Symmetric TEM_{00} output from Q-switched quasi-concentric laser resonator with line-shaped end-pumping profile

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Abstract: We report a 12.2 W pulsed TEM_{00} output from Q-switched quasi-concentric laser resonator with line-shaped end-pumping profile, with the repetition rate of 30 kHz and optical-optical efficiency of 27.1%. The laser output mode is symmetrized in two directions in terms of beam quality, waist radius, and waist position.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched.

References and links

1. N. Hodgson, K. D. Griswold, W. A. Jordan, S. L. Knapp, A. A. Peirce, C. C. Pohalski, E. A. P. Cheng, J. Cole, D. R. Dudley, A. B. Petersen, and W. L. Nighan, Jr., "High-power TEM-mode operation of diode-pumped solid state lasers," Proc. SPIE **3611**, 119–131 (1999).
2. L. McDonagh, R. Wallenstein, R. Knappe, and A. Nebel, "High-efficiency 60 W $TEM_{(00)}$ Nd:$YVO_{(4)}$ oscillator pumped at 888 nm," Opt. Lett. **31**(22), 3297–3299 (2006), http://www.opticsinfobase.org/abstract.cfm?URI=ol-31-22-3297.
3. Q. Liu, X. Yan, X. Fu, M. Gong, and D. Wang, "183 WTEM_{00} mode acoustic-optic Q-switched MOPA laser at 850 kHz," Opt. Express **17**(7), 5636–5644 (2009), http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-17-7-5636.
4. J. Liu, C. Wang, C. Du, L. Zhu, H. Zhang, X. Meng, J. Wang, Z. Shao, and M. Jiang, "High-power actively Q-switched Nd:$GdVO_4$ laser end-pumped by a fiber-coupled diode-laser array," Opt. Commun. **188**(1-4), 155–162 (2001).
5. Y. F. Chen, T. M. Huang, C. C. Liao, Y. P. Lan, and S. C. Wang, "Efficient high-power diode-end-pumped TEM_{00} Nd:YVO_4 laser," IEEE Photon. Technol. Lett. **11**(10), 1241–1243 (1999).
6. K. Du, N. Wu, J. Xu, J. Giesekus, P. Loosen, and R. Poprawe, "Partially end-pumped Nd:YAG slab laser with a hybrid resonator," Opt. Lett. **23**(5), 370–372 (1998), http://www.opticsinfobase.org/abstract.cfm?URI=ol-23-5-370.
7. P. Shi, D. Li, H. Zhang, Y. Wang, and K. Du, "An 110 W Nd:YVO_4 slab laser with high beam quality output," Opt. Commun. **229**(1-6), 349–354 (2004).
8. K. M. Du, D. J. Li, H. L. Zhang, P. Shi, X. Y. Wei, and R. Diart, "Electro-optically Q-switched Nd:YVO_4 slab laser with a high repetition rate and a short pulse width," Opt. Lett. **28**(2), 87–89 (2003), http://www.opticsinfobase.org/abstract.cfm?uri=ol-28-2-87.
9. J. I. Mackenzie, and W. A. Clarkson, "Circular output from a high power Nd:YLF slab laser," Proc. SPIE **6871**, 68710 (2008).
10. A. Minassian, B. Thompson, and M. J. Damzen, "Ultrahigh-efficiency TEM_{00} diode-side-pumped Nd:YVO_4 laser," Appl. Phys. B **76**(4), 341–343 (2003).
11. M. Gong, Q. Wang, L. Huang, and Y. Wang, "Compact TEM_{00} Nd:YVO_4 slab laser end pumped by an LD bar," Laser Phys. **18**(7), 827–830 (2008).
12. M. Gong, X. Fu, and Q. Wang, "Determination of Thermal Lensing and Dynamic Operating Point of Quasi-concentric Laser Resonator with Line-shaped End-pumping Profile: The Influence of TEM_{00} Beam Size," IEEE J. Quantum Electron. (Accepted for publication).

1. Introduction

End-pumped solid-state laser by fiber-coupled laser-diode (LD) has widespread uses mainly because of its high intensity and good mode matching between the pump mode and laser beam [1–5]. However the configuration with fiber-coupled LDs suffers from the limit on pump power level against excessively large thermal gradient on the pump surface. In addition, the output power and pump mode distribution from the fiber is sensitive to the bend, vibration and

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replacement of the fiber, bringing in an unstable factor on the output characteristics of the solid-state laser. By contrast, the LD source with lens coupling instead of fiber coupling has the advantage of large pumping area and thus higher available pump power, low cost and insensitiveness to environment disturbances.

Researches on the solid-state laser pumped by the lens-coupled LD have realized laser outputs with high efficiency and good beam quality [6–8]. J.I. Mackenzie et al. demonstrated 50 W of near- diffraction-limited output from a Nd:YLF slab oscillator, in which the cavity mode is highly elliptical at the gain medium and has a near-unity aspect ratio at the output coupler [9]. A. Minassian et al. reported a Nd:YVO_4 laser in the bounce amplifier geometry with a line-shaped pumping profile, producing 23.1 W TEM_{00} output at the pump power of 39.5 W [10]. We reported a quasi-concentric laser resonator employing a line-shaped end-pumping profile (QRLE), in which a Nd:YVO_4 slab was pumped by a single LD bar, producing a TEM_{00} continuous-wave laser output with the output power of 15.84 W and an optical-optical efficiency of 39.6% [11]. Furthermore, we took into account the quartic phase deformation in the calculation of optical path difference due to the line-shaped pumping profile in QRLE, and obtained a nonlinear thermal effect curve describing the dependence of the thermal focal power D on the TEM_{00} mode size w_p at the thermal lens [12]. In ref. 12, dynamic operating point in QRLE was determined with both the thermal effect condition presented by the thermal effect curve and the resonator condition described by the U-shaped w_p-D curve. In addition, we confirmed the validity of stable performance of the laser working in the subcritical region at which the operating point does not satisfy $\partial w_p/\partial D = 0$. The design of QRLE demonstrates a tremendous potential in the industrial application such as the laser marking system and laser show system that require robust and compact laser source with low power and low cost.

However, the symmetry of TEM_{00} output from the configuration with a line-shaped pumping profile is not as good as that from the fiber-coupled LD case, in terms of beam quality value, waist radius, and waist position. For the high efficiency TEM_{00} output achieved from [11], as described in Fig. 1(a), both the beam quality value M^2 and beam waist radius W_0 were asymmetric in X and Y direction, as $M_x^2 = 1.15/M_y^2 = 1.41$, and $W_{0x} = 0.63$ mm/$W_{0y} = 0.40$ mm, while the beam waist positions were as well asymmetric in two directions that corresponded to an astigmatism. The asymmetric nature, which originates from the asymmetric beam quality from the LD bar without fiber coupling, would reduce the laser beam intensity and alignment precision, bringing in much inconvenience to subsequent beam shaping system and making it difficult to meet the required machining accuracy in several industrial applications such as the laser marking system and advanced manufacturing systems.

In this paper, we present the symmetrization of beam quality of QRLE, with the design method and experimental results, and report the realization of a 12.2 W highly symmetric TEM_{00} output in Q-switching operation from QRLE, with high pulse repetition rate of 30 kHz and the optical-optical efficiency of 27.1%.

2. Experimental setup

The configuration of experimental setup was similar to that presented in [11], as shown in Fig. 2. A 0.3 at. % doped Nd:YVO_4 slab was chosen as the gain medium, of which the light-pass surfaces had the dimension of 16 mm × 2 mm, antireflection coated for transmission of the pump and laser beam, while the slab thickness was 2 mm. The slab was conduction cooled on the top and bottom faces by water-cooled cooper heat sinks, and pumped by a single LD bar at the central wavelength of 808 nm, with the fast axis collimated having a maximum output power of 45 W. After the coupling lenses, the pump beam formed a focus region on the slab end surface with a line-shaped pumping profile.

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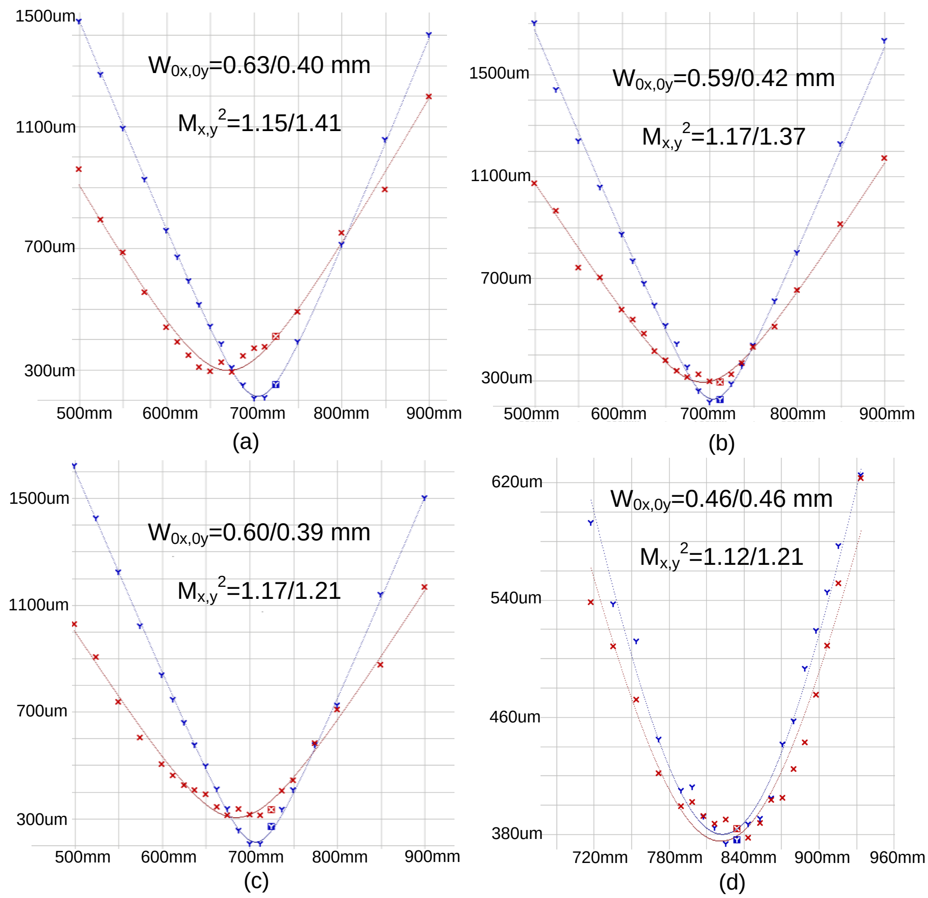

Fig. 1. The measured beam quality through the symmetrization process: (a) asymmetric beam quality, waist radius, and waist position; (b) waist position symmetrized; (c) beam quality and waist position symmetrized; (d) symmetric beam quality, waist radius, and waist position. (Horizontal axis: beam spot position; vertical axis: beam spot size)

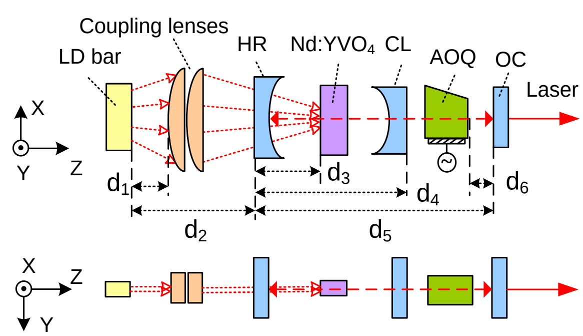

Fig. 2. Configuration of experimental setup

The resonator was built with a cylindrical high reflector (HR, radius of curvature of 110 mm in X-axis, antireflection coated at pump wavelength), a planar output coupler (OC) of 25% transmission, and a cylindrical lens (CL, focal length of –25 mm in X-axis) put within the cavity. The resonator appeared to be a quasi-concentric type in the X-Z plane, as well as a plane-plane type in the Y-Z plane. Furthermore, an acoustic-optic Q-switch (AOQ) was placed between CL and OC for Q-switching operation. The relative positions of all components of the resonator were described by d_1 to d_6 respectively, in which we set $d_3 = 5$ mm, $d_5 = 105$ mm and $d_6 = 3$ mm. It should be noted that d_4 is an important parameter to determine the TEM_{00} mode size in X direction, adjustment of which is able to realize a tradeoff between the output power and beam quality, while the mode matching in Y direction is controlled by the total cavity length [11].

3. Experimental results

The symmetrization of TEM_{00} output from QRLE was realized in three steps. First, the asymmetry of beam waist positions in X and Y direction was eliminated. In the experiment, we observed that the variation of two waist positions gradually enhanced as the pump power increased, therefore we believed that the astigmatism occurred from the variation of alignment degree of the cavity in two directions due to asymmetric thermal lensing. The resonator output coupler was finely tuned while the cooling temperature of LD source and the slab was carefully kept steady, and thus the TEM_{00} output was obtained without astigmatism as shown in Fig. 1(b).

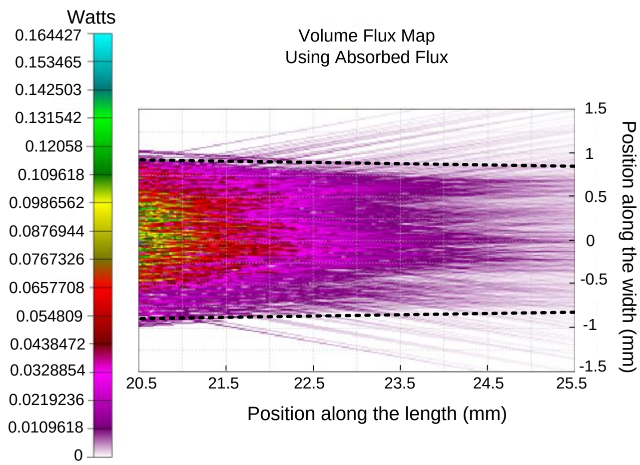

Fig. 3. Optimized mode matching between pump mode and TEM_{00} mode

Second, the beam quality value was symmetrized. $M_y^2 = 1.37$ in Fig. 1(b) was a little high compared with $M_x^2 = 1.17$ for a near-diffraction-limit output, because that the pump mode size was overlarge with respect to the beam mode size within the crystal in Y direction, due to a long distance between the LD source and slab. Thus, in order to shorten the distance for better beam quality in Y direction while maintaining the good mode matching in X direction, we redesigned the parameters of coupling lenses, using two tightly-packed cylinder lenses with the focal length of 30 mm individually to focus the pump size in X direction and setting $d_1 = 8$ mm and $d_2 = 20$ mm. The line-shaped pump region at the pump surface was around 2 mm × 0.4 mm. Figure 3 describes the absorbed pump power distribution at the slab cross section with the dimension of 9 mm × 16 mm (only the area of central 3 mm width and front 5 mm length from the pump face is shown), simulated by the ray-tracing software Tracepro, in addition to which the dash line represents the theoretical TEM_{00} mode within the slab in X direction (with the radius of around 0.9 mm), calculated based on the experimental parameters. Obviously Fig. 3 demonstrates a fairly good mode matching between the pump mode and laser mode. In this case, the beam quality value was symmetrized as $M_x^2 = 1.17/M_y^2 = 1.21$ as shown in Fig. 1(c).

Third, the waist radius size in two directions was symmetrized. Figure 4 shows the theoretical TEM_{00} mode radius in X direction at the thermal lens and at the output mirror. The intersection point between the thermal effect curve (dot line) and the U-shaped curve (square-marked line) represents the dynamic operating point of QRLE working in the subcritical

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region [12]. The CL we used in [11] has the focal length of –25 mm, corresponding to the TEM_{00} mode radius of 0.3 mm in X direction at the output mirror as predicted in Fig. 4 (as described by the intersection point between the dash line and the triangle-marked solid-line), while the mode radius in Y direction at the output mirror was estimated as 0.2 mm. The theoretical estimation had a quite good agreement with the experimental result in Fig. 1(a) (full-width of W_{0x} = 0.63 mm/W_{0y} = 0.40 mm). In order to symmetrize the waist radius, we changed the focal length of CL to –20 mm, and adjusted d_4 for the translation of U-shaped curve until the curve had the same intersection point with the thermal effect curve as the previous case. Therefore the TEM_{00} mode radius at the output mirror was reduced to 0.2 mm in X direction (as described by the intersection point between the dash line and the triangle-marked dot-line), and the waist radius of the beam output from QRLE was finally symmetrized in two directions, as shown in Fig. 1(d). The spatial forms of TEM_{00} output before and after the symmetrization of waist radius are respectively demonstrated in Fig. 5(a) and Fig. 5(b).

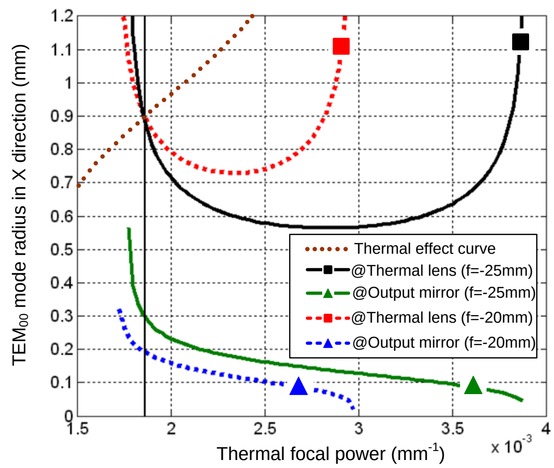

Fig. 4. Variation of operating point due to different cavity design

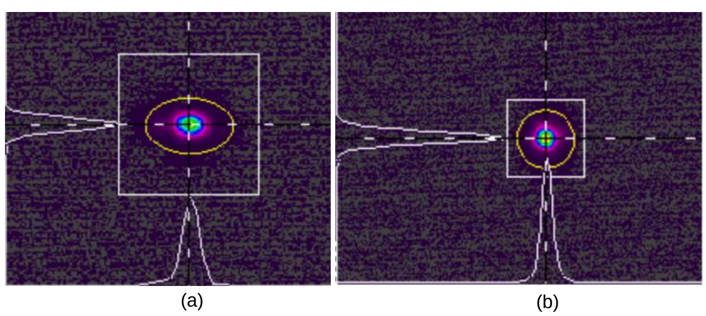

Fig. 5. Spatial form of TEM_{00} output: (a) asymmetric waist radius; (b) symmetric waist radius

With the optimized parameters of the pump system and cavity for symmetric TEM_{00} mode, 16.2 W TEM_{00} output was achieved in CW operation from QRLE at the pump power of 45 W, with the optical-optical efficiency of 36%. In addition, Q-switching operation of QRLE was carried out. The output power and pulse instability at different repetition rate are presented in Fig. 6, showing that the pulsed output has higher power but worse peak-peak stability as the pulse repetition rate increases. At the pulse repetition rate of 30 kHz, 12.2 W pulsed output was obtained at the pump power of 45 W, with the pulse duration of 14 ns (FWHM), the instability of pulse peak value <2.5%, and the optical-optical efficiency of 27.1%. The obtained laser output mode was symmetric without astigmatism, with the beam

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quality of $M_x^2 = 1.12/M_y^2 = 1.21$, and the waist radius of $W_{0x} = 0.46$ mm/$W_{0y} = 0.46$ mm, as shown in Fig. 1(d). The oscilloscope traces of pulses series and overlapping of the multi-pulses at 30 kHz are shown in Fig. 7.

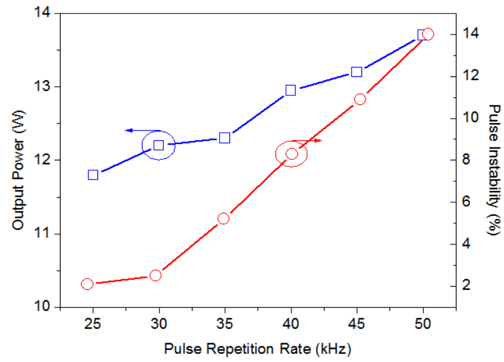

Fig. 6. Output power and pulse instability at different repetition rate

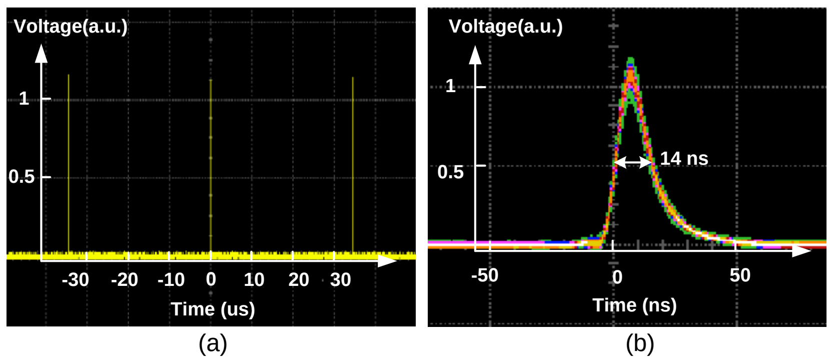

Fig. 7. Oscilloscope trace of (a) pulses series at 30 kHz (10 μs/div); (b) overlapping of the multi-pulses at 30 kHz (50 ns/div)

4. Conclusion

We symmetrize the TEM_{00} output in X and Y direction from QRLE in terms of beam quality value, waist radius size, and waist position, by optimizing and adjusting the resonator parameters. In addition, 12.2 W symmetric TEM_{00} pulsed output at the pulse repetition rate of 30 kHz was achieved at the pump power of 45 W, with the pulse duration of 14 ns (FWHM), the instability of pulse peak value <2.5%, and the optical-optical efficiency of 27.1%. The symmetric TEM_{00} pulsed output well fits the requirement of laser marking system and other industrial applications. Near-diffraction-limit beam with higher power are expected to be generated from QRLE with both-end-pumping profile, multi-slab oscillator and MOPA configuration.

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