Optics Communications 367 (2016) 259–263

Contents lists available at ScienceDirect

Optics Communications

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

A novel measurement scheme for the radial group delay of large-aperture ultra-short laser pulses

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ARTICLE INFO

Article history:
Received 12 November 2015
Received in revised form
14 January 2016
Accepted 20 January 2016
Available online 4 February 2016

Keywords:
Femtosecond phenomenon
Ultrafast lasers
Ultrafast measurement
Correlators

ABSTRACT

In femtosecond high-peak-power laser system, the radial group delay (RGD) of the pulse front introduced by conventional lens-based beam expanders can significantly decrease the achievable focal intensity, especially when it is larger than the pulse duration. In order to quantitatively analyze and compensate the RGD, a novel measurement scheme based on self-reference and second-order cross-correlation technology is proposed and applied to measure the RGD of the large-aperture ultra-short laser pulses directly. The measured result of the RGD in a 200 TW Ti:sapphire laser system is in good agreement with the theoretical calculation. To our knowledge, it is the first time to realize the direct RGD measurement of large-aperture ultra-short laser pulses.

1. Introduction

Thanks to the invention of chirped pulse amplification (CPA) [1] and optical parameters chirped pulse amplification (OPCPA) [2], peak power of the femtosecond laser pulse has been able to reach multi-hundred terawatt and even multi-petawatt level nowadays [3–6]. Associated with the rapid development of the femtosecond high-peak-power laser, the diameter of the output pulse is increasing correspondingly (tens to hundreds of millimeter), which implies that the pulse front distortion resulted from conventional lens-based beam expanders should be taken into consideration. Compared to lens-based beam expanders, reflection-type beam expanders will not suffer pulse front distortions. However, a spherical mirror beam expander will have remarkable astigmatism due to its geometry, and an off-axis parabolic mirror beam expander is difficult to manufacture and it is too sensitive to the beam alignment [7]. Therefore, most of the high-peak-power laser systems are still equipped with the lens-based beam expanders. When laser pulses travel through a lens-based beam expander, the central part of the pulse front is delayed in time domain with respect to the other parts of the pulse front. The time delay referred above is dependent on the beam size and the focal length of the lenses, and it is radial symmetric across the beam. Therefore it is known as "radial group delay (RGD)" [8–11]. Due to the RGD, the different radial portions of the pulse front arrive at the focal region at different time. In the case of RGD is larger than (or comparable to) the pulse duration, the achievable focal intensity of the ultra-short laser pulses can be dramatically decreased. Thus, the RGD is a significant issue for large-aperture femtosecond high-peak-power laser system.

In order to quantitatively analyze the effect of RGD, some diagnostic techniques based on Michelson interferometer have been proposed, which can be generally classified into three categories: spatial interference, spectral interference and temporal correlation [11–15]. These methods have been theoretical proposed and some of them have been applied to measure the RGD resulted from lens or telescopes successfully. However, limited by the necessity of ideal reference pulses, it is difficult to apply these methods to the RGD measurement of large-aperture ultra-short laser pulses directly. Recently, an interesting method has been proposed for the spatiotemporal characterization of ultra-short laser pulses, which can generate reference pulse by inserting extra components in one arm of the Michelson interferometer [16]. However, the introduction of extra components increases the complexity and difficulty in the RGD measurement, especially in the direct RGD measurement of the large-aperture ultra-short laser pulses, which generally require large-size components in the RGD measurement device. Another method based on self-reference has also been proposed [17,18], but it has not been demonstrated in high-peak-power laser system, and the required large-size optics for large-

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http://dx.doi.org/10.1016/j.optcom.2016.01.056

aperture laser pulse measurement also may be a limitation.

In this work, by utilization of Michelson interferometer, a novel measurement scheme based on self-reference and second-order cross-correlation technology is proposed to measure the RGD of large-aperture ultra-short laser pulses directly. As indicated by Bor [8,9] and other works [12–15,19,20], RGD induced by lens or lens-based beam expanders is radial symmetric and quadratic dependent on the beam radius. Therefore, half of the laser beam can be sampled as the reference pulse. Such a self-reference method can work without any extra struggle for a desired reference pulse, and can reduce the size of the required optical elements in the RGD measurement device. Therefore this novel measurement scheme is easily applicable to large-aperture ultra-short laser pulses. This measurement scheme has been applied to measure the RGD in a 200 TW Ti:sapphire laser system [21], the output pulse beam size of which is about 80mm in diameter. The measured result of the RGD is in good agreement with the theoretical calculation. To our knowledge, it is the first time to realize the direct RGD measurement of large-aperture ultra-short laser pulses.

2. Theoretical analysis

The phenomenon of RGD was first pointed out and calculated using ray tracing by Bor [8]. According to the analysis of Bor [8,9], the relative time delay for the output pulse front at arbitrary ray with respect to the pulse front at axial ray from a beam expander can be defined as

$$T(r) = \frac{-r^2}{2cf_2(n-1)}\left(-\lambda\frac{dn}{d\lambda}\right)\left(1+\frac{1}{M}\right). \tag{1}$$

Here both of the lens in the beam expander are assumed to be made of the same material, r is the distance of arbitrary ray from the axis, f_2 is the focal length of the second lens in the beam expander, λ is the central wavelength, n is the refractive index of lens material, c is the velocity of light in vacuum, M is the magnification factor of the beam expander. For Keplerian expander, the magnification M is positive while it is negative for Galilean expander. Thus, for the same magnification factor, the Galilean expander makes less contribution to RGD than the Keplerian expander. Unless achromatic lenses are applied, the cascaded beam expanders in femtosecond high-peak-power laser system can lead to additive amount of RGD.

For an axisymmetric quadratic curve AOB ($T_1=ar^2$), which is similar to the RGD introduced by beam expanders, it obeys an interesting geometric law, which is shown in Fig. 1. If we divide the quadratic curve AOB equally into two parts AO and OB, and translate AO to A′O′ ($T_2=a(r-r_0)^2-c$). Ensure that A′O′ and OB correspond to the same vertical coordinates. Then we can find that the difference-values between the two curves A′O′ and OB is a linear function of the r-coordinate ($\Delta T=2ar_0r+c'$). Moreover, the slope (k) of the linear function is equal to the twice of the product of the radius (r_0) and coefficient (a) of the quadratic curve, namely $k=2ar_0$. Therefore, according to the difference-values between the two curves (A′O′ and OB), we can deduce the distribution of the quadratic curve (AOB). In other words, once the relative time delay between the two half-pulse fronts is known, the RGD of the laser pulse can be determined.

According to the above geometrical law, a novel RGD measurement scheme based on self-reference and second-order cross-correlation is proposed. The arrangement of the RGD measurement scheme is depicted as Fig. 2(a). The laser beam under investigation is equally divided into two beams by M1, and each beam can serve as the reference pulse with respect to the other beam under the condition that the RGD is radial symmetric. The

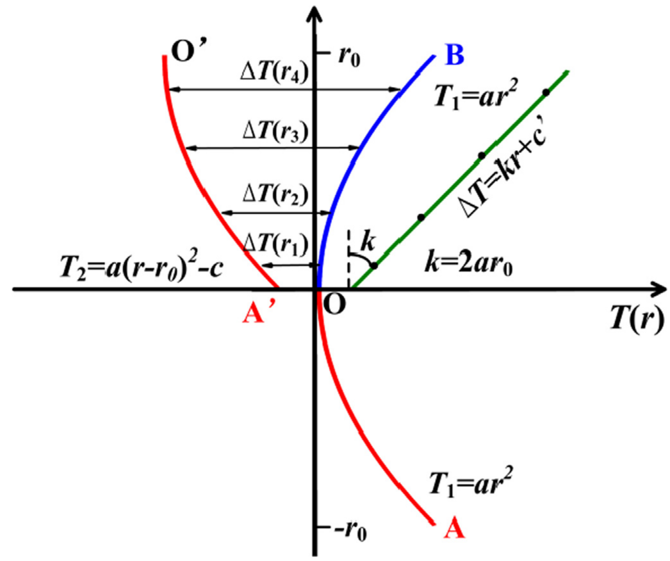

Fig.1. The difference-value distribution between the two half-parts of an axisymmetric quadratic curve, which is a linear function.

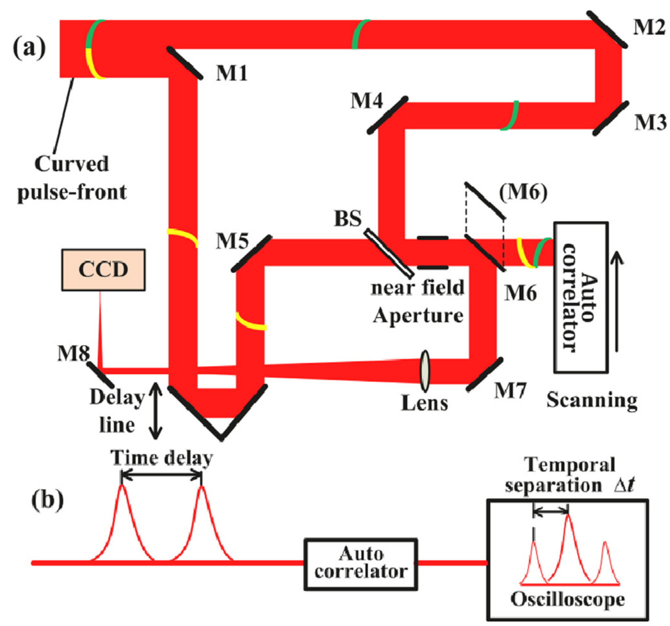

Fig. 2. (a) The arrangement of the RGD measurement scheme for large-aperture ultra-short laser pulses. (b) A schematic of the measured correlation signal of a pulse pair.

two beams are then injected into the two arms of the Michelson interferometer, respectively. A near field aperture and a far field CCD (LW230, Spiricon), which are installed behind the beam splitter, are used to help the alignment. The high resolution (4.4 μm) of the CCD and the long focal length ($f=2$ m) of lens used in the far field monitoring can ensure that the two beams propagate with the same direction. In our measurement, the misalignment between the two laser beams is controlled below 10 μrad, corresponding to a temporal delay below 1.3 fs across the 40 mm beam. After adjusting the relative time delay between the two arms, the two overlapped beams are delivered into a commercial autocorrelator. A 4 mm-diameter iris diaphragm is installed on the entrance of the autocorrelater. When the autocorrelater is scanned by a high-precision translation stage during the measurement, the center of the iris diaphragm can be used to determine the position of the measured laser beam. In this work, the value of the relative