

Characterization of Ultrashort Laser Pulses Using Frequency-Resolved Optical Gating (FROG)

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Abstract:

Frequency-Resolved Optical Gating (FROG) is a key technique in nonlinear optics, providing comprehensive spatiotemporal characterization of ultrashort laser pulses, including both intensity and phase. By spectrally resolving a nonlinear autocorrelation trace into a spectrogram, FROG overcomes the limitations of conventional intensity-only measurements. Through iterative phase retrieval, FROG extracts critical parameters such as pulse duration, chirp, and temporal structure with sub-femtosecond precision. Its versatility makes it indispensable in ultrafast science, supporting applications from attosecond spectroscopy to ultrafast laser development. In this paper we are interested to characterize the pulse with width duration : 20 fs, 10 fs and 5 fs using a FROG technique. We showed that each pulses duration presents unique challenges and opportunities for characterization. Using 20 fs pulse simulations require less computational power due to relatively slower dynamics, allowing for quicker retrieval with less sensitivity to noise. With 10 fs pulse is more detailed simulations needed to account for broad bandwidth and potential nonlinear effects. Then using 5 fs pulse require the most detailed and computationally intensive simulations, particularly to mitigate noise and account for rapid phase changes.

1. Frequency-Resolved Optical Gating (FROG)

1.1. Definition

The all-optical pulse characterization techniques discussed earlier overcome the technological limitations of electronics, enabling intensity and phase measurements of ultrashort pulses that conventional detectors cannot resolve temporally. However, none of these methods have been adapted for ultrahigh-repetition-rate pulses in telecom applications, and few offer sufficient sensitivity. In parallel, Frequency-Resolved Optical Gating (FROG) techniques have been extensively developed and generalized to high-repetition-rate pulse trains. It is thus natural to extend such systems to Telecom applications, particularly Second-Harmonic Generation FROG (SHG-FROG).

1.2. Principle

The general principle involves correlating the pulse under test with a variable-delay gate function. By adjusting the delay between the gate and the pulse, a nonlinear process (e.g., second-harmonic generation) selects a portion of the pulse, and the resulting spectrum is recorded.

Varying the gate delay allows analysis of successive pulse slices, constructing a spectrogram (or FROG trace) in a delay-frequency representation [1–6]:

$$S(\omega, \tau) = \left| \int_{-\infty}^{+\infty} E(t) g(t - \tau) e^{-i\omega t} dt \right|^2 \quad (1)$$

Here, $g(t - \tau)$ is the gate function, $E(t)$ the pulse electric field, τ the delay, and ω the frequency.

This spectrogram is a smoothed version of the Wigner distribution of the input pulse. Critically, the spectral evolution with delay encodes both intensity and phase information via $E(t)$. The challenge lies in retrieving $E(t)$ from $S(\omega, \tau)$.

Since an independent gate is rarely available, FROG systems duplicate the pulse and use the replica as the

gate (fig.1). Thus, FROG autocorrelates the pulse while spectrally resolving the signal for each delay τ via an optical spectrum analyzer (OSA) [7-9].

For a nonlinear signal $E_{\text{sig}}(t, \tau)$, the spectrogram becomes:

$$S_{\text{FROG}}(\omega, \tau) = \left| \int_{-\infty}^{+\infty} E_{\text{sig}}(t, \tau) e^{-i\omega t} dt \right|^2 \quad (2)$$

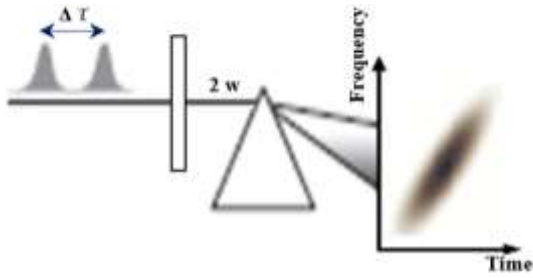


Figure 1. Illustrative diagram of the FROG system: Two replicated pulses, with a delay τ , are sent through a doubling crystal. The resulting signal is spectrally dispersed and recorded as a function of τ and frequency.

For SHG-FROG, where $E_{\text{sig}}(t, \tau) = E(t)E(t - \tau)$, the trace takes the form:

$$S_{\text{FROG}}^{\text{SHG}}(\omega, \tau) = \left| \int_{-\infty}^{+\infty} E(t) E(t - \tau) e^{-i\omega t} dt \right|^2 \quad (3)$$

Retrieving $E(t)$ is nontrivial because the gate is as unknown as the pulse. However, while 1D Fourier problems have infinite solutions, the 2D nature of FROG constraints (e.g., $E_{\text{sig}}(t, \tau) = E(t)E(t - \tau)$ for SHG) enables unique solutions via iterative algorithms. The retrieved pulse's validity is assessed by comparing experimental and reconstructed FROG traces using mean squared error (MSE).

However, the problem remains to determine $E(t)$, since the gate is as poorly known as the pulse. We therefore need a way to retrieve the phase and intensity of $E(t)$. By denoting the Fourier transform of $\tilde{E}_{\text{sig}}(t, \tau)$ is the Fourier transform of $E_{\text{sig}}(t, \tau)$ with respect to τ , the spectrogram's intensity becomes [10]:

$$S(\omega, \tau) = \left| \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \tilde{E}_{\text{sig}}(t, \Omega) \exp(i\omega t + i\Omega \tau) dt d\Omega \right|^2 \quad (4)$$

where Ω represents the Fourier conjugate variable of the delay τ . From this last expression, it becomes clear that the measured quantity can be understood as the squared amplitude of the two-dimensional Fourier transform of $\tilde{E}_{\text{sig}}(t, \Omega)$. It can easily be shown that once $E_{\text{sig}}(t, \Omega)$ is known, it directly

yields the electric field of the input pulse (t). Indeed, $E(t) = E_{\text{sig}}(t, \Omega = 0)$.

Fortunately, unlike the one-dimensional problem, where there is an infinite number of solutions associating a function with a known Fourier transform, the problem becomes solvable in a two-dimensional space under certain assumptions.

In the case of pulse characterization, the additional information that allows for solving the problem comes from the knowledge of the mathematical form of $E_{\text{sig}}(t, \tau)$, and thus of $\tilde{E}_{\text{sig}}(t, \Omega)$, as for example in a SHG-FROG system where $E_{\text{sig}}(t, \tau) = E(t)E(t - \tau)$ is known. In practice, the inversion is performed using an iterative algorithm that searches for the physical signal corresponding to the experimental FROG trace while satisfying the imposed mathematical constraints. The relevance of the retrieved pulse can then be assessed by calculating the mean square difference between the experimental FROG trace and the trace recalculated from the found field. Additional experimental data, such as autocorrelation functions and optical spectra, also help to ensure the validity of the procedure [11-14].

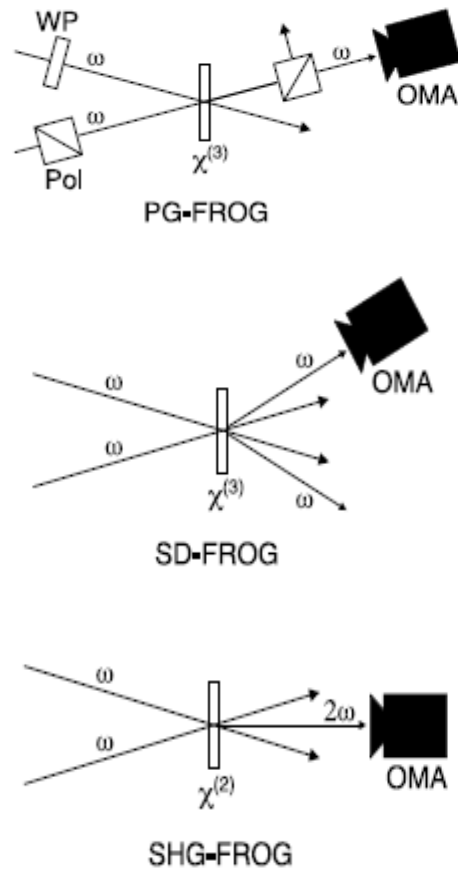


Figure 2. Three different FROG geometries: PG-FROG and SD-FROG use third-order nonlinearity, whereas SHG-FROG is based on second-order nonlinearity.

1.3 FROG beam geometry

The nonlinear interaction used in the FROG device determines the exact shape of the FROG trace (fig.2): Polarization Gate (PG), Stimulated Diffraction (SD), and Second Harmonic Generation (SHG). These three geometries utilize the interaction between two replicated pulses [15].

The shape of the field in equation 2 depends on the FROG geometry; for example, for PG-FROG, we obtain:

$$E_{sig}^{PG}(t, \tau) = E(t)|E(t - \tau)|^2 \quad (5)$$

Whereas in SD-FROG, the field signal is:

$$E_{sig}^{SD}(t, \tau) = E^2(t)|E^*(t - \tau)|^2 \quad (6)$$

And for SHG-FROG, we have :

$$E_{sig}^{SHG}(t, \tau) = E(t) E(t - \tau) \quad (7)$$

The most sensitive FROG technique is SHG-FROG, which is based on second-order nonlinear interaction. This variant of FROG will be discussed in detail.

1.4 Second Harmonic Generation FROG

The second harmonic generation FROG (SHG-FROG) is simply the FROG geometry demonstrated so far using second-order nonlinearity. This low order makes the SHG-FROG the most sensitive of all the other FROG geometries (fig.3). As a result, SHG-FROG is desired for the characterization of low-energy pulses from an oscillation system.

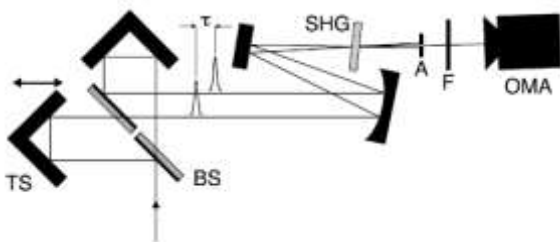


Figure 3. SHG-FROG System: The experimental setup used in SHG-FROG is identical to that of the intensity autocorrelator. The only difference is that the detector is replaced by a spectrometer. (BS, beamsplitter; TS, motorized translation stage; SHG, second-order nonlinear medium; A, aperture; F, filter; OMA, spectrometer).

2. Pulse Retrieval Algorithm

2.1. Principle of Generalized Projections

Among the different algorithms capable of retrieving the field $E(t)$ from its FROG trace, those based on

the principle of "generalized projections" stand out for their reliability. Starting from a given FROG trace, the goal of the algorithm is to find, through successive iterations, the field $E(t)$ that led to this representation. Two types of convergence constraints are then employed for the convergence of the algorithm [16]: First, the experimental data, of course. The recorded trace $E_{FROG}^{SHG}(w, \tau)$ must correspond to the square modulus of the Fourier transform with respect to t of the signal found, $E_{sig}(t, \tau)$.

$$S_{FROG}^{EXP}(w, \tau) = \left| \int_{-\infty}^{+\infty} E_{sig}(t, \tau) e^{i.w.t} dt \right|^2 \quad (8)$$

Then, the nonlinear process imposed by the experimental setup. The signal $E_{sig}(t, \tau)$ retrieved from the FROG trace must be able to be generated from a physical field $E(t)$ through the chosen nonlinear process (see next section), for example [16]:

$$E_{sig}(t, \tau) \propto \begin{cases} E(t)E(t - \tau) \\ E(t)E(t - \tau)^2 \\ E(t)^2 E^*(t - \tau) \\ E(t)|E(t - \tau)|^2 \end{cases} \quad (9)$$

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Where:

$E(t)E(t - \tau)$ FROG with second harmonic generation

$E(t)E(t - \tau)^2$ FROG with third harmonic generation

$E(t)^2 E^*(t - \tau)$ FROG with induced diffraction

$E(t)|E(t - \tau)|^2$ FROG with optical gate

The objective of the algorithm is thus to determine, for a given experimental FROG trace, the correlation field $E_{sig}(t, \tau)$ that simultaneously satisfies the two constraints imposed by equations (8) and (9). The principle of generalized projection techniques is graphically illustrated in Fig. 4. As for the functions that satisfy the constraint of the experimental data, they form another set, represented in the lower part of the diagram. The solution $E_{sig}(t, \tau)$ is found at the intersection of these two sets and thus directly provides the field $E(t)$ of the pulse to be characterized.

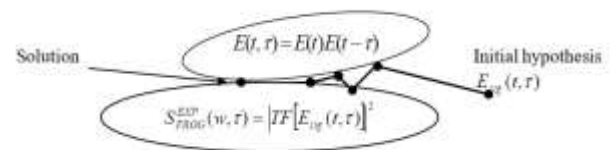


Figure 4. Principle of generalized projections used in the iterative algorithm of the FROG system.

2.2. Iterative algorithm [14]

The experimental FROG trace is recorded discretely with respect to the delay and frequency (typically 128×128 points or 256×256 points). The complex quantities manipulated are defined for discrete values of time and frequency : t_i, τ_j, f_i with $i=1, \dots, N, j=1, \dots, N$. To describe the generalized projection procedure, the envelope of the pulse will thus be written as $E^{(K)}(t_i)$ that of the correlation signal obtained through the nonlinear process $E_{sig}^{(K)}(t_i, \tau_j)$ and its Fourier transform $\tilde{E}_{sig}^{(K)}(f_i, \tau_j)$ (1)(12) with respect to time. The exponent (k) indicates that these different quantities are obtained after the k – th iteration of the algorithm. The principle of this algorithm is illustrated in the following Fig. 5.

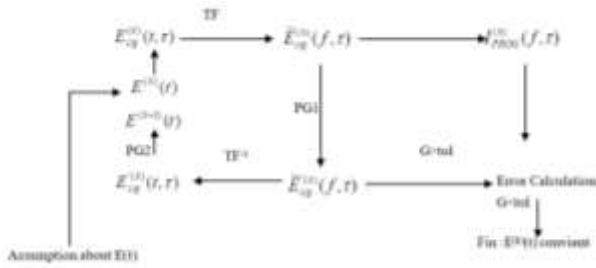


Figure 5. Diagram of the iterative algorithm used in a FROG system based on generalized projections

Starting from an initial hypothesis $E(t)$ for the pulse field, the program calculates the correlation signal corresponding to the chosen nonlinear process ($E(t)E(t - \tau)$ if SHG-FROG). The Fourier transform of this correlation signal is then computed. The first projection PG1 onto the set representing the experimental constraints is then performed. This projection is simply carried out by replacing the amplitude $\tilde{E}_{sig}^{(K)}(f_i, \tau_j)$ with the square root of the experimentally recorded FROG trace $I_{FROG}^{EXP}(f_i, \tau_j)$ so that:

$$\tilde{E}'_{sig}(f_i, \tau_j) = \sqrt{I_{FROG}^{EXP}(f_i, \tau_j)} \frac{\tilde{E}_{sig}^{(K)}(f_i, \tau_j)}{\tilde{E}_{sig}^{(K)}(f_i, \tau_j)} \quad (10)$$

The quantities $\tilde{E}'_{sig}(f_i, \tau_j)$ obtained in this way satisfy the constraint of the experimental data and preserve the phase that the algorithm has found for them. The current iteration then concludes with an inverse Fourier transform of $\tilde{E}'_{sig}(f_i, \tau_j)$ and the projection PG2 of the obtained signal $\tilde{E}'_{sig}(f_i, \tau_j)$ onto the set of functions corresponding to the nonlinear process. The sought signal $E^{(K+1)}(t_i, \tau_j)$ must correspond to the signal closest to $E'_{sig}(t_i, \tau_j)$ that satisfies the mathematical form of the correlation given by equations (9). Given

these quantities $E'_{sig}(t_i, \tau_j)$, this projection amounts to finding $E^{(K+1)}_{sig}(t_i, \tau_j)$ that minimizes the distance Z by :

$$Z = \sum_{i,j=1}^N \left| E'_{sig}(t_i, \tau_j) - E^{(K+1)}_{sig}(t_i, \tau_j) \right|^2 \quad (11)$$

Assuming the choice of the nonlinear process as second harmonic generation, this leads to searching for the N complex quantities $E^{(K+1)}(t_i)$ that minimize the function [15]:

$$Z = \sum_{i,j=1}^N \left| E'_{sig}(t_i, \tau_j) - E^{(K+1)}(t_i)E^{(K+1)}(t_i - \tau_j) \right|^2$$

2.1. Error evaluation

Once the envelope of the field $E^{(K+1)}(t_i)$ is found, an error estimation allows us to determine the relevance of this retrieval. This FROG error, denoted as “G”, is calculated by taking the mean square deviation between the experimental FROG trace S_{FROG}^{EXP} and that constructed from the wave $E^{(K+1)}(t_i)$, $S_{FROG}^{(K+1)}$ from which :

$$G = \sqrt{\frac{1}{N^2} \sum_{i,j=1}^N \left| S_{FROG}^{EXP}(w_i, \tau_j) - \alpha S_{FROG}^{(K+1)}(w_i, \tau_j) \right|^2} \quad (13)$$

The solution is then found through successive projections: Starting from an arbitrary point in this space, it is projected onto one of the constraints by determining the closest point in that set. Once this first iteration is completed, the new point is then projected onto the set corresponding to the second constraint. The retrieval error is calculated at each iteration by the mean square deviation between the experimental FROG trace and the trace associated with the wave extracted from the iteration. This error allows for controlling the convergence of the algorithm during successive iterations. The process repeats until the solution $E_{sig}(t, \tau)$ is obtained [16].

3.FROG simulations and results

To effectively compare the FROG measurements for 20 fs, 10 fs, and 5 fs laser pulses (Fig. 6, 7 and 8), it's essential to examine several key aspects, including the characteristics of the pulses.

Each pulse duration requires specific simulation techniques adapted to its complexity and characteristics. Simulations typically involve: Using classical or quantum models to describe the interaction of the pulse with nonlinear media. Implementing FROG retrieval algorithms (e.g., generalized FROG or amplitude-and-phase retrieval) to process the resulting FROG trace.

Figure 6 with 20 fs pulses the FROG trace shows clear and distinct features, making it relatively easy to extract the intensity and phase information. The low noise level in the measurements indicates a stable experimental setup.

In Fig. 7 when we used 10 fs pulses width the quality of the FROG trace is moderate. While the pulse can still be characterized effectively, certain artifacts may appear due to increased background noise and dispersion issues. This necessitates careful calibration of the system.

Finally in Fig. 8 with 5 fs pulses width the FROG traces exhibit significant noise and complexity, making it challenging to extract reliable intensity and phase profiles. The high-frequency oscillations present in the intensity profile suggest rapid changes in the pulse shape, complicating measurements.

The intensity profile in Fig. 10 resembles a smooth Gaussian shape, indicating a well-behaved pulse that can easily be modeled. In Fig. 11 the intensity profile is broader and exhibits some oscillations, which could indicate the emergence of higher-order spectral components. These oscillations are partly due to the pulse's nonlinear interactions and the dispersion of optical components. In Fig. 12 the intensity profile is complex, displaying rapid fluctuations that indicate significant sensitivity to changes in phase. The detailed structure includes higher-order frequency components that can obscure the main pulse characteristics.

Concerning the phase retrieval Accuracy in Fig. 10(B) the phase retrieval is quite accurate, yielding a reliable representation of the temporal phase. This precision supports detailed analysis of ultrafast processes and is essential for applications where phase stability is critical, such as coherent control. In Fig. 11(B) although the phase information is generally retrievable, there may be some inaccuracies introduced by background noise and artifacts, which could affect the clarity of ultrafast dynamic studies. When we used 5 fs pulses in Fig. 12(B) the phase retrieval is often problematic due to high sensitivity to noise and disturbances. The rapid oscillations complicate phase recovery algorithms, leading to difficulties in accurately representing the true pulse shape.

The temporal resolution and computational complexity: The temporal resolution improves with shorter pulse widths, enabling researchers to probe faster dynamics in molecular and electronic systems. However, as pulse duration increasingly decreases, the number of features present in the pulse profile complicates the measurement. The computational complexity required to accurately retrieve data increases significantly with shorter pulse durations. The complex dynamics and resulting FROG traces necessitate the use of advanced algorithms that can handle this intricacy. For 5 fs pulses, the high computational demands require substantial resources and refined algorithmic approaches to ensure fidelity in retrieval.

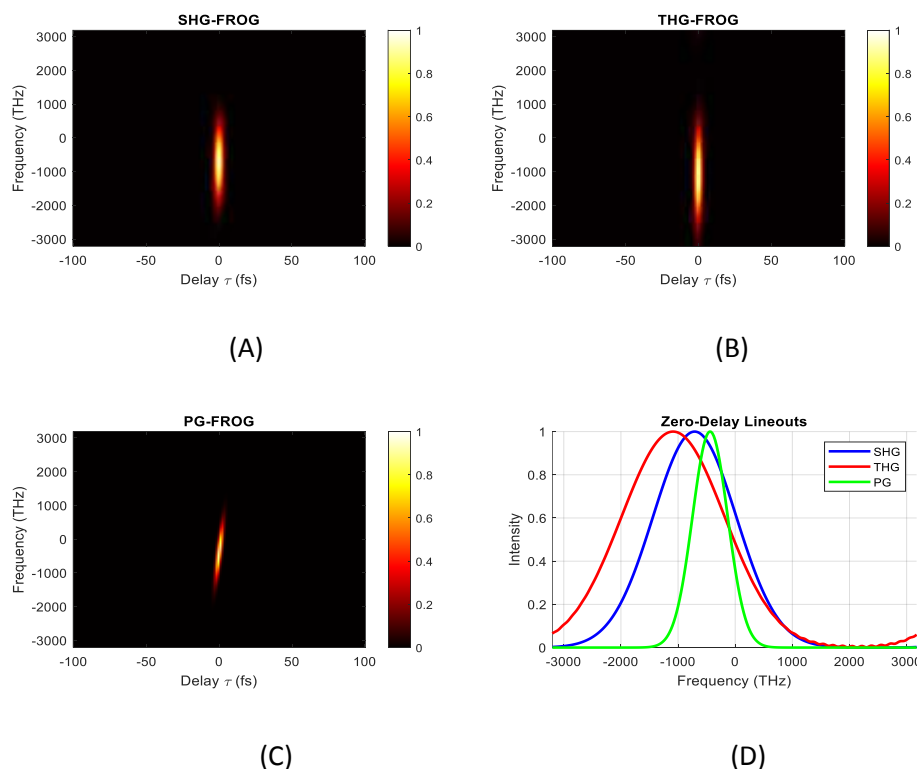


Figure 6. Characterization of 20 fs pulse width with chirp $C=5$: (A) SHG-FROG method, (B) THG-FROG method, (C) PG-FROG method, (D) Intensities retrievals

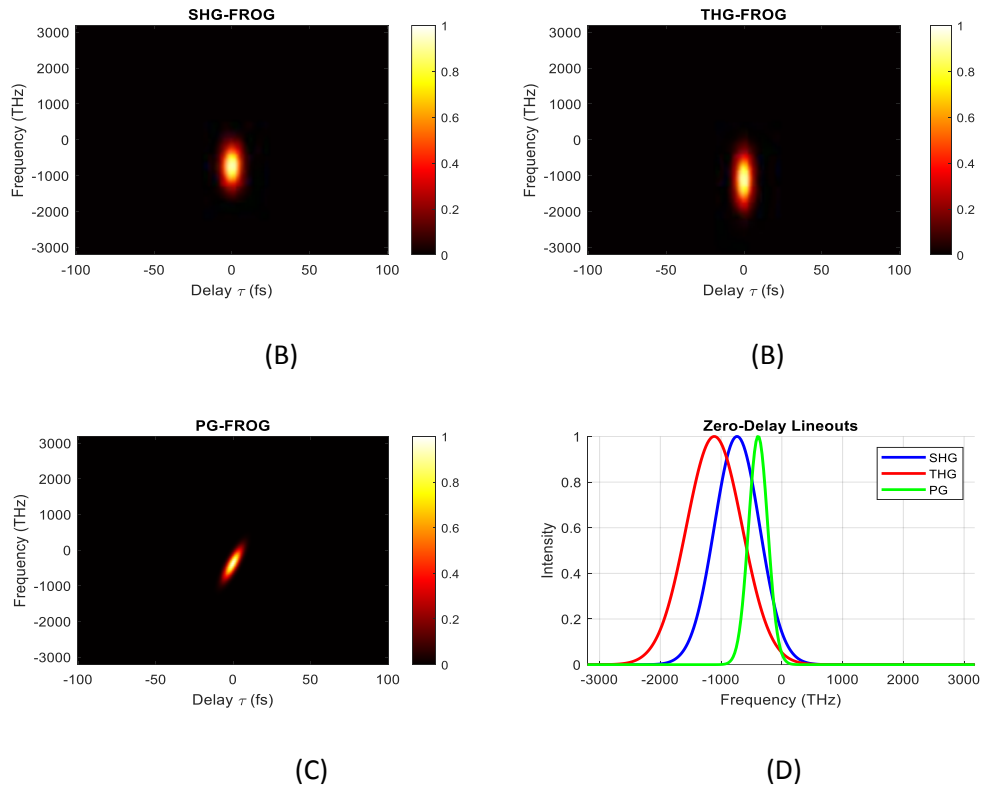


Figure 7. Characterization of 20 fs pulse width with chirp $C=5$: (A) SHG-FROG method, (B) THG-FROG method, (C) PG-FROG method, (D) Intensities retrievals

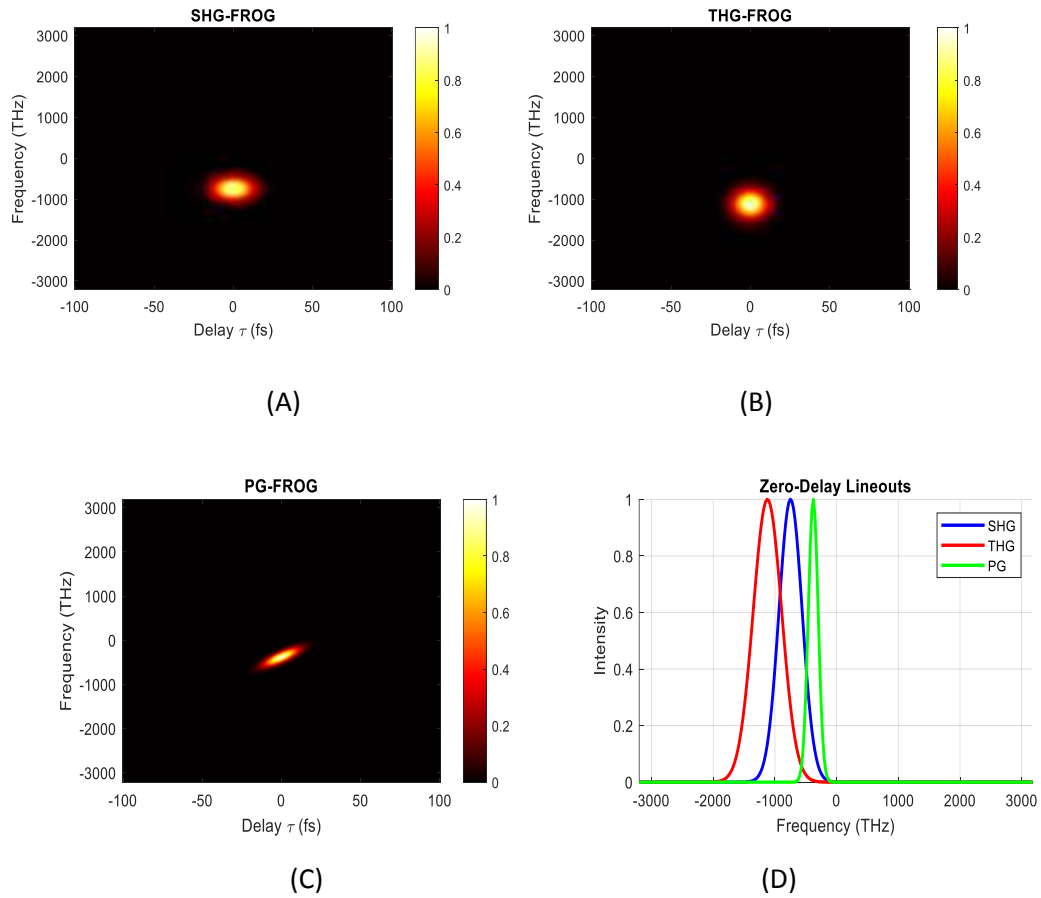


Figure 8. Characterization of 5 fs pulse width with chirp $C=5$: (A) SHG-FROG method, (B) THG-FROG method, (C) PG-FROG method, (D) Intensities retrieval

The ability to characterize ultrashort pulses using FROG measurement techniques results in valuable insights into fundamental physical processes. For practical applications, particularly in the fields of ultrafast optics and coherent control, accurate retrieval of both phase and intensity is critical.

Results from 20 fs and 10 fs pulses are directly applicable in time-resolved spectroscopy and imaging techniques, leading to advancements in ultrafast chemical reactions and material studies. The challenges associated with 5 fs pulse measurements underscore the necessity for improved techniques and technologies that can enhance reliability.

Further improvements in FROG techniques and the development of algorithms that minimize noise impact are essential for maximizing the potential of ultrafast laser systems. Research may also benefit from integrating machine learning approaches to better handle retrieval processes for complex pulse profiles.

A spectrogram visually in Fig. 9 represents the spectrum of frequencies of a signal as it varies with time. It displays how the signal's frequency content evolves over time. It is typically computed using the Short-Time Fourier Transform (STFT), which involves segmenting the signal into short time intervals and performing Fourier transforms on each segment. Commonly used in audio signal processing, speech analysis, music analysis, biomedical signals (e.g., EEG, ECG), and various fields of engineering. Useful for identifying time-varying frequency components in non-stationary signals. Provides a clear visualization of how frequency content changes over time.

The time window size can be adjusted to trade off time and frequency resolution, allowing tailored analysis according to the signal characteristics. Choice of window size can lead to limitations in temporal and frequency resolutions; a small window enhances time resolution but reduces frequency resolution, and vice versa. May require expert interpretation to analyze complex signals, especially in the presence of noise.

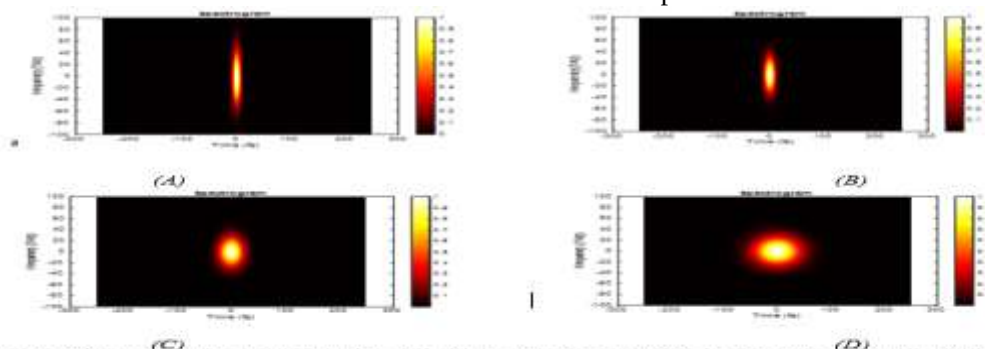


Figure 9 Spectrogram technique (A) 5 fs, (B) 10 fs, (C) 20 fs and (D) 30 fs method, (C) PG-FROG method, (D) Intensities retrieval

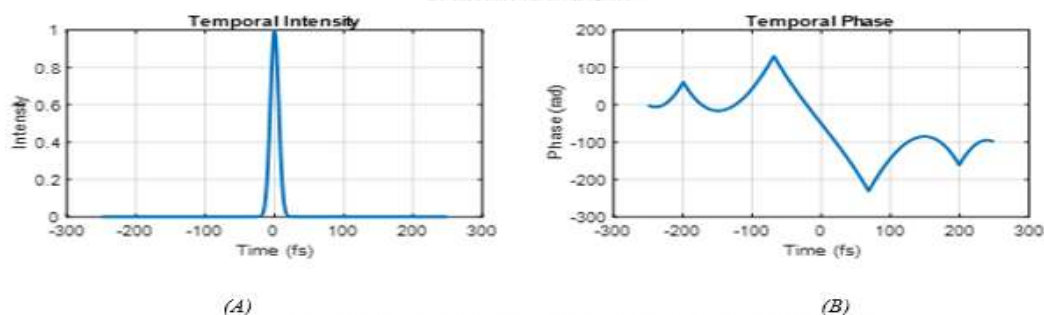


Figure 10 Intensity and phase retrievals for 20 fs pulse width

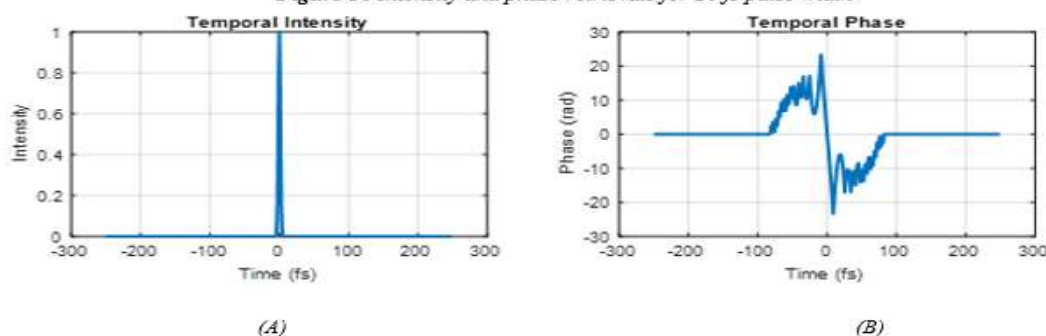


Figure 11 Intensity and phase retrievals for 5 fs pulse width

The rapid oscillations complicate phase recovery algorithms, leading to difficulties in accurately representing the true pulse shape.

The temporal resolution and computational complexity: The temporal resolution improves with shorter pulse widths, enabling researchers to probe faster dynamics in molecular and electronic systems. However, as pulse duration increasingly decreases, the number of features present in the pulse profile complicates the measurement. The computational complexity required to accurately retrieve data increases significantly with shorter pulse durations. The complex dynamics and resulting FROG traces necessitate the use of advanced algorithms that can handle this intricacy. For 5 fs pulses, the high computational demands require substantial resources and refined algorithmic approaches to ensure fidelity in retrieval.

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4. Conclusion

Frequency-Resolved Optical Gating (FROG) is a versatile technique for complete characterization of ultrashort laser pulses, providing simultaneous measurement of temporal intensity and phase. Unlike conventional autocorrelation, FROG generates a spectrogram by spectrally resolving a nonlinear autocorrelation trace, enabling full pulse reconstruction via iterative phase retrieval algorithms. Widely used variants include SHG-FROG (second-harmonic generation), PG-FROG (polarization gating), and XFROG (cross-correlation FROG), each optimized for specific pulse regimes. FROG enables precise determination of pulse duration, chirp, and complex temporal profiles, making it indispensable in ultrafast optics for applications such as femtosecond spectroscopy, laser development, and nonlinear dynamics. Its robustness and accuracy have established FROG as a gold standard in ultrashort pulse diagnostics.

Frequency-Resolved Optical Gating (FROG) is a powerful technique for characterizing ultrashort laser pulses, enabling full reconstruction of their intensity and phase profiles. Below, we discuss its application to 20 fs, 10 fs, and 5 fs, along with key retrieval challenges and results. The technique successfully retrieves both intensity and phase profiles, enabling precise determination of pulse duration, chirp, and temporal structure.

However, retrieval accuracy is influenced by several factors:

Pulse duration as 5fs effects pose challenges due to their broad bandwidth and susceptibility to dispersion artifacts, requiring careful calibration of nonlinear processes (e.g., SHG efficiency in SHG-FROG). Using 10 – 20 fs pulses are more straightforward to measure but still demand precise alignment and high-resolution spectrographs to minimize errors. The retrieval errors typically remain below 1 – 5% for well-optimized setups, but can increase for few-cycle pulses due to spectral overlap ambiguities. The phase errors are more critical, often ranging from 0.1 – 0.5 rad for 10 – 20 fs pulses but may exceed 1 rad for 5 fs pulses if dispersion compensation is inadequate. The noise and dynamic range of the spectrometer also impact fidelity, particularly for weak pulse wings or pre-/post-pulses.

FROG remains a gold standard for ultrashort pulse measurement, but its accuracy must be carefully assessed for sub – 10 fs pulses. Future advancements in ultrabroadband nonlinear crystals and machine-learning-assisted retrieval could further reduce errors, particularly for intensity and phase reconstruction of few-cycle pulses.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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