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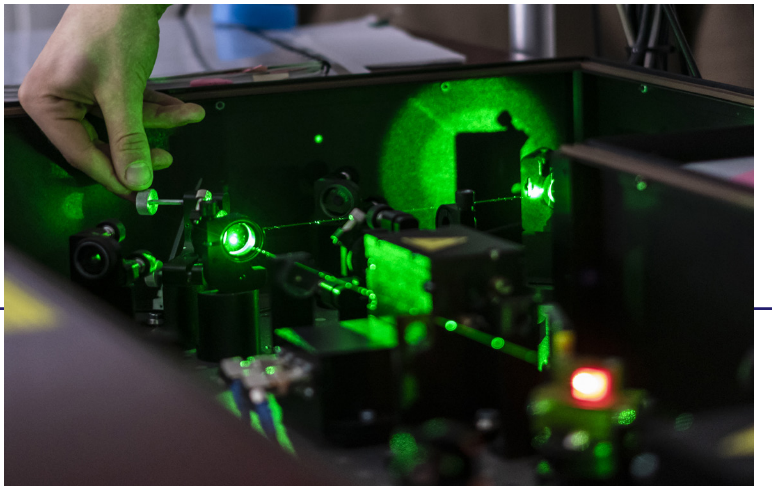
APPLICATION NOTE:
FREQUENCY RESOLVED OPTICAL GATING

Techniques

- Ultra Fast Laser Measurement

Keywords

- FROG
- Laser
- Optical Gating
- Laser Characterization
- Micromachining
- Fluorescence



Introduction

Ultrafast mode-locked lasers are rapidly becoming commonplace for both research and industrial applications ranging from multiphoton fluorescence microscopy to micromachining. As mode-locked lasers increase in popularity, so does the need for accurate and reliable laser characterization systems. Unfortunately, the very thing that makes these lasers so desirable as a measurement tool - their short pulse width - makes them extremely difficult to be measured themselves. In this application note we will explore one of the most popular techniques for ultrafast laser characterization, which relies heavily on spectral measurement action: frequency-resolved optical gating (FROG). As well as the key requirements for spectrometers used in FROG systems.

Fundamentals of Ultrafast Laser Measurement

Since ultrafast laser pulse width is typically the limiting factor for the measurement system's temporal resolution, it begs the question: what is short enough to measure the pulse? Because there is typically nothing shorter, the best way to measure the laser pulse width is the pulse itself. At first glance, this may sound nonsensical, but the mathematical underpinning is reasonably well established in correlation theory, known more specifically as autocorrelation.

$$I(\tau) = I(t) \star I(t) = \int_{-\infty}^{\infty} I(t)I(t-\tau)d\tau$$

Eq 1

While the mathematical formulation of autocorrelation can be overwhelming, it basically describes the product of the pulse with itself as a function of delay time (τ). Figure 1 shows an animation of a step-by-step autocorrelation, where the dotted green line represents the delay pulse, and the black line **represents the autocorrelation.** In practice, autocorrelation is accomplished by splitting the beam into two different optical paths where half of the beam is sent through a variable delay line. The two beams are recombined in a nonlinear material, such as a second harmonic generator (SHG), as shown in figure 2. The intensity of the SHG signal follows the relationship:

$$I(\tau) \propto \left|\chi^{(2)}\vec{E}(t)\vec{E}(t-\tau)\right|^2$$

Therefore, measuring the intensity as a function of delay time results in the laser pulse's autocorrelation. Therefore, measuring the intensity as a function of delay time results in the laser pulse's autocorrelation.

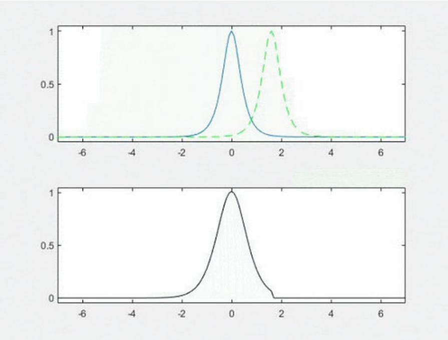


Figure 1: Simulation of a soliton waveform, sech(t-τ), scanned across a stationary soliton, sech(t) to demonstrate the process of performing an autocorrelation.

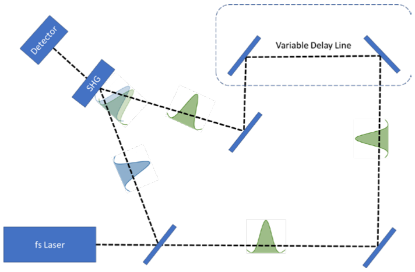


Figure 2: Schematic representation of a second harmonic generation (SHG) autocorrelator

As far back as the 1960s, laser engineers have used delay-based autocorrelators to characterize ultrafast laser pulses, but this method has two significant drawbacks.

As demonstrated in figure 1, the full width half maximum (FWHM) of the autocorrelation is not the same as the FWHM of the original pulse. In some cases, such as the soliton pulse shown in figure 1, the difference can be as simple as a scalar multiple. The conversion factor can be far more complicated for other pulse shapes. Therefore, it is necessary to know the pulse shape before analyzing it, which is often impractical. Additionally, autocorrelators only measure the laser pulse's amplitude, not the phase, providing only partial characterization at best. In the early 1990s, Rick Terbion and his team at Sandia National Labs1 went beyond just collecting the intensity. This team had the visionary idea to replace the detector with a spectrometer, as shown in figure 3, which resulted in a 2-dimensional dataset (also known as a spectrogram) measuring frequency as a function of delay time. This plot, now known as a frequency-resolved optical gate (FROG) trace, could then be Fourie transformed, to recovering the amplitude and phase information. Now, complete characterization of the laser pulse can be measured without any prior knowledge of the pulse shape. Figure 4 shows a simulated FROG trace for an 800nm mode-locked laser with a 100fs FWHM pulse width and a 6.7nm linewidth. While we have only discussed the use of SHG as the nonlinear method in both the autocorrelator and the FROG, there are many different nonlinear techniques used in practice. Techniques include polarization gating, self-diffraction, and third-harmonic generation, each of which has its unique advantages and disadvantages.

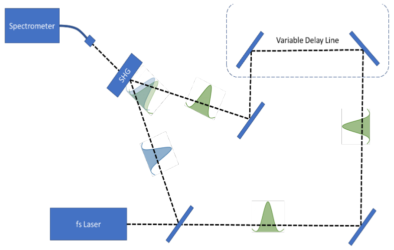


Figure 3: Schematic representation of a second harmonic generation frequency-resolved optical gate (SHG FROG).

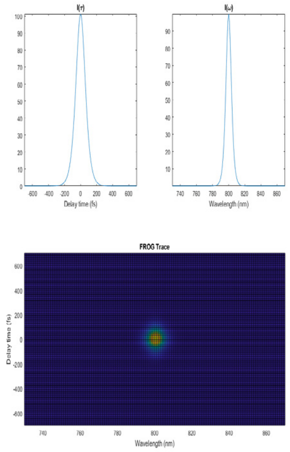


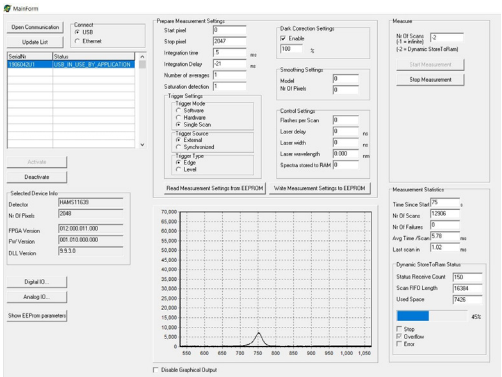
Figure 4: Simulated intensity (top left) and spectral (top right) profile of an 800nm, 100fs pulse width laser, along with the associated FROG trace (bottom).

Spectrometer Requirements

FROG traces consist of coupled temporal and spectral measurements, and spectrometer requirements can be divided into the same two subcategories to avoid confusion. Speed and dynamic range are the dominant considerations for a successful FROG trace, similar to other gated spectroscopy applications. With that in mind, it is essential to reiterate that the speed of data acquisition is in no way correlated to the laser's pulse width or pulse repetition rate. Each spectral integration will likely contain a large number of individual laser pulses. The speed requirements are dependent on the number of data points that are required to capture the autocorrelation function (delay-gate) and how well it can be triggered with the delay line. The spectrometer's dynamic range is also crucial for providing an intensity resolution needed for autocorrelation. As a result, CMOS detectors are always preferable to CCD detectors because of their faster readout speeds and extensive dynamic ranges.

Even though most CMOS cameras' detectors' minimum integration time is on the order of 10 microseconds, the major bottleneck occurs when the spectrometers' readout electronics have to transfer the data from the detector to the computer. Avantes' dynamic store to RAM capabilities represent a significant leap forward in high-speed spectral readout. The dynamic store to RAM feature allows the user to save scans to the RAM buffer onboard the instrument while simultaneously offloading the spectra to the computer. The AvaSpec-ULS2048CL-EVO is now capable of continually acquiring spectra at a rate of 2 kHz because of this feature. Figure 5 shows an example of the new graphical user interface (GUI) when using dynamic store to RAM.

This rate can be increased even further by reducing the number of active pixels


MainForm

Connect: ● USB ○ Ethernet

SerialNr	Status
1906042U1	USB_IN_USE_BY_APPLICATION

Selected Device Info
Detector: HAMS11639
Nr Of Pixels: 2048
FPGA Version: 012.000.011.000
FW Version: 001.010.000.000
DLL Version: 9.9.3.0

Prepare Measurement Settings
Start pixel: 0
Stop pixel: 2047
Integration time: .5 ms
Integration Delay: -21 ns
Number of averages: 1
Saturation detection: 1

Trigger Settings
Trigger Mode: ○ Software ○ Hardware ● Single Scan
Trigger Source: ● External ○ Synchronized
Trigger Type: ● Edge ○ Level

Dark Correction Settings
☑ Enable
100 %

Smoothing Settings
Model: 0
Nr Of Pixels: 0

Control Settings
Flashes per Scan: 0
Laser delay: 0 ns
Laser width: 0 ns
Laser wavelength: 0.000 nm
Spectra stored to RAM: 0

Measure
Nr Of Scans (-1 = infinite) (-2 = Dynamic StoreToRam): -2

Measurement Statistics
Time Since Start: 75 s
Nr Of Scans: 12906
Nr Of Failures: 0
Avg Time /Scan: 5.78 ms
Last scan in: 1.02 ms

Dynamic StoreToRam Status
Status Receive Count: 150
Scan FIFO Length: 16384
Used Space: 7426
45%
☐ Stop
☑ Overflow
☐ Error

☐ Disable Graphical Output

Figure 5: Graphical output of Dynamic Store to RAM.

AvaSpec-ULS2048CL-EVO

being used on the detector. However, this should be used with caution as it will impact the spectral resolution. For effective spectral characterization, it is crucial to make sure that a spectrometer can provide high resolution and high sensitivity. Even though ultrafast lasers are relatively broad (particularly by laser standards), FROGs utilize the small change in spectral linewidth to help differentiate small changes in spectral pulse width; therefore, high spectral resolution is still a necessity. Avantes has long been a leader in high-resolution miniature spectrometers, offering a wide range of high-groove density gratings and replaceable entrance slit options. For example, the AvaSpec-ULS2048CL-EVO can be configured with a 1200/mm groove density grazing blazed at 750 nm and a 10-micron entrance slit to provide 0.25 nm resolution from 750nm to 900nm spectral range. These features make the AvaSpec-ULS2048CL-EVO the ideal choice for characterizing mode-locked Ti:Sapphire lasers. The new AvaSpec-ULS2048CL-EVO with ultra-fast USB3.0 communication provides high speed communication up to 2.5 KHz which can be increased slightly by selecting a smaller subset of pixels for data acquisition. This allows for high speed without sacrificing resolution For effective spectral characterization, it is crucial to make sure that a spectrometer can provide high resolution and high sensitivity. Even though ultrafast lasers are relatively broad (particularly by laser standards), FROGs utilize the small change in spectral linewidth to help differentiate small changes in spectral pulse width; therefore, high spectral resolution is still a necessity. Avantes has long been a leader in high-resolution miniature spectrometers, offering a wide range of high-grove density gratings and entrance slit options. For example, the AvaSpec-ULS2048CL-EVO and AvaSpec-ULS4096CL-EVO instruments both can be configured with a 1200/mm groove density grazing blazed at 750 nm and a 10-micron entrance slit to provide 0.14 nm (4096) or 0.25 nm (2048) resolution from 750nm to 900nm spectral range. These features make the AvaSpec-ULS2048CL-EVO and the AvaSpec-ULS4096CL-EVO ideal choices for characterizing mode-locked Ti:Sapphire lasers.

Contact Us for More Information

For more information about the full range of laboratory and OEM spectrometer options available from Avantesm, including our new dynamic store to RAM capabilities, please feel free to visit the website at **www.avantesusa.com** or give us a call at +1 (303)-410-8668, where our knowledgeable applications specialists are standing by to help.

References

- [1] Trebino, R., DeLong, K.W., Fittinghoff, D.N., Sweetser, J.N., Krumbügel, M.A., Richman, B.A. and Kane, D.J., 1997. domain using frequency-resolved optical gating. Reviewof Scientific Instruments, 68(9), pp.3277-3295.Measuring ultrashort laser pulses in the time-frequency