Armenian Journal of Physics, 2019, vol. 12, issue 1, pp. 107-112

Similaritonic Method on Ultrashort Pulse Duration Measurement by Oscilloscope

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Received 04 March 2019

Abstract: In this work, we developed and experimentally examined a real-time single-shot technique of femtosecond pulse duration measurement based on similariton spectrotemporal imaging and measuring temporal profile via electrical oscilloscope. The method is easy in implementation, since it uses only a piece of single mode fiber and an oscilloscope.

Keywords: Ultrafast optics, Fiber optics, Similaritons

1. Introduction

During the last decades, the advancement of laser physics, and particularly advancements in generation of ultrashort pulses (few tens of femtoseconds), led to the applications of ultrafast optics in various fields of science. Ultrashort laser radiation is now used in non-contact probing of materials, modern microscopy, advanced telecommunication devices, precision drilling, etc. This broad use of ultrashort laser sources brought the demand for simple and easy-to-use devices for laser pulse diagnostics in femtosecond time scale. There are several methods of laser pulse shape determination. The frequency-resolved optical gating (FROG) [1] and GRENOUILLE [2] are nonlinear-optical techniques, which provide precise information on temporal shape and phase of the pulses through iterative phase-retrieval procedures. Another approach to the signal characterization problem is the spectral interferometric technique, which is used in SPIDER [3], SPIRIT [4] and SORBETS [5]. Spectral interferometric techniques have the advantage of non-iterative phase retrieval, which is later put on the measured spectrum to recover the temporal shape of the pulse. The technique of multiphoton intrapulse interference phase scan (MIIPS) [6,7] recovers the pulse phase by the uses of adaptive optics and feedback from second harmonic generation process to compensate the phase of the pulse down to transform-limited. Despites these advanced and highly precise methods of pulse shape and phase diagnostics, for many modern applications of femtosecond radiation, only information about the pulse duration is necessary. The autocorrelator is one of the most popular devices in any modern laser laboratory. It uses feedback from second harmonic generation to calculate the autocorrelation trace of the sample signal. Duration of pulse is then retrieved from autocorrelation duration, if pulse form is known.

Another interesting and important advancement in ultrafast measurement techniques is the dispersive Fourier transformation (DFT) [8-11]. DFT is a method that allows to overcome the speed limitations of traditional spectrometers, allowing fast, real-time spectral measurements. DFT method is based on the analogy between Fraunhofer diffraction and dispersion. The DFT method uses a dispersive element and a single-pixel photodiode for the implementation of fast continuous single-shot measurements [12] and overcomes the speed limitation of traditional spectrometers. DFT process converts the spectral information into the temporal domain, in a stretched pulse. This stretched pulse can reach nanosecond duration (in comparison to the initial femtosecond pulse), which allows to measure the pulse shape using high-speed photodiodes and electronic oscilloscope. Optical spectroscopy based on DFT method allows the measurement of signal with repetition rate in MHz or even GHz domain. The advantage of such measurement of spectrum over the usual time-averaged measurement is that it can be used in single-shot setups, allowing the capturing of non-stationary processes and rare events, that would otherwise be impossible to register. Implementation of DFT method requires a large and linear GVD element, which allows the frequency-to-time mapping without distortions.

The goal of this work was the experimental study of the method of femtosecond pulse duration measurement based on generation of nonlinear-dispersive (NL-D) similariton [13]. Particularly, it is demonstrated that the spectral measurements in this technique can be replaced by temporal measurements, using the DFT method.

2. Principle

The similaritonic technique for femtosecond pulse duration measurements is based on the spectral properties of NL-D similariton. NL-D similariton is generated under the combined impact of Kerr nonlinearity and second-order dispersion [14] in passive (without gain) fibers. NL-D similariton has bell-shape spectral and temporal profiles and a parabolic phase independent of the input pulse parameters. It was experimentally demonstrated that the spectral bandwidth of the NL-D similariton generated from pulses with near-Gaussian shape is inversely proportional to the square root of the input pulse duration [15].

Our numerical simulations show the following relation of similariton spectrum: $\Delta\omega = \sqrt{(C/\nu)(\bar{P}/\Delta t_0)}$, where $\Delta\omega$ is the FWHM spectral width of similariton, $C = n_2 k_0 (\beta_2 S)^{-1}$ depends on fiber parameters (n_2 is Kerr nonlinear parameter, k_0 is the wavenumber, β_2 is the group-velocity dispersion (GVD) parameter and S is the cross-section area of the fiber core), ν is the repetition rate, $\bar{P}$ is the average power and Δt_0 is the initial pulse FWHM duration. The NL-D similariton duration is uniquely determined by its spectral width and the dispersive characteristics of the fiber in which it is generated. $\Delta t = \Delta\omega / \gamma$, where Δt is the similariton FWHM duration, $\gamma = (\beta_2 z)^{-1}$ is the chirp coefficient, z is the fiber length. Therefore, the input pulse duration is given by: $\Delta t_0 = (C k_2 z / \nu)(\bar{P} / \Delta t^2)$. Both numerical and experimental studies showed the following relation between the temporal durations of similariton and the input pulse: $\Delta t \approx \sqrt{\bar{P} / \Delta t_{AC}}$, where Δt_{AC} is the autocorrelation duration of the input pulse. Hence, the measurement of similariton duration and average power of radiation gives us the initial pulse duration.

3. Experiment

Schematic

The experimental setup is shown in Fig. 1. Mode-locked Ti:sapphire laser oscillator (Coherent Verdi 10 + Mira 900F) was used with the following parameters: $100\,fs$ FWHM pulse duration, $9nm$ spectral bandwidth, $800nm$ central wavelength, $1W$ average power at $76MHz$ repetition rate. First, pulses were chirped both positively or negatively, in an SF11-prism pair-based dispersive delay line (DDL). Afterwards, the duration of chirped pulse was measured by an autocorrelator (AC). Afterwards, the chirped pulses passed through single-mode fiber (SMF) ($\sim 1m$ long Thorlabs $780HP$) and the spectrum of generated NL-D similaritons was recorded using Ando AQ-6515A optical spectrum analyzer (OSA).

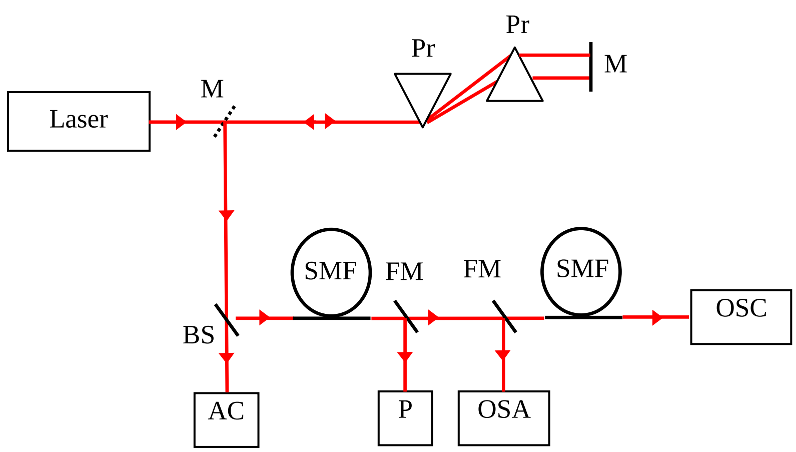

Figure 1: Experimental setup: M-mirror, FM-flip mirror, BS-beam splitter, Pr-prism, SMF-single mode fiber, OSC-oscilloscope, P-powermeter, OSA-optical spectrum analyzer, AC-autocorrelator.

For the electronic oscilloscope measurements, similaritons were stretched further to nanosecond domain using 600-m long SMF. Both OSA and oscilloscope measurements gave the spectral width of the NL-D similariton. Studies were carried out for initial pulses with AC durations of $\Delta t_{AC} \sim 150-600\,fs$ at FWHM, and similariton spectra of $43-89nm$ at FWHM, in the range of radiation average powers of $\overline{P} \sim 450-530mW$.

Results

The aim of our research was to develop simple similaritonic technic for single-shot, real-time measurements of duration of ultrafast laser pulses. The method is developed to measure duration of femtosecond pulses based on spectral peculiarities of NL-D similariton. Due to the parabolic phase of the similariton pulse, its duration has linear dependence from the spectral width. Hence, spectrometer can be replaced by electrical oscilloscope to enable acquiring single-shot measurements in real time.

In our experimental study, we shaped chirped pulses with $200-600\,fs$ AC duration from laser pulses with initial AC duration of $150\,fs$. We used SF11 prism-pair based DDL to chirp pulses both negatively and positively. Then, pulses were coupled into 1m Thorlabs $780HP$ optical fiber to generate similaritons with spectral width of $43-89nm$ and mean power of $450-530mW$.

Figure 2 shows the AC measurements of $150\,fs$ initial pulse (a) and spectrum of generated similariton (b) with 10x spectral broadening $(\Delta\omega = 89nm)$. This spectrum has bell-shape form (characteristic for similariton). Afterwards, this similariton is stretched up to $6.3ns$ in a $600m$ long SMF. Temporal shape of output pulse measured by nanosecond oscilloscope is shown in Fig. 2(c). Comparison of the similariton spectrum and the stretched pulse (Fig. 2(b) and (c) respectively), the stretched pulse shape reproduces the spectral shape of the similartion from which it was shapes. Thus, we can state that DFT takes place in these results. Afterwards, we have tested the method for different pulse durations, which covered the range of $150-600\,fs$ AC durations, and included both negatively and positively chirpedpulses. This was done using prism-pair based dispersive element, where positive chirp was applied by allowing the pulse to travel through long distances inside the prism material. Dependences of initial pulse duration from spectral width and duration of similariton are shown in Fig.3.

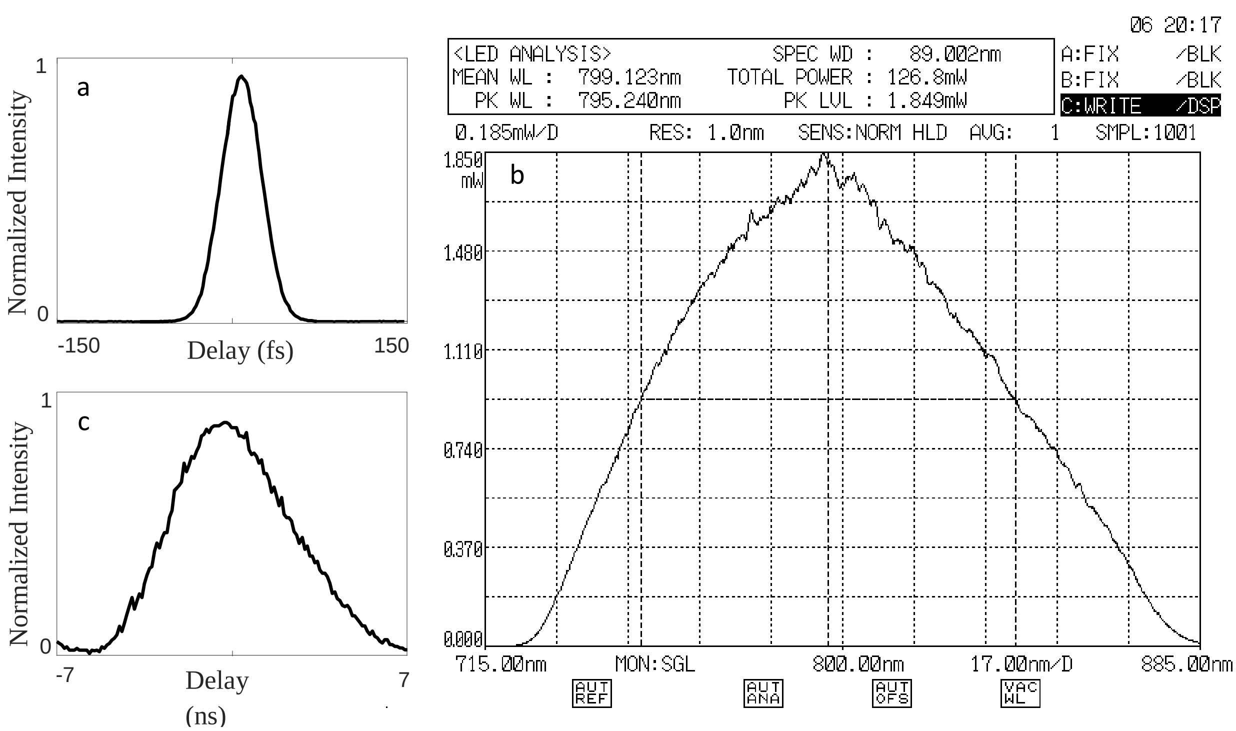

Figure 2: Results of experimental studies: autocorellation of initial pulse (150fs) (a), generated similariton spectrum (89nm) (b) and temporal profile of the similiariton (6.3ns) (c).

Here, blue circles correspond to spectral and red circles to temporal measurements. Plus (+) or minus (-) signs correspond to positively and negatively chirped pulses, respectively. These results are normalized on the square root of the test pulse average power.

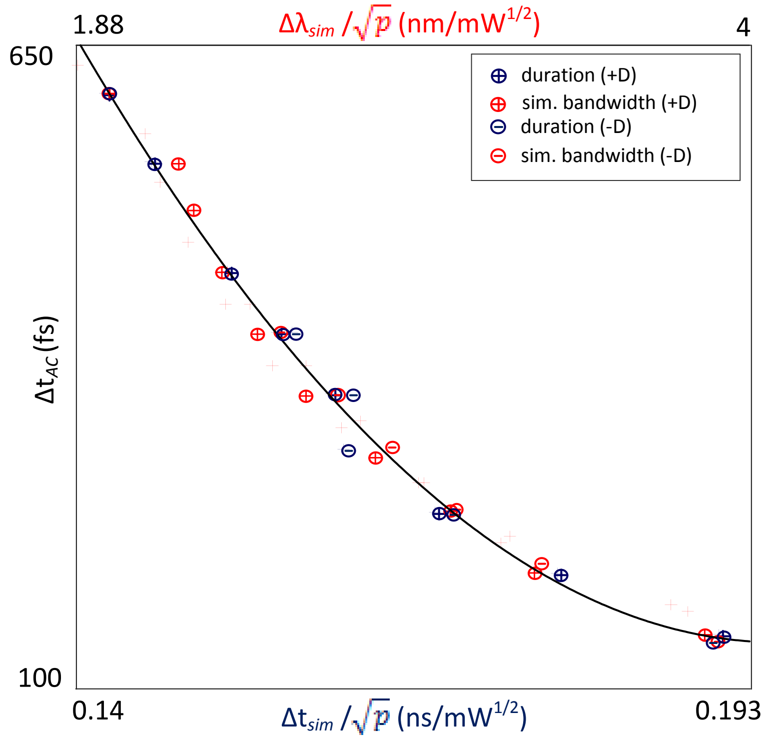

Figure 3: Pulse autocorrelation duration versus similariton FWHM duration and spectral bandwidth normalized on the square root of the laser average power.

As one can see, temporal measurements (performed by an oscilloscope) are in a good agreement with spectral measurements (performed by an OSA). These experimentally acquired dependencies are also in a good accordance with our theoretical predictions ($\Delta t \sim \sqrt{P/\Delta t_{AC}}$). Moreover, the accordance takes place for pulses with both negative and positive slope of the chirp. These results allow us to state, that the similariton-based method of pulse duration measurement can indeed be performed in a single-shot, real-time setup, using nanosecond electronic oscilloscope.

4. Conclusion

To conclude, we have experimentally studied a similariton-based technique, which allows the real-time measurements of femtosecond pulse duration. This technique can be implemented in the similaritonic method of pulse duration determination, where single-pulse temporal profile can be registered using nanosecond oscilloscope as an alternative to averaged spectral measurements.

Author Contributions

The authors equally contributed to all steps of the paper preparation.

Funding

This work has been partially supported by Grant No. 18A-1c46 from the Science Committee of the Ministry of Education and Science of Armenia.

Acknowledgments

The author is grateful to his colleagues at Yerevan State University and CANDLE SRI for the fruitful discussions and help during the research

Conflicts of interest

The authors declare that there are no conflicts of interest regarding this paper.

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