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Method to mosaic gratings that relies on analysis of far-field intensity patterns in two wavelengths

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Abstract

We propose an experimental method to coherently mosaic two planar diffraction gratings. The method uses a Twyman–Green interferometer to guarantee the planar parallelism of the two sub-aperture gratings, and obtains the in-plane rotational error and the two translational errors from analysis of the far-field diffraction intensity patterns in two alignment wavelengths. We adjust the relative attitude and position of the two sub-aperture gratings to produce Airy disk diffraction patterns in both wavelengths. In our experiment, the repeatability of in-plane rotation adjustment was 2.35 μrad and that of longitudinal adjustment was 0.11 μm. The accuracy of lateral adjustment was about 2.9% of the grating period.

Keywords: Diffraction grating; Tiled gratings; Grating compressor; Far-field diffraction pattern; Chirped-pulse amplification

1. Introduction

Large-aperture diffraction gratings play an important role in many technical fields. In astronomical spectroscopic telescope systems, large-aperture gratings are used for the spectral analysis of the faint light from far away stars [1]. Chirped-pulse amplification (CPA) systems employing a large-aperture diffraction grating pair compressor are capable of producing ultrashort high-intensity laser pulses, which can be used in inertial confinement fusion systems and many other physics fields.

However, to manufacture large-size gratings is technologically difficult and financially impractical. An alternative is to mosaic several small gratings into a large-aperture one. Mazzacurati and Ruocco [2] analyzed the possibility of the grating mosaic in 1990. Zhang et al. [3] presented design results of a pulse compressor consisting of mosaic grating pairs and discussed the theoretical errors caused by different angular misalignments. Harimoto [4] calculated and simulated the far-field patterns produced by mosaic gratings and set up an alignment tolerance criterion, which provided the possibility to align gratings based on analyzing the far-field patterns. Kessler et al. [5] applied a Fourier-transform method to the interferogram to obtain the misalignments information and performed accurate servo loop control for aligning gratings. They produced a near Airy disk focal spot with the aligned grating assembly, and maintained a 650-fs CPA laser pulse with a compression grating replaced by the assembly. However, they employed a phase-compensative method, which may fail to work in multiple wavelength or shorter pulse applications. Moreover, if the wavelength or incident angle of the diagnostic beam differs from that of the use beam, the phase-compensation scheme working well in the diagnostic system may become invalid for the use system [6,7]. Bunkenburg et al. [8] employed a Mach–Zehnder interferometer to monitor and correct the alignment errors in the mosaic grating assemblies, and they adjusted a single grating to compensate the differential errors due to eight gratings within a compressor with four grating assemblies. Zeng and Li [9] proposed a method to mosaic gratings with

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a two-color heterodyne interferometer. The phase errors caused by the lateral gap and longitudinal offset were separated with two wavelengths, but the detection of angular misalignments was not considered in that work.

We propose a far-field pattern analysis based approach to making a perfect mosaic of two sub-aperture gratings. We aim at substituting any single grating, for example in the pulse compressor, with this perfect mosaic without introducing phase errors in any wavelength or incident angle. In order to obtain the three angular misalignments, we monitored a Twyman–Green interferogram and carefully analyzed the symmetry in the shape of the far-field diffraction patterns. For the translational misalignments, the symmetry in the shape of far-field patterns in the two wavelengths were analyzed and compared. Based on the error information, the attitude and position of the gratings were adjusted manually until perfect far-field diffraction patterns (that is Airy disk) were achieved for both wavelengths. In the following part we will first give the definition of the coordinates and the alignment parameters between two sub-aperture gratings and show the parameters' effects on the far-field pattern shapes, especially on the symmetry of the pattern. Then we will describe the detailed algorithm to reveal misalignments from far-field patterns. The experimental results will be given at the end.

2. Principles of alignment

2.1. Description of alignment parameters

There are six degrees of freedom between two adjacent gratings. We fix one grating G_1 and take its grating plane as the x–y plane as shown in Fig. 1. The y-axis is parallel to the grating grooves and the z-axis is perpendicular to the grating plane. Suppose a reference grating G_0 and G_1 form a perfect mosaic, so that they can substitute for a single large grating without introducing wave-front aberration

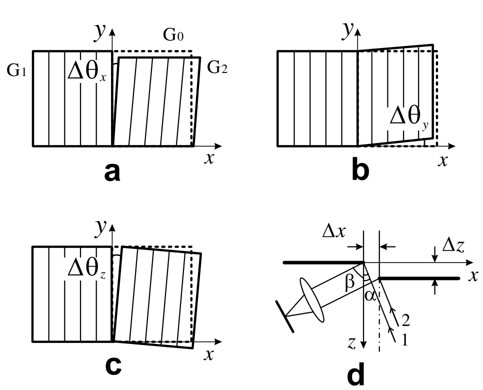

Fig. 1. Definitions of the coordinates and alignment parameters: (a) front view: angular error $\Delta\theta_x$, (b) front view: angular error $\Delta\theta_y$, (c) front view: angular error $\Delta\theta_z$ and (d) top view: lateral gap Δx and longitudinal offset Δz.

at any wavelength. G_0 and G_1 should meet three requirements [6]: their grating surfaces must be coplanar, their grooves must be parallel to each other, and their lateral gap must be an integer multiple of the grating period. Comparing a coarsely aligned grating G_2 with G_0, we can obtain its attitude and position by rotating G_0 around the x-axis a tilt angle $\Delta\theta_x$ (Fig. 1a), around the y-axis a tip angle $\Delta\theta_y$ (Fig. 1b), around the z-axis by an in-plane rotation angle $\Delta\theta_z$ (Fig. 1c), and by translating G_0 along the x, y and z-axis by the lateral gap Δx, the shift Δy and the longitudinal offset Δz (Fig. 1d), respectively. Among these parameters, Δy is parallel to the groove direction of the gratings and does not contribute to the phase difference between the beams diffracted from the two gratings. In terms of these parameters or misalignments, the perfect mosaic requirements can be quantified as: $\Delta\theta_x = 0$, $\Delta\theta_y = 0$ and $\Delta z = 0$; $\Delta\theta_z = 0$; $\Delta x = nd$, where d denotes the grating period and n is an integer.

2.2. Effects of different parameters

Because only three distinct types of phase differences exist between two nearly aligned light beams, the five alignment parameters can be classified into three groups [4]. Translational errors Δx and Δz bring in a piston phase difference between the two beams. The angular errors $\Delta\theta_x$ and $\Delta\theta_z$ alter the diffraction direction and result in a tilt phase difference, and similarly the angular error $\Delta\theta_y$ causes a tip phase difference. According to the theoretical analysis in Refs. [3,5], the three types of phase differences have distinct signatures in the far-field diffraction pattern, by use of which the alignment states of the sub-aperture gratings can be monitored.

2.2.1. Piston phase difference

The lateral gap Δx and longitudinal offset Δz both contribute to piston phase difference. For an incident light beam of the wavelength λ with the incident angle α and diffraction angle β as shown in Fig. 1d, the piston phase difference $\Delta\Phi_{12}^{\lambda}$ between the outgoing light beams 1 and 2 diffracted at the adjacent edges of the two gratings can be derived from their optical path difference as

$$\Delta\Phi_{12}^{\lambda} = \frac{2\pi}{\lambda}[\Delta x \cdot (\sin\alpha - \sin\beta) + \Delta z \cdot (\cos\alpha + \cos\beta)]. \quad (1)$$

For the normal incident situation and the −1st-order diffraction, it becomes

$$\Delta\Phi_{12}^{\lambda} = \frac{2\pi}{d}\Delta x + \frac{2\pi}{\lambda}(1 + \cos\beta) \cdot \Delta z. \quad (2)$$

Because the contribution of Δz to $\Delta\Phi_{12}^{\lambda}$ depends on the wavelength but that of Δx does not, we can distinguish the effects of Δx and Δz by using two distinct wavelengths. If we adjust Δz so that the phase differences in the two wavelengths are in-phase, that is $\Delta\Phi_{12}^{\lambda_1} - \Delta\Phi_{12}^{\lambda_2} = 2n\pi$, the longitudinal offset Δz should be an integer multiple of the synthetic wavelength $\overline{\lambda_{12}}$ that equals