Highly simplified device for ultrashort-pulse measurement

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We show that a frequency-resolved optical gating device using (1) a thick nonlinear crystal to replace the usual thin crystal and spectrometer and (2) a Fresnel biprism to replace the beam splitter and delay line yields a remarkably simple single-shot ultrashort-pulse intensity-and-phase measurement device with no sensitive alignment parameters and significantly greater sensitivity.

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Despite recent great advances in ultrashort-pulse measurement, no technique is both simple and accurate. The earliest popular method, autocorrelation, is neither simple nor accurate: It requires recombining two pulses in a carefully aligned second-harmonic-generation (SHG) crystal. This recombination involves carefully aligning three sensitive degrees of freedom (two spatial and one temporal) and maintaining them while scanning the delay. Worse, unless the crystal is dithered,[1] the phase-matching-bandwidth condition mandates a thin SHG crystal, yielding a very weak signal and hence poor measurement sensitivity, compounding alignment difficulties.

Full intensity-and-phase measurement requires a more advanced technique, such as frequency-resolved optical gating (FROG).[2] FROG incorporates an autocorrelator, so it inherits the alignment issues mentioned above. Alternatives to FROG are even more complex, involving, for example, collinear beam propagation, which by itself involves no less than five sensitive alignment degrees of freedom (four spatial and one temporal). Furthermore, these alternative devices contain numerous other components, such as frequency filters, delay lines, and even interferometers, typically adding many more alignment degrees of freedom.

Consequently, we introduce here a remarkably simple SHG FROG device that overcomes essentially all these difficulties (see Figs. 1 and 2). First, we replace the beam splitter, delay line, and beam-combining optics with a single element, a Fresnel biprism.[3] Second, we use a thick SHG crystal, which not only gives considerably more signal but also simultaneously replaces the spectrometer. The resulting device, which we call GRENOUILLE (grating-eliminated no-nonsense observation of ultrafast incident laser light e-fields), has zero sensitive alignment degrees of freedom and hence is extremely simple to align. It is also inexpensive and compact. Furthermore, since GRENOUILLE produces, in real time directly on a CCD camera, traces that are identical to those of SHG FROG, it yields the full pulse intensity and phase (except the direction of time).

When a Fresnel biprism[3] (a prism with an apex angle close to 180°) is illuminated with a wide beam, it splits the beam in two and crosses these beamlets at an angle as in conventional single-shot autocorrelator and FROG beam geometries, in which the relative beam delay is mapped onto horizontal position at the crystal. But, unlike conventional single-shot geometries, the beams here are automatically aligned in space and time, a significant simplification. Then, as in standard single-shot geometries, the crystal is imaged onto a CCD camera, where the signal is detected versus position (i.e., delay) in the horizontal direction.

FROG also involves spectrally resolving a pulse that has been time gated by itself. GRENOUILLE (Figs. 1 and 2) 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 the crystal varies with angle. Thus, the thick crystal also acts as a spectrometer. 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 as a near-linear function of (vertical) position. The resulting signal at the camera will be a SHG FROG trace with delay running horizontally and wavelength running vertically.

The key issue in GRENOUILLE is the crystal thickness. Ordinarily, achieving sufficient phase-matching bandwidth requires minimizing the group-velocity

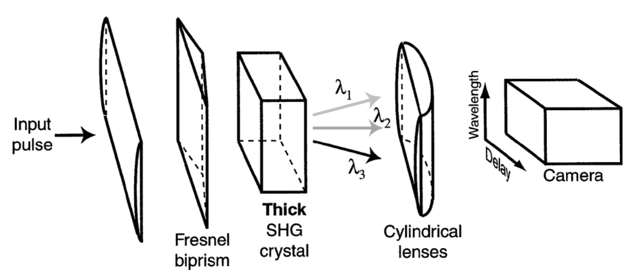

Fig. 1. GRENOUILLE uses a Fresnel biprism to replace the beam splitter, delay line, and beam-recombining optics. It also utilizes a thick SHG crystal that acts as both the nonlinear optical time-gating element and the spectrometer. A full single-shot SHG FROG trace of intensity versus delay (horizontal) and frequency (vertical) results.

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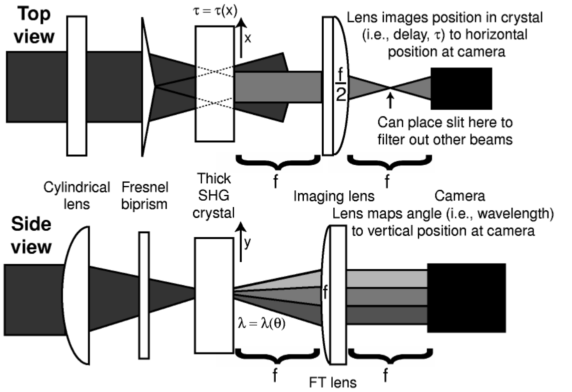

Fig. 2. Side and top views of the GRENOUILLE beam geometry of Fig. 1. Convenient focal lengths are shown for the two final cylindrical lenses (f and $f/2$). Note that the beam becomes a vertical line just before the camera, a convenient place for a slit to filter out any extraneous beams, ensuring a good signal-to-noise ratio.

mismatch (GVM): The fundamental and the second harmonic must overlap for the entire SHG crystal length, L. This condition is GVM $\times L \ll \tau_p$, where τ_p is the pulse length, GVM $\equiv 1/v_g(\lambda_0/2) - 1/v_g(\lambda_0)$, $v_g(\lambda)$ is the group velocity at wavelength λ, and λ_0 is the fundamental wavelength. For GRENOUILLE, however, the opposite is true. The phase-matching bandwidth must be much less than that of the pulse:

$$\mathrm{GVM} \times L \gg \tau_p\,, \tag{1}$$

which ensures that the fundamental and the second harmonic cease to overlap well before exiting the crystal, which then acts as a frequency filter. The use of a thick crystal as a frequency filter in standard SHG FROG has been demonstrated in simultaneous work.[4]

However, the crystal must not be too thick, or group-velocity dispersion (GVD) will cause the pulse to spread in time, distorting it:

$$\mathrm{GVD} \times L \ll \tau_c\,, \tag{2}$$

where GVD $\equiv 1/v_g(\lambda_0 - \delta\lambda/2) - 1/v_g(\lambda_0 + \delta\lambda/2)$, $\delta\lambda$ is the pulse bandwidth, and τ_c is the pulse coherence time (approximately the reciprocal bandwidth, $1/\Delta\nu$), a measure of the smallest temporal feature of the pulse. Since GVD < GVM, this condition is ordinarily already satisfied by the usual GVM condition. But here it is not necessarily satisfied, so it must be considered.

Combining these two constraints, we have

$$\mathrm{GVD}(\tau_p/\tau_c) \ll \tau_p/L \ll \mathrm{GVM}\,. \tag{3}$$

There exists a crystal length L that satisfies these conditions simultaneously if

$$\mathrm{GVM}/\mathrm{GVD} \gg \mathrm{TBP}\,, \tag{4}$$

where we have taken advantage of the fact that τ_p/τ_c is the time–bandwidth product (TBP) of the pulse. Relation (4) is the fundamental equation of GRENOUILLE.

For a near-transform-limited pulse (TBP $\sim$ 1), this condition is easily met because GVM $\gg$ GVD for all but near-single-cycle pulses. Consider typical near-transform-limited Ti:sapphire oscillator pulses of $\sim$100-fs duration, where $\lambda_0 \sim 800$ nm and $\delta\lambda \sim 10$ nm. Also, consider a 5-mm β-barium borate (BBO) crystal—$\sim$30 times thicker than is ordinarily appropriate. In this case, expression (3) is satisfied: 20 fs/cm $\ll$ 100 fs/0.5 cm = 200 fs/cm $\ll$ 2000 fs/cm. Note that, for GVD considerations, shorter pulses require a thinner, less-dispersive crystal, but shorter pulses also generally have broader spectra, so the same crystal will provide sufficient spectral resolution. For a given crystal, simply focusing near its front face yields an effectively shorter crystal, allowing a change of lens or a more expanded beam to "tune" the device for shorter, broader-band pulses. Less-dispersive crystals, such as KDP, minimize GVD, providing enough temporal resolution for accurate measurement of pulses as short as 50 fs. Conversely, more-dispersive crystals, such as $LiIO_3$, maximize GVM, allowing sufficient spectral resolution for measuring pulses as narrow band as 4.5 nm ($\sim$200-fs transform-limited pulse length at 800 nm). Still longer or shorter pulses will also be measurable but with less accuracy (although the FROG algorithm can incorporate these effects and extend GRENOUILLE's range). Note that the temporal-blurring effect found in thick nonlinear media[5] does not occur, and hence is not a problem in the SHG geometry.

We tested GRENOUILLE using a beam expanded to $w = 11$ mm, focused into a 5-mm-thick BBO crystal using a 200-mm focal-length cylindrical lens. The effective confocal parameter of $\sim$2-mm resulted in an $\sim$2.8-nm (FWHM) phase-matching bandwidth at a given angle (potentially insufficient spectral resolution can be deconvolved easily) and a spectral range of 50 nm across the range of exit angles. (We note that a 2-mm BBO crystal would have better matched our pulse.) Other components included a Fresnel biprism with an apex angle of 168° and 100- and 50-mm focal-length cylindrical lenses—the precise, extremely simple geometry of Figs. 1 and 2. A Sony XC-77 CCD camera and a Spiricon LBA PC-100 capture card recorded traces. We calibrated the GRENOUILLE frequency axis by transversely sliding a spectrometer in the plane of the CCD array, recording wavelength versus position. A nearly perfect linear 5.1 nm/mm calibration resulted. We obtained the delay calibration by using the frequency calibration given above and measuring a double pulse, whose trace has characteristic features indicating the double-pulse separation.

We demonstrated GRENOUILLE by measuring a chirped pulse from a KM Labs Ti:sapphire oscillator and comparing the result with that of a calibrated multishot FROG. Femtosoft Technologies' FROG code was used to retrieve both pulses. Figures 3(a)–3(f) show these measurements and the good agreement that was obtained. All traces were 128 by 128 pixels, and the FROG errors were 0.010 and 0.009 for the GRENOUILLE and FROG measurements, respectively. The GRENOUILLE signal strength was $\sim$1000 times greater than that of a single-shot FROG

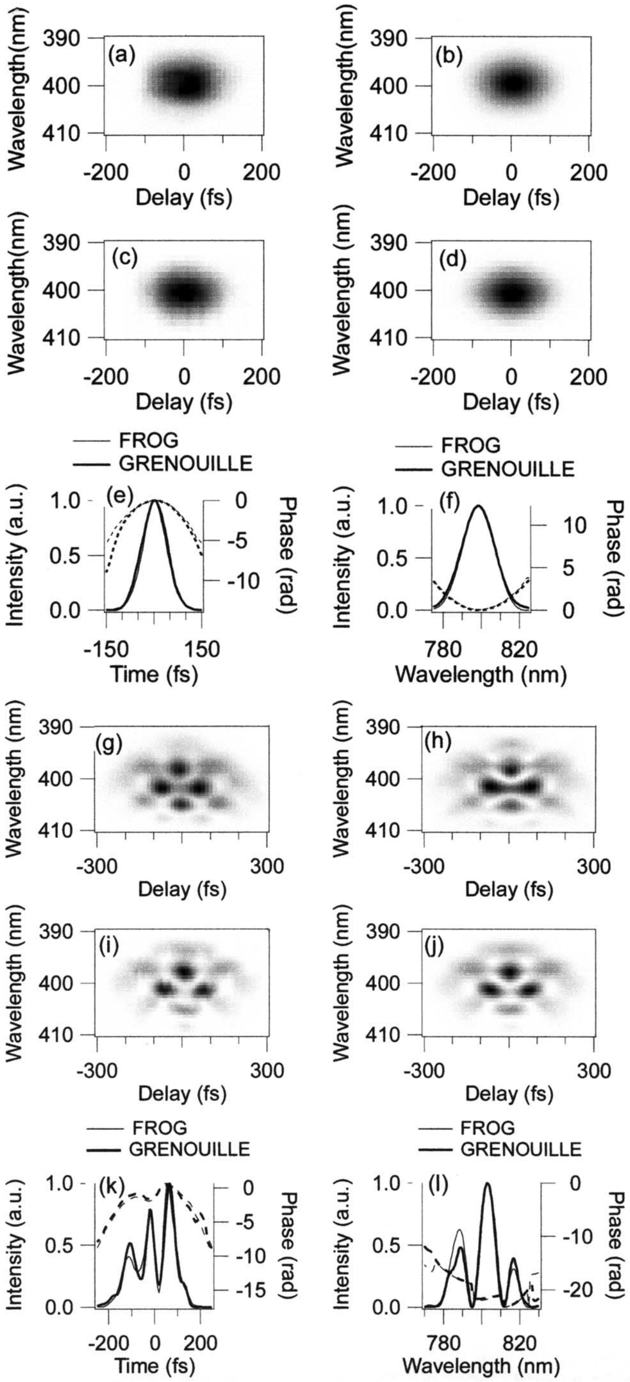

Fig. 3. Comparisons of GRENOUILLE and (multishot) FROG measurements of test pulses. (a) Measured and (b) retrieved GRENOUILLE traces for a chirped pulse; (c) measured and (d) retrieved FROG traces for the same chirped pulse; (e) retrieved intensities (solid curves) and (f) phases (dashed curves) for the time and frequency domains, respectively; (g)–(l) same as (a)–(f) but for a much more complicated double-chirped pulse of two highly chirped pulses separated by one pulse width.

and also much greater than that of an equivalent autocorrelator.

We also measured a double-chirped pulse, two strongly chirped pulses separated by approximately one pulse width. With structure in both delay and frequency, a double-chirped pulse puts GRENOUILLE to the test; if the GVM is too small, frequency resolution will be inadequate; if the GVD is too large, the pulse will spread, and the temporal structure will be lost. Furthermore, if the depth of field of the imaging optics is less than the crystal width, trace structure will also wash out. Figures 3(g)–3(l) show that GRENOUILLE accurately retrieves the intensity and phase of this complicated pulse. The FROG errors for the 128×128 traces were 0.031 and 0.013 for the GRENOUILLE and FROG measurements, respectively.

There are other issues to consider in regard to GRENOUILLE: As with other single-shot techniques, a clean beam profile with a minimum of spatial chirp is required. Extremely short pulses will lengthen in the biprism and the first lens, but simple theoretical backpropagation of the pulse through these elements remedies this. Alternatively, an all-reflective GRENOUILLE including a Fresnel bimirror can be built.

We believe that GRENOUILLE is ideal for most ultrafast laser diagnostics. Only a few simple optical elements are required, and no sensitive alignment is required. It is also extremely compact and more sensitive than other pulse diagnostics, including even those that do not yield the full intensity and phase.

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