Measurement of the Complete Electric Field of an Ultrashort Laser Pulse from a Single-Exposure Digital Hologram

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Abstract. Using a very simple apparatus, we generate multiple digital holograms in a single-exposure interferogram from which we experimentally reconstruct the complete electric field, $E(x,y,z,t)$, of a potentially complex ultrashort laser pulse in a single shot.

1. Introduction

In many situations, such as the measurement of high-intensity or scattered pulses, it is desirable to characterize an ultrashort laser pulse completely in space and time. Two-dimensional sensors are commonly used to obtain 2D information, $E(x,\omega)$ or $E(x,y)$, from a single exposure [1], and if an additional scan of the frequency, delay, or position is performed, it is possible to obtain the electric field, $E(x,y,\omega)$, as long as a train of identical pulses is available. Once a 3D measurement is accomplished, the z-dependence of the field is readily obtained by numerical evaluation of a diffraction integral. In fact, we recently showed that a self-referenced multi-shot measurement of the full 4D field $E(x,y,z,t)$ is possible using wavelength-scanned digital holography [2].

In this work, we present a method that similarly yields the complete field $E(x,y,z,t)$, but now from a *single* exposure—and using a much simpler apparatus. It obtains 3D (and hence 4D) intensity-and-phase information on a single shot by simultaneously recording multiple 2D holograms in a larger 2D interferogram. Specifically, we simultaneously record many (~20) digital holograms, each at a different wavelength, and each using a common pre-characterized reference pulse. As a result, we obtain the complete intensity-and-phase characterization of $E(x,y,\omega)$, and therefore of $E(x,y,z,\omega)$, on a single shot. The device uses a holographic element to achieve this in a very simple manner.

2. Experimental setup

The pulse under test illuminates a low-density 2D diffraction grating, which diffracts numerous orders, yielding a slightly tilted 2D array of replicas of this input pulse (Fig. 1a). The diffraction grating consists of small (10×10 μm) reflective chrome squares on a glass substrate, spaced by 50 μm. This optic can be used in transmission or reflection (if dispersion must be avoided). At the same time, a previously measured, spatially smooth, reference pulse is spectrally dispersed and crossed with the array of unknown pulses, generating an array of holograms (Fig. 1b). This array of holograms is then captured by a high-resolution camera.

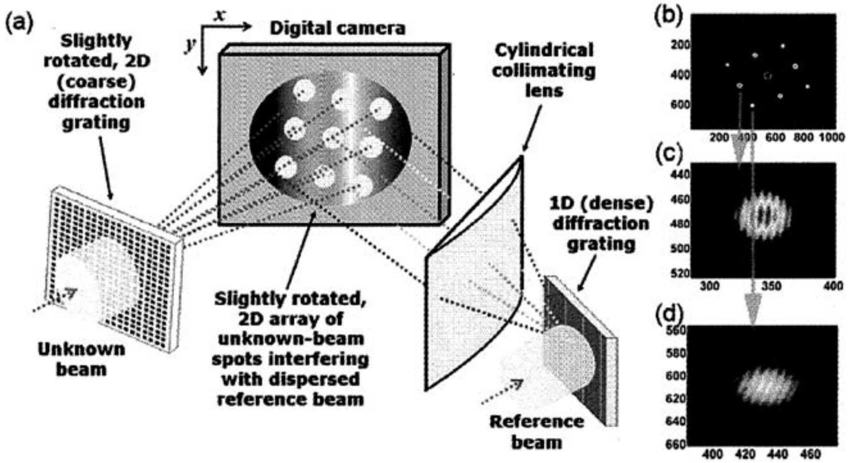

Fig. 1: **(a)** Schematic of our single-shot complete-pulse-diagnostic setup. **(b)** Individual digital holograms of the replicas of the unknown pulse interfering with the reference beam. **(c–d)** Magnified images of two digital holograms

Due to the slight rotation of the 2D grating, each hologram occurs at a different color, specifically, that of the dispersed reference pulse at each hologram's position (the additional colors in the unknown pulse contribute no fringes and are eliminated by filtering). Fourier synthesis of the relatively broadband pulse from the various retrieved fields, $E(x,y,\omega_n)$, at each of the various frequencies, ω_n, is then straightforward [2].

3. Results

We demonstrate our technique using ultrashort pulses from a Ti:Sapphire oscillator. Because of the high repetition rate (>80 MHz) of the laser, multiple pulses are used while the data is recorded. Single-shot measurements are possible, however, since only a single camera frame of data needs to be recorded in this linear technique.

Because we can measure the intensity and phase of $E(x,y,\omega)$ relative to the reference pulse, it is possible to extract from the measured data the spectral phase of the pulse under test, i.e., the phase $\varphi(\omega)$ of $E(x = 0,y = 0,\omega)$. To demonstrate this, we modified the spectral phase of the pulse under test to reproduce two typical situations: we first used a thin glass window to create a group delay, and therefore a linear spectral phase, then a thick window, which introduces a large amount of group-delay dispersion, and therefore a parabolic spectral phase. Both spectral phases obtained from these experiments are consistent with independent measurements.

The profiles $E(x,y;\omega_k)$ of different frequencies ω_k are Fourier-transformed to the time domain to obtain $E(x,y,t)$. If a beam with horizontal spatial chirp (created by a pair of gratings) is used as the test pulse, a linear coupling is introduced between x and t in the phase $\psi(x,y,t)$ of $E(x,y,t)$, and therefore the instantaneous frequency $\partial\psi/\partial t$ depends linearly on position x, and is constant along the y axis, as can been seen on Fig. 2.

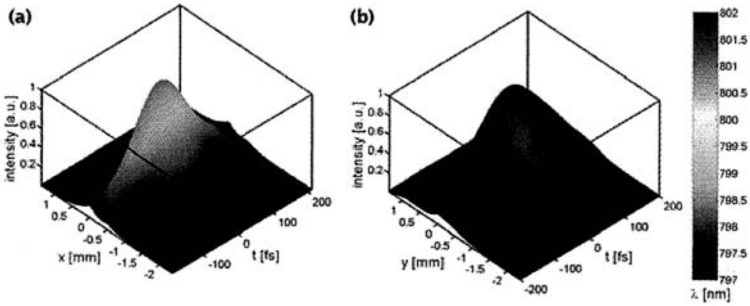

Fig. 2: **(a)** x-t slice of the measured electric field $E(x,y,t)$ of a pulse with spatial chirp. The vertical axis shows the electric field intensity $|E(x,t)|^2$ and the color shows the instantaneous wavelength derived from the phase $\varphi(x,t)$. The spatial gradient of color shows the spatial chirp along the x direction. **(b)** y-t slice of the same measured electric field. No spatial chirp is present along the y direction, as expected

4. Conclusion

We have demonstrated a simple, fast, linear, and general method for measuring the complete spatio-temporal electric field of a *single* ultrashort laser pulse. Multiple holograms are recorded on a high-resolution 2D camera, and the complete field $E(x,y,\omega)$ is reconstructed after data processing. A typical measurement consists of a set of ~20 frames of ~100×100 complex values, corresponding to the intensity and phase of $E(x,y)$ measured at ~20 wavelengths. When more complex pulses need to be measured, it is sufficient to increase the resolution of the camera, to allow for more wavelengths and/or more positions to be sampled. We believe this very simple method will have a wide range of applications for amplified, shaped, or scattered pulses, whether the single-shot capability is used or not.

References

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