Similariton for femtosecond signal analysis

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Abstract. The similariton-based spectral interferometry and pulse spectrotemporal imaging in a similariton-induced temporal lens are comparatively experimented, as two applications of similariton to ultrafast optics, particularly, for signal analysis problem on femtosecond timescale. Generation of the 50-THz bandwidth similariton provides a few-femtosecond temporal resolution for accurate and aberration-free measurements of these self-referencing methods.

1. Introduction

The problem of femtosecond signal analysis currently employs the powerful arsenal of contemporary optics, involving the methods of nonlinear and adaptive optics, Fourier optics and holography, spectral interferometry, etc. The nonlinear-optical technique of FROG [1], the most popular, provides complete determination of the temporal amplitude and phase by recording high-resolution spectrograms, which are further decoded by means of iterative phase-retrieval procedures. The approach of spectral interferometry (SI) [2] and its developments to the methods of SPIDER [3] and SPIRIT [4] have the advantage of non-iterative phase retrieval. These methods are based on the spectral phase retrieval, spectrum measurement, and reconstruction of a temporal pulse. For the pulse direct measurement, the method of pulse spectrotemporal imaging (STI) through temporal lensing is more promising, having as a principal limit of resolution the ~1 fs nonlinear response time of silica [5]. Its recent modifications, implemented in the silicon chip [6] and similariton-induced parabolic temporal lens [7], provide accurate, high-resolution direct measurement of a pulse in the spectrometer as in the femtosecond optical oscilloscope (FO). Many modern scientific and technological problems, however, demand both the amplitude and phase information, possible through additional interferometric measurements. This motivates the urgency of SI methods for the complete characterization of femtosecond signal. The classic method of SI is based on the interference of the signal and reference beams spectrally dispersed in a spectrometer, with the spectral fringe pattern caused by the difference of spectral phases [2]. The known spectral phase of the reference permits to retrieve the spectral phase of signal, and, together with the spectrum measurement, to recover the complex temporal amplitude of the signal through Fourier transformation. The SI-measurement is as accurate as any interferometric one, and the setup is rather simple, but its application range is restricted by the bandwidth of the reference. To avoid this restriction, the self-referencing methods of spectral shearing interferometry are developed [3,4], promoting the SI modifications to the class of the most popular methods, compatible with the FROG [1], at the expense of more complicated optical arrangement.
We develop a new method of similariton-based SI, which keeps the simplicity of the principle and configuration of the classic SI [2], along with its self-referencing performance. We experimentally examine the similariton-based SI in comparison with a prototype of the FO based on the pulse STI in the similariton-induced temporal lens. The use of similariton upgrades both the reference-based methods up to self-referencing ones.

2. Similariton-based spectral interferometry versus spectrotemporal imaging

Similaritons, pulses with the distinctive property of self-similar propagation, recently attract the attention of researchers, due to fundamental interest and prospective applications in ultrafast optics and photonics [8,9]. The self-similar propagation of the high-power pulse with parabolic temporal, spectral, and phase profiles was predicted in [10]. In practice, the generation of such parabolic similaritons is possible in active fibers, such as rare-earth-doped fiber amplifiers [11-13] and Raman fiber amplifiers [14], as well as in the laser [15]. The generation of parabolic similariton has been also proposed in a tapered fiber with decreasing normal dispersion, using either passive dispersion-decreasing fiber [16] or a hybrid configuration with Raman amplification [17]. Another type of similariton was generated in a conventional uniform and passive (without gain) fiber under the combined impacts of Kerr nonlinearity and dispersion [18]. In contrast to the parabolic similariton with parabolic amplitude and phase profiles, this nonlinear-dispersive similariton has only parabolic phase but maintains its temporal (and spectral) shape during the propagation, as well. Our SI studies of this type of pulses [18] showed the linearity of their chirp, with a slope given only by the fiber dispersion. This property leads to the spectrotemporal similarity of nonlinear-dispersive similariton, with accuracy given both by spectral broadening and pulse stretching. Both the parabolic similariton of active fiber and nonlinear-dispersive similariton of passive fiber are of interest for applications in ultrafast optics, especially for pulse compression [19,20] and shaping [21], similariton referencing temporal lensing, STI and SI [22]. The SI study provides the complete characterization and mathematical description of the nonlinear-dispersive similariton of up to 5 THz bandwidth [18]:

\[ A_{j}(t) = |\tilde{A}_{j}(f)| \exp\left[-i \phi_{j}(f)\right]_{f=0}, \quad \phi_{j}(f) = -\phi_{0}(f) = \beta_{j} f^2 / 2 \]

(1)

for the slowly varying amplitude \( A_{j}(t) \) and phase \( \phi_{j}(f) \), where \( \tilde{A}(f) = \text{FT}[A(t)] \) is the complex spectral amplitude with spectral phase \( \phi(f) \), \( C = (\beta_{j} f)^2 \) – chirp factor, \( \beta_{j} \) – coefficient of second order group velocity dispersion, \( t \) – running time, \( \omega \) – frequency, and \( f \) – fiber length. For comparison, the pulse pure dispersive propagation in temporal Fraunhofer zone results in the “spectron” pulse \( A_{j}(t) = \tilde{A}_{j}(f) \exp(i\beta_{j} f^2 / 2)_{f=0} \), with the same dispersion-induced phase. The applications of similariton demand to check and generalize this key peculiarity for broadband pulses. The studies of broadband similariton serve as a basis for the development of a novel method of similariton-based SI for the femtosecond pulse complete characterization. Below the studies directed to its development in comparison with the method of pulse STI in the similariton-induced temporal lens are presented. Application of similariton to the reference-based methods upgrades them up to the self-referencing ones, substantially improving their performance due to the enlarged application range along with the simplicity of the principle and configuration.

Describing the principle of similariton-based SI, the part of signal beam is injected into a fiber to generate the nonlinear-dispersive similariton-reference, with the complex spectral amplitude \( \tilde{A}(f, \omega) = |\tilde{A}(f, \omega)| \exp[i\phi(f, \omega)] \). The residual part of the signal, with complex spectral amplitude \( \tilde{A}(0, \omega) = |\tilde{A}(0, \omega)| \exp[i\phi(0, \omega)] \), is coupled with the similariton in a spectrometer with an appropriate time delay. The spectral fringe pattern \( S_{SI}(\omega) = 2|\tilde{A}(0, \omega)||\tilde{A}(f, \omega)| \cos[\phi(0, \omega) - \phi(f, \omega)] \), on the background of the signal and similariton spectra, completely covers the signal spectrum \( S(0, \omega) = |\tilde{A}(0, \omega)|^2 \), and the whole phase information becomes available, for any input signal. The known spectral phase of the similariton-reference allows to retrieve the signal spectral phase \( \phi(0, \omega) \), and by measuring also the
signal spectrum, to reconstruct the complex temporal amplitude \( A(0,t) \) of the signal through Fourier transformation. Thus, the method of similariton-based SI joins the advantages of both the classic SI [2] and spectral shearing interferometry [3,4], combining the simplicity of the principle and configuration with the self-referencing performance. Examining the similariton-based SI, we compare its measurements with the ones carried out by a prototype of FO-based on the pulse STI in the similariton-induced temporal lens in the sum-frequency generation process (SFG). Our comparative study, involving also theoretical and autocorrelation check, along with the study of the similariton-based SI, serves also for the inspection of the prototype of similariton-based FO, the measurements of which previously were compared with the autocorrelation only [7].

The method of SFG-STI for direct femtosecond scale measurements is based on the conversion of temporal information to the spectral domain in a similariton-induced parabolic temporal lens [7,22-24]. The setup of the similariton-based SI is modified to FO by replacing the temporal delay with a dispersive delay line in the idle arm, and placing a nonlinear crystal for SFG at the system output. In the spectral domain, the dispersive delay works as a parabolic phase modulator, and the signal \( \tilde{A}(0,\omega) \) passed through is described as \( \tilde{A}(d,\omega) = \tilde{A}(0,\omega) \exp(i\phi_d \omega^2/2) \), with the given coefficient \( \phi_d \approx -C_d^{-1} \). In the fiber arm, we have a nonlinear-dispersive similariton with the known parameters as in the case of similariton-based SI. In both arms of the setup, we have practically linearly chirped pulses, and the temporal and spectral complex amplitudes repeat each other in the temporal Fraunhofer zone, i.e. spectrum pulses are formed [7]: \( A(d,t) \propto \tilde{A}(d,\omega) \), and \( A(f,t) \propto \tilde{A}(f,\omega) \) with \( \omega = C_d f t \). Under the conditions of the opposite and same value chirps \( C_f = -C_d = C \), and constant similariton spectrum throughout the signal spectrum, the output temporal SFG-signal repeats the input spectral amplitude: \( A_{SFG}(t) \propto A(d,t) \times A(f,t) \propto \tilde{A}(0,\omega) \). Accordingly, the output spectral and input temporal amplitudes repeat each other \( \tilde{A}_{SFG}(\omega) \propto A(0,t) \), and the output SFG-spectrum displays directly the input temporal pulse: \( S_{SFG}(\omega) = |\tilde{A}_{SFG}(\omega)|^2 \propto |A(0,t)|^2 = I(0,t) \), with the scale \( \omega = C t \). The resolution of such a similariton-based FO is given by the transfer function of the similariton’s spectrum [7], and FO with a similariton-reference of the bandwidth of a few tens of nanometers provides the direct measurement of temporal pulse in a spectrometer, exceeding the resolution of the achievement of silicon-chip-based ultrafast optical oscilloscope [6] by an order of magnitude.

In the experiment, a standard Coherent femtosecond laser system is used, with the following parameters of radiation: 100 fs pulse duration, 76 MHz repetition rate, 1.6 W average power, 800 nm central wavelength. Different amplitude- and phase-modulated pulses at the setup input are shaped. Afterwards the radiation is splitted into high- and low-power parts. The low-power part is directed to the temporal delay or dispersive delay line (SF11 prism pair with the reverse mirror) for similariton-based SI and STI, respectively. In the second path, the high-power pulse, with average power of up to 500 mW, is injected into a standard single-mode fiber (1.65m, Newport F-SPF PP@820 nm) by a microscope objective (10×) to generate similaritons. For the SI-measurements, these two pulses are coupled directly into the spectrometer and the SI fringe pattern and signal spectrum are registered. To retrieve the spectral phase, the Fourier-transform algorithm of the fringe pattern analysis is used [24]. For the FO-measurements, a BBO nonlinear crystal at the input of spectrometer is placed, and the SFG-spectrottemporal image is registered directly. The similariton-based SI- and FO- measurements are carried out together with the autocorrelation check by a standard APE PulseCheck autocorrelator. First, the similariton-based SI is tested for the laser pulses stretched and chirped in SF11 glasses of different thickness, comparing the results with the autocorrelation measurements. The coefficients of the dispersion-induced parabolic spectral phases are \( \alpha = \phi(\omega) = 1.94 \times 10^3, 4.94 \times 10^3, 6.34 \times 10^3, \) and \( 10.78 \times 10^3 \) ps\(^2\) for the 0, 2, 3, and 5-cm glasses, respectively. The SI-reconstructed pulses, correspondingly, have durations of 108, 197, 252, and 365 fs, in a good accordance with the measured autocorrelation durations of 156, 298, 369 and 539 fs.
Afterwards, measurements for multi-peak pulses are carried out together with the autocorrelation check. The SI calibrating measurement of the $\alpha$ coefficient for similariton, using the known laser pulse as a reference, gives the value $\alpha = 2.1 \times 10^{-2} \text{ ps}^2$, in accordance with the expression $\alpha = \beta_2 f$ with the values $f = 49 \text{ cm}$ and $\beta_2 = 40 \text{ fs}^2/\text{mm}$ for 850 nm (provided by the fiber manufacturer). Then different multi-peak signal pulses are shaped inserting thin glass plates in parts of the beam. The beam parts passed through the plates obtain time delay with respect to the free-propagated part. The power proportion among the peaks is adjusted by moving the plates. The thicknesses of the plates give the time delay between the peaks; e.g. a 0.12 mm thick glass plate gives a 200 fs delay, if assuming the refractive index of the plate equal to 1.5. Using double- and triple-peak signal pulses, we carry out SI-measurements and compare the results with measured autocorrelation tracks. As Fig. 1 shows, having the spectrum (b, thin solid line) and SI-retrieved spectral phase (b, thick solid) of pulse, its temporal profile (c, solid) is reconstructed through Fourier transformation. To check the precision of our measurements through similariton-based SI, we calculate the autocorrelation of reconstructed pulse (d, thick solid) and compare it with the intensity autocorrelation measured at the input of the system (d, thin solid). The spectral shape of nonlinear-dispersive similariton (a) ensures the fulfillment of necessary conditions for the parabolicity of the spectral phase of similariton. The structure of the similariton spectrum (a), strange at first glance, is typical for short lengths of nonlinear-dispersive interaction, and is observed also for parabolic similaritons generated in fiber amplifiers [25]. The solid and dashed curves correspond to the pulse reconstruction with the spectral phase coefficients $\alpha = 2.1 \times 10^{-2} \text{ ps}^2$ and $\alpha = 1.995 \times 10^{-2} \text{ ps}^2$ (5% difference), respectively.

Fig. 1. Reconstruction of double-peak pulse (shaped by a 130-μm thick glass) through similariton-based SI: (a) spectrum of nonlinear-dispersive similariton; (b) retrieved spectral phase and measured spectrum; (c) reconstructed pulse temporal profile; and (d) autocorrelation tracks. Solid and dashed curves are for $\alpha = 2.1 \times 10^{-2} \text{ ps}^2$ and $\alpha = 1.995 \times 10^{-2} \text{ ps}^2$ (5% difference), respectively, and the thin solid one in (d) is the measured autocorrelation track.
Fig. 2 shows the analogue procedures for a pulse with more complex sub-structure. The application range and limitations of similariton-based SI are conditioned by the parameters of input radiation and fiber, which are necessary to generate the similariton-reference with parabolic phase. Fig. 1 and 2 illustrate the experiment for the typical regime preceding the similariton shaping: results for double- and triple-peak signal pulses are shown.

Finally, we compare the measurements of the similariton-based SI and FO, together with a theoretical check. The double-peak signal pulses are shaped with the spectral domain amplitude- and phase-modulation given by the peaks’ temporal distance $T$ and their proportion $\mu$. The temporal amplitude $A(t) = A_0(t) + \mu A_0(t + T)$ corresponds to the complex spectral amplitude $\tilde{A}(\omega) = \tilde{A}_0(\omega) \rho(\omega) \exp[i\phi(\omega)]$, with the $\rho(\omega) = \sqrt{1 + \mu^2 + 2\mu \cos(\omega T)}$ amplitude- and $\phi(\omega) = \arctan([\sin(\omega T)/\mu^{-1} + \cos(\omega T)])$ phase-modulation. To shape such double-peak pulses, the laser beam is expanded and a thin glass plate in its part is placed, as explained above. The similariton-based SI and FO are comparatively experimented using the double-peak signal pulse: the SI-reconstructed pulses are compared with spectrotemporal images of the signal. Fig. 3 illustrates this experiment: the quantitative accordance of the measured spectrum and retrieved spectral phase with the theoretical curves leads to an accurate pulse reconstruction through similariton-based SI (dotted). An accurate STI (solid) is ensured by the similariton of the bandwidths of $\geq 40$ nm. The differences between these independent SI- and FO-measurements and theoretical curve (dashed) are hardly seen, evidencing both the accuracy of the mentioned measurements and the potential of similariton-based methods.

Thus, the methods of similariton-based SI and STI are experimentally demonstrated as two applications of similariton. The reference-based methods become self-referencing by the use of similariton. Obviously, the demonstrated methods of femtosecond signal characterization can be implemented also by the use of “standard” parabolic similaritons generated in active or dispersion
decreasing fibers. In a recent progress in the generation of parabolic broadband similaritons, bandwidths of up to 11 THz (40 nm at 1050 nm central wavelength) are achieved [25]. However, the use of the nonlinear-dispersive similariton generated in a piece of standard passive fiber currently is more beneficial, providing larger bandwidths and thus larger application ranges with technically simpler experimental arrangement.

![Graph](image)

**Fig. 3.** Comparison of similariton based SI and FO for a double-peak signal pulse. Dotted, solid and dashed curves are for SI, STI and simulation, respectively.

### 3. Characterization of broadband similaritons generated in passive fiber

The applications of similariton to ultrafast optics demand the generation and study of broadband similariton i.e. generalization of Eq. (1). Particularly, the resolution of the femtosecond oscilloscope, based on the similariton-induced parabolic lens, is given by the bandwidth of similariton, and the application range for similariton-based SI is as large as broadband the similariton-reference is [7,22-24]. The pulse compression ratio is also as high as the spectral broadening factor is [19,20].

We applied the chirp measurement technique through spectral compression and frequency tuning in the SFG process [23,24] for broadband similaritons of up to 50-THz bandwidths with the experimental setup of FO. The intensity profile of broadband similariton can be measured by means of the cross-correlation technique, using the SFG-interaction of similariton with the laser pulse as a reference. A spectral detection of the SFG-signal will give also information on the chirp of similariton, modifying the cross-correlation technique to the cross-correlation frequency-resolved optical gating (XFROG) [26]. Our additional modification, the use of a dispersively chirped reference pulse, provides a spectrally compressed SFG-signal in a wider spectral range, and thus, more efficient measurement [23,24]. The SFG-interaction of up- and down-chirped pulses results in the chirp cancellation and spectral compression, and a temporal delay between these two pulses leads to the frequency shift of the SFG-signal, according to the concept of the temporal lens [7]. The temporal delay between the SFG-interacting pulses in the range of ± 16 ps results in a ± 20 nm wavelength shift for the 22 times SFG-spectrally compressed signal (down to 0.12 nm at 400 nm central wavelength), corresponding to the chirp measurement of similariton in the span range of 160 nm (75 THz) at 800 nm central wavelength. Resulting experimental 3D pattern completely characterizes the generated broadband similariton, giving by projections the temporal and spectral profiles of the intensity \( I(t) \) and \( I(\lambda) \), and the curve \( \lambda(t) \) connected with the chirp \( \phi(t) = \dot{\lambda}(t) \) [23,24]. The processing of experimental data
gives the polynomial \( \dot{\phi}_f(\omega) = -15.06 \times 10^3 \text{ fs}^3 \times \omega^2 - 81.13 \times 10^3 \text{ fs}^2 \times \omega \) for derivative of spectral phase. Fig. 4 shows the extracted spectral phase of similariton \( \phi_f(\omega) \). The circles in Fig. 4 are the measured experimental points; the dashed and solid curves are for the polynomial and parabolic fits, respectively.

Thus, the complete characterization of 50-THz bandwidth nonlinear-dispersive similariton states that only fiber dispersion determines its phase (chirp). The third order dispersion (TOD) of the fiber results in the same additional phase for broadband nonlinear-dispersive similariton and spectron:

\[
\Delta \phi(f,t) \approx \Delta \phi(f,\omega) \bigg|_{\omega=\omega_t} = - (\beta_3 f / 6) \omega^3 \bigg|_{\omega=\omega_t} \approx - \beta_3 (6 \beta_3^2 f^2)^{-1} t^3 \quad (\beta_3 \text{ is the TOD coefficient}).
\]

The \( \sim 1\% \) accuracy of the parabolic fit for the spectral phase of the 50-THz bandwidth similariton gives the range of applications for aberration-free similariton-based STI and SI.

4. Conclusion

We develop and implement a similariton-based self-referencing method of SI for the complete characterization of femtosecond signal. The method is based on the similariton generation from the part of signal and its use as a reference for the interference with the signal in the spectrometer. Therefore, the method of similariton-based SI combines the advantage of the simple principle and configuration with the self-referencing performance. We experiment the similariton-based method of SI in comparison with the measurements carried out with the prototype of femtosecond oscilloscope based on the STI in a similariton-induced temporal lens. Our comparative study, carried out together with theoretical check and autocorrelation measurements, evidences the quantitative accordance and high precision of both the similariton-referencing methods of SI and STI for accurate femtosecond scale temporal measurements. The similariton-based STI has the advantage of direct pulse measurement leading to the development of a femtosecond optical oscilloscope, but it does not give the phase information without additional interferometric measurement. The novel method of similariton-based SI, with a rather simple setup and self-referencing performance, provides the complete (amplitude and phase), high-resolution characterization of femtosecond signal.

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