# Picosecond optical vortex converted from multigigahertz self-mode-locked high-order Hermite–Gaussian Nd:GdVO$_4$ lasers

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We report on a gigahertz self-mode-locked high-order Hermite–Gaussian (HG) Nd:GdVO$_4$ laser. With a pump power of 2.2 W, the average output power for the TEM$_{0,m}$ modes from $m=9$ to $m=0$ are among 350–780 mW at a repetition rate of 3.5 GHz. The mode-locked pulse width is in the range of 20–25 ps for various HG TEM$_{0,m}$ modes. With a simple cylindrical-lens converter, the mode-locked HG beams are converted to generate picosecond optical vortex pulses. © 2009 Optical Society of America

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Optical vortex beams [1,2] that possess orbital angular momentum because of a phase singularity have been extensively used in the study of optical tweezers [3–7], trapping and guiding of cold atoms [8–10], rotational frequency shift [11,12], and entanglement states of photons [13]. Several devices, including spiral phase plates [14], computer-generated holographic converters [15], and astigmatic mode converters (AMC) [16], have been successfully demonstrated to transform high-order Hermite–Gaussian (HG) modes into optical vortex beams.

Optical vortex pulses have recently been attracting great interest because they can open up various fields, including high-quality material processing [17], controllable specificity of chiral matter [18], and nonlinear frequency conversion [19]. Furthermore, optical vortex pulses in picosecond or femtosecond laser fields can be potentially utilized to investigate high-field laser physics [20–23]. However, AMC cannot be used directly, since conventional mode-locked lasers are usually designed to emit the fundamental TEM$_{00}$ mode. Therefore, it is highly desirable to develop high-order HG mode-locked lasers for generating ultrafast vortex pulses.

Recently, the large third-order nonlinearities of Nd-doped vanadate crystals have been successfully exploited to achieve the self-starting self-mode-locking operation without the need of any additional components [24]. In this Letter we report for the first time (to our knowledge) on a multigigahertz self-mode-locked high-order HG Nd-doped GdVO$_4$ laser with an off-axis pumping scheme. With a pump power of 2.2 W, the average output powers for 3.5 GHz mode-locked HG modes vary in the range of 350–780 mW for the TEM$_{0,m}$ modes from $m=9$ to $m=0$. The mode-locked pulse width is found to be approximately 20–25 ps for various HG TEM$_{0,m}$ modes, with $m=0$–9. We also use simple AMC to convert the mode-locked HG TEM$_{0,m}$ beams into Laguerre–Gaussian (LG) modes for generating picosecond optical vortex pulses.

Figure 1 depicts the experimental setup for the self-mode-locked high-order HG TEM$_{0,m}$ laser with an off-axis pumping scheme [25,26]. The cavity configuration is a simple concave-plano resonator. The active medium is an $a$-cut 0.25 at. % Nd:GdVO$_4$ crystal with a length of 10 mm. Both end surfaces of the Nd:GdVO$_4$ crystal were antireflection coated at 1064 nm and wedged 2° to suppress the Fabry–Perot etalon effect. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The water temperature was maintained around 20 °C to ensure stable laser output. The laser crystal was placed very near (2–3 mm) the input mirror, which was a 50 cm radius-of-curvature concave mirror with antireflection coating at 808 nm on the entrance face and with high-reflectance coating at 1064 nm ($>99.8\%$) and high transmittance coating at 808 nm on the second surface. A flat wedged output coupler with 15% transmission at 1064 nm was used throughout the experiment. The pump source was a 2.5 W, 808 nm fiber-coupled laser diode with a core diameter of 100 $\mu$m and an NA of 0.16. A focusing lens with 5 mm focal length and 85% coupling efficiency was used to reimage the pump beam into the laser crystal. The average pump size was approximately 70 $\mu$m. The optical cavity length was set

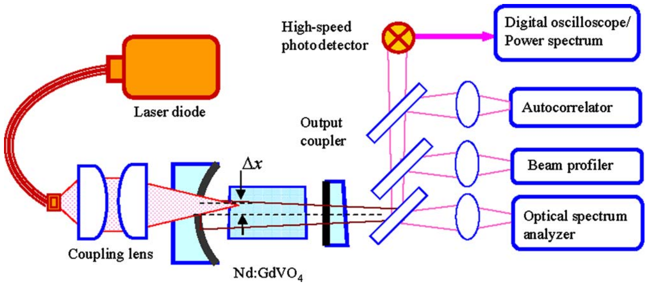

Fig. 1. (Color online) Schematic of a self-mode-locked high-order HG TEM$_{0,m}$ laser with an off-axis pumping scheme.

to be approximately 4.3 cm with the corresponding free spectral range (FSR) of 3.5 GHz.

First of all, the pumping beam was focused right on the optical axis of the laser cavity to obtain the maximum output power for the $\mathrm{TEM}_{0,0}$ mode. After finely adjusting the cavity alignment, the laser output can be found to display a stable self-mode-locking operation. Subsequently the high-order HG $\mathrm{TEM}_{0,m}$ mode-locked lasers can be generated with off-axis pumping [25,26]. The larger the off-axis displacement $\Delta x$ is, the higher the HG $\mathrm{TEM}_{0,m}$ order is. With varying $\Delta x$ from 0 to 0.5 mm, the average output power was found to decrease gradually from 780 to 350 mW at a pump power of 2.2 W, as shown in Fig. 2. Ten HG $\mathrm{TEM}_{0,m}$ modes were generated during the variation of off-axis displacement. The inset of Fig. 2 shows the experimental patterns that were measured using a CCD camera. All observed HG $\mathrm{TEM}_{0,m}$ modes are found to be in the pure longitudinal mode-locking regime. Note that once the pump power reaches the lasing threshold, the laser system instantaneously steps into a stable mode-locked operation without any mechanical perturbation. The locking mechanism is presumed to be the Kerr effect. However, the laser system has high stability over day-long operation and is insensitive to mechanical vibrations and air current. As a result, some auxiliary mechanism seems to exist in the locking process. Bai *et al.* [27] proposed a novel self-mode-locking mechanism in narrowband lasers based on the analysis of the gain-line splitting induced by an intracavity laser field. Although the present experimental results are fairly consistent with this mechanism, further identification is still needed.

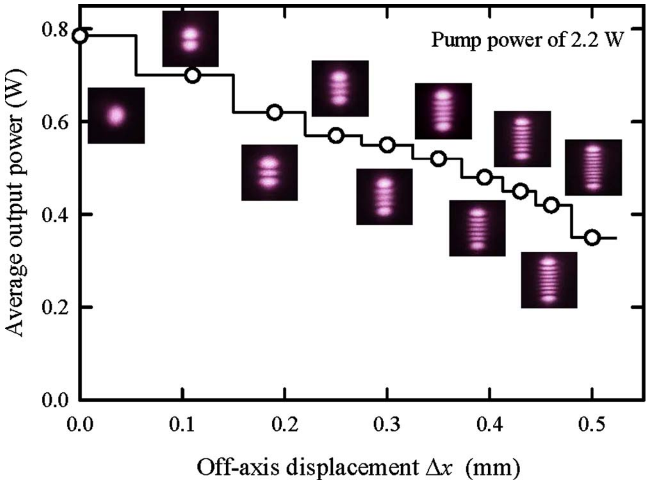

Fig. 2. (Color online) Dependence of the average output power on the variation off-axis displacement. Inset, transverse patterns observed in the mode-locked operation.

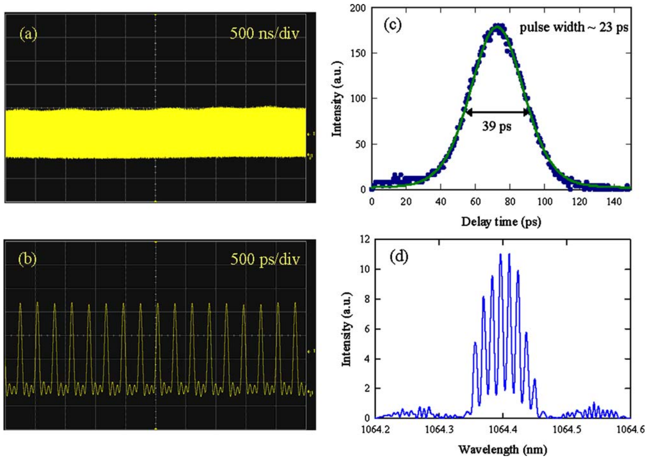

Fig. 3. (Color online) Pulse trains on two different time scales: (a) time span of 5 $\mu$s, demonstrating mode-locked pulses; (b) time span of 5 ns, demonstrating the amplitude oscillation. (c) Autocorrelation trace of the output pulses. (d) Corresponding optical spectrum. All results are for HG $\mathrm{TEM}_{0,5}$ mode.

The mode-locked pulses were detected by a high-speed InGaAs photodetector (Electro-optics Technology, Inc. ET-3500 with rise time 35 ps), whose output signal was connected to a digital oscilloscope (Agilent DSO 80000) with 10 GHz electrical bandwidth and a sampling interval of 25 ps. Figures 3(a) and 3(b) show the pulse trains for the $\mathrm{TEM}_{0,5}$ mode on two different time scales, one with time span of 5 ns, demonstrating mode-locked pulses, and the other with time span of 5 $\mu$s, demonstrating the amplitude stability. It can be seen that the pulse trains display full modulation, and the complete mode locking is achieved. The corresponding power spectrum is measured by an rf spectrum analyzer (Advantest, R3265A) with bandwidth of 8.0 GHz. Experiment results reveal that the relative frequency deviation of power spectrum, $\Delta\nu/v$, is smaller than $10^{-4}$ over day-long operation, where $v$ is the center frequency of the power spectrum and $\Delta\nu$ is the frequency deviation of FWHM. The laser was cw mode locked at 3.5 GHz with only weak noise at the relaxation oscillation frequency around 2 MHz, and the difference between the peak of mode-locked frequency and that of relaxation oscillation frequency was experimentally found to be larger than 55 dBm. The overall characteristics are almost the same as the results observed for the self-mode-locked fundamental $\mathrm{TEM}_{0,0}$ mode [24]. The pulse width at the cw mode-locked operation was measured with an autocorrelator (APE pulse check, Angewandte physik & Elektronik GmbH). Assuming the $\mathrm{sech}^2$-shaped temporal profile, the FWHM was measured to be in the range of 20–25 ps for HG $\mathrm{TEM}_{0,m}$ modes with $m=0-9$. The result for the $\mathrm{TEM}_{0,5}$ mode is shown in Fig. 3(c). The spectral information of the laser was monitored by a Fourier optical spectrum analyzer (Advantest, Q8347) that is constructed with a Michelson interferometer with resolution of 0.003 nm. Figure 3(d) shows the optical spectrum for the $\mathrm{TEM}_{0,5}$ mode. It can be seen that the longitudinal mode with 3.5 GHz is clearly resolved and the FWHM of the spectrum is approximately 0.1 nm. Consequently, the time–bandwidth product of the mode-locked pulse is approximately 0.4, indicating the pulses to be frequency chirped. On the whole, there are no significant difference for the mode-locked performances of the HG $\mathrm{TEM}_{0,m}$ modes with $m=0-9$.

The mode-locked HG $\mathrm{TEM}_{0,m}$ beam was converted into the mode-locked LG $\mathrm{TEM}_{0,m}$ beam with a cylindrical-lens mode converter outside the laser resonator, as shown in Fig. 4(a). The focal length of the cylindrical lenses was $f = 25$ mm, and the distance was precisely adjusted to be $\sqrt{2}f$ for the operation of the $\pi/2$ converter. Figure 4(b) depicts the results of the transformation of HG modes, shown in Fig. 2, to the corresponding LG modes. It can be seen that the mode-locked LG $\text{TEM}_{0,m}$ modes are successfully generated for azimuthal index from 0 to 9.

In conclusion, we have realized an efficient 3.5 GHz self-mode-locked $\text{Nd:GdVO}_4$ laser for HG $\text{TEM}_{0,m}$ modes with $m = 0-9$. The average output powers for the $\text{TEM}_{0,m}$ modes from $m = 9$ to $m = 0$ were among 350–780 mW at a pump power of 2.2 W. The mode-locked pulse width was found to be in the range of 20–25 ps for various HG $\text{TEM}_{0,m}$ modes. With a simple cylindrical-lens converter, the picosecond optical vortex pulses have been generated by converting the mode-locked HG beams into LG modes. We believe that the generated picosecond optical vortices can be potentially beneficial to a number of applications.

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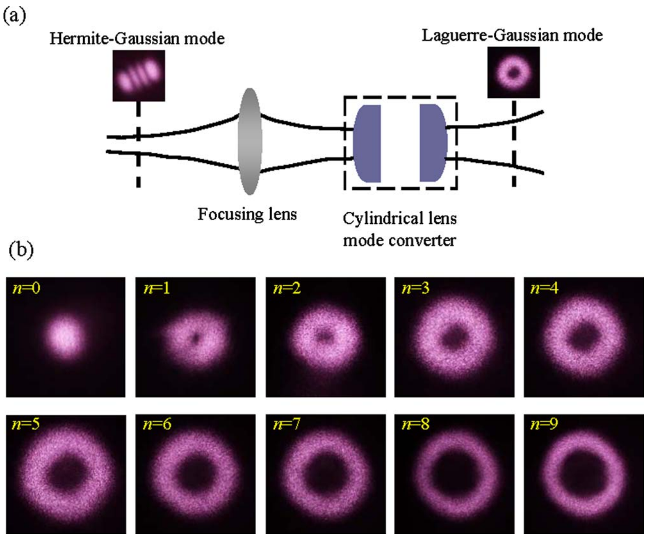

Fig. 4. (Color online) (a) Schematic of a cylindrical-lens mode converter. (b) Converted LG modes transformed from the HG modes shown in Fig. 2.

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