Piston phase alignment of tiled grating assemblies by use of temporal coherence of ultra-short pulse

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Multi-kilojoule petawatt lasers using chirped-pulse amplification need large-scale compression gratings. Tiled-grating approach has been adopted in several systems to meet the size requirements, grating tiles need to be precisely phased to ensure a transform-limited focal spot when focusing high-energy laser pulses in the target. Piston error of segmented gratings induced the focal spot to split when it arrived at multiple of the half wavelength. Alignment method using ultra-short pulse capable of controlling the absolute piston phase error within one half wavelength is proposed.

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High-power, solid-state lasers, using the chirped-pulse amplification (CPA) scheme, incorporate pulse compressors containing holographic gratings. The most promising grating technology is a holographically formed grating combined with a multi-layer dielectric (MLD) coating to form a highly efficient grating used in reflection. Gratings with larger apertures can further extend the short-pulse energy capability of petawatt laser systems; however, the fabrication process of MLD reflection gratings is very difficult so that limits the ultimate size of an individual grating to less than 1 m. The coherent summation of multiple gratings to form a larger grating provides an alternative to meter-sized MLD. A tiled-grating compressor (TGC) is capable of handling greater laser energy than a grating-aperture-limited compressor. When properly aligned, they will act as a monolithic optical element[1,2].

As shown in Fig. 1, there are five degrees of freedom between each adjacent pair of gratings within a tiled-grating system: tip, tilt, rotation, in-plane shift, and out-of-plane shift. However,only three distinct types of optical path differences exist between closely aligned grating pairs. Relative shifts along the x and z axes result in a differential piston phase between the grating pairs. Similarly, relative rotations about the x and z axes result in a differential tilt phase between the adjacent gratings. Relative rotation about the y axis results in an additional tilt, while the relative shift along the y axis is inconsequential since it is parallel to the groove of the grating. Relative tilt resulting from relative groove rotation about the x axis can be used to compensate relative groove rotation. In addition, the out-of-plane shift, also referred to the piston phase error, can be used to compensate the residual error caused by the finite space between adjacent gratings. The effect of piston misalignment was modeled thoroughly. Theoretical simulations show the far-field irradiance resulting from relative piston-type phase error between two tiled gratings. A half-wave piston-type error causes the focal spot to split into two symmetric spots of equal energy and irradiance. It is observed experimentally that the majority of the focal spot degradation occurs closer to the half-wave error, indicating a relative insensitivity in the vicinity of piston phase error, which is a multiple of 2π.

Computer simulations of one tiled-grating assembly (TGA) interface show that tip, tilt, or piston misalignment between the gratings affect the Strehl ratio, which is defined as the ratio of the peak irradiance of an aberrated focal spot to that of an aberration-free focal spot[3]. These computer simulations show that piston is the most sensitive drift parameter for two gratings and that the effects of piston error are cyclical with period of $\lambda/2$.

There are many ways to correct the piston phase error of the segmented gratings, usually the illumination source is continuous wave (CW), monochromatic laser light, the CW laser light probes the gratings and is transmitted to electronic cameras to record both the fringe pattern and the corresponding focal spot. Analysis of this fringe pattern yields differential tip, tilt, and piston[4], most of differential tip and tilt errors could be minimized in a closed-loop cycle, however, the absolute piston error cannot be determined because the relative piston could only be set within $2\pi N$, where N denotes the integer, even utilizing a high-resolution mechanical indicator combined with motorized actuators of the closed-loop system, the absolute piston could reduce to less than one wavelength. Moreover, the property of the focal spot is dependent on the stability and the precision of the closed-loop cycle system. We proposed a method which used the ultra-short pulse incidence, the piston can be controlled within sub-wavelength.

Using the femtosecond pulse reflected by the mirror as the reference beam of interferometer, reflection light from tiled gratings as the other interferometric beam, aligned the mirror and tiled grating assemblies respectively to equal the optical path of the two beams, thus if the piston error between the segmented gratings is aligned within coherent range, fringe pattern will be observed, as shown

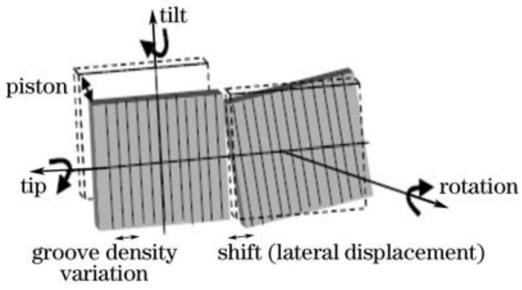

Fig. 1. There are five degrees of freedom between each adjacent pair of gratings within a tiled-grating system.

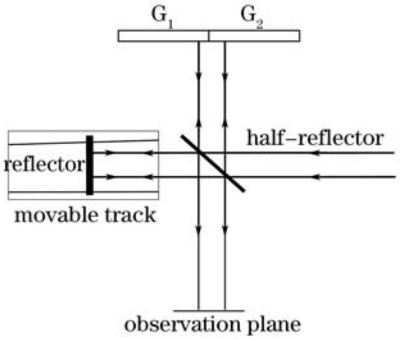

Fig. 2. Setup of controlling the piston error utilizing ultra-short laser pulse.

in Fig. 2. Following that we aligned the adjustable segmented grating to turn the two piece fringe patterns into one piece including conformity of density and direction, moreover, if the two piece fringe changed in-step when aligning tip-tilt position of the reflection mirror slightly, it is shown that the tiled gratings assemblies have been controlled under good condition. Because of the high sensitivity of the observation instrument, we can detect the appearance and disappearance of two piece fringes simultaneously within a fractional range of the coherent distance, so it is possible to align the piston to zero. As we know, the coherent length of femtosecond pulse is very short, about several micron order, so that the detection length would be much shorter. Accordingly, the piston between two sub-aperture gratings has been controlled within sub-micron. It is possible to reach more precise if much shorter laser pulse is available[5].

In the experiment, a Michlson interferometer was built according to the principle of Fig.2, central wavelength of 800 nm, Fourier-transform-limited pulse width of 30 fs with the beam diameter of 10 mm is the laser source to illuminate a pair of Jobin Ivon 80×110 (mm) gratings, with 1480 groove/mm, mounted on a manual adjustable stand. The operational laser pulse had to be attenuated by several attenuators to decrease high power of laser pulse. A shearing plate, inserted in the Michlson cavity, as shown in Fig. 2, separated pulse laser in to two beams, one beam to the tiled gratings, the other to the movable reflector. The interferogram was received by a charge coupled device (CCD) camera. To obtain the absolute piston, we assembled a high-resolution mechanical indicator behind the reflection mirror. Figure 3 shows the optimal piston error measured in experiment.

The coherent length of femtosecond laser pulse used in the experiment is about 24 μm, the range that the fringe faded in and out, which was detected, is about 1.2 μm for single pass, about 1.5 times of wavelength. In fact, it should be more precise for the coherent length is 9 μm before passing through the amplifier media. After that the operational laser pulse in the experiment had been stretched into 80 fs, so the optimal absolute piston measured departed from the prediction which could be controlled within fraction of one micron.

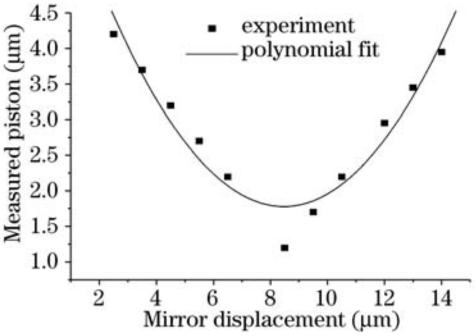

Fig. 3. Experimental and fitting results of absolute piston error.

In conclusion, we have demonstrated that the piston error of TGAs could be controlled within one half-wavelength utilizing the ultra-short laser pulse if the pulse duration was short enough. It is reported that the shortest ultra-short laser pulse duration is about 4.5 fs, corresponding coherent length about 1.2 μm, detection length about 0.12 μm, which means the controllable absolute piston, less than half-wavelength of usual available laser. Utilizing temporal coherence characterisctic of femtosecond laser pulse, more precise control of piston error in tiled gratings is possible.

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