Extremely simple device for measuring 1.5-μm ultrashort laser pulses

Selcuk Akturk, Mark Kimmel, and Rick Trebino

School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA
akturk@socrates.physics.gatech.edu

Abstract: We have demonstrated an experimentally very simple and sensitive GRENOUILLE device for measuring the intensity and phase vs. time and spatio-temporal distortions of 100-fs to few-ps 1.5-μm pulses using the nonlinear-optical crystal Proustite. We show that the dispersive and nonlinear-optical characteristics of Proustite are critical for achieving very simple and reliable measurements of such pulses from fiber lasers and optical parametric amplifiers.

OCIS codes: (320.7100) Ultrafast measurements; (320.7080) Ultrafast devices

References and Links

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1. Introduction

Sources of 1.5-μm ultrashort laser pulses are becoming ever more important and prevalent. Mode-locked fiber lasers [1], for example, are typically experimentally simple, robust, and single spatial mode. Moreover, they generate moderately intense ultrashort pulses, ~100 fs to ~1 ps long, making them useful, not only for telecommunications, but also for nonlinear-optical applications. At present, several commercial fiber lasers are available with various pulse characteristics [2]. Another important source of ultrashort pulses in this spectral region is optical parametric oscillators (OPO's) and amplifiers (OPA's), which yield pulses of about the same length, but which can achieve considerably higher energies. Several commercial OPO's and OPA's are also available.

The temporal intensity-and-phase behavior of fiber-laser, OPO, and OPA pulses can be quite complicated. Worse, OPO and OPA pulses are frequently contaminated with the spatio-

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temporal distortions, spatial chirp and pulse-front tilt. Unfortunately, the device often used to measure them, the autocorrelator, yields only very limited temporal-intensity information and, of course, no pulse-phase information. And extracting quantitative information regarding spatio-temporal distortions from an autocorrelation is difficult. More powerful methods, such as frequency-resolved optical gating (FROG) [3], which is a spectrally resolved autocorrelation, yield this information, but they are experimentally more complex than autocorrelation. Alternative methods to FROG are even more complex.

An ultrasimple and elegant variation on FROG, called GRENOUILLE (GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser-Light E-fields) [4,5] (see Fig. 1), was recently introduced and demonstrated for measuring Ti:Sapphire laser pulses (that is, from ~ 700 to ~ 1000 nm) over the pulse-length range of < 20 fs to ~ 1 ps. GRENOUILLE can also measure spatial chirp and pulse-front tilt easily and without modification to its apparatus [6,7] .

Extension of the GRENOUILLE idea to ~ 1.5-μm wavelengths is not straightforward, however. GRENOUILLE uses a thick second-harmonic-generation (SHG) crystal to spectrally resolve the autocorrelator signal pulse, and commonly used SHG crystals have insufficient dispersion to do so at ~ 1.5 μm, a wavelength range where the dispersion of most materials is very low. In this letter, we show, however, that an all-but-forgotten SHG crystal, Proustite, has sufficient dispersion and yields an ideal GRENOUILLE device for this wavelength range. We then use it to measure fiber-laser pulses and 1.5-μm pulses with pulse-front tilt.

2. GRENOUILLE and Its Extension to 1.5-μm pulses

GRENOUILLE operates by using a simple Fresnel bi-prism to split the beam into two beams automatically crossed in space and time in the crystal with relative delay mapped onto transverse position. It also uses a thick crystal that phase-matches a small and different fraction of the pulse bandwidth for each output angle, allowing the crystal to operate, not only as an autocorrelating element, but also as a spectrometer. This yields a very simple, compact FROG device that requires almost no alignment. GRENOUILLE also measures the spatio-temporal distortions, spatial chirp and pulse-front tilt, without modification [6,7]. Spatial chirp shears, and pulse-front tilt displaces, the otherwise symmetrical trace.

The challenge in designing a GRENOUILLE for the 1.5-μm wavelength region, and fiber lasers in particular, is the relatively small bandwidths (usually < ~ 40 nm) of pulses for the relatively long pulses relative to Ti:Sapphire lasers. At first glance, this simplifies the problem: longer pulses suffer less from group-velocity dispersion (GVD) in the optics and, especially, the thick crystal. On closer examination, however, the crystal must also be dispersive enough that its finite phase-matching bandwidth is able to resolve the spectrum of the second-harmonic signal. Equivalently, it should have a relatively large group-velocity mismatch (GVM), which is a challenge in the relatively nondispersive 1.5-μm wavelength range. Therefore, in order to build a GRENOUILLE to measure pulses with narrow spectra, we require a crystal with relatively high dispersion. We find, however, that the common (low-dispersion) nonlinear crystals used in the visible and near-infrared ranges are effective for measuring only considerably shorter 1.5-μm pulses[8] (where there are few currently available sources, and other, more fundamental, challenges must be met before a relevant GRENOUILLE can be designed). Worse, the nonlinearities of standard crystals also drop in this wavelength range, reducing the device sensitivity. Therefore, the problem of measuring fiber-laser, OPO, and OPA pulses with GRENOUILLE is not trivial, and it relies on the existence of a suitable nonlinear crystal (The detailed procedure on crystal selection for GRENOUILLE can be found in [9]).

#5105 - $15.00 US Received 24 August 2004; revised 8 September 2004; accepted 9 September 2004

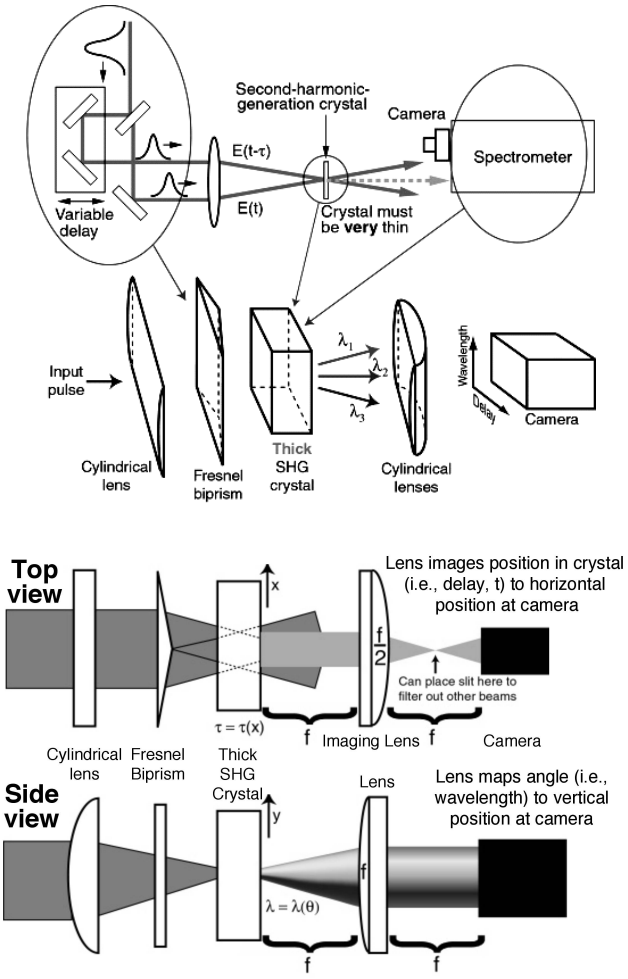

Fig. 1. (Top). A FROG device (above) and its simpler version, GRENOUILLE (below). (Bottom) Top and side views of GRENOUILLE.

For this purpose, we investigated numerous nonlinear crystals. BBO and $LiNbO_3$ are common crystals that phase-match at 1.5 μm, but they both have very small GVM in this region, preventing their use as a GRENOUILLE crystal. $LiIO_3$ has a relatively large GVM, but it still does not yield sufficient spectral resolution for our purposes. Of less common crystals, GaSe has suitable GVM but, due to its mechanical properties, it is not possible to cut it at a particular angle. New crystals, such as $AgGaGeS_4$, and cannot yet be grown thick enough. And older crystals, which appear promising from properties reported many years ago, such as Cinnabar, are no longer available.

Fortunately, we have found that a nearly forgotten, crystal, Proustite (Ag_3AsS_3), has a larger phase-matching dispersion (~ 10 times that of $LiIO_3$) and a stronger nonlinear-optical coefficient (~ 15 times that of $LiIO_3$) and matches GRENOUILLE's requirements for this range very well (see Fig.2).

More quantitatively, GRENOUILLE uses the large GVM in the thick crystal to spectrally resolve the signal pulse. This condition can be expressed as [3,4]:

$$L \quad GVM >> \tau_p$$

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where L is the crystal interaction length, and τ_p is pulse length. The condition to have negligible GVD is[3,4]:

$$L \quad GVD << \tau_c$$

where τ_c is coherence time.

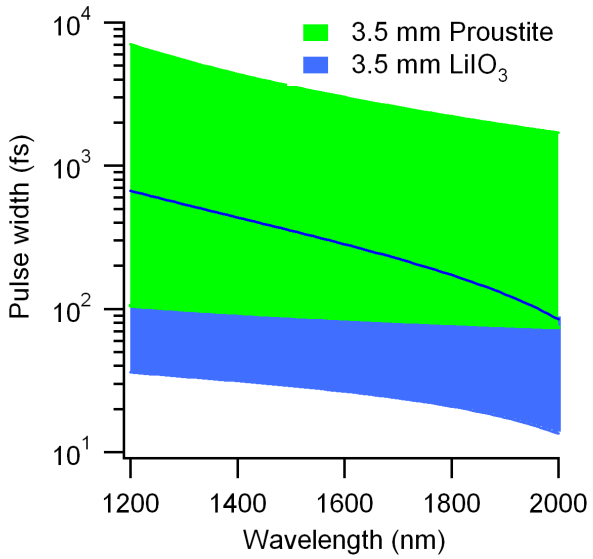

Fig. 2. Pulse-width range measurable using a GRENOUILLE with a 3.5 mm Proustite crystal (green region) or alternatively a 3.5 mm $LiIO_3$ crystal (blue region). The upper limit of each region represents the limit set by the spectral resolution of the crystal (L GVM = τ_p). The lower limit of each region represents the limit set by GVD induced by the crystal (L GVD = τ_c). The green curve in the blue region shows the lower limit of the area of the region of pulses measurable using Proustite. Note that $LiIO_3$ is ideal for measuring pulses about 100 fs long, but it cannot measure pulses longer than a few hundred fs.

Applying these conditions to 200-fs (16.5-nm bandwidth), 1.5-μm pulses in Proustite, we find: GVM = 1.71×10^4 fs/cm, and GVD = 93.9 fs/cm. A crystal length of 3.5 mm yields L GVD = 32.8 fs, and L GVM = 6 ps. These values are comfortably far from each other, thus satisfying both of the above two constraints, allowing accurate pulse measurements. A 3.5-mm Proustite yields 0.92 nm spectral resolution at 1.5 μm, which allows accurate measurement of pulses as long as several ps. The crystal GVD will broaden a transform-limited 100-fs pulse to only 109 fs (using half the crystal length). Finally, a full beam divergence angle of 4.0° in the crystal yields 85 nm of spectral range.

3. Experiment

We measured pulses from a Menlo Systems TC-1550-B fiber laser, operating near 1570 nm with an output power of 20.5 mW (25 MHz repetition rate). The design parameters of our Proustite GRENOUILLE were as follows: the fiber output was collimated with a fiber collimator (beam diameter 2.9 mm) and then expanded with a 5x refractive telescope. A 75-mm-focal-length cylindrical lens then focused the beam. A biprism (apex angle 160°) split the beam into two and crossed them inside the 3.5 mm Proustite crystal. A pair of back-to-back plano-convex 50-mm-focal-length spherical and cylindrical lenses then mapped the GRENOUILLE trace onto a 1/2" CCD camera, 100 mm away from the crystal. The image was then captured using a Spiricon SP-LTA video capture card, and the intensity and phase retrieved from the resulting FROG traces using the Femtosoft SHG FROG code.

#5105 - $15.00 US Received 24 August 2004; revised 8 September 2004; accepted 9 September 2004

Figure 3 shows the measured and retrieved GRENOUILLE traces. For comparison, we also measured the same pulses using a conventional multi-shot FROG (see Fig. 3). All these measurements are in excellent agreement with each other, verifying the accuracy of the GRENOUILLE.

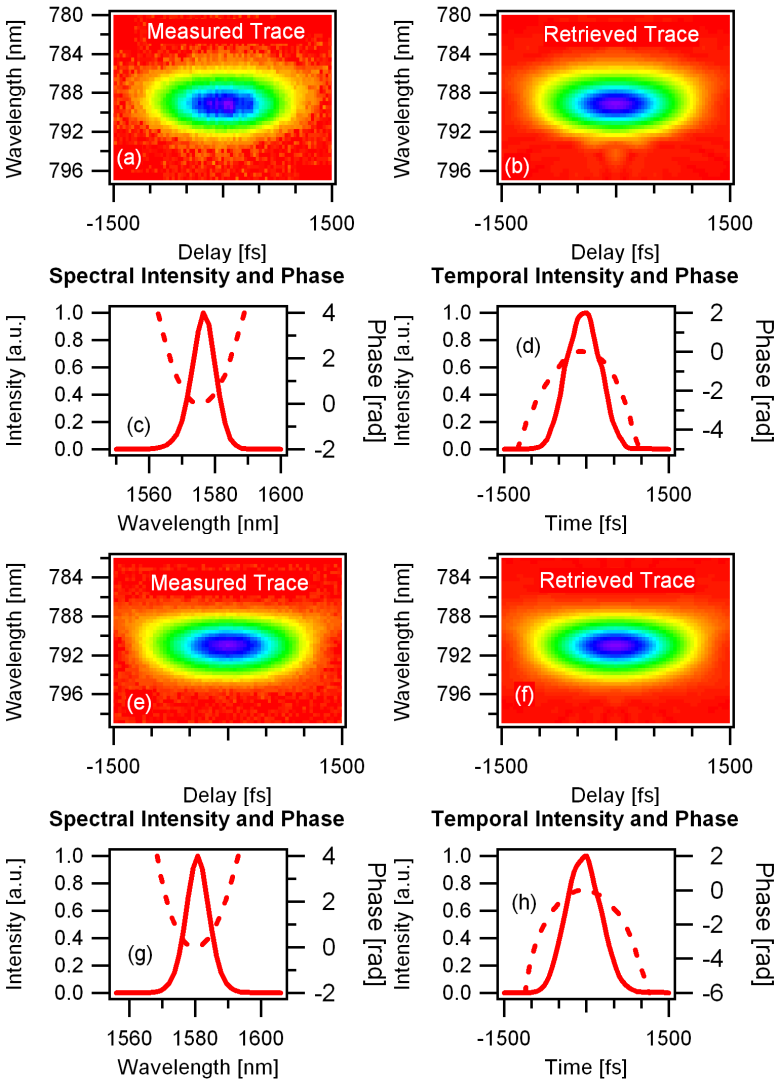

Fig. 3. Tests of our 1.5-μm GRENOUILLE: (a) measured GRENOUILLE trace; (b) retrieved GRENOUILLE trace (FROG error:0.0055); (c-d) retrieved temporal and spectral intensity and phase (the retrieved pulse width is 779 fs and the bandwidth is 8.2 nm); (e) measured multi-shot FROG trace; (f) retrieved multi-shot FROG trace (FROG error:0.0023); (g-h) retrieved temporal and spectral intensity and phase (the retrieved pulse width is 765 fs and the bandwidth is 8.1 nm).

In order to test the device's ability to measure complicated pulses as well as at other near-IR wavelengths, we performed another set of measurements, this time using the IMRA Femtolite Series tunable fiber laser operating near 1700 nm. At the output we used an air-spaced etalon (125-μm separation), which generated multiple pulses in time and fringes in frequency. We measured the resulting complex output with GRENOUILLE and obtained an excellent measurement of the pulse train (Fig. 4). These results show that the device is capable

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of resolving the fine structure in frequency due to the high spectral resolution of Proustite. The same traces can also used for calibration purposes (knowledge of the etalon spacing determines both the separation of the various regions in the traces in both delay and frequency).

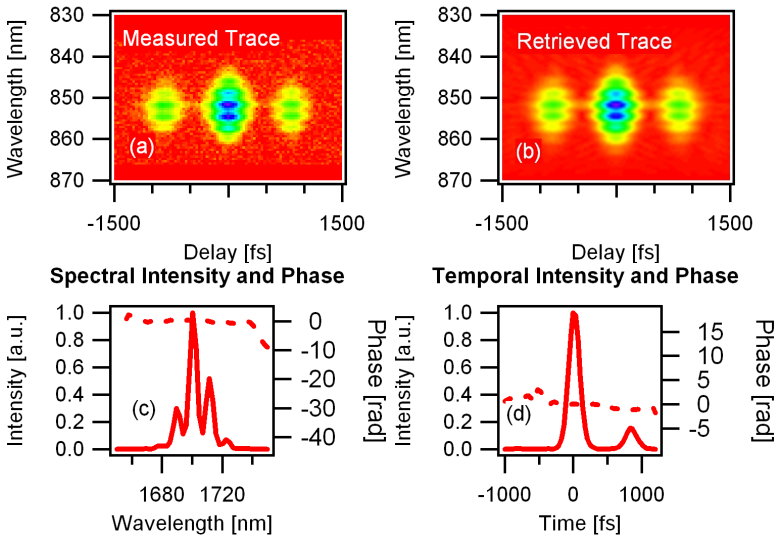

Fig. 4. Tests of our 1.5-µm GRENOUILLE with more complicated pulses: (a) Measured and (b) retrieved GRENOUILLE traces (FROG error 0.0055) for a double pulse; (c-d) retrieved spectral and temporal intensity and phase.

As mentioned earlier, GRENOUILLE also measures pulse-front tilt very sensitively[6]. Specifically, pulses with pulse-front tilt have GRENOUILLE traces with a shift in delay relative to the otherwise symmetrical GRENOUILLE trace (which is otherwise centered at zero delay). While fiber lasers are generally free from pulse-front tilt, OPO and OPA pulses are very likely to be contaminated with pulse-front tilt (and other spatio-temporal distortions). Therefore, it is important to be able to monitor this effect, and it would be convenient to be able to do so using the same device that is used for intensity and phase measurements.

To demonstrate pulse-front tilt measurements with GRENOUILLE we introduced pulse-front tilt by introducing both spatial and temporal chirp[10]. We used a prism pair to generate spatial chirp, and by pushing one prism in and out of the beam, we varied the pulse-front tilt. Figure 5 shows two GRENOUILLE traces with different amounts of pulse-front tilt (the spatial chirp in the beam was too small to measure using GRENOUILLE).

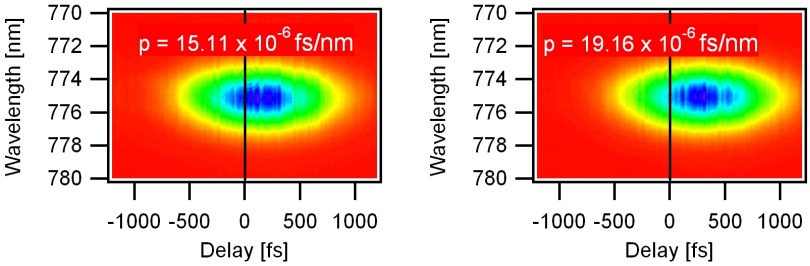

Fig. 5. GRENOUILLE traces for pulses with different amount of pulse-front tilt. The shift of the trace reveals and measures the pulse-front tilt. Note that these traces are not centered at zero delay, and the trace with greater pulse-front tilt has greater displacement from zero delay, as expected.

#5105 - $15.00 US Received 24 August 2004; revised 8 September 2004; accepted 9 September 2004

Extending GRENOUILLE to wavelengths beyond ~ 2 μm will require yet another unusual crystal. Proustite's phase-matching curve reaches a minimum between 3 and 3.5 μm, so its phase-matching dispersion becomes too small for application to GRENOUILLE in that region (See Fig. 6.) However, Proustite is ideal for GRENOUILLE devices for measuring pulses between 1.2 and 2 μm, and a thicker (thinner) Proustite crystal could in principle measure longer (shorter) pulses at these wavelengths.

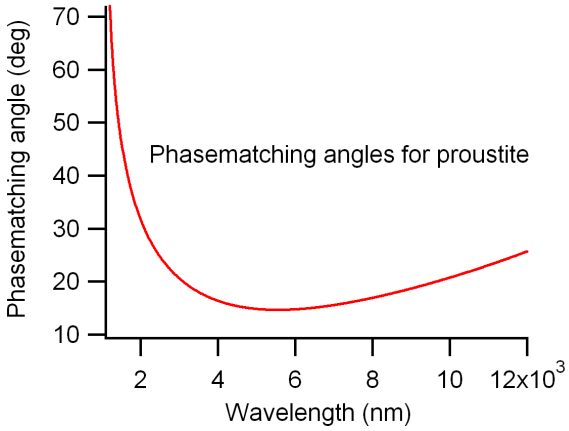

Fig. 6. Phase-matching curve for Proustite. Proustite also begins to absorb very strongly below 600μm.

4. Conclusion

In conclusion, we have shown that, by using the nonlinear-optical crystal, Proustite, a GRENOUILLE can be designed to measure 100-fs to few-ps pulses near 1.5 μm generated by fiber lasers, OPO's and OPA's. Due to the high spectral resolution that Proustite provides, the device can measure pulses with spectra as narrow as ~ 1 nanometer. Moreover, the design remains as simple and as compact as previously developed Ti:Sapphire GRENOUILLEs, providing easy alignment, high sensitivity, spatio-temporal-distortion measurement, and real-time operation.

Acknowledgments

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