Laser Physics Letters

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To cite this article: Igor A Litvin and Gary King 2018 *Laser Phys. Lett.* **15** 106201

OPEN ACCESS
IOP Publishing | Astro Ltd Laser Physics Letters
Laser Phys. Lett. 15 (2018) 106201 (5pp) https://doi.org/10.1088/1612-202X/aad943

Letter

Controllable beam shaping of coherent and incoherent beams by a laser amplifier

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Received 15 May 2018
Accepted for publication 8 August 2018
Published 29 August 2018

Abstract
We propose the technique for a controllable manipulation of the transverse intensity distribution of an output beam by the temporal adjustment of a transverse gain profile in a laser amplifier. It was created by an independent manipulation of the output powers of each of the two pump diodes. The output beam of the laser amplifier is able to vary both the output power and the transverse intensity distribution. Additionally, it was shown experimentally that this technique is valid for the case of incoherent laser beam shaping.

Keywords: laser amplifiers, laser beam shaping, incoherent laser beam shaping

(Some figures may appear in colour only in the online journal)

1. Introduction

Laser beams with a non-Gaussian intensity profile can be advantageous in the fields of laser materials processing, medicine and others. The methods of producing such beams can be divided into two classes; namely extra [1, 2] and intra-cavity beam shaping [3, 4]. In laser based applications—such as additive manufacturing, laser surface engineering, biology and medicine involving time evolving processes—it is important to have a controllable intensity beam shape (of a laser beam) with a low response time [5, 6]. Recently, an intra-cavity spatial light modulator (SLM) was successfully implemented to produce controllable beam shaping inside a laser cavity [7]. However, this technique had some limitations with respect to the scaling up of the output power due to the low-damage thresholds of the SLMs. Additionally, the SLM has a long response time that limits implementation with high-speed applications. Moreover, variation of reflectivity for different grey scale levels (phase) of the intra-cavity SLM create additional problems for controllable intra–cavity beam shaping [8]. A second method is to manipulate a gain profile in the laser crystal to perform intra-cavity beam shaping (to), which would control the weighting of the desired mode in the output beam. This technique allows simultaneous and controllable variation of both the output power and the transverse intensity distribution of the laser beam [9]. The disadvantage of this technique is the limitation for the spatial shape intensities of the output beam by laser cavity geometry. In this work we propose and experimentally verify the technique for the controllable manipulation of the transverse intensity distribution of an output beam by the temporal manipulation of a transverse gain structure in a laser amplifier. Such behavior of the laser output intensity profile was created by the independent manipulation of the output powers of each of the two pump diodes. The output beam of this laser configuration would have the ability to vary both the output power and the transverse intensity distribution simultaneously. Moreover, we have shown that the process works with incoherent laser beams similarly.

2. Theoretical principles and simulation

In [10] the analytical equation for the correlation between the intensity profiles of the seed and the pump beams after the

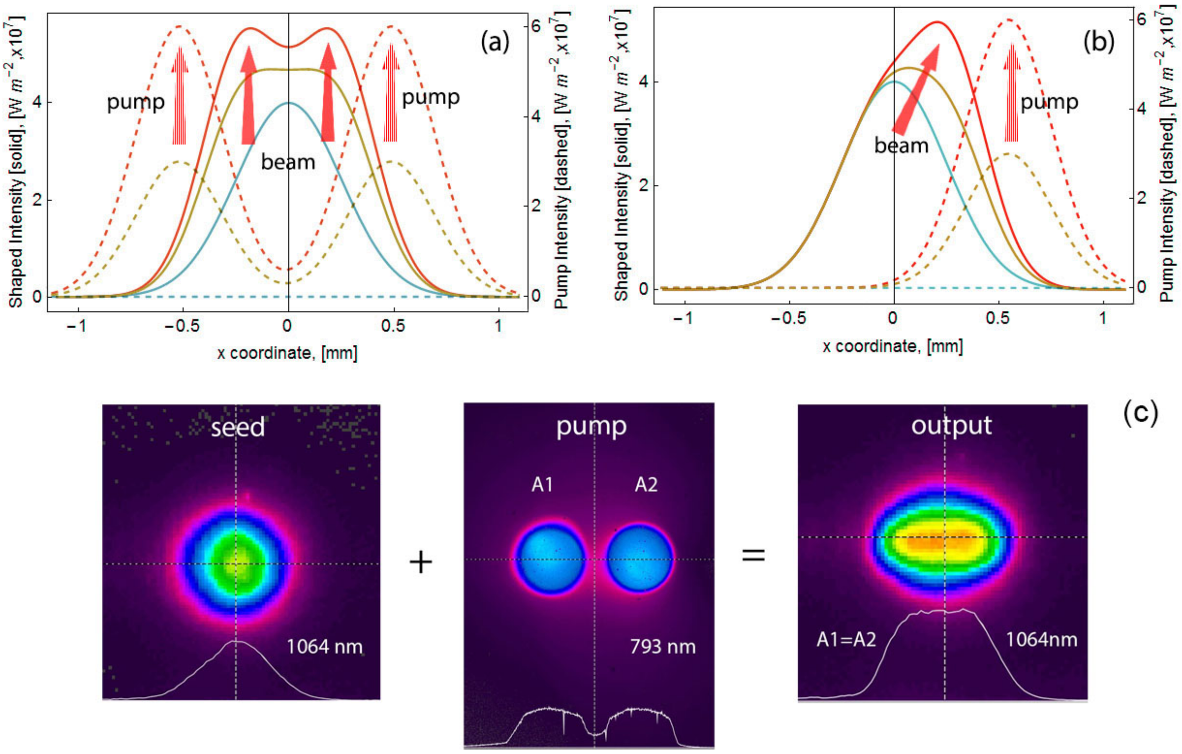

Figure 1. (a) The simulation of the resulting controllable beam shaping of a 4 Watt Gaussian beam ($w_0 = 0.5$ mm) after the laser amplifier, based on equation (1). The amplifier was pumped by two Gaussian beams with adjustable pump powers symmetrically displaced about the optical axis ($w_0 = 0.4$ mm). In figure (b) the amplifier was pumped by a single off-axis Gaussian beam. The simulation parameters were chosen to be identical to the experimental ones. (c) The experimental result of beam shaping from a Gaussian to a flat-topped beam in one transverse coordinate by two offset pump beams.

laser amplifier for four levels of laser gain in the unsaturated regime was developed. The resultant equation in the Cartesian coordinates (x,y,z) is

$$I_s(x,y,L) = I_s(x,y,z_0) + I_s(x,y,z_0)\,\frac{\sigma_e}{\sigma_a}\left(Ln_{tot}\sigma_a + \log\left[\frac{h\nu_p + \tau_2\,\sigma_a I_p(x,y,z_0)}{h\nu_p e^{Ln_{tot}\sigma_a} + \tau_2\,\sigma_a I_p(x,y,z_0)}\right]\right), \qquad (1)$$

where $I_s(x,y,L)$ and $I_s(x,y,z_0)$ are the intensity profiles of the seed beam at the initial and output planes, and $I_p(x,y,z_0)$ is the intensity profile of the pump beam. $h\nu_p$ ($h\nu_s$) is the energy per photon at the pump (seed) wavelength, σ_a is the absorption cross section of the active ions in the ground energy level n_1, σ_e is the emission cross section of the upper laser energy level n_2 and τ_2 is the lifetime of level n_2. The conservation of the ions ($n_{tot} = n_1 + n_2$) has been assumed.

Based on equation (1), we are able to predict the behavior of the intensity shape of the seed beam after the laser amplifier with a controllable gain profile. The validation of the analytical equation can be determined by following the formula for the maximum pump intensity $I_p^{max}(z_0) = \delta\, h\nu_p/(1-\delta)\sigma_a\tau_2$, where $\delta = n_2^{max}/n_{tot}$ is the ratio of the density of ions in the upper laser level to the total density of the ions, which cannot exceed 14%–16% [10]. The result of the simulation is presented in figure 1(a) and (b).

We see from figure 1 that it is possible to perform controlled beam shaping of the amplified Gaussian beam by adjusting the power of the pump beams. In this way we were able to increase the flatness of the amplified Gaussian beam by gradually increasing the powers of each of the two displaced Gaussian-like pump beams. Moreover, the independent manipulation of the pumped beam powers allows for an asymmetrical beam shaping realization (see figure 1(b)).

3. Experimental verification

To confirm the simulations mentioned in the previous chapter, we designed and experimentally implemented a laser amplifier with similar behavior. The amplifier consisted of a (0.6%)Nd:YAG ceramic crystal as the gain media; with constant doping concentrations and two laser diode pump sources with separated power controls (A1 and A2 at figure 1(c)). The pump beams created a controllable and uneven gain profile, which resulted in varying amplifications at different transverse positions. The spatial intensity distribution of the gain in the ceramic crystal and the pump power adjustment enabled an uneven and controllable amplification of the seed beam, which resulted in the desired beam shape of the output beam (see figure 1(c)).

In figure 1(c) we presented a schematic of the amplification with two uneven and symmetrically displaced pump beams based on an actual experimental result. Moreover, the independent control of the individual pump spots power allow for an asymmetric adjustment of the output beam shape, which

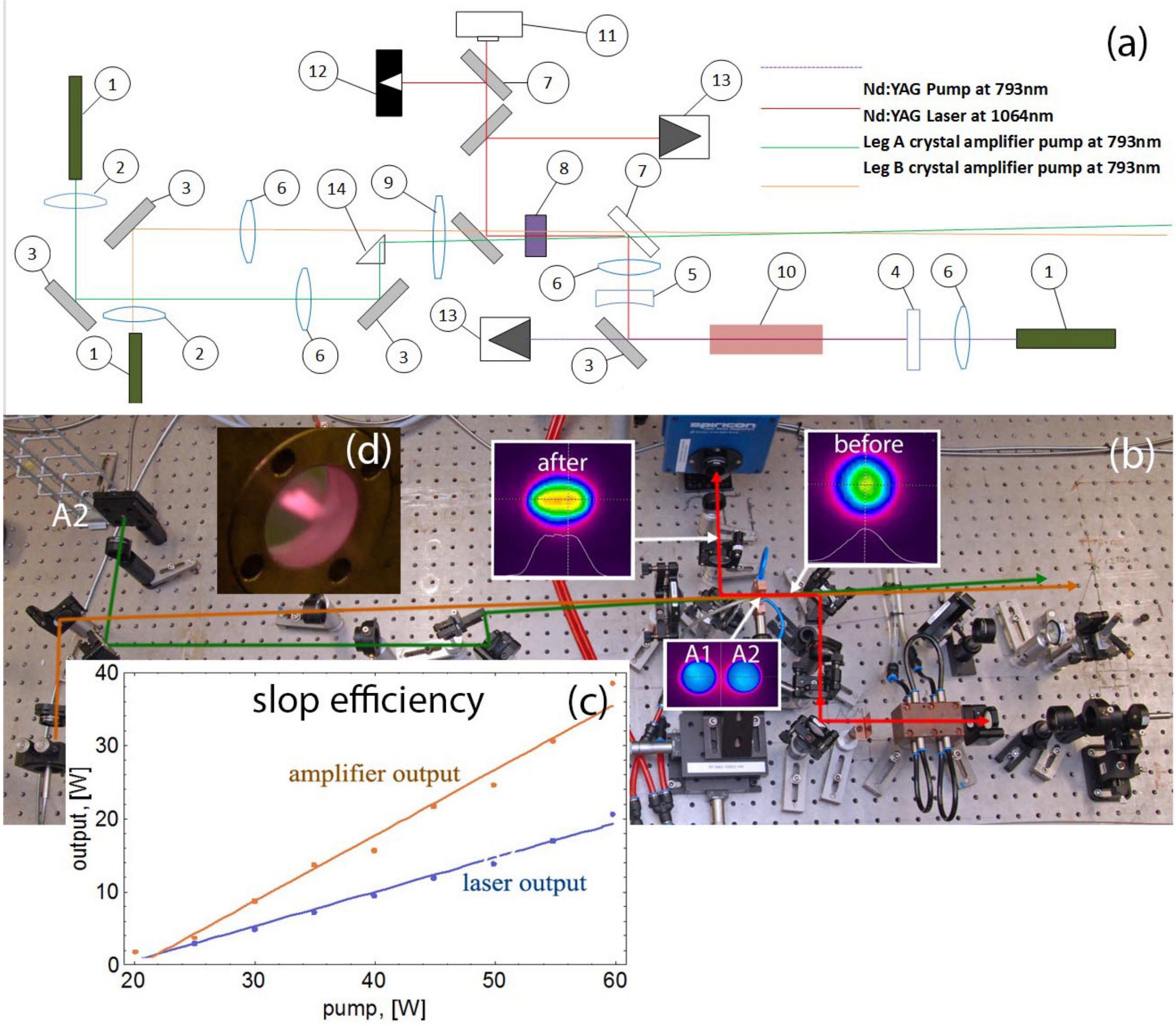

Figure 2. Schematic layout (a) and experimental setup (b) of the amplifier with electronically controllable gain where 1—fibre coupled laser diode, 2—collimating lenses, 3—silver fold mirrors, 4—mirror (HR1064nm and AR 793 nm), 5—80% output coupler (1064 nm), 6—focusing lens, 7—mirror (HR 1064 nm), 8—(0.6%) Nd:YAG ceramic crystal, 9—pump focusing lens, 10—Nd:YAG crystal, 11—CCD camera, 12—100 W power reader head, 13—beam dump, 14—folding prism. A double beam pump fluorescence of amplifier crystal is shown in (d). (c) Slop efficiency for the output laser beam (Gaussian intensity profile) before and after laser amplifier for transformation of Gaussian beam into flat–top beam.

can be useful in the specific laser surface engendering processes. The schematic layout and tested experimental setup of the device is presented in figure 2(a).

The seed laser consists of a Jenoptik fibre coupled laser diode (see figure 2(a) ①) emitting pump light at 793 nm. This is focused, using a converging lens (see figure 2(a) ⑥) into the ceramic Nd:YAG (0.4%) gain material (see figure 2(a) ⑩). A resonator, with a high reflecting mirror for the laser wavelength at 1064 nm and anti-reflection coating for the 793 nm pump light (see figure 2(a) ④) on one side, and an 80% partially reflecting output coupler (see figure 2(a) ⑤) with a 300 mm radius of curvature, was built around the gain material. A fold mirror (see figure 2(a) ③), which had a high transmission for the 793 nm wavelength and a high reflectance for 1064 nm light was used to fold the resonator through 90°. The excess pump light was dumped into a light trap (see figure 2(a) ⑬) and only the 1064 nm laser light was allowed to propagate to the rest of the system.

The emerging Gaussian laser beam passed through a diverging lens that formed a beam of the correct diameter inside the amplifier material, was once again reflected through 90° and into the amplifying ceramic Nd:YAG (0.6%) (see figure 2(a) ⑧). Once it passed through, the crystal the beam was reflected through another 90° with a 1064 nm high reflector (see figure 2(a) ③). The mirror also allowed 793 nm of light to pass through un-attenuated, this to accommodate the two amplifying pump beams that would later enter the crystal. The 1064 nm wavelength was then guided to the diagnostic set up (see figure 2(a) ⑪ & ⑫).

Because the standard 1-inch diameter optical fold mirror components created a large angle at which the two independent pump beams entered the amplification medium, one of the beams had to be folded to reduce this angle as much as possible.

Two more Jenoptik fibre-coupled laser diodes (see figure 2(a) ①) were placed at approximately 90° to the optical axis of the amplification crystal, collimated with lenses (see figure 2(a) ②) and then folded through 90° with two mirrors (see figure 2(a) ③) towards the amplification crystal (see

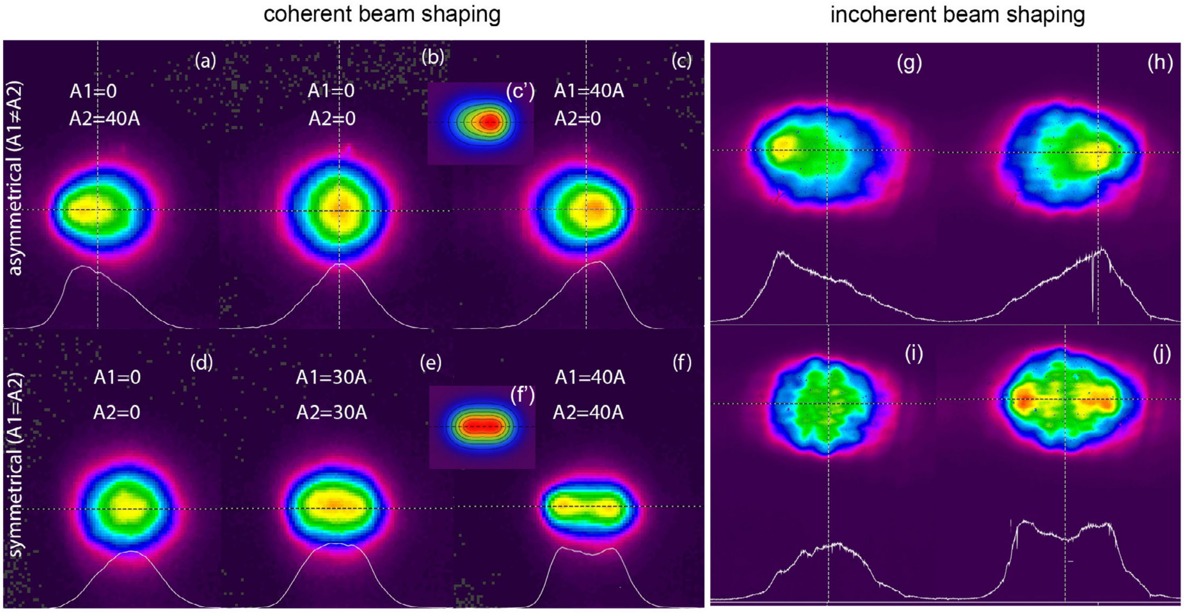

Figure 3. (a)–(f) The symmetrical and asymmetrical beam shape variation by a laser amplifier with controllable gain (see attached visualization 1 (manual control) and visualization 2 (electronic control)). (c′) and (f′) The respective 2D simulation of controllable beam shaping by a laser amplifier based on two independently controlled pump laser diodes. The parameters for the simulation (pump powers, beam widths, wavelengths, spontaneous and stimulated emission (absorption) cross sections and so on) are based on the respective experimental setup. (g)–(j) The symmetrical and asymmetrical beam shaping of the incoherent seed beam.

figure 2(a) ⑧). Leg B was aimed directly through two lenses ((see figure 2(a) ⑥) and (see figure 2(a) ⑨) that focussed the beam to a point inside the amplification crystal. Leg A was aimed through the first focussing lens (see figure 2(a) ⑥), reflected with a mirror (see figure 2(a) ③) into a small high-reflecting folding prism coated for the pump wavelength, through the second focussing lens (see figure 2(a) ⑨) and into the amplifying crystal. By moving the first focussing lens, leg A was focussed to the same position in the amplifier crystal as leg B. Leg A was manipulated using the mirror (see figure 2(a) ③) just before the prism and the prism itself to achieve the correct gap between the two beams.

The amplified beam was reflected away from the crystal optical path striking an attenuating mirror with 99.8% reflectivity onto a Gentec 100 W power reader head. The remaining laser beam entered a Pyrocam lll Beam diagnostic camera. All the optical lenses, mirrors and partial reflectors used in this experiment were supplied by Layertec.

The obtained amplification efficiency was around 15% maximum. The efficiency rose with an increase of the pump and seed beam powers. Based on extrapolation of current experimental result, we believe that it is possible to reach up to 40% efficiency for higher powers of pump and seed beams. Additionally, we are able to increase the efficiency by placing the displaced pump beams close to the optical axe to reach a higher intensity of the seed beam.

4. Coherent beam shaping

From performed experiments, we were able to conclude that the two independently adjustable power supplies in the laser amplifier enabled the electronic control of the transversal intensity shape of the output beam.

The resulting output intensity variation of both the Gaussian beam into flat-top beam and asymmetrical beam shaping are presented in figures 3(a) and (f).

As a result, the manual manipulation of the pump diode power results in a controllable variation of the transverse intensity profile of the output beam as predicted in the simulations (see the chapter: ‘theoretical principles and simulations’). The experimentally obtained beam shaping matched the simulation accurately (see figures 1(c) and 3(a)–(f)). The number of pump diodes can be changed as required for particular applications and beam profiles. The switching time between any two required intensity profiles was only limited by the pump diode switching time capability, while taking into account the relatively rapid gain development process.

5. Incoherent beam shaping

Based on a derivation of equation (1) [10], we can conclude that there would be no limitation with the coherency of the seed beam in the amplification process and therefore we were able to perform similar beam shaping with an incoherent seed beam. In order to prove the assumption, we replaced the coherent seed beam with an incoherent beam of the same wavelength.

In figure 3(g)–(j) we presented the experimental results of the beam shaping of an incoherent laser beam using a laser amplifier with controllable gain. The experimental setup was identical to the setup used in a coherent beam shaping experiment (see figure 2). The only change was the replacement of the coherent laser beam source with an incoherent one. The incoherent beam was obtained by increasing the number of modes constituting the output beam of the seed laser. This increase was obtained by removing the intra–cavity aperture from the seed laser and simultaneously increasing the pump power. This laser modification dramatically reduced the quality of the outgoing beam due to an increase in the sum of the transverse modes in the output beam. For this particular case, the M2 parameter increased from 1.2 to 20. The experimental results show that the proposed beam shaping technique has no limitations on the coherency of shaped beam.

6. Conclusion

In summary, the technique for a controllable manipulation of the transverse intensity distribution of an output beam by the temporal manipulation of a transverse gain structure in a laser amplifier (see attached visualization 1 and visualization 2) was proposed and tested successfully. Based on theoretical and experimental results described above we are able to conclude that this technique can be seen as an alternative approach to controllable manipulation of beam shape intensity profiles. The technique can be used in the areas where controllable manipulation of a high-power laser beam is required. The output beam of the proposed laser amplifier configuration is able to vary both the output power and the transverse intensity distribution simultaneously. Additionally, the unique feature of this technique is the ability to perform controllable laser beam shaping of incoherent laser beams. The amplification efficiency achieved was in the order of 15%. However, based on the extrapolation of the current experimental result, we see that it is possible to reach up to 40% efficiency for higher pump powers and seed beams.

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