Extremely simple device for measuring 20-fs pulses

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We demonstrate an extremely simple frequency-resolved optical-gating device (GRENOUILLE) capable of measuring pulses with spectra wider than 100 nm. Its nearly all-reflective geometry minimizes the material dispersion, allowing accurate measurement of pulses as short as 19 fs. © 2004 Optical Society of America

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Ultrafast lasers are generating ever-shorter[1–3] pulses ever more conveniently. Unfortunately, pulse measurement devices, especially for ~20-fs pulses and their large bandwidths, have remained complex, yielding the risk that the device could induce the very distortions it purports to measure. Thus it is important to develop a simple, accurate, and convenient method for measuring such short pulses.

To date, the simplest device for accurately measuring the intensity and phase of ultrashort pulses is grating-eliminated no-nonsense observation of ultrafast incident laser-light e-fields[4] (GRENOUILLE), an elegant variant of frequency-resolved optical gating[5] (FROG). GRENOUILLE involves two innovations (see Fig. 1). First, it uses a Fresnel biprism to split the beam into two beams crossed in space and time in the crystal. Second, it uses a thick crystal that phase matches a small and different fraction of the pulse bandwidth for each output angle. This allows the crystal to operate not only as an autocorrelating element but also as a spectrometer. Thus the Fresnel biprism replaces FROG's beam splitter and beam-combining optics, and the thick crystal replaces FROG's thin crystal and spectrometer, yielding a simple, compact FROG device that requires no alignment. GRENOUILLE also measures the spatio-temporal distortions, spatial chirp, and pulse-front tilt without modification.[6,7]

However, previously reported implementations of GRENOUILLE could measure pulses only as short as ~50 fs. One factor limiting its accurate measurement of shorter pulses is material dispersion in its transmissive optics, including the necessarily thick crystal. Another factor is that in GRENOUILLE the entire pulse spectrum must be phase matched by the crystal for some beam angle. Because GRENOUILLE uses the crystal's phase-matched wavelength versus angle dependence to measure the pulse spectrum, a larger divergence angle (i.e., tighter focus) in the nonlinear crystal is required for broader-band pulses. The resulting shorter confocal parameter of the beam then reduces the effective crystal length, reducing spectral resolution. In short, GRENOUILLE design is an overconstrained problem, and it is not clear that a solution exists for a given pulse measurement problem, especially one involving a very short pulse.

Fortunately, these problems can be solved by use of a more tightly focused, nearly all-reflective GRENOUILLE device with a thinner crystal (but still thick by normal autocorrelator or FROG standards). Specifically, we replace all but one optic before the second-harmonic generation (SHG) crystal with reflective components. The resulting device uses a (reflective) Cassegrain telescope, rather than the Keplerian telescope. This avoids dispersion (and many aberrations), but the beam hole could conceivably introduce diffraction effects, biasing the measurement, which involves mapping delay onto position. However, after the Fresnel biprism, these effects occur at the outside edges of the crossed beams at the crystal, where they do minimal harm because the intensity is the least there. Our design also uses a cylindrical focusing mirror. It uses only one transmissive optic, the Fresnel biprism, but the short pulses to be measured require only a small range of delays and hence a very small beam-crossing angle (~1.5°). Thus the biprism apex angle is so close to 180° (177°) that it can be made extremely thin (ours is ~1.3 mm, but it could be even thinner). Finally, the thick crystal required to spectrally resolve (by phase matching) a 20-fs pulse is also thinner: only 1.5 mm.

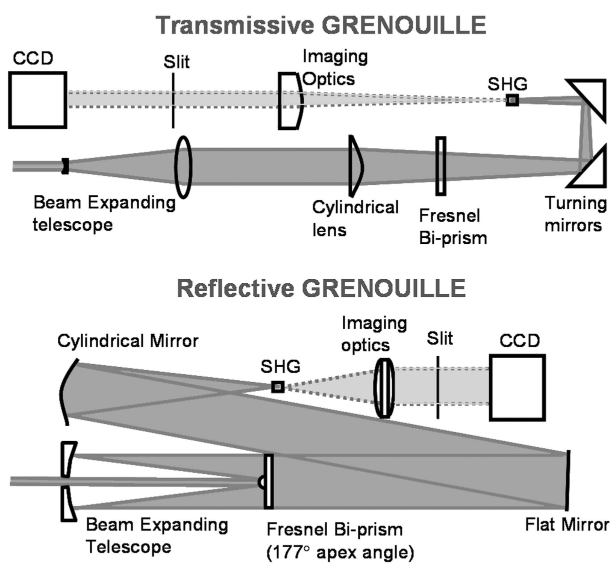

Fig. 1. Compact GRENOUILLE geometries. Previous transmissive design for measuring pulses as short as 50 fs (top) and reflective GRENOUILLE design for measuring ~20-fs pulses (bottom).

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As a result, material dispersion is negligible for even a sub-20-fs pulse.

On the other hand, the device must be able to measure pulses with bandwidths of ~50 nm, so it should have ~100 nm of bandwidth itself. Although we showed previously that the wavelength range of GRENOUILLE can be extended by angle dithering the input beam at the crystal,[8] we find that simply focusing more tightly into the crystal achieves the required 100-nm spectral range. This, however, yields a shorter beam confocal parameter, decreasing the effective interaction length in the crystal and hence reducing the device spectral resolution. Fortunately, because of their broadband nature, shorter pulses require less spectral resolution. With these improvements a GRENOUILLE device can be made that is as simple and as elegant as the transmissive GRENOUILLE previously reported (Fig. 1) but capable of accurately measuring much shorter pulses (20 fs).

GRENOUILLE obtains spectral resolution through group-velocity mismatch[4,5] (GVM): The product of the crystal interaction length (L) and the GVM must exceed the pulse length (τ_p),

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

which is the opposite of the usual GVM (phase-matching) condition.

On the other hand, the crystal must not be so thick that it has significant group-velocity dispersion (GVD). Since the shortest temporal component of the pulse is the coherence time (τ_c), we have

$$(L/2)\mathrm{GVD} \ll \tau_c\,.$$

Note that we have used $L/2$ here because the pulse contributes signal to the trace throughout the crystal, and $L/2$ corresponds to the position with the average pulse distortion.

These conditions become more difficult to satisfy as the pulse shortens and the GVD approaches the GVM. For a single-cycle pulse for which $\tau_c \sim \tau_p$ and the GVD approaches the GVM, these conditions cannot be satisfied.

Fortunately, for 20-fs pulses that are not too complex they can be satisfied, and, coupled with FROG's ability to see through systematic error (the trace overdetermines the pulse), the results will be accurate. Figure 2 shows our device's operating range.

Specifically, for 20-fs (47-nm bandwidth), 800-nm pulses in β-barium borate (BBO), the GVM = 3.3×10^3 fs/cm and the GVD = 104 fs/cm. A crystal length of 1.65 mm yields $(L/2)\mathrm{GVD} = 8.5$ fs and $L \times \mathrm{GVM} = 539$ fs. These values allow pulse measurements without preprocessing or modifications to the FROG algorithm (although this is possible). Our spectral resolution is 3.0 nm, which allows accurate measurement of longer pulses as well (Fig. 2). The crystal GVD will broaden a transform-limited 20-fs pulse to at most 26.6 fs after the crystal, but the value at the center of the crystal, 21.7 fs, better assesses the device accuracy. Finally, a full beam divergence angle of 4.4° in the crystal yields 120 nm of spectral range.

A collimated beam entered the device and was expanded by the negative primary (R = 20 mm) (cemented to the back of the biprism). The secondary (R = 200 mm) recollimated the beam, and the biprism (apex angle 177°) split it into two beams. The crossing beams were focused to overlapping line foci by use of a slightly off-axis cylindrical mirror (R = 200 mm).

Although a 3.5-mm BBO crystal was used, the focus was at the front of the crystal, and the effective crystal length (the length over which significant second-harmonic light is generated) was considerably shorter: only ~1.65 mm. Since most of the SHG occurred near the focus, the remaining crystal length was unused and irrelevant. (We determined the interaction length by placing a variable-spacing etalon in the beam to create a train of pulses with accompanying spectral fringes. We increased the etalon spacing, decreasing the spectral fringe spacing, until GRENOUILLE could no longer resolve these fringes. This resolution then yields the effective crystal length.)

The second harmonic then propagated to a 1/2" (1.27-cm) CCD camera, 100 mm away, using a pair of back-to-back plano–convex 50-mm focal-length spherical and cylindrical lenses, halfway between the focus and the CCD. The effective focal length of the lens pair was 25 mm for the delay axis, resulting in 1-to-1 imaging in the relative-delay direction and a 1-fs/pixel delay resolution (480 pixels, using a Data Translation DT 3120 capture card). In the wavelength direction the effective focal length of 50 mm mapped the angle (i.e., wavelength) to position. The result was a SHG FROG trace at the camera.

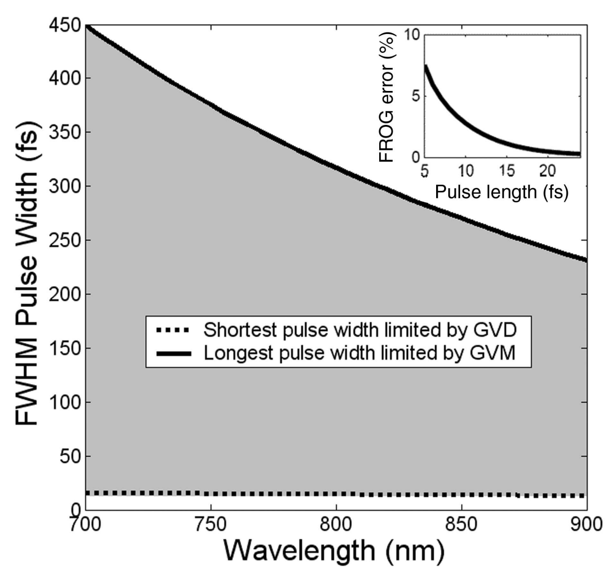

Fig. 2. Pulses measurable by use of GRENOUILLE with a 1.65-mm BBO crystal. The solid curve represents the (upper) limit set by the spectral resolution of the crystal ($L \times \mathrm{GVM} = \tau_p$). The dashed curve represents the (lower) limit set by the GVD induced by the crystal [$(L/2)\mathrm{GVD} = \tau_c$]. Inset, theoretical FROG error versus pulse width due to crystal dispersion.

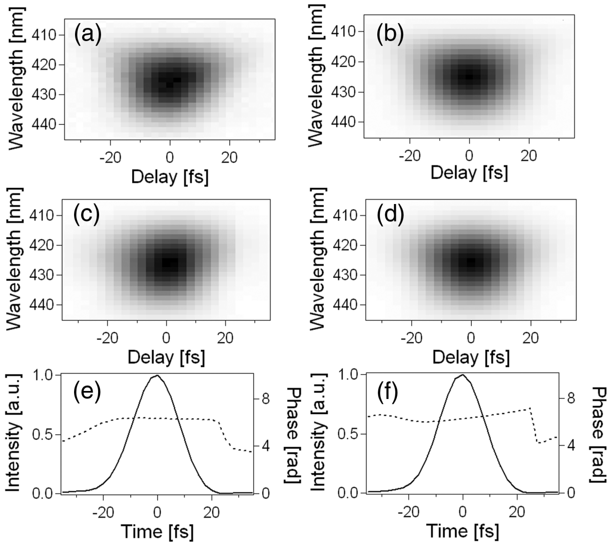

Fig. 3. Comparisons of short-pulse GRENOUILLE and multishot FROG measurements: (a) measured GRENOUILLE trace, (b) measured multishot FROG trace, (c) retrieved GRENOUILLE trace (FROG error of 0.00497), (d) retrieved multishot FROG trace (FROG error of 0.00482), (e) retrieved intensity and phase versus time for GRENOUILLE measurements (temporal pulse width of 19.73 fs FWHM), (f) retrieved intensity and phase versus time for multishot FROG measurements (temporal pulse width of 19.41 fs FWHM).

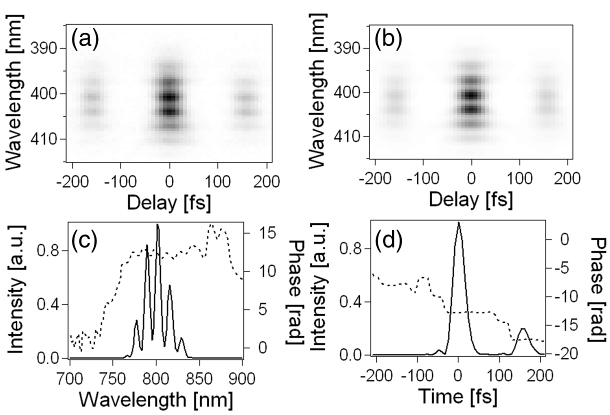

Fig. 4. (a) Measured and (b) retrieved GRENOUILLE traces (FROG error of 0.00643) for a double pulse. Note the characteristic fringed double-pulse trace. (c) Spectrum and spectral phase and (d) intensity and phase versus time for a double pulse.

A KM Labs Ti:sapphire oscillator operating with ~60 nm (FWHM) of bandwidth and an external prism pulse compressor yielded ~20-fs pulses, which we measured with a conventional multishot FROG and with our GRENOUILLE. The Femtosoft FROG code retrieved the intensity and phase for both measurements. Figure 3 shows measured and retrieved traces and the retrieved intensity and phase for both measurements, all in excellent agreement. The minor discrepancy is likely due to drift in the pulse between the measurements. The pulse that GRENOUILLE retrieved in these measurements is 19.73 fs FWHM—the shortest pulse ever measured with GRENOUILLE.

To test GRENOUILLE's ability to measure complex pulses, we placed a (23.8-μm) air-spaced etalon in the beam before the GRENOUILLE to create a multiple pulse, which we measured with GRENOUILLE. Figure 4 shows the measured and retrieved GRENOUILLE traces and retrieved intensity and phase versus time. These measurements clearly show that GRENOUILLE is capable of revealing the fine structure in both frequency and delay. We also used these traces for calibration of both the delay and wavelength axes.[9]

In conclusion, we have shown that, despite its simplicity, we can design a GRENOUILLE device that can accurately measure pulses as short as 20 fs. We achieve this by eliminating most of the transmissive optics and carefully selecting the focusing and imaging optics. Furthermore, the geometry remains simple and compact and retains GRENOUILLE's ease of alignment, sensitivity, real-time operation, intuitive feedback, and ability to measure spatiotemporal distortions.

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