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High-Energy Nanosecond Optical Vortex Output From Nd:Yag Amplifiers

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ABSTARCT:*Optical vortex amplification up to the joule level using flash-lamp-pumped Nd:YAG amplifiers has been demonstrated for the first time. In experiment, vortex seed pulses were converted from a conventional Q-switched Nd:YAG laser output by a spiral phase plate and amplified with two Nd:YAG amplifier stages. A maximum output energy of optical vortex up to 995 mJ has been achieved at 10 Hz in a 10-ns pulse, corresponding to an amplification factor of 295%. A maximum second-harmonic energy up to 470 mJ was generated from the amplified vortex output by using a KD*P crystal. The prospects of joule nanosecond vortex pulses generation by this approach were discussed.*

INTRODUCTIONoptical vortex beams have gained remarkable attention in the last decade, as the unique phase distribution and orbit angular momentum (OAM) [1] of such beams enhance many laser-based applications in different fields, such as optical trapping and manipulation of particles [2-4], quantum information and optical telecommunication [5, 6], and so on. It was also demonstrated in our previous reports that vortex beam is a promising strategy to alleviate atmospheric influence on free space optical communication link [7]. Particularly, high-energy (or high-power) vortex laser beams enable new processing strategies in laser material processing [8, 9]. It has been reported that owing to OAM of optical vortex, clearer and smoother processed surfaces were obtained with less ablation threshold fluence, in comparison with a non-vortex annular beam [8]. High energy vortex beams can be utilized to high-speed parallel processing, with diffractive methods to produce multiple focal spots [10, 11] Moreover, high-energy (or high-power) vortex beams are also beneficial to the study of nonlinear optical effects such as optical parametric oscillation [12] and second harmonic generation (SHG) [13] of optical vortices. Therefore, these impressive works stimulate the requirement of high-energy (or high-power) optical vortex beams and their frequency extension to meet the absorption bands of materials. Optical vortex beams can be obtained relatively easily by computer-generated holograms [14], a spiral phase plate (SPP) [15], or mode conversion in an optical fiber [16], and so on. Vortex beams can also be generated directly within a laser cavity by exploiting thermal lensing [17, 18], circular absorber [19] or spot defect mirror [20], and so on. Another popular strategy for direct generation of vortex beams in an end-pumped solid state laser is to use an annular-shaped pump beam with the spatially-matched intensity distribution for the LG0n mode in the laser resonator [21, 22]. Recently, researchers from Chiba University reported the generation of a high-power optical vortex laser output in a multimode Yb fiber amplifier by off-axis core launching of the TEM00 mode beam and controlling the bending

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stress of the fiber [23, 24]. 10.7 W output of continuous-wave vortex beam at 1064 nm was reported with a MOPA system employing fiber amplifier as well [25]. However, most of these methods were carried out with fiber amplifier, which is difficult to achieve higher energy. In this paper, the amplification of optical vortex in two flash-lamp-pumped Nd:YAG amplifier stages is reported. This amplifier system yielded 995 mJ of nanosecond optical vortex output at 1064 nm, corresponding to a peak power of 99.5 MW. To the best of our knowledge, this is the first study of optical vortex amplification in bulk solid-state amplifier, and the highest vortex energy yet to be obtained in power amplifier. A maximum second harmonic generation of up to 470 mJ from the amplified output was also achieved.

EXPERIMENTS AND RESULTS The schematic diagram of the experiment setup is shown in Fig.1. A conventional flash-lamp-pumped Q-switched 1064-nm Nd:YAG laser was used as the master laser. The master laser was based on a Gaussian coupled resonator, with a Nd:YAG rod diameter of 8.5 mm, to generate a near-Gaussian spatial profile at the laser output. It had an output energy of ~ 400 mJ, and a pulse width of 10 ns at a pulse repetition frequency of 10 Hz. An optical isolator, formed with a polarizing beam splitter (PBS), a Faraday rotator and a half-wave plate (HWP), was used to prevent any strong backward output from the amplifier to enter the master laser. A SPP made of fused silica shaped the output of the master laser to produce optical vortex with topological charge l=1. Propagation loss in the SPP was measured to be approximately 6 %. This vortex beam was used as vortex seed beam to be amplified later. A variable beam splitter, formed by a HWP and a PBS, was used to continuously vary the transmitted energy of the vortex seed beam. The vortex seed beam was then directed into two amplifiers, both of which consisted of an Nd:YAG rod (9.5mm in diameter, 62mm long) in a diffuse reflecting, flash-lamp-pumped chamber. During the experiments, the oscillator lamp was pumped at 180 J and the amplifier lamps were pumped at 150 J. Two energy detectors (PD, Ophir PE50BF-DIF-C) were used to monitor the energies of the vortex seed beam and the amplified output beam

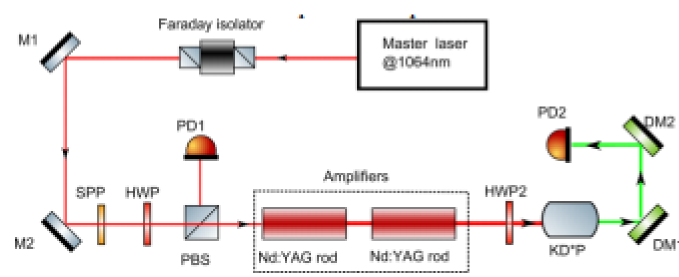

Fig. 1.Experimental setup of high-energy nanosecond vortex laser system.M1 and M2, total reflective mirrors for 1064 nm.SPP, spiral phase plate. HWP1 and HWP2, half wave plates for 1064 nm. PD, energy detectors. DM1 and DM2, dichroic mirrors

A. 1064 nm nanosecond vortex Nd:YAG power amplifier

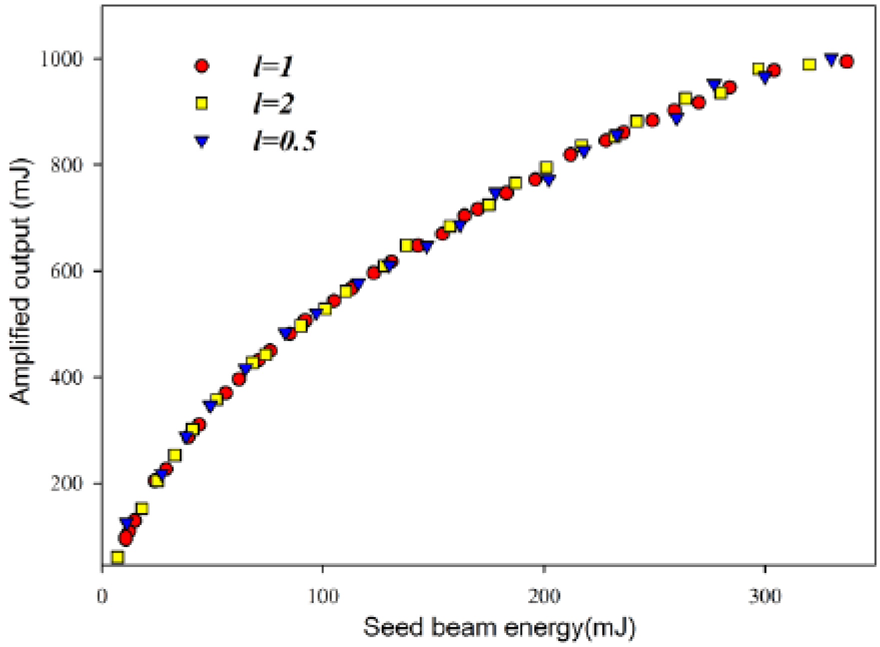

Fig. 2. Amplification output energy as a function of the vortex seed beam energy.

As shown in Fig. 2, a maximum energy of 995 mJ was obtained at a vortex seed energy of 337 mJ, with topological charge l=1. To the best of our knowledge, this is the highest value yet to be obtained for a vortex output from power amplifier. The amplification results for vortex beam with topological charge l=2 and l=0.5 are also shown in Fig. 2, with negligible difference under our experimental condition. It should be noted that the following results are based on vortex seed beam with topological charge l=1. The amplified output was sampled by a wedged plate beam-splitter and sent through a convex lens with 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. The amplified vortex output had an annular spatial profile due to a phase singularity (Fig. 3 (a)).Its intensity profile kept almost the same with that of the vortex seed, as shown in Fig. 3 (b). Its wavefront was examined using interference fringe produced by the vortex, and its reference plane wave. As shown in Fig. 4 (a), the clear dislocation pattern indicates that the amplified output retained helical wave front with the topological charge l=1.

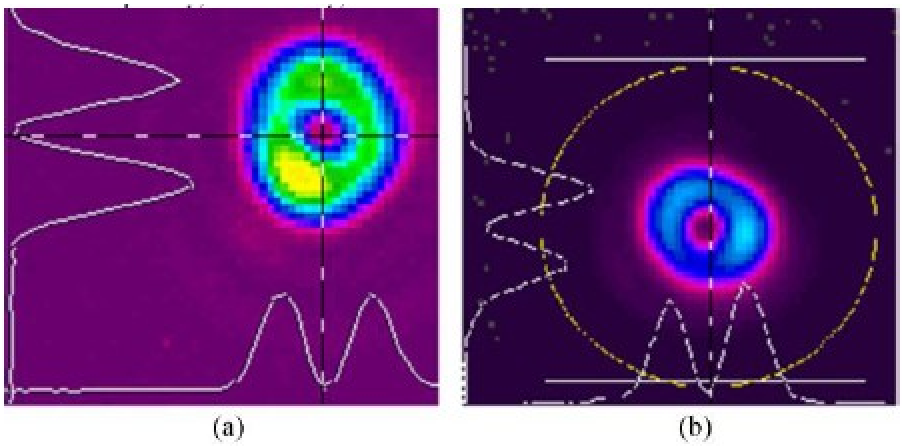

Fig. 3. Intensity profile of (a) the amplified vortex output; (b) the corresponding vortex seed beam with topological charge l=1.

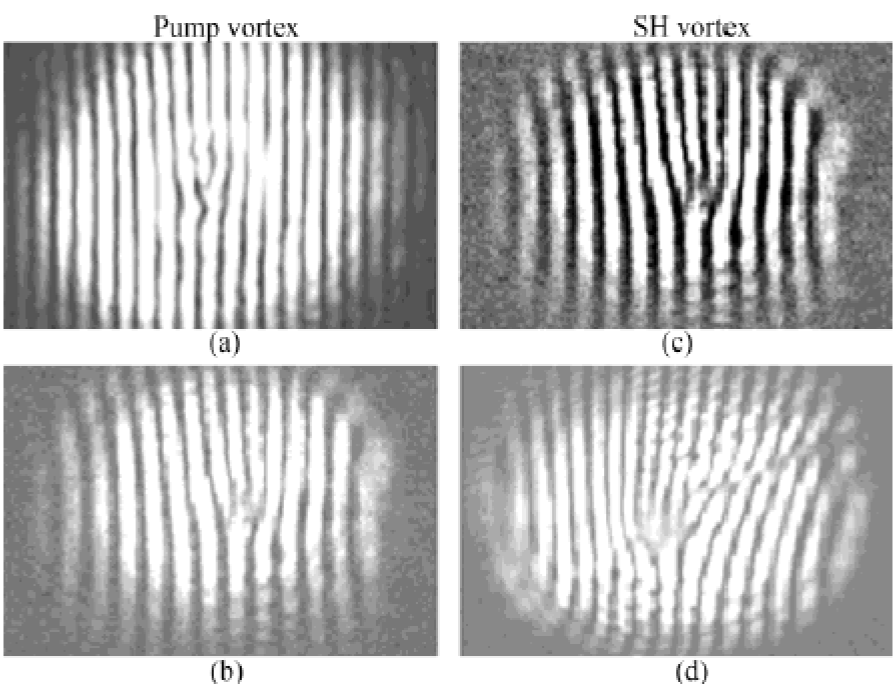

Fig. 4. Interference fringe of pump vortices (a) l=1 and (b) l=2 with plane reference wave; (c), (d) Interference fringe of the corresponding SH beams with plane reference wave, respectively.

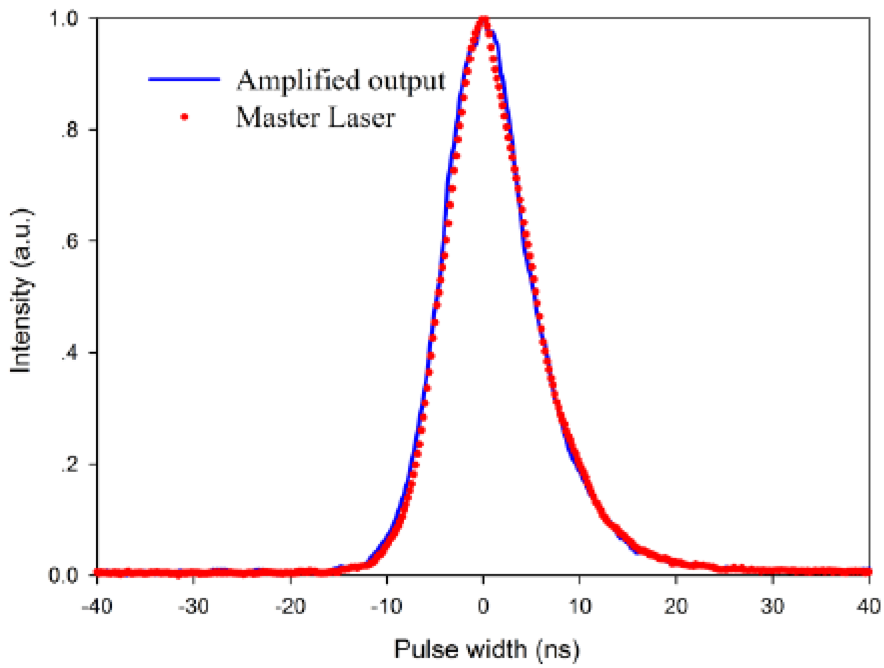

Fig. 5.Temporal evolution of the master laser and the amplified vortex output.

The pulse width of the amplified vortex pulse was measured to be 10 ns, which is almost identical to that of the master laser (Fig. 5). Therefore, the maximum peak power of the amplified vortex output could be evaluated to be 99.5 MWshows experimental results of the beam-propagation parameter, M2, measured by a commercial M^2 measuring instrument (Ophir, M2-200s). As shown in Fig. 6 (a), the amplified vortex output exhibitedM2x=3.07 and M2y=2.923 in the horizontal and vertical direction respectively, while the vortex seed beam exhibited M2x=2.788 and M2y=2.608 (Fig. 6 (b)). This difference may be caused by spatial distortion such as nonuniform pumping, diffraction effects and thermal distortion in the amplifiers. As we know, the theoretical value of M2 for vortex beam with topological charge l=1, is 2. The difference between the measured result and the theoretical value should be ascribed to the master laser, which exhibited M2x=1.529 and M2y=1.419 These results indicate that the beam quality of the amplified vortex output should be possible improved by improving that of the master laser.

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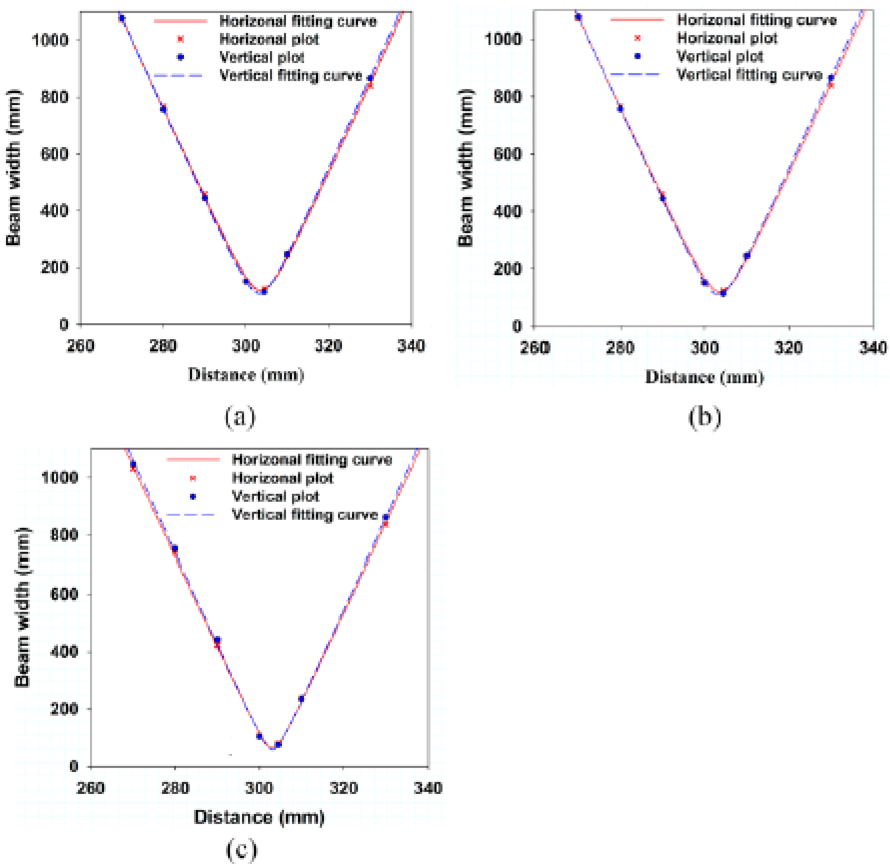

Fig. 6. Beam propagation of (a) the amplified vortex output and (b) the corresponding vortex seed (l=1)and (c) the master laser.

B. Second harmonic generation of the amplified vortex output

As an example of the application of high energy vortex output, SHG of the amplified vortex output was performed. It would be expected that high energy vortex pulse should lead to high energy and high efficiency output of frequency conversion. In addition, during laser ablation, frequency extension is necessary to meet the absorption bands of different materials. Therefore, the amplified vortex output was then directly sent to a KD*P crystal without focusing. The KD*P crystal was cut for type II phase match, for second harmonic generation (SHG) from 1064 nm to 532 nm. Polarization of the fundamental beam was adjusted with a second half wave plate (HWP2) for perfect phase matching depending upon the orientation of the second-harmonic (SH) crystal. After the nonlinear interaction, the SH output was

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separated from the residual fundamental beam by two dichroic mirrors (DM).

In order to measure the topological charge, the fundamental beams were sent to interference with flat-wavefront reference beam. Figure 4 (a) and Fig. 4 (b) represent the interference

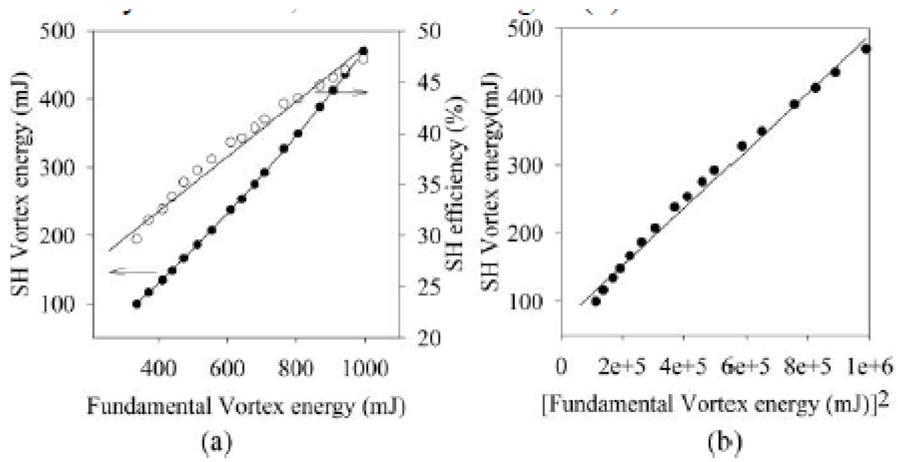

Fig. 7. (a) Variation of the SH vortex energy and efficiency as a function of the fundamental vortex energy (*l*=1). (b) Dependence of SH vortex energy with the square of the fundamental vortex energy. Lines are guide to eyes.

fringe of the fundamental beams with topological charge *l*=1 and 2, respectively, as evidenced by the characteristic fork patterns. It was reported that the topological charge of the SH beam is doubled in SHG [13, 26-28]. Therefore, the interference fringe of the SH beams and their reference plane wave were examined. As shown in Fig. 4 (c) and Fig. 4 (d), the topological charge of the corresponding SH beams is equal to two and four, respectively. These results confirm the conservation of OAM in SHG. Reference 23 reported that phase singularities of optical vortices separate due to the walk-off effect arising from the birefringence of the nonlinear media. However, we have not observed any such splitting in the SH vortices. This can be attributed to the low spatial walk-off ($\rho \approx 25$ mrad) of the KD*P crystal, and the large diameter (9.5 mm) of the fundamental vortex beam.

Figure 7 (a) shows the vortex SH energy and SH efficiency as a function of the fundamental vortex energy with topological charge *l*=1, and Fig. 7 (b) shows the vortex SH energy as a function of the square of the fundamental vortex energy. As evident from Fig. 7 (a), the vortex SH and efficiency show quadratic and linear dependence on the fundamental vortex energy, respectively. The maximum SH energy was measured to be 470 mJ, corresponding to a maximum single-pass conversion efficiency as high as ~47 %. However, the linear dependence of the SH energy on square of the fundamental vortex energy clearly indicates that the SH energy is possible to further increase with the increase of fundamental energy without any saturation, as shown in Fig. 7 (b).

CONCLUSION

A new optical vortex amplifier system was proposed, based on two flash-lamp-pumped Nd:YAG amplifier stages and a SPP. Up to 995 mJ of optical vortex output with topological charge *l*=1 has been generated, corresponding to a peak power of 99.5 MW. To the best of our knowledge, this is the first study of optical vortex amplification in bulk solid-state (Nd:YAG) amplifier, and the highest vortex pulse energy output obtained from power amplifier. The power scaling in the system might be impacted by the amplified spontaneous emission and preleasing [23]. Further power scaling of the system is possible by using a more powerful master laser and increasing the number of power amplifiers. The high-energy optical vortex output from power amplifier enabled us to generate a frequency-doubled vortex output with high energy and high efficiency. In experiment, 470mJ of SHG from the amplified optical vortex was obtained using a nonlinear KD*P crystal.

Further, the high-energy nanosecond vortex generation should benefit numerous application areas requiring various high energy (or high power) vortex beam, such as nonlinear optics and laser ablation. This technique has the advantage of simplicity for generating high energy optical vortex, and hence could be easily extend to regenerative amplifiers or chirped-pulse amplifiers to amplify ultra-short vortex pulses, by replacing the spiral plate with a Q-plate [29].

Moreover, the high-energy vortex output makes it possible to extend the vortex frequency to an infrared region by an optical parametric oscillator [12] or to an ultraviolet region by sum frequency generation [30,31].

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