Optics Communications 405 (2017) 368–371

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

The implementation of temporal synthetic aperture imaging for ultrafast optical processing

Xiaoxiang Zhao [a], Shaoqiu Xiao [b,*], Cheng Gong [a], Tao Yi [b], Shenye Liu [b]

[a] The School of Physical Electronics, University of the Electronics and Technology of China, Chengdu 610054, China
[b] Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang, Sichuan, 621000, China

ARTICLE INFO

MSC 2010:
00-01
99-00

Keywords:
Temporal imaging
Ultrafast optics
Synthetic aperture
Resolution

ABSTRACT

A new technique of temporal imaging, called temporal synthetic aperture imaging (TSAI), is proposed to achieve higher time resolution of the imaging system for ultrafast optical processing. The proposed technique combines several of independent small-aperture systems together to get a higher time resolution and better image quality as a large-aperture system. It can solve the problem that an oversized aperture time lens is difficult to achieve in practice. In this paper, after analyzing the filtering effect, a novel implementation method of TSAI is presented. In order to verify the correctness, we demonstrate a decuple magnification of a signal with two 1ps width pulse separated 2ps, using a synthetic aperture by the system simulation.

1. Introduction

With the development in research of ultrafast optics, the generating and measurement of the ultrafast optical pulses need more kinds of flexible and effective method. Temporal imaging [1–5], which is an analog signal processing technique based on a space–time duality, can perform kinds of waveform manipulation such as compressing [6–9], broadening [1,10–16] or Fourier transform, etc. The technique applies to not only period but also single-shot signals with arbitrary waveform, and it is in real-time without software post processing. So it has high value in the ultrafast optics.

Temporal imaging system is usually composed of the dispersive media and the time lens. The propagation of narrow-band pulse through dispersive media is equivalent to paraxial diffraction in spatial imaging, while the time lens is a temporal equivalent of spatial lens. Time lens, the function of which is just quadratic phase modulation (QPM) in the time domain, can be realized by electro-optic phase modulator (EOPM), cross-phase modulation (XPM) or four wave mixing (FWM) [17–20], etc. The temporal resolution of the time lens is the most important features in ultrafast optical processing, and the above types of time lens has several picoseconds and a few hundreds of femtosecond resolution at most, respectively . According to the reference [1,17], it is known that the resolution depend from the quadric phase modulation curve (PMC) of time lens. When the parabola has higher curvature or longer duration, the time lens has higher resolution. So the improvement of the time lens resolution is subject to the maximum phase shift of the modulation technique.

In this paper , a method of the TSAI that can improve the time lens resolution is present. In the new method, the technique of QPM does not change and is mentioned previously, such as EOPM, XPM or FWM, while the phase modulation curve (PMC) is not one parabola but combination of several parabolas. Each parabola independently images a part of the input pulse. After the independent images are properly phase shifted and time shifted, the superposition of them is just the image of the total input signal. Because the TSAI has severalfold modulation duration with no changes of the parabola curvature and the maximum phase shift, it can achieve higher resolution basing on the current modulation technique. The duration of QPM is usually defined as the time lens aperture (TLA), so the proposed method is called TSAI.

The paper is organized as follow. In Section 2, the filtering effect caused by the TLA in the temporal imaging is introduced. In Section 3, an implementation method of TSAI is proposed. There is a simulations with OptiSystem to verify the TSAI in Section 4. The conclusion is summarized in Section 5.

2. The filtering effect caused by TLA

The fundamental temporal imaging can be obtained by preceding and following a time-lens with dispersion [3]. the time lens imparts

* Corresponding author.
E-mail address: xiaoshaoqiu@uestc.edu.cn (S. Xiao).

http://dx.doi.org/10.1016/j.optcom.2017.08.012
Received 9 June 2017; Received in revised form 7 August 2017; Accepted 8 August 2017
0030-4018/

a quadratic phase shift to the input signal. Its processing in the time domain can be written as

$$Q(\tau) = \exp\left(i\frac{\tau^2}{2D_f}\right) \times P(\tau) \tag{1}$$

where D_f is the focal GDD of the time lens, and $P(\tau)$ is the pupil function to model the effect of an aperture. When the time lens aperture (TLA) is infinite, the pupil function equals one.

In the temporal imaging, the expression that relate the output profile $f_{out}(\tau)$ with the input profile $f_{in}(\tau)$ can be represented as

$$f_{out}(\tau) = \left[f_{in}(\tau) \otimes \exp\left(-\frac{i\tau^2}{2D_{in}}\right) \cdot Q(\tau)\right] \otimes \exp\left(-\frac{i\tau^2}{2D_{out}}\right) \tag{2}$$

where D_{in} and D_{out} are GDD of the two dispersion respectively, $\otimes$ denotes the convolution operation, and τ is retarded time variable.

Assuming that the TLA effect can be ignored, and the temporal imaging condition $1/D_{in} + 1/D_{out} = 1/D_f$ is met, Eq. (2) can be simplified as

$$f_{out}(\tau) = \frac{1}{\sqrt{M}} f_{in}\left(\frac{\tau}{M}\right) \exp\left(\frac{i\tau^2}{2MD_f}\right) \tag{3}$$

where $M = -D_{out}/D_{in}$ is the magnification factor. It is obvious that the output waveform $f_{out}(\tau)$ is a replica of the input waveform $f_{in}(\tau)$ scaled in time [3].

When the TLA effect cannot be ignored, the mathematics calculation becomes more complicated. The output can be written in terms of a superposition integral as

$$f_{out}(\tau) = \int_{-\infty}^{+\infty} h(\tau;\tau_0) f_{in}(\tau_0) d\tau_0 \tag{4}$$

where $h(\tau;\tau_0)$ is the response of the system at the time τ to an impulse applied at time τ_0. According to Eq. (2), it is known that

$$h(\tau;\tau_0) = \exp\left[i\left(\frac{\tau_0{}^2}{2D_{in}} + \frac{\tau^2}{2D_{out}}\right)\right] \int_{-\infty}^{+\infty} P\left(t_0\right) \cdot \exp\left[-i\left(\frac{\tau - M\tau_0}{D_{out}}\right) t_2\right] dt_0. \tag{5}$$

After the following variable substitution $\tilde{\tau}_0 = M\tau_0, \tilde{t}_0 = t_0/D_{out}$ is introduced, the output is transformed to

$$\begin{aligned} f_{out}(\tau) &= \left(f_{in}\left(\frac{\tau}{M}\right) \cdot \exp\left(i\frac{\tau^2}{2M^2D_{in}}\right)\right) \\ &\otimes \left(\int_{-\infty}^{+\infty} P\left(\tilde{t}_0 D_{out}\right) \cdot \exp(-i\tau\tilde{t}_0) d\tilde{t}\right) \times \exp\left(\frac{i\tau^2}{2D_{out}}\right) \\ &= \left(f_{in}(\frac{\tau}{M}) \cdot \exp\left(i\frac{\tau^2}{2M^2D_{in}}\right)\right) \otimes F\left\{P\left(\tilde{t}_0 D_{out}\right)\right\} \times \exp\left(\frac{i\tau^2}{2D_{out}}\right) \end{aligned} \tag{6}$$

where $F\{\bullet\}$ signifies Fourier transformation.

The convolution in time domain is corresponding to the multiplication in the frequency domain. The convolution relationship in the frequency domain is represent as

$$\begin{aligned} G_x(\Omega) &= F\left\{\left(f_{in}\left(\frac{\tau}{M}\right) \cdot \exp\left(i\frac{\tau^2}{2M^2D_{in}}\right)\right)\right\} \cdot F\left\{F\left\{P(\tilde{t}_2 D_{out})\right\}\right\} \\ &= 2\pi \cdot F\left\{\left(f_{in}\left(\frac{\tau}{M}\right) \cdot \exp\left(i\frac{\tau^2}{2M^2D_{in}}\right)\right)\right\} \cdot P(-\Omega D_{out}) \end{aligned} \tag{7}$$

where $G_x(\Omega)$ is the Fourier spectrum of the convolution in Eq. (6).

Because the time duration of the input is very short in temporal imaging system for broadening ultrafast pulse, $\tau^2/(2M^2D_{in})$ approximately equal to a constant. Then Eq. (7) can be approximate to

$$G_x(\Omega) = 2\pi \cdot \exp(i\phi_{add}) F\left\{f_{in}(\tau/M)\right\} \cdot P(-\Omega D_{out}) \tag{8}$$

where ϕ_{add} is a constant depended on the deviation of the optical pulse from the time origin, and it is named as aperture additional phase (AAP).

Putting the approximate solution into Eq. (6), the output can be represent as

$$f_{out}(\tau) \propto \exp\left(\frac{i\tau^2}{2D_{out}}\right) \exp(i\phi_{add}) F^{-1}\left\{F\left\{fin\left(\frac{\tau}{M}\right)\right\} P(-\Omega D_{out})\right\} \tag{9}$$

where $F^{-1}\{\bullet\}$ denotes inverse Fourier transformation.

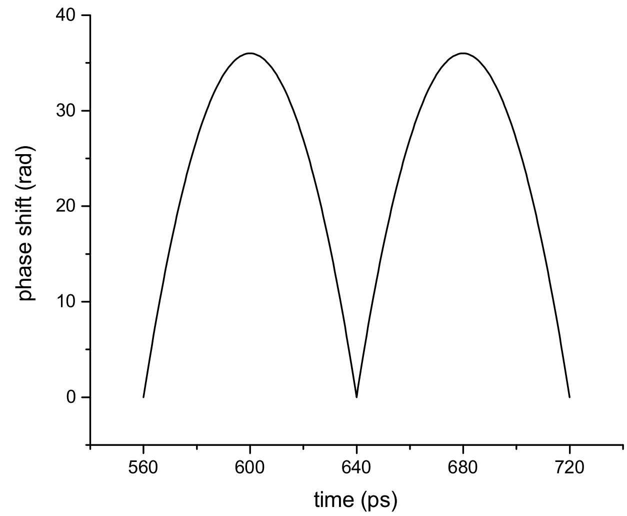

Fig. 1. The PMC of the time lens.

It is held that the output $f_{out}(\tau)$ is not the replica of the input $f_{in}(\tau)$, but a specific frequency band of input . The signal which is really imaged can be written as

$$f'_{in}(\tau) = F^{-1}\left\{F\left\{f_{in}(\tau)\right\} P(-\Omega D_{in})\right\}. \tag{10}$$

D_{in} can be replaced by D_f in the imaging system for ultrafast pulse, since they are approximately equal.

The system with finite TLA can only image a specific frequency band of the input signal, and the passband depends on the pupil function and the focal GDD, which can be called as the filtering effect caused by TLA. It can be considered that the temporal resolution is caused by the filtering effect. When the wider frequency band is imaged, the system has higher resolution.

3. An implementation of the TSAI

The PMC of the TSAI proposed in this paper is combined by several parabolas. The curve in Fig. 1 looks like a PMC which is composed of two parabolas. According to the previous section, each parabola can be regarded as an independently time lens aperture (ITLA), and can image a specific frequency band of the input signal independently. Since there is time differences and phase differences among these independent images, the directly superposition of them cannot accomplish TSAI.

Suppose the modulation curve vertex (MCV) of an ITLA is at $\Delta\tau_1$, the equation modeling the ITLA in time domain can be represent as

$$Q_1(\tau) = \exp\left(i\frac{(\tau - \Delta\tau_1)^2}{2D_f}\right) P_1(\tau). \tag{11}$$

When the pupil function $P_1(\tau) = 1$, the image of the ITLA can be written as

$$\begin{aligned} f_{out1}(\tau) &= \left[f_{in}(\tau) \otimes \exp\left(-\frac{i\tau^2}{2D_{in}}\right) \cdot Q_1(\tau)\right] \otimes \exp\left(-\frac{i\tau^2}{2D_{out}}\right) \\ &= \frac{1}{\sqrt{M}} f\left(\frac{\tau}{M} + \frac{M\Delta\tau_1}{M+1}\right) \\ &\times \exp\left[i\left(\frac{\tau^2}{2MD_f} + \frac{\Delta\tau_1{}^2}{(M+1)2D_f} - \frac{\tau \times \Delta\tau_1}{MD_f}\right)\right]. \end{aligned} \tag{12}$$

So the motion of the MCV bring image motion, which includes time-shift and phase-shift.

If the image of ITLA is manipulated by time shift with

$$\varepsilon_{\tau 1} = \Delta\tau_1 M^2/(M+1),$$