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High-power xenon lamp-pumped Er:YAP pulse laser operated in free-running and acousto-optical *Q*-switching modes

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We demonstrate a high-energy and high-power pulse laser on a xenon lamp-pumped Er:YAP crystal. The laser performance and thermal focal lengths under different working frequencies are discussed. The results show that the thermal lens effect is gradually aggravated with the increase of working frequencies, and even working at 100 Hz, a single pulse energy of 234 mJ can be achieved. A maximum average power of 41.5 W is achieved with a working frequency of 20 Hz and slope efficiency of 2.82%. This output power is much higher than other xenon lamp-pumped erbium laser devices. A *Q*-switched laser is demonstrated by using the TeO_2 crystal, the maximum output energies of 11.5 mJ and 3.5 mJ are obtained at 50 and 100 Hz, the corresponding peak powers are 93.4 kW and 17.2 kW, respectively. The laser wavelengths and beam quality factors are also characterized in the free-running and *Q*-switched modes. A higher pulse energy and peak power laser could be achieved further by improving the damage threshold of TeO_2 acousto-optical *Q*-switching. All the experimental results illustrate that the xenon lamp-pumped Er:YAP laser is a promising candidate for high-power and high-frequency mid-infrared laser devices.

Keywords: Er:YAP crystal, xenon lamp-pumped, mid-infrared laser, acousto-optical *Q*-switching

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1. Introduction

It is well known that 2.7–3 μm lasers located at the strong absorption peak of water and the atmospheric transparency window in the range of some special wavelengths have potential applications in laser surgery, remote sensing, gas monitoring, detection, spectroscopy measurement, and material processing, etc.[1–3] Moreover, they can also be used as pump sources to obtain longer wavelength mid-infrared lasers, such as Fe^{2+}- and Dy^{3+}-doped lasers and optical parameter oscillator (OPO) lasers.[4–7] Especially for *Q*-switched lasers with pulse durations of ns level, which possess much advantages in the field of laser surgery and OPO due to their narrow pulse widths and high peak power.

Erbium lasers are known as an ideal source of high-power mid-infrared laser radiation, ∼ 3 μm lasers can be obtained by transitions of $^4I_{11/2} \rightarrow {}^4I_{13/2}$. Among three kinds of rare earth-doped lasers (Er^{3+}, Ho^{3+} and Dy^{3+}), Er^{3+}-doped lasers have attracted much attention because they possess more mature commercial pump sources, including the xenon lamp and InGaAs laser diodes (LDs).[8,9] However, the development of large energy LD pump sources still faces many challenges, leading to the single pulse output energy of LD-pumped Er^{3+} lasers being limited to hundreds of mJ.[10] Xenon lamp-pumped Er^{3+}-doped lasers, by contrast, possess lower laser efficiency and serious thermal lens effect, but they can obtain higher single pulse energy. In addition, xenon lamp-pumped Er^{3+}-doped lasers own the advantages of high output energy, low cost, and ease of commercialization. Therefore, high-energy and high-power xenon lamp-pumped Er^{3+}-doped lasers have important application prospects, e.g., in the fields of laser surgery and OPO lasers.

Up to date, by using the xenon lamp-pumped method, Cr,Er:YSGG, Er:YAG and Cr,Er:YAG crystals have been widely studied as the laser gain media, with all the single pulse energies exceeding 1 J.[11,12] However, the output energy is of difficulty to further enhance due to the serious thermal lens effect. In recent years, Er:YAP has attracted much attention as an excellent mid-infrared laser crystal. The YAP crystal possesses higher thermal conductivity and thermal shock parameters, which are helpful to realize high-power and high-frequency laser output.[13] Moreover, YAP has a lower phonon energy and natural birefringence property, the former is beneficial for improving the laser efficiency and the latter can decrease the thermal depolarization loss and then enhance the laser output energy.[14,15] Therefore, Er:YAP crystal is a promising medium to realize a high-power (energy) mid-

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infrared laser output, and it is expected to obtain a high pulse energy and high-frequency laser under xenon lamp-pumped conditions.

The acousto-optical (AO) *Q*-switched techniques have the advantages of narrow pulse width and high repetition rate. In the recent years, the AO modulator materials used around the 3 μm waveband mainly include germanium (Ge) and paratellurite (TeO_2) crystals.[16,17] The TeO_2 crystal possesses a higher damage threshold than Ge crystal,[18] which makes the TeO_2 crystal expectedly an ideal material for high peak power AO *Q*-switched pulse laser at 3 μm.

In this work, a xenon lamp-pumped and high-power Er:YAP laser is demonstrated with working frequencies of 10–100 Hz. The influences of working frequencies on the thermal lens effect and laser performance are studied by recording the thermal lens focal length at different working frequencies. A *Q*-switched laser is demonstrated by using the TeO_2 crystal under different working frequencies. All the results indicate that the xenon lamp-pumped Er:YAP laser is a promising method to achieve high-energy and high-working-frequency laser outputs.

2. Laser experimental setup

A Φ 4 mm × 105 mm crystal rod was cut and processed from a high-quality *b*-axis 15 at.% Er:YAP crystal, which possesses better spectroscopy and laser performance according to our previous study.[15] The experimental laser setup was designed and constructed as shown in Fig. 1. A close-coupled ceramic optical resonator with a lamp-crystal rod spacing of 7.5 mm was used, the much smaller lamp-crystal rod spacing is beneficial to improve the lamp-pumped efficiency and laser efficiency. The resonant cavity is a flat-flat cavity structure with a geometric length of 190 mm. The xenon lamp with inner diameter of 5 mm, arc length of 90 mm, and whole length of 174 mm was used as the pump source. The temperature of cooling water was kept at 20 ℃. The high-reflection (HR) mirror was coated with a (> 99.5%) HR film near 2.79 μm, and the output coupler (OC) mirror was utilized with transmissions of 10% at 2.79 μm. The laser output energy was measured by an energy meter (Ophir PE50-DIF-C).

Two power supplies were used to power the xenon lamp, and then the xenon lamp luminescence to pump the Er:YAP crystal. One is a high-frequency energy pump power supply, named as power supply 1 that can work in the frequencies of 1–100 Hz, pump energies of 7–63 J, and pump pulse width of 200 μs, the capacitor is 87.5 μF. The other is a high-energy pump power supply, named as power supply 2, which can work in the frequencies of 1–20 Hz, pump energies of 2–150 J, and pump pulse width of 10–600 μs, the capacitor is 3750 μF. In this work, a TeO_2 crystal was used as AO *Q*-switching, both facets of the *Q*-switch were coated with anti-reflection film in the wavelength range from 2.7 μm to 3 μm. The *Q*-switching was set near the laser rod and driven by an RF driver at 41 MHz. The laser pulse profile was recorded by an infrared detector (VIGO System S.A., PVM-10.6) and displayed on a digital oscilloscope (Tektronix MDO3104, 20 Gs/s sampling rates, 1 GHz bandwidth).

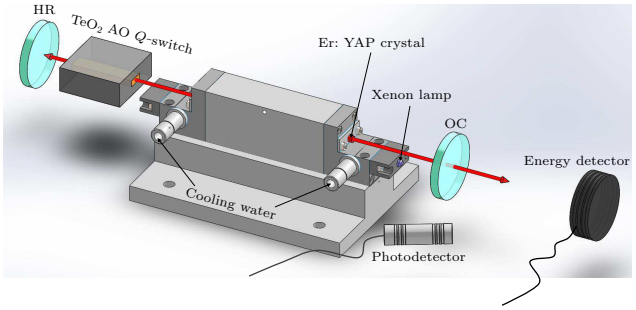


Fig. 1. Experimental setup of the xenon lamp side-pumped and AO *Q*-switched Er:YAP laser.

3. Result and discussion

3.1. Xenon lamp pumped Er:YAP laser

The laser performance of xenon lamp-pumped Er:YAP crystal under the working frequencies of 10–100 Hz is studied by using the power supply 1, the result is shown in Fig. 2(a). Under the working frequencies of 10 Hz, 20 Hz, 50 Hz, and 100 Hz, the maximum output energies of 1121 mJ, 1207 mJ, 722 mJ, and 234 mJ are obtained with the slope efficiencies of 2.06%, 2.18%, 2.00%, and 1.26%, corresponding to the output power of 11.21 W, 24.14 W, 36.1 W, and 23.4 W, respectively. The laser output energy and output power under 10 Hz and 20 Hz have not been further enhanced due to the maximum pump energy limit of the power supply. Thus, the laser performance of xenon lamp-pumped Er:YAP laser is also studied by using the power supply 2 to achieve a high-energy pulse laser output.

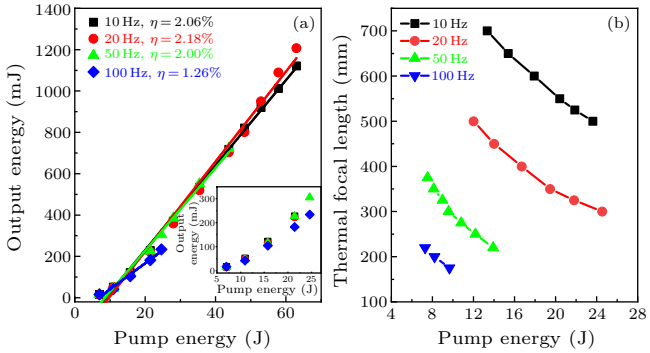


Fig. 2. (a) Laser output energy and (b) thermal focal lengths of xenon lamp pumped Er:YAP crystal versus pump energy under different working frequencies.

Accordingly, the influence of the working frequency on thermal lens focal lengths are recorded, as shown in Fig. 2(b). It is obvious that the thermal focal lengths shorten with the increase of pump energies, which is owing to the accumulation

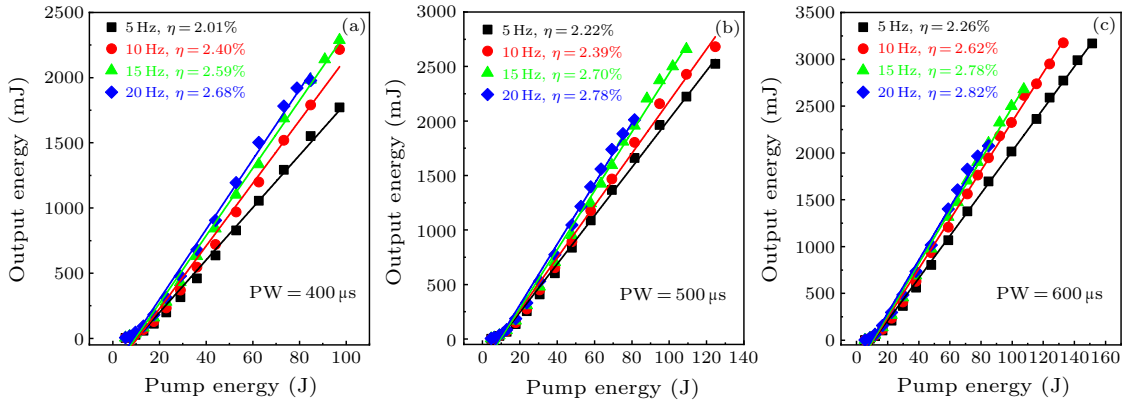


Fig. 3. Laser performance of xenon lamp pumped Er:YAP crystal with a different pump pulse width (PW) operated at 5 Hz, 10 Hz, 15 Hz, and 20 Hz: (a) PW = 400 μs, (b) PW = 500 μs, and (c) PW = 600 μs.

of waste heat gradually increasing with the pump energies, and the thermal lens effect progressively aggravates. With the increase of working frequencies, the thermal focal lengths significantly shorten, because the pump power has multiplied with the increase of working frequencies.

By using the power supply 2, the laser performance of xenon lamp-pumped Er:YAP crystal is studied with different working frequencies and pump pulse widths. The maximum output energy of 3170 mJ, 3175 mJ, 2680 mJ, and 2075 mJ are obtained with slope efficiencies of 2.26%, 2.62%, 2.78%, and 2.82% under the working frequency of 5 Hz, 10 Hz, 15 Hz, and 20 Hz, respectively. The maximum average output power of 41.5 W is achieved with pump pulse width of 600 μs and working frequency of 20 Hz. As shown in Fig. 3, the output energy exhibits a little enhanced tendency with the increase of working frequencies and pump pulse widths. The former is because the crystal can be pumped more efficiently under the higher working frequencies. In addition, a longer pump pulse width (shorter than the lifetime of the laser upper level) is beneficial to accumulate more energy on the laser upper level and then to improve the laser performance. To the best of our knowledge, this is the highest maximum average output power operated in xenon lamp-pumped Er^{3+}-doped laser. This value is higher than many LD side-pumped Er^{3+}-doped 3 μm lasers (including diode pumped Er:YAP lasers).[11–13,19–22]

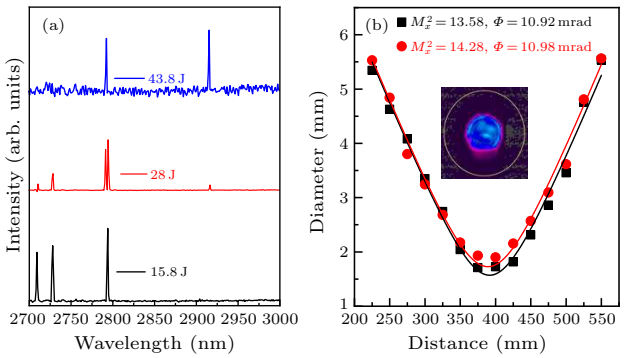


Fig. 4. (a) Laser wavelength variation with the pump energy of the xenon lamp-pumped Er:YAP crystal. (b) Beam quality and profiles of xenon lamp pumped Er:YAP laser in the free-running mode.

The generated laser wavelengths with xenon lamp-pumped Er:YAP crystal were also measured, showing a variation with pump power in Fig. 4(a). Three laser wavelengths of 2710 nm, 2728 nm, and 2794 nm are observed under low pump power. With the increase of pump power, the laser wavelength of 2916 nm appears and its intensity strengthens gradually with the increase of pump power. The similar red-shifting behaviors have been reported in many other erbium doped lasers. With the increase of pump power, the re-absorption process would be enhanced and the laser tends to oscillate at longer wavelength.[23]

The laser beam quality of the xenon lamp-pumped Er:YAP laser in the free-running mode is measured under the output energy of 720 mJ at 10 Hz. The beam profiles are obtained after passing through a CaF_2 lens with focal length of 300 mm, the beam diameters as a function of the propagation distances are shown in Fig. 4(b). The laser beam quality M_2 factors in the x and y axes are fitted and calculated to be 13.58 and 14.28, corresponding to the far-field divergence angles of 10.92 and 10.98 mrad, respectively. An obvious multimode laser is obtained, the beam quality is promising to improve by inserting the intra-cavity iris aperture and optimizing the cavity structure.

3.2. AO *Q*-switched Er:YAP laser

By using the experimental setup shown in Fig. 1, an AO *Q*-switched laser is demonstrated in Er:YAP crystal. The characteristic curves of the output energies and pulse durations varying with the pump energy under different working frequency are shown in Fig. 5, the pulse profiles under the maximum output energies are shown in Fig. 6. During the experiment, the delay time between the pump pulse and AO *Q*-switching is optimized to be 183 μs to obtain a maximum output energy. Under the pump energy of 14.5 J, maximum output energy of 13.2 mJ and minimum pulse duration of 136 ns are obtained at 10 Hz, corresponding to a peak power of 97 kW. The maximum output energies gradually decrease to 12.8 mJ, 11.5 mJ, and 3.5 mJ, and the pulse duration increases to 137 ns,

156 ns, 204 ns, corresponding to the peak power of 93.4 kW, 73.7 kW, and 17.2 kW, respectively, when the working frequencies increase to 20 Hz, 50 Hz, and 100 Hz. With the increase of working frequency, the output energies gradually reduce and the pulse durations gradually become longer. Especially, when the working frequency increases to 100 Hz, the output energy decreases to the one quarter and the pulse duration increases to the 1.5 times of that at 10 Hz, which should be due to the serious thermal lens effect, as shown in Fig. 6. However, the higher pulse energy has not be been achieved due to the limit of low damage threshold of TeO_2 crystals.

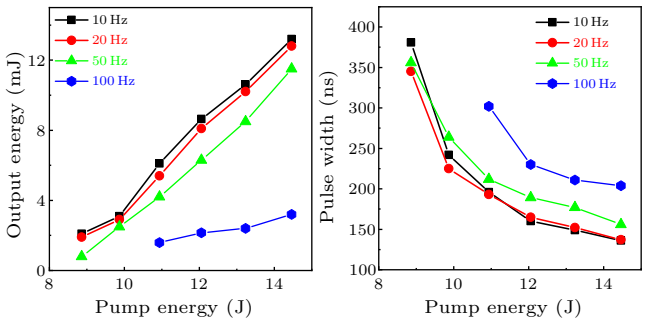


Fig. 5. Output energies and pulse durations varying with the pump energy.

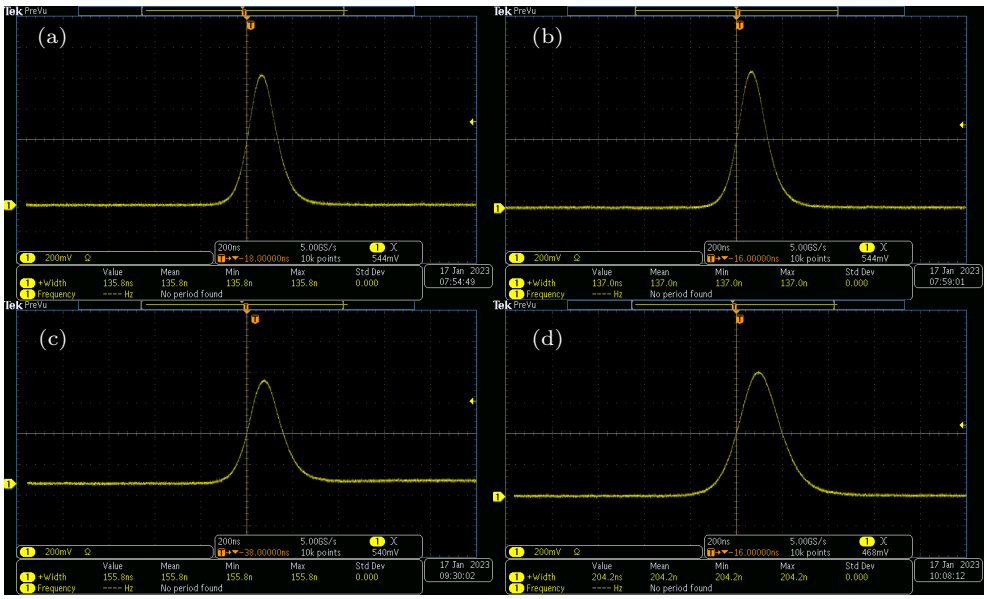


Fig. 6. Image of a Q-switched pulse profile taken from an oscilloscope (pump energy 14.5 J) at (a) 10 Hz, (b) 20 Hz, (c) 50 Hz, (d) 100 Hz.

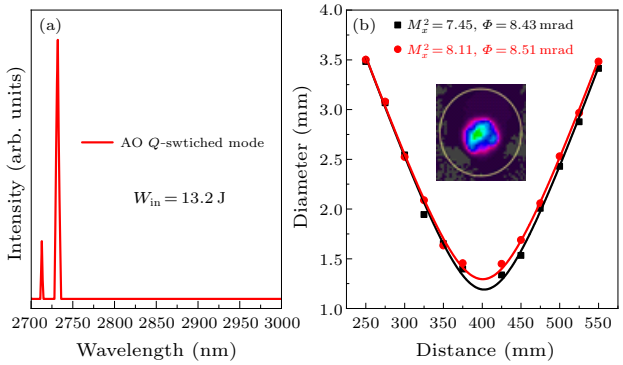


Fig. 7. (a) Laser wavelength and (b) beam quality of the xenon lamp-pumped Er:YAP crystal in the AO Q-switching mode.

The generated laser wavelengths with xenon lamp-pumped Er:YAP crystal in the Q-switching mode were also measured, as shown in Fig. 7(a). Only the laser wavelengths of 2710 nm and 2728 nm are observed, which should be due to the fact that the inset of AO Q-switching increases more energy loss and results in the threshold of 2794 nm laser risen. There is expected to obtain the laser wavelengths of 2794 nm and 2912 nm, and both the wavelengths have been observed in the free-running mode (Fig. 4(a)) and our previous work.[24] However, the pump power has not been increased to prevent damaging the Q-switching. The laser beam quality of the xenon lamp-pumped Er:YAP laser in the AO Q-switching mode is measured under the output energy of 11.05 mJ at 10 Hz. As shown in Fig. 7, the M^2 factors in the x and y axes are fitted and calculated to be 7.45 and 8.11, corresponding to the far-field divergence angles of 8.43 mrad and 8.51 mrad, respectively.

4. Conclusions

In summary, we have demonstrated a high-power and high-energy Er:YAP laser pumped by a xenon lamp. The single pulse energies of 722 mJ and 234 mJ are achieved even when the working frequencies increase to 50 Hz and 100 Hz, the corresponding powers are 36.1 W and 23.4 W, respectively. A maximum average power of 41.5 W is realized at a working frequency of 20 Hz, corresponding to the single pulse output energy of 2075 mJ and slope efficiency of 2.82%. This output power is much higher than other xenon lamp-pumped and many diode-pumped erbium laser devices. In the AO Q-switched mode, the maximum output energies (13.2 mJ,

12.8 mJ, 11.5 mJ, and 3.5 mJ) and minimum pulse durations (136 ns, 137 ns, 156 ns, and 204 ns) are obtained under the working frequencies of 10 Hz, 20 Hz, 50 Hz, and 100 Hz, respectively. The M^2 factors of the xenon lamp-pumped Er:YAP crystal are obtained to be 13.58/14.28 and 7.45/8.11 in the free-running and AO Q-switched modes, respectively. The laser output energy and laser efficiency are promising to be improved further by enhancing the crystal heat management, such as thermal bonded pure YAP crystal as heat sink, to compensate the thermal lensing effect by inserting optical elements in the cavity. All the experimental results illustrate that the xenon lamp-pumped Er:YAP laser is a promising candidate for high-power and high-energy mid-infrared laser devices.

Acknowledgments

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