MesaPhotonics
1550 Pacheco St.
Santa Fe, NM 87505
505.216.5015
www.mesaphotonics.com

What do we mean by pulse measurement of an Ultrafast Laser Pulse?

Ultrafast laser pulses have durations from just a few picoseconds to less than a femtosecond. Even the fastest electronics cannot measure pulses this short. Thus, we must measure these pulses indirectly using the fastest methods known—optical methods. Perhaps the most popular method for measuring ultrafast laser pulses is a technique called Frequency Resolved Optical Gating (FROG).

Obtaining the intensity (pulse temporal profile) and phase (spectral content as a function of time), I(t) and φ(t) (or $\tilde{I}(\omega)$, the pulse spectrum and ϕ(ω), the time arrival of spectral components) is called full characterization of the pulse. (Because of the Fourier transform relationship between the temporal and spectral domains, obtaining the intensity and phase in either domain is equivalent.) Common phase distortions include linearly chirping, where the phase (either the time domain or frequency domain) is parabolic, but the spectral content changes linearly. When the frequency is increasing in time, the pulse is said to have positive linear chirp; negative linear chirp is when the high frequencies lead the lower frequencies. Higher order chirps are common, but for these, differentiation between spectral and temporal chirp is required because spectral phase and temporal phase are not interchangeable.

Frequency-Resolved Optical Gating

Frequency-resolved optical gating (FROG), developed by Kane and Trebino,[1] completely characterizes an ultrafast laser pulse. FROG measures the spectrum of a particular temporal component of the pulse (see Fig. 1) by spectrally resolving the signal pulse in an autocorrelation-type experiment using an instantaneously responding nonlinear medium. As shown in Fig. 1, FROG involves splitting a pulse and then overlapping the two resulting pulses in an instantaneously responding $\chi^{(3)}$ or $\chi^{(2)}$ medium. Even though any instantaneous nonlinear interaction may be used to implement FROG, perhaps the most intuitive is the polarization-gating configuration. In this case, induced birefringence due to the electronic Kerr effect is used as the nonlinear-optical process. In other words, the "gate" pulse causes the $\chi^{(3)}$ medium, which is placed between two crossed polarizers, to become slightly birefringent. The polarization of the "gated" probe pulse is rotated slightly by the induced birefringence allowing some of the "gated" pulse to leak through the second polarizer. This is referred to as the signal. Because most of the signal emanates from the region of temporal overlap between the gate pulse and the probe pulse, the signal pulse contains the frequencies of the “gated” probe pulse within this overlap region. The signal is then spectrally resolved, and the signal intensity is measured as a function of wavelength and delay time τ. The resulting trace of intensity versus delay and frequency is a spectrogram, a time- and frequency-resolved transform that intuitively displays time-dependent spectral information of a waveform.

The spectrogram can be expressed as:

$$S_E(\omega,\tau) = \left| \int_{-\infty}^{\infty} E(t) g(t-\tau) e^{-i\omega t} dt \right|^2$$

where E(t) is the measured pulse's electric field, g(t-τ) is the variable-delay gate pulse, and the subscript E on S_E indicates the spectrogram's dependence on E(t). The gate pulse g(t) is usually somewhat shorter in length than the pulse to be measured, but not infinitely short. This is an important point: an infinitely short gate pulse yields only the intensity I(t) and conversely, a CW gate yields only the spectrum I(ω). On the other hand, a finite-length gate pulse yields the spectrum of all of the finite pulse segments with duration equal to that of the gate. While the phase information remains lacking in each of these short-time spectra, having spectra of an infinitely large set of pulse segments compensates this loss. The spectrogram has been shown to nearly uniquely determine both the intensity I(t) and phase φ(t) of the pulse, even if the gate pulse is longer than the pulse to be measured (although if the gate is too long, sensitivity to noise and other practical problems arise).

While less intuitive, second harmonic generation (SHG) FROG (See Fig. 1) is more practical for most applications because a $\chi^{(2)}$ nonlinearity requires a much less intensity than the $\chi^{(3)}$ nonlinearity used in the optical Kerr effect. Also, experimentally, SHG FROG, which is utilized by most commercial FROG devices, is a spectrally resolved autocorrelation. Rather than measure just the intensity of the second harmonic, the second harmonic light is spectrally resolved. In the SHG FROG case, the measured signal intensity $I_{FROG}(\omega,\tau)$, after the spectrometer is:

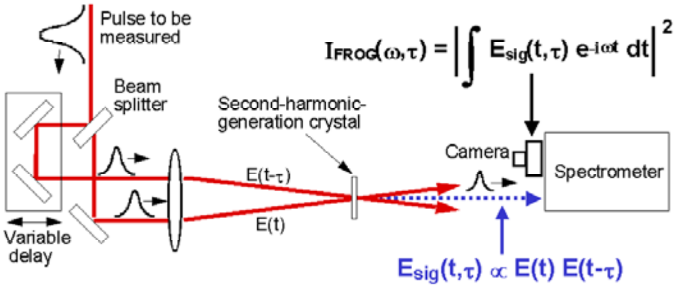

Fig. 1. Schematic diagram of a second harmonic generation (SHG) FROG device. The FROG trace is obtained by spectrally resolving the output from an autocorrelator as a function of time delay between the two pulse replicas.

$$I_{FROG}(\omega,\tau) = \left|\int_{-\infty}^{\infty} E(t)E(t-\tau)e^{-i\omega t}dt\right|^2$$

We see that the SHG FROG trace is a spectrogram of the pulse E(t) although the gate, E(t-τ), is the pulse itself. Because the gate is unknown too, standard methods to extract E(t) cannot be used. A 2D phase retrieval algorithm must be used.

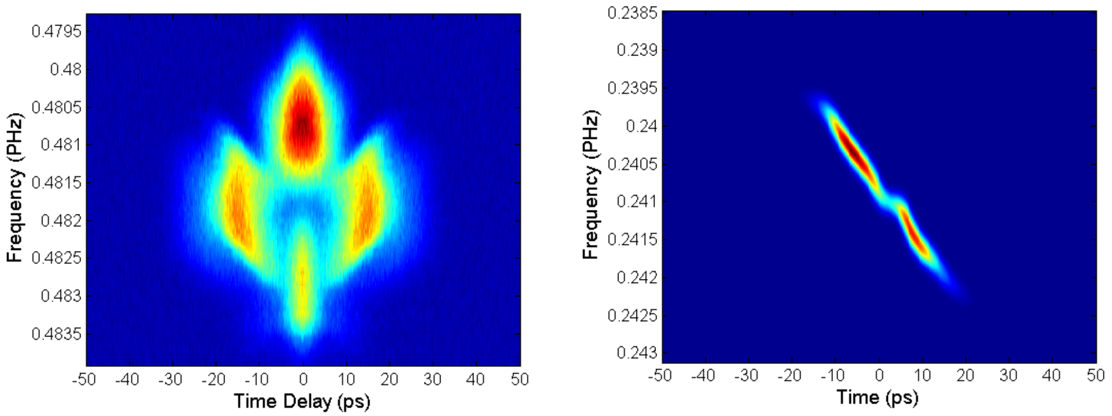

Fig. 2. Above left: an SHG FROG trace of a pulse breaking up in a passively mode-locked quantum dot diode laser. Shown on the right is the spectrogram of the retrieved pulse. The spacing of the pulses is about 13 ps.

Obtaining the pulse intensity and phase – Principal Components Generalized Projections

A 2-D phase retrieval algorithm[2] extracts the pulse information from the measured spectrogram. This algorithm converges to a pulse that minimizes the difference between the measured and the calculated FROG trace. Dr. Daniel J. Kane, the founder of Mesa Photonics, LLC, developed the fastest algorithm, called Principal Component Generalized Projections (PCGP), because it removes the need for minimization used in other FROG inversion algorithms. It is based on the idea that a FROG trace can be constructed from an outer product of two vectors representing the pulse and the gate; construction of new guesses for the pulse and gate pulses are reduced to the calculation of two eigenvectors. This calculation is implemented as very fast matrix-vector multiplications. Indeed, our improved algorithm can retrieve pulses from FROG traces at over 30 Hz and is the basis of the phase retrieval software sold by Mesa Photonics, LLC.[3] <u>Because of the development of the PCGP algorithm, Dr. Daniel J. Kane is the sole inventor of real-time FROG</u>.

References

1. D. J. Kane and R. Trebino, IEEE J. Quantum Electron. 29, 571 (1993).
2. R. Trebino, D. J. Kane, J. Opt. Soc. Am. A 10, 1101 (1993).
3. D. J. Kane, IEEE J. Quantum Electron. 35, 421 (1999).