Nanosecond vortex laser pulses with millijoule pulse energies from a Yb-doped double-clad fiber power amplifier

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Abstract: Nanosecond vortex pulses were generated using a stressed, large-mode-area, Yb-doped, fiber amplifier with an off-axis coupling technique for the first time. A pulse energy of 0.83 mJ (corresponding to a peak power of 59 kW) was achieved at a pump power of 25.7 W. The optical-optical efficiency was measured to be 31%. The millijoule nanosecond vortex pulses will be potentially applied to novel material processing, such as metal microneedle fabrication.

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1. Introduction

Amplitude and wavefront control of laser beams has been extensively investigated in an effort to generate high-energy laser pulses with arbitrary intensities and wavefront profiles. Such laser pulses will reduce the time and cost of material processing techniques, such as laser ablation and micromachining. The generation of optical vortex pulses [1,2] that have doughnut-shaped spatial profiles and possess orbital angular momentum due to a phase singularity has been attracting interest. Vortex pulses have the potential to be used in various technologies, including laser ablation [3], high-density plasma confinement [4], controlling the specificity of chiral materials [5], and super-resolution microscopes based on stimulated emission depletion [6,7]. In particular, millijoule level vortex pulses can be potentially applied to novel material processing, such as metal microneedle fabrication with less accompanying debris [8].

Okida et al. demonstrated the direct generation of continuous-wave high-power vortex output from a diode-pumped neodymium vanadate bounce amplifier having an asymmetric cavity configuration [9,10]. Chard et al. generated nanosecond vortex pulses from a compact side-pumped non-astigmatic Nd:YVO$_4$ bounce laser with active Q-switching [11]. However, the physical mechanism of vortex formation in side-pumped bounce lasers is not fully understood. Furthermore, the spatial quality of the vortex output is very sensitive to the pump condition of the amplifier. The pulse energy of the output was also limited to be <200 μJ.

We proposed a new technique for generating high-power vortex output. It employs an off-axis coupled, stressed, Yb-doped, double-clad fiber power amplifier in combination with a diode-pumped solid-state master laser [12]. We have successfully demonstrated picosecond vortex output with an average power of 25 W and a peak power of 34 kW using an off-axis coupled, stressed, large-mode-area, 4-m-long fiber amplifier with a mode-locked neodymium doped vanadate (Nd:YVO$_4$) master laser [13]. This technique, requiring no phase elements for mode conversion, permits the rotational direction of the vortex to be controlled by merely varying the stress applied to the fiber amplifier.

The fatal drawback to ps fiber vortex lasers, showing easy power-scalability owing to their relatively wider spectral band-width, is their low pulse energy. A high energy (millijoule level) fiber vortex laser, in which the optical damage originating due to severe stimulated Brillouin scattering (SBS) effects will impact its power scaling, is not a continuation of our previous ps work, but a challenging project.

In the present work, we generated millijoule nanosecond vortex pulses from a stressed large-mode-area fiber amplifier in combination with an actively Q-switched Nd:YVO$_4$ master laser. Using this system, a maximum pulse energy of 0.83 mJ was obtained (which corresponds to a peak power of 59 kW). The optical–optical efficiency from the pump diode to the vortex output was measured to be 31%.
2. Experiments

Figure 1 is a schematic diagram of the experimental setup. A homemade end-pumped Q-switched Nd:YVO\textsubscript{4} laser with an acousto-optic modulator was used as the master laser. It had an output power of \( \sim 3.5 \) W and a pulse width of 14 ns for pulse repetition frequencies (PRF) in the range of 10–50 kHz. An optical isolator consisting of a polarizing beam splitter (PBS), a Faraday rotator (FR), and a half-wave plate (HWP) was used to prevent optical feedback by stimulated Brillouin scattering (SBS) [14] at high pumping levels. It had a polarization extinction ratio of \( \sim 40 \) dB. A polarization-maintaining, large-mode-area, Yb\textsuperscript{3+}-doped double-clad fiber [15] (core diameter: 30 \( \mu \text{m} \); core numerical aperture (NA): 0.06; clad diameter: 400 \( \mu \text{m} \); clad NA: 0.46; cut-off value: 5.3; length: 3 m) was used as the amplifier. To suppress the existence of the undesired higher-order modes and generate selectively the first-order vortex mode, the fiber was bent into a \( \sim 15\)–cm-diameter loop. Further, its exit facet was also capped so as to prevent optical damage. Both facets of the fiber were angled at 8° relative to the fiber amplifier to prevent parasitic oscillation. A 975-nm fiber-coupled laser diode with a 200 \( \mu \text{m} \) core diameter was used as the pump source. Its output was delivered using imaging optics with a magnification factor of 1 to ensure high efficiency coupling with the cladding of the fiber amplifier.

The collimated master laser output was delivered by relay optics. It was injected off axis into the fiber amplifier by a \( \times 10 \) objective lens (NA: 0.25). This provided efficient in-phase coupling for the two orthogonal LP\textsubscript{11} modes. The optical coupling efficiency of the master laser to the fiber amplifier (defined as the ratio of the transmitted master laser power through the fiber core without pumping to the incident master laser power onto the fiber) was measured and found to be \( \sim 10\% \). By using two modified polarization controllers (PolaRITE, General Photonics, 7.5 cm long), we slightly bent the fiber to one direction and the opposite direction, thus minimizing the depolarization of the output owing to this bending of the fiber. We then also clamped the fiber to provide on appropriate stress to the fiber amplifier, which converted the LP\textsubscript{11} modes into a vortex mode. The polarization extinction ratio (PER) of the vortex output was typically measured to be 5:1, while it was measured to be 16:1 without any bending and stress. The magnitude of the stress to the fiber was not measured quantitatively. The output power of anti-clockwise vortex was the same as that of the clockwise one.

Figure 2 shows a plot of the vortex pulse energy as a function of the pump power. The PRF was then fixed to 10 kHz. A maximum pulse energy of 0.83 mJ was obtained at a pump power of 25.7 W, which corresponds to an optical–optical efficiency from the diode to the vortex output of 31%. The vortex output had a doughnut-shaped spatial profile due to a phase singularity (Fig. 3(a)). We investigated the interferometric fringes generated by combining the
vortex output with a spherical reference beam. Fringes with a single-arm spiral were obtained, which indicates the presence of a phase singularity in the vortex output [16,17] (Figs. 3(b) and (c)).

![Fig. 2. Vortex and backward output energies as a function of pump power.](image)

As mentioned in our previous papers [12,13], the rotational direction of the phase singularity could be controlled by merely varying the stress applied to the fiber amplifier. The vortex output exhibited an almost ideal beam propagation parameter $M^2$ of 2.1 (Fig. 4) and a pulse width of 14 ns without any pulse broadening (Fig. 5(a)). The output pulses were estimated to have a peak power of 59 kW. Figure 5(b) shows the experimental lasing spectra of the master laser and the amplified vortex output (plotted on a logarithmic scale) measured using an optical spectrum analyzer (Advantest, Q8381) that had a spectral resolution of 0.1 nm. There was negligible undesired amplified spontaneous emission (ASE), which is generated by insufficient energy extraction from the central region of the Yb-doped core. Backward-propagating output due to SBS frequently hinders power scaling of systems [18,19]. The SBS gain $g$ is given by

$$g = \frac{g_B I L}{1 + \Delta \nu / \Delta \nu_B},$$

where $g_B$ is the SBS gain coefficient, $I$ is the peak intensity of the vortex output, $L$ is the fiber length, $\Delta \nu$ is the spectral linewidth of the vortex output, and $\Delta \nu_B$ is the SBS gain band, respectively. As shown in Fig. 5(c), the spectral linewidth $\Delta \nu$ of the amplified vortex output was measured to be ~90 GHz using a solid etalon (free-spectrum range: 192 GHz, finesse: ~20) (Fig. 5(c)). By substituting $I = 8.3 \times 10^9$ W/cm$^2$, $g_B = 5 \times 10^{-11}$ m/W, and $\Delta \nu_B = 50$ MHz into Eq. (1), the SBS gain is estimated to be ~6, which is close to the SBS threshold.
Above a pump power of 28 W, the backward-propagating pulse energy increased to above 0.1 mJ and the complex dynamics of the output pulse due to SBS was observed (Fig. 5(d)). The backward-propagating pulse energy (~50 μJ) was almost negligible below a pump power of 25.7 W (cf. Figure 2).

Figure 6 shows the average power and pulse width of the vortex output as functions of the PRF at a pump power of 25.7 W. The average output power was typically 8.3 W with a pulse width of 14–15 ns for PRFs in the range of 10–50 kHz. The pulse width of the output was almost the same as that of the master laser at any PRFs.
3. Conclusion

The generation of nanosecond vortex pulses with millijoule pulse energies has been demonstrated from a diode-pumped, Q-switched Nd:YVO₄ master laser in combination with a stressed, off-axially coupled, large-mode-area Yb-doped fiber power amplifier. A maximum pulse energy of 0.83 mJ (equivalent to a peak power of 59 kW) was obtained at a pump power of 25.7 W. The vortex direction could be controlled by merely varying the stress applied to the fiber amplifier. The quantum efficiency of the Yb amplifier connected to a 1064 nm Q-switched laser was ~92%. At this stage, the optical–optical efficiency from the pump diode to the vortex output was limited to be 31% by the SBS effects. Further power scaling of the system without SBS and optical damage of the fiber end facet is possible by using a fiber amplifier with a larger core diameter and a smaller NA (i.e., a large-mode-area photonic-band fiber amplifier) [20].

Using 1.5 μm lasers based on Yb-Er codoped fiber is an alternative solution for high power pulse lasers. Our vortex lase technique will also be potentially applied to generate 1.5 μm lasers based on the Yb-Er codoped fiber [21].

Frequency extension of the vortex output without spatial separation of the phase singularity is also possible by utilizing nonlinear frequency conversion devices without walk-off effects (e.g., periodically poled stoichiometric lithium tantalite [22]).

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