Ultrashort Pulse-beam Characterization Using Femtosecond Interferometric Shack-Hartmann Frequency Resolved Optical Gating

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Abstract: We introduce a self-referenced system that retrieves the full spatio-temporal profile of an ultrashort pulse using a Shack-Hartmann and second harmonic generation FROG. The key feature is the precise co-location of a spectral phase measurement at one spatial position with the spectrally resolved spatial measurements.

1. Introduction

Pulse-beam characterization is an important problem in optical physics, particularly as cutting edge experiments demand the use of ever shorter pulses (10's of fs or shorter) and more exotic beam profiles. The spatio-temporal profiles of such wide-bandwidth pulses can be complicated, so full characterization of the coupled temporal and spatial profiles of the pulse are required for valid results. Traditional pulse characterization devices extract the spatial or temporal profile of the pulse, separately; e.g. M-squared measurement combined with a frequency resolved optical gating (FROG) measurement [1] or spectral phase interferometry for direct electric-field reconstruction (SPIDER) [2] pulse characterization. Existing spatio-temporal characterization techniques are complex to implement and are not self-referenced. When optics such as prisms, gratings, and short focal-length lenses are used, complex spatio-temporal distortions can be introduced to the pulse. Moreover, it is now more common than ever to exploit spatial chirp and other spatio-temporal shaping techniques. Therefore, a simple apparatus that provides a reliable spatio-temporal characterization will find broad application.

2. Experimental set up and analysis

We implement an optical system that retrieves the full spatio-temporal profile of a self-referenced ultrafast laser pulse called Femtosecond Interferometric Shack-Hartmann Frequency Resolved Optical Gating (FISHFROG). A block diagram of the FISHFROG apparatus is shown in Fig. 1. A pulse is incident into a scanning Mach-Zehnder interferometer (I of Fig. 1), producing exact spatio-temporal replicas of the pulse. The interferometer consists of two thin, low-dispersion, high wavefront quality beam splitters. To provide temporal delay between the replicas, a delay stage is placed in one arm of the interferometer (II of Fig. 1). The interferometer produces two sets of duplicate pulses (four pulses in total). Two pulses are imaged through the 'FISH' (Shack-Hartmann) and two pulses are imaged through the FROG legs of the system (III of Fig. 1) simultaneously. The first set of replicas are imaged through a 4F imaging system onto a Shack-Hartmann wavefront sensor (WFS) (IV of Fig. 1). The other set of replicas are imaged through a reflective imaging system, focused through a doubling crystal which generates a frequency-doubled signal that is measured by a fiber spectrometer (V of Fig. 1). Both imaging systems relay a common reference plane in front of the interferometer (VI of Fig. 1), which is used for a one-time calibration. The calibration consists of a diffraction limited aperture placed at the reference plane and a spot-field image and frequency-doubled spectrum is collected. The spectral phase in the WFS image is set directly to the spectral phase reconstructed from the spectrum.

The 4F imaging system of the FISH leg does not impart any spatial phase onto the copies of the input pulse. Additionally, the reflective imaging system of the FROG leg does not impart any temporal dispersion onto the copies of the input pulse. The Shack-Hartmann device collects spot-field images and the fiber spectrometer collects frequency-doubled spectra for each delay point of the temporal scan. The collection of FROG scans results in a collinear FROG (cFROG) trace. Any errors in the delay stage are corrected in post processing through the use of a Michelson interferometer which is coupled to the delay stage of the Mach-Zehnder interferometer (II of Fig. 1).

Both the spot-field images and cFROG trace are interpolated onto a linear delay axis. The collection of spot-field images are then Fourier transformed along the delay direction, producing a three-dimensional array with axes of (space, space, temporal-frequency). This represents a monochromatic spot-field image for each frequency in the input spectrum. Each spot-field image is then processed to produce the spatial phase and amplitude for each frequency in the input spectrum. The linearized cFROG trace is Fourier transformed in two-dimensions and filtered to retain the DC component of the trace and then inverse Fourier transformed. The resulting trace yields the equivalent of a non-collinear FROG trace. The filtered FROG trace is processed using the Principal Components Generalized Projections (PCGP) algorithm [3] to produce a reconstruction of the spectral amplitude and phase for one (calibrated) spatial position. The complex spatial and spectral reconstructions are combined to form the

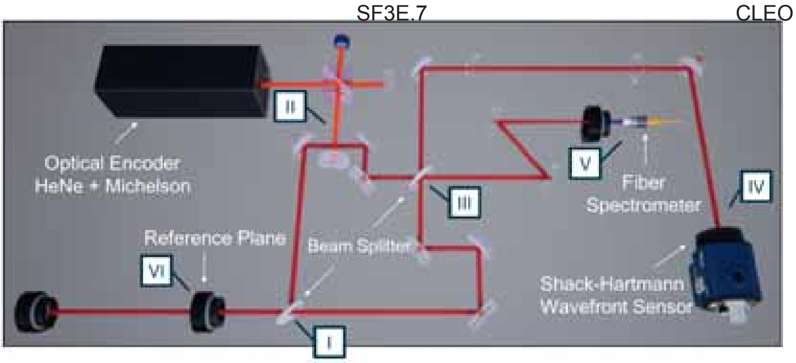

Fig. 1. Schematic of FISHFROG. An ultrafast laser pulse is incident into a Mach-Zehnder interferometer (I) where the pulse is duplicated within the interferometer. One arm of the interferometer contains a delay stage to provide temporal delay between the replicas (II). The replicas within the interferometer are duplicated again by the output of the interferometer (III) and simultaneously imaged through a 4F imaging system onto a WFS (IV) as well as a reflective imaging system through a second harmonic generation (SHG) FROG setup (V). Both of the imaging systems relay a common reference plane upstream of the interferoemter for calibration purposes (VI).

full spatio-spectral profile of the incident pulse, and then Fourier transformed to produce the full spatio-temporal profile of the incident pulse.

We use a custom-built Ti:sapphire regenerative amplifier system with 30 fs pulse duration at 1 kHz and 808 nm as our input to FISHFROG. The laser system is detuned to introduce high order spectral phase onto the laser pulse. The filtered version of the measured cFROG is shown in Fig. 2(a) with the frequency-doubled interference and background removed. The reconstructed FROG trace, shown in Fig. 2(b), is decomposed into the following pulse intensity (Fig. 2(c)) and spectral phase (Fig. 2(d)) profile. The reconstructed spatio-temporal profile of the pulse is shown in Fig. 2(e).

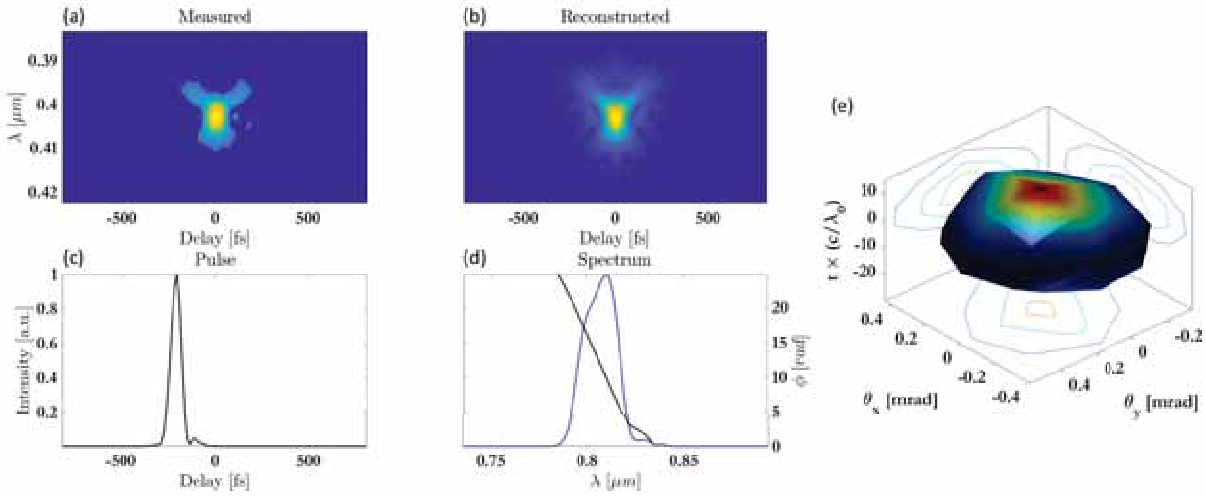

Fig. 2. (a) Filtered version of measured cFROG trace (b) Reconstruction of filtered cFROG trace (c) Reconstructed pulse intensity (d) Spectrum and spectral phase of reconstructed pulse (e) Spatio-temporal reconstruction of pulse where θ_x and θ_y are the corresponding spatial frequencies scaled by the central wavelength and time is scaled by the central frequency.

The post-processing of the FISHFROG scan with the detuned pulse results in a frequency-doubled spectrum centered on 402.87 nm with a 69.3105 fs pulse width and 21.6174 nm of bandwidth. High order phase is evident in the spectrum profile (Fig 2(d)) which is also consistent with the form of the FROG traces (Fig. 2(a) and Fig. 2(e)).

The authors gratefully acknowledge funding through SBIR DE-SC0021499.

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