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# A Q-switched Ho:YAG laser with double anti-misalignment corner cubes pumped by a diode-pumped Tm:YLF laser

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## HIGHLIGHTS

- The Ho:YAG laser with double corner cubes was anti-misalignment.
- The transmission of laser cavity could be changed by rotating quarter-wave plate.
- The output energy was 9.9 mJ, with pulse width of 53 ns and PRF of 100 Hz.

## ARTICLE INFO

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## ABSTRACT

We report the acousto-optically Q-switched Ho:YAG laser with double anti-misalignment corner cubes pumped by a diode-pumped Tm:YLF laser. In the continuous-wave operation of Ho:YAG laser, the maximum s-polarized output power of 3.2 W at 2090.3 nm was obtained under the absorbed pump power of 12.9 W by rotating the fast axis of quarter-wave plate to change the output transmission of laser cavity. The corresponding optical-to-optical conversion efficiency was 24.8% and the slope efficiency was 55.7%. When one of the corner cubes was rotated to 11.8° around vertical direction or 6.7° around horizontal direction, the laser could still operate stably. For the Q-switched operation, the pulse energy of Ho:YAG laser was 9.9 mJ with a pulse width of 53 ns at the repetition rate of 100 Hz, resulting in a peak power of 186.8 kW. The beam quality factor $M^2$ of Ho:YAG laser was 1.3.



## 1. Introduction

Solid state lasers operating at 2 µm eye-safe spectral region have attracted considerable attention in a variety of applications, including differential absorption lidar (DIAL) measurements of $CO_2$ and $H_2O$ [1], coherent Doppler lidar [2], medicine [3,4] and pumping the optical parametric oscillators (OPOs) [5]. Ho-doped crystals are attractive materials to generate 2 µm high-energy lasers because their emission cross sections are much higher than Tm-doped crystals. [6,7] However, Ho-doped crystal cannot be pumped by 790 nm semiconductor lasers directly. A common way to overcome this shortage is to use Tm and Ho co-doped crystals. But, Tm and Ho co-doped systems have reduced effective upper-state lifetimes and energy storage efficiencies, and increased thermal load of the crystal due to the deleterious effect of up-conversion losses at high pump level and reverse transfer between the excited $^3F_4$ and $^5I_7$ states of Tm and Ho respectively [8,9]. With the rapid development of high power Tm-doped laser, the Ho-doped laser pumped by Tm-doped laser can overcome most of difficulties of Tm and Ho co-doped systems. Ho:YAG is an attractive material to generate 2 µm lasers due to its excellent thermal and mechanical properties [10]. In addition, Ho:YAG crystal is more capable to generate high energy pulse because of the large stimulated emission cross section and long upper state lifetime of $Ho^{3+}$.

In engineering applications, strong anti-misalignment, good output performance and small volume of a laser is needed. The insensitivity to angular position, impact and temperature of corner cubes makes them attractive as an anti-misalignment retroreflector [11]. The incident light on the corner cube from an arbitrary direction can be returned in the direction that is counter-parallel to the incident beam. This property makes the corner cube cavity insensitive to misalignment at any azimuthal angles [12,13]. Therefore, the corner cubes could be employed in semiconductor and solid state lasers as laser cavities. In 2000, K.Y. Wu et al. reported a single-frequency Nd:YAG laser by using corner cube prism. The single-frequency output power of 100 mW was obtained when the pump power was 15 W [14]. In 2006, W.Q. Gao proposed a passively Q-switched Nd:YAG laser with corner cube. By rotating the angle of corner cube, the pulse energy chan-

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ged from 159.5 mJ to 174.4 mJ and the fluctuation of pulse width was 2.95 ns [11]. In 2013, Y. Cheng demonstrated coherent combination of six solid state lasers by using a corner cube. The combining efficiency of 95.6% was achieved when the combining output energy was 15.3 J [15]. However, the structure of double anti-misalignment corner cubes at 2 μm has not been applied in laser cavities.

In this paper, we report a linearly polarized Q-switched Ho:YAG laser with double anti-misalignment corner cubes pumped by a 1908 nm Tm:YLF laser. Two polarizers with high transmission for p-polarized light and high reflectivity for s-polarized light at the laser wavelength were utilized to obtain s-polarized laser output. The transmission of Ho:YAG laser cavity could be changed by rotating the quarter-wave plate [16]. A maximum s-polarized laser output power of 3.2 W was achieved when the absorbed pump power was 12.9 W. When one of the corner cubes was rotated to 11.8° around vertical direction or 6.7° around horizontal direction, the Ho:YAG laser could still operate stably. The output energy of Q-switched Ho:YAG laser was 9.9 mJ, with a pulse width of 53 ns and a repetition frequency of 100 Hz. The beam quality factor $M^2$ of Ho:YAG laser was 1.3.

## 2. Experimental setup

The experimental configuration of Q-switched Ho:YAG laser with double anti-misalignment corner cubes was shown in Fig. 1. The pump source was a 1908 nm Tm:YLF solid state laser with a maximum output power of 30.6 W. The laser from pump source was collimated in Ho:YAG crystal with a beam radius of 0.35 mm. The dimension of Ho:YAG rod was 45 mm long and 4 mm in diameter. The doped concentration of $Ho^{3+}$ was 0.5 at.%. The Ho:YAG rod was wrapped indium foil and installed on a copper heat sink bonded on a thermoelectric cooler (TEC) to control the temperature at 288 K precisely. Both sides of the crystal were coated with antireflection (AR) coatings at 1.9 μm and 2.1 μm. The mirror $f_2$ and mirror $f_5$ were both plane convex mirrors with focal length of 240 mm. The mirror $f_3$ and mirror $f_4$ were both plane concave mirrors with curvature radius of 75 mm. Mirrors $f_2$, $f_3$, $f_4$ and $f_5$ were placed symmetrically to compensate the thermal lensing effect of Ho:YAG laser and increase the spot size of resonant laser in the location of polarizer $TFP_1$ and polarizer $TFP_2$ to avoid damage them under Q-switched operation. The material of two corner cube prisms was JGS3 with a diameter of 40 mm and a height of 35 mm. The incident surface of corner cube was coated with high transmission coating at 2.1 μm. The three reflecting surfaces of corner cube were uncoated and the accuracy of three orthogonal angles was ±2″. The total cavity length was about 1.13 m. An acousto-optic modulator (GOOCH & HOUSEG Company, QS041-10M-HI8) was inserted into the cavity to generate Q-switched operation. The maximum radio-frequency (RF) power of the acousto-optic Q-switch was 50 W. Two polarizers $TFP_1$ and $TFP_2$ were considered as output coupler coated with high reflectivity coating at 1.9 μm, and high reflectivity coating for s-polarized light and high transmission coating for p-polarized light at 2.1 μm. The quarter-wave plate coated with high transmission coating at 1.9–2.1 μm was inserted to change the output transmission of the whole resonant cavity. The Q-switched Ho:YAG laser had a ring resonant cavity, which was convenient for the next injection-seeding due to its bidirectional output. Moreover, the Q-switched laser with small volume and strong anti-alignment was necessary for the transmitter of differential absorption lidar (DIAL).

## 3. Experimental results and discussion

In the continuous-wave operation of Ho:YAG laser, the total bidirectional output power as a function of absorbed pump power was shown in Fig. 2. The power meter used in the experiment was a Coherent PowerMax. The maximum output power of 3.2 W was obtained when the absorbed pump power was 12.9 W, corresponding to the optical-to-optical conversion efficiency of 24.8% and the slope efficiency of 55.7%. The output power could be changed by rotating the quarter-wave plate because the polarization state of oscillating laser in the cavity was changed. So, the optimal output transmission of the Ho:YAG laser with double anti-misalignment corner cubes could be found by rotating the quarter-wave plate. When the absorbed pump power was 12.9 W, the output power from two polarizers under different rotating angles of quarter-wave plate was shown in Table 1. Under the initial condition, the fast axis of quarter-wave plate was in the vertical direction.

To prove the anti-misalignment property of corner cubes, the right corner cube was rotated around horizontal and vertical direc-

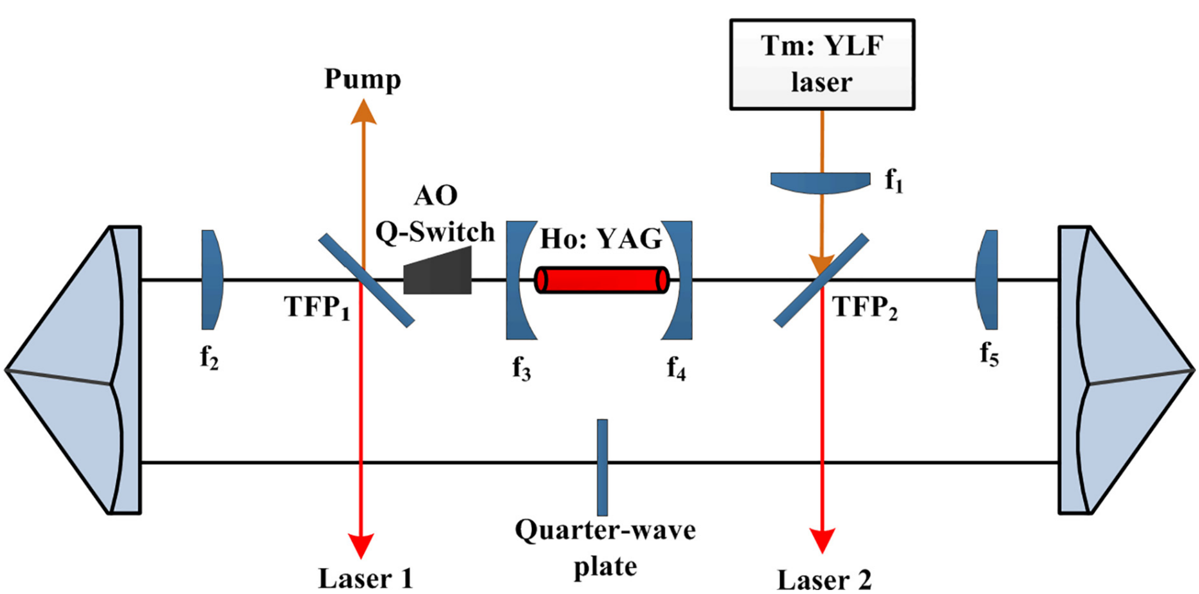


**Fig. 1.** Experimental setup of Q-switched Ho:YAG laser.

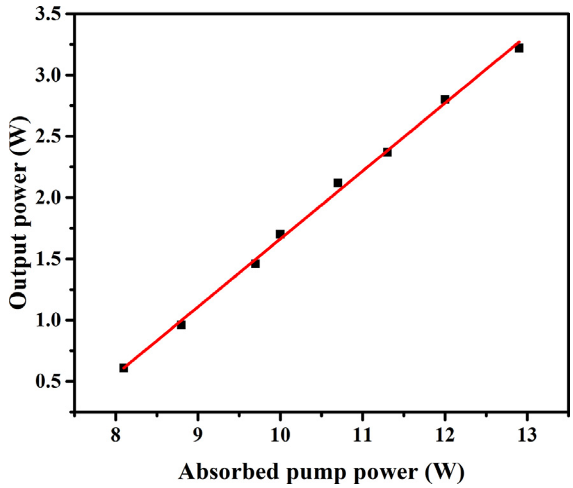


**Fig. 2.** Total output power of continuous-wave Ho:YAG laser versus the incident absorbed pump power.

**Table 1**
Output power under different rotating angles of quarter-wave plate.

| Angle of quarter-wave plate (°) | Output power 1 (W) | Output power 2 (W) |
|---|---|---|
| 0 | 1.72 | 1.48 |
| 30 | 1.52 | 1.25 |
| 60 | 1.8 | 1.31 |
| 90 | 0.91 | 0.83 |
| 120 | 0 | 0 |
| 150 | 0 | 0 |
| 180 | 1.69 | 1.5 |
| 210 | 1.46 | 1.33 |
| 240 | 1.25 | 1.20 |
| 270 | 0.86 | 1.1 |
| 300 | 0 | 0 |
| 330 | 0 | 0 |
| 360 | 1.72 | 1.48 |

tions when the absorbed pump power of 12.9 W. The output power versus rotating angles around horizontal and vertical directions were shown in Tables 2 and 3. The power of Ho:YAG laser was decreased, but the Ho:YAG laser still operate stably when one of the corner cubes was rotated to 11.8° around vertical direction or 6.7° around horizontal direction

The output energy from 100 Hz to 1 kHz operation was shown in Fig. 3. The energy meter used in the experiment was a Coherent LabMax-Top. For 100 Hz operation, the output pulse energy of 9.9 mJ was achieved under the absorbed pump power of 12.9 W. For 1 kHz operation, the output pulse energy reached 2.8 mJ when the absorbed pump power was 12.9 W. The pulse signal of Q-switched Ho:YAG laser was detected by an InGaAs detector (Beijing Lightsensing Technologies Ltd, LSIPD21-0.3). At different repetition rates, the laser pulse width versus absorbed pump power was shown in Fig. 4. It could be found clearly that the pulse width shortened sharply when the pump power increased. The pulse width was shorter from 100 Hz to 1 kHz operation at the same pump power. As a result, the pulse width was 53 ns at the repetition rate of 100 Hz when the absorbed pump power was 12.9 W.

**Table 2**
Output power versus rotating angles around vertical direction.

| Rotating angles (°) | Output power 1 (W) | Output power 2 (W) |
|---|---|---|
| 0 | 1.72 | 1.48 |
| 1.5 | 1.62 | 1.39 |
| 3.6 | 1.51 | 1.14 |
| 8.6 | 1.52 | 0.91 |
| 11.8 | 1.48 | 0.76 |

**Table 3**
Output power versus rotating angles around horizontal direction.

| Rotating angles (°) | Output power 1 (W) | Output power 2 (W) |
|---|---|---|
| 0 | 1.72 | 1.48 |
| 1.6 | 1.71 | 1.38 |
| 3.9 | 1.63 | 1.39 |
| 5 | 1.48 | 1.23 |
| 6.7 | 1.21 | 1.11 |

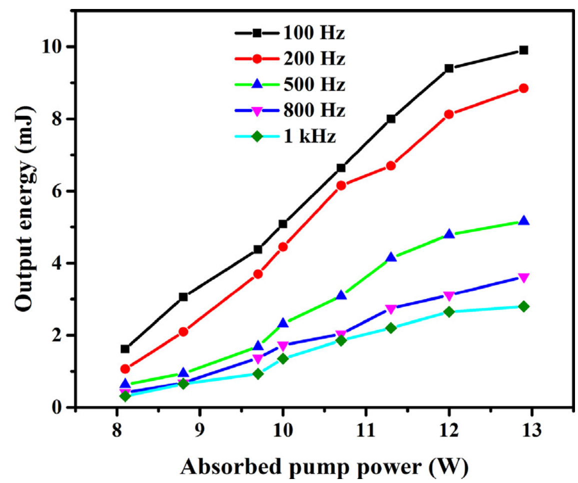


**Fig. 3.** Output energy power versus absorbed pump power under different repetition rates.

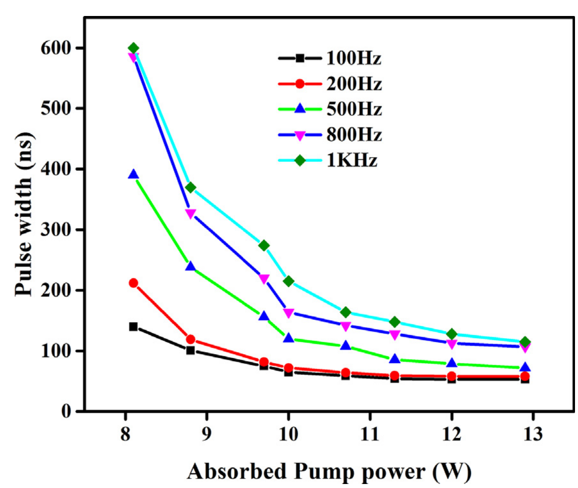


**Fig. 4.** Pulse width versus absorbed pump power at different repetition rates.

The output spectrum of Ho:YAG laser was recorded by a wavemeter (Bristol 721A, ±0.2 pm accuracy), as shown in Fig. 5. The wavelength was centered at 2090.3 nm. The output beam radius of Ho:YAG laser was measured by the 90/10 knife-edge method at several positions, as shown in Fig. 6. By fitting Gaussian beam standard expression to experimental data, the beam quality factor $M^2$ of 1.3 was obtained.

## 4. Conclusion

In conclusion, we proposed an acousto-optically Q-switched Ho:YAG laser with double anti-misalignment corner cubes. The

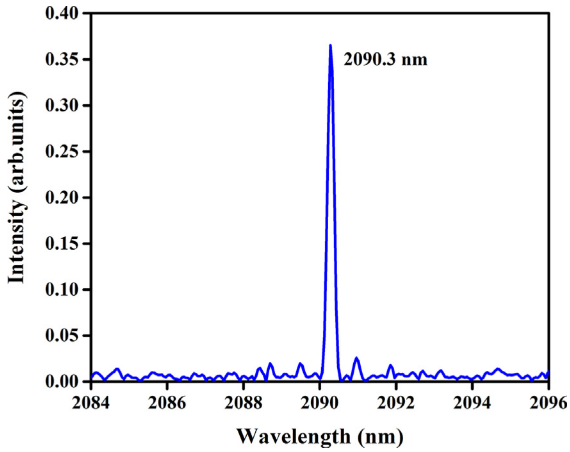


**Fig. 5.** Output wavelength of Ho:YAG laser.

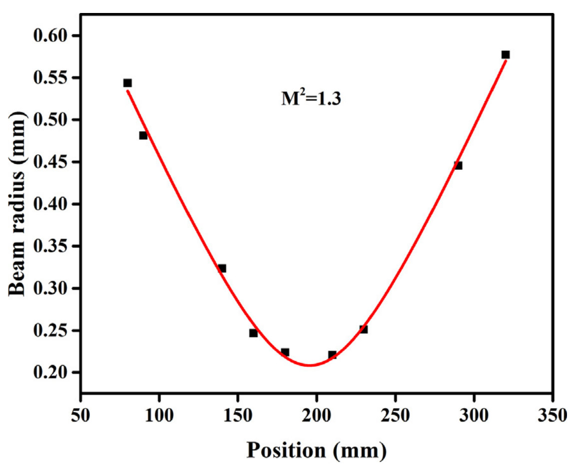


**Fig. 6.** The output bam radius of Ho:YAG laser.

bidirectional s-polarized light output was obtained by utilizing two polarizers. Continuous-wave output power of 3.2 W at 2090.3 nm was achieved under the absorbed pump power of 12.9 W by rotating the fast axis of quarter-wave plate to change the output transmission of laser cavity. The corresponding optical-to-optical conversion efficiency with respect to the absorbed pump power was 24.8% and the slope efficiency with respect to the absorbed pump power was 55.7%. When one of the corner cubes was rotated to 11.8° around vertical direction or 6.7° around horizontal direction, the Ho:YAG laser could still operate stably. For the Q-switched operation of Ho:YAG laser, the pulse energy was 9.9 mJ with a pulse width of 53 ns and a repetition rate of 100 Hz. The output pulse energy reached 2.8 mJ with a pulse of 115 ns at a repetition rate of 1 kHz. The beam quality factor $M^2$ of 1.3 was obtained by fitting Gaussian beam standard expression to experimental data.

## Conflict of interest

The authors declared that they have no conflicts of interest to this work.

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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## References

[1] T.Y. Dai, Y.L. Ju, B.Q. Yao, Y.J. Shen, W. Wang, Y.Z. Wang, Single-frequency, Q-switched Ho:YAG laser at room temperature injection-seeded by two F-P etalons-restricted Tm, Ho:YAG laser, Opt. Lett. 37 (11) (2012) 1850–1852.
[2] 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 (8) (2013) 9541–9546.
[3] R.L. Blackmon, J.R. Case, P.B. Irby, S.R. Trammell, N.M. Fried, Fiber-optic manipulation of urinary stone phantoms using holmium:YAG and thulium fiber lasers, J. Biomed. Opt. 18(2) (2103) 028001.
[4] C. Gao, R. Wang, Z. Lin, M. Gao, L. Zhu, Y. Zheng, 2 μm single-frequency Tm: YAG laser generated from a diode-pumped L-shaped twisted mode cavity, Appl. Phys. B 107 (1) (2012) 67–70.
[5] C. Kieleck, A. Berrou, B. Donelan, B. Cadier, T. Robin, M. Eichhorn, 6.5 W $ZnGeP_2$ OPO directly pumped by a Q-switched $Tm^{3+}$-doped single-oscillator fiber laser, Opt. Lett. 40 (6) (2015) 1101–1104.
[6] B.M. Walsh, N. Barnes, M. Petros, J. Yu, U.N. Singh, Spectroscopy and modeling of solid state lanthanide lasers: application to trivalent $Tm^{3+}$ and $Ho^{3+}$ in $YLiF_4$ and $LuLiF_4$, J. Appl. Phys. 95 (7) (2004) 3255–3271.
[7] B.M. Walsh, N.P. Barnes, B. Di Bartolo, Branching ratios, cross sections, and radiative lifetimes of rare earth ions in solids: application to $Tm^{3+}$ and $Ho^{3+}$ ions in $LiYF_4$, J. Appl. Phys. 83 (5) (1998) 2772–2787.
[8] T.Y. Fan, G. Huber, R.L. Byer, P. Mitzscherlich, Spectroscopy and diode laser-pumped operation of Tm, Ho:YAG, IEEE J. Quant. Electron. 24 (6) (1988) 924–933.
[9] H.J. Strauss, W. Koen, C. Bollig, M.J.D. Esser, C. Jacobs, O.J.P. Collett, D.R. Preussler, Ho:YLF & Ho:LuLF slab amplifier system delivering 200 mJ, 2 μm single-frequency pulses, Opt. Exp. 19 (15) (2011) 13974–13979.
[10] B.Q. Yao, C. Zheng, X.M. Duan, Y.J. Shen, J. Wang, Y.Q. Du, A graphene-based passively Q-switched Ho:YAG laser, Chin. Phys. Lett. 31 (7) (2014) 99–102.
[11] W.Q. Gao, G.M. Yao, L.X. Xu, Y. Cheng, H. Ming, J.P. Xie, Passively Q-switched $Nd^{3+}$:YAG laser with corner cube, Chin. Opt. Lett. 4 (6) (2004) 332–335.
[12] G.S. Zhou, A.J. Alfrey, L.W. Casperson, Modes of a laser resonator with a retroreflecting corner cube mirror, Appl. Opt. 21 (9) (1982) 1670–1674.
[13] M.X. Shen, S.M. Wang, L.G. Hu, D.M. Zhao, Mode properties produced by a corner-cube cavity, Appl. Opt. 43 (20) (2004) 4091–4094.
[14] K.Y. Wu, S.H. Yang, C.M. Zhao, G.H. Wei, Single-frequency Nd: YAG ring lasers with corner cube prism, Chin. Phys. Lett. 17 (10) (2000) 728–730.
[15] Y. Cheng, L. Xu, Q. Wan, M.Z. Zhu, C.W. Mi, C.Y. Tan, S.F. Wei, X. Chen, Mutual injection phase locking coherent combination of solid-state lasers based on corner cube, Opt. Lett. 38 (23) (2013) 5150–5152.
[16] V.S. Srikanth, Corner cube prism Resonator with polarized output: new configuration, Proc. of SPIE 5708 (2005) 303–310.