ultrashort laser pulses for input into GRENOUILLE. GRENOUILLE (Fig. 2) consists of cylindrical lenses, a Fresnel biprism, a thick SHG crystal, and a CCD camera.

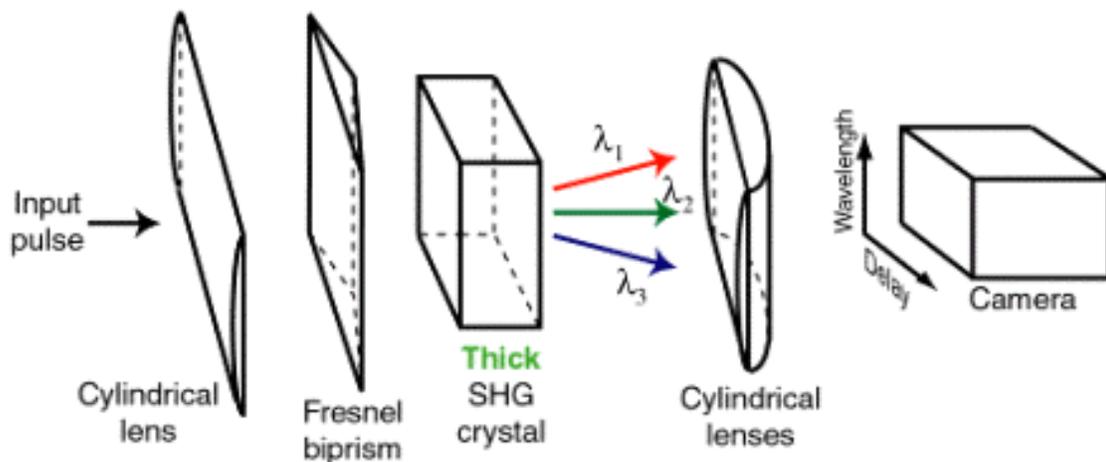


Fig. 2: Illustration of the GRENOUILLE setup. Source: Reference [2].

The initial cylindrical lens ($f = 10$ cm) focuses light in the y direction (normal to the table) and onto a 3-mm-thick lithium iodate (LiIO_3) nonlinear crystal, which sits at the

focus of the lens. The Fresnel biprism, which splits the beam in half and overlaps the resulting two halves, is placed between the initial lens and the SHG crystal. After the lens, another cylindrical lens ($f = 10$ cm) re-collimates the beam in the y direction. Immediately after, another cylindrical lens ($f = 5$ cm) focuses light in the x direction (parallel to the table). A slit, placed at the focus of this third lens, filters out background light and allows the GRENOUILLE trace to pass through. A CCD camera then images the beam 10 cm after the set of back-to-back lenses. Figure 3 illustrates the beam's propagation through GRENOUILLE in both the x and y profile.

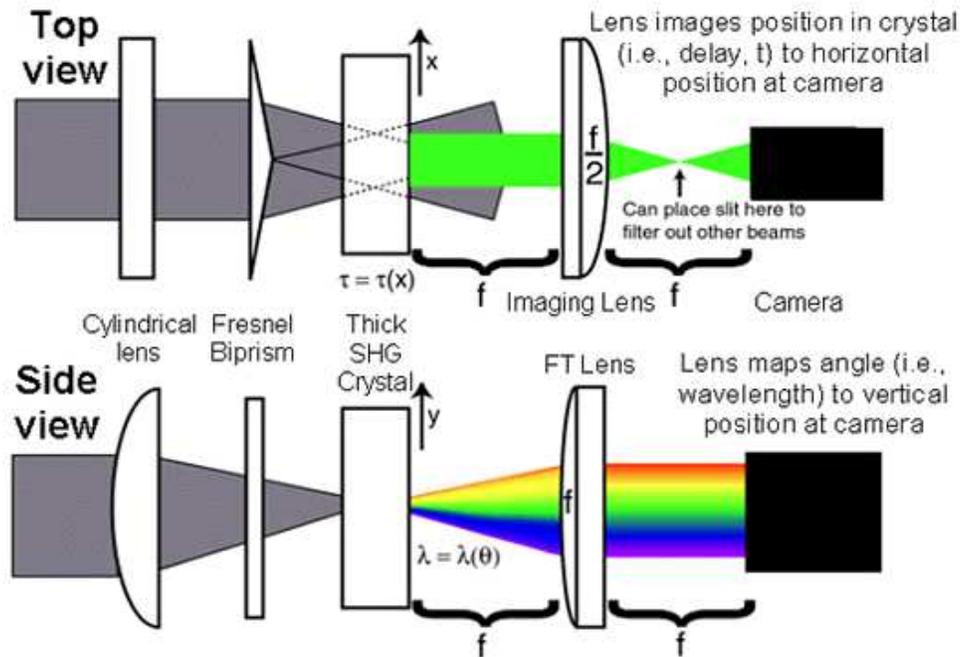


Fig. 3: The laser pulse's propagation through GRENOUILLE in the x and y profile. Source: Reference [2].

GRENOUILLE was built on a breadboard that is easily transported around the lab. Two irises define a beam line to which the laser pulses are aligned. The beam is then expanded to approximately 1 cm in diameter by telescoping lenses before it reaches GRENOUILLE. Throughout the setup, several optical elements sit on translation stages

that allow fine adjustments along an axis. The second lens in the telescope, the crystal, and the CCD camera all rest on these stages so that they can be aligned at foci of lenses in the system. The actual GRENOUILLE implemented in lab is shown in Figure 4.

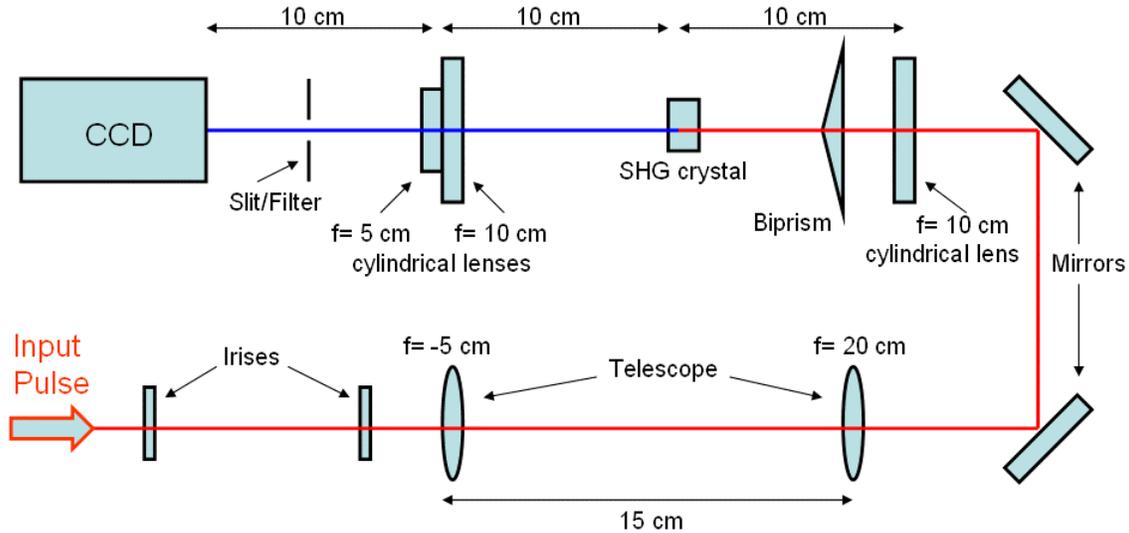


Fig. 4: Schematic of the actual GRENOUILLE.

The information-processing part of building GRENOUILLE encompassed taking images with the CCD camera and analyzing them. Software written by Trebino's group at Georgia Tech analyzes FROG traces by taking an image and trying to reconstruct the electric field and phase necessary to produce a particular pulse. The software needs the pixel values from the CCD image in a 1D list, so a Labview program was written to convert the resulting CCD images into a list that can be put into the FROG software. Another program was written that integrates pixel values along either the time axis or the wavelength axis. This program is used in GRENOUILLE calibration.

To calibrate GRENOUILLE well, two pulses displaced in time should be sent through GRENOUILLE. A value for second per pixel is obtained for the time axis from knowing how much time elapses between pulses and observing their separation in the

trace. The two pulses cause interference patterns in a central band in the image, and the wavelength per pixel value comes from observing the spacing between peaks of intensity. A double pulse was created using an autocorrelator which split the input beam into two halves and recombined them later after a known delay was introduced between the two. However, in GRENOUILLE, neither the two peaks nor the interference pattern was observed when the double pulse was sent through the system. This issue must be investigated further in order to obtain the necessary calibration.

To take data before the end of the REU program, a less precise calibration was made. The spectrum of the pulse was determined using an Ocean Optics spectrometer, and the full width at half maximum (FWHM) of the spectrum divided by the FWHM of the FROG trace's wavelength profile provided the wavelength-axis calibration. The time calibration was done by estimating the input-pulse duration and dividing that time by the FWHM of the FROG trace's time profile. Once these calibrations were made, ultrashort pulses from the Ti:Sapphire oscillator were measured.

Results

GRENOUILLE was calibrated using an Ocean Optics spectrometer. A FROG trace was taken, and using a Labview program, the pixels were integrated in the wavelength domain. The FWHM of the measured spectrum was compared to the FWHM of the wavelength integration data to obtain a value for wavelength per pixel in the trace. The wavelength calibration turned out to be 0.0457 nm per pixel. The shape of the Ocean Optics trace and the FROG trace from GRENOUILLE are both Gaussian with a dip in the middle (Fig. 5). The similarities in these shapes are encouraging. Figure 5(a) was generated by taking the spectrum before the second-harmonic generation and dividing

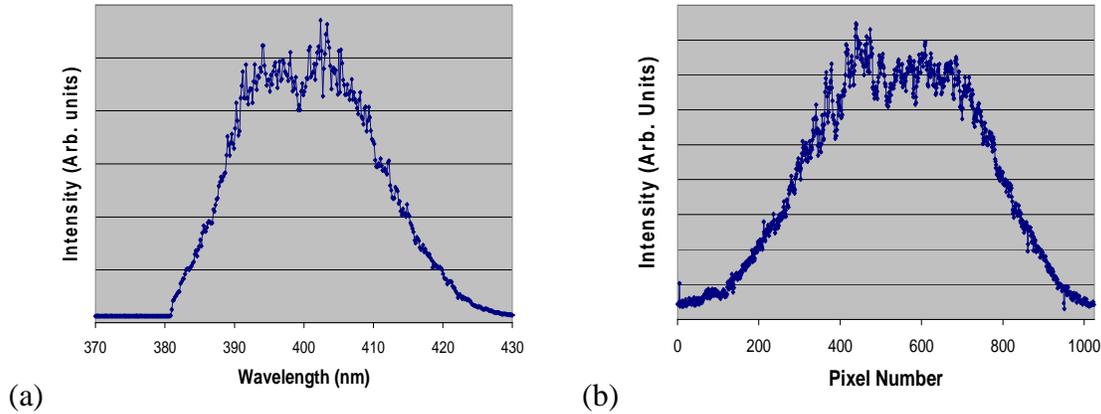


Fig. 5: a) Second harmonic spectrum measured by Ocean Optics, and b) integration of the wavelength domain of a FROG trace

it by 2. Thus, the FWHM of 23.7 nm in the second harmonic corresponds to a FWHM of 47.4 nm in the IR spectrum—the spectral width of the pulse.

Figure 6(a) shows an example of a trace taken using GRENOUILLE. The retrieved pulse (Fig. 6(b)) from the software is shown as well. The theoretical pulse is 26.58 fs in duration and has a spectral width of 50.54 nm (Fig. 6(c)). This calculated spectral width generally agrees with the measured spectral width of 47.4 nm. This agreement is also encouraging. The error between the experimental trace and the theoretical trace is 0.004667. This error is computed as a pixel-by-pixel rms average throughout the trace. Errors less than 0.005 are considered acceptable; however, traces from the existing FROG setup have yielded errors close to 0.001. The experimental image has two side bands that are due to diffraction effects of the slit used to filter out background second harmonic light. This effect caused an asymmetry in the experimental trace that is not present in the reconstructed FROG trace, most likely producing the high error.

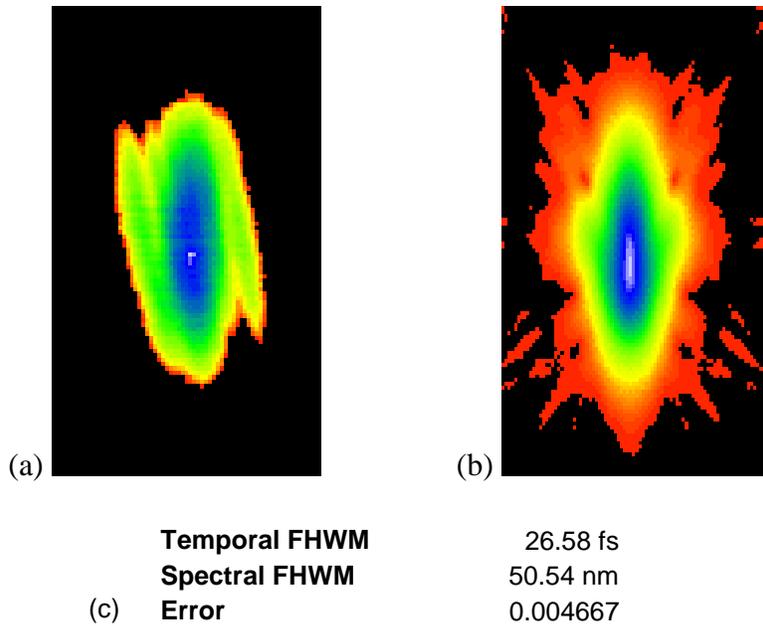


Fig. 6: a) Experimental FROG trace taken from GRENOUILLE, and b) reconstructed FROG trace using Frog3 software. Delay is plotted along the horizontal axis, and wavelength is plotted along the vertical axis. The color scale is normalized such that black is zero intensity, white is an intensity of 1, and other colors range from red ($\ll 1$ in intensity) to blue (~ 1 in intensity). c) Pulse characteristics recovered by Frog3 software.

Conclusions

GRENOUILLE has returned several consistent and reasonable pulse measurements. However double pulses put into GRENOUILLE have not returned traces in agreement with theory. Without this good double-pulse trace, GRENOUILLE calibration is not precise, and data taken with the current setup cannot be considered completely reliable. Further work must be done to address the calibration issue.

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