High-Sensitivity, Simple Frequency-Resolved-Optical-Gating Device

Travis Jones, Peter Šušnjar, Rok Petkovšek, and Rick Trebino

***Abstract*— We introduce a practical self-referenced device for the complete temporal intensity-and-phase measurement of few-femtojoule-level fs and ps pulses based on the simple version of frequency-resolved-optical gating, called GRENOUILLE. We replace the usual crossed-beam line-focus geometry with a point-focus near-collinear-beam geometry and a traditional delay line that allows a longer path length in the nonlinear medium, yielding greater sensitivity. As an initial demonstration of the device, we measured moderately complex pulses at energies as weak as 24 fJ with high signal-to-noise ratio. We confirmed the results measured using our technique to that of a standard GRENOUILLE and a high-resolution spectrometer.**

***Index Terms*— Ultrafast optics, ultrafast measurements, frequency-resolved optical gating, GRENOUILLE.**

I. Introduction

ULTRASHORT laser pulses require detailed intensity-and-phase measurement in order to achieve the required degree of control over the pulse. Such measurement techniques are now readily available. However, an important frontier in this field is the measurement of low-intensity light pulses with energies of ∼10 fJ, especially those with relatively long pulse lengths of ∼10 ps. For example, such pulses will likely play key roles in next-generation optical telecommunications. Weak pulses can also occur when only a small fraction of the power is available for measurement in a continuous monitoring arrangement in which the bulk of the pulse energy is required for an application. Also, fiber lasers, which necessarily have small beam areas, often emit low-energy ps pulses that are too weak to measure with current pulse-measurement techniques. Finally, a common approach for many additional applications of short-pulse laser systems is to begin with a low-pulse-energy oscillator, whose characteristics can be manipulated with ease, and then amplify the resulting pulses to high energies in one or more amplifier stages (so called MOPA – master oscillator, power amplifier configuration). For flexible operation, a gain-switched diode can also be implemented as the oscillator, which is typically highly chirped and therefore requires custom chirp compensation to reach the desired shorter pulse duration [1]. However, if the oscillator pulse cannot be measured, it is difficult to know what to do when the measurable high-energy pulse lacks the desired properties: which device is at fault, the oscillator or the amplifier?

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Measuring pulses directly from a laser requires a self-referenced technique, and a reliable and general such technique is frequency-resolved optical gating (FROG) [2]–[5]. FROG, like essentially all other pulse-measurement techniques, however, was designed for measuring pulses from relatively high-power fs lasers. These methods typically require the use of thin nonlinear-optical crystals and so cannot measure weak pulses.

A practical self-referenced technique for the complete measurement of weak ps pulses has been a long-standing unsolved problem that has attracted numerous extremely clever, yet only partial, solutions. For example, fast detectors and ultrahigh-bandwidth oscilloscopes are common, but such oscilloscopes are extremely expensive (>$100,000), fragile, and complex; they yield only the pulse intensity and not the phase; and they lack the temporal resolution to measure pulses shorter than ∼50 ps, far too slow for many applications. In addition, many techniques can measure very weak pulses [6], [7], but they require a previously measured reference pulse. One self-referenced method, a version of FROG, has been shown capable of measuring extremely weak (∼1 fJ), fs pulses, but it requires an aperiodically poled $LiNbO_3$ waveguide in order to achieve a long interaction length in the nonlinear medium for greater sensitivity, which is difficult to work with, expensive, and not readily available [8], [9]. Another version of FROG has achieved pJ sensitivity using an optical fiber as the nonlinear medium, but it is difficult to align and involves detection at the input wavelength (typically 1.5 μm), which requires an expensive IR camera [2], [10]. Others use high-speed modulators or other ultrahigh-bandwidth electronics, which are also very expensive [11]–[18]. Still others involve very complex apparatuses, such as tomography [19]. Some involve techniques that only measure the coherent artifact and so cannot distinguish a stable train of short simple pulses from an unstable train of longer more complex pulses [20]. Thus, it has simply not been possible to measure the complete intensity and phase of weak laser pulses in a way that is both reliable and practical. The lack of such a technique discourages laser-system monitoring and severely complicates potential new telecommunications approaches, in which details of the pulse's intensity and phase (e.g., phase-shift-keying) often play key roles.

To solve this problem, we report here a practical, self-referenced, and highly sensitive FROG technique for measuring weak fs and ps pulses in time, based on FROG's experimentally simpler version, known as GRating-Eliminated No-nonsense Observation of Ultrashort Incident Laser Light E-fields (GRENOUILLE). To measure such long, weak pulses, we make three key modifications to the standard GRENOUILLE arrangement: 1) we replace GRENOUILLE's Fresnel biprism and line-focus beam geometry with a collinear point-focus beam geometry and optimal focal-spot size, 2) we scan the delay in the traditional manner, and 3) we use an even-thicker second-harmonic-generation (SHG) crystal. Together, these changes maximize the interaction length, the pulse intensity within the crystal, and hence the SHG conversion efficiency and overall device sensitivity. It is similar to the "Poor Man's FROG" of Radzewics and coworkers [21], except that it uses collinear, not crossed, beams, and the angle of the crystal is not scanned (the entire spectrum is simultaneously collected vs. angle). This new device is considerably more sensitive than the above device and current GRENOUILLEs due to its simultaneous use of collinear beams and a point focus. It is also more sensitive than autocorrelators and FROGs due to its much thicker crystal. We refer to this new technique as Collinear GRENOUILLE (CG), to be distinguished herein from Standard GRENOUILLE (SG).

II. A Highly Sensitive FROG for Measuring Weak Pulses in Time

Like SG, CG also uses the natural angular phase-matching dispersion of a thick crystal to provide the necessary spectral resolution to measure a pulse [21], [22]. Sufficient spectral resolution is achieved by ensuring that the product of the group-velocity mismatch (GVM) between the fundamental and SH light, and the interaction length of the crystal, L, is much larger than the temporal length of the measured pulse, $\tau_p : GVM \times L \gg \tau_p$. Note that this is the opposite of the usual pulse-measurement-device condition. The length of the crystal is instead limited by the much less stringent condition involving group-velocity *dispersion* (GVD) between the extreme wavelengths in the bandwidth of the fundamental pulse. As a result, we ensure that $GVD \times L \ll \tau_c$, where τ_c is the coherence time (the duration of the shortest temporal structure) of the input pulse, as in SG.

As mentioned, to enable the measurement of such long, weak pulses, we replace SG's Fresnel biprism and line-focus beam geometry with a collinear point-focus beam geometry and optimal focal-spot size. This improves the device efficiency by increasing the intensity of the input pulse at the nonlinear crystal. We note that using a collinear geometry and scanning the relative delay with a traditional translation stage sacrifices SG's single-shot functionality, but for the high-rep-rate (up to 100 GHz) trains of weak pulses typically encountered, single-shot operation is inappropriate and is always sacrificed for improved sensitivity. Indeed, even without its single-shot capability, GRENOUILLE, like other FROG variations, can still tell whether a given pulse train is stable and provide the best available measurement of the typical pulse in that case [3]–[5].

Furthermore, when using a collinear geometry, one could generate an "interferometric FROG" (IFROG) trace [23]. Such fringe-filled traces have been used for few-fs pulses and have some advantages for such extremely short pulses. However, collecting such a fringe-filled trace for, say, a $\sim$10 ps pulse, increases the data collection time, and is not necessary since a standard SHG FROG trace already yields a complete temporal measurement of the pulse without the fringes. For these reasons, we believe these fringes should be removed, and they can be, by carefully under-sampling the IFROG trace [24], Fourier filtering [24], or dithering one arm of the interferometer [8]. To demonstrate, in the two measurements reported here, we performed one fringe-resolved measurement, where we used Fourier filtering to remove the fringes and extract the SHG FROG trace as in [24], and one where the fringes were washed out by dithering the fixed arm of the interferometer as in [8].

Lastly, we note that measuring pulses also requires efficient conversion of the complete spectrum of the pulse. In birefringent nonlinear crystals, phase-matching is fulfilled for a single wavelength at a single angle relative to the crystal's optical axis due to angular variation of the extraordinary refractive index. By focusing the beam tightly into a nonlinear crystal, sufficient divergence of the beam can be used to cover all of the phase-matching angles within the spectrum of the pulse. However, the same angular variation also produces spatial walk-off between the fundamental and second-harmonic beams and consequently reduces conversion efficiency. Thus, when selecting the focusing conditions there is a trade-off between the shortest measurable pulse and the weakest measurable pulse. Simply put, the tighter the focusing, the shorter the pulse (i.e. the more broadband a pulse) that can be measured, while focusing more loosely provides a longer interaction length and better conversion efficiency, enabling the measurement of weaker pulses.

III. Experimental Setup

To test our device, we performed two experiments using the output of a KM Labs Ti:Sapphire oscillator, which emitted $\sim$7.5 nJ pulses with 30 nm bandwidth FWHM at a repetition rate of 90 MHz. In the first experiment, we tested our device's ability to measure complex pulses at relatively high pulse energies and compared it to an SG device. The experimental setup is shown in Fig. 1. We generated a complex pulse by sending the output of our oscillator through a 23.8 μm-spaced etalon with 50% reflectivity on both surfaces. This created a pulse consisting of a series of pulses each separated by 159 fs. A Swamp Optics BOA compressor was then used to compensate for the group delay dispersion in the setup. In this first experiment, the input pulse energy was relatively high, around 550 pJ. This first experiment serves as a proof-of-principle measurement of the CG technique.

Our CG used a balanced Michelson interferometer in which the beams were split and recombined using a 3-mm-thick

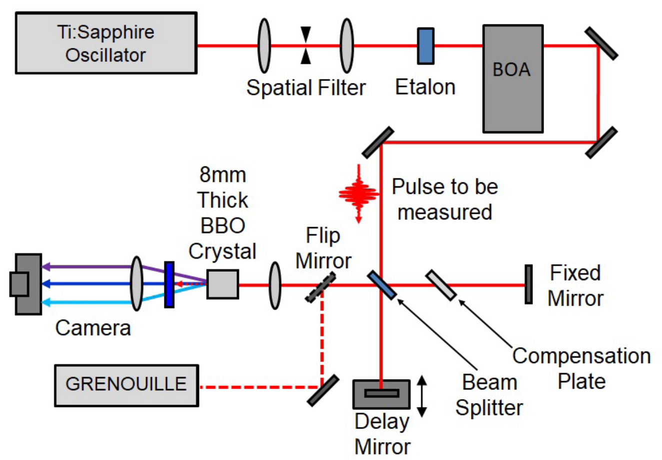

Fig. 1. Experimental setup used in proof-of-principle demonstration of Collinear GRENOUILLE (CG). The measured pulse was generated by sending a collimated beam through a 23.8 μm etalon. Any dispersion caused by the etalon and other elements later in the setup was compensated by a BOA compressor. After the BOA, the pulse to be measured entered the apparatus, which consisted of a dispersion-balanced Michelson Interferometer, a spherical focusing lens, an 8-mm-thick SHG crystal, a blue glass filter, a spherical lens, and a camera.

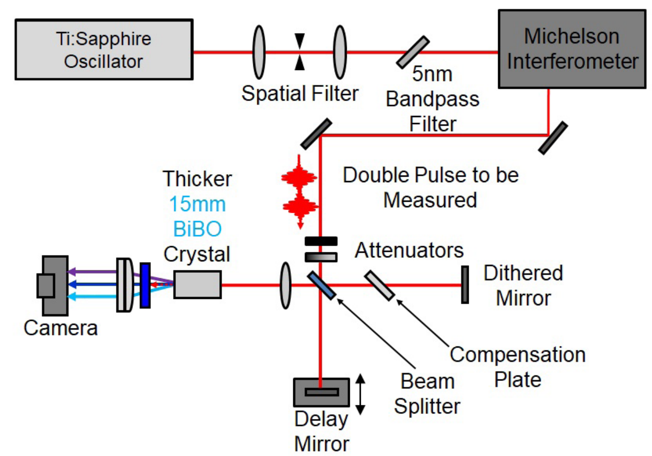

Fig. 2. Experimental setup used in second (more sensitive) demonstration of CG. A 5 nm, 1.3 ps double pulse was created using a 5 nm band pass filter and a Michelson interferometer. This used a 15 mm BiBO crystal as the nonlinear medium, which provides improved SH conversion efficiency and spectral resolution over BBO for near-800 nm light. A pair of cylindrical lenses was also used after the crystal to map crystal exit angle to position on the camera in the dispersive dimension and image the SHG light onto a few pixels in the non-dispersive dimension. Incorporation of this lens pair allowed us to better overcome the noise in the camera.

50/50 plate beam-splitter made of N-BK7 glass. Dispersion between the arms of the Michelson was balanced using a 3-mm-thick anti-reflection coated compensation plate of the same material. A Newport MFN25PP translation stage was used to vary the length of the delay arm of the Michelson interferometer. A flip mirror was placed after the beam-splitter of the Michelson to allow for easy transition between CG and SG measurements. For the 30 nm bandwidth pulses measured in this initial demonstration, the task of ensuring complete phase-matching was given priority over conversion efficiency, so a relatively tight focus was used to cover the relatively large range of phase-matching angles involved. Thus, when the flip mirror was out of the beam path, the beams were focused relatively tightly using a 50 mm spherical lens onto an 8 mm Type-I BBO. The unconverted fundamental light was removed using a bandpass colored glass filter (Thorlabs, FGS900-A) while the frequency-resolved SH light was mapped onto a Pixelink Pl-A741 camera using a 15 cm spherical lens. A CG trace was captured by scanning the delay arm of the Michelson 5000 steps at the finest step size which was 0.49 fs. This measurement took roughly 85 min to complete. A pause of $\sim$0.7 s was used to let the stage settle before acquiring the spectrum at each delay. It is worth noting here that this acquisition time could be significantly reduced if a fast camera and stage combination similar to that in [23] is used. Later, a conventional SHG FROG trace was extracted from the CG trace using Fourier filtering and background subtraction [24]. After the CG measurement, the delay mirror was placed near zero delay, the flip mirror was placed in the beam path, and the fundamental light was then measured using a standard Swamp Optics GRENOUILLE (8-50).

In the second experiment, we tested the measurement sensitivity of our device by measuring a weak double-pulse with 1.3 ps separation. The setup is shown in Fig 2. In this experiment, the output of our oscillator was sent through a 5 nm bandpass filter and an additional Michelson interferometer, which was used to generate the double pulse. The pulse was attenuated using a pair of variable attenuators, such that the measured average power before entering the measurement apparatus was reduced to 4.3 μW. Given our 90 MHz repetition rate, this yields an average double-pulse total energy of nearly 48 fJ and thus a measurement sensitivity of $\sim$24 fJ per pulse.

Due to its higher nonlinear coefficient, higher GVM, and lower Poynting vector walk-off angle near 810 nm compared to BBO [25], in this measurement, we used a 15 mm BiBO crystal as the SHG crystal. We also used a 100 mm lens to focus the beams into the crystal. As mentioned, the size of the beam at the focus is an important parameter to consider, because it impacts both phase matching and conversion efficiency. Although we did not measure the profile of the focused beam using the 100 mm lens, we did make two such measurements using a 150 mm and 125 mm focusing lens which yielded FWHM beam diameters of 38.3 μm and 32.8 μm, respectively. Based on these measurements, we estimate the spot size using the 100 mm lens to be 27 μm $\pm$ 2 μm. Using the methods discussed in [26] and [27] we estimate in Fig. 3(a) the spectral resolution and in Fig. 3(b) the phase-matched SH bandwidth vs. focused beam diameter. Specifically, we estimate that our 27 μm spot size should yield a spectral resolution of $\sim$0.077 nm and support $\sim$1.6 nm of SH bandwidth—an SH bandwidth close to that expected from our spectrally narrowed pulse ($\sim$1.7 nm). Furthermore, this spot size yields a confocal parameter, $b = 2\pi n w_0^2/\lambda_0$, of 10.3 mm and an L/b ratio of $\sim$1.46 which is should also be close to the theoretical value for optimal conversion efficiency according to [28], where our A and B are approximately 40 and 14 respectively.

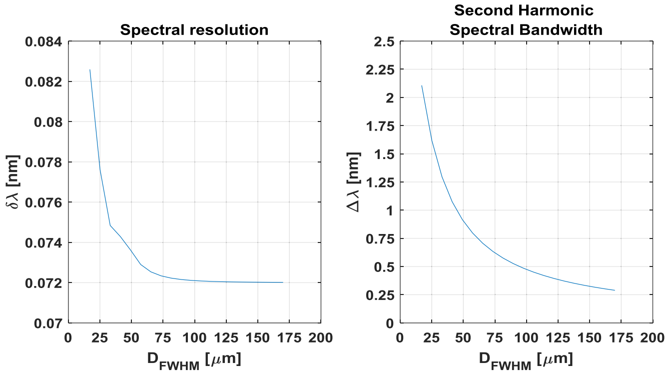

Fig. 3. Theoretical plots of (a) spectral resolution and (b) phase-matched second harmonic (SH) spectral bandwidth (FWHM) vs. focused beam diameter using a 15 mm BIBO crystal. A spot size of 27 μm phase matches ∼1.6 nm of SH bandwidth.

Following the crystal, vertical and horizontal cylindrical lenses—with 100 mm and 50 mm focal lengths respectively—were also introduced to form a makeshift anamorphic lens placed 10 cm after the focus. The vertical lens, placed one focal length away, mapped wavelength onto position on a detector, while the horizontal lens imaged the second harmonic light from the crystal onto only 4-5 pixels of our sensor in the non-critical dimension thus improving our signal to noise ratio. To remove the interferometric fringes in this measurement, we dithered the fixed arm of the measurement apparatus by attaching a piezo chip to the fixed mirror and driving it with a frequency of 50 Hz and an amplitude corresponding to nearly half the fundamental wavelength. Although much more sensitive cameras exist, such as the I-CCD used in [8], we again used our modest Pixelink camera to record the trace. However, notably, this time a 0.5 s integration time was used and 10 frames were averaged at each delay for an effective integration time of nearly 5 s. The trace was measured using 160 delay steps at 27 fs per step. This measurement took approximately 15 min. We compared this measurement to a high-resolution spectrometer, as this pulse was outside the measurement range of our available GRENOUILLE.

IV. Results and Discussion

In Fig. 4(a), we plot our measured CG trace from the first experiment. By summing over the vertical dimension of the CG trace, we can obtain the interferometric autocorrelation (IAC) which we plot, normalized relative to the background, in Fig. 4(b).

Similar to [24], we performed a 2D Fourier-filtering and subtracted a background equal to the average of 70 delays at the end of the trace to extract the standard SHG FROG trace from the CG trace. All experimental CG traces were calibrated using the characteristic peaks in the traces and a curve-fitting scheme as described in [29].

In Fig. 5, we plot the measured and retrieved results obtained using both CG and SG from the first experiment. The measured CG (Fig. 5(a)) and SG (Fig. 5(c)) traces were binned to a 256 × 256 array. We retrieved each pulse using the newly developed and highly reliable RANA Approach for SHG FROG [30], [31]. The FROG errors for the SG and CG traces were 0.0068 and 0.0062 respectively. Figures 5(e) and 5(f) attest to the excellent agreement achieved between the CG and SG retrieved results.

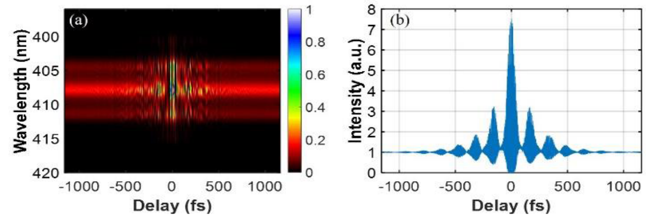

Fig. 4. (a) Measured SHG IFROG trace and (b) normalized Interferometric Autocorrelation. Although a slightly less than 8:1 peak-to-background ratio was obtained for the IAC, this does not affect the accuracy of the measurement.

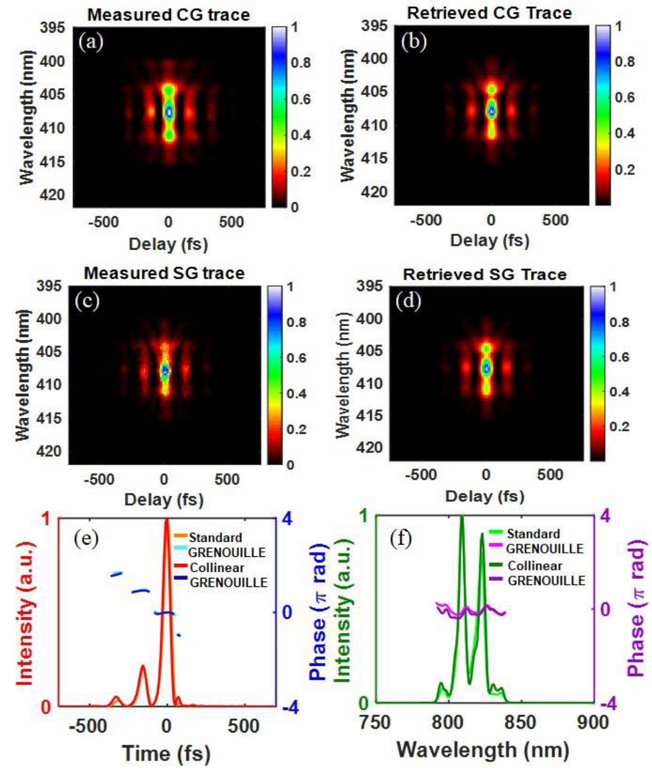

Fig. 5. Results from the first, proof-of-principle Collinear GRENOUILLE (CG) experiment. Measured and retrieved results for CG and standard GRENOUILLE (SG) of a pulse consisting of a train of pulses. (a) Measured CG trace, (b) retrieved CG trace, (c) measured SG trace, (d) retrieved SG trace. A comparison of the pulse (e) temporal and (f) spectral intensity and phase retrieved from the collinear and standard GRENOUILLE traces.

In Fig. 6, we plot the results from the second, more sensitive measurement of a double pulse. After light Fourier-filtering and background subtraction, this trace was also binned to a 256×256 array. Since our focal spot size phase-matched an SH bandwidth slightly narrower than the expected SH bandwidth from our pulse, we then performed a standard frequency-marginal correction to the measured trace [2]. Alternatively, a tighter focusing lens could have been used, which would yield a smaller spot size and would phase-match a broader SH

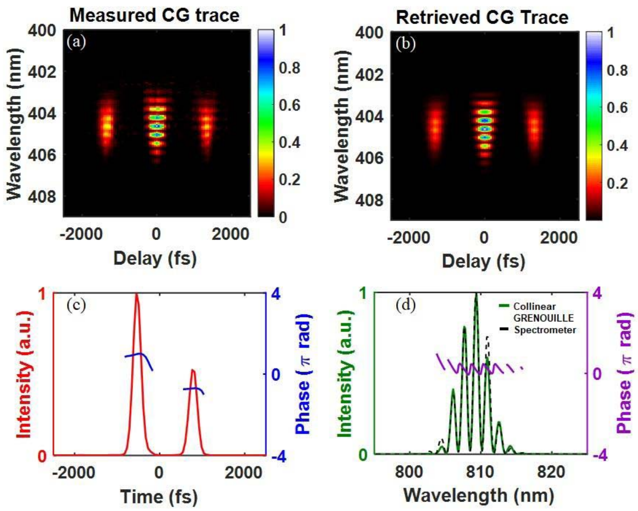

Fig. 6. Results of the second, high-sensitivity experiment: (a) Measured trace after frequency marginal correction and (b) retrieved CG traces. (c) Retrieved pulse temporal intensity and phase and (d) spectral comparison to high-resolution spectrometer.

bandwidth, more easily capturing the entire bandwidth of our pulse. We again retrieved the pulse using the RANA Approach for SHG FROG. The FROG error for this CG measurement was 0.0066. Upon close inspection of the trace, residual spectral fringes can be seen in the side lobes of the trace, which should not be present after background subtraction. We believe these residual fringes are a result of either instability in the Michelson that generates the double pulse or more likely a stray reflection. Despite this, very good agreement was still achieved between CG and the high-resolution spectrometer.

V. Conclusion

To summarize, we have developed a practical, self-referenced pulse-measurement technique for weak picosecond pulses based on GRENOUILLE. To enhance GRENOUILLE's sensitivity, we traded its crossed-beam line-focus geometry and single-shot functionality for a point-focus collinear-beam geometry and a delay line. Using GRENOUILLE's thick crystal, along with a collinear beam geometry, maximizes SHG efficiency and makes Collinear GRENOUILLE substantially more sensitive than current GRENOUILLEs and FROGs. Our demonstration of the Collinear GRENOUILLE technique involved measuring two complex pulses: one consisting of a relatively high-energy train of multiple pulses produced by an etalon and a 48 fJ double pulse from a Michelson interferometer. We confirmed the results of our measurements with a standard GRENOUILLE and a high-resolution spectrometer, respectively, achieving excellent agreement in both cases.

Sensitivity can be further improved using a more sensitive camera and/or by accepting a lower signal-to-noise ratio in the measured trace, the latter of which is readily handled by the FROG algorithm [2] in conjunction with the RANA approach. These modifications should take the sensitivity to sub-fJ levels. Also, as the repetition rate of lasers increases, for example, to the nearly 100 GHz rep rates expected of next-generation telecommunication systems, even weaker and/or longer pulses should be measurable using this device. For this reason, this technique could be used to measure telecom pulses by employing different SHG crystals suitable for the relevant wavelength region.

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