Power scaling of a picosecond vortex laser based on a stressed Yb-doped fiber amplifier

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Abstract: Power scaling of a picosecond vortex laser based on a stressed Yb-doped fiber amplifier is analyzed. An output power of 25 W was obtained for 53 W of pumping, with a peak power of 37 kW. Frequency doubling of the vortex output was demonstrated using a nonlinear PPSLT crystal. A second-harmonic output power of up to 1.5 W was measured at a fundamental power of 11.2 W.

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1. Introduction

Optical vortices [1,2], with an annular far-field spatial profile and orbital angular momentum due to a phase singularity, have applications to optical tweezers [3,4] and quantum information [5]. Intense optical vortex pulses would open up various new technologies, including super-resolution microscopes [6,7], material micro-processing [8], and plasma physics [9].

High-power 1.06-μm and 1.3-μm vortex outputs from side-pumped Nd-doped vanadate bounce lasers based on Nd:YVO$_4$ and Nd:GdVO$_4$ [10,11] have been demonstrated in the continuous-wave and nanosecond regimes. Output powers of over 10 W have been achieved.

A master-oscillator power-amplifier using a stressed large-mode-area fiber amplifier in combination with an off-axis injection technique is an alternative way to produce high-power vortex outputs. Recently, a high-power picosecond vortex output from a stressed large-mode-area 3-m-long fiber amplifier was demonstrated in combination with a mode-locked mixed-vanadate master laser [12]. A maximum output power of 8.5 W with a peak power of 12.5 kW was obtained. This technique allows selective control of the rotational direction of the vortex by varying the stress applied to the fiber amplifier.

In the present paper, power scaling of the vortex output from a master-oscillator power-amplifier is analyzed based on a stressed large-mode-area fiber amplifier in combination with off-axis injection. The average output power from the Yb-doped fiber amplifier was as high as 25 W for a pump power of 53 W, with a peak power exceeding 34 kW. Frequency-doubled output without any spatial separation of the vortices was also achieved, with a doubled orbital angular momentum of up to 1.5 W, corresponding to a 12% conversion efficiency.

2. Experiments

2.1 High-power picosecond vortex laser

Figure 1 is a schematic diagram of the experimental setup. The master laser was a homemade continuous-wave mode-locked Nd:YVO$_4$ laser [13–15] using a semiconductor saturable absorber mirror [16] with a modulation depth of ΔR = 2%. Its output had a lasing frequency of 1064.4 nm, a pulse width of 7.6 ps, and a pulse repetition frequency (PRF) of 90 MHz. The output power of the master laser was 4 W. A polarization-maintaining large-mode-area Yb$^{3+}$-doped double-clad fiber (with a length of 4 m or 3 m, a core diameter of 30 μm, a core NA of 0.06, a cladding diameter of 400 μm, and a cladding NA of 0.46) was used for the amplifier. The cutoff value of the fiber amplifier was estimated to be 5.3 [17]. The fiber amplifier was pumped by a 975-nm laser diode with an output power of 53 W. To avoid optical damage to the fiber facet at high pump levels, the exit facet of the fiber amplifier was end-capped and mounted on a metal block cooled by a water chiller. To avoid parasitic oscillation in the fiber amplifier, both end faces of the fiber were cut at 8° relative to the normal to the fiber. The fiber was bent into a hoop with a radius of ~13 cm.

The collimated master laser output was delivered by relay optics and off-axis injected into the fiber amplifier using a 10 x objective lens with an NA of 0.25, yielding highly efficient in-phase coupling for the two orthogonal LP$_{11}$ modes. The optical coupling efficiency of the master laser to the fiber amplifier was measured to be ~25%. Appropriate stress on the fiber amplifier was provided using a homemade device, a modified polarized controller (PolARITE, General Photonics), that converted the LP$_{11}$ modes to vortex modes.
A maximum output power of 25.3 W for a 4-m-long fiber was achieved at a pump power of 52.8 W, corresponding to an optical-optical efficiency from the diode to the vortex output of 47.9% (cf. Figure 2). The output for a 4-m-long fiber exhibited no rollover, even at high pump levels. In contrast, a 3-m-long fiber (used in previous work) has a low slope efficiency of only 35%, and its output power is limited to 16 W, due to insufficient absorption in the fiber amplifier. The power ratio of p-polarized and s-polarized components in the vortex output was 5:1.

As shown in Fig. 3(a), the output had a doughnut-shaped spatial profile due to a phase singularity. Interferograms formed between the output and a spherical reference beam are shown in Figs. 3(b) and 3(c) [18,19]. The rotational direction of the phase singularity was selectively changed by varying the stress in the fiber amplifier. As shown in Fig. 4, the beam-propagation parameter, $M^2$, of the vortex output was also measured to be 2.2, and was almost identical to the theoretical value, 2. These results indicate that our present system can provide vortex output with high quality. The vortex output had a temporal pulse width of 8.2 ps (cf. Figure 5(a)), corresponding to a peak power of 34.2 kW. The power scaling in the system might be impacted by the significant amplified spontaneous emission (ASE), owing to insufficient energy extraction from the center part of the Yb-doped core. For verifying the ASE fraction, the lasing spectra of the master laser and the amplified vortex output with a logarithmic scale were also measured (cf. Figure 5(b)). Further power scaling of the system will be possible, since the lasing spectra of the amplified vortex output includes no undesired ASE fraction and it is identical with that of the master laser.

To investigate the performance of the system in a conventional Gaussian output, the master laser was also axially injected into the fiber amplifier. The output from the fiber amplifier had a Gaussian spatial profile and its power was almost identical to that of the vortex output.
Fig. 2. Vortex output power as a function of the pump power.

Fig. 3. Spatial profiles of the vortex output. (a) is intensity profile; (b) and (c) are interferograms formed between the vortex output and a spherical reference beam.

Fig. 4. Beam-propagation of the vortex output.
2.2 Frequency-doubled vortex output

The frequency doubling of the vortex output is now considered. A nonlinear crystal of PPSLT with dimensions of 1 mm x 2 mm x 15 mm was mounted in an oven that maintains a temperature of ~33°C. The vortex output emitted from the fiber amplifier was focused down to a 300-μm-diameter spot at the PPSLT crystal using a 100-mm-focal-length spherical lens. The maximum incident power into the PPSLT was limited to 11.2 W so as to avoid thermo-optical and photorefractive effects. The output power of the frequency-doubled vortex was measured to be 1.5 W for an incident vortex power of 11.2 W (cf. Figure 6). The second-harmonic conversion efficiency was estimated to be 12%.

As discussed elsewhere, separation of vortices due to walk-off in a nonlinear crystal [20], such as KTP, frequently occurs, although the net topological charge is preserved, as shown in Fig. 7(a). A periodically-poled nonlinear crystal, such as PPSLT [21], enables second-harmonic generation based on type-0 phase matching without walk-off, thus preventing the spatial separation of vortices.

Figures 7(b) and 7(c) show that the frequency-doubled vortex output has an annular spatial profile with a doubled topological charge. To confirm the performance of the PPSLT, a KTP crystal was substituted for it. The vortex output was more loosely focused to a 400-μm spot to avoid spatial separation of the vortices, resulting in a conversion efficiency of only 1.1%. These results demonstrate that the PPSLT is capable of frequency doubling the vortex output with a doubled topological charge at high efficiency.
Fig. 7. Spatial forms of the second harmonics of the vortex output. (a) is the spatial separation of phase singularities due to walk-off in the KTP crystal; (b) is the intensity profile of the second harmonics; and (c) shows second-harmonic interference fringes.

4. Conclusion

Power scaling of the vortex output from a master-oscillator power-amplifier has been demonstrated based on a stressed large-mode-area fiber amplifier by optimizing the absorption efficiency of the amplifier. Over 25.3 W of picosecond vortex output from a stressed Yb-doped system has been achieved in combination with a continuous-wave mode-locked Nd:YVO$_4$ master laser. The corresponding peak power and optical-optical efficiency were estimated to be 34.2 kW and 47.9%, respectively.

A 1.5-W frequency-doubled vortex output has also been demonstrated with a doubled topological charge without spatial separation of the vortices, using a PPSLT crystal. A second-harmonic conversion efficiency of 12% was measured. A high-power picosecond vortex output at visible wavelengths would be useful for the laser ablation of semiconductors, such as silicon. This laser system for generating high-power vortex outputs without requiring phase elements can be extended to generate high-energy nanosecond or continuous-wave outputs by replacing the master laser.

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