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Bidirectional grating compressors

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ABSTRACT

A bidirectional grating compressor for chirped pulse amplifiers is presented. It compresses a laser beam simultaneously in two opposite directions. The pulse compressor is shown to promote chirped pulse amplifiers' output energy without grating damages. To verify the practicability, an experiment is carried out. In addition, a crosscorrelation instrument is designed and set up to test the time synchronization between these two femtosecond pulses.

1. Introduction

Many high-energy chirped pulse amplifiers(CPAs) have been set up to achieve laser pulses with ultra-high peak power density [1–3]. In a CPA's amplification stages, the chirped nanosecond pulses could be amplified to ten-joules of energy. In a CPA's compression stage, a suitable compressor should be employed to eliminate the strong frequency chirp in the broadband laser pulses and therefore to output femtosecond pulses [4,5]. Afterwards, ultra-intense and ultra-short laser pulses can be obtained.

Avoiding the induced high-order nonlinear interaction of optical material, the reflection-type diffraction gratings are nowadays the most suitable dispersion elements for pulse compressors. However, located in the end stage of a CPA, the compressor grating surfaces suffer high energy laser pulses and are feasible to be damaged. It is believed that the damage threshold of the golden compressor gratings is above 0.1 joule per square centimeter to femtosecond pulses and above 0.4 joule per square centimeter to nanosecond pulses. So the laser beam has to be adequately magnified in size. The demand for large-aperture optical elements brings the processing difficulties and the beam quality deteriorations. Especially, large-aperture gratings become the bottleneck of the development of higher-energy CPAs.

The fundamental four-grating compressor [6] is shown as the section I in Fig. 1. The diffraction grating g1 is parallel with g2, and g3 with g4. These two pairs of grating are mounted on mirror images to each other. Due to diffraction, the broadband beam becomes diverged after g1 and collimated after g2, see the dashed line in Fig. 1. The grating g3 and g4 restores the beam. G1, being as the input grating of the compressor, suffers the strongest energy. G4, being as the output grating of the compressor, suffers the greatest power.

In a bidirectional grating compressor, the fundamental four-grating layout remain, but the amplified beam to compress is divided into two parts, see Fig. 1. One part enters the grating compressor following the original route, another following the converse route. Due to the symmetric layout of the grating compressor, both parts can be properly compressed simultaneously.

To output the compressed pulses, the beam wavevector in a bidirectional grating compressor should be tilted upwards or downwards with a tilt angle α and have a component parallel to the grating grooves. The grating diffraction equation should be used in the vector form [7,8], rather than in the conventional scalar form. The phase expression of the grating compressors [5,6] should be made corresponding adjustment.

Consider a unit wavevector with a frequency of ω having a tilt angle α. Its component parallel to the grating grooves is just reflected by the grating surface while its projection on the normal plane to the grating grooves is just diffracted. The grating diffraction equation can be rewritten as:

$$\sin\theta + \sin\gamma = \frac{2\pi c}{d\omega\cos\alpha} \tag{1}$$

where c is the light speed, γ is the fixed incident angle, θ is the diffraction angle, and d is the grating spacing. It can be concluded that the phase expression of the grating compressors [5,6] remains correct only if ω is substituted with $\omega\cos\alpha$. Furthermore, the dispersion ratio of the third-order to the second-order can be given as:

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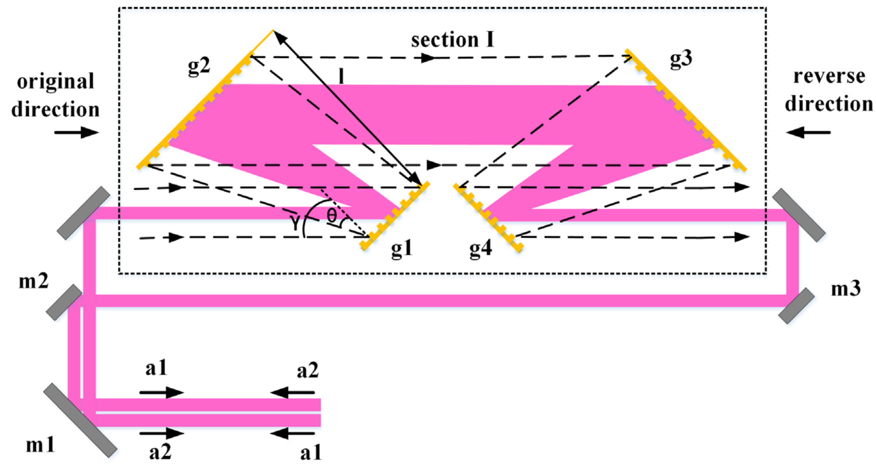

Fig. 1. An example of the bidirectional grating compressor. Section I: a fundamental four-grating compressor. g1–g4 are gratings, the others are planar mirrors.

$$\rho = \phi'''(\omega)/\phi''(\omega) = -\frac{12\pi^2}{\omega}\cdot\frac{1+\sin\theta\sin\gamma}{\cos^2\theta}. \tag{2}$$

In a CPA, the compressor's ρ is exactly determined according to the dispersion of the expander and material. It is evident from Eq. (2) that the phase ratio ρ is dependent of the diffraction angle θ and independent of the distance$l$between the parallel gratings. With a suitable ρ, both the second-order and the third-order dispersions can be eliminated at the same time by modulating l. It can be derived that the partial derivative of ρ with respect to the tilt angle α at $\alpha=0°$:

$$\partial\rho/\partial\alpha|_{\alpha=0} = 0. \tag{3}$$

When α is introduced into a grating compressor, the compressor phase will be changed and CPA's system phase mismatch will take place. By the way of modulating the distance l, the second-order phase mismatch would be eliminated. Due to the insensitivity of the phase ratio ρ to α, the third-order phase mismatch can be eliminated at the same time.

In a bidirectional grating compressor, each grating surface is illuminated twice. To g1 and g4, the first illumination duration is up to 100,000 longer than the last one. Such two pulses have different damage mechanism. The distance between g2 and g3, without effects on pulse phase, can be designed to elongate the time interval of illuminations. If the time interval is long enough, the total energy load can be increased. The suitable time interval would be determined in future damage tests.

In a bidirectional grating compressor, the amplified beam to compress should be divided into two parts, which brings extra loss of energy. The loss comes from the edge of the planar mirror (m2 in Fig. 1) which is normally 5–10 mm. The larger the laser beam, the energy loss proportion is less. To a high energy CPA system, the beam should be magnified to more than 100mm. So the extra loss proportion can be reduced to less than 10%. The diffraction due to the sharp edge of m2 would lead to poor beam quality. So a serrated mask is a must to improve the beam propagation.

In recent years, splicing technology of Ti:sapphire crystals for CPAs has been proposed [9] to suppress the parasitic lasing and improve the amplification efficiency. The laser beam is divided by the splicing crystal. The bidirectional grating compression will also be a good choice to the splicing crystal amplifiers.

2. Experiment

An experimental bidirectional grating compressor is built up as Fig. 1. The experiment setup is based on an existing petawatt CPA system [4], which runs at a repetition of 10 Hz in this experiment and outputs low-energy pulses. Although the grating compressor remains, the beam path before the compressor is reformed. The pulse to compress is split into two beams by the plane mirror m2. One beam, a1, follows the original route and goes into the grating compressor. It comes back with the help of the plane mirror m3 after the compressor. Another beam, a2, goes in the converse route directed by m2. The optical path from g1 to g4 is about 4 m, namely a time interval of 13 ns. To avoid the femtosecond pulses go backwards to the amplification system, the plane mirror m1 is tilted upwards (~0.5°) so that the compressed pulses can output above the input.

The relative time delay between pulses a1 and a2 should be eliminated so that the total energy can reach the destination at the same time. An ordinary laser pulse from a femtosecond CPA has a pulsewidth of 30 fs, in other words, the optical path difference should be shorter than 1 μm. If pulses to combine go along different route in CPA, they will meet different optical instruments and suffer different disturbances. So the optical path difference fluctuates at random and the relative time delay will tend to be out of control. In theory, the bidirectional grating compressor can avoid such trouble.

In experiment, an instrument to measure the relative time delay is designed. The autocorrelation trace of the laser pulses, being used to measure the pulsewidth, cannot be used to get the information about the relative time delay between two laser pulses. A cross-correlation instrument is designed to determine the time delay between beams, see Fig. 2. B1 and b2, respectively parts of a1 and a2 in Fig. 1, reflected by mirror m4, m5 and

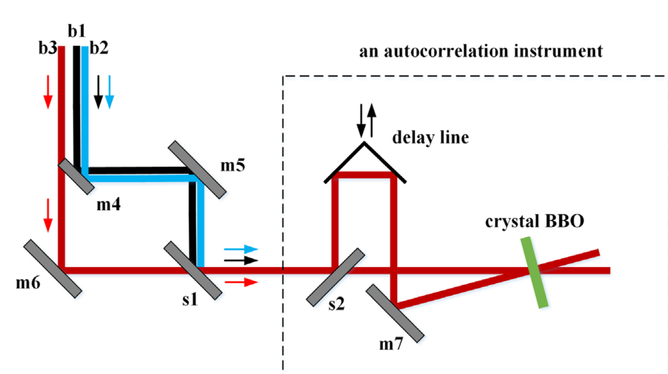

Fig. 2. A cross-correlation instrument to determine the time delay. b1–b3 are beams, m4–m7 are plane mirrors, s1 is a 1:1 beam splitter.