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Chirped pulse digital holography for measuring the sequence of ultrafast optical wavefronts

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ABSTRACT

Optical setups for measuring the sequence of ultrafast optical wavefronts using a chirped pulse as a reference wave in digital holography are proposed and analyzed. In this method, multiple ultrafast object pulses are used to probe the temporal evolution of ultrafast phenomena and they are interfered with a chirped reference wave to record a digital hologram. Wavefronts at different times can be reconstructed separately from the recorded hologram when the reference pulse can be treated as a quasi-monochromatic wave during the pulse width of each object pulse. The feasibility of this method is demonstrated by numerical simulation.

1. Introduction

In conventional holography, the optical wavefront from a three dimensional object is recorded as an interference pattern using a reference wave in a photosensitive medium and the wavefront is reconstructed from the recorded medium using the reference wave [1]. In digital holography, interference patterns are recorded in a CCD (or CMOS) sensor and the wavefront is reconstructed by numerical calculations using a computer.

In off-axis digital holography, a reference wave is tilted by an angle θ with respect to an object wave. This angle has to be less than $\sin^{-1}(\lambda/2\Delta x)$ to record the interference pattern, where λ is the wavelength and Δx is the element size of a CCD. This limits the maximum spatial frequency recorded in a hologram. To increase the spatial frequency bandwidth of the recorded holograms, phase-shifting digital holography has been proposed, where an on-axis ($\theta = 0$) reference wave is used. In phase-shifting digital holography, multiple (usually four) interferograms are recorded with reference waves with different relative phases with respect to object wavefront and the object wavefront is reconstructed by a computer [2]. Recently, single-step phase-shifting digital holography, where a CCD combined with a micro phase plate array was used to record a digital hologram in a single step, has been developed [3].

Conventional [4,5] as well as digital [6–8] holography have been used to record the sequences of wavefronts of ultrafast phenomena such as crack propagation in transparent material [4], optical breakdown in PMMA [5], and plasma formation of air ionization [7,8]. In these studies, angular multiplexed holograms were recorded and multiple reference waves with different delay times and angles with respect to the object wave were used for recording the sequences of ultrafast wavefronts. The object wavefronts at different times were reconstructed using the corresponding reference waves used to record the hologram. Four wavefronts of plasma formation with the time separation of about 1 ps were obtained with 150 fs laser [7]. Also, three wavefronts with the time separation of 300 fs were obtained with 50 fs laser [8]. However, both studies used rather complex optical setups for obtaining multiple reference waves with different delay times and angles. Single-step phase-shifting digital holography was used to record the phase change induced by spark discharge using a single 96 fs pulse [9]. Also, light-in-flight recording of a single femtosecond pulse has been demonstrated using phase-shifting digital holography [10].

In this paper, the digital holographic recording and the reconstruction of the sequence of object wavefronts using multiple ultrashort object pulses and a single chirped reference pulse are proposed and analyzed. The chirped reference pulse can be obtained by passing a transform-limited pulse through a dispersive optical element, such as a high refractive index glass, and its instantaneous frequency changes with time. By using a chirped reference pulse and interfering it with an ultrashort object pulse at time t_1, only an optical wave with the instantaneous frequency $\omega(t_1)$ in the reference pulse interferes with the object pulse if the pulse width of the object pulse is sufficiently short, and the spatial frequency of the recorded interference pattern becomes $\omega(t_1)x\sin\theta/(2\pi c)$, where θ is the tilt angle of a reference wave in the x direction and c is the velocity of light. By interfering an ultrashort object pulse at different time t_2 with the same reference wave, the spatial frequency of the interference pattern changes to

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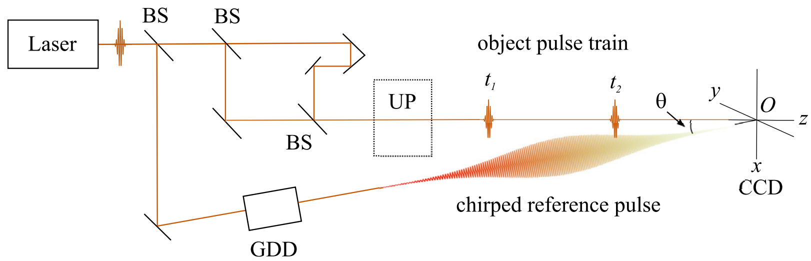

Fig. 1. Optical setup for chirped pulse digital holography. Here, BS is a beam splitter and GDD is an optical element with large group delay dispersion. UP shows the area where the ultrafast phenomena is probed.

$\omega(t_2)x\sin\theta/(2\pi c)$. In this way, multiple interference patterns at different times can be recorded by using a single CCD sensor without changing the actual angle θ of the reference wave, which simplifies the optical setup considerably compared with previous studies. Here it is shown that this method works when the reference wave can be treated as a quasi-monochromatic wave during the pulse width of each objective pulse. We analyze the case where the off-axis reference pulse is used in this paper. However, similar approaches using a chirped reference pulse to record multiple interference patterns may also be used in a single-step phase-shifting digital holography, by using multiple CCD sensors with appropriate wavelength filters, for example, to extract interference patterns at different instantaneous frequencies.

2. Methods

In Fig. 1, an optical setup for chirped pulse digital holography is shown. We consider to use a single ultrashort optical pulse from a laser, whose beam size may be expanded to match the size of the phenomena to be probed. It is divided into two pulses by a beam splitter and one of the pulses is converted to a chirped reference pulse by passing it through an optical element with large group delay dispersion. Multiple (two in this figure) probe pulses are created from the other pulse by using an optical setup similar to an interferometer. Pulse trains with more than two pulses may be created by using a pulse shaper [11]. The wavefronts of these probe pulses are modified by ultrafast phenomena at different times. These pulses are interfered with a chirped reference pulse with a tilt angle θ with respect to object pulses in the x direction at times t_1 and t_2, and a hologram is recorded in a CCD sensor.

Here, the pulse from a laser is assumed to have a Gaussian shape with the pulse width $T_p = 1.665T_0$ and its temporal center angular frequency is ω_0. After probing ultrafast phenomena, object pulses are assumed to be given as follows,

$$O(x,y,t) = \sum_j O_j(x,y) e^{-(t-t_j)^2/(2T_0^2)} e^{-i(\omega_0(t-t_j))}. \tag{1}$$

where, each pulse has a wavefront $O_j(x,y)$ at time t_j. These pulses propagate along the z axis and a CCD sensor is situated at $z = 0$. A chirped reference pulse is assumed to have a uniform wavefront and is given as follows,

$$R(x,y,t) = e^{i(\omega_0+2ht)x\sin\theta/c} e^{-i(\omega_0+ht)t}, \tag{2}$$

where h is a chirp constant and the instantaneous temporal angular frequency $\omega(t)$ changes linearly with time as follows,

$$\omega(t) = -\frac{d\varphi}{dt} = \omega_0 + 2ht, \tag{3}$$

where $\varphi = -(\omega_0 + ht)t$ is the temporal phase of a chirped pulse. The spatial frequency of the hologram recorded at time t_j by a CCD sensor depends on the instantaneous frequency $\omega(t_j)$ of the reference pulse. Thus, by using the reference wave that corresponds to the spatial frequency at t_j, it is possible to reconstruct the wavefront $O_j(x,y)$ at t_j separately after separating the spatial frequency components of other object pulses.

Since we assume to use ultrashort pulses, the signal recorded by a CCD sensor is given by the time integration as follows,

$$I(x,y) = \int |O(x,y,t) + R(x,y,t)|^2 dt = \int (|O|^2 + OR^* + O^*R + |R|^2) dt. \tag{4}$$

The term containing $|R|^2$ is constant and that containing $|O|^2$ is given by

$$\int |O|^2 dt = \sqrt{\pi} T_0 \left(\sum_j |O_j|^2 + \sum_{j,k>j} e^{-((t_j-t_k)^2)/(4T_0^2)} (O_j O_k^* e^{i\omega_0(t_j-t_k)} + C.C.) \right), \tag{5}$$

where $C.C.$ represents complex conjugate and the last term can be neglected if the time separation between pulses is much larger than the pulse width.

The interference term can be calculated as follows,

$$\int OR^* dt = e^{-i\omega_0 x\sin\theta/c} \times \int \sum_j O_j \times e^{(-1/(2T_0^2)+ih)t^2 + (t_j/T_0^2 - i2xh\sin\theta/c)t} dt e^{-t_j^2/(2T_0^2)+i\omega_0 t_j} = \sqrt{\frac{2\pi T_0^2(1+2ihT_0^2)}{1+4h^2T_0^4}} e^{-i\omega_0 x\sin\theta/c} \sum_j O_j \times e^{(-t_j+2ix\sin\theta h T_0^2/c)^2(1+2ihT_0^2)/(2T_0^2(1+4T_0^4h^2)) - t_j^2/(2T_0^2)+i\omega_0 t_j}. \tag{6}$$

In this equation, $2hT_0$ represents the frequency change during the pulse width of each objective pulse. If the reference wave can be treated as a quasi-monochromatic wave during the object pulse width T_0, the condition $2hT_0^2 \ll 1$ is satisfied. When this condition (we call it as the quasi-monochromatic condition) of a chirped reference wave is satisfied, we obtain the following equation after ignoring terms of order $(2hT_0^2)^2$ and higher,

$$\int OR^* dt \simeq \sqrt{2\pi} T_0 (1 + ihT_0^2) \times \sum_j O_j e^{i(\omega_0 t_j + ht_j^2)} e^{-ix(\omega_0+2ht_j)\sin\theta/c}. \tag{7}$$

From this equation, we can see that the wavefront $O_j(x,y)$ at time t_j is recorded at the instantaneous frequency of the reference pulse, $\omega(t_j) = \omega_0 + 2ht_j$. Thus it can be reconstructed by separating its spatial frequency components from other objective wavefronts.

As a concrete example of a chirped reference pulse, we show the case where it is obtained from an original pulse with duration T_0 by applying the quadratic group delay dispersion given by $\varphi_2 = \gamma T_0^2$, where γ is a chirp parameter. The reference pulse in this case can be written as follows [12],

$$R(x,y,t) = \frac{1}{(1+\gamma^2)^{1/4}} e^{-(1+i\gamma)t^2/(2T_0^2(1+\gamma^2))} \times e^{i(\omega_0+\gamma t/(T_0^2(1+\gamma^2)))x\sin\theta/c} e^{-i\omega_0 t}. \tag{8}$$