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Theoretical and experimental research of tiling error compensation method based on a small-size mirror for large-aperture tiled-grating compressors

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ABSTRACT

Tiled-grating techniques have been adopted in many multi-kilojoule petawatt laser facilities to meet the size requirements for compression gratings. To realize coherent tiling, we propose a new simple method of tiling error compensation for large-aperture tiled-grating compressors. In this method, errors are controlled by adjusting a small-size mirror. We theoretically analyze that this method improves errors tolerances many times higher than that of traditional compensation method and approaches the limit of adjustment accuracy. An experiment also has been carried out to demonstrate the feasibility. The method significantly reduces the difficulty of tiling, increases the stability of large-aperture tiled-grating compressor system and could be applied to coherent combination of large-aperture short laser beams.

1. Introduction

Chirped-pulse amplification (CPA) technology enables the realization of ultrahigh intensities that can reach focused intensities of approximately 10^{21} W/cm^2, and it has been widely adopted in multi-kilojoule petawatt laser facilities [1–3]. As a critical optical element, a diffraction grating is used to provide negative dispersion to recompress the pulse [4]. The use of CPA promotes the demand for meter-sized gratings necessary for increasing the output capability of laser systems; however, the aperture of gratings cannot be further improved with the current state-of-the-art diffraction gratings. In the tiled-grating (TG) approach proposed by Zhang et al. [5], multiple gratings are tiled coherently to form a larger grating, this approach represents an effective technique for meeting aperture requirements, and it has been adopted in many multi-kilojoule petawatt laser facilities [6–8].

Previous theoretical and experimental studies of TG [6–17] have generated useful results and show that tiling errors can be compensated for by in-pairing and should be strictly controlled to achieve the basic coherent condition of the output pulses. Tiling errors can be in-paired as the following three groups according to their effect on the focal spot [9]: X tilt and groove spacing fabrication error, Y tip and Z twist, and piston and shift. The in-paired compensation decreases the amount of control variables to three. Usually, to provide for convenient adjustment, tilt, tip, and piston errors are selected to achieve coherent tiling. For a TG compressor to form a focal spot with 90% of the diffraction-limited energy distribution, the tip, tilt, and piston errors cannot exceed more than a few tens of submicroradians and nanometers [10,11]. Many traditional adjustment methods, such as direct drive large-aperture tiled-grating (LATG) by nanometer precision driver, have been proposed [1,11–15] to limit the tiling errors to within the tolerances. However, LATG is more sensitive to the environment and more difficult to achieve mechanical stability maintenance than common ones [1,6]; moreover, the high demands for adjustment accuracy and stability decrease the practicality of this approach in most systems, because the strict requirements for accuracy and stiffness for the drivers and TG mounts correspond to high technical and economic costs. Furthermore, the direct drive will exacerbate the wavefront error of LATG and it is generally difficultly to achieve diffraction-limitation with a large-aperture laser beam [6,12,13].

In this paper, a method based on a small-size mirror of tiling error compensation for LATG is proposed and experimentally demonstrated. This method can reduce the accuracy demands for

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individual grating and improve the stability of compressor systems than direct drive. In Section 2 we will elucidate the basic theory of the method and introduce a computing method of TG. Section 3 discusses the simulation results. The experimental results will be given in Section 4. Conclusions are drawn in Section 5.

2. Theory model

2.1. Method model

A two-pass Z-type compressor (Fig. 1(a)), which is a typical compressor type [8], is introduced to implement the method, although this method can also be applied to a single-pass Z-type compressor. The schematic diagram is shown in Fig. 1. Two small-size mirrors and a collimating beam expanding system are inserted into the optical path. The laser beam is reflected by M1 and M2 and then collimated and expanded by L3 and L4 before entering the compressor. Then, the beam hits the gratings G11 and G12 with an incident angle α and is diffracted to G21 and G22. Next, the beam reaches the folding mirror M3, and the tilt angle of M3 makes the beam tilt down with a small angle to be sent back to G21 and G22. After a double pass through the grating tiles, the beam is reflected by M4 and focused on a CCD by L5. The phases of the entire compressor output pulses are labeled the sum of the left phase and the sum of the right phase as illustrated in Fig. 1(b). The system stability is the core issue in a TG compressor, and the structure of TG mounts and the mode of adjustment for TGs are the two main factors affecting the stability. In our method, the all-individual grating can be accurately fixed, which can improve the system stability because of increased stiffness of TG mounts, and more stable than adjustable TGs. To achieve the basic coherent addition, the phase differences between the two pulses are zeroed by adjusting M1. Apart from LATGs, the stability performance of TG compressor system will be increased despite of use of an extra tiled mirror, because the influence of small-size mirror on system stability is smaller than LATGs.

The structure of TG is displayed in Fig. 2, the still grating G12 is fixed, and the motion grating G11 can be adjusted relative to G12 to reach the ideal grating tiling condition. A coordinate system is set up, the X-Y plane is parallel to G12's surface, the Y-axis is parallel to G12's grooves, the Z-axis is the normal direction of G12's surface, and the X coordinate of G12 is positive while G11 is negative. Five kinds of tiling errors are recognized as follows, two piston tiling errors (shift Δx and piston Δz), three rotational tiling errors, (tilt $\Delta\theta_x$, tip $\Delta\theta_y$, and twist $\Delta\theta_z$). The groove spacing fabrication error ΔN also has an effect on focal spot and is defined the sixth error. The additive phases of the laser beam caused by tiling errors can be expressed as

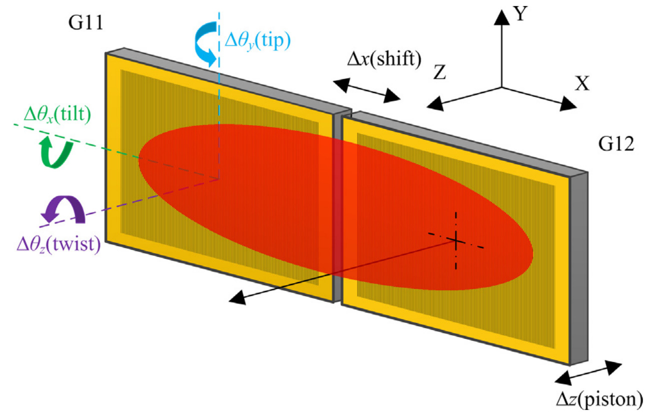

Fig. 2. Five tiling errors between two adjacent gratings, still grating (G12) and motion grating (G11).

$$\begin{cases} \Delta\phi_{\Delta\theta_x} = -2k(\cos\alpha + \cos\beta(\omega_0))\Delta\theta_x \\ \Delta\phi_{\Delta\theta_y} = -2k(1 + \cos\beta(\omega_0)/\cos\alpha)\Delta\theta_y \\ \Delta\phi_{\Delta z} = -2k(\cos\alpha + \cos\beta(\omega_0))\Delta z \end{cases} \quad (1)$$

where k is wavenumber, ω_0 is the central frequency of laser beam, α is the incident angle of compressor, and $\beta(\omega_0)$ is the diffraction angle.

Similar to small-size mirror, combining matrix optics and ray-tracing method, the additive phases of laser beam caused by small-size mirror can be represented as

$$\begin{cases} \Delta\phi_{\Delta\theta'_x} = -2k\Delta\theta'_x/M \\ \Delta\phi_{\Delta\theta'_y} = -2k\Delta\theta'_y/M \\ \Delta\phi_{\Delta z'} = 2k\Delta z'\cos\theta \end{cases} \quad (2)$$

where $\Delta\theta'_x$, $\Delta\theta'_y$, and $\Delta z'$ are the tilt angle, tip angle, and piston displacement of M1 relative to M2, respectively. $M = f_4/f_3$ is the magnification of collimating beam expansion system; f_4 and f_3 are

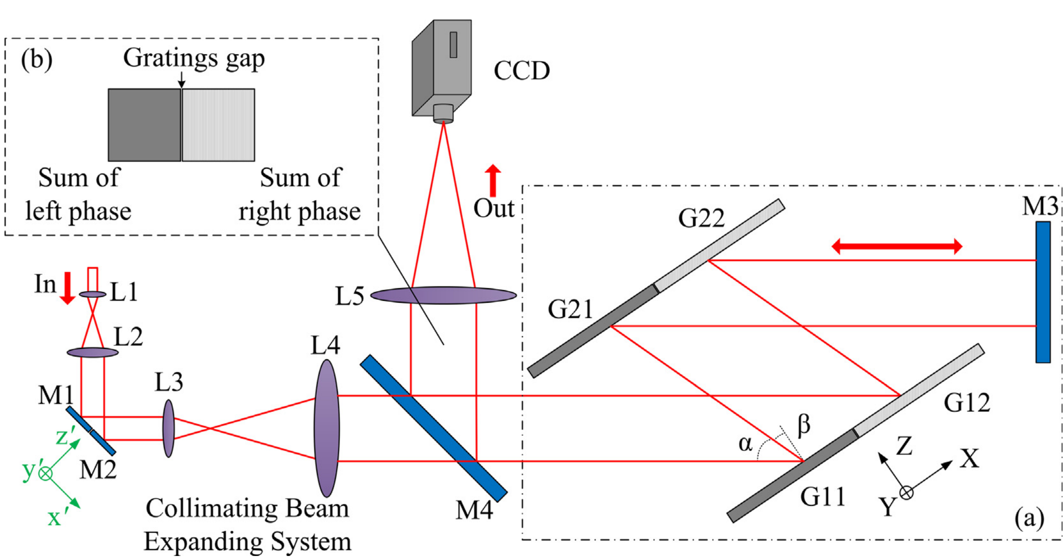

Fig. 1. Schematic diagram of two-pass Z-type TG compressor based on a small mirror.