Matched wavelength and incident angle for the diagnostic beam to achieve coherent grating tiling

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Design and operation of a practical, accurate alignment diagnostic system is important for the grating tiling technology, which is supposed to be applied in a chirped-pulse amplification system to increase the output power. A diagnostic method is proposed and demonstrated for grating tiling. Provided that the wavelength and incident angle of the diagnostic beam are properly set, the far-field of the main laser beam and that of the diagnostic beam can vary in the same way with the tiling errors between the sub-aperture gratings. Therefore, rotational and translational errors can be controlled and compensated according to the far-field of the diagnostic beam. The real-time monitoring and alignment can be achieved without disturbing the main beam.

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Chirped pulse amplification technology has rapidly accelerated the development of short-pulse, high-energy, and high-irradiance lasers, and provided many new opportunities for studies in light-matter interaction and inertial confinement fusion. However, the aperture size and damage threshold of diffraction gratings, which are often used in a pulse compressor, limit the short-pulse energy of a high intensity laser system. Because making grating of large size is both technologically and financially impractical, many researchers try to take an alternative way, such as tiling two or more gratings into a single one. Theoretical research[1−4] has been made about the influences of various alignment errors on performance of a tiled grating, but experimental reports are few[5−7]. It is partly due to the difficulty in design and operation of a tiled grating aligning diagnostics[8].

The alignment errors between any two sub-aperture gratings can be grouped into three compensating pairs[6]: longitudinal piston and lateral piston (i.e. gap width), in-plane rotation and angular tip, line-density error and angular tilt. Compensation between pairs will be convenient and effective only if each differential error is kept small. But under ordinary conditions, the far-field of the diagnostic beam and that of the main laser beam are not accordant, because the phase delay between the diffraction beams from the sub-aperture gratings depends on both the wavelength and the incident angle of the incoming light. It was believed that the diagnostic beam that utilizes an alignment laser must operate at the same wavelength and angle of incidence as the high-energy chirped-pulse laser beam[8] (i.e. the main laser beam). In this Letter, we report that the diagnostic beam can perform at a different incident angle from the main beam. With a matched wavelength and incident angle, the diagnostic beam can monitor the far-field of the main beam in real time, because the out-of-beam setup enables the main beam to reach the target without let or hindrance. It is more important that the matched wavelength and incident angle are suitable for the case that there is a line-density difference between sub-aperture gratings, as well as for the case that there is not.

A schematic diagram of tiled-gratings-compressor is presented in Fig. 1. Gratings G_1 and G_2 are parallel to each other, with nominal line-density of 1700 line/mm, composing a single-pass compressor. G_2 is comprised of two sub-aperture gratings (G_{2-1} and G_{2-2}), and the main laser beam (centered at 1053 nm) will be compressed through G_1 and G_2. The beam emergent from G_2 is reduced in size by lenses L_1 and L_2, focused by L_3, and then the far-field distribution pattern is magnified by a 10× microscope objective and recorded by a CCD camera.

We can use a diagnostic beam to monitor relative orientation of the sub-aperture gratings. Far-field patterns of the 1st-order and the 0th-order diffraction beams are both magnified by the same microscope and recorded by CCD_1. The diagnostic beam passes through the optic components in orders as follows,

BS_1-M_1-M_2-G_2-M_3-G_2-M_2-M_1-BS_1-L_4-CCD_1
(the 0th-order),
BS_1-M_1-M_2-G_2-M_4-G_2(1)-M_5-M_6-BS_1-L_4-CCD_1
(the 1st-order).

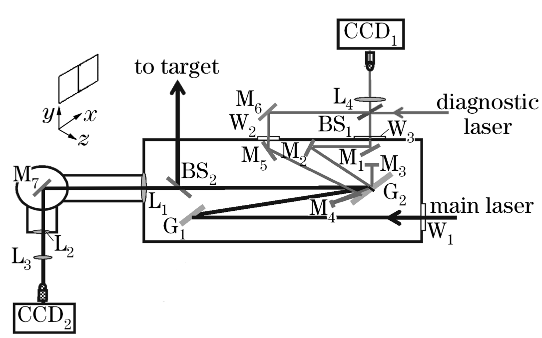

Fig. 1. Schematic for experimental setup. BS_1-BS_2: beam splitter; M_1-M_7: high-reflectivity mirror; L_1-L_4: lens; W_1-W_3: window; CCD_1-CCD_2: CCD camera; G_1: single grating; G_2: tiled grating.

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In the above G_2 means the beam falling on two sub-aperture gratings simultaneously, and $G_{2(1)}$ means the beam falling on G_{2-1} only. To weaken the transmitting diffraction effect because of the much smaller size in the horizontal direction and not to introduce once again tiling alignment errors, the 1st-order diffraction beam reflected from M5 is diffracted by G_{2-1} only. The 0th-order focal spots is used to adjust preliminarily the sub-aperture gratings coplanar.

If a He-Ne laser beam acts as a diagnostic beam, it is usually observed that the 1st-order far-field patterns of diagnostic beam and the main laser beam cannot keep a single spot pattern at the same time. The asynchronism will be more prominent in the case of there being line-density difference between the sub-aperture gratings. When the 1st-order far-field of the diagnostic beam is a perfect single spot, the main laser's far-field pattern may be two separate spots at a large separation. This may make it very hard to achieve real-time monitoring.

Now we will show how to properly choose wavelength and incident angle for the diagnostic beam to realize real-time monitoring. Firstly we assume that there is little line-density difference between the sub-aperture gratings. As Fig. 2 shows, a plane wave is incident on the tiled gratings with a propagation direction θ_i from the grating normal. Assume that the surfaces of these two sub-gratings had been adjusted to be parallel to each other, and the grooves had been done the same. Because of line-density difference, the 1st order diffraction beams O_1A_1 and O_2A_2 from these two gratings are not parallel. Assume that G_{2-2} is rotated around y axis (orthogonal to the paper) through angle θ_y, so that the two diffraction beams from the two gratings are parallel, $O_1A_1 /\!/ O_2B_2$. In this case we can get the equation

$$\sin(\theta_i - \theta_y) + \sin(\theta_r - \theta_y) = (n - \Delta n)\lambda, \quad (1)$$

where θ_i and θ_r are the incidence and diffraction angles upon the reference grating G_{2-1}, Δn is line-density difference between the two sub-aperture gratings, which means the line-densities are n and $n - \Delta n$ for G_{2-1} and G_{2-2}, respectively. θ_i and θ_r satisfy the equation

$$\sin\theta_i + \sin\theta_r = \lambda/d = \lambda n \quad (2)$$

for G_{2-1}, where $d = 1/n$ is the grating groove period. When θ_y is small, according to Eqs. (1) and (2), the following equation can be obtained

$$\theta_y(\cos\theta_i + \cos\theta_r) = \Delta n\lambda. \quad (3)$$

In order to get a single focal spot pattern for the monitoring laser beam and for the main laser at the same time, Eq. (3) must be satisfied for both; thus

$$\frac{\cos\theta_{i1} + \cos\theta_{r1}}{\lambda_1} = \frac{\cos\theta_{i0} + \cos\theta_{r0}}{\lambda_0}, \quad (4)$$

where θ_{i0} and θ_{r0} are the incident angle and the 1st-order diffraction angle for the main laser beam upon the reference grating (G_{2-1}), while θ_{i1} and θ_{r1} are of the same meanings for the monitoring laser beam. Equation (2) is also satisfied for both laser beams, so

$$\frac{\sin\theta_{i1} + \sin\theta_{r1}}{\lambda_1} = \frac{\sin\theta_{i0} + \sin\theta_{r0}}{\lambda_0}. \quad (5)$$

The phase difference $\Delta\phi_z$ between the two beams from two sub-aperture gratings, is given by

$$\Delta\phi_z = 2\pi[(\sin\theta_{ij} + \sin\theta_{rj})\Delta x - (\cos\theta_{ij} + \cos\theta_{rj})\Delta z]/\lambda_j, \quad (6)$$

where $j = 0, 1$ and Δx, Δz are the gap width and longitudinal piston error between sub-aperture gratings, respectively. Note that although the wavelength and angles depend on j, $\Delta\phi_z$ does not.

According to Eqs. (4)—(6), it is evident that alignment errors will affect the far-field pattern of the main laser and that of the diagnostic laser in the same manner. In this way we can easily and directly monitor the tiled-gratings-compressor in real time, and we can compensate not only the line-density difference but also the translational error (gap width and longitudinal piston error). It is more interesting and valuable that the wavelength and incident angle of the diagnostic beam are independent of the amount of line-density difference, as long as it is small, although we begin with a line-density difference Δn to get the Eqs. (4) and (5). Given parameters of the main laser, combining Eqs. (4) and (5) we can choose proper wavelength and incident angle for the diagnostic laser. Surely, availability of the laser source and convenience of the optics layout should be taken into account. For a given diagnostic wavelength there are two solutions, θ_1 and θ_2. If θ_1 is the incident angle, θ_2 is the diffraction angle; if θ_1 is the diffraction angle, θ_2 is the incident angle.

In our experiment, the nominal line-density of the tiled gratings was 1700 line/mm, with a little difference of 0.16 line/mm between the sub-aperture gratings, and incident and diffraction angle of the main laser of wavelength 1053 nm were 67.0° and 60.4°, respectively. Figure 3 was obtained according to Eqs. (4) and (5), which displays the incident and diffraction angles of the diagnostic laser

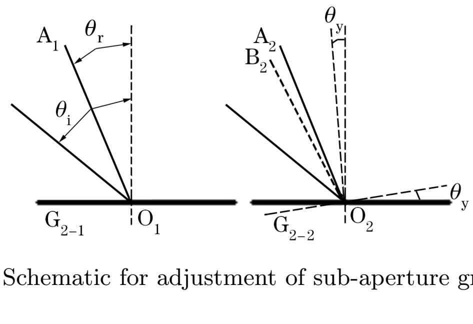

Fig. 2. Schematic for adjustment of sub-aperture gratings.

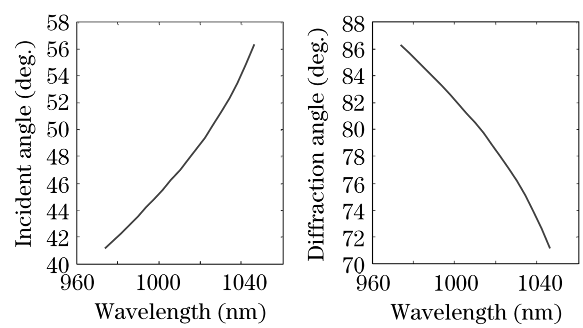

Fig. 3. Incident and diffraction angles versus wavelength of the diagnostic laser.

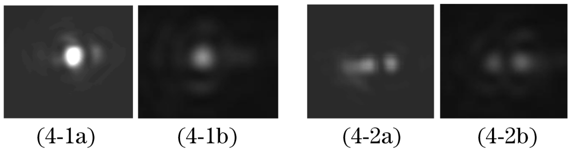

Fig. 4. Far-field of the main laser beam (a) and that of the diagnostic laser beam (b) vary in the same manner with different tiling errors. (a) $2n\pi$ tiling phase error; (b) $(2n+1)\pi$ tiling phase error.

versus wavelength, which can be interchanged mutually. The wavelength of diagnostic laser used in the experiment was 998.8 nm, so the incident angle satisfying Eqs. (4) and (5) turned out to be 44.96° or 82.45°.

Figure 4 shows that the far-field of the main laser beam and that of the diagnostic laser beam vary in the same manner with different tiling errors between the sub-aperture gratings. In addition, the measured single focal spot diameter of the main laser beam was 1.5 times of that of diffraction limited.

In conclusion, we have proposed and demonstrated a diagnostic method for grating tiling. With a matched wavelength and incident angle of the diagnostic beam, rotational and translational tiling error can be controlled and compensated conveniently. Real-time monitoring and alignment can be more easily achieved. This method is suitable for the case that bandwidth of the main laser is not too wide, and can be expected to be used in a compressor of other configuration.

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