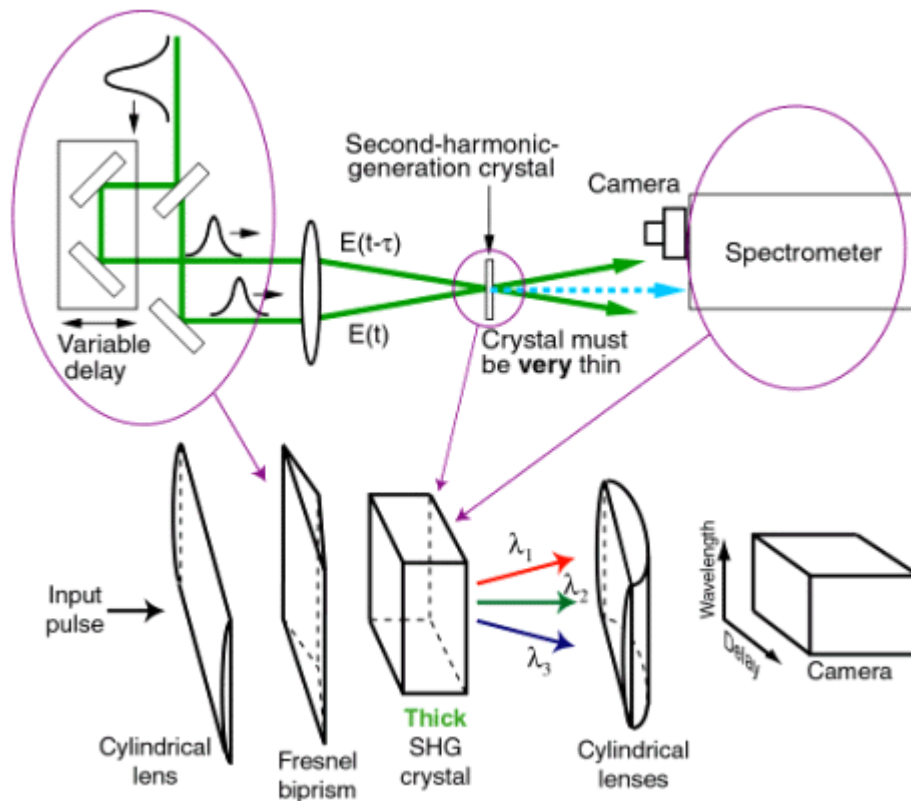


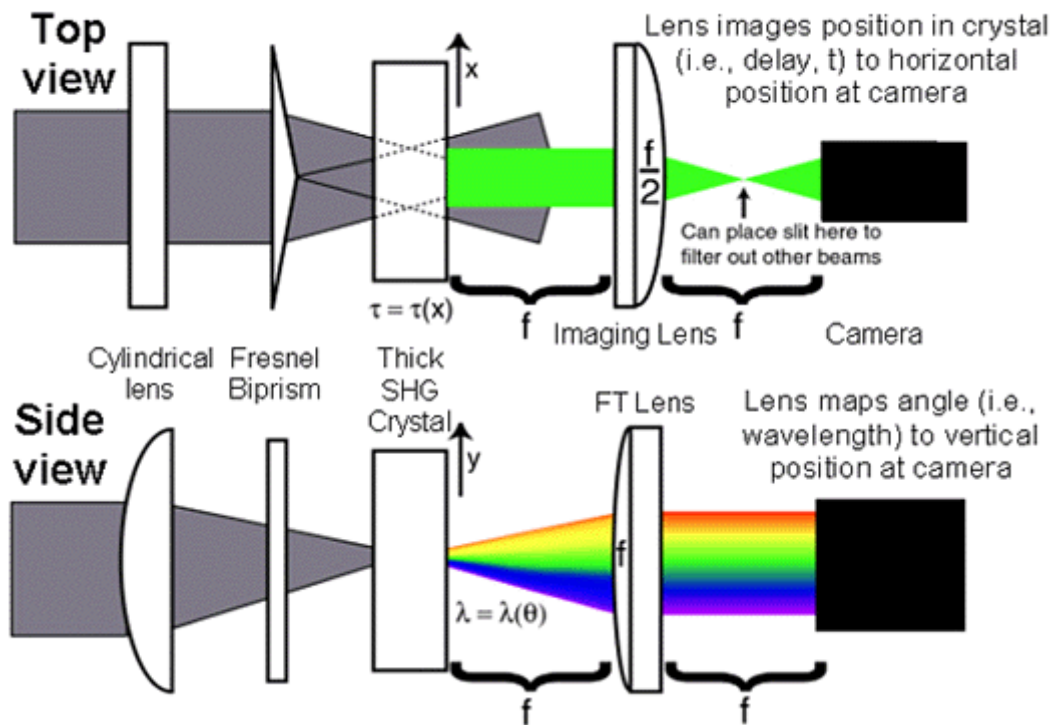
## GRENOUILLE Tutorial

Measuring ultrashort laser pulses—the shortest events ever created—has always been a challenge. For many years, it was possible to create ultrashort pulses, but not to measure them. Techniques such as spectrometry and autocorrelation were available but provided only a vague measure of a pulse. Worse, autocorrelation is actually a fairly difficult measurement to make. It requires splitting the pulse into two replicas and then focusing and recombining them (overlapping them in space and time) in a second-harmonic-generation (SHG) crystal. This involves carefully aligning three sensitive degrees of freedom (two spatial and one temporal). It is also necessary to maintain this alignment while scanning the delay. Worse, the phase-matching-bandwidth condition mandates a thin SHG crystal, yielding a very weak signal and poor measurement sensitivity. This latter problem compounds alignment difficulties. As a result, an autocorrelator is a time-consuming and high-maintenance undertaking; it requires significant table space; and commercial devices cost ~ \$20,000 or more.



**Fig. 1.** Top: SHG FROG. While SHG FROG is the simplest intensity-and-phase ultrashort-pulse-measurement device, there are a few components of it that we'd like to eliminate to simplify it. Bottom: GRENOUILLE, which involves replacing the complex elements of SHG FROG with simpler ones. GRENOUILLE uses a Fresnel biprism to replace the beam splitter, delay line, and beam-recombining optics. It maps delay to position at the crystal. GRENOUILLE also utilizes a thick SHG crystal acting as both the nonlinear-optical time-gating element and the spectrometer. A complete single-shot SHG FROG trace results. Most importantly, however, GRENOUILLE has zero sensitive alignment parameters.

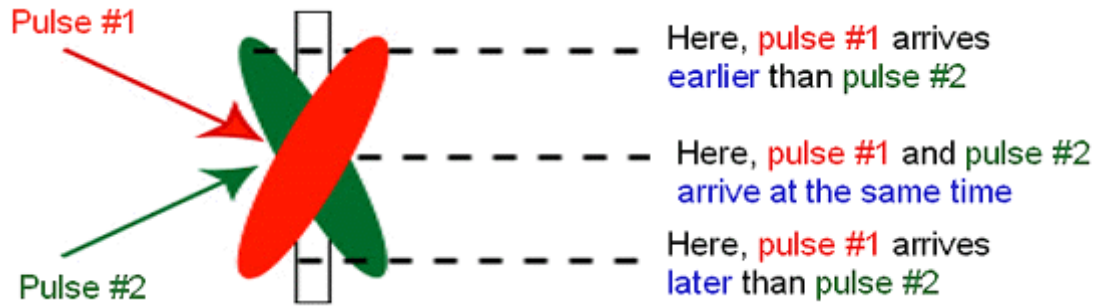
In the past decade, great advances in the field of ultrashort-pulse measurement have occurred. New classes of more powerful methods now yield much more information, in particular, the full intensity and phase of the pulse vs. time. But simplicity has never been the goal. In fact, these new techniques have actually increased in complexity. They all incorporate an autocorrelator and add—sometimes a great many—additional components.



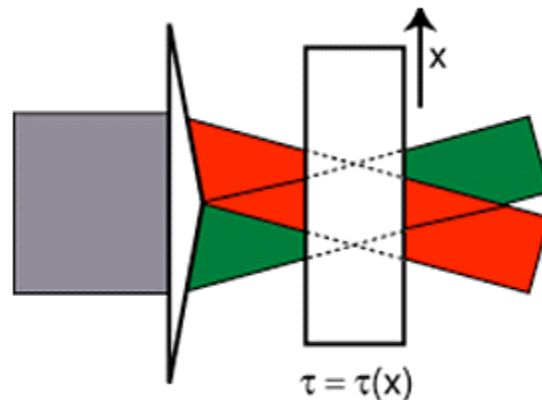
**Fig. 2.** Side and top views of the GRENOUILLE beam geometry of Fig. 1. Here, convenient focal lengths are shown for the two final cylindrical lenses ( $f$  and  $f/2$ ).

The most popular full intensity-and-phase measurement technique, Frequency-Resolved Optical Gating (FROG)[1], adds a spectrometer to an autocorrelator (see Fig. 1). A simple grating-lens home-made spectrometer that introduces no additional sensitive alignment degrees of freedom can be appended to an autocorrelator to make an excellent FROG, but FROG still inherits the autocorrelator's complexity, size, cost, maintenance, and alignment issues. Alternatives to FROG are, unfortunately, even more complex. Some involve two beams propagating collinearly with a precisely given delay, which by itself introduces no less than five sensitive alignment degrees of freedom (four spatial and one temporal). Furthermore, alternative devices often contain numerous additional components, such as frequency filters, additional delay lines, and even interferometers within interferometers, yielding as many as a dozen or more sensitive alignment degrees of freedom and increasing significantly the complexity, size, cost, maintenance, and potential for systematic error. And most lack much-needed feedback as to measurement accuracy.

Recently, however, we introduced a remarkably simple FROG device that overcomes all of these difficulties [2]. It (see Figs. 1 and 2) involves first replacing the beam splitter, delay line, and beam combining optics with a single simple element, a Fresnel biprism[3]. Second, in seemingly blatant violation of the phase-matching-bandwidth requirement, it uses a thick SHG crystal, which not only gives considerably more signal (signal strength scales as the approximate square of the thickness), but also simultaneously replaces the spectrometer. The resulting device, like its other relatives in the FROG family of techniques, has a frivolous name: GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE, which is the French word for "frog").



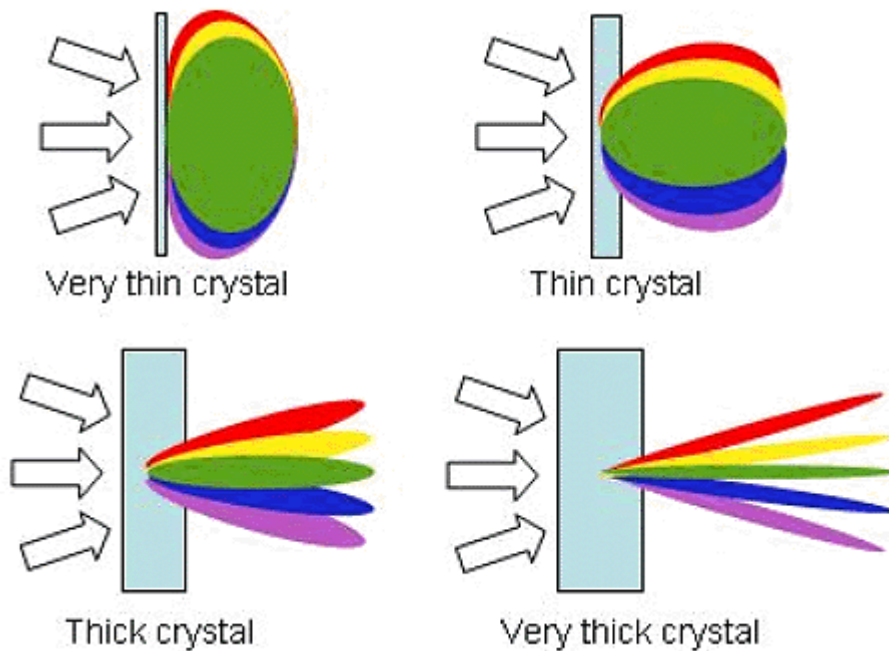
**Fig. 3a.** Crossing beams at an angle maps delay onto transverse position.



**Fig. 3b.** Crossing beams at an angle using a Fresnel biprism (different colors are used to distinguish the beams). Note that the beams are automatically aligned in space and time.

A Fresnel biprism [3] (a prism with an apex angle close to  $180^\circ$ ) is a device usually used in classrooms to illustrate interference. When a Fresnel biprism is illuminated with a wide beam, it splits the beam into two beamlets and crosses them at an angle yielding interference fringes. While fringes aren't relevant to pulse measurement, crossing beams at an angle is exactly what is required in conventional single-shot autocorrelator and FROG beam geometries, in which the relative beam delay is mapped onto horizontal position at the crystal (See Fig. 3). But, unlike conventional single-shot geometries, beams that are split and crossed by a Fresnel biprism are automatically aligned in space and in time, a significant simplification. Then, as in standard single-shot geometries, the crystal is imaged onto a camera, where the signal is detected vs. position (i.e., delay) in, say, the horizontal direction.

FROG also involves spectrally resolving a pulse that has been time-gated by itself. GRENOUILLE combines both of these operations in a single thick SHG crystal. As usual, the SHG crystal performs the self-gating process: the two pulses cross in the crystal with variable delay. But, in addition, the thick crystal has a relatively small phase-matching bandwidth, so the phase-matched wavelength produced by it varies with angle (See Fig. 3). Thus, the thick crystal also acts as a spectrometer.



**Fig. 4.** Thin and thick SHG crystals illuminated by converging broadband light and polar plots of the generated colors vs. crystal exit angle. Note that the very thin crystal (ordinarily required in pulse-measurement techniques) generates the second harmonic of all colors in the forward direction. The very thick crystal, on the other hand, does not and, in fact, acts like a spectrometer. The thick crystal thus acts like a thin crystal and a spectrometer.

Two additional cylindrical lenses complete the device. The first cylindrical lens must focus the beam into the thick crystal tightly enough to yield a range of crystal incidence (and hence exit) angles large enough to include the entire spectrum of the pulse. After the crystal, a cylindrical lens then maps the crystal exit angle onto position at the camera, with wavelength a near-linear function of (vertical) position.

GRENOUILLE has many advantages. It has few elements and so is inexpensive and compact. It operates single-shot. And it is considerably more sensitive than current devices. Furthermore, since GRENOUILLE produces (in real-time, directly on a camera) traces identical to those of SHG FROG, it yields the full pulse intensity and phase (except the direction of time). In addition, several feedback mechanisms on the measurement accuracy that are already present in the FROG technique work with GRENOUILLE, allowing confirmation of—and confidence in—the measurement. And it measures the beam spatial profile. Even better, it measures the most common spatio-temporal pulse distortions, spatial chirp and pulse-front tilt. But best of all, GRENOUILLE is extremely simple to set up and align: it involves no beam-splitting, no beam-recombining, and no scanning of the delay, and so has zero sensitive alignment degrees of freedom!