Optics Communications 347 (2015) 59–63

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Actively Q-switched and vortex Nd:YAG laser

Zhiqiang Fang, Yao Yao, Kegui Xia, Jianlang Li *

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

ARTICLE INFO

Article history:
Received 31 October 2014
Received in revised form
9 February 2015
Accepted 19 February 2015
Available online 20 February 2015

Keywords:
Solid-state laser
Diode-pumped
Vortex beam
Q switch

ABSTRACT

We reported an efficient and actively Q-switched Nd:YAG laser that emitted the first order Laguerre–Gaussian mode with right-handedness helical wavefront. In the experiment, the pump light was converted into annular profile through off-focus coupling in a conventional multi-mode fiber. The laser cavity, consisting of a laser crystal and an output coupler and incorporating an acousto-optic Q switch and an etalon, was simple and compact. The Q-switched performance of the laser was given in detail.

1. Introduction

The first-order Laguerre–Gaussian (LG_{01}) mode, which is known as one solution of the paraxial wave equation, is characterized by doughnut-shaped cross section and spiral phase wavefront [1–3]. The existence of an exponential term $\exp(-im\phi)$ in its amplitude expression, where ϕ is the azimuthal angle varying from 0 to 2π and the mode index $m=1$, grants an orbit angular momentum (OAM) to the beam photon. These features make this vortex light beam valuable for numerous applications such as optical trapping and manipulation [4,5], super-resolution microscopy [6], quantum communication and information [7], material processing [8,9] and etc. And also these important applications have attracted lots of attentions to focus on the generation of such vortex beam with high power and high beam quality.

Until now, the straightforward routes to generate vortex LG modes are direct illumination of light on diffractive optical elements [10], spiral phase plate [11] or mode converter composed of cylindrical lens pairs [12], and etc. Alternatively, for the capability of scaling to high power and high brightness, LG modes can be generated directly from the laser resonator by exploiting various intracavity components, including spiral phase plate [13], thermal lensing effect [14–16], circular absorber [17,18] or spot defect mirror [19] and others inside the laser cavity.

Another efficient way to excite LG modes, especially in the laser-diode (LD) end-pumped solid-state laser, is to reshape top-hat or Guassian pump light into annular one [20–25]. This transverse shape transformation of pump light renders its efficient spatial match with the annular field distribution of LG_{01} mode inside laser crystal, and thereafter induces highly efficient excitation of LG_{01} mode. For example, by applying a capillary fiber, the pump beam was re-formatted into annular intensity distribution [22–25], and thereafter a single-frequency vortex output was obtained in Nd:YAG laser [24–26]. And also we proposed the utilization of a conventional multi-mode (MM) fiber to convert pump light into annular intensity profile under off-focus coupling, and demonstrated both continuous-wave and passively Q-switched Nd:YAG laser with radially polarized LG_{01} mode output and high laser efficiency [27,28].

In this paper, we report an actively Q-switched Nd:YAG optical vortex laser by utilizing annular-shaped pumping. The laser cavity has simple and compact plano–plano configuration. The annular pump light is originated from mode conversion in a conventional multi-mode fiber under defocal coupling. By applying such deployment, this laser emits linearly polarized LG_{01} beam with right-handedness helical wavefront.

2. Experimental setup

The experimental setup of the Q-switched laser is shown schematically in Fig. 1(a). The laser cavity is 19-cm long and is comprised of a Nd:YAG laser crystal and a plane output coupler with 5% transmission at 1064 nm. The laser crystal has a dimension of Ø10 mm × 2 mm and a 1.0 at% doping concentration of neodymium ions. Its front surface is coated for high transmission at 808 nm and total reflection at 1064 nm, and its rear surface is antireflection-coated at 1064 nm. The laser crystal is embedded into two copper plates and both copper plates had a 2-mm-

* Corresponding author.
E-mail address: apuli@siom.ac.cn (J. Li).

http://dx.doi.org/10.1016/j.optcom.2015.02.037
0030-4018/

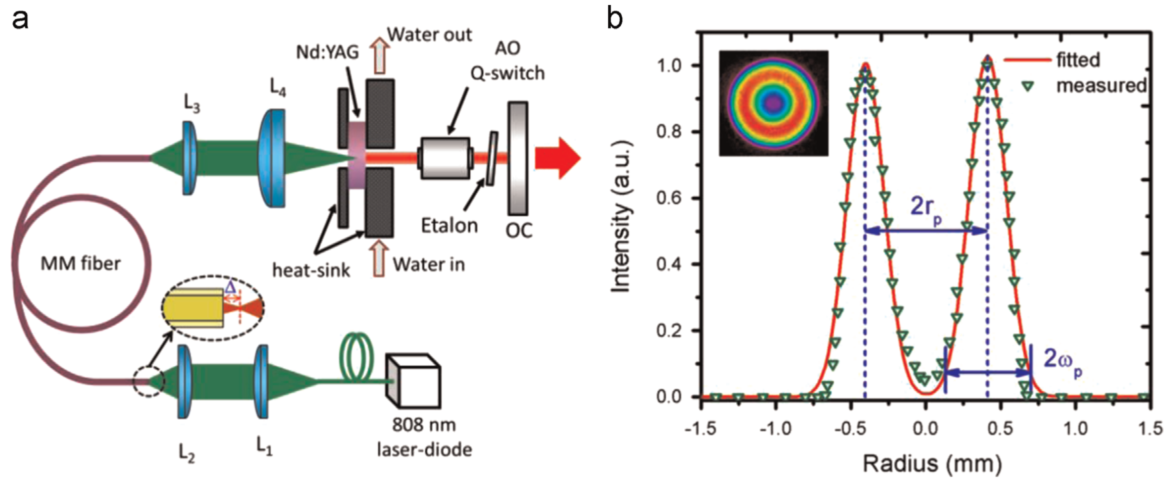

Fig. 1. (a) Experimental setup of acousto-optical Q-switched Nd:YAG laser and (b) measured and fitted line intensity profiles of pump light at L_4's focal plane when $\Delta \approx 90$ μm, in which the parameters of annular pump field r_p=0.4 mm and ω_p=247 μm, respectively. Inset: Captured intensity distribution of annular pump light.

diameter light tunnel drilled along the cavity axis. The copper plate clingy to the rear surface of Nd:YAG crystal is connected to the 23 °C water cooling. Q-switched operation of the Nd:YAG laser is achieved by utilizing a silica acousto-optic Q-switch (AOM). A 3-mm-thick glass plate is inserted into the cavity as an etalon.

To produce the annular-shaped pump beam, the light from an 808-nm laser diode (LD), coupled by a pigtail fiber with 100-μm core diameter and a numerical aperture (NA) of 0.22, is coupled into a commercial step-index MM fiber (400-μm core diameter and NA=0.37) by a pair of aspherical lenses (L_1 and L_2). The formation of annular intensity profile is realized by adjusting the distance between the focal plane of L_2 and incident port of the MM fiber, as shown in the inset of Fig. 1(a). The off-focus coupling is intended to provide a controllable spatial match of launched mode field of pump light with high-order fiber modes except for the fundamental mode. At ~90 μm defocus distance, about 89% power of pump light is coupled into the MM fiber and the intensity distribution of pump light at the fiber's rear end exhibited an annular shape with a measured conversion efficiency of 75%. The propagation factor (M^2) of obtained annular pump light is measured to be ~380. The more details on the formation of annular pump field were also described in Refs. [26,27].

The annular pump light is delivered into the laser crystal by a collimating lens L_3 and a focusing lens L_4. The intensity profile of annular pump light at the focal plane of L_4 is plotted in Fig. 1(b), in which two parameters r_p and ω_p are defined as the half distance between the two axisymmetric intensity distributions and half width of $1/e^2$ peak intensity, respectively.

3. Results and discussions

In the experiment, the laser showed stable radiation after the power of annular pump light exceeded the threshold power which was 1.9 W in the name of absorbed pump power (P_{abs}). Fig. 2 depicts the average output power of the laser as a function of absorbed pump power at five different repetition rates (k). At a given repetition rate, the average output power increased linearly with the increase of pump power, e.g. k=10 kHz, the slope efficiency of the laser was 30% and the average output power reached 810 mW at P_{abs}=4.4 W. And also the slope efficiency increased from 7.1% to 30% with the increase of repetition rate. In the present arrangement, the thickness of the laser crystal was not optimized and only ~70% pump power was absorbed. To improve the laser efficiency, a longer laser crystal can be adopted. Furthermore, the reflectivity of the OC can be optimized to enhance the energy extraction of laser cavity.

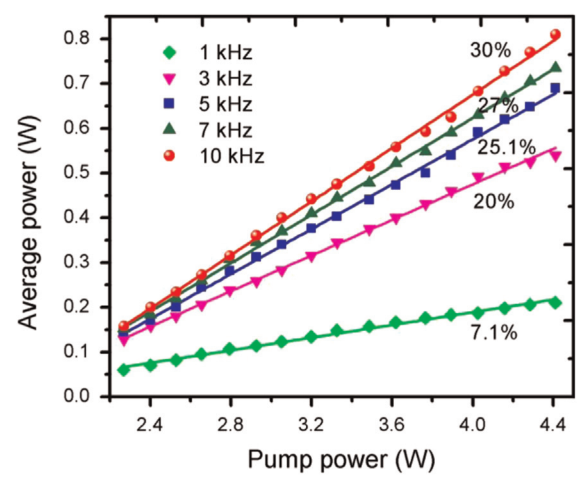

Fig. 2. Average output power as a function of absorbed pump power at different repetition rates of laser pulse.

The laser beam exhibited doughnut-shaped intensity profiles and state of linear polarization within the whole lasing range. Fig. 3(a) and (b) shows the measured far- and near-field intensity distributions of obtained laser beam at P_{abs}=4.4 W, and both of them appear to be hollow and doughnut shaped. Correspondingly, Fig. 4 plots the horizontal and vertical line profiles of laser beam at far field, in which the beam's doughnut-shaped intensity distribution with a central null intensity can be observed. These measured curves of line profiles also were fitted theoretically by using a first order Laguerre–Gaussian (LG_{01}) function, and the experimental data showed good agreements with theoretical results. Further, the propagation factor (M square, M^2) of laser beam was measured, and it was nearly unchanged in the whole pump range. Fig. 5 depicts a measured value of M^2=2.2 at 4.4-W pump power and 10-kHz frequency and was close to the theoretical M^2 value of 2 for a pure LG_{01} mode. All these results verified the laser oscillated in a pure LG_{01} mode.

The phase structure of the laser beam was measured by the interference with a spherical reference wave in a Mach–Zehnder interferometer. Fig. 6(a) shows the applied interferometer schematically. The output beam from the laser cavity was expanded by a beam expander (BE) with a pair of lenses, and then was divided