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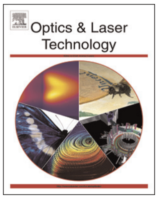

Actively compensation of low order aberrations by refractive shaping system for high power slab lasers

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ABSTRACT

We present a compact refractive shaping system for actively compensating low order aberrations of high power slab lasers. The shaping system includes three spherical lenses and two cylindrical lenses. Both theoretical and experimental investigations were performed to evaluate the compensation capability of the refractive shaping system. For a typical input beam with large low order aberrations of peak-to-valley (PV)$=66.10\lambda$ and root-mean-square (RMS)$=16.05\lambda$, adjusting the distance between lenses, the wavefront aberrations are reduced to PV$=0.48\lambda$, RMS$=0.10\lambda$ for the theoretical simulation and PV$=0.50\lambda$, RMS$=0.11\lambda$ for the experimental result, respectively. It indicates that the main low order aberrations of defocus and 0° astigmatism can be significantly compensated by actively adjusting the distance between lenses and the experimental result agree well with the theoretical simulation.

1. Introduction

High average power solid state lasers with good beam quality simultaneously are important for both industrial and military applications. Zigzag slab configuration with uniform pumping intensity and large surface cooling is considered as the most promising scheme [1–3]. However, at high average powers, laser brightness and beam quality tend to be limited by thermal-based distortion in the slabs, which arises from spatial inhomogeneity in the heat deposition and removal, and thus are not eliminated by zigzag propagation. The adaptive optics (AO) system is usually used to improve the wavefront quality [4–8] and has been successfully used in many different optical systems for deleting the aberrations. However, the maximum stroke of AO usually less than 20 μm and its advantage concentrate on high order aberration correction, the laser beam quality degraded rapidly as AO reached its stroke limit [6–8]. It is noted that thermal effects induced wavefront distortion mainly composed of low order aberrations, such as defocus and 0° astigmatism [5,9], which can be compensated by standard optical elements. In 2000, Hoffnagle et al. presented an aspheric lenses beam shaping system for providing flattop intensity distribution with low output divergence [10] and concentrated on intensity field reshaping. In 2014, Liu et al. introduced a three mirrors reflective shaping system for compensation low order aberration [11], but it is complicated for real time control because it has to dynamically adjust the distance between mirrors and precisely regulate the beam direction, simultaneously.

In this paper, we present a compact efficient lens-based shaping system, which consists of three spherical lenses and two cylindrical lenses, based on machine learning algorithm [12] for actively compensating low order aberration of high power slab lasers. The aberration compensation can be implemented by adjusting the distance between lenses. Optical design software Zemax has been performed to construct the shaping elements and simulate the low order aberrations compensation. The theoretical simulation and experimental investigation were performed. Results show that for an input laser beam with large low order aberration, the wavefront aberration can be reduced about two order of magnitude and the experimental data are excellent agreement with the theoretical simulation. The refractive shaping system has been successfully used in 10 kW level quasi-continuous-wave (QCW) master oscillator power amplifier (MOPA) Nd:YAG slab laser for low order aberrations compensation [13],

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which bridged the gap between large magnitude low order aberrations and finite stroke limit of AO.

2. Optical design

2.1. Design method

When designing the refractive shaping system, the following three factors were considered for matching our experimental configuration:

- The characteristic of the laser beam: the beam of QCW MOPA Nd:YAG slab lasers at 1064 nm is a rectangular spot, with size of 3.2 mm × 32 mm and the divergence of long direction (*y*-direction) is faster than the narrow direction (*x*-direction). The output beam from shaping system is near square 30 mm × 30 mm.
- The overall layout of the shaping system should be less than one meters. The Galilean configuration (negative–positive) is adopted to minimize the overall length and eliminate the real focus.
- A minimum of three elements is needed for a single direction to produce a variable beam expander which provides control over both magnification and collimation.

The initial parameters of the shaping system were defined by the optical design software Zemax under the condition that the input laser beam is perfectly collimated. The layout of the refractive shaping system in the *x*–*z* cross-section is shown in Fig. 1. The beam propagates along *z*-axis.

Fused silica was chosen as the lens material for its high damage threshold [14] and each optical face coated with antireflection (AR) at 1064 nm. The F1 is x-oriented plane-concave cylindrical lens with a radius of curvature (ROC) of +53 mm. The F2 is plane-convex lens with a ROC of +200 mm. The F3 is plane-concave lens with a ROC of +80 mm. The F4 is x-oriented plane-convex cylindrical lens with a ROC of+228 mm. The F5 is plane-convex lens with a ROC of −450 mm. The relative distances between lenses L1, L2, L3 and L4 are from F1 to F2, F2 to F3, F3 to F4 and F4 to F5, respectively, and the location of the F1 was fixed as the reference point. Here F2, F3, F4 and F5 were coaxially mounted on four linear motors, independently, for actively adjusting the distance between lenses.

2.2. Theoretical simulation

In order to dynamically compensate low order aberrations of high power slab lasers induced by thermal effects, there must be some moving elements which satisfied with long travel distance (from 10 mm to 120 mm), high precision, and high degree straightness. We empirically set four moving elements F2, F3, F4 and F5. In the simulation, the input low order aberrations are generated by adding a phase plate on the input reference plane and the residual aberrations are detected at the output reference plane. To fully investigate the compensation capability of the refractive shaping system, we executed a series of low order aberrations compensation, which correspond to the real operational conditions of high power slab lasers. Three typical cases were chosen to show its compensation capability, which cover the entire range of high power slab lasers. Case 1, defocus $Z4=-2.13$, 0° astigmatism $Z5=2.47$, peak-to-valley $(PV)=13.43\lambda$, root-mean-square $(RMS)=3.26\lambda$ and the equivalent x-direction divergence $\theta_x=0.18$ mrad, *y*-direction divergence $\theta_y=1.79$ mrad. Case 2, $Z4=-6.32$, $Z5=7.31$, $PV=39.80\lambda$, $RMS=9.66\lambda$ and the equivalent $\theta_x=0.53$ mrad, $\theta_y=5.29$ mrad. Case 3, $Z4=-10.48$, $Z5=12.16$, $PV=66.10\lambda$, $RMS=16.05\lambda$ and the equivalent $\theta_x=0.87$ mrad, $\theta_y=8.79$ mrad. The three cases mentioned above correspond to 2 kW, 7 kW and 10 kW output powers of our QCW MOPA Nd:YAG slab lasers, respectively. Comparison of wavefront aberrations and optical layout parameters without and with compensation is listed in Table 1.

From Table1, the compensation results of cases 1, 2 and 3 are: $Z4=-0.04$, $Z5=0.05$, $PV=0.37\lambda$ and $RMS=0.06\lambda$; $Z4=-0.05$, $Z5=0.06$, $PV=0.42\lambda$ and $RMS=0.08\lambda$; $Z4=-0.06$, $Z5=0.07$, $PV=0.48\lambda$ and $RMS=0.10\lambda$, respectively. Clearly the wavefront aberrations are decreased several ten to hundred times. The theoretical simulation indicates that the various combination of defocus and 0° astigmatism, which is the predominant aberrations of high power slab laser, can be well compensated by adjusting the distance between lenses.

3. The experimental configuration and control algorithm

3.1. Experimental configuration

To verify the capability of the refractive shaping system for actively compensating low order aberrations, a series of experiments were carried out. The experimental layout is shown in Fig. 2. It mainly consists of low order aberrations generator (LOAG), two beam splitters (BS1, BS2), refractive shaping elements F1–F5 and two Shack–Hartmann wavefront sensors (S–H1, S–H2).

The LOAG includes two x-oriented cylindrical lenses and two y-oriented cylindrical lenses and a light source with rectangular spot at 1064 nm. By adjusting the distance between the lenses, different low order aberrations can be generated to simulate the main wavefront distortions of the high power slab laser. The aberrant laser beam is incident on BS1. The transmitted branch goes to S–H1 through collimated x-oriented cylindrical beam expander F6 and F7 and then beam size will be transformed into 32 mm × 32 mm, while the reflected part pass through the refractive shaping elements to compensate low order aberration. The initial distance between adjacent lenses are $L1=\sim 221$ mm, $L2=\sim 179$ mm, $L3=\sim 141$ mm and $L4=\sim 241$ mm, respectively. After compensated by the refractive shaping elements, the beam is

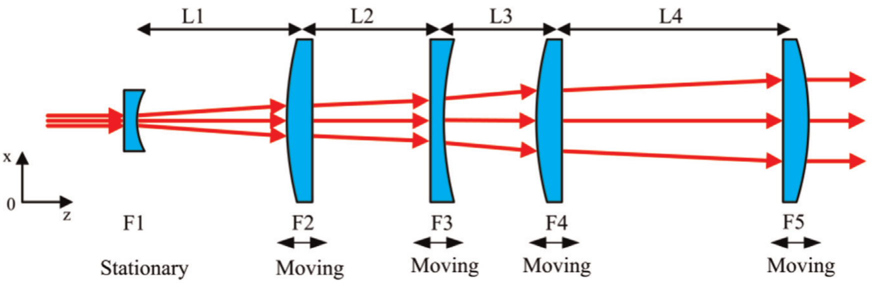

Fig. 1. The layout of the refractive shaping system in the *x*–*z* cross-section.