Generation of Megawatt Optical Vortex Pulses Directly from a Few-mode Fiber Based Mamyshev Oscillator

D. Lin*, Y. Feng, Z. Ren, D. J. Richardson
Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK
*Email: di.lin@soton.ac.uk

Abstract: We demonstrate a few-mode fiber based Mamyshev oscillator capable of generating optical vortex pulses with an energy of ~235 nJ that can be externally compressed to ~76 fs with a peak power of 2.2 MW. © 2022 The Author(s)

1. Introduction

Optical vortex beams are the subject of ever increasing interest due to their relevance and potential for widespread practical application in areas ranging from optical communications to laser-based material processing[1, 2]. Normally, such beams are generated by taking the Gaussian-profiled output beam from a laser and applying a helical phase front external to the laser cavity using a suitable spiral phase plate [3]. This approach works well and can be applied to both continuous-wave and pulsed lasers. However, there are often drawbacks associated with this external-cavity approach due to the power handling capabilities, modal purity, overall mode conversion loss and topological charge dispersion associated with such beam shaping devices. These become of particular concern for the efficient generation of high average power and high peak power femtosecond optical vortex beams with their associated high intensities and broad spectral bandwidth.

Here we propose and experimentally demonstrate the efficient generation of high-peak-power femtosecond optical vortex pulses from a Mamyshev oscillator (MO) based on few-mode polarization-maintaining (PM) ytterbium-doped fibers (YDFs). By employing an appropriate intracavity transverse spatial mode selection technique, ultrafast optical vortex pulses with selectable topological charge of $l = \pm 1$ are successfully generated with an average output power of ~5.72 W at ~24.35 MHz repetition rate, corresponding to a single pulse energy of ~235 nJ. The chirped output pulses are compressed down to ~76 fs in an external grating compressor leading to ~2.2 MW peak power.

2. Experiment and results

A schematic of the experimental setup is illustrated in Fig.1(a), which comprises two concatenated arms. A ~2.2-m length of PM-YDF (Nufern PLMA-YDF-25/250-VIII) is used as the gain medium in each arm. The PM-YDF in the first arm was tightly coiled with a bend diameter of ~7 cm so that it acts as an effectively single mode fiber (SMF) by differentially attenuating the higher-order modes (via induced bend loss) versus the fundamental mode. To reduce the mode coupling and to ensure the effective amplification of the first-order OAM modes within the fiber, the PM-YDF in the second arm was only loosely coiled with a large bending diameter of ~30 cm, and any twisting of the fiber was avoided. The second arm is backward cladding pumped by a 50W multimode 975nm laser diode. All fiber ends of the PM-YDFs were spliced to appropriate silica endcaps with a diameter of ~250 μm which were polished at an angle of ~ 8^{o} to suppress the potential for parasitic lasing. Two reflective ruled diffraction gratings (300lines/mm) in combination with SMFs form the offset bandpass filters required within the MO, each offering Gaussian-shaped spectral transmission profiles – one with a center wavelength set at 1042 nm with a 2.2 nm full-width at half-maximum (FWHM), and the other at 1030 nm with a 1.7 nm FWHM passband. The combination of a pair of quarter-waveplates (QWPs) and a *q*-plate with appropriate rotation angles forms an OAM beam converter that converts a linearly polarized Gaussian-shaped beam into a linearly polarized OAM beam with a controllable topological charge of $l = \pm 1$, or vice

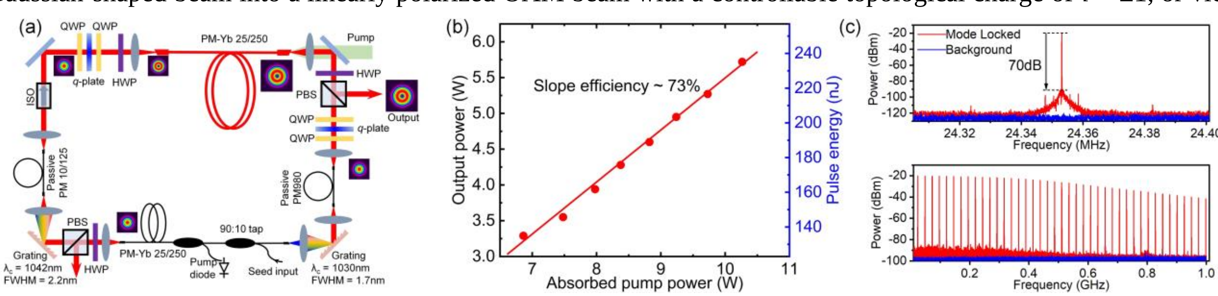

Fig. 1 (a) Schematic of the experimental setup, HWP: half-waveplate, PBS: polarization beam splitter, ISO: isolator; (b) the output power and pulse energy plots; (c) the measured radio frequency (RF) spectrum of the output pulses.

versa. One beam converter is placed just before the PM-YDF of the second arm to convert the incident linearly polarized Gaussian-shaped beam emitted from the first arm into a linearly polarized OAM beam that is then coupled to the few-mode PM-YDF in order to excite the linearly polarized OAM mode within this fiber. Behind the output coupler of the second arm, another OAM beam converter in combination with a short length of SMF, forms a spatial mode correlation filter. This filter strongly attenuates any signal in the undesired OAM mode emitted from the second arm whilst passing light in the desired linearly polarized OAM mode. A free-space polarization independent isolator ensures unidirectional operation.

Mode-locking is initiated by seeding with an external ~2 ps chirped pulse laser source. The MO generates ~2 ps chirped pulses with an average output power that linearly increases to ~5.72W at a repetition rate of ~24.35MHz, corresponding to a maximum single pulse energy of ~235 nJ (as shown in Fig. 1(b)). Fig. 1(c) shows the recorded RF spectrum of output pulses with a span window of 100 kHz and 1GHz, respectively. It shows that the fundamental beat mode has a signal-to-noise ratio of ~70 dB and no sign of multiple pulsing, indicating highly stable mode-locking. Fig. 2(a) shows the output spectrum at maximum pulse energy which is as one would expect for self-phase modulation (SPM) broadening of almost unchirped Gaussian pulse [4]. The bandwidth at the -10dB level extends from 1010 nm to 1070 nm. The output pulses were successfully compressed using a pair of transmission gratings (1000 lines/mm) with a compression efficiency of ~72%, resulting in a maximum compressed pulse energy of ~169 nJ. The intensity autocorrelation (AC) duration of the compressed pulse was measured to ~ 107 fs (FWHM) as shown by the red curve in Fig. 2(b). The calculated transform-limited (TL) pulse has an AC duration of ~79 fs as shown by the black curve, which is ~1.35 times shorter than the measured pulse. Assuming a Gaussian pulse shape, the temporal duration of the compressed pulses in the OAM beam is estimated to ~76 fs with a peak power of ~2.2MW. The inset of Fig. 2(b) shows a clean and single peak AC trace measured with a long range (64 ps) delay window, excluding the existence of any broad pedestal underneath the single pulse and the potential existence of multiple pulses. Fig.2 (c)-(d) show the measured beam profiles for the output OAM modes with opposite handedness of helical phase front as verified through the different spiral interference patterns shown in Fig. 2(e)-(f). The modal purity was measured to ~93% by the mode decomposing method.

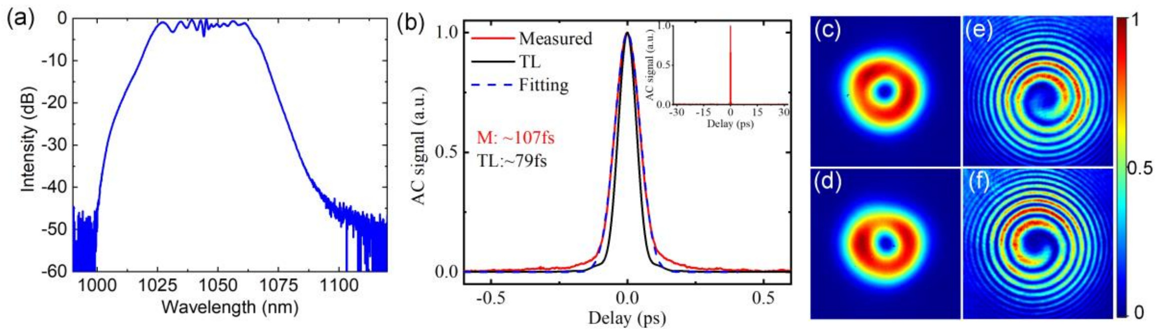

Fig. 2 (a) The measured output spectrum; (b) The measured intensity AC trace of compressed pulses; (c)-(f) The measured intensity profiles for the OAM beams with opposite handedness and corresponding interference patterns.

In conclusion, we have demonstrated a novel approach to efficiently generate megawatt peak power femtosecond OAM pulses with controllable topological charges of $l = \pm 1$ directly from a ring-cavity mode-locked few-mode fiber MO. The generated OAM pulses can be compressed to ~76 fs with a single pulse energy of ~169nJ, leading to an estimated peak power of ~2.2MW. The laser may prove useful for a wide range of applications including laser-based material processing and high-resolution medical imaging.

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5. References

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