**TIGER: TIme-Gated Electric field Reconstruction**

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Herein, a novel self-referenced method for the complete temporal characterization (phase and amplitude) of ultrashort optical laser pulses is presented. The technique, called Time-Gated Electric field Reconstruction (TIGER), measures a second-order nonlinear signal (namely, second-harmonic generation or two-photon absorption) produced by four time-delayed replicas of the input pulse. The delays are spatially encoded in the beam profile using a four-faced pyramidal-like optical element. The presented technique enables single shot measurement and does not require any spectral measurements, in contrast with well-known self-referenced characterization methods. Depending on the chosen geometry, the recorded TIGER signal can be either interferometric (i.e., carrier frequency resolved) or intensimetric. This article describes the principle operation of the device together with a detailed theoretical analysis. TIGER measurements of various laser pulse shapes with their reconstructions are then presented, demonstrating the relevance of this original approach.

1. Introduction

The advent of ultrashort laser sources several decades ago has opened a real breakthrough for observing ultrafast phenomena taking place at femtosecond and picosecond timescales and also for studying the behavior of matter submitted to very intense electromagnetic fields. The production of such ultrashort optical events, the shortest timescale ever produced at this time, has immediately raised the question of their measurements.\(^1\)\(^-\)\(^3\) Indeed, for many applications, the precise knowledge of the time-dependent phase and amplitude of the ultrashort laser pulse is of prime importance. Many self-referenced techniques, with varying experimental complexity and limitations, aiming at characterizing ultrashort laser pulses, have thus been developed.

Spectral Phase Interferometry for Direct Electric field Reconstruction (SPIDER)\(^3\)\(^-\)\(^5\) (resp. Self-Referenced Spectral Interferometry [SRSI])\(^6\) technique is based on the measurement of the spectral interferences between the pulse to be characterized and a replica that is both spectrally and temporally shifted (resp. a nonlinearly filtered replica). Frequency-Resolved Optical Gating (FROG)\(^7\) in all its variants, is based on a spectrally resolved measurement of a nonlinear signal produced by two time-delayed replicas. Chirp-scan\(^8\) (resp. Multiphoton Intrapulse Interference Phase Scan [MIIPS])\(^9\) technique relies on recording the spectrum of a nonlinear signal as a function of a linear frequency chirp (resp. sinusoidal frequency phase) applied to the input pulse. To the best of our knowledge, all the aforementioned techniques are based on spectrally resolved measurements. On the contrary, the presented Time-Gated Electric field Reconstruction (TIGER) technique is able to reconstruct the spectral characteristics (phase and amplitude) of a pulse from a pure time-domain signal, without the need of direct spectral measurements. The retrieval of spectral information by performing only measurements in the time domain has already been used in various branches of ultrafast optics. For instance, it is well known that recording the linear autocorrelation of a pulse (i.e., the signal intensity produced by two time-delayed replicas as the function of the delay) is sufficient to recover the pulse spectrum by a simple Fourier transform, without any need of a spectrometer. Another example of pure time-domain measurements is 2D nonlinear spectroscopy,\(^10\)\(^,\)\(^11\) which uses a sequence of more than two delayed pulses for probing the nonlinear response of the system under investigation. By Fourier transform, the full spectral characteristics of the system can then be retrieved. The method proposed in this article can be viewed as a direct application of 2D nonlinear spectroscopy. However, while 2D nonlinear spectroscopy is intended for the study of a sample provided that the laser pulse is known, the TIGER assumes a known (instantaneous) nonlinear response of the material while the pulse characteristics have to be determined. From the nonlinear signal produced by four time-delayed replicas, the TIGER enables a complete characterization (phase and amplitude) of ultrashort pulses by using a retrieval algorithm.

The article is organized as follows. In Section 2, the principle operation of the TIGER will be developed. First, the way by which four time-delayed pulses are generated will be explained. It will be shown, by geometrical optics calculations, that the use of a four-faced pyramid-like optical element allows to perform single shot measurements while making the device extremely compact. Then, the nonlinear signal produced by the four time-delayed replicas will be derived for both two-photon absorption and second-harmonic generation (SHG) mechanisms. In Section 3, experimental results will be presented for two distinct configurations. First, results recorded using two-photon absorption in
a silicon camera will be detailed. Such a measurement, providing an interferometric signal, enables the characterization of infrared pulses between 1.4 and 2.4 μm. Then, intensimetric TIGER measurements, obtained by using SHG from a Ti:sapphire (Ti:Sa) femtosecond laser, will be discussed. The experimental reconstructions show that the two configurations are very reliable.

2. General Concept

The TIGER technique relies on two basic principles: the creation of four identical temporally delayed subpulses from the pulse to be measured and the record of a second-order nonlinear optical effect with a camera. These two steps are, respectively, performed with a four-faced pyramid-like optical element and either by using the nonlinear response of a CCD camera or by imaging the second-harmonic signal generated in a nonlinear crystal on the camera. The combination of these two elements makes the TIGER extremely compact and particularly easy to align. Let us first present how the four-faced pyramid-like optical element allows to create four time-delayed replicas.

2.1. Geometrical Considerations

The TIGER is based on recording a nonlinear effect induced by four time-delayed replicas. In order to probe all delays in a single shot, a four-faced pyramid-like optical element (Figure 1a), whose geometry is defined by the diagonal apex angle $\Gamma$ (see Figure 1b,c), is introduced in the input beam path. The input face of the pyramid is placed perpendicularly to the beam propagation axis $Z$. The laser beam is sufficiently wide for illuminating the four faces of the pyramid. For each output face, defined by the indexes $(i = 0, 1; j = 0, 1)$ (see Figure 1b), the vector normal to the interface $n_{ij}$ is located in the diagonal plane and is given by

$$n_{ij} = \cos(\Gamma/2)u_{ij} + \sin(\Gamma/2)z$$

where $u_{ij} = [(\sqrt{2})X + (\sqrt{2})Y]/\sqrt{2}$ (see Figure 1b,c). After propagation through the pyramid, the input beam is split into four replicas. The output propagation directions of the replicas $k_{ij}$ are given by

$$k_{ij} = -\sin\theta_d u_{ij} + \cos\theta_d Z = \left(\frac{(-1)^{i+1} \sin\theta_d}{\sqrt{2}}\right) + \frac{(-1)^{i+1} \sin\theta_d}{\sqrt{2}} \cos\theta_d$$

where $\theta_d$ is the deviation angle that writes

$$\theta_d = \sin\left[n\sin\left(\frac{\pi - \Gamma}{2}\right)\right] - \frac{\pi - \Gamma}{2}$$

with $n$ defining the refractive index of the material composing the pyramid at the considered wavelength. Equivalently, the replicas are deviated from the horizontal plane by an angle $\delta_{ij} = (-1)^{j+1}\sin\left(\frac{\pi}{\sqrt{2}}\sin\theta_d\right)$ and by an angle $\alpha_{ij} = (-1)^{j+1}\tan\left(\frac{\pi}{\sqrt{2}}\tan\theta_d\right)$ with respect to $Z$ (see Figure 1d). After some propagation distance, the four replicas spatially overlap. However, the time at which they arrive depends on the spatial position in the plane $(x,y)$.

Using one of the replicas as a time reference, the three other replicas will arrive with delays $\tau_{1,3}$ that write

$$\tau_1 = \frac{\sqrt{2}\sin\theta_d}{c} x$$
$$\tau_2 = \frac{\sqrt{2}\sin\theta_d}{c} y$$
$$\tau_3 = \frac{\sqrt{2}\sin\theta_d}{c} (x + y)$$

where $c$ is the light velocity. Looking at Equation (4), one immediately notices that $\tau_1$ (resp. $\tau_2$) only depends on the $x$ (resp. $y$) coordinate while $\tau_3 = \tau_1 + \tau_2$. It implies that, at the propagation distance where the four beams overlapped, there is direct linear correspondence between the delays $(\tau_1, \tau_2)$ and the $(x,y)$ coordinates. The four-faced pyramid can then be viewed as a bidimensional extension of the Fresnel biprism, which is commonly used in single shot characterization devices for creating two time-delayed replicas in a single spatial dimension.[12,13]

2.2. Interferometric TIGER Signal

Following the results obtained above, at the plane where the four replicas are spatially superimposed, the total electric field can be written as $E(x, y, t, \tau_1, \tau_2) = e_1(x, y, t) + e_2(x, y, t - \tau_1) + e_3(x, y, t - \tau_2) + e_4(x, y, t - \tau_1 - \tau_2) + \ldots$, where $e_i(t) = A_i(x, y, t)e^{\text{ik}x}$ is the complex field at central frequency $\omega_0$ coming from the $i$th face of the pyramid. For the following, it will be assumed that the four beams are perfectly balanced and

![Figure 1](https://www.advancedsciencenews.com/fig1.png)
that the field is sufficiently homogeneous in space for neglecting its spatial variation, i.e., \( A_1(x, y, t) = A_2(x, y, t) = A_3(x, y, t) = A_4(x, y, t) = A(t) \). Using either SHG in a nonlinear crystal or two-photon absorption in a camera, the signal \( S(\tau_1, \tau_2) \) reads

\[
S(\tau_1, \tau_2) \propto \int |E^2(t, \tau_1, \tau_2)|^2 dt
\]

(5)

After cumbersome but straightforward calculations, one obtains that \( S \) can be written as the sum of 25 bidimensional distributions (whatever the pulse shape) oscillating around \( S \) real-valued even function (with respect to both \( \omega \) and \( \tau \)).

\[
S(\tau_1, \tau_2) \propto \sum_{m,n=0,\pm 1,\pm 2} S_{m,n}(\tau_1, \tau_2),
\]

(6)

with \( S_{m,n}(\tau_1, \tau_2) = F_{m,n}(\tau_1, \tau_2)e^{-i\omega_0(m\tau_1+n\tau_2)} \), where \( F_{m,n} \) are slowly varying 2D functions. Figure 2a shows a typical TIGER signal numerically calculated with Equation (5) for a 1.5 \( \mu \)m Gaussian 30 fs Fourier-limited (FTL) laser pulse while Figure 2b shows its bidimensional Fourier transform. As described above, the 2D Fourier transform of \( S \), \( \tilde{S}(\omega_1, \omega_2) \), indeed embeds 25 distinct contributions. Moreover, one can point out that \( S(\tau_1, \tau_2) \) is a real-valued even function (with respect to both \( \tau_1 \) and \( \tau_2 \)) and that the two variables \( \tau_1 \) and \( \tau_2 \) can be permuted. These properties indicate that the knowledge of only 6 contributions over the 25 (namely, \( S_{0,0}, S_{1,0}, S_{1,1}, S_{2,0}, S_{2,1}, \) and \( S_{2,2} \) ) is sufficient for recovering the full signal. After recording the full TIGER signal, each of these components can be isolated by an appropriate bidimensional spectral filtering. It is interesting to detail the analytical formula for some of the contributions. For instance, one has

\[
F_{2,0}(\tau_1, \tau_2) = 2 \int A^2(t)A^2(t-\tau_1)dt
\]

+ \( 4 \int A(t)A(t-\tau_1)A(t-\tau_2)A(t-\tau_1-\tau_2)dt \)

(7)

\[
F_{2,1}(\tau_1, \tau_2) = 2 \int A^2(t)A^2(t-\tau_1)A^2(t-\tau_1-\tau_2)dt
\]

+ \( 2 \int A(t)A(t-\tau_2)A^2(t-\tau_1-\tau_2)dt \)

(8)

As a consequence, one has

\[
\tilde{S}_{2,0}(\omega_1, \omega_2) = 4 \int A(t)A(t-\tau_2)e^{i(\omega_1-2\omega_2)\tau_2}dt
\]

\[
+ 2 \int A^2(t)e^{i(\omega_1-2\omega_2)\tau_2}dt \]

(10)

which is nothing but the expression of the well-known SHG-FROG signal. The fact that the SHG-FROG signal is embedded in the TIGER signal indicates that this technique is able to fully characterize an ultrashort laser pulse. Finally, one can also express the Fourier transform of \( S_{2,1} \) along the first dimension

\[
\tilde{S}_{2,1}(\omega_1, \tau_2) = 4e^{-i\omega_2\tau_2}\mathcal{R} e[\tilde{K}(\omega_1, \tau_2)e^{i(\omega_1-2\omega_2)\tau_2}],
\]

(12)

with

\[
\mathcal{K}(\omega_1, \tau_2) = \left( \int A^2(t)e^{i(\omega_1-2\omega_2)\tau_2}dt \right)^*
\]

\[
\times \int A(u)A(u-\tau_2)e^{i(\omega_1-2\omega_2)u}du
\]

(13)

Figure 3a,b shows the contributions \( \tilde{S}_{2,0} \) and \( \tilde{S}_{2,2} \) extracted from the full TIGER signal displayed in Figure 2a by an appropriate 2D spectral filtering. Figure 3c displays the associated SHG-FROG signal obtained from Figure 3a,b using Equation (11). Finally, Figure 3d displays the absolute value of \( \tilde{S}_{2,1} \) also retrieved from Figure 2a. To conclude, the

**Figure 2.** a) Theoretical TIGER signal calculated with Equation (5) for a 1.5 \( \mu \)m Gaussian 30 fs FTL laser pulse and b) its 2D Fourier transform.
interferometric TIGER signal embeds all necessary information for fully characterizing an ultrashort laser pulse. So as to retrieve the pulse amplitude and phase, one has to use an iterative algorithm so as to fit the map signal. However, considering that the full TIGER interferometric pattern is not mandatory for characterizing a pulse, one can choose to retrieve the pulse characteristics from one specific component of the signal. In particular, one can choose to use the contribution $S_{2,0}$ (namely, the one containing the FROG information), but it appears that this contribution is not background-free (along $\tau_2$) which is a main drawback. The background theoretically corresponds to twice the absolute value of the $S_{2,2}$ contribution so that one could be tempted to extract it by subtracting from $S_{2,0}$ the contribution calculated from $S_{2,2}$ (as shown in Equation (11)). However, from an experimental point of view, as measurements inevitably include noise that differs for the two contributions, this strategy appears not to be very convenient. As a consequence, we chose to use the contribution $S_{2,1}$ in order to retrieve the temporal and spectral characteristics of the pulse. This contribution has the advantage to be inherently background-free. Figure 4 displays the signal $S_{2,1}$ for different spectral phase (Figure 4a,b) or amplitude (Figure 4c,d) modulations applied to a 30 fs laser pulse. The clear phase and amplitude sensitivity of the obtained pattern clearly confirms that this contribution can be used for the retrieval procedure.

Figure 5a depicts the typical experimental setup for measuring the interferometric TIGER signal in the case where direct two-photon absorption in a camera can be used. This is possible if the energy bandgap of the semiconductor is comprised between one and two times the photon energy. For instance, with a silicon camera, this is possible for laser central wavelengths comprised between around 1.4 and 2.4 $\mu$m. Figure 5b shows the typical experimental TIGER setup if SHG is used as a nonlinear effect. When the four replicas nonlinearly interact within the SHG crystal, second-harmonic radiations are generated along nine distinct directions. The interferometric TIGER signal is then obtained by imaging the SHG crystal with a lens that collects all the nine radiations and a dichroic filter placed before the camera rejects the fundamental radiation. However, as noticed just before, recording the full interferometric TIGER signal is not necessary for the complete temporal characterization of a pulse. In the next section, an all-optical method for obtaining an intensimetric TIGER signal will be presented in the case where SHG is used as a nonlinear process.

### 2.3. Intensimetric TIGER Signal in case of SHG

As explained in the previous section, using SHG as a nonlinear process leads to generate second-harmonic radiations propagating along nine distinct directions. This can be easily understood by analyzing the direction of the wavevectors of the four pump pulse replicas. Each second-harmonic radiation, propagating along a particular direction, can then be easily optically isolated by placing an iris diaphragm in the Fourier plane of the imaging lens (see Figure 5c). In particular, a part of second-harmonic radiations are generated along nine distinct directions. The interferometric TIGER signal is then obtained by imaging the SHG crystal with a lens that collects all the nine radiations and a dichroic filter placed before the camera rejects the fundamental radiation. The signal $S$ induced by this contribution alone (i.e., after filtering the eight other contributions in the Fourier plane) recorded with a camera in the image plane of the imaging lens reads

$$S(\tau_1, \tau_2) \propto \int |A(t)A(t-\tau_1-\tau_2) + A(t-\tau_1)A(t-\tau_2)|^2 dt \quad (14)$$

According to Equation (14), the signal recorded this way is intensimetric, i.e., the fast oscillating components within the

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Figure 3. a) Contribution $S_{2,0}$ and b) $S_{2,2}$ obtained after a 2D Fourier filtering of the full interferometric TIGER signal. c) Background-free FROG measurement obtained from (a,b) using Equation (11). d) Contribution $S_{2,1}$ obtained after a 2D Fourier filtering of the full interferometric TIGER signal.

Figure 4. a) Modulus of the contribution $S_{2,1}$ for a 30 fs laser pulse with 1000 fs$^2$ group delay dispersion and b) with 50 000 fs$^3$ third-order dispersion. Contribution $S_{2,1}$ for two 30 fs c) in-phase and d) out-of-phase pulses separated by 60 fs.
TIGER signal vanish. One can also notice that the signal embeds a background signal occurring along the two diagonals defined by \( \tau_1 = \tau_2 \) and \( \tau_1 = -\tau_2 \). Moreover, for \( \tau_1 = 0 \) (or \( \tau_2 = 0 \)), the intensimetric TIGER signal is proportional to the second-order pulse autocorrelation trace. Figure 6 shows three different examples of intensimetric TIGER signal. Figure 6a corresponds to the signal calculated for a 30 fs [at full width at half maximum (FWHM)] FTL pulse, while Figure 6b corresponds to the one calculated for the same pulse but chirped to 100 fs (FWHM). Finally, Figure 6c corresponds to the TIGER signal obtained for two 30 fs FTL pulses separated by 100 fs. The three TIGER maps show noticeable modifications. One has to note that the TIGER exhibits the same indeterminacy as all FROG devices based on a second-order nonlinear process. For instance, the TIGER signal cannot determine the sign of the spectral phase because a negatively chirped pulse provides exactly the same signal as a positively chirped one. In addition, unlike the interferometric method where the fringes give access to the absolute carrier frequency, one cannot determine the central frequency of the laser pulse in case of intensimetric measurement. Intensimetric SHG-TIGER has nevertheless the advantage to release optical constraints imposed by the need to resolve the optical fringes produced by the interferometric method.

3. Results

In this section, the TIGER devices and experimental pulse characterizations for two different configuration are detailed. First, interferometric measurements obtained for a 70 fs noncollinear optical parametric amplifier (NOPA) pumped by a 100 fs Ti:Sa femtosecond laser and emitting between 1.4 and 2.4 \( \mu m \) are presented. Then, intensimetric SHG-TIGER measurements, recorded with a 35 fs 800 nm Ti:Sa femtosecond laser, are discussed.

3.1. Interferometric Two-Photon Absorption Measurements

3.1.1. Experimental Setup

As the central wavelength of the pulses emitted by the NOPA is between 1.4 and 2.4 \( \mu m \), two-photon absorption signal in a silicon (bandgap \( \approx 1.1 \) eV) camera can be used for recording the TIGER signal. Recording an interferometric TIGER signal implies a spatial resolution of the fast oscillations present within the signal. According to above calculations, the fastest oscillations within the signal have a carrier frequency located around \( 2\omega_0 \). From Equation (4) and following the Nyquist theorem, this implies

![Figure 5](image-url)  
Figure 5. a) Two-photon absorption and b) SHG-based interferometric TIGER apparatus. c) Intensimetric TIGER signal using SHG. In this case, an iris diaphragm is placed in the Fourier plane of the imaging lens so as to select only the second-harmonic radiation propagating along the z direction.

![Figure 6](image-url)  
Figure 6. Intensimetric TIGER signal for a) a 30 fs Fourier-transform limited pulse, b) a 30 fs pulse chirped to 100 fs, and c) two 30 fs Fourier-transform limited pulses separated by 100 fs.
The central wavelength of the laser pulse, we use the contribution $S_{2,1}$, which is background-free and therefore less sensitive to the spatial noise. For the retrieval procedure, the signal $S_{2,1}(\omega_1, \tau_2)$ is then undersampled on a $64 \times 64$ frequency-temporal grid and a commercial Levenberg–Marquardt-based fit algorithm is used for retrieving both amplitude and phase of the field in the spectral domain. The algorithm then evaluates the signal according to Equation (8) and minimizes the mean squared error between the experimental signal and the retrieved one.

The results of the retrieval by the algorithm is displayed in Figure 9. The retrieval errors for all presented measurements are approximatively $10^{-4}$. The retrieved pulse has a duration (at FWHM) of approximately 70 fs with a small residual group delay dispersion (around $\pm 370 \text{fs}^2$). In order to test our device, a 1.8 cm-thick fused silica plate is inserted before the TIGER. The results of the retrieval procedure are shown in Figure 10. In this case, the pulse is found to be slightly longer (about 78 fs) with a residual group delay dispersion of $\pm 872 \text{fs}^2$. The group delay dispersion introduced by the plate is then evaluated to be approximately $1240 \text{fs}^2$ (in absolute value), close the theoretical group delay dispersion of fused silica ($-1130 \text{fs}^2$) at the considered wavelength. This observation demonstrates the sensitivity of the TIGER method with respect to the spectral phase of the pulse. In order to also check its sensitivity with respect to the spectral amplitude adequately, a sequence of two FTL pulses separated by 140 fs is produced by using a calibrated multiple order waveplate and a polarizer. Figure 11 shows the obtained results. The TIGER successfully reconstructs the field amplitude spectrum, which is characterized by a sinusoidal modulation of the amplitude along with a sequence of $\pi$-steps for the spectral phase. In the time domain, the retrieval process correctly reproduces the two pulses separated by 140 fs.

In order to retrieve the spectral phase and amplitude of the laser pulse, we use the contribution $S_{2,1}$, which is background-free and therefore less sensitive to the spatial noise. For the retrieval procedure, the signal $S_{2,1}(\omega_1, \tau_2)$ is then undersampled on a $64 \times 64$ frequency-temporal grid and a commercial Levenberg–Marquardt-based fit algorithm is used for retrieving both amplitude and phase of the field in the spectral domain. The algorithm then evaluates the signal according to Equation (8) and minimizes the mean squared error between the experimental signal and the retrieved one.

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where $dx$ is the pixel size of the camera. For this experiment, we used a 12 bit CMOS camera with pixel size $dx = 1.67 \mu m$. Figure 7a shows the deviation angle $\theta_d$ as a function of the diagonal apex of the pyramid $\Gamma$ and b) related resolution for a pixel size $dx = 1.67 \mu m$.

$$\frac{\sqrt{2}\sin\theta_d}{c} dx < \frac{\pi}{2\omega_0}$$

(15)

3.1.2. Experimental Results

The first experiment was devoted to the characterization of the pulses directly coming from the NOPA. The central wavelength was set to $\lambda_0 = 1.8 \mu m$. An energy of approximatively 1 µJ is used for performing single shot measurements. Note that this energy level is the same than the one needed for commercial single-shot FROG devices. Figure 8a shows a typical interferometric signal recorded in this case. The corresponding bidimensional Fourier transform is depicted in Figure 8b. After an adequate spectral filtering, the corresponding contributions $S_{2,0}$ and $S_{2,1}$ can be isolated (see Figure 8c,d).

In order to retrieve the spectral phase and amplitude of the laser pulse, we use the contribution $S_{2,1}$, which is background-free and therefore less sensitive to the spatial noise. For the retrieval procedure, the signal $S_{2,1}(\omega_1, \tau_2)$ is then undersampled on a $64 \times 64$ frequency-temporal grid and a commercial Levenberg–Marquardt-based fit algorithm is used for retrieving both amplitude and phase of the field in the spectral domain. The algorithm then evaluates the signal according to Equation (8) and minimizes the mean squared error between the experimental signal and the retrieved one.

The results of the retrieval by the algorithm is displayed in Figure 9. The retrieval errors for all presented measurements are approximatively $10^{-4}$. The retrieved pulse has a duration (at FWHM) of approximately 70 fs with a small residual group delay dispersion (around $\pm 370 \text{fs}^2$). In order to test our device, a 1.8 cm-thick fused silica plate is inserted before the TIGER. The results of the retrieval procedure are shown in Figure 10. In this case, the pulse is found to be slightly longer (about 78 fs) with a residual group delay dispersion of $\pm 872 \text{fs}^2$. The group delay dispersion introduced by the plate is then evaluated to be approximately $1240 \text{fs}^2$ (in absolute value), close the theoretical group delay dispersion of fused silica ($-1130 \text{fs}^2$) at the considered wavelength. This observation demonstrates the sensitivity of the TIGER method with respect to the spectral phase of the pulse. In order to also check its sensitivity with respect to the spectral amplitude adequately, a sequence of two FTL pulses separated by 140 fs is produced by using a calibrated multiple order waveplate and a polarizer. Figure 11 shows the obtained results. The TIGER successfully reconstructs the field amplitude spectrum, which is characterized by a sinusoidal modulation of the amplitude along with a sequence of $\pi$-steps for the spectral phase. In the time domain, the retrieval process correctly reproduces the two pulses separated by 140 fs.

$$\frac{\sqrt{2}\sin\theta_d}{c} dx < \frac{\pi}{2\omega_0}$$

(15)
3.2. Intensimetric SHG Measurements

Despite its extreme simplicity, the two-photon absorption-based interferometric TIGER is limited to a given spectral range depending on the material composing the pixel of the camera. For central wavelength ranging from 1.4 to 2.4 μm, a simple silicon camera can be used, as shown in the above section. For central wavelengths ranging from approximately 1.7 to 3.4 μm, a camera with InGaAs-based pixels could be used. If one wants to extend the concept to lower wavelengths, to the best of our knowledge, no bidimensional sensor with sufficiently small pixels and allowing two-photon absorption is yet so far available. In order to generalize the concept for lower wavelengths, a SHG-based TIGER was developed. As explained in Section 2.3, recording the full interferometric signal is not mandatory for retrieving the temporal and spectral characteristics of the pulse. The advantage of using an intensimetric approach in this case is to lift the necessity to spatially resolve the interference fringes, which can be somehow challenging when using an imagery optical system. This section describes the experimental setup and the experimental results obtained with the SHG-based intensimetric TIGER setup.

3.2.1. Experimental Setup

Figure 5c shows the principle of the experimental setup developed for characterizing our 35 fs Ti:Sa laser pulse. The diagonal apex of the pyramid is 160°. The SHG crystal is a 50 μm-thick BBO. The imaging lens is a f = 3 cm focal length biconvex lens placed at a distance 2f. After the lens, an iris diaphragm is placed in the Fourier plane (i.e., at a distance f after the lens) so as to select only the second-harmonic radiation that propagates along the z axis. Then, the camera is placed at 4f from the crystal. In the case of intensimetric measurements, one has to calibrate the magnification of the imaging system, which was not the case with the interferometric two-photon absorption-based setup. So as to calibrate the magnification of the imaging system, a bipulse (two identical pulses separated by 140 fs) was created by using a calibrated multioorder waveplate and a polarizer. In this case, three lobes separated by Δτ₁ = 140 fs are expected at τ₂ = 0 (and vice versa). It then allows to find the space–time calibration coefficient for our setup. Figure 12a shows the experimental TIGER signal obtained with this temporal shaping. The retrieved TIGER signal is displayed in Figure 12b, while the temporal intensity profile (resp. spectral intensity and phase)

Figure 9. a) Experimental signal Ŝ_{21}(ω₁, τ₂) and b) retrieved signal for the laser pulse (λ₀ = 1.8 μm) coming from the NOPA. Retrieved c) spectral intensity and d) phase. Retrieved e) temporal intensity profile and f) phase.

Figure 10. a) Experimental signal Ŝ_{21}(ω₁, τ₂) and b) retrieved signal for the laser pulse (λ₀ = 1.8 μm) after propagation within a 1.8 cm fused silica plate. Retrieved c) spectral intensity and d) phase. Retrieved e) temporal intensity profile and f) phase.
is shown in Figure 12c (resp. Figure 12d). As shown, the fitting procedure successfully retrieves the temporal and spectral characteristics of the laser pulse. Again, the present configuration successfully reconstructs the sinusoidal modulation of the amplitude along with the sequence of \(\pi\)-steps for the spectral phase, demonstrating the sensitivity of the measurement with respect to both spectral phase and amplitude.

### 3.2.2. Experimental Results

We then use the intensimetric TIGER device for characterizing the output laser pulse. An input pulse energy of approximately 1.2 \(\mu\)J was used for single shot operation. This energy is of the same order as the typical energy needed with commercial single shot FROG devices. The detection limit of our device was approximately 50 nJ when integrating over several pulses at the repetition rate of our laser (1 kHz). Figure 13 shows the final outputs of the measurements. The pulse duration is found to be approximately 34 fs, close to the FTL limit. This observation is in good agreement with the relatively flat spectral phase observed in the retrieved spectral field in Figure 13d.

Finally, another measurement has been done by putting in the laser beam path a 5 mm-thick SF11 plate, introducing a calibrated group delay dispersion of 950 fs\(^2\). The measurement and retrieval are shown in Figure 14. As shown, the phase retrieved by the TIGER is again in very good agreement with the expectation.
mid-like optical element for generating four time-delayed pulses could also be used for performing single shot 2D spectroscopy experiment.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

femtosecond laser pulse, pulse characterization, second-harmonic generation

4. Conclusion

In this article, an original device enabling a single shot and full characterization of ultrashort laser pulses is presented. Unlike all other existing techniques, the TIGER device does not use any spectral measurement. Instead, the device is based on recording a second-order nonlinear effect created by four time-delayed replicas of the pulses to be measured. These replicas are generated by inserting a four-faced pyramid-like optical element that converts the two transverse directions in two independent time delays. After describing the general principle operation of the device, theoretical and experimental results using two-photon absorption performed directly in the camera sensor were presented. This approach, which is relevant for the characterization of infrared laser pulses, is limited in terms of wavelength range. We have therefore shown (both theoretically and experimentally) that SHG can also be exploited. In this case, the signal can be filtered by a spatialFourier filtering. The performance of the overall setup for the pulse reconstruction is of high quality for both configurations. The device is extremely compact and easy to align. It does not require any spectrometer or imaging spectrometer and the intensimetric configuration only needs a relatively low resolution camera. Finally, it is worth to emphasize that the four-faced pyramid-like optical element for generating four time-delayed pulses

Figure 14. a) Experimental and b) retrieved SHG-based intensimetric TIGER signal after propagation through a 5 mm SF11 plate. c) Retrieved temporal intensity profile. d) Retrieved spectral intensity (solid blue) and phase (dashed-dotted line). The red solid line in (d) corresponds to the theoretical phase introduced by the SF11 plate.

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