Generation of Laguerre-Gaussian beam from end-pumped and c-cut $Nd:YVO_4$ laser

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We demonstrate an end-pumped, c-cut $Nd:YVO_4$ laser that emitted first-order Laguerre-Gaussian (LG_{01}) beam by adjusting the position of focused pump beam relative to laser crystal. The pumping light reached the laser crystal has circular and solid intensity profile. The laser is compact and stable, and the obtained LG_{01} beam power reaches 202 mW with ~25% slope efficiency.

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Nowadays the Laguerre-Gaussian (LG) beam labeled by doughnut-shaped intensity pattern finds many important applications including material processing, optical manipulation, super-resolution microscopy, and others[1−4]. The methods to produce such beam are categorized into the passive and active methods. The former mentions the extra-cavity beam conversion via computer-generated hologram, spatial light modulator, etc.[5,6]. The latter concentrates on the direct emission of desired mode from the laser resonator, usually performed by applying various intra-cavity components like spiral phase element or axis-symmetrical grating mirrors[7−11], or by utilizing pump-dependent astigmatic thermal lens in an asymmetric laser cavity[12,13]. Nevertheless, these approaches either relied on complicated, purposefully designed, and therefore expensive devices[7−11] or required high pumping power[14,15]. Meanwhile Chen *et al.* reported the LG-mode emission in an end-pumped solid-state laser by applying doughnut-shaped pumping usually formed at the position away from the focal plane of the pump light from a fiber-coupled laser diode (LD) source[12,13]. This method is simple and does not require any additional intracavity component.

In this letter, we demonstrated an end-pumped neodymium-doped yttrium vanadate ($Nd:YVO_4$) laser, and this laser emitted first-order LG modes (LG_{01}) mode efficiently by managing the distance between pump light's focal plane and laser crystal. In our case, the transverse profile of focused pump light reaching laser crystal remained circular and solid intensity distribution and this was different from that in Refs. [12,13], where a doughnut-shaped pumping profile was necessary to match the mode field of first- or higher-order LG mode.

In the experiment, we adopted c-cut $Nd:YVO_4$ crystal as gain medium which was based on several advantages and considerations. Firstly, this crystal has a broad pump absorption band as well as large absorption cross section around pumping wavelength and thus is more tolerant to temperature variations of pumping diode. In addition, its high emission cross section is beneficial for low-threshold oscillation of laser resonator. Furthermore, although being a naturally birefringent crystal, the c-cut orientation of it not only induces non-polarization-dependent absorption to perpendicularly-incident pumping light, but also sustains the laser oscillation of axis-symmetrical radiation modes including LG_{01} mode.

The schematic diagram of experimental setup is shown in Fig. 1. The pump source was a 808-nm fiber-coupled LD with a 105-μm fiber core diameter and 0.22-numimerical aperture (NA). The pump light was firstly collimated by lens L1 with 8-mm focal length and then was focused into the front surface of the gain medium by another lens L2 (focusing lens) with 40-mm focal length. A piece of c-cut $Nd:YVO_4$ crystal which has 1.5 at.-% Nd^{3+} doping concentration and the dimension of 5×5×5 (mm) was used as the gain medium. The crystal's front surface was coated for high transmission at 808 nm and high reflection at 1 064-nm thus acting as one cavity mirror, while its rear surface was anti-reflectively coated at 1 064 nm. This crystal was surrounded by the ambient condition without any cooling. The distance between L2 and the laser crystal's front surface was defined as d. A plane mirror with 90% reflectivity at 1 064 nm was employed as the output coupler (OC), and placed at a distance of L (which is equal to laser cavity length) behind the laser crystal's front surface. In the experiment, the laser power and beam profile were monitored with a power meter and charge-coupled device (CCD) camera, respectively.

Figure 2 plotted the measured intensity profiles of pump light at different distance d behind the low-numerical-aperture focusing lens L2, in which the pump light at front and back of the focal plane showed the circular and solid intensity distribution.

In the first step of our experiment, the cavity length L and the distance d were set rigidly equal to 16 and 40 mm respectively, and then output power of TEM_{00}-mode

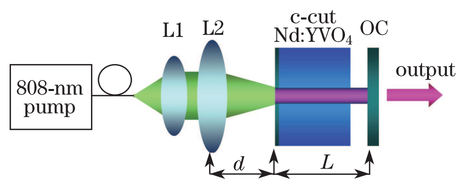

Fig. 1. Schematic diagram of laser-diode end-pumped $Nd:YVO_4$ laser.

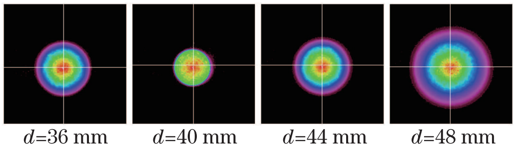

Fig. 2. Measured intensity profile of pump light at different distances d behind focusing lens L2. The focal plane situated at $d = 40$ mm.

laser oscillation was maximized by adjusting the tip/tilt angle of OC at a low pump power, typically within the range of 2.0–2.2 W. This approach assured the parallel placement between the front surface of gain medium and OC. Thereafter when the modification to the cavity condition (d or L) was made, either through moving the focusing lens or by shifting the OC along the cavity axis, the intensity pattern of the output beam was observed to change significantly with the incident pump power.

Firstly we investigated the influence of position of focusing lens on the profile of emitted laser beam at fixed cavity length. Figure 3 shows the variations of intensity distributions of output beam with pump power under different values of d at $L = 16$ mm, where the numbers above each pattern depicted the corresponding beam powers. It was clearly seen the LG_{01}mode could be lased either when the focusing spot of pumping beam fall outside of gain medium at an appropriate range of pump power, as roughly indicated in the triangular area. As seen, for a fixed value of d among 40–46 mm, the intensity distributions of laser beam can appeared to be doughnut-shaped LG_{01} mode in several different ranges of pump power. For example, at $d = 43$ mm, the laser operated in two-lobe Hermite-Gaussian (HG) mode at near-threshold pump power, and became LG_{01} mode within the pump power range of 2.2–3.0 W with a maximum power of 126 mW and highest slope efficiency of 25%, and further the laser tended to emit high-order LG mode at higher pump power. While for a smaller distance like $d = 38$ mm where the focusing spot of pumping beam located just inside of gain medium, the laser almost kept TEM_{00}-mode oscillation and just showed a preparatory tendency to emit LG_{01} mode at the maximum pump power available. For a larger distance of d like $d = 48$ mm, where the focusing spot of pumping beam lying far away from gain medium, the transition of laser mode form HG mode to higher-order mode occurred quickly with slight increment of low pump power.

According to results shown in Fig. 3, when d was increased to the extent of larger than L2's focal length, the LG_{01} and higher-order modes were more likely to be aroused. As seen in Fig. 1, the moving of L2 away from laser crystal enlarges the transverses pumping area and thus transverses gain area in the laser crystal, while the increase of pump power reinforces the gain along longitudinal direction. Therefore when the laser gain with specified transverse and longitudinal distributions has maximum overlap with mode volume of LG_{01} beam, this mode can be excited. The detailed and qualitative explanation to this mode-selective mechanism could be expected in succedent literature.

The effect of cavity length on laser beam was also investigated at fixed position of focusing lens. Figure 4 plotted the variation of intensity distributions of laser beam with pump power under different values of L at $d = 43$ mm, where the numbers above each pattern depicted the corresponding beam powers. It can be clearly discerned that, for short cavity length like $L = 11$ mm, the LG_{01} mode could not be produced in the whole range of pump power. While for longer length of laser cavity ($L \geqslant 12$ mm), the laser emitted LG_{01} mode at a certain ranges of pump powers, as shown in the selected tetragonal area. Especially, when $L = 20$ mm, LG_{01} mode was produced in the wide range (2.6–3.1 W) of pump power with nearly 25% slope efficiency and a maximum output power of 202 mW.

The measured intensity evolutions along two orthogonal line profiles (horizontal and vertical directions) of the LG_{01} mode obtained at $L = 16$ mm, $d = 43$ mm and 2.6-W pump power were plotted in Fig. 5, which are identical with respective fitted curves by LG function. This result showed the LG-function distributed nature of obtained beam. Simultaneously, the polarization state of this laser beam was checked by using a linear polarizer. Figure 6 plotted the transmitted intensity distribution through the polarizer when the polarizer was rotated, where the doughnut-shaped profile at different orientations of the polarizer's axis verify the laser beam was randomly polarized and this result confirmed the validity of the LG_{01}-mode lasing. Moreover the propagation

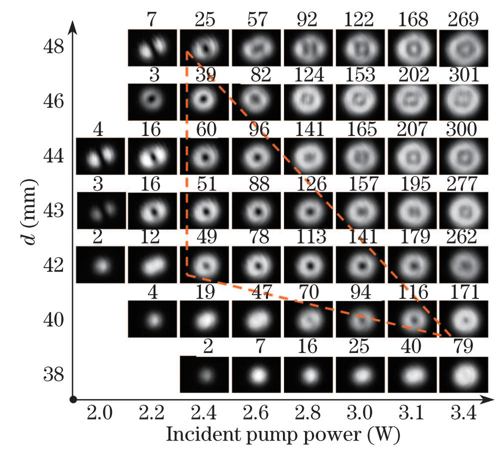

Fig. 3. Variation of intensity distributions of laser beams and their respective powers (mW) with pump power under different d at L=16 mm.

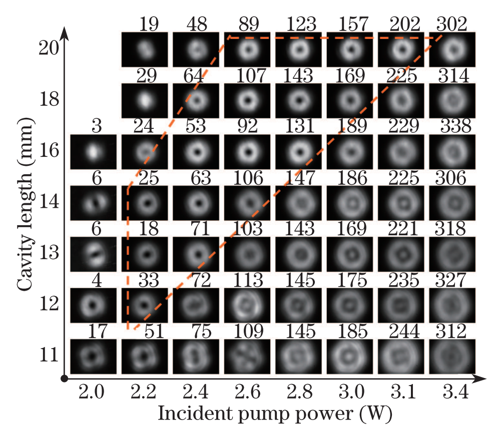

Fig. 4. Intensity distributions of output beam as functions of both pump power and L at d=43 mm.

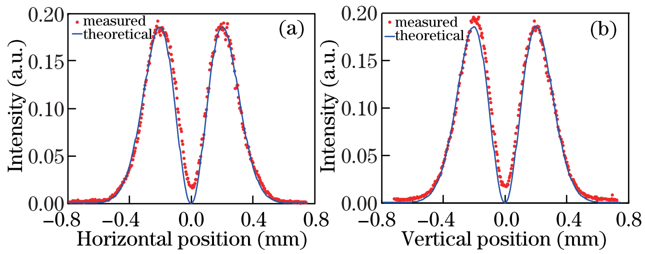

Fig. 5. Measured and fitted intensity evolutions along (a) horizontal and (b) vertical line profiles of obtained LG_{01} mode.

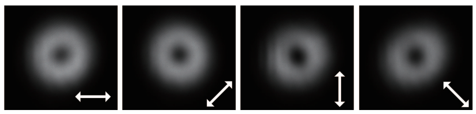

Fig. 6. Transmitted intensity distributions through the linear polarizer when the polarizer is rotated, in which white arrows indicte the corresponding direction of polarizer's axis.

factor-M square (M^2) of this LG_{01} mode was also measured to have the values of $M_x^2 = 2.17$ and $M_y^2 = 2.21$, and these data manifested the obtained LG_{01} mode had near-diffraction-limited beam quality.

In conclusion, we demonstrate an end-pumped, c-cut $Nd:YVO_4$ laser operating at LG_{01} mode by adjusting the distance between focal plane of pump light and laser crystal. This laser is simple and compact, while its LG_{01}-mode operation is stable and reproducible. The beam power of obtained LG_{01} mode reaches 202 mW at 3.1-W pump power with ∼25% slope efficiency. The efficient LG_{01}-mode laser is valuable for many applications.

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