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Precompensation of gain nonuniformity in a Nd:glass amplifier using a programmable beam-shaping system

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ABSTRACT

A programmable liquid crystal beam-shaping system was installed for a 200-mJ optical parametric chirped-pulse amplification (OPCPA) system front end and was applied to dramatically improve the beam uniformity in the subsequent amplifier. A highly nonuniform beam profile caused by gain inhomogeneity in the amplifier was pre-compensated by the beam shaping system using significantly improved open-loop and closed-loop algorithms. The details of the improved algorithms will be described. The issues of running a liquid crystal device with a high-energy, ultrashort-pulse laser, such as damage risk and temporal contrast degradation, will be addressed.

1. Introduction

A dynamic beam-shaping system using a liquid crystal spatial light modulator (SLM) has undergone a successful transition from initial proof-of-principle demonstrations [1,2] to an implementation in a high-energy laser such as the OMEGA EP at the University of Rochester [3]. The operation principle of the beam-shaping system is based on the phase-only carrier method, which enables one to have arbitrary two-dimensional (2-D) control of both the laser-beam fluence and the wavefront by adjusting the modulation depth and the bias of the carrier phase. A liquid crystal on silicon (LCOS) SLM can be used to create a programmable high-frequency carrier phase. Closed-loop operation of such a device paired with feedback from a near-field camera or a wavefront sensor dramatically improves the performance [2].

Gain precompensation [4] and spot shadowing [5,6] are important applications of a dynamic beam shaper in high-energy lasers. The precompensation of gain inhomogeneity in amplifiers reduces the peak-to-mode in fluence distribution in such a way that the total energy of the beam can be increased without risking damage to the optics. The gain precompensation in OMEGA EP long-pulse (ns) beamlines is achieved in multiple steps using both static and dynamic beam shapers [3,7]. The dynamic beam shaper is located in the low-energy front end, where a residual 2-D correction map is applied to improve the overall system gain precompensation performance and the uniformity of the final output beam. A similar gain precompensation experiment was performed in another facility for a Nd:glass amplifier but with insignificant improvement in beam uniformity [8].

In this paper we present a more-challenging application of dynamic beam shaping in the context of a 50-J, 700-fs optical parametric chirped-pulse amplification (OPCPA) system. The high degree of gain saturation in the optical parametric amplification (OPA) crystals precludes the possibility of installing the SLM before the OPA. The incident beam energy on an SLM installed after the OPA is high enough, however, to damage the device if not carefully managed. Pulse contrast degradation caused by the secondary reflection from the front surface of the SLM cover glass is a non-negligible problem in this pulse-width regime. It introduces a prepulse 30-ps before the main pulse. We have been able to mitigate or remove these problems. The details of our approach will be described later.

Significant improvements and diversifications in the algorithms and the mode of operations of the carrier method have been made. First, a large discrepancy was found between the analytic transmission function derived in [1] and the experimental function. An empirical formula is introduced here that agrees better with the measurements. It greatly improves the accuracy of the open-loop algorithm. The closed-loop algorithm introduced in [2] is based on incrementing or decrementing a fixed unit-step size of the digital command map. It can be inefficient to use a fixed step size where many steps are required for convergence. A more-efficient closed-loop algorithm will be discussed.

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The type of carrier used in the carrier beam-shaping method is not limited to a one-dimensional (1-D) rectangular carrier. A checkerboard-pattern carrier was successfully used in the laser-cavity mode shaping in [9]. The choice of the transmitted diffraction order does not need to be the zeroth order. A sawtooth-shaped carrier beam can maximize the diffracted energy into the first-order diffraction term, where the first-order term is chosen to be the main transmitted beam. Such mode of operation is fail-safe since the beam can propagate only in the presence of a carrier.

Improvements to the carrier beam-shaping algorithms will be discussed followed by detailed descriptions of the laser system and the experimental results.

2. Improvement and diversification of the original carrier beam shaping method

In the original phase-only carrier beam-shaping method, a rectangular carrier phase is applied to an SLM. A beam incident on the SLM acquires high-frequency modulation in phase and diffracts into the zeroth- and first-order diffractions. As the modulation peak-to-valley (p–v) approaches π, more energy diffracts into the first- and higher-order diffractions. The diffracted beams are filtered and only the zeroth-order beam is allowed to pass. In this way the intensity transmission factor can be adjusted by controlling the modulation depth of the carrier phase. A 2-D transmission map as a function of carrier amplitude can be generated to achieve a desired beam shape. This principle can be modified in such a way that the first-order diffraction beam passes, whereas the zeroth-order beam is blocked. The benefit of such a configuration is that the beam does not propagate when the SLM fails to introduce the carrier, which is a useful feature for fail-safe operation in a high-energy laser. The disadvantage is that the maximum transmission cannot exceed 50% because the first-order diffractions are equally split. The low efficiency can be improved by using a sawtooth carrier phase (blazed grating) instead of a rectangular one. The diffraction efficiency of the first-order diffraction for the sawtooth carrier phase can be very high. These two modes of operation are schematically shown in Fig. 1, where Fig. 1 (a) describes the original carrier beam-shaping setup and Fig. 1 (b) shows the modified carrier method in Littrow configuration. We refer to the first configuration as the normal mode and the second one as the diffractive mode. For later discussions, the transmission [$T(x,y)$] of a carrier method in the near field of each setup after filtering is defined as

$$T(x,y) = \frac{E_{0\text{th order}}(x,y)}{E_{\text{inc}}(x,y)}, \quad (1)$$

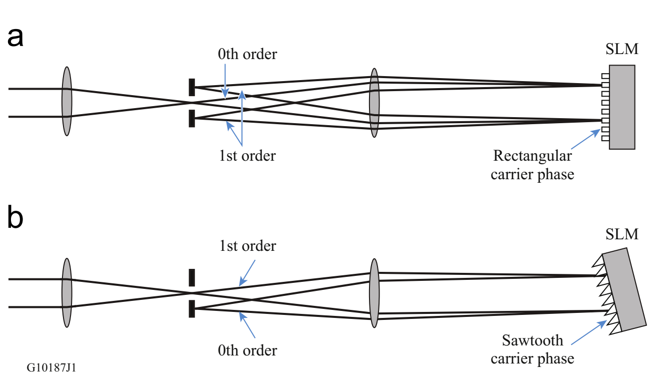

Fig. 1. Two modes of carrier-beam shaping: (a) normal mode using the zeroth-order beam as the main beam; (b) diffractive mode using the first-order beam as the main beam.

and

$$T(x,y) = \frac{E_{1\text{st order}}(x,y)}{E_{\text{inc}}(x,y)}, \quad (2)$$

for normal- and diffractive-mode methods, respectively. E_{inc} is the incident local energy on the SLM, and $E_{0\text{th order}}$ and $E_{1\text{st order}}$ are the local reflected energy contained in the zeroth- and the first-order diffraction beam, respectively.

2.1. Improvement in the open-loop algorithm

The algorithm described here assumes using an LCOS-SLM device whose voltage-to-phase-retardation response is linearized by using a look-up-table (LUT). Use of an LUT does not completely remove the small variations in phase retardation in individual pixels of an SLM. In our case, the variation is $\pm 6\%$. In an open-loop algorithm, we attempted to achieve the best beam-shaping performance in a single step, neglecting these small variations. We used a reflective LCOS-SLM from Hamamatsu (X10468-03). The phase of an individual pixel is controlled by applying voltage on the nematic liquid crystal sandwiched between two parallel-aligned alignment layers. The SLM has 600×800 20-μm pixels over a $12 \times 16\text{-mm}^2$ area. A phase retardation from 0 to 2 waves can be independently introduced on each pixel.

2.1.1. Normal mode

The theoretical normal-mode transmission for a rectangular carrier phase with $\pm 2\pi A$ fluctuation was shown to be $|\cos(2\pi A)|^2$ in [1]. The actual transmission deviates, however, from the theoretical prediction. The theoretical and measured transmission curves are shown in Fig. 2. The transmission loss from the SLM's reflectivity (93%) was not included in the calculation or measurements. The plot of blue circles is the theoretical prediction, whereas the colored solid lines are the transmissions measured at three different carrier frequencies by varying the carrier amplitude (A) from 0 to 1 wave. The transmission at each carrier frequency was averaged over nine different points on the SLM. The black, blue, and red solid lines correspond to the carrier periodicity of two, four, and six pixels, respectively. The measured transmission curves show discrepancies with the theoretical curve in which the location of the first minimum is farther away from the theoretical 0.25 and the second peak is lower than 1. Another theoretical transmission curve based on a sinusoidal carrier is shown by the plot of purple circles. The analytic transmission function of a sinusoidal carrier is a Bessel function (J_0). Comparison of the analytic and measured transmission curves shows that the measured transmission has characteristics somewhere between the rectangular and sinusoidal carriers. The deviation from the rectangular-carrier transmission curve becomes larger as the carrier frequency increases. This suggests that the corners of the actual carrier wave are rounded and this effect becomes more pronounced at high frequency. Based on this observation, the empirical transmission function can be expressed using both cosine and Bessel functions as follows:

$$T(A) = (1-c)[(1-a)\cos(2\pi bA) + aJ_0(2\pi bA)]^2 + c, \quad (3)$$

where T is the transmission as a function of carrier amplitude A. The fit parameters (a, b, c) for each averaged transmission curve are given in Table 1. The numerically fit transmission functions are shown as dashed lines in Fig. 2.

The locations of the first minima calculated from the analytic function with the given fit parameters are shown in the A_{min} column. The minimum transmission is the same as c. The value of c is shown to the fourth digit to emphasize the fact that there is a low level of leak even at "zero" transmission. The extinction is better at a lower carrier frequency.