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43 W, 7 ns constant pulse duration, high-repetition-rate langasite cavity-dumped Ho:YAG laser and its appilcation in mid-infrared ZGP OPOs

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ABSTRACT

In this paper, we demonstrate a langasite (LGS) electro-optic Ho:YAG cavity-dumped laser that suppresses the gain dependence of pulse duration in Q-switched lasers. A constant pulse duration of 7.2 ns was achieved at a repetition rate of 100 kHz. Benefiting from the LGS crystal has no significant reverse piezoelectric ring effect and thermally induced depolarization, a stable pulse train was achieved at an output power of 43 W. For the first time, the application of cavity-dumped laser in mid-infrared (mid-IR) $ZnGeP_2$ (ZGP) optical parametric oscillator (OPO) has been realized, providing a reliable way to achieve high repetition rates and short nanosecond pulse times for high-power mid-infrared ZGP OPOs. The average output power was 15 W, corresponding to a pulse duration of 4.9 ns and a repetition rate of 100 kHz.

1. Introduction

2 μm lasers with nanosecond pulse duration are the sources for material processing, infrared countermeasures, and remote sensing [1–4]. High power nanosecond pulsed lasers are obtained mainly by Q-switched techniques [5–7]. At higher repetition rates, the available gain of each pulse decreases, increasing the pulse build-up time. As the repetition rate increases, the pulse duration is not constant. Reducing the length of the cavity is one of the main way to obtain short nanosecond pulse duration laser, which results in a smaller intracavity fundamental mode. This means an increased thermal load on the gain medium, leading to severe thermal lensing effects and spot aberrations [7]. Therefore, the high-power Q-switched laser generally operates at a repetition rate of less than 50 kHz and has a pulse duration of tens of nanoseconds.

Different from the conventional Q-switched lasers, the cavity-dumped laser uses a time-varying output coupler instead of the constant transmittance output coupling mirror as a reliable way to achieve high-power short nanosecond pulsed laser [7]. Firstly, the intracavity energy was stored as photons, suppressing the gain dependence of pulse duration. Constant pulse duration was achieved independently of the gain medium and repetition rates. Theoretically, the pulse duration depends only on the cavity length [8]. Secondly, the intra-cavity peak power of cavity-dumped laser will not be greater than the output peak power, effectively reducing the thermal load on the gain medium and the probability of laser-induced damage [9]. The electro-optic crystal was the key component of the high power electro-optic cavity-dumped laser. At present, several electro-optic crystals are widely used: $RbTiOPO_4$ (RTP), β-BaB_2O_4 (BBO), $LiNbO_3$ (LN), all have inevitable disadvantages, which limit their application in cavity-dumped lasers [10–12]. Due to the piezoelectric ringing effect, the maximum repetition rate at which LN can operate was limited to 1 kHz. LGS electro-optic crystals have no reverse piezoelectric ring effect when operating at a high repetition rate. LGS crystals do not have thermally induced depolarization compared to the RTP and the BBO crystal during high power operation. The thermally induced depolarization phenomenon makes the oscillating laser unable to maintain a single polarization at the time-varying output coupler, leading to a deterioration of the dynamic extinction ratio. Limits the maximum power that BBO crystals and RTP crystals can work with. The optical damage threshold of LGS crystals is as high as 950 MW/cm^2, which is nine times that of LN crystals [13].

An important pump laser for the mid-IR ZGP OPO was the 2-μm pulsed lasers, which essentially determines the performance of the entire system. At present, the main pump source of high-power mid-IR ZGP OPO is actively Q-switched laser [2–4]. High repetition rate Q-switched lasers with pulse durations of tens of nanoseconds due to the reduction in gain. When such a laser is applied to the mid-IR ZGP OPO for frequency conversion, it leads to a decrease in efficiency and an increase in

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pulse duration [7]. A reduced pump spot profile was required to achieve high efficiency OPO operation.This makes it difficult for high-power mid-IR ZGP OPO to achieve higher repetition rates and short nanosecond pulse duration simultaneously.

In this paper, we demonstrate a cavity-dumped laser with an LGS crystal as a Pockels cell, achieving a constant pulse duration of 7.2 ns corresponding to a repetition rate of 100 kHz. Since the LGS crystal has no significant reverse piezoelectric ring effect and thermally induced depolarization, a stable pulse train was achieved at an output power of 43 W. A reliable way to achieve high repetition rates and short nanosecond pulse duration for high-power ZGP OPO was provided, using a cavity-dumped laser as the pump source. A mid-IR laser with a pulse duration of 4.9 ns and an output power of 15.0 W was obtained at a repetition rate of 100 kHz. At the maximum output power of the ZGP OPO, the beam quality factors M^2 in the vertical and horizontal directions was 1.58 and 1.70, respectively.

2. Experimental setup

The experimental setup of the LGS electro-optical cavity-dumped laser pumped mid-infrared ZGP OPO was shown in Fig. 1. The Ho:YAG cavity-dumped laser was a dual-ended pumping configuration. Two home-made 1908 nm Tm:YLF solid-state lasers were used as pump sources with an output power of 50 W. Both pump laser waists were focused on the front third of the crystal with a radius of 0.50 mm. The gain medium was a rod-shaped Ho:YAG crystal (length: 60 mm, diameter: 6 mm) with a doping concentration of 0.6 at.%. To counteract the strong thermal lensing effect, a concave-convex cavity structure was designed. The structure consisted of two flat 45° dichroic mirrors (M1), two high reflectivity mirror (M2, M3). M2 was a convex mirror with a curvature of 200 mm and a distance of 80 mm from the nearer crystal end. M3 was a concave mirror with a curvature of 400 mm and a distance of 305 mm from the nearer crystal end. The cavity length of this structure was 445 mm.

The time-varying output system of the cavity-dumped laser was composed of a thin film polarizer (TFP), an LGS electro-optic crystal, and a quarter-wave plate (QWP). The TFP (R > 99.8% at 2.1 μm s-polarized and T > 95.0% at 2.1 μm p-polarized) was placed at 45° as an output mirror. The LGS crystal and QWP were inserted between the highly reflective concave mirror M3 and TFP to control the polarization of the oscillating laser. The LGS crystal used for the experiment had a length of 48 mm and a cross section of 4 × 4 mm^2. The transmission surfaces of the LGS electro-optic crystal [Provided by Chendu Dien Photoelectric Technology] were coated with AR coating at 2 μm and the YZ surfaces were coated with Au. The output coupling system was based on a Z-cut LGS crystal, operating in the transverse field regime and pulse-on mode. According to the formula $v_{4/\lambda} = \lambda/4n_3^0\gamma_{11}(l/d)$ [1], the theoretical quarter-wave voltage of the LGS crystal was 2956 V. The practical voltage was set to 2988 V, which was roughly equal to the theoretical value. An electro-driver with a rise-and-fall time of 5 ns was used to apply a quarter-wave voltage. The vertically polarized radiation will rotate into a horizontally polarized beam after passing through the QWP and the LGS crystal twice.

A combination of a half-wave plate (HWP) and a TFP was used to vary the power injected into the ZGP OPO without changing the spot profile. To reduce the oscillation threshold and improve the conversion efficiency, the mid-IR OPO was designed as a compact ring cavity structure. The ring cavity was mainly composed of three dichroic mirrors (M4) and an output mirror (M5) with a length of 180 mm. A plane mirror, M4, had a transmittance of 93% for the p-polarized at 2.1 μm and a reflectance of 99.8% for the s-polarized at 3–5 μm. An output coupler, M5 had a 97% transmittance for the p-polarized at 2.1 μm and 50% transmittance for the s-polarized at 3–5 μm. M6 was the same dichroic as M4 to separate the remaining pumping laser from the mid-infrared laser. A type-I matching ZGP carystal with θ = 54.7° was used to obtain mid-IR laser. The dimensions of the ZGP crystal was 6 × 6 mm^2 (in cross section) × 30 mm (in length).

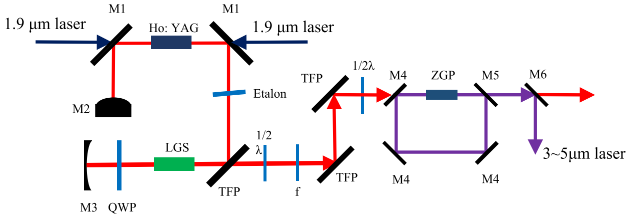

Fig. 1. A diagram of the experimental setup for pumping mid-infrared ZGP OPO with an Ho:YAG cavity-dumped laser (using LGS as a Pockels cell).

3. Experimental results and discussions

The output characteristics with the concave-convex cavity were measured shown in Fig. 2. Rotating the QWP to change the polarization of the oscillating laser, the TFP could be considered as a constant transmittance output mirror. The output characteristics were first tested without the LGS crystal in the cavity. The maximum continuous wave (CW) output power was 54.5 W. The optical-to-optical conversion efficiency at 54.5 W was 53.9% and a slope efficiency of 67.0%. Inserting the LGS crystal, the maximum CW output power decreased to 49.9 W due to the increase in cavity loss, corresponding to an optical-to-optical conversion efficiency of 49.4% and a slope efficiency of 60.6%. At the highest CW output efficiency, the angle of the QWP was determined. A rectangular wave voltage was applied to the LGS for standard E-O Q-switched experiments. The highest output power was 49.5 W at 50 kHz, corresponding to an optical-to-optical conversion efficiency of 49.0%. When operated in cavity-dumped mode, the maximum output power of 50 kHz was 41.3 W, corresponding to an optical-to-optical conversion efficiency of 40.9% and a slope efficiency of 51.0%. The maximum output power of 100 kHz was 43.0 W, corresponding to an optical-to-optical conversion efficiency of 42.6% and a slope efficiency of 52.3%.

The photon population accumulation time was the key factor to determine the intracavity energy during its period. To maximize efficiency, the cavity-dumped event should be triggered at the maximum intracavity energy, with different repetition rates corresponding to different accumulation times. Fig. 3 shows the output characteristics at different accumulation times when the repetition rates were set to 50 and 100 kHz. At 50 and 100 kHz, the high voltage times were set to 200 and 100 ns, corresponding to maximum output powers of 41.3 and 43.0 W, at a maximum pumping power of 101 W, respectively. The maximum

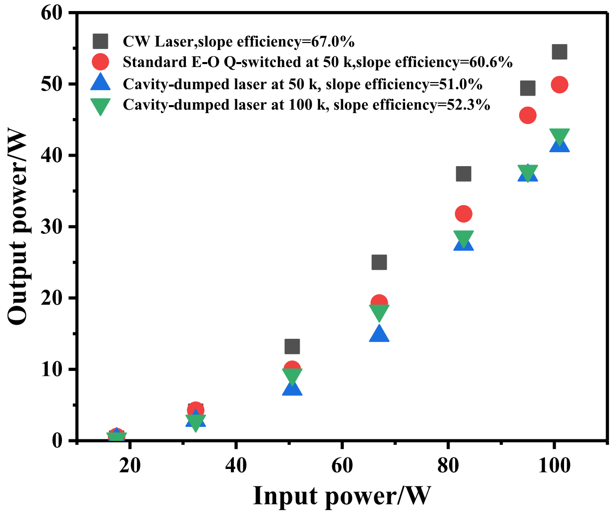

Fig. 2. Output characteristics with a concave-convex cavity structure.

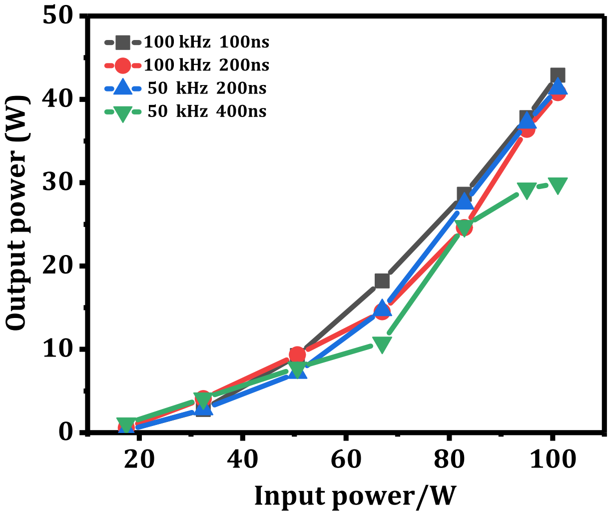

Fig. 3. Output characteristics of cavity-dumped laser for different accumulation times at 50 and 100 kHz.

output power drops to 29.9 and 40.8 W when the photon population accumulation time were 400 and 200 ns for 50 and 100 kHz, respectively. When the intracavity energy reaches its maximum, too long accumulation time will lead to a decrease in intracavity photons, which will cause a decrease in efficiency.

At a certain cavity length, the accumulation time corresponds to the number of oscillations in the cavity. For high repetition rates cavity-dumped lasers, more precise control of the number of oscillations was required to obtain stable pulses when obtaining a high efficiency output. At high repetition rates, the time interval between adjacent pulses was shorter than the upper-level-lifetime of the gain medium, resulting in insufficient time for the gain of each pulse to recover to a stable value. The amplification process of the pulses interacted with each other. Fig. 4 (a) shows a temporal pulse train of 50 kHz repetition rate. The first pulse was cycled through the cavity for amplification, continuously extracting energy from the gain medium. When the number of oscillations exceeded a certain value, the gain at the end of this amplification was too small and the initial gain of the second pulse was too small. Even for the same number of oscillations, the energy extracted in the second pulse was small. However, this provided a large initial gain for the third pulse, and the process continued to cycle back and forth, causing the peak power of the cavity reversal pulse to bounce between multiple values. The number of oscillations cannot be controlled more precisely due to the modulation accuracy of the electro-optical modulator driver (EOM) we use. Improving the control accuracy of the accumulation time of the EOM makes it possible to obtain highly stable pulse trains at 50 kHz. At 100 kHz, the accumulation time was set to 100 ns, the stable temporal pulse train is shown in Fig. 4(b). Tektronix oscilloscopes were used to record pulse trains, model DPO 5204B, with a sample rate setting of 2.5G/S. By recording multiple sets of pulse intensity, the RMS stability of the pulse intensity was 2.06%. The stable pulse train indicated that the LGS crystal, which operates at 100 kHz, has no piezoelectric ringing effect.

A typical temporal pulse shape with a repetitionrate of 100 kHz was recorded as shown in Fig. 5(a). In fact, the fall time of the high-voltage switch and the extinction ratio of TFP were key factors affecting the pulse duration, resulting in an actual pulse duration being larger than the theoretical value. A constant pulse duration of 7.2 ns was achieved. The pulse shape is symmetrical with no significant change at the trailing edge. The switching of the high voltage caused strong electromagnetic interference. The small pulse peak of the trailing edge was mainly due to the switching of the high voltage. Therefore, there was no significant thermally induced depolarization in the LGS crystal compared to the RTP crystal and the BBO crystal during high power operation [7]. At repetition rate of 50–100 kHz, the pulse duration varies between 7.17 and 7.28 ns at maximum output power. The main reason for the variation of pulse duration was fluctuations of the high-voltage fall time at different repetition rates of the EOM. This will directly affect the switching speed of the Pockels cell. Since the cavity-dumped laser used a time-varying output system to replace a constant transmittance output mirror in conventional Q-switched laser, the gain dependence of pulse duration was suppressed. Thus cavity-dumped lasers could achieve a constant pulse duration independent of the repetition rates.

The output spectrum of the cavity-dumped laser at 100 kHz was measured, as shown in Fig. 6(a). The center wavelength of the output spectrum was 2096.9 nm, and the spectral bandwidth was 0.1 nm. A 0.05 mm F-P was inserted in the cavity to limit the output wavelength to near 2096.9 nm. Fig. 6(b) shows the measured spot radius were fitted to the the Gaussian beam standard expression at an output power was 43 W. The calculated horizontal and vertical beam quality factors M^2 were 1.05 and 1.14, respectively.

The output characteristics of a 30 mm ZGP crystal operating at different repetition rates were shown in Fig. 7. To avoid laser - induced damage inside the crystal, the beam waist of pump laser was focused outside ZGP crystals. The same spot profile of pump laser was used at different repetition rates. The size of the pump spot on front-end faces of the crystal was 0.42 mm (in horizontal direction) and 0.38 mm (in vertical direction). Since, pulse durations of cavity-dumped lasers were independent of repetition rates, oscillation threshold of the mid-infrared OPO was a constant at different repetition rates. The oscillation threshold of OPO was 0.03 J/cm^2, with a corresponding peak power of 4.10 MW/cm^2. At 100 kHz, the output power of ZGP OPO was 15.0 W, corresponding to the slope efficiency of 54.0% and the optical–optical conversion efficiency of 34.8%. For the same pump spot profile, a single pulse at a lower rate has a higher power density. For the same threshold, the leading power of the OPO oscillation was greater as the repetition rate rises, resulting in a drop in OPO output power. After the OPO reached the starting threshold, the slope efficiency of the OPO at different repetiton rates was approximately equal. Reducing the pump spot size at 100 kHz can effectively increase the output power as well as the efficiency of the crystal.

A typical time pulse shape of the ZGP OPO operating at a repetition

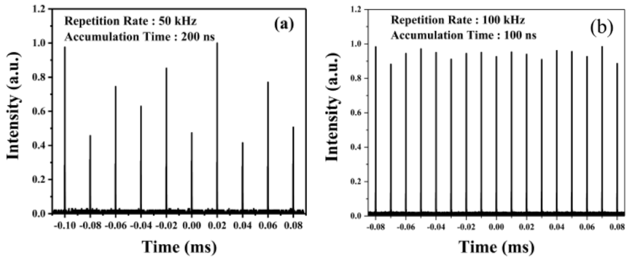

Fig. 4. (a) Temporal pulse trains with an accumulation time of 200 ns at 50 kHz. (b) Temporal pulse train with an accumulation time of 100 ns at 100 kHz.

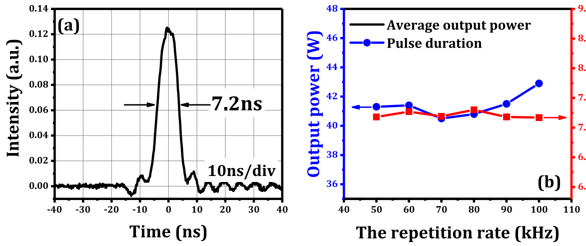

Fig. 5. (a) A typical temporal pulse shape at 100 kHz. (b) At different repetition rates, maximum output power and corresponding pulse duration of the cavity-dumped laser.

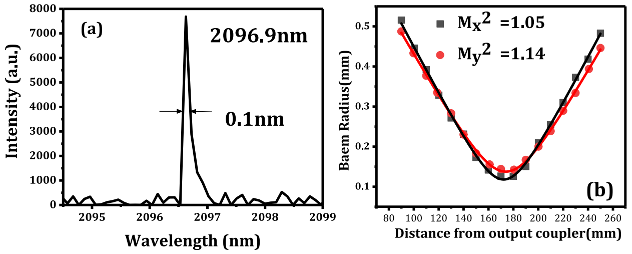

Fig. 6. (a) Output spectrum of the cavity-dumped laser. (b) The spot size at output power 43 W was mesasured by 10/90 knife-edge method.

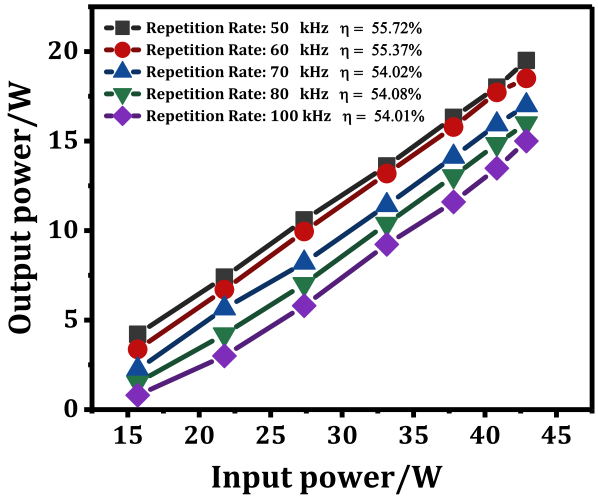

Fig. 7. Output power of a 30 mm length ZGP crystal at different repetition rates.

rate of 100 kHz was shown in Fig. 8(a). A pulse duration of 4.9 ns was achieved at output power of 15.0 W. The pulse duration of mid-IR laser was 68.0% narrower compared to the cavity-dumped laser due to the temporal gain narrowing effect of the nonlinear frequency conversion process. Fig. 8(b) shown the spot radius measured with the 90/10 knife-edge method when the output power was 15.0 W. The calculated horizontal (in × direction) and vertical (in y direction) beam quality factors M^2 were 1.58 and 1.70, respectively. Raising the repetition rates of the pump laser further increases thermal load on ZGP crystals. Severe thermal loading leads to the buildup of higher order modes in the OPO cavity, which deteriorates the quality of the mid-infrared laser beam. A spectra of the ZGP OPO was measured, and the central wavelengths of signal laser and idle laser were 3796.4 nm and 4450.5 nm.

4. Conclusion

In summary, we provided a high repetition rate, short nanosecond pulse duration Ho: YAG cavity-dumped laser. The cavity-dumped laser benefited from the good performance of the LGS crystal, a stable pulse train was achieved at an output power of 40 W, corresponding to a constant pulse duration of 7.2 ns and a repetition rate of 100 kHz. With the cavity-dumped laser as the pump source, a compact mid-IR ZGP OPO was designed. At an output power of 15.0 W, the shortest pulse duration of the mid-IR laser was 4.9 ns with a repetition rate of 100 kHz. The mid-IR laser with beam quality factors M^2 of 1.58 (in × direction) and 1.70 (in y direction) was achieved.

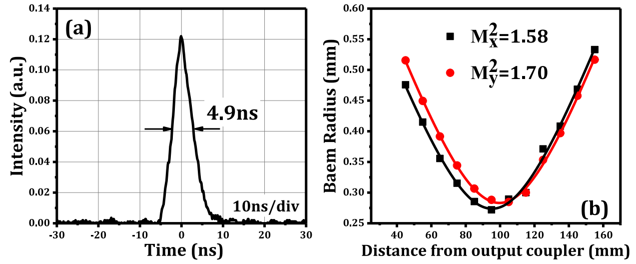

Fig. 8. (a) Typical temporal pulse shape of the mid-infrared ZGP OPO operating at 100 kHz. (b). At output power 15 W, the spot size of OPO was measured and beam quality factors M^2 was calculated.

CRediT authorship contribution statement

Junhui Li: Conceptualization, Investigation, Methodology, Validation, Formal analysis, Data curation, Writing – original draft. **Disheng Wei:** Data curation, Writing – original draft. **Baoquan Yao:** Conceptualization, Funding acquisition, Resources, Supervision, Writing – review & editing. **Shuyi Mi:** Resources, Supervision. **Ke Yang:** Resources, Validation. **Jinwen Tang:** Software, Writing – review & editing. **Tongyu Dai:** Visualization, Writing – review & editing. **Xiaoming Duan:** Writing – review & editing. **Youlun Ju:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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