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REGULAR PAPER

High-energy nanosecond radially polarized beam output from Nd:YAG amplifiers

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Abstract Radially polarized laser beam amplification up to the 772 mJ using flash-lamp-pumped Nd:YAG amplifiers was demonstrated. In the experiments, a nanosecond radially polarized seed beam was converted from a conventional Q-switched Nd:YAG laser output with a polarization converter and then amplified with two Nd:YAG amplifier stages. A maximum amplification output energy up to 772 mJ was achieved at 10 Hz with a 10-ns pulse, corresponding to an amplification factor of 323%. Excellent conservation of polarization was also obtained during the amplification.

Keywords Laser amplifiers · Radial polarization · Nd:YAG laser

1 Introduction

Radially polarized beams, as a kind of cylindrical vector beams [1], have attracted increased attention in the last few years. As a result of smaller spot formation and remarkable focusing features [2–5], radially polarized beams have a strong influence on almost every kind of laser material processing, including metal cutting, welding, and drilling [6–8]. They will also be used for many applications, including laser communication in free space [9], polarization information encryption [10], and particle manipulation [11].

Radially polarized beams can be converted from linearly polarized beams with an extra-cavity polarization converter [12, 13]. They can also be generated directly within a laser cavity [14–17]. A radially polarized laser system with sufficient laser power is required for industrial applications [18]. Hence, amplification of a radially polarized beam in fiber amplifiers has been proposed [19–22]. A thin-disk multipass amplifier has also been demonstrated, which delivered radially polarized picosecond pulses at an average output power of 635 W with 2.1 mJ of energy per pulse [23]. The Nd:YAG laser is one of the most common types of lasers in many laboratories and factories. It was recently demonstrated that Nd:YAG amplifiers can be used to generate high-energy nanosecond vortex beams [24]. However, until now, to the best of our knowledge, there are few reports about the amplification of radially polarized beams in Nd:YAG lasers. Linearly polarized beams will be depolarized when amplified in a bulk crystal because of thermally induced effects, such as thermal lensing and stress-induced birefringence [25]. However, cylindrically polarized beams will not suffer from these effects; therefore, the initial polarization state is conserved when amplified in such gain media.

To evaluate the suitability of Nd:YAG amplifiers to amplify cylindrically polarized beams, we investigated the amplification of radially polarized beams in two flash-lamp-pumped Nd:YAG amplifiers. We obtained a nanosecond radially polarized beam at 1064 nm with an energy of 772 mJ. In addition, the conservation of the polarization state of the radially polarized beam was confirmed. To the best of our knowledge, this is the highest energy radially

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polarized nanosecond laser beam yet to be obtained with power amplifiers.

2 Experiments and results

We employed an optical arrangement to amplify a radially polarized beam, as shown in Fig. 1. We used a conventional flash-lamp-pumped Q-switched 1064-nm Nd:YAG laser as the master laser. The master laser consisted of a Nd:YAG rod with a diameter of 8.5 mm, which was integrated in an actively water cooled glass tube, permitting an efficient heat removal. The laser had an output energy approximately 350 mJ and a pulse width of 10 ns with the linear polarization. An optical isolator was used to prevent any strong backward beam from entering the master laser. A variable beam splitter, formed by a half-wave plate (HWP) and a polarizing beam splitter (PBS), was used to continuously vary the transmitted energy of the master laser output. A super-structured space variant polarization converter (S-waveplate, Altechna) was used to convert the linearly polarized output from the master laser into a radially polarized seed beam. Two amplifiers, both of which consisted of a Nd:YAG rod (9.5 mm in diameter, 62 mm long) were used to amplify the seed beam. The energies of the radially polarized seed beam and the amplified output were measured with two energy detectors (PD, Ophir PE50BF-DIF-C). During the experiments, the oscillator lamp was pumped at 180 J and the amplifier lamps were pumped at 150 J with a pulse repetition frequency of 10 Hz.

As shown in Fig. 2, a maximum amplification output energy of 772 mJ was obtained at a maximum radially polarized seed energy of 239 mJ, which corresponded to an amplification factor of 323%. It was clearly observed that the amplification factor decreased as the seed beam energy increased. This was due to a thermal drift of some elements in the setup [21] and the doughnut-shaped mode [22].

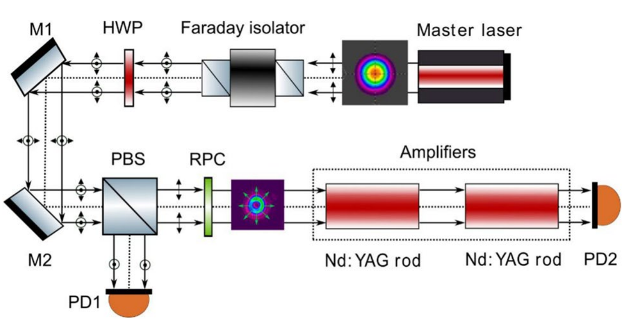

Fig. 1 Experimental setup of radially polarized laser system. *HWP* half-wave plates for 1064 nm. M1 and M2, total reflective mirrors for 1064 nm. *PBS* polarizing beam splitter for 1064 nm. *RPC* radial polarization converter. PD1 and PD2, energy detectors

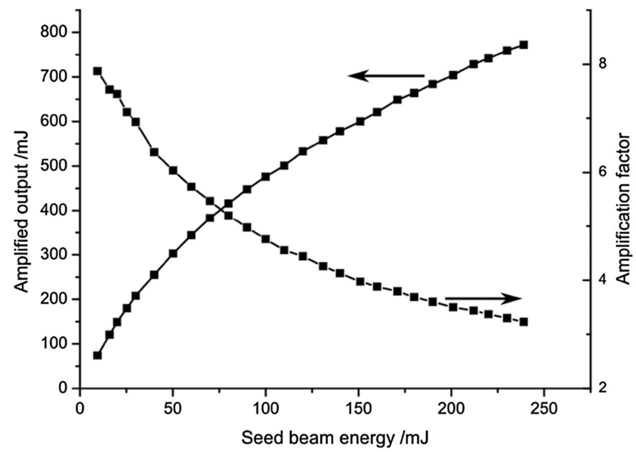

Fig. 2 Amplification output energy and amplification factor as a function of the seed beam energy

During the following experiments, a customized beam sampler (shown in Fig. 3), which was formed with two wedged plate beam splitters, was used to sample the amplified output. The two planes of reflection were adjusted to be orthogonal to each other to ensure that the sampled beam had S and P polarization components that were identical to the original beam. Figure 4 shows the experimental results of the beam quality factor, M^2, measured by a commercial M^2 measuring instrument (Ophir, M2-200s). As shown in Fig. 4a, the amplified radially polarized output exhibited $M_x^2 = 3.2$ and $M_y^2 = 3.1$ in the vertical and horizontal directions respectively, while the radially polarized seed beam exhibited $M_x^2 = 2.9$ and $M_y^2 = 2.8$ (Fig. 4b). This difference may be caused by spatial distortion, such as nonuniform pumping, diffraction effects, and thermal distortion in the amplifiers. The theoretical value of M^2 for a radially polarized beam is 2, since the fundamental doughnut beam

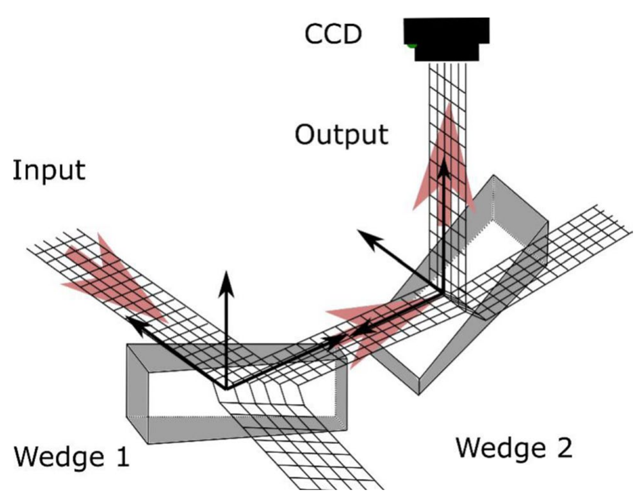

Fig. 3 Setup of the beam sampler

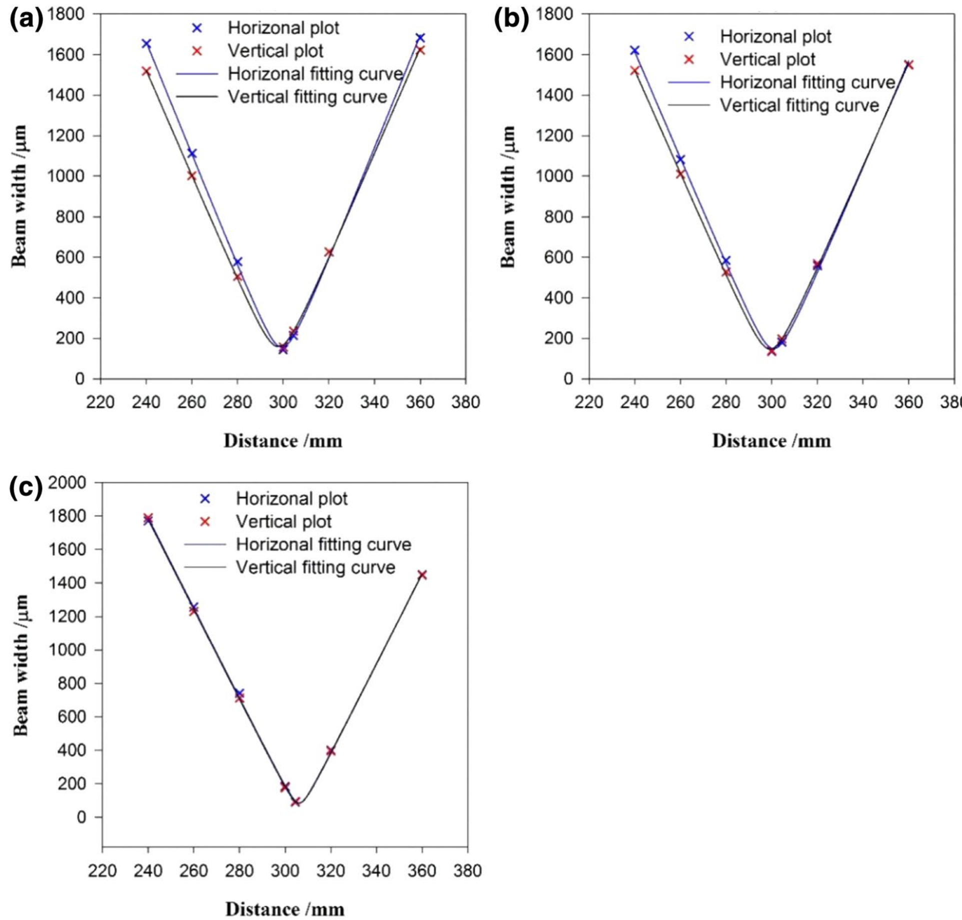

Fig. 4 Beam quality factor of **a** amplified output, **b** radially polarized seed beam, and **c** master laser output

is the Laguerre–Gaussian, LG01* mode [23]. The difference between the experimental and theoretical results may be due to the master laser, which exhibited $M_x^2 = 1.7$ and $M_y^2 = 1.7$ (Fig. 4c), respectively.

As shown in Fig. 5, the pulsewidth of the amplified beam was measured to be 10 ns, which was almost identical to that of the master laser. Therefore, the maximum peak power of the amplified output was 77.2 MW.

The beams were sampled by the beam sampler and then sent through a convex lens with a focal length of 300 mm. Images were observed in the focus using a CCD-based beam profiler (Ophir, SP620U). Neutral-density filters were placed in front of the camera to avoid damage. Figure 6a–e present the intensity distributions of the radially polarized seed beam. The total intensity distribution is shown in Fig. 6a. The seed beam exhibits a doughnut-shaped beam profile with a dark center. To measure the polarization state of the seed beam, a linear polarizer was placed before the CCD. The intensity distribution of the seed beam after passage through a linear polarizer is shown in Fig. 6b–e. The transmission direction of the polarizer is indicated by the arrows. Two lobes of the intensity distribution can be observed, and the azimuthal position changed with rotation of the analyzer axis. These results confirmed that the seed beam converted by the polarization converter was radially polarized.

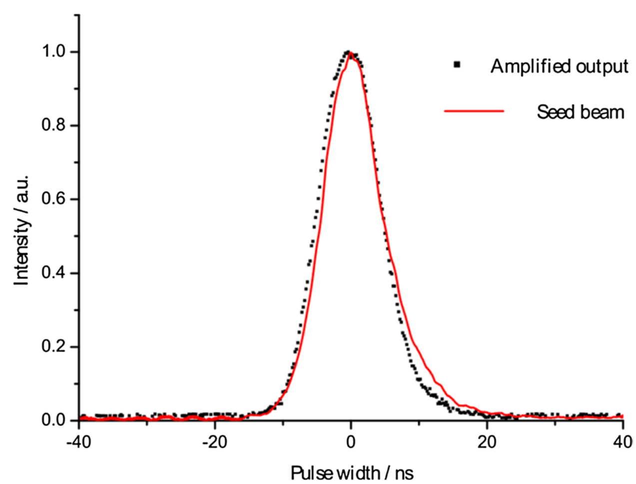

Fig. 5 Temporal evolution of the master laser (*red line*) and the amplified output (*black dot*)

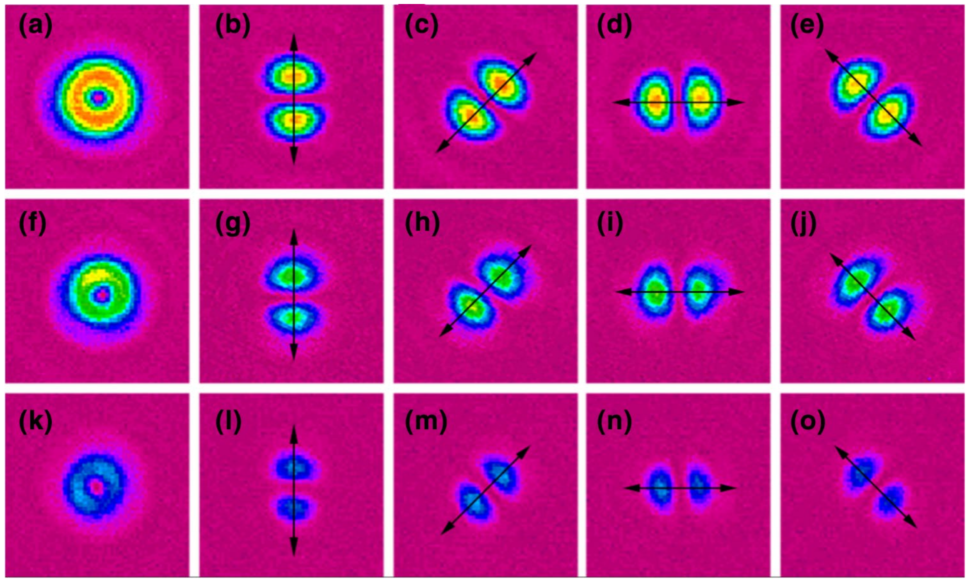

Fig. 6 Far-field intensity distribution of the seed beam at maximum energy (*top row*). Transmitted beam through the amplifiers (*second row*). Amplified output at maximum pumping (*bottom row*). **a, f, k** Total intensity distributions. **b–e, g–j**, and **l–o** Intensity distributions after passage through a linear polarizer. *Each arrow* indicates the direction of the polarizer

Figure 6f–j presents the intensity distributions of the seed beam transmitted through the two amplifiers without flash-pumping. Figure 6f demonstrates the total intensity distribution. Figure 6g–j shows the intensity distribution after passage through the linear polarizer. The transmitted beam maintained the doughnut shape. Meanwhile, there was no obvious rotation of the polarization distributions around the beam axis compared to the seed beam itself. This indicated that the influence of the birefringence in the Nd:YAG rods on the polarization distribution was negligible.

Figure 6k–o shows the intensity distributions of the amplified output at the maximum pumping energy. Figure 6k demonstrates the total intensity distribution. Figure 6l–o shows the intensity distribution after passage through the linear polarizer. The intensity and polarization distributions of the radially polarized beam were maintained during amplification in the Nd:YAG amplifiers. This was because the cylindrical vector beams, such as radially and azimuthally polarized beams, were free from the depolarization effect. During the above measurements, neutral-density filters with different optical densities were used to match the different energy of the laser beams, which caused the color in the three rows of Fig. 6 to appear to be different.

3 Conclusion

The amplification of radially polarized beam in the Nd:YAG amplifiers was investigated in detail. Up to 772 mJ of the radially polarized beam was obtained at 10 ns, corresponding to a maximum peak power of 77.2 MW. We demonstrated that the polarization of the radially polarized seed beam was excellently conserved, while there is a slight degradation of the beam quality during amplification. The polarization converter used in this paper had a propagation loss of approximately 30% because of the reflection due to uncoating and the scattering of the super structure. A higher energy seed beam with higher energy amplification output would be achieved if a converter had better transmittance, such as one made of segmented half-wave plates [26, 27]. Further power scaling of the system is possible using a more powerful master laser and increasing the number of power amplifiers. The generation of a high-energy nanosecond radially polarized beam will benefit numerous applications requiring various high-energy (or high-power) radially polarized beams, such as laser ablation and optical communications.

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