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Pulse Duration and Pulse Energy Measurement: Industrial Use and Material Processing

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Abstract

For many applications, the pulse information from a (ultra-fast) laser datasheet is sufficient. If, however, you are dealing with ultrashort pulse lasers that underlie non-linear distortion effects (e.g. fiber lasers), pulsed lasers with changeable pulse durations (e.g. pulse compressor) or, if your application results strongly depend on stable pulse conditions, or if you are in the production of a series of lasers and you need to develop your own pulse quality metrics, this paper will be useful in guiding you. We review pros and cons of well-established pulse properties measurement techniques, including autocorrelation, SPIDER and FROG. Furthermore we address the challenges of developing pulse properties measurement tools that are specifically suitable for applications in industrial material processing and medical applications. With respect to this, we introduce a new promising alternative technique: Normalized Non-linear Efficiency ("NNE") to gain control of important pulse parameters, including peak power and pulse energy measurement techniques.

Keywords: Pulse Duaration; Pulse Energy; Autocorrelator; Normalized Non-linear Efficiency; Ultrashort Laser Pulses; Peak Power

1. Ultrashort Pulses and Their Relevance for Industrial Applications

Ultrashort laser pulses (USP) are getting more and more interest e.g. for cold ablation material processing due to their specific features, as there are

- Extremely high peak powers, which are used e.g. for increasing the efficiency of otherwise minor nonlinear effects (for example High Harmonics Generation),
- Very short durations which are applied for investigations of extremely fast processes or for avoiding thermal effects in material processing (due to the short interaction time).

This allows for efficient and very localized (micro-) material processing in a well-defined way; e.g. metal micromachining (Harzic & Dausinger et al. 2005), fine holes in injection nozzles or cutting eye flaps (Cornea processing in Ophthalmology; Holzer & Auffarth et al. 2006). In some applications such as photochemistry or special material processing of "difficult" materials even more complex pulse structures and patterns have been used (Wollenhaupt & Baumert et al. 2012).

With the introduction of USP fiber lasers the application of ultrashort pulses became easier on the one hand (handling, price …) but also a bit more critical on the other hand, because the physics of the pulse generation process include various nonlinear effects which may easily corrupt the pulse performance. Thus these pulses are not ideally Gaussian or sech² shaped as used from other laser systems.

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2. Common Measurement Methods

An ultrashort laser pulse is a complex system with intensity modulations, with possible phase shifts between the different spectral components ("Chirp") or even a variation in space (spatial chirp), at the end all leading to modifications of the interaction of the pulse within the intended application. Therefore it is important to characterize and monitor these pulses. This complexity of an USP is a big challenge for its complete characterization.

A first and simple approach is it to look at the intensity over time (envelope of the electromagnetic waves, Fig.1) neglecting the phase issues. It can be characterized by its length ("pulse duration"), but this is not completely describing the pulse – very obviously its intensity profile vs time can vary ("pulse shape").

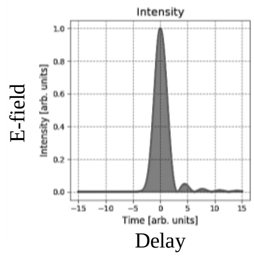

Fig. 1 Intensity plot (E-field)/ Envelope of electromagnetic waves: Typical E-field function over time.

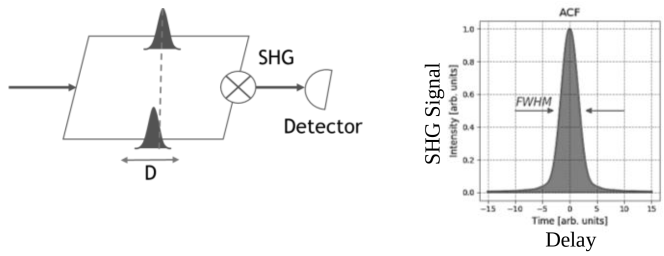

Fig. 2a The pulse is spilt into two identical copies and then focused into a nonlinear optical crystal to generate a Second Harmonics Signal (SHG); 2b Typical autocorrelation function SHG signal over time

Already the measurement of the pulse duration is difficult, because ultrashort pulses are shorter than the response time of most opto-electronical detectors and oscilloscopes, which means that one would characterize the system response function instead of the pulse duration. At least an elaborate deconvolution would be required.

2.1. Autocorrelator Measurement

The simplest and most common method for the characterization of the duration of an USP is measuring an autocorrelation function (ACF). This is a correlation measurement between the pulse and an identical copy of itself, i.e. using the pulse as its own sampling reference (Klemens 2016).

The principle is shown in figure 2a. The pulse is sent into a Michelson interferometer where it is spilt into two identical copies. Behind the output of the interferometer these two pulse copies are focused into a nonlinear optical crystal to generate a Second Harmonics Signal (SHG), whose intensity depends quadratically on the incident intensity (Fig. 2b). This new signal is measured with a detector. When the length of one interferometer arm is varied (generating a delay D), the two pulse copies overlap more or less accordingly, depending on their duration (length). As a result the length of the pulse can be measured from the intensity distribution versus the delay.
The necessary detector does not need to be a fast one, because it is sufficient that it matches the speed of the delay variation which is typically in the Hz-range. This (specific) scheme is an integrating technology, i.e. the input pulses have to be available for the entire delay scan and the ACF is resulting from the interaction of many pulses.

Due to its simplicity the autocorrelation technique is not suited to resolve unambiguously subtleties, as for example pulse shape, substructures, asymmetries etc. or pulse structures outside the scanning range.

Despite its limitations the autocorrelation method is popular because of its simple layout and its robustness, giving a single measure for the duration of the pulse. Furthermore this technique is very versatile and can be applied for nearly any wavelength.

More detailed information about the pulse parameters require more sophisticated and more expensive instruments, which in general are also more difficult to handle. Two of them are mentioned in the following chapter and a comparison of the methods is shown in table 1.

2.2. FROG and SPIDER

Simple autocorrelation measurements contain insufficient information to completely reconstruct a pulse. Advanced methods may additionally determine the chirp of a pulse, i.e. the dependence of the frequency on time. In FROG (Frequency-resolved Optical Gating), the pulse to be measured and its copy are superimposed in a nonlinear crystal (as with the autocorrelator) and then analyzed in a spectrometer (Klemens 2016). The result is a spectral pattern that represents the temporal delay of the different wavelength components. From this 2D-pattern the complete field distribution can be retrieved. In SPIDER (Spectral Phase Interferometry for Direct Electric-field Reconstruction; Stibenz & Steinmeyer et al. 2006), the wavelength components of the pulse to be measured overlap with a spectrally shifted copy of the same pulse. This setup allows for the direct pulse form measurement in the spectral domain (amplitude and phase) even in a single shot approach.

3. A New Approach: Normalized Non-linear Efficiency (NNE)

The above described methods sample the electrical field distribution over a limited time window (scan range) only. Further, only relative intensities within the scan range are taken into account.

The advantage of the NNE method is, in contrast to e.g. an autocorrelator, that it has no temporal measurement window limitation (Fig. 3). Instead the pulse and all pre- and post-pulses as well as any other background energies of a laser are taken into account. Thus, the measured ratio between average power and non-linear efficiency gives a close estimate of the effective peak power of a laser system. This makes this method ideal for the evaluation or optimization (e.g. laser compressor settings) of lasers used for any kind of material processing where non-linear efficiency is essential. Additionally, monitoring a laser with this method will instantly indicate any changes in laser performance such as double pulsing, changing peak and average power, or pulse duration. Furthermore, a NNE measurement tool has no need for movable parts, allowing for a compact and extremely robust design.

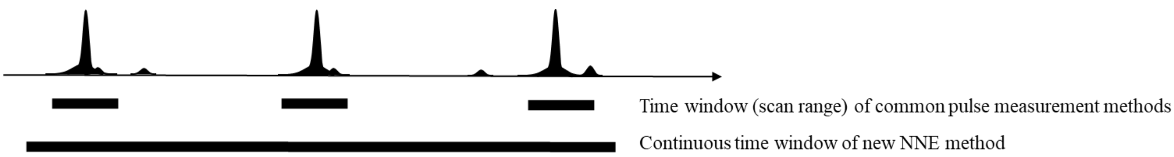

Fig. 3 The temporal measurement window of common measurement methods (e.g. AC, FROG, SPIDER) in comparison to NNE.

A Normalized Non-linear Efficiency (NNE) detector consists of two basic components. The first one is a detector that is sensitive for the incident wavelength of the laser with a response linear to the average power of the laser. The second component is a detector that is intentionally not sensitive to the wavelength of the laser to be measured. Instead its response is correlated to a second order process called Two-photon absorption (TPA) where two coincident photons are needed to generate a photocurrent. Therefore, the TPA efficiency and thereby the response of the second detector is proportional to the peak intensity of the laser pulses. Taking into account, as a third parameter, the repetition rate of the laser, the relative peak power as well as the pulse quality in terms of pulse duration can be easily derived.

Such a device can be used for basically any ultrashort pulsed laser if the peak power of the pulses is sufficient enough for the TPA effect and where two detectors can be engineered in such a way as described above. It allows to find the optimal compressor settings or other parameters that lead to the shortest pulse or in general to optimize the non-linear efficiency of the laser for material processing. Finally, this method is ideal to monitor lasers during up time for operation mode changes or in particular during warm-up.

4. Comparison of Pulse Characterization Methods

Especially the methods AC, FROG and SPIDER have proven themselves in the scientific community for many years. All these methods offer a different depth of information about pulse characteristics. In addition, they differ in their applicability for various parameter corridors (e.g. pulse duration and wavelength range), and their suitability for industrial requirements, especially in terms of complexity and costs. The following table gives an overview on the most important differences.

Table 1. Comparison of Pulse Characterization Methods for Industrial Applications

	NNE	AC	FROG	SPIDER
Measurement Parameter	Non-linear Efficiency; Relative peak power; Relative pulse duration; Rep. rate	Pulse Duration (ACF); Relative pulse intensity	Iterative retrieval of complete E-field in spectral and temporal domain incl. amplitude and phase	Complete E-field in spectral and temporal domain incl. amplitude and phase
Parameter Coverage (typ.)	50 fs ... > 10 ps 500 nm ... 2000 nm	10 fs ... 400 ps 200 nm ... 16 µm	20 fs ... > 6 ps 400 nm ... < 2000 nm	5 fs ... > 500 fs 450 nm ... 1300 nm
Typ. Applications	Monitoring of fs and ps lasers, especially fiber-lasers	Pulse duration measurement of all kinds of fs and ps laser sources	Full pulse characterization of most kinds of fs and ps laser sources	Full pulse characterization, esp. for very short pulses; single-shot capability
Footprint (typ.)	< 50 x 50 mm	< 150 x 150 mm	> 300 x 200 mm	> 500 x 500 mm
Price Range (typ.)	< 5000 EUR	5000 - 15000 EUR	15000 – 25000 EUR	> 20000 EUR
Strengths	Low cost; Small form factor for easy integration, Continuous measuring window; Focuses on effect. peak power rather than pulse duration	Versatile for different pulse durations and wavelengths; Accepted standard way of pulse duration measurement	Relatively simply setup comparable to AC; Versatile for different pulse durations and wavelengths	Provides full pulse shape information; Few-cycle measurements / Single-shot measurements possible
Challenges	Setup needs to be adapted to the specific laser parameters	Meas. window limited to the time of the pulse duration to be measured; Mechanically scanning system	High costs; Fitting algorithm makes data interpretation more complex	Different parameter ranges often require an optimized single-setup; High cost; Large footprint

5. Conclusion

We reviewed pros and cons of well-established pulse duration measurement techniques, including autocorrelator, SPIDER, FROG and NNE. Regarding NNE, we have shown that the ratio between average power and non-linear efficiency can be used to measure the effective peak power of a laser system Furthermore, we've concluded that the relative simplicity and cost-effectiveness of NNE makes this method ideal for the evaluation, optimization (e.g. laser compressor settings) and monitoring of lasers used for any kind of material processing where non-linear efficiency is essential.

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