High power single-longitudinal-mode Ho^{3+} :YVO₄ unidirectional ring laser

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We demonstrate a single-longitudinal-mode Ho^{3+} :YVO₄ unidirectional ring laser based on the acousto-optic effect, utilizing the features of the acousto-optical Q switch and half-wave plate to achieve unidirectional operation. The maximum power achieved in the single-longitudinal-mode at 2053.9 nm is 941 mW when the absorbed power is set as 4.4 W, yielding a nearly 50% slope efficiency. The M^2 factor is 1.1. The results show that such a technique offers a potentially promising new method for achieving a high power and narrow linewidth 2 µm single-longitudinal-mode laser.

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A 2 µm single-longitudinal-mode laser has the characteristics of eye safety and good transparency in the atmosphere. It has important applications in the areas of laser lidar, high resolution spectroscopy, and achieving $3-12 \ \mu m \ lasers^{[1,2]}$. So far, many configurations have been applied to achieve the single-longitudinal-mode lasers near $2 \ \mu m$, such as the coupled cavity laser^[3], twisted-modecavity laser^[4], the microchip laser^[5], the nonplanar ring laser, the intracavity etalons laser⁶, etc. Among them, the nonplanar ring laser^[7,8]</sup> and twisted-mode-cavity laser^{<math>[9]}</sup></sup> are two common ways to obtain high power singlelongitudinal-mode operation, while they are applicable to only isotropic gain medium and are difficult for achieving single-longitudinal-mode operation with a long cavity length, which result in limiting the narrower linewidth output. Instead, a unidirectional ring laser utilizing the feature that the acousto-optic (AO) device has for different diffraction losses for different polarization beams can resolve the aforementioned issue. The unidirectional ring laser realized by the AO technique has the advantage of a long cavity design and a low insertion loss, which makes it possible to achieve a narrow linewidth and high power output simultaneously. In addition, this technique also has a wide spectral operating range and can be used to produce Q-switching of the single-frequency output^[10]. A $2 \ \mu m$ single-longitudinal-mode laser is used for the lidar system, where the improvement of these two characteristics will enhance the performance (resolution, detection range, and precision) of the whole lidar system. In earlier years, the unidirectional Nd^{3+} -doped ring lasers at 1 μm were demonstrated. In 1991, Clarkson and Hanna reported an Nd:YAG laser, which has a 32 mm long resonator^[11]. A travelling-wave AO Q switch is inserted in a simple standing-wave resonator, and its maximum single frequency power is 100 mW. In the same year, they used the same method to construct a unidirectional operation of an Nd:YLF ring laser^[12] with a maximum output power

of 340 mW. Yet, the output characteristics of single-longitudinal-mode ring lasers at 2 µm are rarely investigated. In 2004, Shen *et al.* reported an Ho:YAG ring laser with a short cavity length (536 mm) in which a travelling-wave TeO₂ AO modulator (AOM) is used to acquire unidirectional oscillation^[13]. However, to realize a narrower linewidth output of 2 μ m, the longer cavity length is needed, which leads to the increase of the longitudinal mode numbers and threshold pump power. Finally, the higher radio frequency (RF) power of the AO device is required. An effective method for solving this problem is to use two half-wave plates. Two half-wave plates placed on either side of the AO device are used to increase the loss difference between the counter-propagate beam, and the diffraction efficiency is improved. Combined with the feature of the AO Q switch, the ring laser can easily realize unidirectional single-longitudinal-mode operation.

In this Letter, we introduce a new method and results for the unidirectional operation of a single-longitudinalmode Ho:YVO₄ unidirectional ring laser with an AO Qswitch and two half-wave plates. An Ho:YVO₄ birefringent crystal used as the laser gain medium for its stabilized chemical properties, good mechanical properties, large laser emission cross-section, and high thermal conductivity, which allowed for the high efficiency of the singlelongitudinal-mode operation. The highest singlelongitudinal-mode power is 941 mW with an absorbed power of 4.4 W, and the slope efficiency reached is 50%. To our knowledge, this is the first time the polarization dependent diffraction loss has been exploited in order to increase the directional loss differences of a 2 μ m laser.

Figure <u>1</u> depicts the experimental layout of the singlelongitudinal-mode Ho^{3+} :YVO₄ unidirectional ring laser. The pump source used is a 1938 nm Tm:YAP laser, which has a maximum power of about 18 W with an M^2 factor of ~1.6. The pump beam has a horizontal polarization. It is focused by a plane convex lens with a 160 mm focal length



Fig. 1. Layout of the $Ho:YVO_4$ unidirectional ring laser.

and plane concave mirror M1. At the location of the Ho:YVO₄ crystal, the beam radius in the x and y directions were about 100 and 103 μ m, respectively. The total length of the ring cavity is 1.38 m, consisting of four mirrors. Plane concave mirrors M1 and M2 are both coated for high reflectivity at 2.05 μ m and high transmission at $1.94 \ \mu m$ with a curvature radius of 400 and 300 mm, respectively. Planar mirror M3 is coated with a high reflection coating at $2.05 \ \mu m$ and a high transmission at $1.94 \mu m$. Planar mirror M4 has a transmissivity of 15%at the laser wavelength. The angle between the M2–M4 arm and the M3–M4 arm is 20°. The laser gain medium is an A-cut Ho:YVO₄ crystal with dimensions of 3 mm \times $3 \text{ mm} \times 20 \text{ mm}$ and a dopant concentration of 0.6 at.%. The coated ends of the crystal ensure the high transmittance at 1.94 and 2.05 μ m. With the increase of pump power, the absorption efficiency of the $Ho:YVO_4$ crystal is gradually decreased due to the ground state loss. The single-pass absorption is only 25.6% when the incident pump power is 17.6 W. The Ho:YVO₄ crystal is placed to insure lasing on the horizontal polarization. In order to avoid the effects of astigmatism, we select the optimal parameters of the resonator to make the mode in the tangential and sagittal planes almost the same, even under the different thermal focal lens of the $Ho:YVO_4$ crystal. When the thermal focal lens of the $Ho:YVO_4$ crystal ranged from 200 to 1000 mm, the beam radius of tangential and sagittal planes at the location of the $Ho:YVO_4$ crystal kept within 0.18–0.184 mm, and the location of the beam waist remained almost the same. This design is helpful for the pump mode matching and TEM_{00} mode laser output.

An AO Q switch (Gooch and Housego, QS041-10M-H18) and two half-wave plates are inserted into the resonator to enforce the unidirectional operation. The material of the Q switch is crystal quartz with a transmission of 99.6% at $2.05 \,\mu\text{m}$. The rated RF power is 50 W with an RF of 40.68 MHz. The diffraction efficiency of the AO Q switch is different for different input polarization states, and the vertical oscillation can be completely cut off by the AO Q switch. The AO Q switch is adjusted to be tilted slightly away from the Bragg angle, and so that the opposite direction lasing can suffer different diffraction losses. Two half-wave plates are used to make the polarization state of counter-propagating beams different in the AO Q switch. The angle between the optical platform and the fast axis of the left half-wave plate (see Fig. 1) is 45° . In the clockwise direction, the horizontal polarization emitted by the Ho:YVO₄ crystal can be converted to vertical polarization by the left half-wave plate, and the vertical oscillation can be completely cut off by the AO Q switch, whereas in the counterclockwise direction there will be combination of polarization states, which is dependant on the right half-wave plate angle. By regulating the angle of the right half-wave plate carefully, the beam in this direction cannot be cut off by the AO Q switch. Then, the unidirectional operation can be observed.

When the AO Q switch (AOM) and two half-wave plates were removed from the cavity, the Ho:YVO₄ laser was ran in bidirectional mode. The output power of the bidirectional laser is given in Fig. 2. Figure 2(a) shows the output power as a function of the pump power. Without the AOM and plates, the maximum power is 1.6 W with the pump power of 17.6 W, and the slope efficiency is 14.5%. The insertion loss of the AO Q switch is about 11%. With the AOM and plates inserted, the maximum power is 1.14 W under the pump power of 17.6 W, corresponding to a slope efficiency of 11.1%. Considering the pump power losses (including the losses of coating) and the unabsorbed pump power, the output power versus the absorbed pump power is given in Fig. 2(b). Shown as the black dotted line in Fig. 2(b), the maximum power is 1.6 W under the absorbed power of 4.5 W, and the threshold power is 2.68 W. With the AOM and two half-wave plates inserted into the cavity, the maximum power is 1.14 W when the absorbed power is set as 4.5 W, and the slope efficiency achieves 54%, shown as the red solid line in Fig. 2. The output power becomes lower because of the insertion losses induced by the AO Q switch. In Fig. 3,



Fig. 2. Output power of the bidirectional ${\rm Ho:}{\rm YVO}_4$ laser versus the pump power.



Fig. 3. Wavelength of the bidirectional $Ho:YVO_4$ laser.

the wavelength is located on 2052.0 nm recorded by a wavemeter (Bristol, 0.7 pm resolution).

The output longitudinal mode of the bidirectional Ho:YVO₄ laser was measured by a Fabry–Perot scanning interferometer [Thorlabs, SA200-18B, 1.5 GHz free spectral range (FSR)]. Shown in Fig. <u>4</u>, the yellow line is the driving voltage of a piezo actuator, and the blue line is the intensity of the longitudinal modes. Many modes are visible and the multi-mode oscillations are chaotic.

When the RF power (almost 50 W) was applied to the AO Q switch, the possible single-longitudinal-mode operation was monitored by the Fabry–Perot scanning interferometer. The laser longitudinal mode was measured by the same Fabry–Perot scanning interferometer and displayed by a digital oscilloscope (LeCory, WaveSurfer, $64 \times s$, 600 MHz bandwidth). The Fabry–Perot spectrum was periodically repeated in the oscilloscope. Figure <u>5</u> is the time behavior of the laser spectrum spanning 50 ms. As displayed in Fig. <u>5</u>, the two peaks are separated by the 1.5 GHz FSR, and the unidirectional Ho:YVO₄ laser had only one longitudinal mode.



Fig. 4. Fabry–Perot spectrum of the bidirectional $\mathrm{Ho:}\mathrm{YVO}_4$ laser.



Fig. 5. Fabry–Perot spectrum of the single-longitudinal-mode $\rm Ho: YVO_4$ unidirectional ring laser.

Single-longitudinal-mode power of the unidirectional Ho:YVO₄ laser is displayed in Fig. 6. Figure 6(a) shows that the maximum output power is 941 mW at the pump power of 17 W, and the slope efficiency is 10.2%. Shown as Fig. 6(b), the threshold power is about 2.68 W, and the maximum power at the absorbed pump power of 4.4 W is about 941 mW. The slope efficiency reaches 50%. Figure 7 shows the spectra of this unidirectional Ho:YVO₄ laser, and the wavelength of 2053.9 nm was observed by the wavemeter. The output wavelength is different from the bidirectionally Ho:YVO₄ laser, and this may be caused by the differences originating from the measured errors and nonlinear loss of the AOM for different wavelengths. The knife-edge method is used to measure the beam quality factor M^2 . Figure 8 shows the beam radius versus the distance from the lens. The M^2 of 1.1 is obtained by nonlinearly fitting the measured data. When the RF power was 30 W, the maximum unidirectional singlelongitudinal-mode power was only 92 mW under the absorbed pump power of 2.78 W. The RF power in this Letter is much larger (compared with those published earlier), which may be attributed to the differences in material and the size of the AO Q switch. The results indicate that the higher single-longitudinal-mode power could be obtained with higher RF power.

In conclusion, we report a single-longitudinal-mode Ho^{3+} :YVO₄ ring laser based on the AO effect. An AOM and two half-wave plates are used to achieve unidirectional operation. The highest single-longitudinal-mode power of 941 mW at 2053.9 nm is obtained, and the slope



Fig. 6. Output power of the single-longitudinal-mode ${\rm Ho:}{\rm YVO}_4$ unidirectional ring laser.



Fig. 7. Wavelength of the single-longitudinal-mode ${\rm Ho:}{\rm YVO}_4$ unidirectional ring laser.



Fig. 8. Beam radius versus the distance from the focusing lens.

efficiency is 50%. The M^2 factor is 1.1. The results illustrate that this technique can realize high power single-longitudinal-mode output at $\sim 2 \ \mu m$.

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