1514 nm eye-safe passively Q-switched self-optical parametric oscillator based on Nd³⁺-doped MgO:PPLN

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We examined a 1514 nm eye-safe passively Q-switched self-optical parametric oscillator. The nonlinear crystal is an *a*-cut Nd:MgO:PPLN crystal, and the size of the crystal was 6 mm × 2 mm × 30 mm with 0.4 at.% Nd³⁺ doped and a grating period of 29.8 μm. When the crystal absorbed 12.8 W, the output maximum single-pulse energy reached 39 μJ, and a pulse width of 6.1 ns at a repetition rate of 5.4 kHz was obtained. The peak power was 6 kW, giving a slope efficiency of 42%.

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Efficient 1.5 μm eye-safe laser sources are of great interest in various applications such as laser radar, active imaging, and remote sensing[1–3]. Er³⁺-doped solid-state lasers[4], Raman lasers[5], and optical parametric oscillators[6] (OPOs) are the main methods to obtain 1.5 μm eye-safe lasers. In comparison with the first two techniques, the optical parametric oscillation technique based on periodically poled crystals can realize a high repetition rate, a large effective nonlinear coefficient, and a narrow pulse width[7–9]. The volume of the resonator can effectively be compressed by the passively Q-switched system[10]. At present, the OPO passively Q-switched technique is still a discrete system, such as PPLN or KTP pumped using a Nd:YVO₄ laser[11,12]. As compared to the passively Q-switched discrete system OPO, adoption of the self-optical parametric oscillator (SOPO) method can greatly improve the functional integration and introduce a new technique path to obtain a 1.5 μm passively Q-switched laser, which can be of great significance for miniaturization and integrated development. In 2012, Y. H. Chen's group performed 2D polarization of the Nd:MgO:PPLN crystal, and realized three physical processes of laser gain, optical parametric oscillation self Q-switched, and a repetition rate of 1 kHz in a system with only one optical element. A 1525 nm eye-safe laser with an output of 3.3 μJ was achieved[13].

In this study, we used the Nd:MgO:PPLN as the gain medium of fundamental light and 1.5 μm parametric light to realize a wavelength of 1514 nm as the eye-safe passively Q-switched output. In the experiment, the characteristics of the passively Q-switched wavelengths of the fundamental light and 1514 nm parametric light were studied. When the crystal absorbed 12.8 W and the input fundamental light power was 1.03 W, the output parametric light pulse energy reached 39 μJ,

and the pulse width of 6.1 ns at 5.4 kHz repetition rate was obtained.

Figure 1 shows a schematic diagram of the self-optical parametric oscillator. A diode single-end-pumped Nd:MgO:PPLN crystal was used here. The length of the resonator was 65 mm. The size of the Nd:MgO:PPLN crystal was 6 mm × 2 mm × 30 mm with 0.4 at.% Nd³⁺ doped. Both surfaces of the gain medium were coated for antireflection at 810 nm, 1080–1090 nm, 1.4–1.7 μm, and 3–5 μm. The laser crystal was wrapped with indium foil and mounted in a water-cooled copper holder. The pump source was an 813 nm fiber-coupled continuous laser diode with a core diameter of 400 μm and a numerical aperture of 0.22. The pump light was transmitted through the 1:1.5 coupling mirror group (transmission coupling efficiency reached 97%) and focused on the Nd:MgO:PPLN crystal center. A flat mirror M_1 was coated for high-transmittance at 810 nm and high-reflection at 1084 nm, 1.4–1.7 μm, and 3.5–4.2 μm. The output mirror M_2 was plane-concave (radius of curvature $R = 150$ mm), and its concave face was coated for 20% transmittance at 1.4–1.7 μm and high reflection at 1084 nm. Cr⁴⁺:YAG was used as the saturable absorber to realize passive

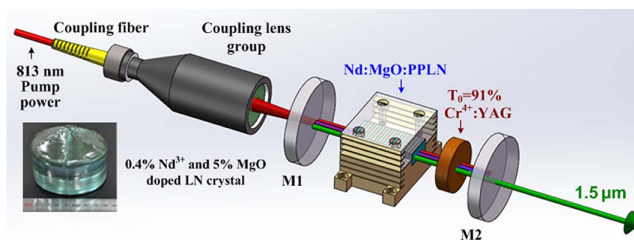

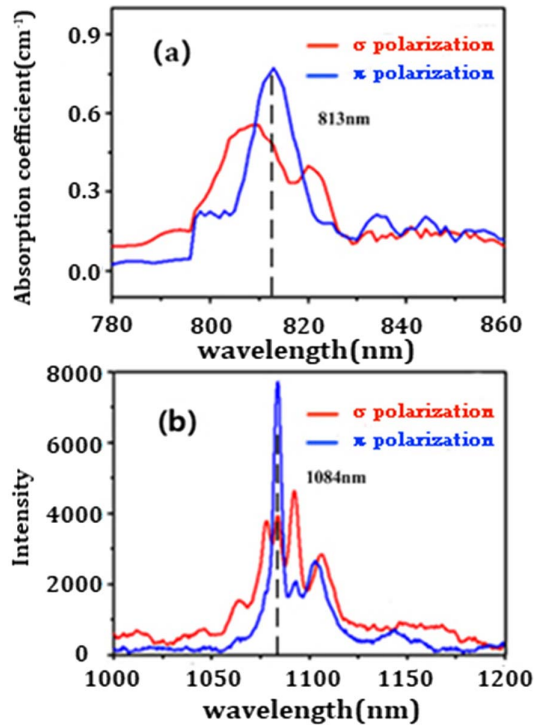Fig. 1. Schematic diagram of the 1514 nm SOPO (Cr⁴⁺:YAG with transmission of 91%).

Fig. 2. (a) σ-polarized absorption spectrum and π-polarized fluorescence absorption spectrum of Nd:MgO:PPLN, (b) σ-polarized absorption spectrum and π-polarized fluorescence emission spectrum of Nd:MgO:PPLN.

Q-switching. The Cr^{4+}:YAG with a transmission of 91% was placed near the beam waist.

To find out the suitable pump source, the polarized absorption spectrum of the crystal was measured at room temperature, as shown in Fig. 2. Polarized fluorescence characteristics of crystals were measured using a TRIAX550 high-resolution fluorescence spectrometer. The fluorescence absorption centers for σ polarization and π polarization were 809 and 813 nm, respectively, and the fluorescence emission centers were 1078, 1093, and 1084 nm. To meet the requirements of being quasi-phase-matched, the Nd:MgO:PPLN crystal was cut along an axis corresponding to the σ polarization. It is worth mentioning that parametric light was generated by the nonlinear frequency conversion in fundamental light. Referring to the nonlinear frequency coupling equation, both fundamental light and parametric light have corresponding photon flux densities. The photon flux density of the parametric light is closely related to the Q-switched peak power. Therefore, a saturable absorber with small transmittance was selected. The peak power of the 1.5 μm parametric light increased and a narrower pulse width was obtained.

First, we investigated the 1084 nm output lasing performance when M_2 of the cavity was replaced by a plane-concave mirror. This mirror had a 6% transmission at a wavelength of 1084 nm and its radius of curvature was 150 mm. Figure 3 shows the relationship between the absorbed power of the crystal and the output power.
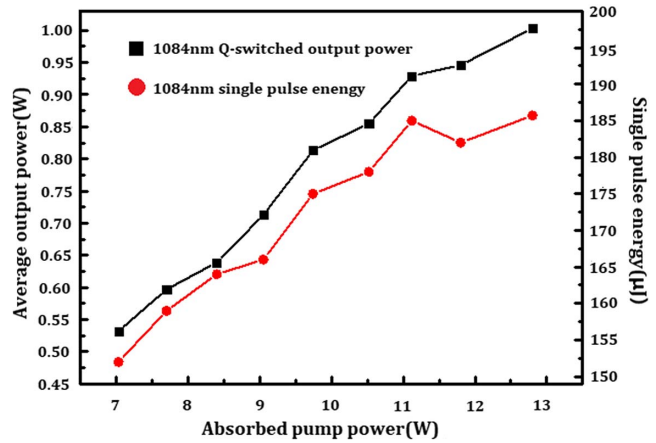

Fig. 3. 1084 nm output power and signal single-pulse energy of a Q-switched laser using Cr^{4+}:YAG, depending on absorbed pump power.

The output power increased almost linearly with the crystal's increased absorbed power. When the crystal absorbed 12.8 W, the highest passively Q-switched output power was 1.03 W and the corresponding single-pulse energy at 1084 nm was 185.7 μJ. It is evident that single-pulse energy and output power increased as the diode power absorbed by the crystal increased. The peak power gradually increased, the output pulse energy became relatively stable, and no saturation state was observed. Additionally, the highest peak power of 11 kW was obtained with a slope efficiency of 43%.

Figure 4 describes the repetition rate corresponding to a different single-pulse energy when the pulse width and the output pulse energy were 17.8 ns and 185.7 μJ, respectively, at a 5.4 kHz repetition rate. The pulse width detector type is Thorlabs DET10 A/M (800–2600 nm), and the oscilloscope type is MD03054 (500 MHz).

Subsequently, the results of the spectrum measurements with an AQ6373 spectrometer (350–1200 nm by Yokogawa, Japan), are shown in Fig. 5. The output wavelength was relatively stable.
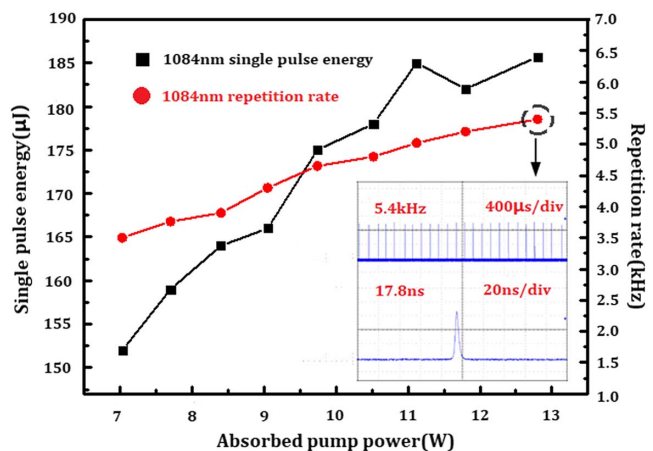

Fig. 4. Single-pulse repetition rate and pulse energy versus absorbed pump powers for passively Q-switched 1084 nm fundamental light.
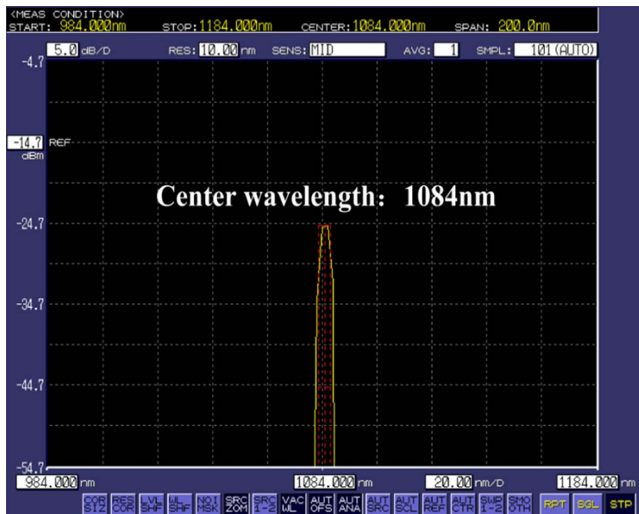
Fig. 5. 1084 nm output spectrum of the passively Q-switched laser.

Fig. 7. 1514 nm eye-safe output spectrum of the passively Q-switched laser.

The output mirror M_2 was replaced by a plane-concave mirror with 20% transmission at the wavelength of 1.4–1.7 μm and radius of curvature of 150 mm. In the experiment, when the fundamental light threshold was 0.454 W, 1.5 μm parametric light started to oscillate in the resonator. The relationship between the single-pulse energy of 1514 nm parametric light and fundamental light is shown in Fig. 6. As the single-pulse energy of the fundamental light increased, the energy of the 1514 nm parametric light gradually increased, and no saturation state was observed. Finally, the highest passively Q-switched output pulse energy of 39 μJ (6 kW peak power) was obtained with a pulse width of 6.1 ns at a 5.4 kHz repetition rate, thereby achieving a slope efficiency of 42%. Further, we measured output spectra with an AQ6375 spectrometer (1200–2400 nm by Yokogawa, Japan), as shown in Fig. 7. Finally, we simply measured the power of the idler light. M_2 of the cavity was replaced
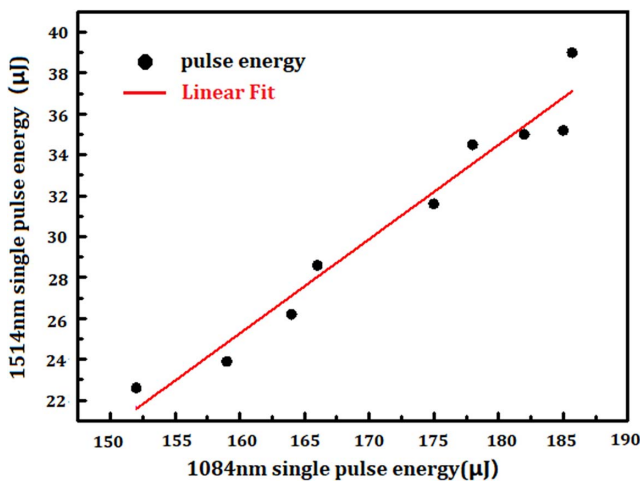
by a plane-concave mirror ($R = 150$ mm). This mirror is coated for high transmittance at 3.5–4.2 μm and high reflection at 1084 nm and 1.4–1.7 μm. We measured the idler light output single pulse energy as approximately 12.4 μJ with a corresponding wavelength of 3816 nm (measured by an ARCoptix FTIR-C-20-1203 infrared Fourier spectrometer using a spectral range of 2.5–12 μm).

The repetition rate and pulse width are shown in Fig. 8. It is worth mentioning that the pulse width of the 1514 nm parametric light is much smaller than the pulse width of the fundamental light because the photon number density of the parametric light is closely related to the Q-switched peak power in the OPO. After the fundamental light exceeds the threshold, the parametric light starts oscillating. At this time, the fundamental light energy was consumed rapidly. The photon flux density of the parametric light became instantaneously zero, and the parametric light was quickly cut off. This indicates that in the OPO, the pulse width of the parametric light will be much smaller than that of the fundamental light. From the Fig. 8, a small pulse near the main pulse is observed. While the parametric light was quickly

Fig. 6. 1084 nm single-pulse energy and 1514 nm single-pulse energy.
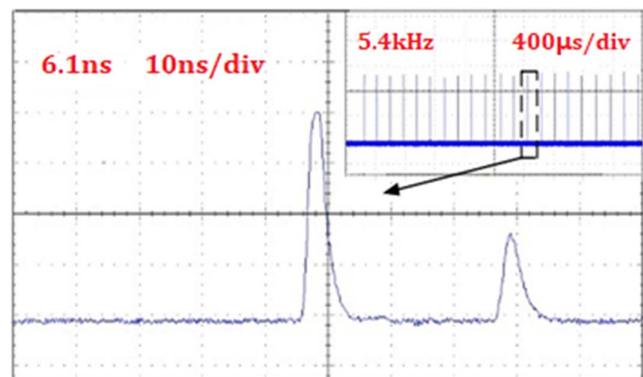

Fig. 8. 1514 nm fundamental light repetition frequency and single-pulse width.

consumed, a part of the fundamental light energy remained, which can continue to produce the next pulse. However, since the remaining fundamental light photon flux density is not sufficient to produce a high intensity pulse, the height of the small pulse is much smaller than the height of the main pulse. The next process of population inversion will then proceed. Moreover, the nonlinear crystal has a frequency stabilization function.

In conclusion, we demonstrated an *a*-cut Nd:MgO: PPLN eye-safe passively *Q*-switched laser emitting at 1514 nm. A maximum single-pulse energy of 39 µJ was achieved at the absorbed pump power of 12.8 W, corresponding to the slope efficiency of 42%. Using a Cr^{4+}:YAG crystal for the 6.1 ns laser pulses, a repetition rate of 5.4 kHz and a peak power of 6 kW were obtained. The laser gain and optical parametric oscillations integrated into the same crystal and being passively *Q*-switched can compress the volume of the resonator and be used as a new approach for production of a 1514 nm eye-safe laser.

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