Characterization of ultra-short laser pulses

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Application Note

Introduction

The first Rubin laser in the year 1960 was a pulsed laser. In the following years cw lasers were developed, but the pulsed lasers were more exciting since they open a new field of research due to high intensity and its resulting nonlinear effects. But the shorter the pulses became, the more challenging their characterization was.

Today's fs pulses are much shorter than the rise time of ultrafast photo diodes. New techniques have been developed. By now we can divide into interferometric methods like SPIDER (spectral phase interferometry for direct electric field reconstruction) [1] or MEFISTO (measurement of the electric field by interferometric spectral trace observation) [2] and spectrographic methods like FROG (frequency-resolved optical gating) [3] or TASC (temporal analysis of spectral components) [4].

These methods lack of unique field retrievals of arbitrary pulses. This is a severe problem if the laser pulse is structured as for example in soliton molecules due to well separated frequency components [5].

Problem of uniqueness

Non-self-referenced methods like XFROG or XSPIDER may be able to retrieve phase and intensity uniquely, but require a well-known reference pulse. This implies errors, which directly propagate into the results.

In [6] it was rigorously proven that no ambiguities are present if the spectrogram of a blind-FROG measurement is non-centro-symmetric. The VAMPIRE (very advanced method for phase and intensity retrieval of e-fields) [7], a spectrographic self-referencing cross-correlation technique, utilizes that by means of a conditioning filter. VAMPIRE is similar to the double-blind FROG method, but it has a conditioning filter and a new algorithm [8], which uses the spectra of the input pulses as constraints. The general setup idea is shown in Fig. 1. For the characterization of a laser the reference pulse (signal 2) may be a copy of input pulse (signal 1) which is modified by the conditional filter to fulfill the requirements for a unique retrieval.

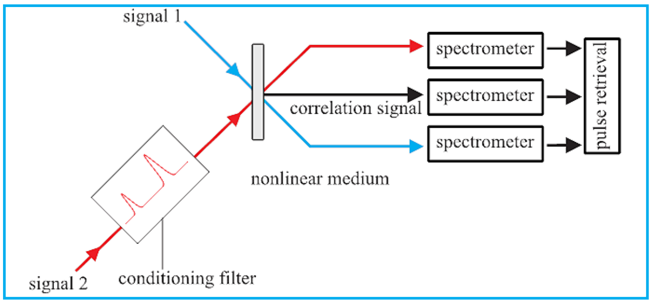

Fig. 1: VAMPIRE scheme: signal 1 (input pulse) and signal 2 (reference pulse) overlap in space and time in the nonlinear medium. The correlated signal as well as signal 1 and 2 will be analyzed in a spectrometer and used for pulse retrieval.

Experimental setup

In our single-shot VAMPIRE we created the reference pulse (signal 2) by using a copy of signal 1 and modifying it in a Mach-Zehnder interferometer to fulfill the requirements for unique retrieval. Both signals are focused to a line that overlap in space and time in the nonlinear crystal.

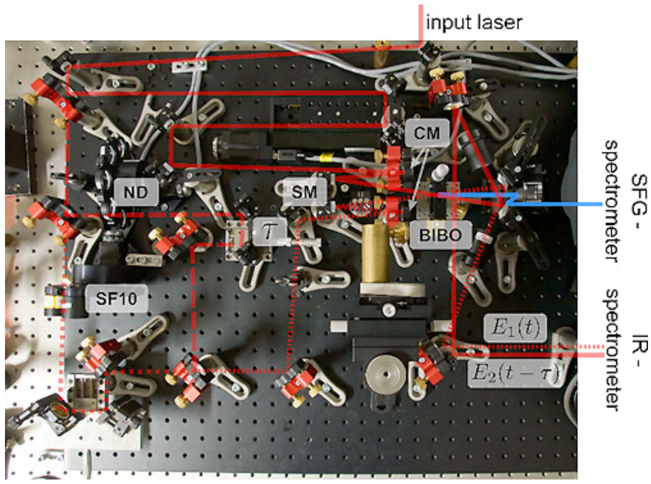

Fig. 2: Experimental single-shot mirror based VAMPIRE setup (ND: neutral density glass, CM: cylindrical mirror, SM: spherical mirror, SFG: sum frequency generation, IR: infrared)

While there are no special requirements for the IR spectrometer to measure signal 1 and 2, the sum frequency generation (SFG) spectrometer requirements are much harder. The spectrometer must be almost astigmatism free otherwise the spectrogram would be distorted and a reconstruction may fail. But even more important is a sensitive camera since the SFG signal intensity is quite low compared to signal 1 and 2. We built an astigmatism compensated spectrometer and used the Andor EMCCD camera iXon3 DU888 DC-BBB as detector.

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It is an electron multiplying CCD (EMCCD) camera which has a great advantage over a conventional CCD; especially for the initial adjustment or after changing the nonlinear crystal. If the crystal is misaligned or if the pulses do not overlap in space and time, one could not detect a SFG signal at all with a conventional CCD. But using a high EM gain makes short exposure times possible and therewith one can even use the video mode. This way one can "play" with all parameters like focus, rotation angles of the crystal, delay or position of the three created lines to quickly find the SFG signals. This is an enormous advantage over a conventional CCD. The Andor software is very powerful and handy. Using different color schemes makes it easier to grasp the total information of the image at once. With the help of a region of interest and its characteristic values, like "maximum count" and "mean", it is obvious whether the image is over exposed or not.

Measurement

In Fig. 3 we present first results from Ti:sapphire laser. For a complete set of data it is necessary to measure all spectra at the same time, which was quite simple due to the trigger connectors of the camera. However, we do not show the spectra of signal 1 and 2, but only the electric field of the spectrogram in Fig. 3a). This is square root of the measured camera image having the frequency scale perpendicular to the slit axis and the time along the slit axis. It is important to have a good signal to noise ratio (SNR), since the algorithm retrieves the complex electric fields and uses the absolute values of the field as constraint. If the image had a bad SNR, the field had an even worse SNR. Having a 14 bit AD converter, a high quantum efficiency [9] and an electron multiplier is very helpful in this matter. Fig. 3c) and 3d) show the retrieved pulses and their phase. From these retrieved pulses a spectrogram has been calculated, which is shown in Fig. 3b) to compare with the measured spectrogram. Both look very similar and imply a good reconstruction of the electric fields. We can see, that the laser and its unmodified copy have a quadratic temporal chirp. The modified copy of the laser has a quadratic temporal phase as well, but with the opposite sign. The reason is a 45 mm thick slab of SF10 in the conditioning filter which is also responsible for this asymmetry in the trace.

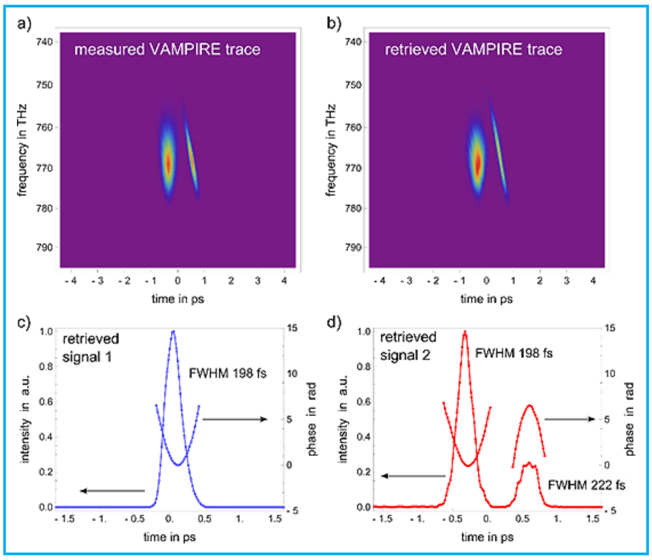

Fig. 3: a) measured absolute electric field (root of measured intensity); b) reconstructed spectrogram using the retrieved signals 1 and 2; c) retrieved signal 1; d) retrieved signal 2

Despite all the positive we have to mention that the Andor iXon3 EMCCD camera uses a frame transfer chip. That means that after the exposure has finished the whole image is shifted to a covered chip below and afterwards read out. When using short exposure times (10 ms or shorter) it happens that very weak lines of intensity along the shift direction may be observed due to the fact, that the chip is exposed to light during the transport time. This is very critical in our case especially because we use the square root of the signal. But this can be avoided by longer exposure times. LOT-QuantumDesign as distributor informed us about this issue prior to our order, but we wanted to mention it in this context. For very short exposure times a global shutter is necessary, but this implies a lower quantum efficiency.

Conclusion

The Andor EMCCD camera iXon3 DU888 DC-BBB is a very sensitive and powerful camera with an adequate software that is exactly what we needed for our measurement of the spectrogram in our VAMPIRE application. This way we were able to demonstrate that single-shot VAMPIRE is a viable possibility for single-shot pulse characterization.

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