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Development of a Single-Longitudinal-Mode Ho:YAG Laser Based on Corner Cube *

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We present a Tm-doped fiber laser pumped Fabry–Perot etalons Ho:YAG laser based on a corner cube. A maximum single-longitudinal-mode and fundamental transverse mode output power of 478 mW at the wavelength of 2091.06 nm is achieved with a pump power of 16.3 W, corresponding to an optical-to-optical efficiency of 2.9% and a slope efficiency of 7.9%. The single-longitudinal-mode and fundamental transverse mode are less sensitive to the rotating of the corner cube. The results indicate the potential impact of a single-longitudinal-mode Ho:YAG laser with corner cube geometry to improve the anti-maladjustment stability.

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Single-longitudinal-mode lasers operating in the 2-μm eye-safe spectral range are useful for various applications such as coherent Doppler lidar, laser remote sensing, high-resolution spectroscopy, nonlinear frequency conversion to the 3–12 μm spectral region.[1–3] The Fabry–Perot (F-P) etalon is the simplest way to achieve single-longitudinal-mode operation compared with other methods such as short cavity, coupled cavity, twisted-mode-cavity, Fabry–Perot etalon and non-planar ring cavity. Recently, much attention has been paid to single-longitudinal-mode Tm^{3+}-doped or Tm^{3+}, Ho^{3+}-doped lasers with F-P etalons.[4,5] However, a large quantum defect between the pump wavelength and the lasing wavelength and severe upconversion losses in Tm and Tm^{3+}, Ho^{3+}-doped crystal cause the severe thermal effect, which limits the output power of the single-longitudinal-mode lasers in room temperature.[6,7] With the development of the 1.9 μm Tm-doped fiber laser, the high power single-longitudinal-mode Ho-doped laser pumped by a Tm-doped fiber laser becomes an attractive research area. In addition, YAG crystals become important and are applied widely owing to optically isotropic properties, high mechanical strength and large heat conductivity.[8]

The strong anti-jamming, frequency stability and small volume of the single-longitudinal-mode lasers are extremely useful and important in engineering applications. The corner cube prism is the reflection characteristic of spatial orientation and is insensitive to vibration, impact, and temperature changes.[9] Light entering the bottom face of the corner cube prism at any incidence is reflected from all three internally reflecting surfaces and is returned parallel to the input light beam, which causes the corner cube resonator to be less sensitive to misalignment in any direction[10,11] and the disturbance of the thermal effect is effectively reduced. The major factor of corner cube resonator misalignment is the prism vertex deviates from the optical axis, causing the change of the laser mode volume. However, it can be overcome easily in the corner cube prism location design. Due to these advantages, we introduced the corner cube prism into the intracavity etalons laser, which availably reduces the effects of the mechanical instability on the laser. In 2000, Wu *et al.* reported a non-planar Nd:YAG ring laser with corner cube and the maximum single-frequency output power 100 mW was obtained under a pump power of 15 W.[12] In 2010, Ma *et al.* reported a passively Q-switched Nd:YAG laser pumped by flashlamp which had high stable performance of average output pulse energy and threshold voltage in a wide temperature range.[13] In 2013, Cheng *et al.* adopted a corner cube prism to realize coherent beam combination of six Nd:YAG lasers and the combined output energy was 15.3 mJ.[14] In the early reports, the corner cube prism mainly applied in 1.06 μm lasers to operate steadily under fierce vibration conditions. Up to now, the corner cube prism has not been employed in the intracavity etalons Ho:YAG 2 μm laser to improve the anti-maladjustment stability.

In this Letter, we demonstrate a single-longitudinal-mode Ho:YAG laser based on the corner cube. Three intracavity etalons are inserted to ensure the laser oscillates in the single longitudinal mode. To achieve fundamental transverse mode op-

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eration, we adopt an aperture to select the transverse mode. A maximum-single-longitudinal-mode and fundamental-transverse-mode output power of 478 mW at 2091.06 nm was achieved with a pump power of 16.3 W, corresponding to an optical-to-optical efficiency of 2.9% and a slope efficiency of 7.9%. Effects of rotating the corner cube around its vertex on the longitudinal-mode and transverse mode are also investigated. The single longitudinal mode and fundamental transverse mode are less sensitive to the rotating of the corner cube. The results in this work confirm that interest shall carry on with the corner cube resonator, which has the potential for improving anti-maladjustment of a 2 μm single-longitudinal-mode Ho-doped laser.

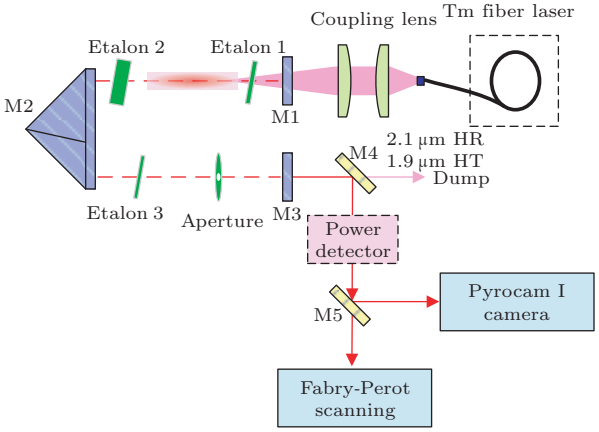

Fig. 1. Schematic diagram of the single-longitudinal-mode Ho:YAG laser based on a corner cube.

Figure 1 shows the experimental setup of the single-longitudinal-mode Ho:YAG laser based on a corner cube. The Ho:YAG rod (4 mm in diameter and 50 mm in length with 0.5 at.% Ho^{3+} doping concentration) used in the oscillator was pumped by a Tm-doped fiber laser that provided up to 20 W of CW power through a 25 μm core, 0.22 NA fiber. Both end faces of the crystal were coated with antireflection (AR) films at 1908 nm ($T > 98\%$) and 2.1 μm ($T > 99.9\%$). The 1908 nm pump light, shaped by a coupling lens system to achieve the best mode matching, was injected into the rod and absorbed along the length of the gain medium. The Ho:YAG rod was wrapped with indium foil and installed on a copper heat sink cooled by a TEC cooler. The temperature of the Ho:YAG rod was held at 15℃. The resonator consisted of two plane mirrors and one corner cube prism. Plane mirror M1 and corner cube prism M2 both were coated with high transmission at the pump wavelength and high reflectivity at the laser wavelength. The material of the corner cube prism was JGS3 with a diameter of 20 mm and a height of 18 mm. Three reflecting surfaces of the corner cube were uncoated and the accuracy of the three right angles was $\pm 2''$. The corner cube was made with rational location design in the resonator. M3 was a plane output coupler with a transmissivity of 25% at 2.1 μm. Three F-P etalons made from YAG (1 mm, 6 mm and 0.5 mm in thickness) without coating were inserted in the cavity to achieve the single-longitudinal-mode oscillation. An adjustable aperture was inserted in the cavity to ensure the Ho:YAG laser oscillated in the fundamental transverse mode. The 45° plane mirror M4 with high reflectivity at 2.1 μm and high transmission at 1.9 μm was used to remove the residual pump light. The 45° plane mirror M5 with a transmissivity of 50% at 2.1 μm divided the laser into two parts, which was used to simultaneously detect the transverse mode and the longitudinal mode. For the end-pumped structure, the turning mirror is the simplest way to employ the corner cube prism which could ameliorate the sensitive detuning characteristic of the resonator. To analyze the stability of this laser, the stable operating zone of the resonator was calculated by ABCD matrix, considering thermal lensing in the Ho:YAG crystal. Under a wide range of the thermal lensing values, the laser was still operated in the stable zone and the oscillating spot almost remained the same, which allowed it to match well with the pump light. Due to the reflection characteristic of spatial orientation in the corner cube prism, the detuning angle of this corner cube resonator is substantially larger than the flat–flat resonator.[15] Furthermore, the detuning angles of input and output mirrors also become larger by utilizing the corner cube prism, thus anti-maladjustment stability of the laser system can be conveniently improved. In addition, the high-precision controlling of the Tm-doped fiber laser current and the temperature control device can be helpful to the stability of output power and frequency of the intracavity etalons Ho:YAG laser.

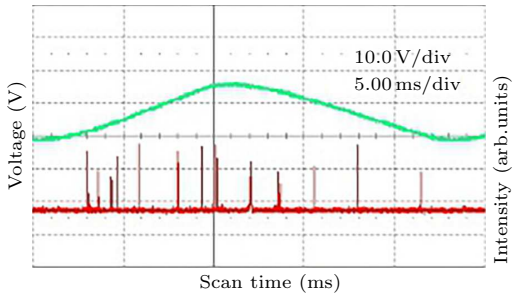

Fig. 2. F-P spectra of the Ho:YAG laser based on a corner cube with free running.

The free-running operation (etalons were not inserted in the cavity) of the Ho:YAG laser based on a corner cube was first investigated. The longitudinal mode of the free running Ho:YAG laser was monitored by an F-P interferometer (a free spectral range of 1.5 GHz, 7.5 MHz resolution) and recorded by a digital storage oscilloscope (LeCroy WaveSurfer 64Xs), as shown in Fig. 2. As can be seen, the free running Ho:YAG laser typically operated on multimode oscillation and the competition of each mode was very in-

tense. The output power is shown in Fig. 3. A maximum output power of 2.89 W was achieved at the pump power of 19.5 W, corresponding to an optical-to-optical efficiency of 14.8% and a slope efficiency of 30.3%.

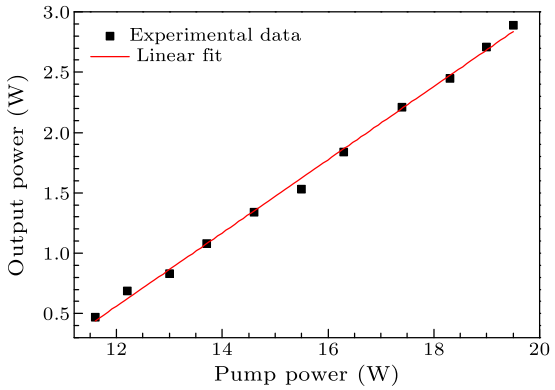

Fig. 3. Output power of the Ho:YAG laser based on a corner cube with free running.

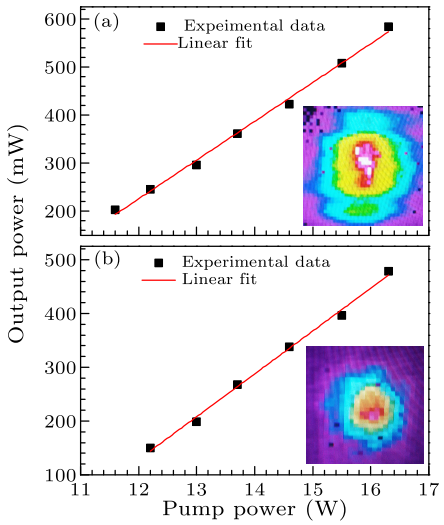

Fig. 4. Output power of the single-longitudinal-mode Ho:YAG laser (a) without an insert aperture and (b) with an insert aperture. The insets in (a) and (b) are the two-dimensional beam profiles.

Three F-P etalons were inserted into the cavity, to obtain a single-longitudinal-mode laser. Generally the thin etalon can suppress all far modes oscillation and the thick etalon compresses the laser linewidth further. When regulating the angle of the three etalons carefully, the transmission ratio peak of three etalons can be adjusted consistently with the maximum value of the gain medium curve, then the laser can obtain the single-longitudinal-mode oscillation. As shown in Fig. 4(a), up to 584 mW output power was obtained, corresponding to a slope efficiency of 8.0% and an optical-to-optical efficiency of 3.6%. The inset in Fig. 4(a) shows that the laser was not oscillating in the fundamental transverse mode, caused by the corner cube having machining errors and three edges of the corner cube having diffraction loss.[16]

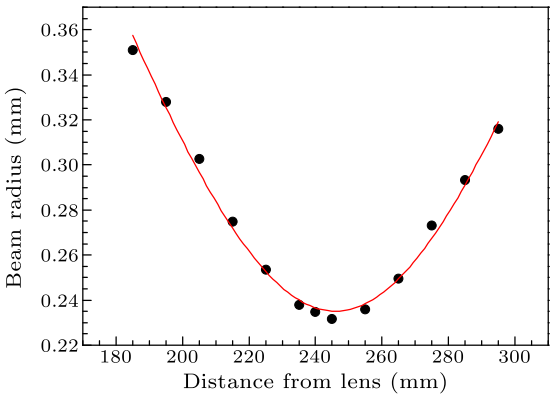

Fig. 5. Beam quality of the single-longitudinal-mode Ho:YAG laser based on corner cube.

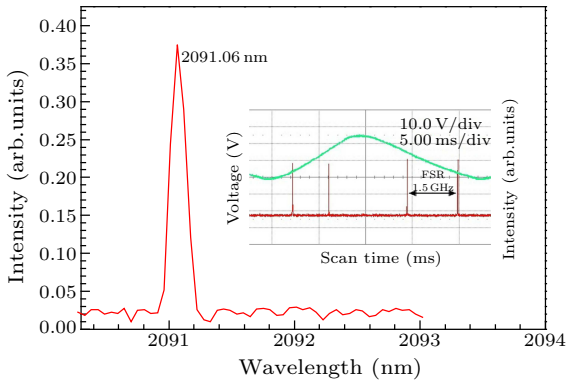

Fig. 6. Output wavelength and F-P spectra of the single-longitudinal-mode Ho:YAG laser.

To achieve the Ho:YAG laser simultaneously oscillate in the fundamental transverse mode and the single longitudinal mode, an adjustable aperture was inserted into the resonator to select the fundamental transverse mode. As shown in Fig. 4(b), a maximum output power of 478 mW was achieved with a pump power of 16.3 W, corresponding to an optical-to-optical efficiency of 2.9% and a slope efficiency of 7.9%. Meanwhile, the inset in Fig. 4(b) shows that the output beam spatial profile was close to the fundamental transverse mode. The beam quality factor M^2 was measured by the 90/10 knife-edge technique. As shown in Fig. 5, by fitting the beam radius to the Gaussian beam propagation equation to these data, the beam quality factor of 1.5 was determined. The single-longitudinal-mode oscillation was also observed. As can be seen in Fig. 6, two modes are visible in one FSR. The output wavelength of the Ho:YAG laser was measured by the wavemeter (WA-1500, EXFO, 0.7 pm resolution), and the laser was emitting at 2091.06 nm (around 0.15 nm spectral bandwidth). Based on the retroreflection property of the corner cube,[17] the effects of rotation of the corner cube prism around its vertex on the single longitudinal mode and the fundamental transverse mode were also observed, respectively, in the scanning F-P spectrum and in a Pyrocam

I camera from Spiricon, and it is shown that the laser was still operated on the single longitudinal mode and the fundamental transverse mode.

In summary, we have reported a single-longitudinal-mode Ho:YAG laser based on a corner cube. By inserting three F-P etalons and one aperture into the cavity, a maximum single-longitudinal-mode and fundamental-transverse-mode output power of 478 mW at 2091.06 nm is achieved at the pump power of 16.3 W, corresponding to an optical-to-optical efficiency of 2.9% and a slope efficiency of 7.9%. The single longitudinal mode and fundamental transverse mode are less sensitive to the rotating of the corner cube around its vertex, which is verified in the experiment. The further optimization of the laser anti-maladjustment performance should be possible by use of two corner cube prisms. This experiment provides a new way to improve the anti-maladjustment stability of high power single-longitudinal-mode laser at 2 μm.

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