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High-power and high-efficiency 4.3 μm ZGP-OPO

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In this paper, a high-power and high-efficiency 4.3 μm mid-infrared (MIR) optical parametric oscillator (OPO) based on $ZnGeP_2$ (ZGP) crystal is demonstrated. An acousto-optically Q-switched Ho $Y_3Al_5O_{12}$ laser operating at 2.1 μm with a maximum average output power of 35 W and pulse width of 38 ns at a repetition rate of 15 kHz is established and employed as the pump source. A doubly resonant OPO is designed and realized with the total MIR output power of 13.27 W, including the signal and idler output power of 2.65 W at 4.07 μm and 10.62 W at 4.3 μm. The corresponding total optical-to-optical and slope efficiencies are 37.9% and 67.1%, respectively. The shortest pulse width, beam quality factor, and output power instability are measured to be 36 ns, $M_x^2 = 1.8$, $M_y^2 = 2.0$, and RMS $< 1.9\%$ at 8 h, respectively. Our results pave a way for designing high-power and high-efficiency 4–5 μm MIR laser sources.

Keywords: mid-infrared laser; optical parametric oscillator; nonlinearity.

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1. Introduction

High-power and high-efficiency 4.3 μm mid-infrared (MIR) laser sources have attracted much attention and been widely used in the fields including medicine, atmospheric detection, remote sensing, and photoelectric countermeasures[1–5]. Compared with other methods, the optical parametric oscillator (OPO) is regarded as the most efficient and promising technique for obtaining 4–5 μm MIR lasers with the advantages of high power, high efficiency, good beam quality, wide tunability, etc. As the key element of OPO, the nonlinear optical crystal plays a significant role in output laser characteristics and directly determines the output power and conversion efficiency. The $ZnGeP_2$ (ZGP) crystal has the merits of high effective nonlinear coefficient (75 pm/V), wide optical transmission range (2–12 μm), good thermal conductivity [36.0 W/(K·m)], high damage threshold (30 GW/cm^2), and so on[6–8]. Based on the above merits, a 4.3 μm MIR ZGP-OPO with high power and high efficiency is studied, even though it must be pumped by the laser source with a wavelength beyond 2 μm because of its strong absorption at the near infrared wavelength.

The biggest challenge for a high-power and high-efficiency ZGP-OPO is how to develop a high-power/energy 2 μm pump source with good beam quality[9–11]. To date, there are mainly three ways to produce 2 μm lasers: OPO laser sources[7,12,13], thulium (Tm)-doped crystalline and fiber lasers[14–16], and holmium (Ho)-doped crystalline lasers[10,11,17–21]. In 2004, Haidar *et al.* realized a ZGP-OPO pumped by $KTiOAsO_4$ (KTA)-OPO, generating MIR lasers tunable from 5.5 to 9.3 μm with maximum pump to idler conversion efficiency of 8.25%[7]. The schematic was very complex, and the undesirable beam quality of the first-stage OPO limited further improvement of the conversion efficiency. In 2008, Creeden *et al.* firstly, to the best of our knowledge, reported a ZGP-OPO directly pumped by a pulsed Tm^{3+}-doped fiber laser at 1.99 μm, generating 3.4–3.9 μm and 4.1–4.7 μm MIR lasers with a slope efficiency of 35%[14]. However, the pumping wavelength is near the transmission band-edge of ZGP, resulting in high absorption and heavy thermal effect and thus relatively low conversion efficiency. Recently, Ho^{3+}-doped solid-state lasers directly pumped by an ~1.9 μm laser offer a series of advantages, including high short-pulse extraction efficiency, low quantum defect, and sufficient redshift to the band-edge of ZGP, and become the main pump source for ZGP-OPO. In 2014, Yao *et al.* used a 2.1 μm acousto-optically (AO) Q-switched Ho:$Y_3Al_5O_{12}$ (YAG) laser pumped by four Tm:$YLiF_4$ (YLF) lasers to pump two ZGP crystals with a rectangle configuration and obtained MIR laser output with a central wavelength of 3.94 μm for the signal and

4.5 μm for the idler, corresponding to the slope efficiency of 44.6%[11]. In 2017, Ji *et al.* realized an MIR ZGP-OPO pumped by high-energy 2.09 μm Ho:YAG laser with an output energy of 1.28 mJ and a slope efficiency of 41.7% around 4 μm[21]. In 2018, Schellhorn *et al.*[22] used 2.05 μm Ho^{3+} $LuLiF_4$ (LLF) master oscillator power amplifier (MOPA) with 100 Hz repetition rate as the pump source of ZGP-OPO, obtaining up to 36 mJ of MIR pulse energy in the 3–5 μm range.

In this paper, a Tm^{3+}-doped fiber laser end-pumped AO *Q*-switched Ho:YAG laser with average output power of 35 W and pulse width of 38 ns at 2.091 μm is established. Then, by using a ZGP crystal as the nonlinear OPO convertor, 2.65 W at 4.07 μm for the signal and 10.62 W at 4.30 μm for the idler are achieved, corresponding to the total MIR conversion efficiency and slope efficiency of 37.9% and 67.1%, respectively. In addition, the output spectrum and power characteristics are emphatically investigated. The results can pave a way for designing high-power and high-efficiency 4–5 μm MIR laser sources.

2. Experimental Setup

The schematic of the ZGP-OPO is shown in Fig. 1. The pump source is an AO *Q*-switched Ho:YAG laser. Two high-power Tm^{3+}-doped fiber lasers with the central wavelength of 1908 nm are used to end pump two Ho:YAG crystals, forming the tandem connection resonator. The pump lights are focused onto the crystals with a diameter of 700 μm by two lenses with the focal length of 500 mm, respectively. Two 45° mirrors with high-transmission (HT) coating at 1908 nm ($T > 99.3\%$) and high-reflection (HR) coating at 2091 nm ($R > 99.8\%$) for s-polarized components are used to adjust the output beam to be linearly polarized, avoiding the use of polarizing devices and decreasing the loss of the resonator. Two Ho:YAG crystals with dimensions of 3 mm × 3 mm × 20 mm and doping concentration of 0.8% are selected as the gain medium, which are wrapped with indium foil and placed in a copper block cooled by water at a temperature of 17°C. The plane input mirror (IM) is HT coated at 1.9 μm and HR coated at 2.1 μm.

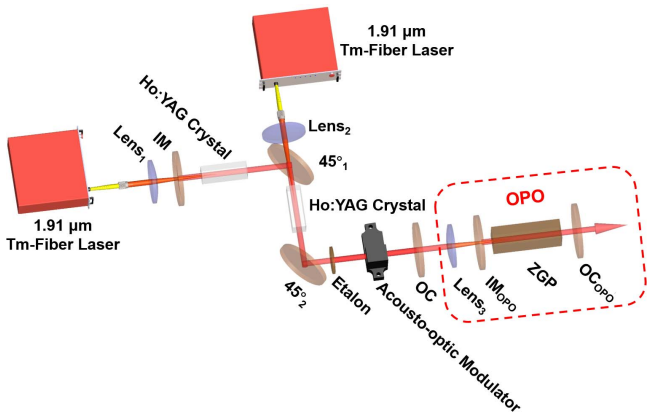

Fig. 1. Experimental schematic.

The output coupler (OC) with a radius of 200 mm and transmission of 40% at 2.1 μm is used. An acousto-optic *Q*-switch is used as the modulator for laser pulses generation. In addition, a 0.1 mm thick YAG etalon is used to realize the longitudinal mode selection.

The AO *Q*-switched Ho:YAG laser is utilized to pump the ZGP-OPO. The output laser is focused into the center of the ZGP crystal with a radius of 600 μm by a lens with a focal length of 150 mm. The OPO cavity consists of a ZGP crystal and two CaF_2 mirrors separated by 35 mm. The ZGP crystal is 6 mm × 6 mm × 25 mm in size with type I phase matching ($\theta = 55°$ and $\varphi = 0°$), and the two faces are antireflection (AR) coated at 2.09 and 4.0–4.5 μm. It is also wrapped with indium foil and placed in a copper block cooled by water at 18°C. IM_{OPO} is a plane mirror AR coated at 2.1 μm and HR coated at 3.6–5.0 μm. OC_{OPO} is a plane mirror HR coated (> 99.9%) at 2.1 μm and with partial transmission of ∼20% at 4.0–4.5 μm, where 20% is for 4.3 μm and 15% is for 4.1 μm. To avoid the pump light reflected back to the Ho:YAG laser, the OPO resonator mirrors are set with a small angle (∼10 mrad) to the pump beam.

3. Results and Discussion

Firstly, the high-power and high-efficiency AO *Q*-switched 2.1 μm Ho:YAG laser is realized. The output power and spectrum are measured by power meter (Newport, 1918-R) and near infrared spectrometer (APE, RS232, Germany), respectively. The experimental results are shown in the Fig. 2. In the continuous wave (CW) regime, as high as 38 W output power is obtained with a central wavelength of 2095 nm and a line width of 4.5 nm under the pump power of 87 W. The corresponding slope and optical-to-optical conversion efficiency are 55% and 43.7%, respectively. In the AO *Q*-switched regime, the maximum average output power is determined to be 35 W with a central wavelength of 2091 nm and a line width of 1.3 nm, corresponding to the slope and optical-to-optical efficiencies of 50.6% and 40.2%. At maximum average power, the shortest output pulse width is 38 ns with a pulse repetition rate of 15 kHz, as shown in Fig. 2(c). The output pulse is detected by an InGsAs fast response photodetector (EOT, ET-5000, USA). The time-domain pulse train and pulse profile are recorded by a digital oscilloscope (1 GHz, Tektronix DPO 7102, USA). Thus, the single pulse energy and peak power are calculated to be 2.33 mJ and 61.4 kW. In addition, the beam quality factor M^2 in the parallel and perpendicular directions measured by a beam quality analyzer (NanoScan by Photon, Inc.) is 1.5 and 1.6, as shown in Fig. 2(d). The established high-power and desirable beam quality Ho:YAG at 2091 nm is the basis for the high-power and high-efficiency ZGP-OPO.

Afterwards, the 2.1 μm laser is used to pump ZGP-OPO. Here, to realize the high-efficiency and low-threshold OPO operation, an external cavity doubly-resonant OPO (DRO) is designed. The output characteristics of ZGP-OPO are shown in Fig. 3. The output power and spectrum are measured by a power meter (PM 100D, Thorlabs, USA) and an MIR

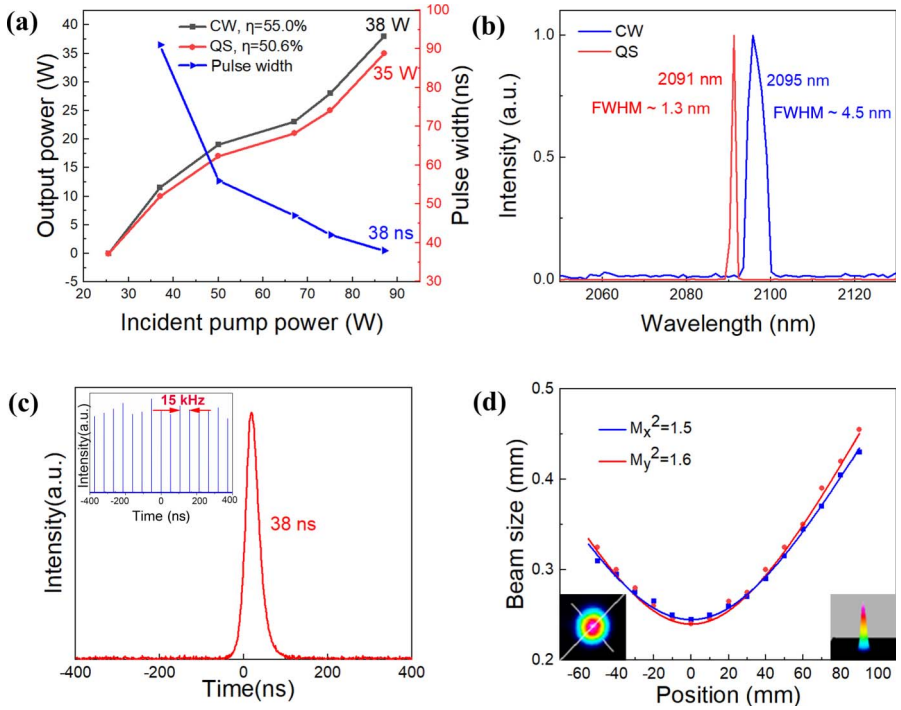

Fig. 2. Output characteristics of 2.1 μm AO *Q*-switched Ho:YAG laser. (a) Average output power and pulse width vary with pump power in the CW and *Q*-switched regimes; (b) laser output spectrum in the CW and *Q*-switched regimes; (c) the pulse profile under the maximum average output power (the insert is the corresponding pulse train with a repetition rate of 15 kHz); (d) the beam quality factor under the maximum average output power (the inserts are 2D and 3D profiles).

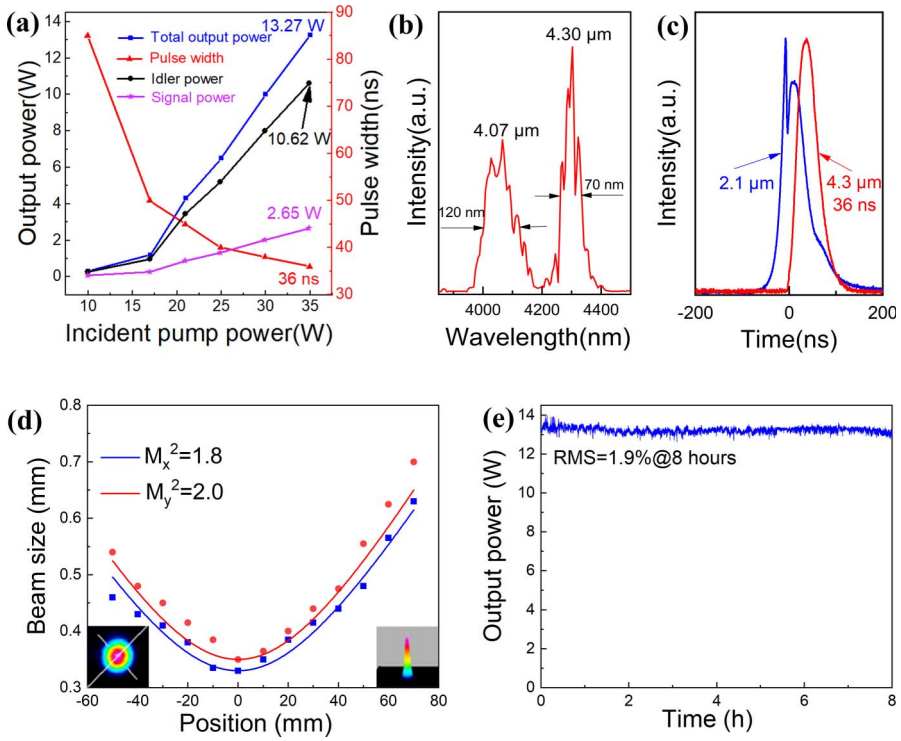

Fig. 3. Output characteristics of ZGP-OPO. (a) Average output power and pulse width vary with pump power; (b) OPO output spectrum; (c) pulse profiles of depleted pump laser and generated OPO laser pulses; (d) beam quality factor of 4.3 μm at the maximum output power; (e) total ZGP-OPO output power stability.

multi-purpose monochromator spectrograph (SOL, MS3504i, Belarus), respectively. It can be seen from Fig. 3(a) that with the increase of pump power, the average output power increases accordingly, while the pulse width gradually decreases. The threshold pump power is determined to be 9 W. The maximum total average power of the OPO reaches up to 13.27 W with the pulse width of 36 ns at the maximum pump power of 35 W, corresponding to the total slope efficiency and optical-to-optical conversion efficiency of 67.1% and 37.9%, respectively. Thus, the single pulse energy and peak power are calculated to be 0.88 mJ and 24.6 kW. It should be noted that the total OPO output power has not reached saturation, which therefore can be further promoted with higher pump power.

The ZGP-OPO output spectrum is measured and shown in Fig. 3(b). The central wavelengths of the signal and idler are determined to be 4.07 and 4.3 μm with an FWHM linewidth of 120 nm and 70 nm, respectively. By using a CaF_2 prism and considering the OPO output spectrum, the output powers of the signal and idler are measured and calculated to be 2.65 W and 10.62 W, respectively. The corresponding optical-to-optical and slope efficiencies of 4.3 μm idler output are 30.3% and 53.7%. The single pulse profiles of the depleted pump laser and generated OPO laser are detected by an InGsAs fast response photodetector (EOT, ET-5000, USA) and HgCdTe MIR photodetector (PVI-2TE-5, VIGO System S.A.) and recorded by digital oscilloscope (1 GHz, Tektronix DPO 7102, USA), as shown in Fig. 3(c). A part of the top of the pump laser pulse is consumed and converted to OPO output, which is consistent with the law of energy conservation[23]. The OPO laser output wavelength tuning can be achieved by slightly rotating the angle of the ZGP crystal. But, limited by the phase matching angle of the ZGP crystal and cavity mirror coating parameters, the output power of the idler reaches its maximum at the wavelength of 4.3 μm. In addition, at the maximum average power of 10.65 W, the beam quality factor of the idler at 4.3 μm is measured by the beam quality analyzer (NanoScan by Photon, Inc.). As shown in the Fig. 3(d), M^2 in the parallel and perpendicular directions are 1.8 and 2.0, respectively. Finally, the total OPO output laser stability is measured to be RMS = 1.9% under 8 h operation, as shown in Fig. 3(e).

4. Conclusion

In conclusion, a high-power AO Q-switched Ho:YAG laser at 2.1 μm with a maximum average output power of 35 W and shortest pulse width of 38 ns at the repetition rate of 15 kHz is established and applied as the pump source of doubly resonant ZGP-OPO. The maximum total average power of ZGP-OPO is determined to be 13.27 W, where 2.65 W is for the signal at 4.07 μm and 10.62 W is for the idler at 4.3 μm, corresponding to the total slope efficiency and optical-to-optical conversion efficiency of 67.1% and 37.9%, respectively. The beam quality factor of $M_x^2 = 1.8$, $M_y^2 = 2.0$ and the output stability of RMS = 1.9% are achieved at the maximum average output power. The results can provide an effective way for 4–5 μm MIR laser generation. The high-efficiency and high beam quality 4.3 μm MIR source we obtained has the great potential for gas detection, medical diagnosis, photoelectric countermeasures, and other fields.

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