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Invited Paper

Spatial beam shaping for high-power frequency tripling lasers based on a liquid crystal spatial light modulator

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ABSTRACT

We propose and demonstrate a spatial beam shaping method to achieve high-quality near-field for a high-power frequency tripling laser system by using a liquid crystal spatial light modulator (SLM). Considering the nonlinear relationship between the output 3ω intensity and the input 1ω intensity of the frequency conversion system and the transmittance nonuniformity of the whole laser system, we introduce an efficient spatial beam shaping method that improves the output near-field beam quality of frequency tripling laser dramatically. Results show that the near-field peak-to-mean value of the frequency tripling laser improves from 1.83:1 to 1.42:1 after spatial beam shaping within four shots. This method provides effective guidance for spatial beam shaping of high-power frequency tripling laser systems.

1. Introduction

High-power ultraviolet (UV) lasers are attractive for a wide range of applications in inertial confinement fusion (ICF) [1] and in industrial and scientific fields [2–4]. Additionally, many physics experiments [5–8] require the third-harmonic generation (THG) of 351 nm light. Furthermore, improvement in the near-field spatial profile uniformity is a mainstay of any prioritized list of improvements since a spatially uniform beam offers the potential for increased margin versus optic damage thresholds and higher overall operating energy output of the beam in high-power lasers [9–13]. Moreover, a high-quality near-field laser beam is more reliable for providing credible data in scientific and physical experiments, such as in the study of the relationship between physical phenomenon and laser fluence [14,15].

Over the past decade, liquid crystal spatial light modulators (SLMs) have been applied in many fields of spatial beam shaping [16–20] and holographic measurement [21,22]. In recent years, SLMs have been popularly adopted in many large-scale laser systems for fundamental frequency (1ω) laser beam shaping [23–26]. To the best of our knowledge, theoretical and experimental results on 3ω laser beam shaping have not been reported in detail for a high-power laser system.

In this paper, we present a high-power dozens-Joule-level nanosecond 3ω laser system and discuss an adaptive beam-shaping system based on an SLM for 3ω laser spatial beam shaping. The shaping method is presented in Section 2, considering several factors that affect the near-field uniformity, including the transmittance nonuniformity of the frequency conversion crystals, and nonlinear effects resulting from the frequency conversion system. The details of our approach will be described later. Experimental results of the high-power frequency tripling system are shown in Section 3. For 3ω laser spatial beam shaping, the main difference compared with 1ω laser shaping is the nonlinear effects in the frequency conversion system. Finally, we give the relationship between the output 3ω intensity and the input 1ω intensity in the type II/type II polarization mismatch scheme used in our laser system for generating 3ω laser.

2. Methods

2.1. Concept of the spatial beam-shaping module

The concept and principle of the proposed configuration spatial beam-shaping module are illustrated in Fig. 1. The main component of the beam-shaping module is the liquid crystal SLM. This element is chosen as the object plane that is relayed onto the

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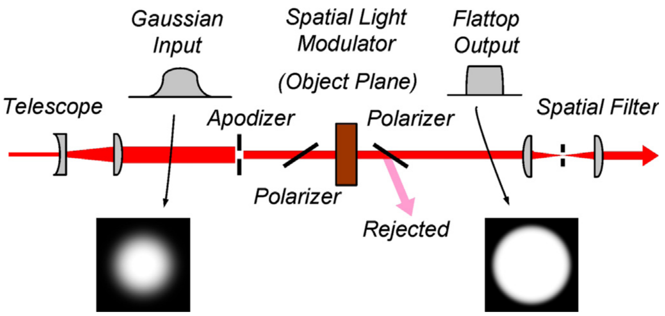

Fig. 1. Schematic of the beam shaper of the laser system.

following elements further along the beam paths. The spatial beam shaping module consists of 3 main sections: the 5 × telescope, the liquid crystal spatial light modulator and the spatial filter. Firstly, the telescope magnifies the Gaussian-shaped spatial beam to uniformly fill the apodizer, and the apodizer can chop the central region, creating a flat-topped intensity region with the beam diameter of 13 mm. Secondly, the laser beam transmits through a polarizer to be *p* polarized. And the local polarization will change a certain angle through the spatial light modulator according to the voltage loaded on the liquid crystal. After the second polarizer, the laser beam spatial intensity modulation can be achieved. The programmable spatial light modulator enables spatial shaping of the beam profile to pre-compensate for the spatial gain distortions in the remaining amplifiers. Finally, the beam passes through a spatial filter with a 1:1 reduction ratio, as the result that high spatial frequencies are removed, and the image plane are relayed to the main amplifier system. The output beam has a soft edge to reduce hard-edged diffractive effects.

As mentioned above, in the spatial beam shaping module, the downstream polarizer enables the polarization modulation to be manifested as an amplitude modulation. The SLM is an active spatial optical modulator with high contrast ratio and high resolution. The electrically addressable SLM (Holoeye LC2002) operates in a transmissive scheme with 600 × 800 pixels with each pixel size of 32 μm. The phase retardation in each pixel, used for regulating the transmittance of the SLM, is controlled by 8-bit command gray map. The programmable spatial beam shaping module based on liquid-crystal SLM was designed to introduce any required compensation beam profile in the laser system [27]. The relationship between the transmittance and the gray level $S(x,y)$ of the SLM are linearized as following:

$$T_{\mathrm{SLM}}(x,y) = S(x,y)C_{\mathrm{SLM}}. \tag{1}$$

where C_{SLM} is the scaling coefficient.

2.2. Spatial beam shaping by using SLM

The near-field profile and phase of the 3ω laser beam strongly depend on the 1ω laser beam. Therefore, the SLM deployed in the front stage can actively control the near-field fluence distribution of the 3ω laser by controlling the 1ω laser. Fig. 2 shows the spatial beam shaping system for the 3ω laser using the image at the output of the system as feedback to control the spatial light modulator at the front end. In the transmission and amplification process before the 1ω output, the system can be seen as quasi-linear and a transfer function $H_{1\omega}(x,y)$ indicates the whole spatial nonuniformity of the 1ω beamline. As a result, the output near-field of the 1ω laser is the product of the input gray scale $S(x,y)$ of the SLM and the transfer function $H_{1\omega}(x,y)$ as follows,

$$S(x,y)H_{1\omega}(x,y) = IO_{1\omega}(x,y). \tag{2}$$

For the frequency conversion system, the nonlinear effect (i.e.

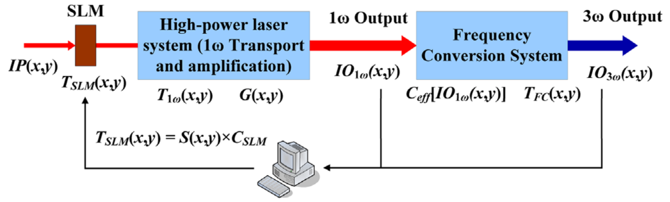

Fig. 2. Schematic illustration of the spatial beam shaping system of the high-power 3ω laser. $T_{1\omega}$ is the transmittance and G is the gain distribution of 1ω laser amplifiers; C_{eff} is the nonlinear frequency conversion efficiency, which is correlated with the 1ω laser beam; T_{FC} is the transmittance of the frequency conversion system; $IO_{1\omega}$ and $IO_{3\omega}$ are the output near-field of the 1ω and 3ω lasers, respectively. (x, y) represents spatial locations in the near-field image plane.

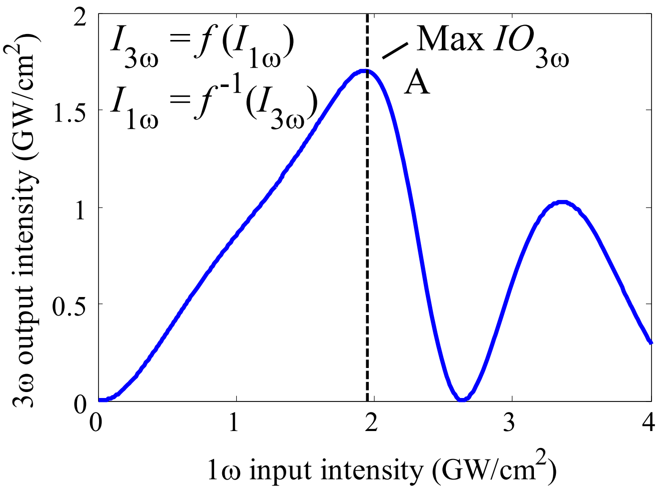

Fig. 3. Overall typical tripling output intensity versus the 1ω input intensity for the frequency conversion system with Type-II doubler and Type-II tripler configurations.

relationship between the output 3ω intensity and the input 1ω intensity) and transmission inhomogeneity of the crystals that influence the 3ω output spatial fluence need to be considered. The 3ω conversion efficiency of the Type-II doubler/Type-II tripler polarization mismatch scheme is simulated [28] which suggests that there is a complex nonlinear relationship between the 3ω output intensity and the 1ω input intensity (see Fig. 3). In general, the high-power laser operates at the low-intensity monotone interval (before point A) where the 3ω output intensity increases with the 1ω input intensity. In the case of the low-intensity input 1ω laser (such as less than about 2 GW/cm^2 in the laser system), the relationship can be described by a nonlinear function f, which is corroborated in the experiment, with f^{-1} representing the inverse of the function f. Therefore, the frequency conversion system can be seen as a nonlinear system. Considering the temporal uniformity of the super-Gaussian pulses, it is found that the laser intensity is equivalent to the fluence.

As shown in Fig. 4, in the first stage, the laser system operates with the SLM encoded by an initial image $S^{(0)}(x,y)$. With one shot, the 1ω and 3ω initial fluence distributions of $IO_{1\omega}^{(0)}(x,y)$ and $IO_{3\omega}^{(0)}(x,y)$ are obtained. In this case, the transfer function $H_{1\omega}(x,y)$ can be calculated from Eq. (2). Based on a target image distribution (a flat-topped image) of the 3ω laser $IO_{3\omega}^{\mathrm{goal}}(x,y)$, we can derive the target image distribution of the 1ω laser $IO_{1\omega}^{\mathrm{goal}}(x,y)$ from Eq. (3). The first compensation image $S^{(1)}(x,y)$ can be calculated based on $IO_{1\omega}^{\mathrm{goal}}(x,y)$, $H_{1\omega}(x,y)$, and the coefficient G_{SLM} of the SLM used for adjusting the output energy [see Eq. (4)]. Eqs. (3) and (4) are given as follows: