Generation of picosecond vortex beam in a self-mode-locked $Nd:YVO_4$ laser*

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In this paper, a self-mode-locked $Nd:YVO_4$ picosecond vortex laser is demonstrated, which can operate on the different Laguerre-Gaussian (LG) modes at 1 064 nm. A π/2 mode converter is utilized to realize the picosecond vortex laser with LG mode transformed from the high-order Hermite-Gaussian (HG) mode. For the proposed laser, the mode-locked pulse repetition rate is 1.81 GHz. The average output powers of LG_{12} mode and LG_{02} mode are 1.241 W and 1.27 W, respectively, and their slope efficiencies are 23.2% and 24%, respectively.

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Over the past decades, vortex laser[1-3] has been attracting much attention due to their unique characteristics. Recently, there has been many reports on the study of pulsed vortex lasers[4-7]. The common vortex lasers include Laguerre-Gaussian (LG) laser beams[6] and high-order Bessel beams[8]. Furthermore, the LG laser modes can be transformed by the high-order Hermite-Gaussian (HG) modes through different ways, such as spiral phase plates[9], computer-generated holograms[10], astigmatic mode converters (AMC)[11,12], etc. Another efficient way to excite LG modes is to reshape top-hat or Gaussian pump light into ring-shaped diode laser beam[5-7]. Among these ways, AMC has the advantages of low cost, a broader wavelength operation range, a high-power damage threshold and simplicity in fabrication.

In the recent years, an intriguing and novel self-mode-locking (SML) picosecond laser that possesses the Kerr-lens effect has attracted increasingly researchers' recognition[13-16] without employing an extra nonlinearity except a gain medium. The third-order Kerr nonlinearity (or intensity-dependent refractive index) is a possible nonlinear interaction to lock the phases of the oscillating longitudinal modes. Combining the third-order Kerr nonlinearity of the laser crystal with a spatially narrow gain profile (soft aperture), the fast saturable absorber can be achieved. So far, the study of combing the SML and vortex laser is very little.

In this paper, we report an SML picosecond $Nd:YVO_4$ vortex laser oscillating on LG modes with different orders at 1 064 nm. A pair of cylindrical lenses is adopted as a π/2 mode converter, i.e., AMC. For conventional mode-locked lasers, the coupling of the longitudinal modes normally requires the operation in the fundamental transversal mode $TEM_{0,0}$, so the AMC can't be used directly. Therefore, the major challenge is to balance the high-order HG modes and the pulse stability for the direct generation of ultrafast optical vortex pulses. With strict design and adjustment, a compact and effective continuous wave (CW) mode-locked vortex laser system is experimentally demonstrated. The mode-locked pulse repetition rate of present laser is 1.81 GHz. With the incident pump power of 6 W, the average output powers of LG_{12} mode and LG_{02} mode are 1.241 W and 1.27 W, and their slope efficiencies are 23.2% and 24%, respectively.

The experimental setup of the SML vortex laser is shown schematically in Fig.1. The pump source used in the experiments is a fiber-coupled 808 nm laser diode (LD). The core size of the fiber is 100 μm in radius with numerical aperture of 0.22. A focusing lens system with a focal length of 50.8 mm and a coupling efficiency of 93% is used to reimage the pump beam into the laser crystal. The pump light is focused into the crystal with a beam compression ratio of 1:1.3. The a-cut $Nd:YVO_4$ laser crystal has the dimension of 3 mm×3 mm×10 mm and the neodymium ion doping concentration of 2% (atomic percent), which is wedged 1° to suppress the Fabry-Perot etalon effect. The laser crystal has a high-transmission (HT) coating (*T*>99.8%) at 808 nm and 1 064 nm. And it is wrapped with indium foil and

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mounted in a water-cooled copper holder for controlling the temperature of 18 °C to ensure stable laser output. The laser cavity comprises a concave mirror M_1 and a flat output coupler (OC). The mirror M_1 is anti-reflection (AR) coated at 808 nm (>98%) and high-reflection (HR) coated at 1 064 nm (>99.8%) with a curvature radius of 100 mm. The flat OC is partial-transmission (PT) coated at 1 064 nm (T=10%). The mirror M_2 is a 5:5 beamsplitter with installing angle of 45° in 900—1 200 nm range, and the mirror M_3 is a flat line mirror which is HR coated at 1 064 nm (>99.8%). The mirror M_4 is a convex mirror with the focal length of 75 mm. The focal lengths of both cylindrical lenses are 40 mm.

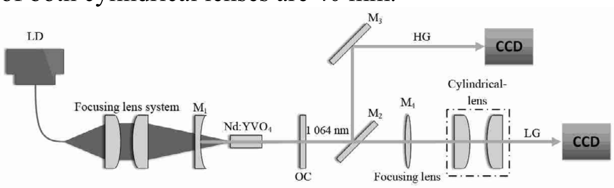
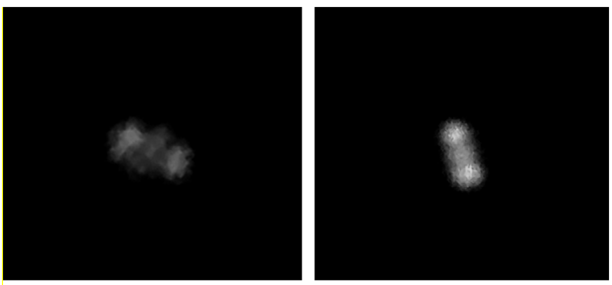


Fig.1 Experimental configuration of the SML Nd:YVO$_4$ vortex laser at 1 064 nm

The mode-locked pulses are detected by a high speed InGaAs photo detector with electrical bandwidth of 5 GHz and a digital oscilloscope (LeCroy Wave pro 7300A) with electrical bandwidth of 3 GHz. The output power is measured by a homemade power meter.

The picosecond vortex laser of LG modes can be obtained with picosecond HG modes by a π/2 mode converter. First of all, the stable self-mode-locking is obtained for $TEM_{0,0}$ mode with fine adjustment of the cavity, where the locking mechanism is arising from the Kerr effect. Subsequently, the high-order $HG_{n,m}$ modes are generated during the variation of angle of laser cavity mirror. For the present experiment, it is found that only specific high-order transverse modes can demonstrate the stable self-mode-locking, including HG_{12} mode and HG_{02} mode. The main reason of this phenomenon is attributed to that the competition of different transverse modes may result in instability of the pulse energy[17]. Fig.2 shows the experimental HG patterns measured with a CCD camera, and Fig.3 shows the intensity distribution of transverse patterns calculated by the MATLAB.



(a) (b)

Fig.2 Transverse patterns observed in the mode-locked operations of (a) HG_{12} and (b) HG_{02}

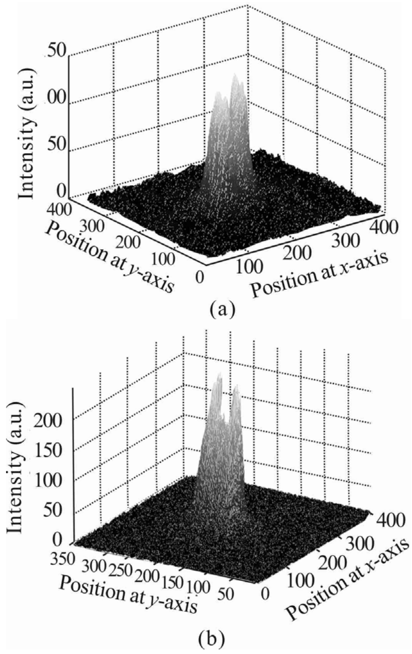


Fig.3 The output beam profiles of transverse patterns of (a) HG_{12} and (b) HG_{02}

Corresponding to the modes of HG_{12} and HG_{02}, Figs.4 and 5 show the mode-locked pulse trains with different incident pump power, respectively. According to Figs.4 and 5, when the pump power is increased to the 4 W, the pulse trains are nearly CW mode locking. A CW mode locking is achieved under the pump power of 5 W. Furthermore, compared Fig.4 with Fig.5, the amplitude stability of SML HG_{12} laser is more stable than that of HG_{02}. The SML optical cavity length is 83 mm which matches exactly with the mode-locked repetition rate of 1.81 GHz. The relationship among the measured pulse width τ , the evaluated pulse duration τ_0, the rising time τ_1 of the photo detector (70 ps) and the rising time τ_2 of the oscilloscope (117 ps) can be expressed as $\tau_0=\sqrt{\tau^2-\tau_1^2-\tau_2^2}$. The rising time can be calculated by $\tau_x \times BW$=0.35, where BW is the electrical bandwidth. The pulse widths of the

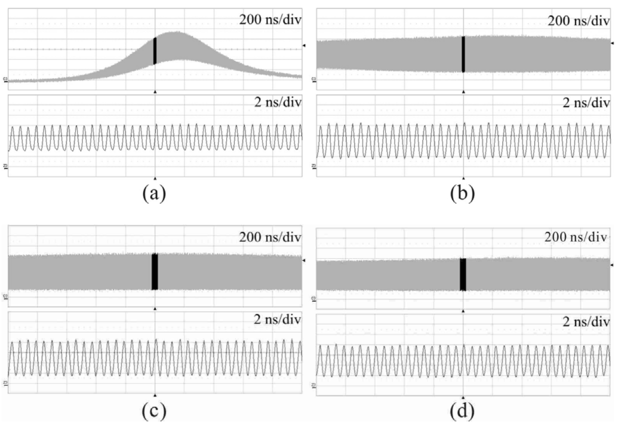


Fig.4 The mode-locked pulse trains (above) and amplitude stability (below) with different incident pump powers of (a) 2 W, (b) 4 W, (c) 5 W and (d) 6 W in the HG_{12} operation

mode-locked laser are about 230 ps (HG_{12}) and 213 ps (HG_{02}) as shown by the oscilloscope. To consider the limits of the instruments, the real pulse widths are less than 185 ps and 164 ps.

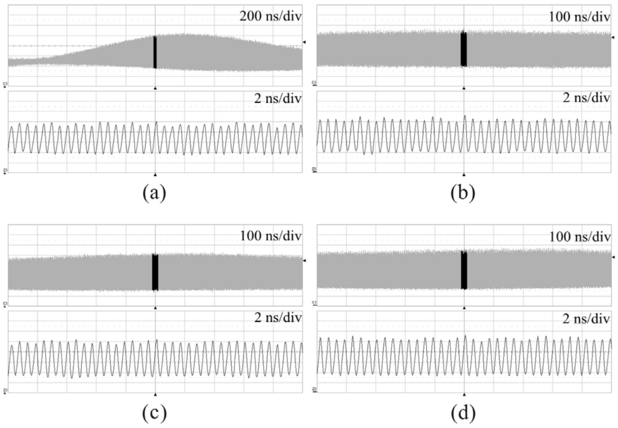


Fig.5 The mode-locked pulse train (above) and amplitude stability (below) with different incident pump powers of (a) 2 W, (b) 4 W, (c) 5 W and (d) 6 W in the HG_{02} operation

The SML $HG_{n,m}$ modes are converted into the SML $LG_{p,l}$ modes with a cylindrical-lens mode converter outside the laser cavity, by introducing a $\pi/2$ phase difference between the HG components, as illustrated in Fig.1. Figs.6 and 7 shows the results of doughnut distribution of LG modes transformed by the HG modes. Fig.6 is recorded by a CCD camera, and Fig.7 is calculated with Fig.6 by MATLAB.

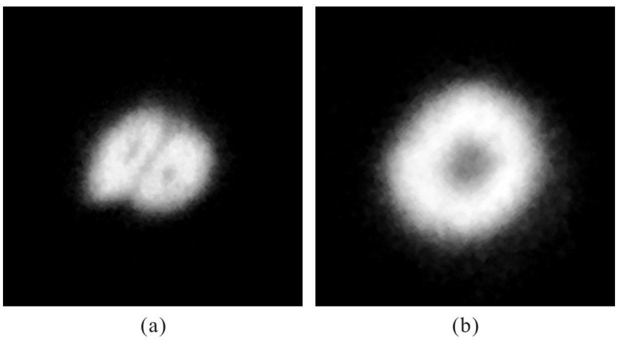


Fig.6 Transverse patterns observed in the mode-locked operations of (a) LG_{12} and (b) LG_{02}

A LG mode can be decomposed into a set of HG modes with the same order[18,19], which means that

$$u_{nm}^{\mathrm{LG}}(x,y,z)=\sum_{k=0}^{N} i^k b(n,m,k) u_{N-k,k}^{\mathrm{HG}}(x,y,z)\ , \tag{1}$$

$$b(n,m,k)=\left[\frac{(N-k)!k!}{2^N n!m!}\right]^{1/2}\cdot\frac{1}{k!}\cdot\frac{\mathrm{d}^k}{\mathrm{d}t^k}[(1-t)^n(1+t)^m]_{t=0}\ , \tag{2}$$

where u is the amplitude of the laser modes, b is the real coefficient, k is the wave number, $N=n+m$ is the order of the mode, and i^k is the factor to a $\pi/2$ relative phase difference between successive components. It should be mentioned that only the principal axes of a HG mode make an angle of 45° with the x and y axes (a diagonal mode), so that a HG mode can be decomposed, using relations between products of Hermite polynomials. According to the M. W. Beijersbergen's theory[11], the input beam of HG mode should have a specific Rayleigh range $Z_R = (1+1/\sqrt{2})f$, where f is the focal length of the cylindrical lens. Besides, the distance between the two cylindrical lenses should be $2d = \sqrt{2}f$. The middle of AMC should be placed on the position of HG laser beam waist, in this condition, the beam is astigmatic only between the two lenses. All these distances have been precisely adjusted for the operation of the $\pi/2$ converter.

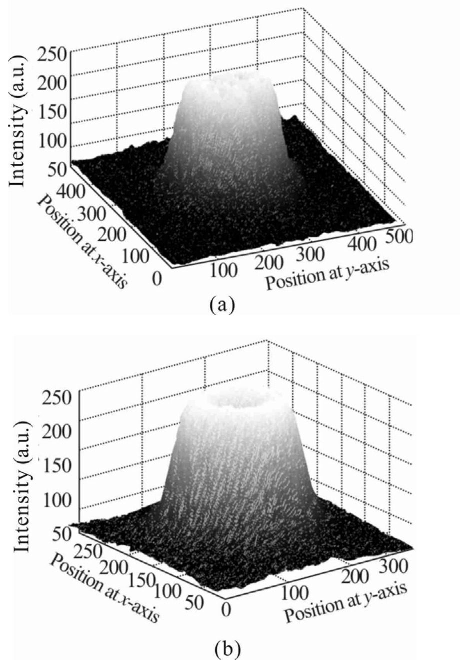


Fig.7 The output beam profiles of transverse patterns of (a) LG_{12} and (b) LG_{02}

Fig.8 depicts the average output power of SML vortex laser at 1 064 nm as a function of incident pump power, and it can be seen that the tendencies of SML LG_{12} and LG_{02} are very similar. Both of lasing thresholds are approximately 0.5 W. The maximum average output power of LG_{02} mode of 1.27 W is slightly higher than that of

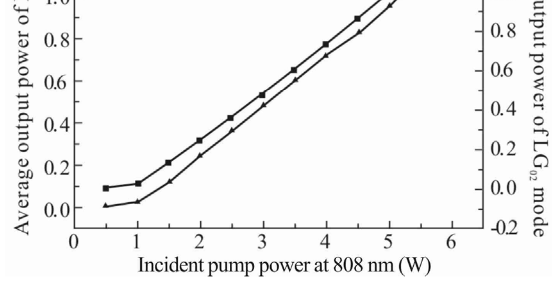


Fig.8 Output power of SML vortex laser with LG_{12} and LG_{02} modes at 1 064 nm versus the incident pump power at 808 nm

LG_{12} mode of 1.241 W. Besides, the slope efficiencies of LG_{12} and LG_{02} are about 23.2% and 24%, respectively.

In conclusion, the SML vortex laser with LG modes based on Nd:YVO_4 crystal is reported. The different high-order $HG_{n,m}$ modes are generated during the variation of angles of laser cavity mirrors. Then it is found that only HG_{12} mode and HG_{02} mode can achieve the stable self-mode-locking. Subsequently, according to the theory of AMC, the suitable focal lengths of cylindrical lens and positions are designed. The HG modes are transformed to be LG modes (vortex beam) by a $\pi/2$ mode converter. Besides, the tendencies of mode-locked LG_{12} and LG_{02} beams are very close. The mode-locked pulse repetition rate is 1.81 GHz. The average output power and the slope efficiency of LG_{12} mode are 1.241 W and 23.2%. And the average output power and the slope efficiency of LG_{02} mode are1.27 W and 24%.

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