Numerical modeling and experimental verification of advanced methods for characterization of broadband optical pulses and optical frequency combs

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Abstract— **We propose novel linear method for measuring ultrafast pulse trains with extremely high pulse repetition rates that are commonly generated in nonlinear microresonators. The method combines single-shot spectral interferometry with the reference pulses and an advanced version of the frequency resolved optical gating algorithm to reconstruct the initially unknown reference pulses.**

I. Introduction

The rapid development of novel ultrafast optical sources requires novel advanced methods for pulse characterisation. The temporal shapes of broadband and ultrashort (femtosecond and picosecond) pulses can not be directly measured by currently available photodiodes; therefore, has to use indirect methods and the corresponding numerical retrieval algorithms.

Although there are many existing pulse shape reconstruction algorithms [1], for emerging applications, such as ultra-high-repetition-rate frequency combs and broadband optical supercontinuum generation resulting in formation of complex pulse shapes, these methods needs to be updated and novel techniques have to be introduced. Frequency combs with a very high repetition rate (corresponding to the comb lines spacing) are being actively studied in the context of femtosecond lasers and microresonators [2]. Measuring a train of broadband (>10 nm) low-energy pulses with an ultrahigh repetition rate in the range from several tens to several thousands gigahertz is a difficult task. Self-referenced methods based on nonlinear interactions are difficult to apply because of very low efficiency of nonlinear processes at low pulse energies. Therefore, methods providing linear response should be used instead.

Here we present an upgraded method based on the frequency resolved optical gating utilizing second harmonic generation (SHG-FROG) for precise characterisation of complicated pulses and propose a novel linear technique for measuring ultrafast pulse trains with extremely high pulse repetition rates that are commonly generated in nonlinear microresonators. These two methods in combination provide a complete route for characterization of temporal profiles of high-repetition rate frequency combs.

We performed rigorous numerical testing of the developed methods and confirmed their ability to reconstruct complicated pulse shapes, which are known to be difficult to reconstruct using existing algorithms.

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II. Methods

We propose using spectral interference between the comb lines and an externally generated strong reference signal to retrieve the relative phase between these two signals. The phase of the reference signal can be measured beforehand, then the unknown phase of the comb can extracted, and the temporal profile of the pulses can be calculated by using the Fourier transform. Thus, the original problem is divided into two parts: 1) accurate measurement of the spectral phase of the reference signal by a self-referenced method, 2) measurement of the relative phase of the comb with respect to the reference signal and reconstruction of the comb temporal shape. Spectral interference between comb and reference pulses can be detected in a single-shot regime using a technique based on the dispersive Fourier transform, which performs mapping of the frequency signal structure to the time domain [3]. The reference signal must have spectral bandwidth wider than the comb spectrum. This can be achieved by spectral broadening of the pulses generated by standard mode-locked lasers; however this makes the phase of the reference signal quite complicated and difficult to retrieve by standard methods. To resolve this issue we propose to use modified SHG-FROG method. The standard FROG method utilizes a Michelson-type interferometer to generate two replicas of the input pulse with relative delays. These two replicas interact in a second-order nonlinear crystal in which a sum-frequency signal is generated and then measured by a

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spectrometer [4]. In the modified version, in addition to the standard FROG trace, the interference trace between the FROG signal and the second harmonic of the initial pulse are measured. This additional measurement provides some information about the phase of the FROG trace. A very robust and fast algorithm was developed to reconstruct the pulse intensity and phase profiles, which can than be used as references for comb diagnostics.

III. Results

In numerical simulations we first tested the ability of the modified FROG method to measure complex pulse shapes with a large phase. We numerically generated several different waveforms consisting of single or double pulses and having large quadratic and cubic phases. Then we simulated the experimental scheme of modified FROG setup. The simulated FROG traces with some added noise were fed into the retrieval algorithm and the reconstructed results were compared with the initially generated fields. An example of numerical simulation is shown in Fig. 1. A double pulse with a large cubic phase was numerically generated and successfully retrieved. In all numerical tests the retrieved pulses coincided with the initially generated ones within the acceptable noise limits. The convergence of the retrieval algorithm was very fast, so only a few tens of iterations were required to retrieve the pulse shape. These simulations confirmed that broadband reference signals even with complex phase profiles can be successfully retrieved.

Then we tested the possibilities of reconstructing the temporal profiles of frequency combs with ultrafast repetition rate. We prepared test signals resembling the combs, generated in silica microresonators with the repetition rate of about 400 GHz and a characteristic pulse duration of 500 fs. To test the system performance we assumed that the pulses were strongly distorted by the influence of the third-order dispersion. We simulated the experimental setup which is capable of simultaneously tracking the phases of 7 comb lines. This experimental setup is currently being constructed at IAP RAS. Our modeling (Fig. 2) showed that even with small number of the measured comb lines the retrieved pulse shapes are quite close to the original shapes, which proves the feasibility of our approach.

We also performed preliminary experimental tests using an early version of our experimental setup, which can measure 4 comb lines simultaneously. To be able to verify the measurement results, we prepared a test comb by propagating a known femtosecond pulse train through a fiber with a known dispersion. The measured phases of the combs lines were in a good agreement with the calculated phases.

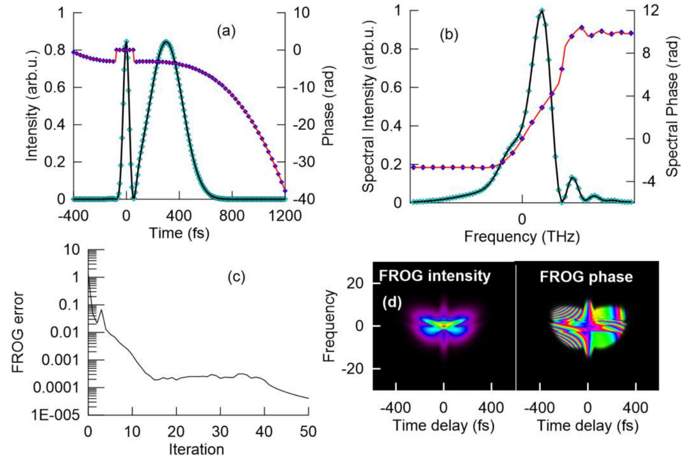

Fig. 1. Simulation of the pulse retrieval: generated field temporal intensity and phase (a, solid black and red curves, respectively), spectral intensity and phase (b, solid black and red curves, respectively); retrieved field temporal and phase profiles (a, cyan and blue rhombs, respectively) and spectral intensity and phase (b, cyan and blue rhombs, respectively); convergence of the FROG error (c), simulated FORG trace intensity and phase (d).

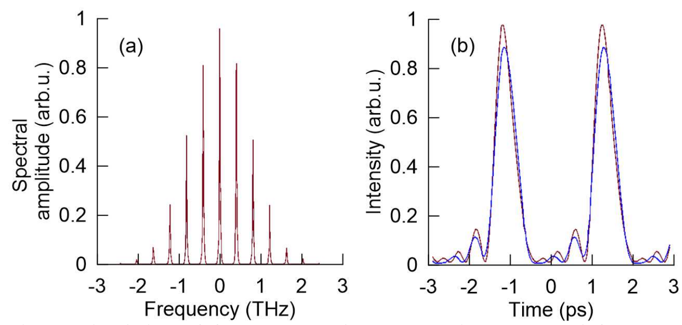

Fig. 2. Simulation of frequency comb reconstruction: generated frequency comb (a) and its temporal profile (b, red curve); retrieved temporal profile (b, blue curve).

In conclusion, we proposed and numerically tested a novel method for reconstructing the temporal shapes of optical frequency combs with an ultrahigh repetition rates. The method combines spectral interferometry with the reference pulses and an advanced version of the FROG algorithm to reconstruct the initially unknown reference pulses.

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