

# Performance evaluation of ZnGeP<sub>2</sub> optical parametric oscillator pumped by a Q-switched Tm,Ho:GdVO<sub>4</sub> laser

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A doubly resonant ZnGeP<sub>2</sub> (ZGP) optical parametric oscillator (OPO) pumped by a novel Tm,Ho:GdVO<sub>4</sub> laser was demonstrated. Cryogenic Tm(5 at.-%), Ho(0.5 at.-%):GdVO<sub>4</sub> laser with high pulse repetition frequency (PRF) of 10 kHz at 2.05 μm was employed as pumping source of ZGP OPO. The 15-mm-long ZGP crystal, 55° cut for I-type phase-matching with low absorption coefficient less than 0.05 cm<sup>-1</sup> at 2 μm, was placed in a plano-plano cavity with resonator length of 30 mm. The ZGP OPO generated a total combined output power of 1.2 W at 3.75 and 4.52 μm under pumping power of 5.3 W, corresponding to slope efficiency of 40% from incident 2-μm laser power to mid-infrared (Mid-IR) output. A widely tunable range from 3.0 to 6.5 μm was achieved by changing the crystal angle only 3.5°.

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High power, high pulse repetition frequency (PRF) (> 10 kHz) tunable solid-state mid-infrared (Mid-IR) lasers are useful in many applications such as laser radar, chemical detection, and countermeasure. Among the nonlinear crystals of AgGaSe<sub>2</sub>, LiNbO<sub>3</sub> (PPLN), ZnGeP<sub>2</sub> (ZGP), output power over 0.4 W from PPLN optical parametric oscillator (OPO) has been achieved at 3.4 μm by Lin *et al.*<sup>[1]</sup>, but PPLN has larger absorption coefficient at the wavelength longer than 3.8 μm, which hinders its applications in Mid-IR OPO. As a Mid-IR nonlinear crystal, ZGP has outstanding fundamental properties. The ZGP with very high nonlinear-optical coefficient ( $d_{\text{eff}} = 75$  pm/V) combines with good optical, mechanical, and thermal properties (thermal conductivity of 18 W/(m·K)), so the ZGP favors efficient high-average-power Mid-IR OPOs<sup>[2]</sup>. In the most powerful mid-IR OPO, Cheung *et al.* presented a 10-W ZGP OPO pumped at 2.05 μm using a cryogenic Tm,Ho:YLF laser<sup>[3]</sup>. Budni *et al.* reported a 4.2-W one pumped by a room temperature Ho:YAG laser<sup>[4]</sup>. We proposed a 0.7-W OPO pumped by a Tm,Ho:YLF laser<sup>[5]</sup>. The low gain of Tm,Ho:YLF medium leads to longer pulse width and unstable pulse amplitude at 2 μm, which prevents the ZGP OPO from power scaling and stability<sup>[6]</sup>. So, another medium, Tm<sup>3+</sup>, Ho<sup>3+</sup>-codoped GdVO<sub>4</sub>, was evaluated for generating 2-μm radiation to pump ZGP OPO.

The thulium in GdVO<sub>4</sub> has considerably greater absorption cross section and broader absorption bandwidth (770 – 820 nm), comparing with that in YAG and YLF, and the wavelength is shifted closer to the emission wavelength of commercially available AlGaAs laser diodes (LD)<sup>[7]</sup>. GdVO<sub>4</sub> host has good thermal-mechanical property and can experience > 12 kW/cm<sup>2</sup> pump density. The Boltzman coupling lifetimes between Tm <sup>3</sup>F<sub>4</sub> and Ho <sup>5</sup>I<sub>7</sub> in GdVO<sub>4</sub> host are 3 ms shorter than 9 ms for Tm,Ho:YAG and 15 ms for Tm,Ho:YLF<sup>[8]</sup>.

Figure 1 shows the scheme of the experimental setup. The Tm,Ho:GdVO<sub>4</sub> crystal was end-pumped by a fiber-coupled LD which delivers maximum 20-W content with fiber core diameter of 0.4 mm and numerical

aperture of 0.22. The LD was temperature-tuned to wavelength of 801 nm and refocused into crystal with approximate beam diameter of 0.6 mm for optimum overlap between the pump beam and the laser beam. The gain medium was a Tm (5 at.-%) and Ho (0.5 at.-%) codoped GdVO<sub>4</sub> crystal with the dimension of 4(width) × 4(height) × 7(length) (mm). Both end faces were antireflection (AR) coated for both the laser wavelength ( $R < 0.3\%$ ) and the pumping light of 801 nm ( $R < 1\%$ ). The crystal was wrapped in indium foil and held in a copper heat-sink connected with a small Dewar filled with liquid N<sub>2</sub>. The input mirror M<sub>1</sub> of Tm,Ho:GdVO<sub>4</sub> laser was a plano-concave one with AR coating at 800 nm on the entrance face ( $R < 0.2\%$ ) and with high-reflection (HR) coating at 2050 nm ( $R > 99.5\%$ ) and high-transmission (HT) coating at 800 nm ( $T > 96\%$ ) on the concave surface. The curvature radius was 400 mm. The output coupler M<sub>2</sub> was a flat water-free fused silica mirror with 60% transmissivity at 2050 nm. The total cavity length was around 110 mm. Infrared fused silica (water free) acousto-optic Q-switch was located between the Tm,Ho:GdVO<sub>4</sub> crystal and the output coupler and oriented such that the optical polarization and acoustic wave vector were mutually orthogonal for optimum scattering. It was rated for 10-W maximum radio frequency (RF) input power at frequency of 27.12 MHz. The modulation loss (with vertical polarization) > 50% at 10 W RF power, which was adequate to prevent intracavity lasing action.

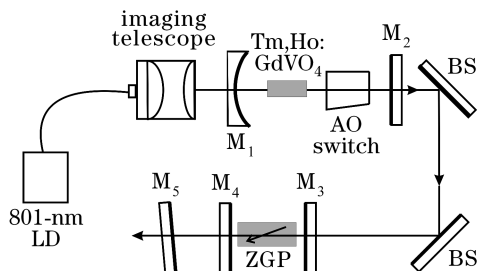


Fig. 1. Experimental configuration of ZGP OPO pumped by a Q-switched Tm,Ho:GdVO<sub>4</sub> laser.

Over 5-W average power at  $2.05\ \mu\text{m}$  was achieved with 17 W of LD power incident onto  $\text{Tm,Ho:GdVO}_4$  crystal. Pulse width measurements were performed using of a fast photovoltaic  $\text{HgCdZnTe}$  detector ( $< 1\text{-ns}$  response time) connected with a TDS 3012B 300-MHz digital oscilloscopes. At a  $Q$ -switch frequency of 10 kHz, we achieved an approximate 23-ns full-width at half-maximum (FWHM) pulse with single pulse energy of about 0.5 mJ, and a peak power of approximate 23 kW.

The  $\text{Tm,Ho:GdVO}_4$  laser output was used to pump a ZGP OPO, which was operated using a simple resonator with two flat mirrors arranged as a linear cavity and configured as a doubly resonant oscillator (DRO). The input dichroic mirror  $M_3$  was coated HT at the  $2.05\ \mu\text{m}$  and HR in the range of  $3.5\text{--}4.5\ \mu\text{m}$ . The output coupler  $M_4$  reflectivity was  $\sim 50\%$  across the entire  $3\text{--}5\ \mu\text{m}$  region. The OPO resonator length was  $\sim 3\ \text{cm}$  and the diameter of the pump beam in ZGP crystal was  $\sim 0.7\ \text{mm}$ .  $M_5$  was the filter of OPO with reflectivity of greater than  $99.5\%$  at  $2.05\ \mu\text{m}$  and with transmissivity of about  $95\%$  across  $3\text{--}5\ \mu\text{m}$ , which separated the OPO signal and idler from the pump.

The ZGP crystal with the dimension of  $6 \times 8 \times 15$  (mm) was AR coated at the pump, signal, and idler. The measured absorption coefficient for o-light at  $2.05\ \mu\text{m}$  was about  $0.05\ \text{cm}^{-1}$ . The crystal was cut for type I phase-matching at  $55^\circ$  to achieve the desired wavelengths. Figure 2 shows the output power versus input power for the ZGP OPO. At the pump drive level of 5.3 W incident upon the OPO crystal, the output average power reached 1.2 W with an overall optical-optical conversion efficiency of 23%, operating at 2.2 times threshold. A linear fit yielded a 40% slope efficiency, and power threshold was approximately 2.4 W of input ( $2.7\ \text{MW/cm}^2$ ). No saturation occurred at this level of pumping power. The higher average power was restricted by the AR-coating damage of ZGP crystal.

At the maximum average power of 5 W, stable temporal profile of multiple pulses overlapped was measured and shown in Fig. 3(a). Temporal profile at the maximum output power of 1.2 W was observed with a  $\text{HgCdZnTe}$  detector and a digital TDS 3012B oscilloscope. The stable pulse train with pulse width of 17 ns was shown in Fig. 3(b).

The spectral content of OPO output was measured with a 0.3-m WDM1 – 3 monochromator and InSb detector. We observed a broad-spectrum envelope with

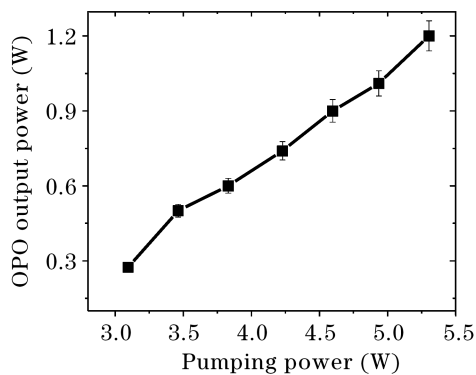


Fig. 2. Output power from ZGP OPO as a function of pumping power.

approximate 150 nm for the signal and 200 nm for the idler. The signal wavelength with peak spectral power was  $3.75\ \mu\text{m}$  (see Fig. 4(a)), and the corresponding idler wavelength was  $4.52\ \mu\text{m}$  (see Fig. 4(b)). Both signal and idler signatures contained a periodic structure, and we attributed the structure to the clustering effect presented in the DRO geometry.

The wavelength of ZGP OPO was tuned by rotating the crystal in the  $x$ - $z$  plane. The angle of ZGP was achieved by a computer controlled stepping motor with  $0.01^\circ$  accuracy. The signal was tunable from 3.0 to

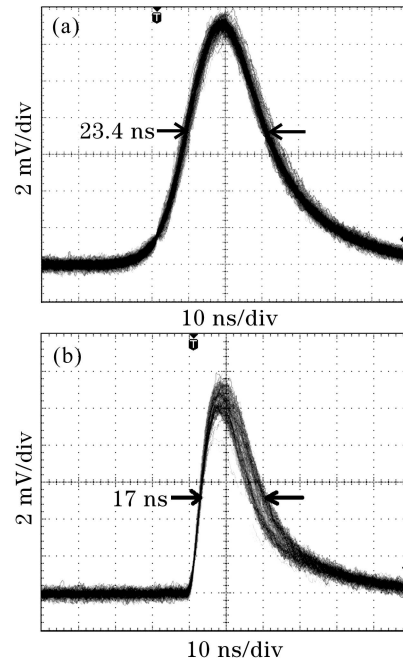


Fig. 3. Overlapped multiple-pulse temporal profile of (a)  $Q$ -switched  $\text{Tm,Ho:GdVO}_4$  laser and (b) ZGP OPO.

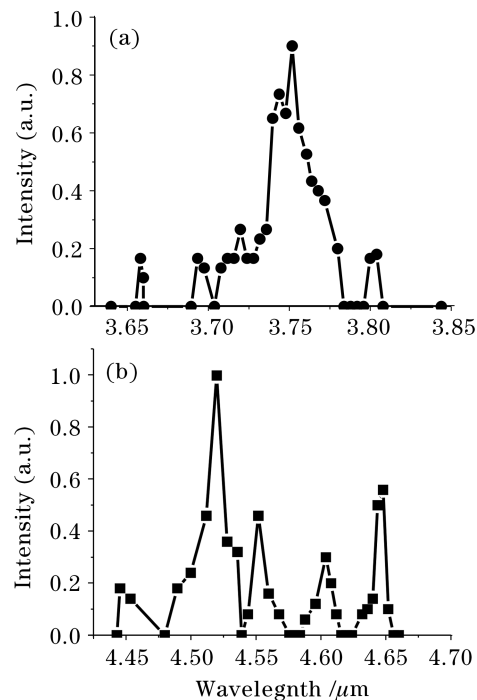


Fig. 4. Spectra of (a) signal and (b) idler from ZGP OPO.

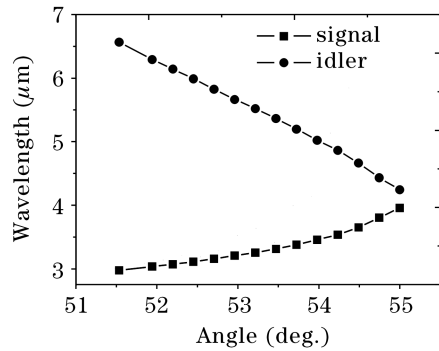


Fig. 5. Output wavelength from OPO dependent on the ZGP crystal angle.

4.1  $\mu\text{m}$  and the idler was tunable from 4.1 to 6.5  $\mu\text{m}$  with the angle change from  $51.5^\circ$  to  $55^\circ$ , as shown in Fig. 5.

OPO output beam spatial profile was observed with thermal-sensitive paper, displaying a high degree of filled circular symmetry once the resonator was aligned, with no evidence of distortion or break up. The measured beam quality  $M^2$  factor was less than 2.6.

In summary, we have evaluated the performance of ZGP OPO pumped by a new type gain medium of Tm,Ho:GdVO<sub>4</sub>. Average power of 1.2 W was generated at combined 3.75 and 4.52  $\mu\text{m}$ , and 3.0–6.5  $\mu\text{m}$  tunable range was obtained from ZGP OPO. It was demonstrated that the Tm,Ho:GdVO<sub>4</sub> laser and ZnGeP<sub>2</sub> crystal were excellent as a pumping source and nonlinear frequency-converting crystal, respectively. High power OPO up to 10 W in the Mid-IR region could be attained by scaling

up the Tm,Ho:GdVO<sub>4</sub> laser output greater than 20 W. The further work will be reported in the future.

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