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High power single-longitudinal-mode Ho:YLF unidirectional ring laser based on a composite structure of acousto-optic device and wave plate

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HIGHLIGHTS

- A 3.73 W Ho:YLF laser operating on single-longitudinal-mode is reported.
- Acousto-optic device and wave plate are used to achieve unidirectional operation.
- A unidirectional single-longitudinal-mode Ho:YLF ring laser is reported for the first time.

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ABSTRACT

We report a unidirectional single-longitudinal-mode Ho:YLF ring laser. An acousto-optic modulator and two half-wave plates were used to enforce the Ho:YLF ring laser in a unidirectional operation. The single-longitudinal-mode output power could reach 3.73 W successfully when the incident pump power was 16.4 W. The corresponding slope efficiency was 27.1%. The wavelength of the single-longitudinal-mode Ho:YLF ring laser was 2063.8 nm. The M^2 factor was 1.12. The results illustrated that the single-longitudinal-mode output power could be further enhanced by increasing the radio frequency power of the acousto-optic modulator.

1. Introduction

High power single-longitudinal-mode laser operation at 2 μm region has numerous applications [1–3], such as LIDAR, optical metrology, free-space communication as well as 3–12 μm generation. Traditionally, many approaches have been used to obtain single-longitudinal-mode operation [4–6], such as the microchip laser, the intracavity etalons laser, the twisted-mode-cavity and the ring laser (unidirectional ring laser and nonplanar ring laser). In order to obtain high power single-longitudinal-mode laser, the ring laser is an attractive techniques due to low insertion loss and flexibility in the choice of resonator design. Typically, in 1991, Clarkson et al. reported a single frequency Nd:YLF unidirectional laser [7]. Its maximum cw single frequency output power was 340 mW. This technique was also used to provide Q-switching of the single-longitudinal-mode operation. The highest peak Q-switched power of 6.2 kW was obtained. Pulsed systems generally achieve higher average powers which is widely used in coherent detection Doppler lidar. In 2004, Shen et al. reported a unidirectional operation of Ho:YAG ring laser by using an acousto-optic device [8]. The maximum single-longitudinal-mode power reached 3.7 W. In 2008, our group demonstrated a high power single-longitudinal-mode Ho:YAG nonplanar ring laser at 2.09 μm [9]. In 2013, Wang et al. reported a single-longitudinal-mode Ho:YAG nonplanar ring laser at 2122 nm [10].

The nonplanar ring laser could produce high power single-longitudinal-mode laser, however, the nonplanar ring laser was only available to the isotropic gain medium, which limit their application scope. The unidirectional ring laser based on an acousto-optic device [11] addresses this matter. Meanwhile, the longer cavity length made the unidirectional ring laser to produce narrower linewidth laser compare to other nonplanar ring lasers. However, the longer unidirectional ring cavity length, the larger threshold pump power, so the unidirectional ring laser needs much more pump power to achieve high power single-longitudinal-mode laser. Because of the limit of the radio frequency power of the acousto-optic device, the unidirectional ring laser cannot operate in a unidirectional mode when the pump power was high enough, therefore, the high power single-longitudinal-mode laser will not come true. For the sake of resolve this problem, one way is to utilize the feature that the acousto-optic device has different

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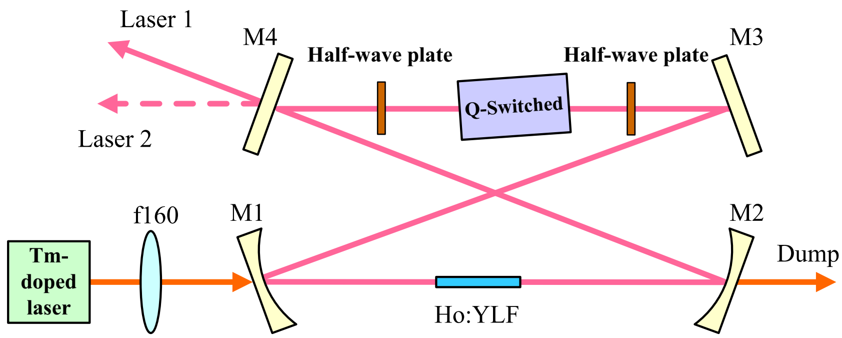

Fig. 1. The schematic of single-longitudinal-mode Ho:YLF unidirectional ring laser.

diffraction losses for different polarizations beam. In the ring laser, the polarization direction of the counter-propagating beam passed through an acoustic-optic device is changed by using two half-wave plates placed on both sides of the acoustic-optic device. Two half-wave plates change the polarization of two direction respectively. The change of polarization direction of the counter-propagating beam results in an increasing loss difference between the counter-propagating beam, which can enhance the maximum pump power of the ring laser operated in unidirectional mode. Accordingly, this technique makes it possible to achieve high power and narrow linewidth single-longitudinal-mode laser output simultaneously.

In this paper, we utilize an acousto-optic modulator with different diffraction losses for different polarizations and two half-wave plates to realize the unidirectional single-longitudinal-mode operation of Ho:YLF ring laser with the cavity length of 1.38 m, which allowed narrower linewidth output. Compared to the Ho:YAG, the emission spectra of Ho:YLF laser is narrower which is helpful to obtain the single-longitudinal-mode output. As we know, this is the first time the polarization dependent diffraction loss has been utilized to increase the directional loss differences.

2. Experimental setup

The schematic of the single-longitudinal-mode Ho:YLF unidirectional ring laser is shown in Fig. 1. The pump source was an 18 W Tm-doped laser at 1.938 μm and focused by a plane convex lens (f = 160 mm). The Ho:YLF crystal was adopted as laser gain medium due to the nature of birefringence and the laser was linearly polarized [12,13]. This is due to the property of the acousto-optic modulator used in this experiment. The Ho:YLF crystal was a-cut. The spot size was around 200 μm in the Ho:YLF crystal that doped with 0.5 at.% and the dimensions of 4 × 4 mm^2 at cross section and 50 mm at length. The crystal was keep at 13 °C by a TEC cooler. The resonator was a 1.38 m bow-tie ring resonator. M_1 and M_2 were both plane concave mirror with a curvature radius of 400 mm and 300 mm, respectively, and coated for high reflectivity at 2.1 μm (R > 99.8%) and high transmittance (T > 99.9%) at 1.9 μm. M_3 was a plane mirror and coated for high reflectivity at 2.1 μm (R > 99.8%). M_4 was a plane output coupler with a transmittance of 15% at 2.1 μm.

An acousto-optic modulator (Gooch & Housego, QS041-10M-H18) can completely hold off vertical polarization oscillation. For other polarization beam, the acousto-optic modulator cannot be hold off. The maximum radio frequency power of the acousto-optic modulator was 50 W. The acousto-optic modulator was adjusted to be tilted slightly away from the Bragg angle and that the opposite lasing could experience different diffraction losses. In order to increasing the diffraction losses in one direction, two half-wave plates were inserted into the cavity. The right half-wave plate converted the horizontal polarization beam into vertical polarization, which could be held off by the acousto-optic modulator. Then the laser 2 direction had no laser output. By adjusting the left half-wave plate, the laser 1 direction could not be held off by the acousto-optic modulator and the unidirectional operation was realized.

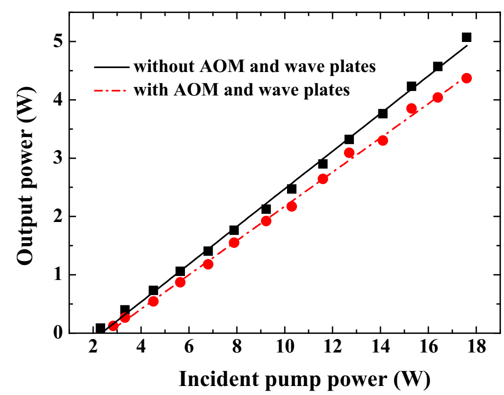

Fig. 2. The output power of the bidirectionally Ho:YLF ring laser.

3. Experimental results and discussion

A cw free-running (without the acousto-optic modulator (AOM) and two half-wave plates) Ho:YLF ring laser was first investigated, shown as the black solid line in Fig. 2. The Ho:YLF laser operated bidirectionally and the maximum combined output power was 5.07 W under the incident pump power of 17.6 W and the threshold power was 2.31 W. The corresponding slope efficiency was 32.3% and the optical-to-optical conversion efficiency was 28.8%. The polarization direction of the free-running laser was horizontal polarization. In this experiment, only an acousto-optic modulator inserted into the cavity could not achieve unidirectional operation. Even though output power of the two directions had a large difference, the single-longitudinal-mode operation was not observed. This result is different from the former research (such as Ref. [8]), which may be attributed to the different material of the acousto-optic modulator. When the acousto-optic modulator (with no radio frequency power applied) and two half-wave plates were inserted into the cavity, the output power was shown as the red dashed line in Fig. 2. The maximum combined output power was 4.37 W under the same pump power and the threshold power was 2.84 W. The corresponding slope efficiency was 29.4% and the optical-to-optical conversion efficiency was 24.8%. The threshold became slightly higher and the slope efficiency became lower, which can be mainly caused by the insertion loss of the acousto-optic modulator.

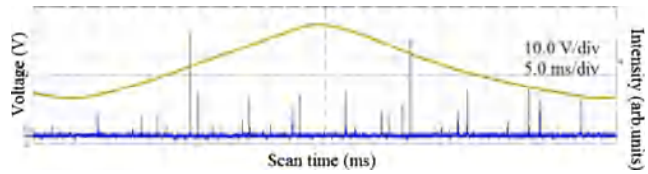

Fig. 3. The F-P spectra of the bidirectionally Ho:YLF ring laser.

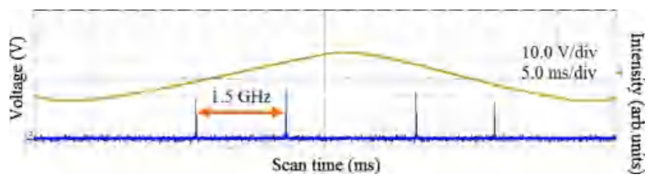

Fig. 4. The F-P spectra of unidirectional operation of the Ho:YLF ring laser.

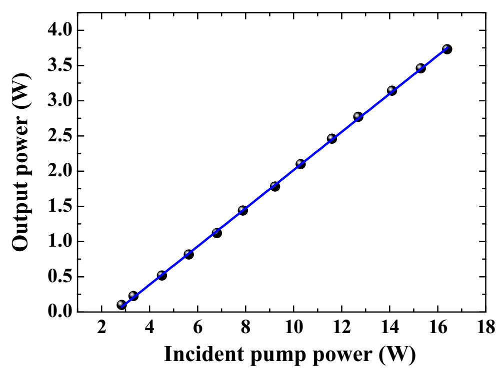

Fig. 5. The output power of the single-longitudinal-mode Ho:YLF ring laser.

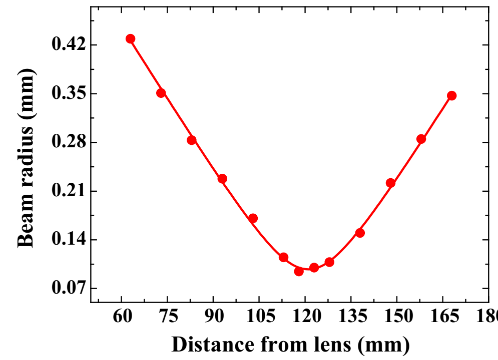

Fig. 6. The beam quality of the single-longitudinal-mode Ho:YLF ring laser.

Table 1
The maximum single-longitudinal-mode output power under different radio frequency power.

Radio frequency power (W)	Pump power (W)	Output power (W)
30	9.23	1.83
35	11.6	2.53
40	13.4	2.99
45	14.7	3.3
50	16.4	3.73

Fig. 3 shows the F-P spectra of the bidirectionally Ho:YLF ring laser measured by a Fabry-Perot (F-P) interferometer (SA200-18B, 1.5 GHz free spectral range). The yellow[1] line means the PZT's driving voltage of Fabry-Perot interferometer and the blue line is the longitudinal-modes. The results show that the laser operated at multimode oscillation. The output wavelength of the bidirectionally Ho:YLF ring laser measured by a wavemeter (Bristol, 0.7 pm resolution) and the center wavelength was 2065.3 nm.

To achieve unidirectional operation of the Ho:YLF ring laser, 50 W radio frequency power was applied to the acousto-optic modulator and the Ho:YLF ring laser operated at single-longitudinal-mode oscillation. The Fig. 4 is the F-P spectra of unidirectional operation of the Ho:YLF ring laser. Only two peaks appeared over the 1.5 GHz free spectral range and the laser was running on single-longitudinal-mode. Fig. 5 shows the output power of the single-longitudinal-mode Ho:YLF ring laser. The maximum single-longitudinal-mode output power was 3.73 W under the incident pump power of 16.4 W and the threshold power was around 2.84 W. The corresponding slope efficiency was 27.1% and the optical-to-optical conversion efficiency was 22.7%. Polarization of the output laser was horizontal which was measured by the Glan prism.

The center wavelength of the single-longitudinal-mode Ho:YLF ring laser was 2063.8 nm, which was different from the bidirectionally Ho:YLF ring laser and this could be attributed to the difference in the optical path in two cases. Fig. 6 shows the beam quality of the unidirectional operation of the Ho:YLF ring laser which was measured by knife-edge method. By non-linear data fitting, we can know that the M^2 was 1.12.

The maximum single-longitudinal-mode output power under different radio frequency power was also investigated, shown in Table 1. As can be seen, with the increasing of the radio frequency power, the maximum single-longitudinal-mode output power became higher, and the threshold power almost remained the same, indicating that the higher single-longitudinal-mode power could be obtained with higher radio frequency power.

4. Conclusion

In this paper, we reported a single-longitudinal-mode Ho:YLF ring laser based on an acousto-optic modulator and two half-wave plates. Unidirectional operation of Ho:YLF ring laser was obtained by increasing the different diffraction loss between counter-propagating beams. The maximum single-longitudinal-mode output power was 3.73 W under the pump power of 16.4 W. Wavelength of the single-longitudinal-mode Ho:YLF ring laser was 2063.8 nm. The results show that this technique can realize 2 μm high power and narrow linewidth single-longitudinal-mode laser.

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References

[1] F. Gibert, D. Edouart, C. Cénac, F.L. Mounier, 2 μm high-power multiple-frequency single-mode Q-switched Ho: YLF laser for DIAL application, Appl. Phys. B 116 (2014) 967–976.

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

[2] F. Gibert, D. Edouart, C. Cénac, F.L. Mounier, A. Dumas, 2-μm Ho emitter-based coherent DIAL for CO_2 profiling in the atmosphere, Opt. Lett. 40 (2015) 3093–3096.
[3] Y.X. Bai, J.R. Yu, P. Petzar, M. Petros, S.S. Chen, B. Trieu, H. Lee, U. Singh, Single longitudinal mode, high repetition rate, Q-switched Ho: YLF laser for remote sensing, in: Conference on Lasers and Electro-Optics, Optical Society of America, 2009, CWH5.
[4] C. He, D.K. Killinger, Dual-polarization modes and self-heterodyne noise in a single-frequency 2.1-μm microchip Ho, Tm:YAG laser, Opt. Lett. 19 (1994) 396–398.
[5] C. Gao, R. Wang, Z. Lin, M. Gao, L. Zhu, Y. Zheng, Y. Zhang, 2 μm single-frequency Tm:YAG laser generated from a diode-pumped L-shaped twisted mode cavity, Appl. Phys. B 107 (2012) 67–70.
[6] J. Wu, Y.L. Ju, T.Y. Dai, Z.G. Zhang, B.Q. Yao, Y.Z. Wang, Development of a single-longitudinal-mode Ho:YAG laser based on corner cube, Chin. Phys. Lett. 33 (2016) 044203.
[7] W.A. Clarkson, D.C. Hanna, Single-frequency Q-switched operation of a diode-pumped Nd:YLF ring laser, Opt. Commun. 84 (1991) 51–54.
[8] D.Y. Shen, W.A. Clarkson, L.J. Cooper, R.B. Williams, Efficient single-axial-mode operation of a Ho:YAG ring laser pumped by a Tm-doped silica fiber laser, Opt. Lett. 29 (2004) 2396–2398.
[9] B.Q. Yao, X.M. Duan, D. Fang, Y.J. Zhang, L. Ke, Y.L. Ju, Y.Z. Wang, G.J. Zhao, 7.3 W of single-frequency output power at 2.09 μm from an Ho:YAG monolithic nonplanar ring laser, Opt. Lett. 33 (2008) 2161–2163.
[10] L. Wang, C.Q. Gao, M.W. Gao, Y. Li, Resonantly pumped monolithic nonplanar Ho:YAG ring laser with high-power single-frequency laser output at 2122 nm, Opt. Exp. 21 (2013) 9541–9546.
[11] W.A. Clarkson, A.B. Neilson, D.C. Hanna, Unidirectional operation of ring lasers via the acoustooptic effect, IEEE J. Quantum Elect. 32 (1996) 311–325.
[12] W. Koen, C. Bollig, H. Strauss, M. Schellhorn, C. Jacobs, M.J.D. Esser, Compact fibre-laser-pumped Ho:YLF oscillator-amplifier system, Appl. Phys. B 99 (2010) 101–106.
[13] H.J. Strauss, D. Preussler, M.J.D. Esser, W. Koen, C. Jacobs, O.J.P. Collett, C. Bollig, 330 mJ single-frequency Ho:YLF slab amplifier, Opt. Lett. 38 (2013) 1022–1024.