

Transverse mode transition and LG₀₁-mode generation in an end-pumped Nd:YVO₄ laser

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Received October 8, 2013; accepted November 19, 2013; posted online December 9, 2013

A laser-diode end-pumped Nd:YVO₄ crystal laser is demonstrated to emit the first-order Laguerre-Gaussian (LG₀₁) mode with 502-mW laser power and 22% slope efficiency. The LG₀₁-mode is lased only when the pumping area locates in the central part of the laser crystal's front surface, and thereafter the symmetrical LG₀₁-HG₀₁-TEM₀₀ mode transition happens when laser crystal is moved laterally inside several-tens-micron area. The possible mechanism responsible for the phenomenon of symmetrical mode transition is also discussed.

OCIS codes: 140.6810, 140.3530, 140.3480, 140.3580.

doi: 10.3788/COL201311.121406.

In the past years, the first-order Laguerre-Gaussian mode (LG₀₁), which is known as one solution of the paraxial wave equation and has doughnut-shaped cross section with spiral phase fronts^[1,2], has attracted much attention due to its important applications in many fields like optical manipulation^[3,4], super-resolution microscopy^[5], and gravitational waves detection^[6], etc.

Techniques to produce such beams are usually categorized into passive and active methods. The former mainly mentions the beam transforming of fundamental Gaussian mode or Hermit-Gaussian mode by using diffractive optical elements^[7,8], spatial light modulators^[3,9,10] or cylindrical lenses pairs converter^[11], etc. The latter is to force a laser resonator to oscillate in the desired mode by adopting the annular pumping^[12–15], spot-defect or grating mirror of laser cavity^[16–18] or thermal-twisted cavity^[18], etc. As we know, these ever-reported methods mentioned the utilization of purpose-designed device^[16–19], high pumping power^[20] or reshaped pump profile^[12–15].

In this letter, we demonstrated a laser-diode (LD) end-pumped Nd-doped yttrium vanadate (Nd:YVO₄) crystal laser which emitted LG₀₁ mode easily and efficiently. This laser had plano-plano cavity and consisted of only two components, laser crystal and plane-mirror-based output coupler. Although our laser cavity seemed similar to that in Refs. [12,13], in our scheme, the pump light reached to laser crystal had circular and solid cross section instead of annular cross section. Further, our experimental results indicated that the laser's beam pattern was sensitive to the lateral position of laser crystal, and LG₀₁-mode emission was realized only when the pumping area was located in the center of laser crystal's front surface. When the pumping area deviated laterally from the center of laser crystal's front surface within a range of several-tens microns, the lasing mode experienced a rapid and symmetrical transition from LG₀₁ mode to the first-order Hermite-Gaussian (HG₀₁) mode and then to TEM₀₀ mode. This result revealed the observation of an interesting phenomenon in LD end-pumped Nd:YVO₄ laser. The details of our investigation were given in the

following sections.

Figure 1 plotted our experimental setup schematically. The pump source was an 808-nm LD coupled by a fiber with a 105- μm core diameter and 0.22 numerical aperture (NA). The radiation from this LD was collimated by lens L1 with 8-mm focal length and then focused into the front surface of the gain medium by lens L2 with 40-mm focal length. The gain medium was a piece of 1.5 at.-% Nd-doped YVO₄ crystal with a dimension of 5 \times 5 \times 5 (mm) and its *c* axis was oriented parallel to cavity axis. Its front surface was dichromatic coated for high transmission at 808 nm and high reflection at 1064 nm, while its rear surface was anti-reflectively coated at 1064 nm. The four lateral faces of this crystal were wrapped by indium film and mounted on an aluminum holder, and no active cooling system was used. A plane mirror with 90% reflectivity at 1064 nm was used as the output coupler (OC). As shown in Fig. 1, this laser resonator had simple plano-plano cavity, formed between the front face of laser crystal and the OC. In the experiment, the laser cavity was kept at a length of 15 mm. And the laser power and beam profile were monitored by a power meter and charge-coupled device (CCD) camera, respectively.

The use of Nd:YVO₄ crystal as gain medium was based on the following considerations. Firstly, its high absorption cross section at pumping wavelength and high emission cross section make itself beneficial for low-threshold oscillation of laser resonator. Furthermore, its *c*-cut

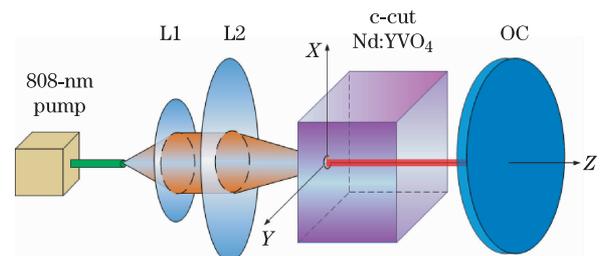


Fig. 1. Schematic diagram of laser-diode end-pumped Nd:YVO₄ laser.

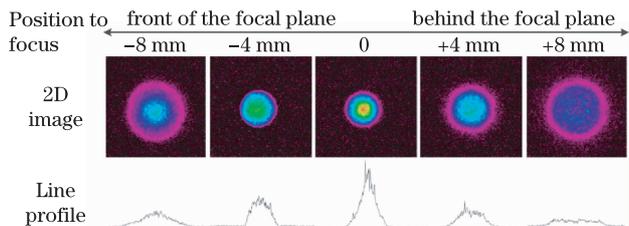


Fig. 2. Measured intensity distributions of pump light, as well as the corresponding line profiles, behind the focusing lens at different defocal distances.

orientation not only induces non-polarization-dependent absorption to pumping light, but also sustains the laser oscillation of axis-symmetrical radiation modes including LG_{01} mode.

With the setup given above, the pumping light from the fiber pigtail of LD was focused to a spot size of approximately $590 \mu\text{m}$ in diameter with a magnification factor of 5. We measured the intensity distribution of pump light around its focal plane. Figure 2 shows the captured intensity distributions of pump beam, as well as the corresponding line profiles, at different defocal distances respectively. As shown in Fig. 2, the pump light had the circular and solid intensity distribution at the focal plane and at a defocal distance ($\pm 8 \text{ mm}$) which already covered the whole length of laser crystal as well as the Rayleigh length of focused pumping beam (4.5 mm). Therefore, in our laser scheme, the pumping light was completely different from the work in Refs. [12,13], in which annular pumping light was necessary to obtain the efficient spatial overlap between the pumping area and the annular volume of LG_{01} mode inside the laser crystal.

In the first step of the experiment, the focused pump light was projected perpendicularly toward laser crystal with the focal plane almost standing with the front surface of laser crystal. Meanwhile, the laser cavity was adjusted carefully to ensure that the output coupler and the front face of laser crystal were parallel to each other. Thereafter the pump power was increased gradually to make the laser oscillate. Next, we finely adjusted the lateral position of laser crystal in both horizontal (X -axis) and vertical (Y -axis) directions while keeping other conditions of laser cavity unchanged. At this time, we found the laser's beam pattern was sensitive to the lateral position of laser crystal.

Figure 3 depicted the variation of the laser's beam pattern with the lateral position of laser crystal at 2.2-W pump power, in which laser crystal was moved along the X -axis and Y -axis directions in a step of $5 \mu\text{m}$ respectively. As observed, when the pumping area was almost on the central position of laser crystal's front surface (denoted as the coordinate origin in Fig. 3), an annular mode was generated. Nevertheless, when the laser crystal was shifted along the lateral direction so that the pumping area deviated the center of laser crystal's front surface, the doughnut shape of laser mode could not be kept, and it gradually switched to two-lobe Hermit-Gaussian-like (HG-like) beam, and then to TEM_{00} laser mode at a farther distance of larger than $75 \mu\text{m}$. It was observed that null line of emerged Hermit-Gaussian laser beam was always parallel with corresponding lat-

eral deviation direction. Furthermore, it also was found that, when laser crystal was moved laterally so that the pumping area was deviated, the beam patterns of the obtained laser mode were axis-symmetrical relative to the central position of laser crystal's front surface. For example, the lasing mode was HG_{01} -like at $x = 25 \mu\text{m}$ and was almost same as that at $x = -25 \mu\text{m}$, and thus these two lasing modes were symmetrical relative to the coordinate origin. To the best of our knowledge, this symmetrical mode-transition phenomenon when laser crystal was moved laterally inside several-tens-micron area was never reported by others.

As we know, in the end-pumped laser crystal, when the pumping area is located in the center of its front surface, the temperature rise and distribution induced by pump absorption generally is centrosymmetrical. Nevertheless, when laser crystal is moved laterally so that the pumping area deviate the crystal's center, the centrosymmetry of the temperature rise and distribution in the crystal is also broken. Thus it is reasonable to associate the position-sensitive pattern of laser mode with the varying thermal lens effect, and speculate that the centrosymmetric thermal lens effect could embleze the emission of annular LG_{01} mode in this plano-plano resonator.

To verify the reproducibility of the phenomena of transverse mode transition, we also conducted a comparable experiment. While keeping other laser conditions unchanged, another c-cut Nd:YVO_4 crystal which had a dimension of $5 \times 5 \times 4 \text{ (mm)}$ and 1.5 at.-% Nd-doped concentration was used as gain medium with its c axis parallel to cavity axis. Figure 4 depicted the variation of the laser's beam pattern with the lateral position of laser crystal at 1.9-W pump power, in which laser crystal was moved along the X -axis. As observed, when the pumping area was almost on the central position of laser crystal's front surface, an annular mode was generated, and when the laser crystal was deviated along the X direction, the similar mode transition from annular beam to two-lobe Hermit-Gaussian-like (HG-like) beam, and then to TEM_{00} laser mode happened.

The influence of the defocal length of pump light on the

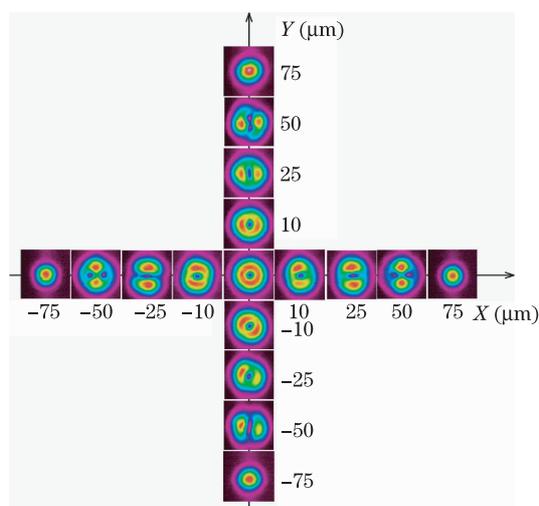


Fig. 3. Typical variations of laser mode measured in far field when moving gain crystal laterally (along two orthogonal directions perpendicular to cavity axis). The coordinate origin was identical with the center of laser crystal's front surface.

laser performance when applying 5-mm-thick Nd:YVO₄ crystal was also investigated. Denoting the distance between the crystal's front surface and the focal plane of the pump light as d , and the positive value of it indicated the focal plane of pumping light fell outside the laser crystal, while the negative value represented the focal plane of pumping light fell inside of laser crystal. For the case of that the pumping area was located at the center of laser crystal's front surface, we also investigated the variations of both beam pattern and power at different values of d . Figure 5(a) plotted the laser beam intensity distributions as a function of pumping power at different values of d . As displayed, either for $d = 0$ where the focal plane of pumping light almost stood with the front surface of laser crystal or for $d = \pm 2.5$ mm, the annular LG₀₁ mode always were generated and could be maintained within a large range of the pump power between 1.78–3.41 W. Thus it is worthwhile to emphasize that, with the assistance of thermal lens effect, LG₀₁-mode operation of this laser could be realized at a wide range of d and also at low pump power.

Further, Fig. 5(b) depicted the corresponding powers of laser beam as functions of incident pump power under different values of d . As seen, at different values of d , the laser powers increased linearly with pump power. For $d = 0$ the laser had an LG₀₁-mode power of 502 mW with 21.9% slope efficiency at 3.41-W pump power; for $d = 2.5$ mm the maximum LG₀₁-mode power was 426 mW with 20.7% slope efficiency; for $d = -2.5$ mm LG₀₁-

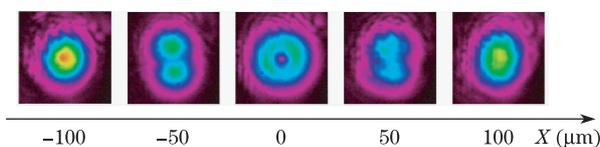


Fig. 4. Laser mode transition measured in far field when moving laser crystal laterally along the X axis. The coordinate origin was identical with the center of laser crystal's front surface.

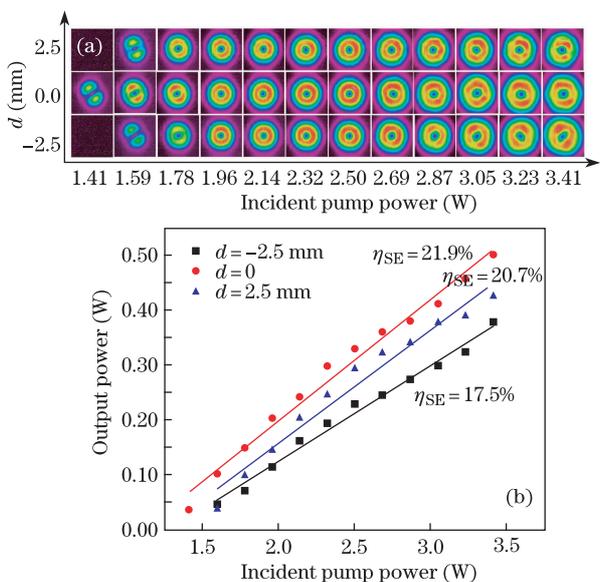


Fig. 5. (a) Intensity distributions of laser mode measured in far field and (b) laser power as functions of incident pumping power at different values of d .

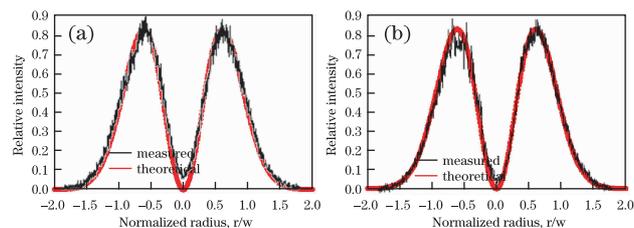


Fig. 6. Intensity distributions of the annular laser mode measured in far field along the horizontal (a) and vertical (b) axis at 2-W pump power and $d = 0$.

mode power reached 378 mW with 17.5% slope efficiency. It was clear that, when the focal plane of pumping light stood with the front surface of laser crystal, this end-pumped laser exhibited low pump threshold, high LG₀₁-mode power and high efficiency.

Figure 6 plotted the typical far-field line profiles of the annular laser mode along two orthogonal directions. As seen the doughnut distributions along these two orthogonal lines were identical to each other. Further, these measured data were also fitted respectively by using a first-order Laguerre-Gaussian function, and the results showed good agreement between the experimental and theoretical LG₀₁-mode intensity distributions. Moreover, the propagation factor- M square (M^2) of this LG₀₁ mode was measured to have the values of $M_x^2 = 2.24$ and $M_y^2 = 2.16$.

In conclusion, we report an end-pumped Nd:YVO₄ laser that generated LG₀₁-mode laser beam. This laser is simple, compact, and its LG₀₁-mode operation is stable and reproducible. The symmetrical LG₀₁-HG₀₁-TEM₀₀ mode transition observed when moving laser crystal laterally in the range of several-tens microns reveals that the thermal lens effect with centrosymmetry is possible mechanism responsible for its LG₀₁-mode operation, although a detailed and theoretical explanation is necessary in further investigation. Furthermore, this laser is potentially efficient, and also the pump power to generate LG₀₁ mode is close to the lasing threshold and thus is quite low. Without any optimization to the laser, the obtained LG₀₁ mode power reaches 502 mW and laser efficiency is $\sim 22\%$. Further optimization to this laser will yield considerable increase in both the LG₀₁-mode power and laser efficiency.

This work was supported by the National Natural Science Foundation of China (No. 61275206) and the National "973" Project of China (No. 2014CB921300).

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