Toward single-shot measurement of a broadband ultrafast continuum

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We discuss the problem of measuring the intensity and phase of a broadband continuum in a single shot, considering three possible methods, and perform preliminary measurements using one of them. Our measurements use transient-grating cross-correlation frequency-resolved optical gating (TG XFROG) with a third-order nonlinear medium, which currently can phase match over 300 nm simultaneously. We demonstrate this technique for a continuum generated in bulk fused silica that is 12.5 mm thick. Due to limited reference-pulse energy, we do not achieve a true single-shot measurement, instead averaging over approximately five shots. The retrieved trace and spectrum contain fine structure, and the retrieved temporal phase is mainly quadratic.

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1. INTRODUCTION

In virtually any medium, powerful ultrashort pulses can undergo extreme spectral broadening, yielding a white-light supercontinuum (SC), one of the most spectacular nonlinear-optical phenomena. Since the first observation of a continuum from glass samples by Alfano and Shapiro in the late 1960s [1], SC generation has been the subject of numerous investigations in a wide variety of solids, liquids, and gases.

One breakthrough in continuum research was the advent of microstructure or photonic-crystal fiber (PCF) in the late 1990s. PCF has led to a revolution in the generation of SC. By shifting the zero-dispersion wavelength of the fiber to the Ti:sapphire laser wavelength range, single-spatial-mode SC, spanning the entire visible spectrum and a significant fraction of the IR, has been generated and studied by many groups [2–4]. With the simple spatial transverse mode characteristic of the fiber, SC generation in PCF is considerably less complex than that in bulk materials, which involves an intricate coupling between spatial and temporal effects [5]. As a result, such SC is even more useful for its numerous applications, including optical parametric amplification, excite-probe spectroscopy, pulse compression [6,7], and as a source of tunable ultrashort pulses from the ultraviolet to the infrared [6].

Due to its widespread use, it is important to understand the mechanisms of SC generation. Although SC generation has been the subject of many publications over many years, the mechanisms of SC generation remain far from well understood due to its inherent complexities and the lack of complete measurements—most SC measurements have been simple spectral measurements (often of admittedly complex spectra). Thus it is important to develop effective and general techniques for its measurement. Unfortunately, most ultrashort-pulse-measurement techniques have not been able to measure such ultrabroadband waveforms. Worse, a continuum's usually complex spatial profile complicates its measurement even more, but, fortunately, the single-spatial-mode nature of a continuum in PCF simplifies the problem considerably, obviating the need for any spatial resolution and making the problem of its measurement only temporal. As a result, in previous publications [4,8], we were able to show that the multishot cross-correlation frequency-resolved-optical-gating (XFROG) technique using an angle-dithered sum-frequency-generation crystal could adequately measure the continuum from PCF on a multishot basis. Our XFROG measurements revealed that the continuum from PCF longer than approximately 1 cm was much more complex and unstable than previously imagined (simple multishot spectral measurements had averaged out its complex spectral structure), and our independent single-shot spectral measurements (using a simple spectrometer) confirmed this [8]. Interestingly, while spectra measured using a spectrometer and averaged over even a few hundred shots showed almost completely washed-out spectral structure and hence a smooth spectrum, FROG-measured spectra showed ultracomplex spectral structure, even when averaged over a few hundred billion shots. Of course, because all of our XFROG measurements were multishot, and so we necessarily assumed that what was being measured remained the same from shot to shot, our multishot XFROG-measured pulse's complex spectral structure can only be considered typical of the continuum spectral structure and not indicative of the precise spectral structure of any given pulse. Additionally, the same applies for the pulse spectral phase and hence the intensity and phase versus time. As an aside, measurements of the continuum made using alternative methods that only measured the spectral phase and that used a multishot-measured, highly smoothed spectrum have simply been wrong. This confusion illustrates the difficulty of measuring a continuum.

As a result, a true single-shot technique for measuring a temporally complex, but spatially smooth, continuum pulse would be ideal for measuring a continuum from PCF. In fact, some continua generated in bulk media are also spatially fairly smooth, and such a technique would be useful in these cases also. One significant challenge, however, is that the continuum spectrum is generally too broad to phase match simultaneously, even when using sum-frequency generation (SFG), which can phase match a broader-band pulse than SHG, and even with an extremely thin nonlinear crystal. Indeed, to achieve sufficiently broadband phase matching in the above-mentioned multishot XFROG measurements, we used an angle-dithered SHG crystal, making such measurements inherently multishot for two reasons, that and the scanning of the delay. Another challenge is that the continuum is very complicated, having a time–bandwidth product as high as several thousand. This necessitates a large temporal range as well as very high temporal and spectral resolutions. Finally, a continuum measurement technique must also have high sensitivity because PCF continua usually have no more than approximately 1 nJ of energy, limited by the small core of PCFs.

As a result, here we discuss the very difficult problem of a true single-shot technique for measuring a spatially smooth spatial-mode continuum and introduce a method for doing so. It is transient-grating (TG) XFROG, which uses a third-order nonlinear-optical process, which can phase match a very broad bandwidth on a single shot, and which represents, we believe, significant progress toward this difficult goal. Our geometry also has a relatively large temporal range as well as relatively high resolutions in both domains, and it has the required sensitivity.

We demonstrate it for measuring a spectral portion of a continuum generated from bulk fused silica that is 12.5 mm thick. We use ZnS as the third-order nonlinear medium in the XFROG device and achieve a phase-matching bandwidth (spectral range) of 300 nm. Unfortunately, due to limited pulse energy in the aged regenerative amplifier used for this work, we did not achieve a true single-shot measurement, instead averaging over approximately five shots. But we believe that our measurement represents a valid proof-of-principle measurement and that only slightly more pump-pulse energy would be sufficient to achieve true single-shot measurements.

2. SINGLE-SHOT BROADBAND BEAM GEOMETRIES

In general, a smooth spatial mode naturally allows single-shot measurements using the well-known large-beam-crossing-angle-and-line-focus-in-the-nonlinear-medium beam geometry, which maps relative delay onto the transverse position. As long as the nonlinear medium is then imaged onto a camera, all delays are sampled on every shot, and single-shot operation is achieved. However, a single-shot technique for measuring a supercontinuum must also be capable of measuring extremely complex pulses in time and frequency. Only the FROG family of techniques and a recent version of spectral interferometry [9] have been shown to be capable of measuring complex pulses. Unfortunately, spectral interferometry requires a well-characterized reference pulse with the same (or broader) spectrum, rendering it inappropriate (if we were to use spectral interferometry, we would have to measure the continuum in order to measure the continuum!).

A continuum measurement technique must also have high sensitivity because continua usually have no more than approximately 1 nJ of energy, limited by the small core of PCFs. The most sensitive self-referenced single-shot techniques are FROG methods using second-order nonlinearities. Unfortunately, with second-order crystals, the maximum phase-matching bandwidth with even an extremely thin 10 μm thick β-barium borate (BBO) crystal is only 100–150 nm when the continuum center wavelength is 700 nm and only tens of nanometers when the center wavelength is 500 nm [8]. Techniques based on surface SHG can have significant bandwidth, but they lack the sensitivity.

More broadband phase matching can be accomplished using a third-order nonlinear-optical beam geometry, such as polarization gating or transient grating [10]. Although such geometries usually have limited sensitivity, they can be made more efficient by using an intense well-characterized reference pulse for two of the three pulses involved. The result is a spectrally resolved cross correlation, or XFROG apparatus, which can be very sensitive. It has the advantage that the reference pulse has no particular wavelength or bandwidth requirements, unlike spectral interferometry. Polarization gating (PG), in which the reference pulse gates the continuum pulse between crossed polarizers, appears ideal due to its automatic phase-matching condition, independent of wavelength, and hence its essentially infinite bandwidth. However, the dispersion of the required high-quality calcite polarizers can be significant, especially in the bluer spectral regions of the pulse. Also, because a relatively large beam will be required, a large polarizer would be required. On the other hand, the transient grating (TG) process can phase match a large bandwidth simultaneously, too. In addition, it is background free and more sensitive: It uses the relatively large on-diagonal element of the nonlinear-optical $\chi^{(3)}$ tensor, which is a factor of 3 larger than the off-diagonal element that PG uses, resulting in a TG FROG signal an order of magnitude stronger than the PG FROG signal, and thus it can achieve a more sensitive single-shot FROG geometry. Although we believe that a PG XFROG device should also work, we have, in this work, concentrated on TG XFROG because it is more accurate and more efficient and also because of the limited energy ($\sim$300 μJ) in the reference pulses available from our regenerative amplifier.

3. EXPERIMENTAL GEOMETRY

Our TG XFROG arrangement is shown in Fig. 1. The first beam splitter splits the input beam in two. The second beam splitter splits one of the beams in two again to generate the two pump beams, which then overlap in time and focus in space to form an index grating in the nonlinear medium. The other beam passes through fused silica to generate a continuum. To avoid damage and to generate the desired continuum bandwidth, the beam energy is controlled by the combination of a wave plate and a polar-

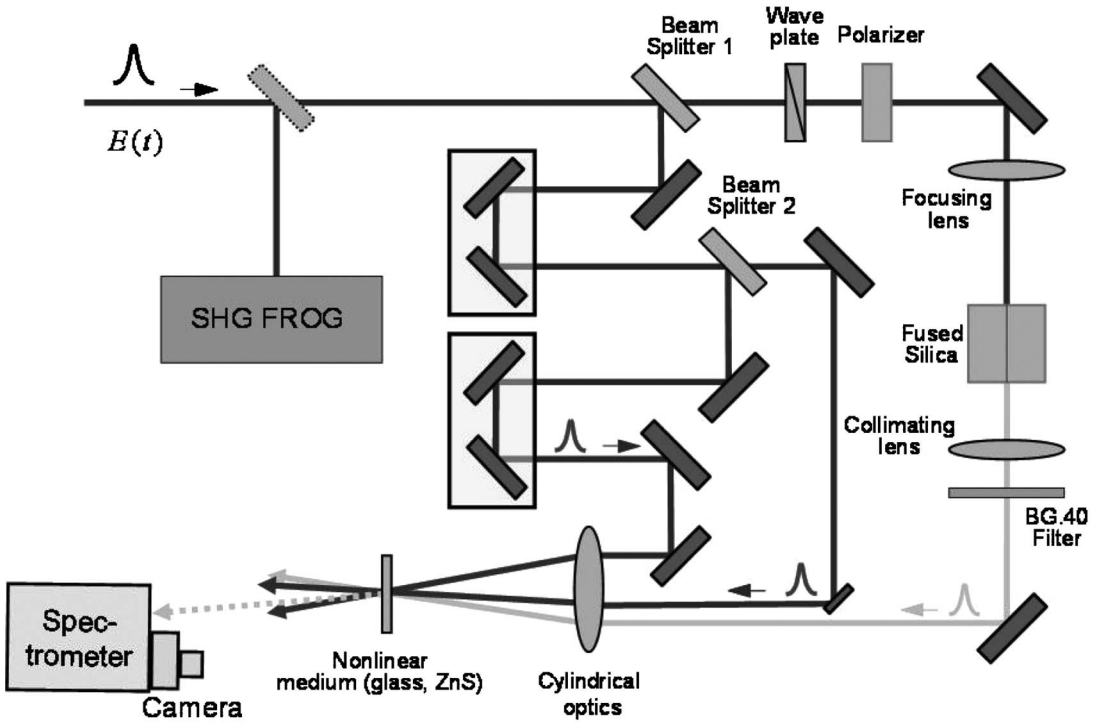

Fig. 1. Schematic diagram of our TG XFROG measurement arrangement. The input beam is measured by a commercial SHG FROG (GRENOUILLE) and split into three beams. Two become pump beams, which eventually form the grating. The other beam generates a continuum from fused silica. The continuum is filtered by a BG 40 filter to yield only its blue component. The three beams are overlapped in time and crossed in space and time in the nonlinear medium. We use cylindrical mirrors in our experiment, instead of cylindrical lenses, for crossing and overlapping them in the nonlinear medium in order to minimize the continuum distortions. We use a lens in the figure because it is easier to draw and optically equivalent.

izer. The continuum generated from the fused silica is then spatially crossed and temporally overlapped in the nonlinear medium and diffracted by the transient grating to produce the signal beam. The four beam angles (three input beams and one signal beam) in TG geometries take the form of the well-known BOXCARS arrangement [11]. In other words, the signal appears as the spot in the corners of a rectangle on a card placed in the beam. The signal is then sent to an imaging spectrometer. As in other single-shot FROG arrangements, due to the crossing angle between the continuum and the gating pump beams and the line focus, the relative delay between the gate and an unknown (continuum) pulse varies transversely across the nonlinear medium, thus mapping delay onto the transverse spatial coordinates. Finally, a camera captures the spectrally resolved TG XFROG signal gated by the known pump pulse, which is itself characterized by a SHG FROG. The FROG algorithm then retrieves the continuum pulse intensity and phase from the TG XFROG trace.

Due to our limited pulse energy, we chose to generate SC in bulk to increase the SC energy available. A Ti:sapphire regenerative amplifier generated 800 nm pulses that were ~200 fs long, ~340 μJ in energy, and at a 1 kHz repetition rate. This pulse was measured using a commercial SHG FROG (a Swamp Optics GRENOUILLE, Model 8-50) in order to use it as a reference pulse. We focused this beam into bulk fused silica yielding a stable SC. The multiple optical elements before the fused silica necessarily had dispersion, so the pulse was prechirped to compensate for the dispersion. The continuum was generated by sending prechirped ~3 μJ, 210 fs pulses through a 250 mm focal length lens (a numerical aperture of 0.01) into 12.5 mm of bulk fused silica. Unlike SC generation in an optical fiber, which is necessarily single spatial mode, a continuum in bulk materials is a highly complex process involving spatial and temporal effects [5]. As a result, the continuum beam had some spatial structure even though we filtered out the conical emission component. However, this structure was not severe (see Fig. 2). The continuum generated from the fused silica was then collimated by a

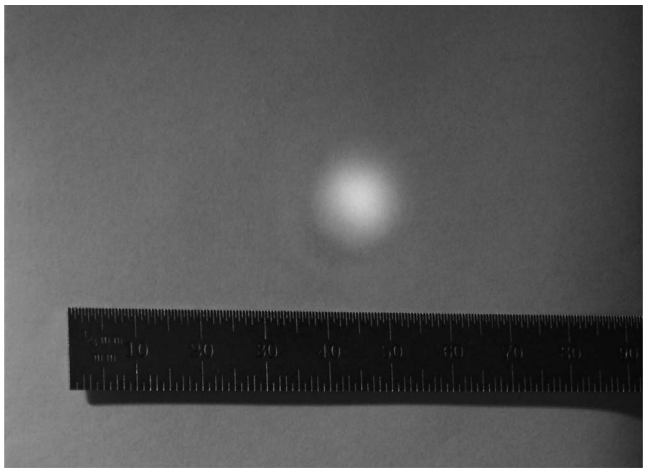

Fig. 2. Spatial profile of the continuum from the bulk fused silica using an ~5 μJ pulse energy. Slight color variations (intensity variations in gray scale) occurred in this beam, so only 3 μJ was used in order to minimize the spatial variations.

lens with a 150 mm focal length and passed through a Schott BG40 filter, which passed the visible and blocked the intense 800 nm portion of the spectrum, which was necessary due to the camera's limited dynamic range. This visible spectral component of the continuum represented the asymmetric blue-broadening characteristic of the SC generation [12].

The delays of the two pump beams were controlled by two translation stages in order to make the continuum and two pump beams overlap in time in the nonlinear medium. To implement TG XFROG in a single-shot beam geometry to measure a few picosecond pulse, a cylindrical mirror of 125 mm focal length focused the two pump beams and the continuum, which crossed at a large angle (13.5°), generating an ~11 ps delay range, shown in Fig. 3. The relative delay between the pumps and the continuum varied transversely across the nonlinear medium. For the nonlinear medium, a ZnS crystal (3 mm thick) was used because this material has a relatively high third-order nonlinear-optical coefficient and is transparent from 380 to 1100 nm, covering the whole continuum spectrum.

Figure 4 shows the phase-matching condition for our TG XFROG. In general, in TG FROG, the three input beams have the same frequency and are arranged so that, on a card, they appear to be on three corners of a rectangle or a square [Fig. 4(a)]. As a result, this geometry automatically satisfies the Bragg condition, or phase-matching condition, independent of the input wavelength [Fig. 4(b)]. However, when measuring the continuum, the center wavelength of the continuum, or the probe, may

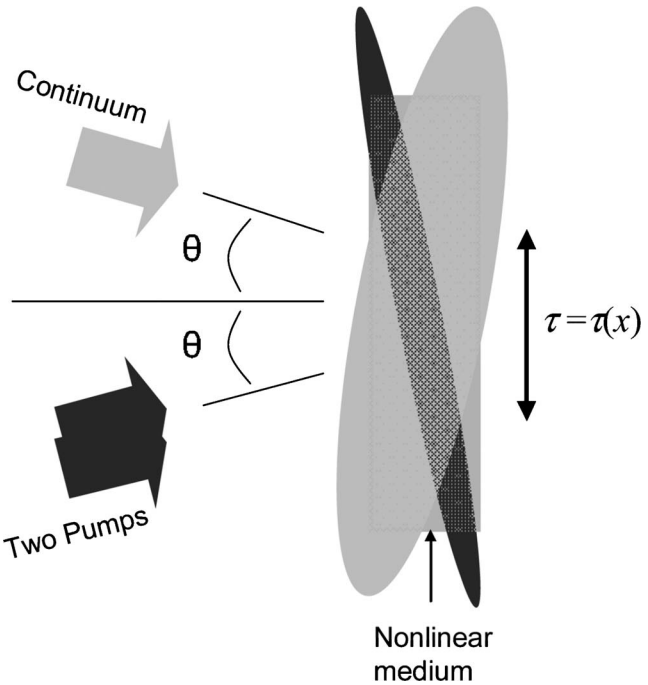

Fig. 3. Schematic of three pulses [two pumps (black) and a continuum (gray)] for a single-shot TG XFROG geometry. The continuum and two pumps cross at an angle θ (13.5 deg), mapping delay onto the transverse position. The two pumps are overlapped in time and space and form a transient grating in the nonlinear medium. The continuum is diffracted by the transient grating.

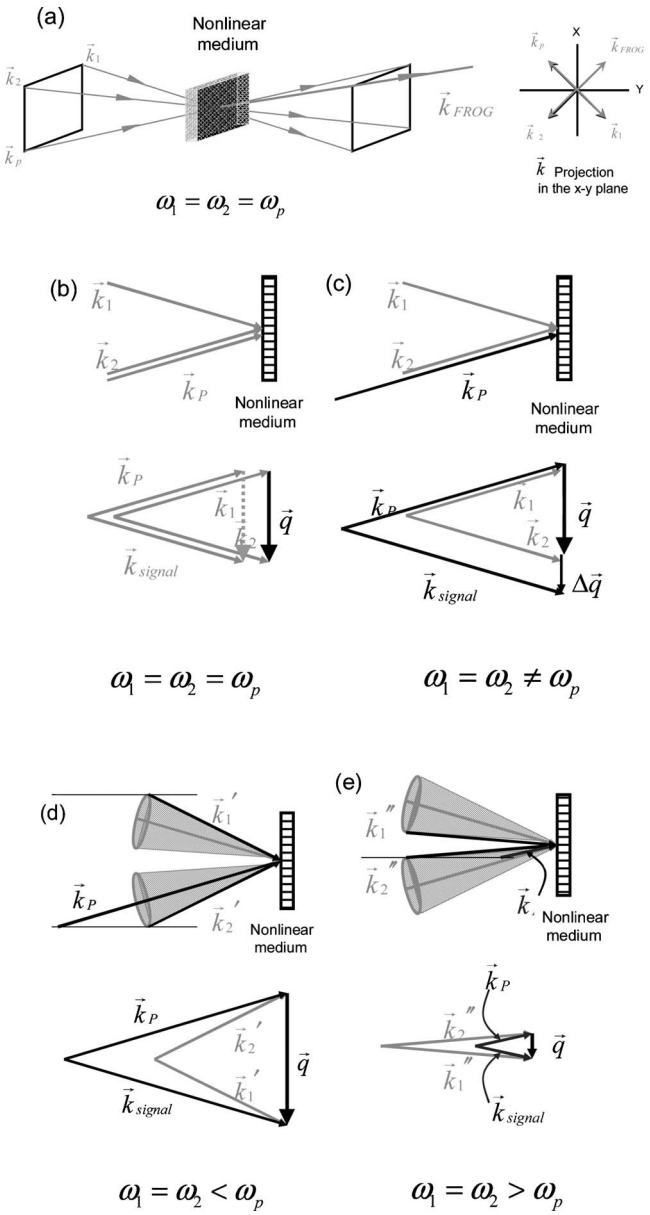

Fig. 4. Phase-matching condition for the TG XFROG. (a) k-vector diagram for TG FROG phase matching. $\vec{k}_1$ and $\vec{k}_2$ are the two pumps. $\vec{k}_p$ is the probe beam to be measured. $\vec{k}_{\mathrm{FROG}}$ is the FROG signal. The signal beam emerges from the other corner of a rectangle of the three-input-beam geometry. The phase-matching condition is $\vec{k}_{\mathrm{FROG}}=\vec{k}_1-\vec{k}_2+\vec{k}_3$. (b) Bragg condition for the TG FROG, where $\omega_1=\omega_2=\omega_p$. (c) When $\omega_1=\omega_2\neq\omega_p$, the Bragg condition is not satisfied, where $\Delta\vec{q}$ is the phase mismatch. (d) Bragg condition for the blue side of the continuum and (e) Bragg condition for the red side of the continuum when we use the focused pump beams. As a result, when the beams are focused, the phase-matching bandwidth increases.

not be the same as one of the pump beams. In this case, there is a phase mismatch $\Delta\vec{q}$ because these three beams cannot satisfy the Bragg condition [Fig. 4(c)]. Therefore, the total phase-matching bandwidth is comparable with the bandwidth of the pump beam. In our TG XFROG, however, because the two pump beams focus into the nonlinear medium, the k vectors have a range of angles and so can achieve phase matching even if they have the same frequency [Figs. 4(d) and 4(e)]. These different k vectors

in the pump beams (at 800 nm) can phase match the k vector on the blue side of the continuum (at 550 nm) [Fig. 4(d)]. Similarly, they can phase match the red side of the continuum [Fig. 4(e)]. As a result, the total phase-matching bandwidth of the TG XFROG is a function of the beam size of the pump beam (before the lens or mirror), the crossing angle of the two pump beams, and the focal length of the cylindrical mirror. Accordingly, the arrangement can phase match from 380 to 1600 nm when using a pump beam diameter of 7 mm and a crossing angle of 4.6°. If a smaller cylindrical lens focal length and a larger beam size are used, the total phase-matching bandwidth of the arrangement increases further.

The continuum was overlapped in time and crossed in space in the nonlinear medium and diffracted by the grating induced by the two pumps to produce the signal pulse. The signal was imaged onto an imaging spectrometer with a 150 line/mm groove density and a 500 nm blaze-angle grating. Unfortunately, our induced-grating efficiency was too low to yield true single-shot operation, and it was necessary to integrate over approximately five pulses to produce a useful data trace. This caused temporal and spectral structure in the trace to wash out due to shot-to-shot jitter in the continuum intensity and phase.

Our measured trace had dimensions of 640×512, which we interpolated and expanded to 4096×4096 for retrieval. The measured TG XFROG trace is shown in Fig. 5. In our setup, the TG XFROG trace is mathematically equivalent to PG XFROG [13,14]. The PG XFROG algorithm retrieved the intensity and phase of the pulse from the measured trace in Fig. 6.

The retrieved temporal phase is mainly quadratic, in agreement with the slope of the TG FROG trace [10,13]. We observe fine structure in the retrieved trace and spectrum not present in the measured trace due to the washing-out effect mentioned earlier caused by averaging over more than one pulse. This type of fine structure, revealed after retrieving relatively smooth measured traces, was previously reported by our group, using multishot SFG XFROG measurements for SC generated from 152 cm microstructure fiber [8]. Like these earlier SC measurements, the explanation for the ability of the FROG algorithm to see the fine structure that we see is that information washed out in one domain remains in the frequency domain in these time-frequency measurements. This is a natural manner for time-frequency domain measurements to operate in. Although the fine structure in the time domain may be smeared out due to a long gate pulse, the large-scale information in the trace in the frequency domain suffices and vice versa because FROG traces contain much redundancy. In the independent-spectrum measurement, unlike a continuum from the microstructure fiber, on the other hand, we cannot see fine structure because the spatial chirp in the beam smears it out. Note that this trace smearing is not due to limited temporal or spectral resolution of our experiment.

Transverse geometrical smearing, which could limit the temporal resolution, is not present because we are spatially resolving the transverse geometrical relative delay in order to obtain the entire range of delays on a single shot. Unlike a single-shot SHG FROG measurement, however, TG FROG and PG FROG geometries do exhibit longitudinal geometrical smearing because the zero-delay point drifts transversely as the two pump beams and the continuum beam propagate through the potentially thick nonlinear medium. The amount of the longitudinal geometrical smearing, $\Delta\tau_{\text{long}}$, is given by $2L\tan(\theta)\sin(\theta)/c$, where L is the interaction length, θ is half the crossing angle, and c is the speed of light in the nonlinear medium [13]. In our TG XFROG setup, $\Delta\tau_{\text{long}}$, which is $\sim$50 fs, is smaller than the temporal resolution of our measurement, which was determined by the camera pixel size ($\sim$150 fs) and so is negligible. The camera resolution was limited by the need to achieve a single-shot XFROG geometry, which required that our camera allow a long delay range ($\sim$11 ps) to measure the resulting 8 ps continuum pulses. It is also worth mentioning that, in TG XFROG, longitudinal geometrical smearing could also smear the spectral resolution a bit, but it is also small compared with the spectral resolution in our set up. Indeed, the retrieved trace, even when reconverted to a 640×512 trace (the same as the measured trace), continues to show the structure, as it should. Note that the gate function in our experiment is $\sim$200 fs because our gate pulse is approximately this length, but, as mentioned, this does not limit our temporal resolution. Recall that a spectrogram can resolve information far below that length of the gate function due to the redundancy of the information present in it.

In this experiment, we use ~3 μJ pulse energy to generate SC and filter out the intense 800 nm portion of the spectrum. The SC pulse energy used for the measurement is less than 1 μJ. In other words, the sensitivity of our

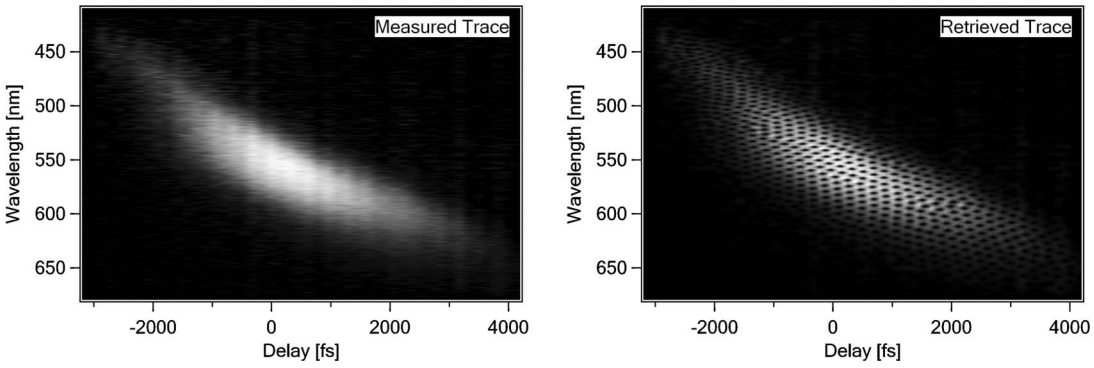

Fig. 5. Measured (left) and retrieved (right) TG XFROG traces for the measurement of the continuum from a 12.5 mm bulk fused silica.

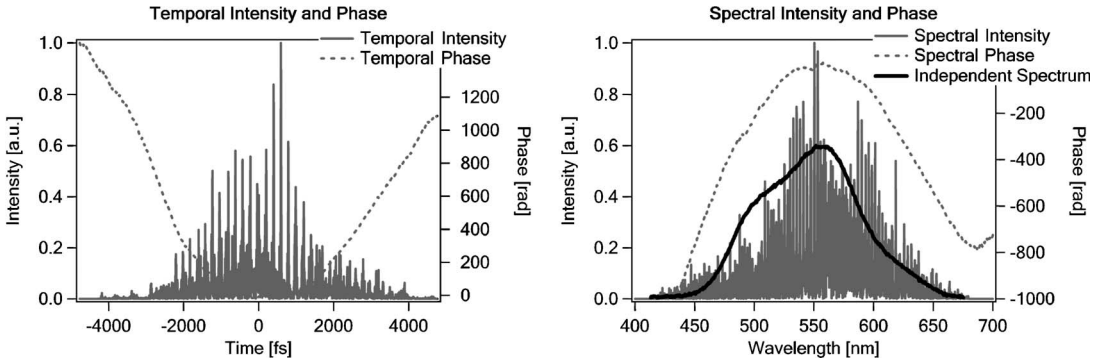

Fig. 6. Left temporal intensity and phase measured using TG XFROG. Right, retrieved spectral intensity and phase of the continuum pulse measured using TG XFROG and the independent spectrum (averaged over many shots) for comparison.

single-shot TG XFROG is ~1 μJ with ~200 fs, ~75 μJ pump pulses. To improve the sensitivity, it is natural to consider other FROG geometries, such as self-diffraction (SD) XFROG, PG XFROG, and SFG XFROG. However, without question, it is impossible to use a SD XFROG geometry because the process is not phase matched, so a very thin medium is required, significantly limiting efficiency. Also, as we mentioned above, because the TG XFROG signal is stronger than the PG XFROG signal by an order of magnitude, a TG geometry has better sensitivity than a PG geometry.

With a single-shot SFG XFROG geometry, in order to measure a SC pulse centered at 550 nm with more than 300 nm bandwidth, an extremely thin crystal would be required, which decreases the measurement sensitivity significantly. For example, if we assume a 100 fs, 100 μJ pump pulse and a 1 μm BBO crytal, which can phase match the SC, the sensitivity of the single-shot SFG XFROG is ~1 μJ, which would be comparable with that of the TG XFROG. Unfortunately, however, a 1 μm BBO crytal can not be obtained. Another option is surface SHG [15], which has an effective interaction length on the order of a wavelength. Use of extremely short interaction lengths of materials can phase match the broadband SC, but it seriously decreases the sensitivity. Worse, the nonlinear susceptibility for surface SHG is ~4 orders of magnitude smaller than that of BBO crystal [16]. We summarized the sensitivities and phase-matching bandwidths for various XFROG geometries in Table 1. Note that although, in a singe-shot SFG XFROG, the sensitivity improves only linearly with increasing pump pulse energy, pump energy improves the sensitivity of single-shot TG XFROG quadratically.

This measurement implies that it is possible to measure a pulse as complex as a continuum from a long microstructure fiber with a single-shot TG XFROG geometry. It is worth mentioning that the maximum time–bandwidth product (TBP) of our setup is ~75, so the device has the capability to measure fairly complex pulses. This number was calculated by taking the ratio of the temporal range and the temporal resolution (the spectral range over the spectral resolution was ~300 and so was not the limit).

4. DISCUSSION

It is natural to ask how one could improve our setup in other ways. Indeed, its main drawback was its insufficient efficiency to achieve true single-shot operation. However, this problem would be easily overcome in most modern labs with higher-power regenerative amplifiers. The intensity of the TG signal beam is proportional to the product of the intensities of the three beams (two are pump beams and the other is the continuum beam). That is $I_{TG} \sim I_{p_1} I_{p_2} I_c$ where I_{TG}, I_{p_i}, and I_c are the intensities of the TG signal, the pump, and the continuum, respectively. In this experiment, we estimate that the efficiency, I_{TG}/I_c, was ~5%, where I_c represents the intensity of the filtered continuum (after the main component of the continuum was filtered out). Therefore, in principle, a TG XFROG device such as ours can measure any continuum, even SC from a microstructure fiber, if the intensity of pump beams is sufficient. In this experiment, we used ~70 μJ and 210 fs pulses for two pump beams. However, 200 μJ pulses, perhaps also shorter than 200 fs long (this is common now), would yield an order of magnitude greater TG efficiency, easily sufficient to generate a strong TG signal beam from a single pulse. Indeed, slightly more energy would allow the measurement of ~2 nJ probe pulse energy, which is the typical pulse energy from microstructure fibers. With currently available regens, 5 mJ of pulse energy is available. However, in this case, crystal damage due to high peak energy of the pump beams will ultimately limit the efficiency.

In addition to this, it is certainly possible to improve the capacity of our setup to measure complex pulses. To

Table 1. Brief Summary of the Sensitivities and Phase-Matching Bandwidths of the Various Single-Shot XFROG Beam Geometries[a]

Geometry	Bulk SFG	Surface SFG	PG XFROG	TG XFROG
Nonlinearity	$\chi^{(2)}$	$\chi^{(2)}$	$\chi^{(3)}$	$\chi^{(3)}$
Nonlinear material	BBO	Al	ZnS	ZnS
Interaction length	~1 μm	~10 nm	3 mm	3 mm
Single-shot sensitivity	~1 μJ	>mJ	~10 μJ	~1 μJ
Phase-matching bandwidth	~300 nm	~Infinity	Infinity	~1.2 μm

[a]For the pump pulse, we assume an 800 nm, 100 fs, 100 μJ pulse. The sensitivity of the surface SFG XFROG is very rough because the nonlinearity varies with the material roughness [16].

do this, it would be necessary to increase the temporal and spectral ranges and the temporal and spectral resolutions. By expanding the size of the pump beam and using a higher-resolution camera, we could obtain a larger temporal range and a higher temporal resolution. However, the temporal resolution, which is limited by the longitudinal geometrical smearing, can only be smaller than 50 fs if the interaction length is limited by using a thinner nonlinear medium (which would limit the efficiency). As a result, the maximum temporal range and the highest temporal resolution our TG XFROG could have are 70 ps and 50 fs, respectively, and the best possible TBP is 1400. In this case, the spectral resolution would need to be improved to 0.2 nm in order to make the spectral range (300 nm) over the spectral resolution more than 1400. Increasing the size of the beams and/or using a larger grating angle, and hence the number of grating lines illuminated, would improve the spectral resolution to 0.2 nm.

5. CONCLUSIONS

We made preliminary measurements using a single-shot technique for measuring continuum from bulk fused silica. Our setup was only sensitive enough to yield a measurement if we integrated over several shots of a continuum generated in bulk material. However, we believe that this method could be used for true single-shot measurements of SC generated from microstructure fibers and any other continuum if the energy of the pump beams is sufficient. We believe that single-shot TG XFROG could be an important measurement technique for understanding the mechanisms of the SC generation.

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