Experimentally simple, extremely broadband transient-grating frequency-resolved-optical-gating arrangement

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Abstract: We demonstrate a simple, essentially alignment-free Transient-Grating Frequency-Resolved-Optical-Gating arrangement using a simple input mask that separates the input beam into three beams and a Fresnel biprism that crosses and delays them. It naturally operates single shot and has no moving parts. It is also extremely broadband and hence should be ideal for measuring pulses from optical parametric amplifiers.

OCIS codes: (320.0320) Ultrafast Optics; (320.7100) Ultrafast measurements.

References and links

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1. Introduction

Despite recent great advances in ultrashort-pulse measurement techniques, much remains to be done. In particular, these devices have relatively small wavelength-tuning ranges, and most are experimentally complex and difficult to align, especially when operating at odd wavelengths. Second-harmonic generation (SHG), the basis of most techniques, has a relatively stringent phase-matching requirement, so, even with angle-tuning, SHG-based devices can operate over only a few hundred nm in the near-IR, and less in the visible, and they require angle-tuning when the wavelength is tuned. In addition, SHG of UV wavelengths is not possible because SHG crystals are opaque at the second harmonic (< 200 nm). With regard to complexity, pulse-measurement devices generally require overlapping two or more beams in space and time, scanning the relative delay, and satisfying the phase-matching condition. Even newly proposed techniques operating at *common* (near-IR) wavelengths are often extremely complex and difficult to work with, involving precisely collinear beams, interferometers, and/or pulse stretchers, and as many as a dozen sensitive alignment parameters.

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Recently, we developed a technique based on the SHG frequency-resolved-optical-gating (FROG) method, which *is* extremely simple and which requires no alignment, except for angle-tuning the wavelength. Called GRating-Eliminated No-nonsense Observation of Ultrashort Incident Laser Light E-fields (GRENOUILLE) [1], it involves replacing the beam-splitter, delay line, and beam-combining optics with a single optical component called a Fresnel biprism, which simplifies the device tremendously. GRENOUILLE is also inexpensive and simple to use. It has also been quite successful at measuring visible and IR pulses over a wide range of pulse lengths, energies, and repetition rates [2, 3]. Unfortunately, GRENOUILLE, like all SHG-based pulse-measurement devices, has a limited wavelength range and cannot operate in the UV.

As a result, a given GRENOUILLE can only measure a fraction of the wavelength range of a particularly broadband device used in many laboratories, the optical parametric amplifier (OPA). The OPA's range is even broader when harmonic generation is also performed. Even excluding the UV range, measuring OPA pulses over the remaining OPA tuning range requires several SHG-based devices. In addition, due to the complexity of OPAs, OPA pulses also tend to suffer from beam wander and a host of other alignment issues, which calls, not only for a broadband device, but also for an ultra-simple, easily aligned one, insensitive to such effects as beam wander.

2. Broadband simplified TG FROG

We present such an arrangement here. In order to achieve broadband operation, especially in the UV, a third-order nonlinear-optical beam geometry (such as self-diffraction, polarization gating, or transient grating) is required [4, 5]. The most versatile, sensitive, and accurate of these is the transient-grating (TG) geometry. However, the TG beam geometry is also the most complex, requiring splitting the pulse into *three* pulses in separate beams, and crossing two of them in space and time to generate a transient grating in a $\chi^{(3)}$ medium that is probed by the third beam, which itself must be carefully aligned. If a TG FROG is desired, the diffracted four-wave-mixing output pulse must then be spectrally resolved vs. delay [5]. As a result, this powerful beam geometry is only occasionally used for pulse measurement [5]. So, in this work, we significantly simplify TG FROG in the spirit of GRENOUILLE, so that it has no sensitive alignment parameters. The resulting arrangement is very easy to set up, is essentially automatically aligned, is inherently extremely broadband, and operates well in the UV. Even better, it is automatically phase-matched for all wavelengths and so does not require re-alignment if the wavelength is tuned. A single such simplified TG FROG arrangement can operate from the UV to the IR with no change of optics or realignment. Like GRENOUILLE, it naturally operates on a single-shot basis. While not currently suitable for measuring pulses from nJ-per-pulse oscillators, it is suitable for measuring microjoule- or higher-energy pulses from a high-power or amplified system or OPA. It also yields a sensitive measurement of the pulse-front tilt, very useful for OPAs, which often also suffer from this distortion.

Figure 1 schematically shows the arrangement. The input beam is split into three beams by a simple mask with three holes. A cylindrical lens focuses the beams to lines in the $\chi^{(3)}$ medium. In the other dimension, a Fresnel biprism crosses the beams in space and time. The angle between the line-focused beams maps delay onto position, so that the relative delay need not be scanned, as long as the crossed beams are imaged onto and spatially resolved by the camera. Two of the beams overlap perfectly in space and time across the glass medium and form a transient grating. The other beam crosses the grating at an angle, and thus varies the relative delay, τ, between the pulses transversely in space. The diffracted signal pulse, which emerges from the interaction region as the fourth beam in the rectangle formed by the three input pulses, is spectrally resolved by a simple grating/lens spectrometer, in which the line focus in the nonlinear medium acts as the entrance slit.

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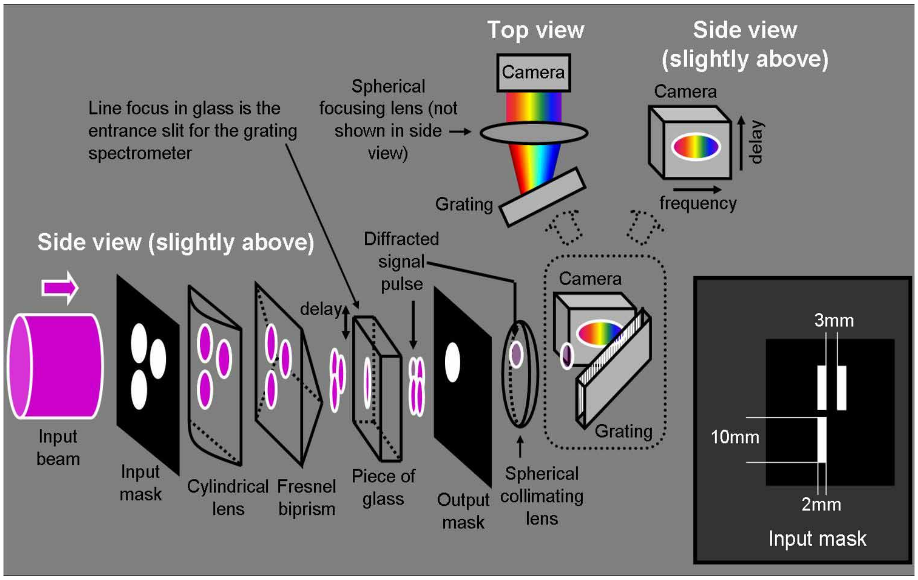

Fig. 1. Simple broadband TG FROG arrangement. The input mask splits the input beam into three beams, which are then overlapped in the $\chi^{(3)}$ medium (ZnS in these initial measurements, but fused silica in a more broadband arrangement that includes the UV). The cylindrical lens yields line foci, mapping the delay onto transverse (vertical) position, allowing single-shot measurement. The upper two beams cross and form a transient grating in the crystal. The lower beam is diffracted by the transient grating and generates an autocorrelation signal beam in the other corner of the rectangle. The line focus then acts as the entrance slit to a home-made spectrometer consisting of a collimating lens, diffraction grating, and focusing lens, yielding a single-shot TG FROG trace with delay running vertically and wavelength horizontally. The inset figure at the lower right shows the shape and size of the (rectangular) holes in the specific input mask that we used in the measurements performed for this work. The shape of the holes is not important, however.

The signal field in TG FROG is: $E_{sig}(t,\tau)=E_1(t)E_2(t)^*E_3(t-\tau)$ where $E_i(t)$ is the ith input pulse. In our arrangement, the TG FROG trace is mathematically equivalent to polarization-gate (PG) FROG, a highly intuitive version of FROG. Because pulse #3 is crossed at an angle to the other two pulses, it is variably delayed, and the signal pulse is given by [5, 6]:

$$I_{FROG}^{TG}(\omega,\tau) \quad = \quad \left| \int_{-\infty}^{\infty} E_1(t)E_2^*(t)E_3(t-\tau)\exp(-i\omega t)\,dt \right|^2 \qquad (1)$$

Because all pulses are identical, this becomes:

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

where we have performed a simple change of variables to yield the desired result. This is just the expression for the PG FROG signal field.

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3. Arrangement

In our arrangement, the input beam was expanded by a 4x telescope (not shown) and was then split by an input mask into three beams as in Fig. 1, as demonstrated previously by M. Li and coworkers [7]. Two of the beams were overlapped in space and time at the third-order nonlinear material by a cylindrical lens, producing a line-shaped transient refractive-index grating (with vertical fringes). The third beam was overlapped and crossed with the others by the Fresnel biprism. Diffraction by the induced-grating produces the signal pulse. For the third-order nonlinear material, we used a 3-mm-thick ZnS crystal, which is transparent from 370 nm to 14 μm. Fused silica can be used for broader-band (UV, visible, and IR) operation, albeit with somewhat less arrangement sensitivity at the longer wavelengths. Our arrangement also included a simple imaging spectrometer, whose entrance slit comprised the line focus in the crystal. The signal was isolated by an output mask, collimated by a spherical lens, and diffracted off a 1200-line/mm groove-density grating. After a spherical focusing lens, a spectral resolved TG-FROG trace resulted on the CCD camera, in which the delay varied vertically and frequency varied horizontally (Fig. 1).

The focal length of the cylindrical lens was 50 mm. The Fresnel biprism had an apex angle of 160°, yielding a delay range of 5 ps [5]. The crossing angle of the two pump beams was about 5.2°, resulting in a transient grating with a ~ 9 μm spatial period when the wavelength is 800 nm [8]. The use of a relatively thick crystal (3 mm) is permitted because the transient-grating process is automatically phase-matched, [8].

Our input mask consists of three rectangular holes (see the inset in Fig. 1). We found that, for our apparatus, thin rectangular holes minimized the scattered light in our trace, but this is not likely to be the case in general. We should also point out that use of a mask could yield error in the measured pulse temporal chirp when spatial chirp is present. However, simple aperturing or spatial filtering before the TG FROG will eliminate this problem.

4. Experiments

We demonstrated our arrangement for both 800-nm and 400-nm pulses with no change of any components between the two measurements. We first describe our measurements of 800-nm pulses, which were from a Ti:Sapphire regen and were ~150-fs long, 500 μJ in energy, and at a 1-kHz-rep-rate. Figure 2 shows the measured and retrieved traces, and the agreement is very good. The FROG error for the 128×128 traces was about 0.57%.

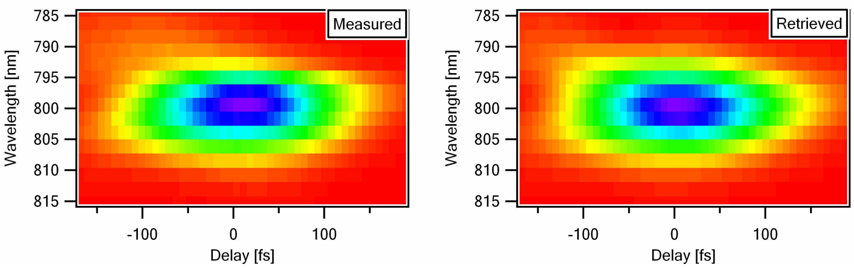

Fig. 2. Measured (left) and retrieved (right) TG FROG traces for our 800-nm pulse measurement.

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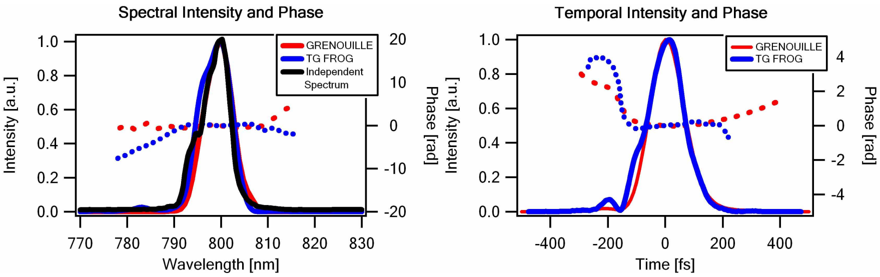

Fig. 3. Retrieved intensity and phase of the pulse using the simplified TG FROG (and GRENOUILLE and independent spectrum for comparison). On the left are the spectral intensity and phase; on the right are the temporal intensity and phase.

To verify the accuracy of our measurement, we also measured the pulse using a commercial GRENOUILLE from Swamp Optics (Model 8-50) and a commercial spectrometer from Ocean Optics (USB 2000). Figure 3 shows these results, and the agreement is good. The pulse's measured FWHM duration and bandwidth that TG-FROG retrieved are 140 fs and 8.3 nm respectively. GRENOUILLE measured a 139 fs pulse in comparison. In the retrieved spectral intensity, the GRENOUIILLE lacked the resolution to see the finest spectral structure of the pulse, which our TG FROG (whose grating spectrometer had higher resolution) could. This causes the minor discrepancy between GRENOUILLE and TG FROG measurements.

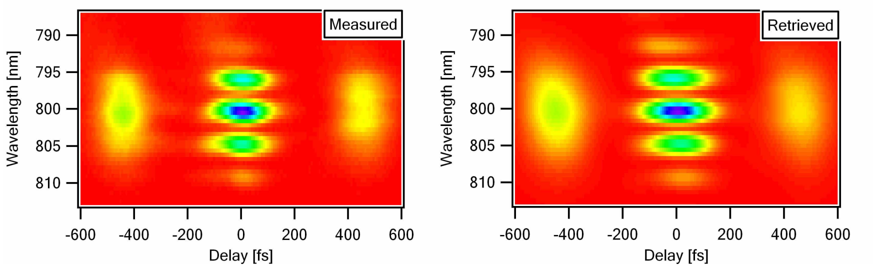

Fig. 4. Measured (left) and retrieved (right) TG FROG traces for a double pulse.

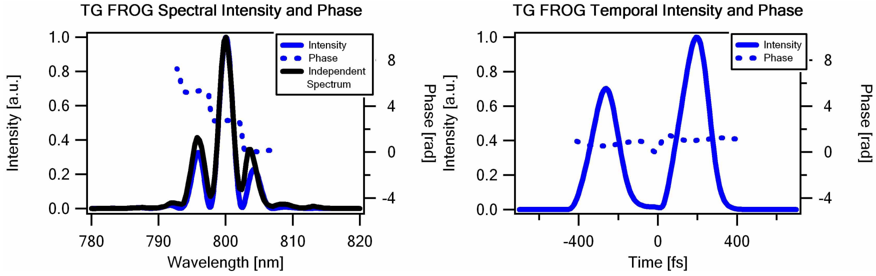

Fig. 5. Left: The retrieved spectral intensity and phase of a double pulse measured using TG FROG and the independent spectrum for comparison. Right: The temporal intensity and phase measured using TG FROG.

In order to test the arrangement's ability to measure complicated pulses, we measured a double pulse generated by a Michelson interferometer using the same arrangement. Because the effective size of the beams generated by the holes in the input mask was ~10mm, this setup yielded a sufficient delay range (~5 ps) to measure a 1 ps long double pulse using the same 160°-apex-angle Fresnel biprism. These beams were overlapped at the focus of the cylindrical lens in the piece of ZnS, yielding the characteristic double-pulse TG FROG trace shown in Fig. 4. The agreement between the measured and retrieved traces (Fig. 4) is good. The FROG error for the 512×512 traces was about 0.36%. The retrieved intensity and phase of the pulse are shown in Fig. 5. To verify the measured pulse, whose time-bandwidth product was too large to be measured with any commercially available device, we also measured the spectrum with a commercial spectrometer (Ocean Optics USB 2000), also shown in Fig. 5, and the agreement is good, provided that we realize that the spectral resolution of our TG FROG was better than that of the spectrometer (0.32nm).

With the same arrangement (no optics were changed), we also measured a 400-nm pulse, generated by second-harmonic generation of the amplified Ti:Sapphire pulses using a 500-µm type-I BBO crystal. The output of the regenerative amplifier was ~ 520mW at 800 nm, and the output of the second-harmonic generation was ~ 85mW (conversion efficiency ~ 16%). The generated UV pulse was sent to the TG FROG arrangement, which measured the 800-nm pulses above. The only realignment required in our TG FROG in order to measure this pulse was to change the grating angle in order for the 400-nm signal to impinge on the camera.

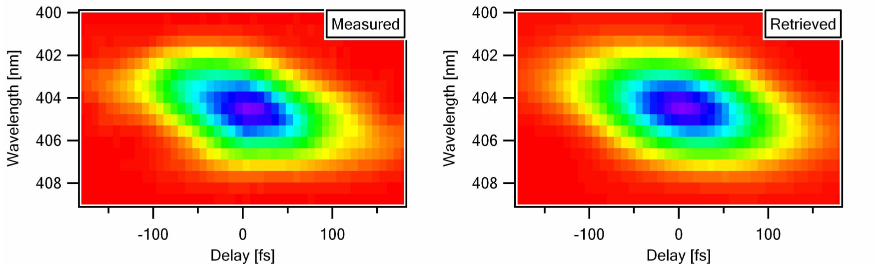

Fig. 6. Measured (left) and retrieved (right) TG FROG traces for the measurement of a 400-nm pulse.

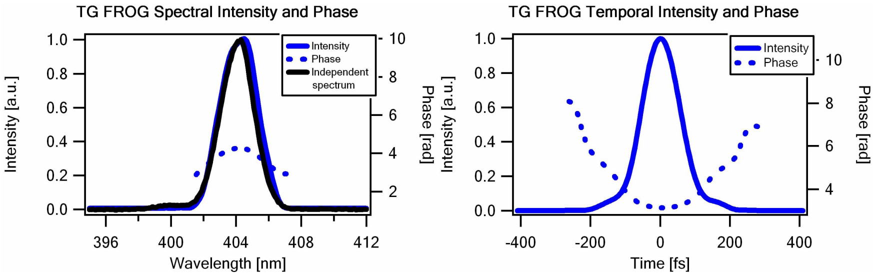

Fig. 7. Left: Retrieved spectral intensity and phase of a 400-nm pulse measured using TG FROG and the independent spectrum for comparison. Right: The temporal intensity and phase measured using TG FROG.

Figure 6 shows the measured and retrieved traces for the 400-nm pulse. The FROG error for the 128×128 traces was about 0.40%. The retrieved intensity and phase of the pulse are shown in Fig. 7. To verify the measured pulse, we also measured the spectrum with a commercial spectrometer (Ocean Optics USB 4000), also shown in Fig. 7, and the agreement is good. The pulse's FWHM duration and bandwidth retrieved by TG-FROG are 130fs and 2.6 nm, respectively. In order to minimize the group velocity dispersion, we used optics made of fused silica because fused silica is less dispersive than BK7 in the 400 nm region. The temporal distortion introduced by the small amount of fused silica in the TG FROG arrangement (~ 5 mm thickness fused silica for the cylindrical lens and the Fresnel biprism) is negligible, compared with the pulse's FWHM.

An experimental issue worth mentioning is that, even though TG FROG enjoys a background-free signal because the signal propagates in a unique direction, stray light can still be a problem because the signal pulse is of the same wavelength and polarization as the stronger input beams. However, placing the output mask in the image plane of the input mask by the cylindrical lens effectively removes most of this stray light. Also, using a small slit after the collimating lens further helps to reduce the stray light. As a result, the arrangement can be compact and can also achieve a good signal-to-noise ratio.

One might ask whether we actually needed the diffraction-grating spectrometer in this arrangement. Recall that the GRENOUILLE technique uses the angular dispersion of the SHG phase-matching condition of the nonlinear medium, so the SHG crystal acts as its own spectrometer and so does not require a diffraction-grating spectrometer. Analogously, here, we actually induce a *grating* in the nonlinear medium, so why not use its phase-matching wavelength vs. angle for spectral resolution and so eliminate the spectrometer diffraction grating? Indeed, the TG induced grating would even diffract the beam in the desired direction, perpendicular to the delay direction, just as in GRENOUILLE. The problem, however, is that the number of fringes here is so small that the resolution of this grating is too poor to resolve the pulses of interest. On the other hand, for pulses of very high energy, for which focusing is not necessary to achieve a strong TG signal, a larger spot size at the nonlinear medium would yield many fringes and so should make a true “TG GRENOUILLE” possible.

In principle, our TG FROG arrangement operates from the UV to the IR. In our particular arrangement, the camera’s response limited the operating range to 380 nm to 1100 nm. As a result, our particular arrangement can operate over a spectral range of 720 nm from the near-UV to near-IR. A more broadband camera could achieve a larger operating range.

5. Conclusions

We demonstrated an extremely broadband TG FROG arrangement, which is able to measure amplified pulses over a broad range of wavelengths with no change of components. Also, we believe that this TG FROG arrangement is the best option for UV pulse measurement limited only by material transmissivity and camera responsivity. While OPAs yield weaker pulses in the UV than in the visible and near-IR, third-order nonlinearities increase in the UV, so the arrangement sensitivity scales reasonably. Finally, while the TG FROG arrangement described here utilizes transmissive components, an analogous essentially all-reflective arrangement can be designed for extremely short pulses.

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