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Automatic phase-locked control of grating tiling

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ABSTRACT

The development of phased-array grating compressor is a crucial issue for the high-energy, ultra-short pulse petawatt-class lasers. Several systems have adopted the tiling-grating approach to meet the size requirements for the compression gratings. Grating tiling need to be precisely phased to ensure a transform-limited focal spot when focusing the high-energy laser pulses onto the target. Monochromatic grating automatic phasing and performance maintaining are experimentally achieved with a far-field CCD camera technique based on a two-tiling system.

1. Introduction

The chirped-pulse amplification output stage of the OMEGA EP petawatt, multikilojoule, solid-state laser, presently under construction at the Laboratory for Laser Energetics, includes four 1×3 tiling-grating assemblies (TGAs) to compress the pulse before it is focused onto the target [1]. The proposed FIREX-I (Fast Ignition Realization Experiment) system at Osaka University contains a multiplexed tiling compressor [2]. TGAs were chosen to reach the required energy levels while staying within the size and damage-threshold limitations of currently available multilayer-dielectric diffraction gratings. Previous theoretical simulations and laser experiments demonstrated that the tiling approach can yield diffraction-limited focal spots [3].

Maintaining the grating–tiling mechanical stability is difficult in most thermal and vibrating environments. Within the framework of Pico2000 petawatt laser at LULI (Laboratoire pour l'Utilisation des Lasers Intense) and OMEGA EP (extended performance) petawatt laser at LLE (Laboratory for Laser Energetics), the monochromatic plane wave grating phasing with an accurate interferometric diagnostic was described [4 and 5]. Using this approach, the segmented mirror arrays have been aligned using interferometers by sensing tip, tilt, and piston. Since gratings are dispersive devices, tiling gratings exhibit three additional degrees of differential error: in-plane rotation (IPR), groove spacing, and lateral piston. These phase errors between grating tiling can be summarized as three-mirror terms and three-grating terms grouped according to their effect on the focal spot [3]. The mirror and grating terms are paired to compensate Y tip and in-plane rotation, lateral piston and longitudinal piston, and X tilt and groove spacing. For wavelength-scale errors, pairing reduces the number of control variables to three. By controlling tip, tilt, and piston among the tiles, the gratings can be properly phased. Bunkenburg et al. [6,7] have demonstrated the phase-locked control of the tiling-grating assemblies using a Mach–Zehnder interferometer. Qiao et al. [5] also demonstrated the interferometry for tiling automation, and firstly demonstrated of two large-aperture tiling-grating compressors, each consisting of four sets of tiling-grating assemblies in OMEGA EP using interferometric tiling technique [8]. Cotel et al. [3] proved that the measured far-field intensity distribution of the tiling small-scale gratings agrees well with the wavefront measured by an interferometer, but the automatic closed-loop tiling method based on the far-field method is not mentioned. Recently, Hideaki Habara et al. [2] utilized three-axis motion sensor to realize high-precision tiling-grating compressor for FIREX.

The near-field interferometric tiling technique has successfully realized gratings automatic tiling. In the practical grating compressor, the high-power 1053 nm analogous laser source for collimating and adjusting tiling gratings hardly meets the narrow spectrum width requirement, so the reference arm in the interferometric system needs much more space making the optical path layout complicated, but the far-field technique can efficiently avoid these disadvantages. In this paper, we build a closed-loop system, consisted of a far-field CCD and PZT actuators, to realize automatic tiling and high-precision phase locking, the simple optical path layout and tiling process are more

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conveniently used in the practical situation. Section 2 describes the diffraction theory of a two-grating tiling system involving the angle errors and longitudinal piston error. According to the calculation results, some optimum algorithms could be used to realize the automatic alignment. Section 3 presents the far-field tiling technique based on the stochastic parallel gradient ascent (SPGA) algorithm, the automatic tiling process is developed and the results of tiling two mediate-aperture reflecting elements using this process are also reported.

2. Analytic far-field parameters

The diffraction grating phase consists of determining the phase errors between two adjacent gratings, which can be caused by relative translations and rotations, and then removing these phase errors using actuators. In the case of a two-grating configuration, a reduction in degrees of freedom can be realized by paired compensation, so tip (θx), tilt (θy), and longitudinal piston (Δz) need to be corrected (Fig. 1).

A circular uniform beam (central wavelength λ=1.053 μm) vertically lights up the gratings gap to form symmetrically straddling two segments, shown in Fig. 2. For this case, the electric field in the near-field plane can be written as

$$E(x,y)=\begin{cases} A\exp(jk(\Delta z+f\theta_x x+f\theta_y y)) & x\geq d/2;\ \sqrt{x^2+y^2}\leq a \\ A & x\leq -d/2;\ \sqrt{x^2+y^2}\leq a \\ 0 & \sqrt{x^2+y^2}>a \end{cases} \quad (1)$$

where d is lateral translation (Δx) also called gratings gap, A is the average input wave amplitude, a is the incident beam radius, f is the focal length. Let f=587 mm, a=20 mm, and d=4 mm, the far-field intensity distribution is performed by fast Fourier transform operation in the case of differential subapertures piston of $\lambda/8$, $\lambda/4$, and $\lambda/2$ (Fig. 3(a)), a grating differential tilt and tip of, respectively, θy=4 μrad, 8 μrad, and 16 μrad (Fig. 3(b)) and θx =4 μrad, 8 μrad, and 16 μrad (Fig. 3(c)).

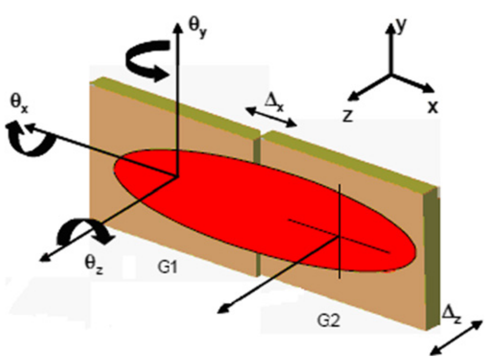

Fig. 1. Phased-array grating compressor scheme with five degrees of freedom between the two adjacent diffraction gratings $G1$ and $G2$ (Δx, Δz, θx, θy, θz).

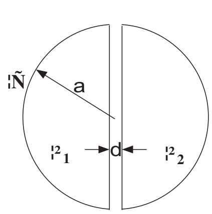

Fig. 2. Geometry of the beam aperture.

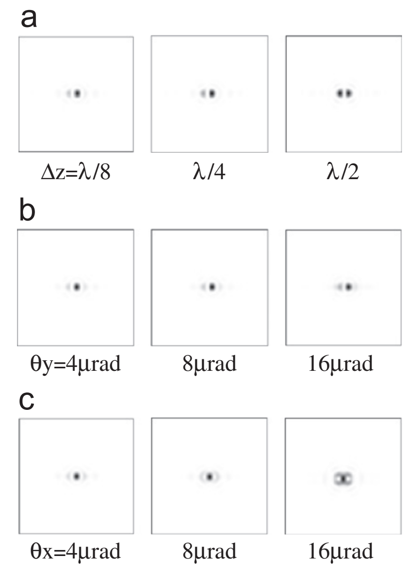

Fig. 3. Theoretical diffraction patterns for a split circular subaperture with the piston and tilt/tip errors.

As piston is increased, the original peak continues to shift downward, and two peaks become equal at a physical step height of $\lambda/2$ between the two halves of the circular subaperture. The change in tip between the subaperture corresponding to a peak-to-valley phase is nearly twice of that in tilt, so tip is more effective on far-field pattern than tilt. Fig. 4 shows the Strehl ratio and encircled energy ratio in 0.5 × diffraction limit (DL) around the peak intensity on the focal plane for tilt/tip-piston errors. The phase sensitivity is clear. When the two segments are in phase, the Strehl ratio and encircled energy ratio have the maximum value. As the angular and piston errors are increased, the values continue to shift downward, so searching for maximum will be done by proper algorithm. The stochastic parallel gradient ascent (SPGA) algorithm shall be applied to synchronal adjust the tilt/tip-piston parameters of one segment maximizing the Strehl ratio or the encircled energy ratio in Section 3 [9,10].

In this discussion, we have implicitly assumed that the surfaces of the segments in question are perfect. In practice this is not the case, for grating, the fabrication errors result in the surface aberrations of approximately 50 nm rms. However, because the surface aberration are mainly in low-frequency domain and the subaperture diameter a=20 mm is small compared with the grating size, it is reasonable to take the calculations in ideal condition. For now, we note that a proper algorithm based on the above ultimately results in a tiling-grating configuration that minimizes the tiling errors.

3. Monochromatic phasing experiments

We have developed a mechanical system prototype to phase two medium-scale flat mirrors instead of diffraction gratings, so only three degrees of freedom between the two 220 mm × 200 mm Al-coated flat mirrors are permitted. Each mirror reposes on two knee-joints and is fixed with nylon screws to reduce the vibrating effect. The lateral piston (Δx) is adjusted with manual translation stage and the longitudinal piston ($\Delta z=(A+B+C)/3$) with three PZT translation stages (4 nm minimum displacement). The tip ($\theta x=(B-C)/1.732r$) and the tilt ($\theta y=(2A-(B+C))/3r$) are also controlled by three PZT translation stages for high resolution to achieve angular rotation less than