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A fiber Mach–Zehnder interferometer for the unique phase retrieval of ultrafast pulses with a 1 THz gap

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Abstract Unique phase retrieval of ultrashort pulses with well-separated frequency components was demonstrated using a cross-correlation technique with a conditioning filter. Here, this filter was designed as an unbalanced fiber Mach–Zehnder interferometer. A pulse-shaping apparatus was used to generate pulses with a 1 THz gap. A fast phase-retrieval algorithm was then employed to reconstruct these pulses. Ambiguities of relative-phase or other characteristics were not found under any circumstances.

1 Introduction

A problem of general interest in femtosecond optics is the full characterization of ultrashort optical signals as complex electric fields. A straightforward method is the use of interferometry where no mathematical problems occur. Spectral phase interferometry for direct electric field reconstruction [1] (SPIDER) and measurement of electric field by interferometric spectral trace observation [2] (MEFISTO) allow field reconstruction by simple algebraic inversion algorithms. Non-interferometric spectrographic techniques such as frequency resolved optical gating [3] (FROG) and temporal analysis of spectral components [4] (TASC) rely on the solution of a phase-retrieval problem. A central question is whether these methods allow to characterize pulses of any arbitrary shape. Upon closer inspection it turns out that none does, as was demonstrated by investigations of the shortcomings of these methods: Pulses with well-separated frequency components cannot be recovered [5, 6]. This is because inside the gap the phase is undefined; in the reconstruction the relative phase of the frequency components above and below the gap can then only be determined up to an arbitrary constant. Such relative-phase ambiguity gives rise to reconstruction errors of the temporal profiles. However, ultrashort pulses with separated frequency components are not so exotic but appear rather frequently. One example is research of soliton molecules in optical fibers [7], but many other experiments in physics, biology, and medicine [8] yield ultrashort pulses of completely unknown shape. In the quest for characterization of any arbitrary pulse shape it is of utmost importance to set out with an optimal design of the setup.

The non-self-referenced variants of FROG and SPIDER like XFROG [9] and XSPIDER [10] can be applied to solve the problem under consideration, but not without difficulties. For instance, the phase reconstruction procedure of XSPIDER yields the derivative of the spectral phase $\phi(\omega)$ with respect to ω instead of the spectral phase itself. Therefore, the offset between the two spectral phase functions of the two well-separated components in the frequency domain remains unknown. Unfortunately, XFROG is also not fruitful because it requires well characterized reference pulses, and there is no general guarantee that it will give a unique solution. However, relative-phase ambiguities can be avoided by the use of blind-FROG under certain conditions [11]. Blind-FROG is a self-referenced cross-correlation technique. Re-

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cent work has demonstrated the necessary conditions for the uniqueness of blind-FROG [6]. Based on this work, we developed a technique called "Very Advanced Method for Phase and Intensity Retrieval of E-fields" (VAMPIRE) [7, 12]. Although VAMPIRE is based on the blind-FROG scheme, it is different enough to warrant a new name. The VAMPIRE scheme contains a conditioning filter which is the key element of this technique because it prevents ambiguities. The VAMPIRE phase reconstruction algorithm generally converges even for complex and noisy pulses and is different from the well known principal component generalized projections algorithm [11].

In what follows, we present a successful characterization of ultrashort laser pulses with a wide spectral gap. A dedicated pulse-shaping apparatus was used for the generation of a 1 THz gap. This particular value is, of course, arbitrary. It was chosen because it constitutes a sizable fraction of the entire spectral width, and therefore creates a hard-to-assess situation which will put the reconstruction to a severe test. Using the VAMPIRE technique, we reconstructed the pulses with our phase reconstruction algorithm. This requires reference pulses which were generated by a conditioning filter, here an unbalanced fiber Mach–Zehnder interferometer with two different types of fiber. An exact characterization of the reference pulses is not necessary.

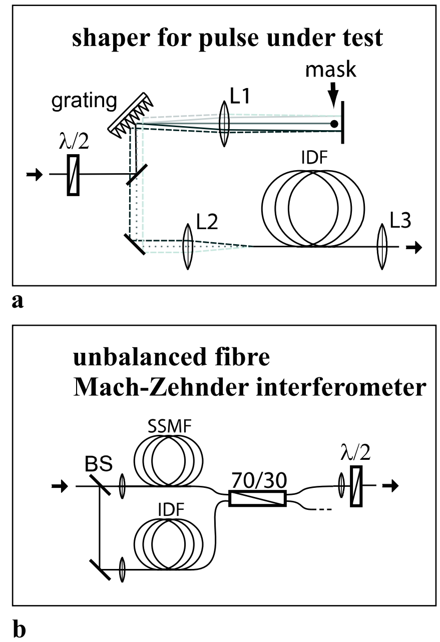

Fig. 1 (**a**) Schematic of the pulse-shaping apparatus to generate a hard-to-assess pulse shape. The grating and lens spatially disperse the frequency spectrum of the pulses. Spectral filtering is accomplished by utilizing a removable mask. Forward and backward beams are separated by a small tilt of the retroreflecting mirror so that both beams propagate in different planes. A short piece of fiber (IDF, 35 cm) optimizes the spatial beam profile. (**b**) Generation of a double pulse with different single pulse parameters (chirp, peak power, duration) for use as reference pulse. The two types of fiber have different dispersion parameters

2 Generation of signal and reference for the VAMPIRE technique

Both signal and reference are derived from the same light source, an optical parametric oscillator pumped by a mode-locked Ti:Sapphire laser. This source produces Gaussian pulses described by $\exp[-(1+iC)t^2/T_0^2]$ with a mild linear chirp of $C \approx 0.41$ and a temporal width of $T_0 = 250$ fs. The center wavelength is tunable; here we tune to 1525 nm. The repetition rate is 57 MHz. The pulses are sent through a variable attenuator, consisting of a half wave plate, and a polarizing beam splitter to set the desired power level for the experiment. Then they enter the pulse shapers, which are shown in Fig. 1.

To generate the pulse under test with a 1 THz gap, the initial Gaussian pulse is spatially dispersed by a blazed grating (600 lines/mm) and focused on the surface of a retroreflecting gold mirror. This mirror is tilted slightly such as to deflect the beam out of the plane of the figure. This way the forward and backward beams are separated. Upon second pass at the grating, angular dispersion is compensated but a spatial chirp of the beam remains. This signal is then passed through a short piece of single mode fiber to obtain a near-perfect spatial profile. In this arrangement a spectral gap can easily be created by a mask in the Fourier plane right in front of the gold mirror. Here we use a piece of 0.4 mm diameter wire. Note that the mask does not affect the spectral phase of those frequency components that can pass. This procedure provides an artificial signal which is suitable to test the correctness of the reconstructed spectral phase.

A suitable reference signal for VAMPIRE is, e.g., a double-peaked structure where both parts have a different chirp and peak power. With such reference a unique reconstruction result is guaranteed [6, 12]. The Gaussian pulse entering the conditioning filter is split into two parts by a 50/50 beam splitter. Either part is launched into a piece of single mode fibers; one has normal dispersion (inverse dispersion fiber, IDF), the other, anomalous dispersion (standard single mode fiber, SSMF). The distal fiber ends are spliced to a fiber coupler with a 70/30 ratio to recombine both parts. This guarantees a perfect spatial overlap. The separation of the pulses can be set by the position of one of the fiber launch platforms. The reference signal has no spectral gaps; its spectral width covers that of the signal. In Fig. 2 the spectra of signal and reference pulse are shown on a logarithmic scale. The intensity in the spectral gap (≈6.5 nm) is on the noise level.

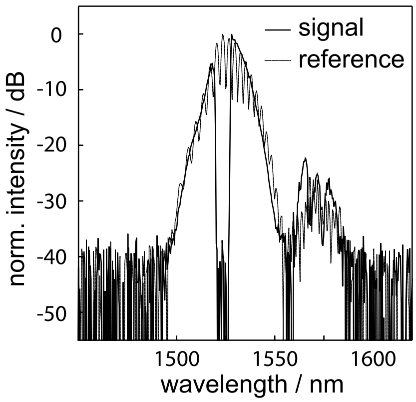

Fig. 2 Spectra of signal, with the cut spectral region, and reference pulse, which covers the spectral region of the signal

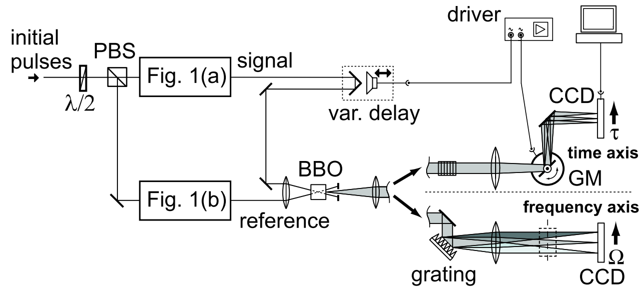

Fig. 3 Schematic of the experimental arrangement. PBS: polarizing beam splitter, BBO: non-linear crystal, GM: galvanometer scanner. The BBO crystal generates the cross-correlation of signal and reference, and a diffraction grating disperses it. The spectra are focused on an electronic camera (CCD) to obtain the VAMPIRE spectrogram. The delay axis is swept by a mirror mounted on a galvanometer scanner actuated synchronously with the variable delay of the signal

3 Experiment

With signal and reference prepared as described, we can use the VAMPIRE setup already employed in [7] with minimal adaptations. Figure 3 is the schematic of the experimental arrangement. Both signal and reference are focused into a non-linear crystal (type I BBO). A retroreflector mounted on the moving membrane of a loudspeaker provides a variable temporal delay between both pulses. A blazed grating (1200 lines/mm) disperses the sum-frequency signal and focuses it onto the light-sensitive element of an Apogee AP7 camera. This camera has a cooled CCD chip of 512 × 512 square pixels of 24 µm pitch. The spectral direction of the VAMPIRE spectrogram is imaged along pixel rows. The temporal deflection along pixel columns is provided by a mirror mounted on a galvanometer scanner, driven in synchronism with the loudspeaker. Due to a slight imprecision in the loudspeaker membrane movement, images from forward and backward scan are not exactly superimposed. Therefore, we block the beam during backward scans with a mechanical shutter. Scanning proceeds at ≈30 sweeps a second. Each scan maps out a complete spectrogram; exposure time control allows one to average over many such spectrograms. In an independent measurement an optical spectrum analyzer (not shown in Fig. 3 for clarity) is used to assess the optical spectra of the pulses.

We took data with and without spectral mask so that the reconstructed spectral phase functions can be compared. In Fig. 4 an example of a measured and a reconstructed VAMPIRE spectrogram is shown. Note that spectrograms are displayed as the amplitude of the electric field. The spectrogram consists of two different correlation structures produced between signal and the two individual pulses of the reference, with a temporal separation of ≈2.8 ps. The structures are tilted with respect to each other and have different intensities. This reflects the particular characteristic of the reference as detailed above.

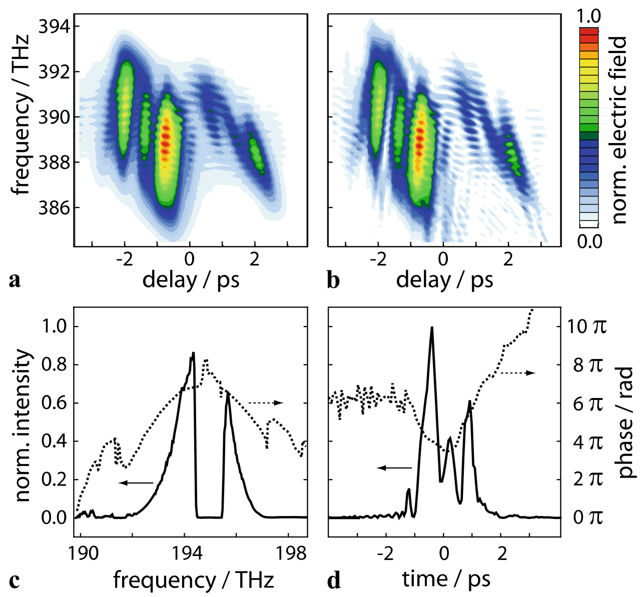

Fig. 4 Measured (**a**) and reconstructed (**b**) VAMPIRE spectrogram (electric field amplitude). (**c**) Independently measured spectrum and reconstructed spectral phase function of the signal. (**d**) Temporal pulse shape and phase function of the signal as obtained from a Fourier transform of (**c**)

The reference remains unchanged during all measurements. This provides a convenient reproducibility check: we compared all reconstructed spectral phase functions of the reference. They differ only in a phase offset and a tilt of the phase function, which trivially corresponds to a temporal shift of the pulse. Other than that, all reconstructions were consistent. In Fig. 5 the averaged spectrum and spectral phase function of the reference pulses obtained from all reconstructions are shown. For each discrete value of the frequency the error based on a standard deviation was calculated for the phase functions.

A comparison of the signal pulse reconstruction is depicted in Fig. 6. Each panel corresponds to five independent

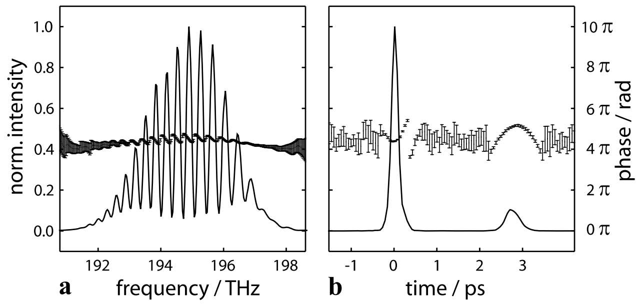

Fig. 5 Spectral (**a**) and temporal (**b**) intensity and phase of the reference pulse obtained from 10 independent measurements. The double pulse structure (**b**) with different chirp and peak power is evident. The pulse separation is ≈2.8 ps

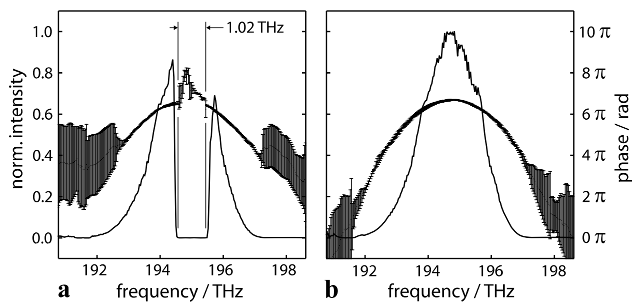

Fig. 6 Measured spectral intensity and retrieved phase of the signal. Averages of five independent measurements each. (**a**) Mask applied. There is a 1 THz spectral gap. (**b**) Mask removed for comparison

measurements. The left and the right panel show the same spectrum; however, the left panel includes the implied spectral mask. In this manner, both reconstructed phase functions can be directly compared. In the regions where the spectral intensity has a value above ≈10% of the peak intensity, the spectral phase error is very small ($<0.05\,\pi$). The spectral chirp has nearly the same value for both pulses. Inside the spectral gap, the phase oscillates around random values. However, on either side of the gap, the relative phase of the unaffected segments of the spectrum remains unchanged. This result is obtained every single time that a reconstruction is made. This is the experimental proof that VAMPIRE can unambiguously reconstruct the spectral phase of well-separated frequency components across a wide gap.

4 Conclusion

In summary, a technique for the unique reconstruction of ultrafast pulses with well-separated frequency components has been demonstrated. The experiment was carried out with ultrashort laser pulses with a 1 THz gap generated by a pulse-shaping apparatus. The chosen spectral gap width is just an example and is not limited to this particular value. Single mode fibers with normal and anomalous dispersion were used as the conditioning filter for the reference pulse, a key element of the demonstrated technique. A fast phase-retrieval algorithm was used to reconstruct the spectral phases. In the procedure demonstrated here neither relative-phase ambiguities nor other ambiguities appear, and there are no stagnations. We believe that at present our method is the only one capable of this performance.

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