

Mid-infrared optical parametric oscillator based on ZnGeP₂ pumped by 2- μ m laser

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We present a 3–5 μ m optical parametric oscillator (OPO) based on ZGP pumped by KTP OPO 2.1- μ m laser. The tuning curves of ZGP OPO are calculated. The $8 \times 6 \times 18$ (mm) ZGP crystal, whose end faces are antireflection coated at 2.1 and 3.7–4.6 μ m, is cut as $\theta=53.5^\circ$, $\phi=0^\circ$. When the pump power of 2.1- μ m polarized laser is 15 W at 8 kHz, 5.7-W output power and 46.6% slope efficiency are obtained with a ZGP type I phase match. Central wavelengths of the signal and idler lasers are 4.10 and 4.32 μ m, respectively. Pulse duration is about 27 ns. Beam quality factor M^2 is better than 1.8. The tunability of 3–5 μ m can be achieved by changing the angle of the ZGP crystal.

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Mid-infrared (MIR) lasers in the 3–5 μ m wavelength region have important applications in many fields, such as military countermeasure, atmosphere monitoring, remote monitoring of special environment, medical cure, spectrum, and so on^[1–4]. Due to its wide tunability, high efficiency, high power, and compact solid-state configuration, the optical parametric oscillator (OPO) is an effective way of generating MIR lasers. Several 10-W output power of MIR lasers have been achieved by PPLN OPO and ZGP OPO^[5–13]. It is very difficult to obtain high-power and high-efficiency MIR lasers beyond 4.2 μ m in PPLN OPO due to the strong absorption in PPLN. Compared with other crystals, ZGP is an ideal nonlinear crystal for OPO operating at 3–10 μ m, and has special merits with longer wavelength than 4.2 μ m. ZGP can offer a unique combination of large effective nonlinear optical coefficient ($d_{\text{eff}}=75$ pm/V), high damage threshold, high thermal conductance, and high stability. Cheung *et al.* reported a type I ZGP OPO pumped by 2.13- μ m Nd:YAG-pumped KTP OPO laser, with 14-W output power for both signal and idler lasers. A 24-W output power was also extracted from two independent ZGP OPO stages pumped by orthogonal polarizations of KTP OPO^[9]. Zhu *et al.* reported 3–5 μ m maximal output power of 14.1 W from the ZGP OPO pumped by a 2.049- μ m Tm, Ho:GdVO₄ laser cooled by liquid nitrogen. The beam quality factor M^2 of the ZGP OPO was 3.6 with 6-W output power^[10]. At present, BAE systems (USA) can produce a ZGP crystal as large as $20 \times 20 \times 30$ (mm), with an absorption coefficient less than 0.05 cm^{-1} at 2.1 μ m^[14]. With the development of the 2- μ m laser and the growth of high-quality ZGP crystal, ZGP OPO pumped by 2- μ m laser shows great potential in high power MIR laser field.

In this letter, we use an intracavity KTP OPO 2.1- μ m laser to pump ZGP OPO. There is a total output power of 5.7 W for 4.10- μ m signal laser and 4.32- μ m idler laser with the pump power of 15 W. The slope efficiency is 46.6%.

The ellipse refractive index equation of birefringent uniaxial crystal, energy conservation, and momentum conservation for three-wave mixing in OPO can be expressed

as

$$\begin{cases} 1/\lambda_p = 1/\lambda_s + 1/\lambda_i \\ n_p/\lambda_p = n_s/\lambda_s + n_i/\lambda_i \\ n_e(\theta) = n_o \times n_e / (n_o^2 \sin^2 \theta + n_e^2 \cos^2 \theta)^{1/2} \end{cases}, \quad (1)$$

where λ_p , λ_s , and λ_i are the wavelength of pump, signal, and idler laser, respectively; n_p , n_s , and n_i are the corresponding refractive indices; n_e and n_o are the refractive indices of the crystal principal axis; θ is the angle between the wave vector and the crystal optical axis.

The Sellmeier equation of ZGP crystal is

$$\begin{cases} n_o^2 = 4.61511 + \frac{5.12798\lambda^2}{\lambda^2 - 0.13624} + \frac{2.16936\lambda^2}{\lambda^2 - 900} \\ n_e^2 = 4.69874 + \frac{5.27924\lambda^2}{\lambda^2 - 0.14399} + \frac{2.09861\lambda^2}{\lambda^2 - 900} \end{cases}. \quad (2)$$

ZGP is a positive uniaxial chalcopyrite crystal. With an ordinary light as the pump, the cut angle φ is 0° for type I phase match (o \rightarrow e+e), and φ of 45° for type II phase match (o \rightarrow o+e). The angle tuning curves of ZGP OPO can be obtained through Eqs. (1) and (2). Figure 1 shows the types I and II phase-matched tuning curves of ZGP OPO when pumped by 2.12- μ m laser. The tuning range of type I phase match is 2.7–9.4 μ m, with the angle tuning of 50.1° – 53.7° . The MIR tunability of 3.6–5 μ m can be achieved by changing the angle from 53.2° – 53.7° . This tiny angle tuning is propitious to the wavelength tuning and the stability of the beam direction, and prevents the deflection of the cavity axis. The tuning range of type II phase match is 2.6–11.3 μ m, with the angle tuning of 59.2° – 85.5° . However, there is an interstice between 3.4 and 5.7 μ m. Type II phase matching is improper for MIR wavelength tuning in the 3–5- μ m range.

The pump wavelength of ZGP OPO is usually near 2.1 μ m because of the strong absorption in ZGP of lasers below 2 μ m. There are mainly two ways of generating 2.1- μ m laser: rare-earth-doped solid laser and OPO. The pump source used in the experiment is the 2.12- μ m laser from KTP OPO pumped by Q-switched Nd:YAG laser.

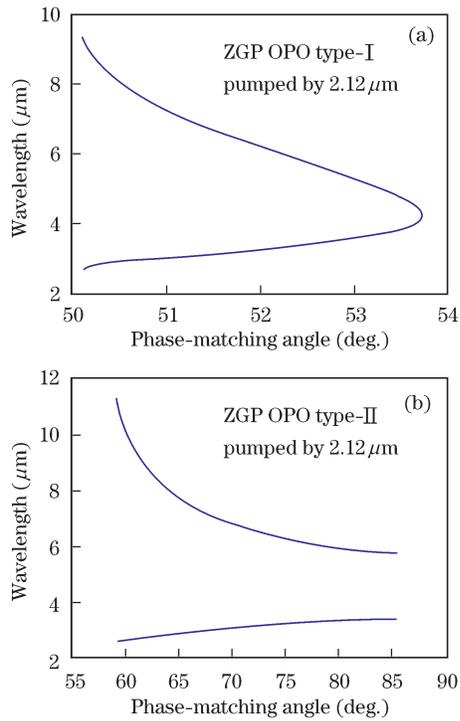


Fig. 1. OPO wavelength tuning curves in ZGP (a) type-I and (b) type-II.

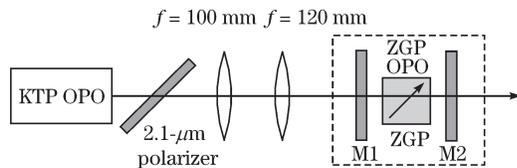


Fig. 2. Schematic of ZGP OPO pumped by 2.1- μm KTP OPO.

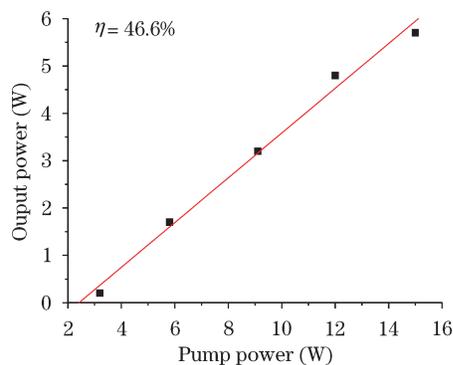


Fig. 3. ZGP-OPO output power versus the pump power of 2.1- μm laser (η is slope efficiency).

High power and good beam quality of 2.12- μm laser can be achieved by compact intracavity KTP OPO. When the output power of KTP OPO 2.1- μm laser is 30 W, the beam quality factor M^2 is better than 1.2. A 2.1- μm polarizer is used for type II degenerate KTP OPO to generate signal and idler beams that are orthogonally polarized. High efficiency and high beam quality of mid-IR lasers can be obtained from ZGP OPO pumped by high beam quality 2.1- μm laser. The setup of the ZGP OPO pumped by 2.1- μm laser is shown in Fig. 2. The

2.1- μm laser from KTP OPO pumps the ZGP crystal after the polarizer and the coupled system, which adjusts the beam size to about 1.2 mm. Flat mirrors M1 and M2 form the resonant cavity of ZGP OPO. M1 is antireflection (AR) coated at 2.1- μm and high reflection (HR) coated at 3.7–4.6 μm . M2 is HR coated at 2.1 μm , and $R=60\%$ at 3.7–4.6 μm . The 8 \times 6 \times 18 (mm) ZGP is cut as $\theta = 53.5^\circ$, $\phi=0^\circ$. Both end faces are AR coated at 2.1 and 3.7–4.6 μm .

When pump power of the p -polarized 2.1 μm laser is 15 W at 8 kHz, output power of 5.7 W and slope efficiency of 46.6% from ZGP OPO are obtained. The output power versus the pump power of 2.1- μm laser is shown in Fig. 3. The output power saturation of ZGP OPO does not appear, so it is possible to obtain higher output power with higher pump power. Figure 4 shows the output spectrum. Central wavelengths of the signal and idler lasers are 4.10 and 4.32 μm , respectively. The transmission rate of the polarizer, the coupled system, and the ZGP crystal are about 95%, 96%, and 83% at 2.1 μm , respectively. The conversion efficiency of ZGP OPO is influenced by the low transmission rate. The conversion efficiency can be enhanced by increasing the coating's transmission rate and reducing the loss in ZGP crystal at 2.1 and 3.7–4.6 μm . The wavelength tunability

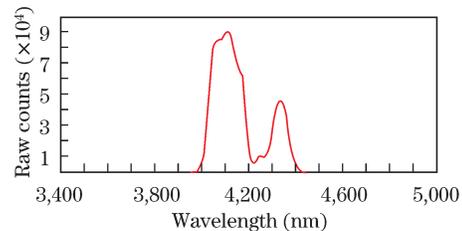


Fig. 4. Spectrum of the output laser from ZGP-OPO.

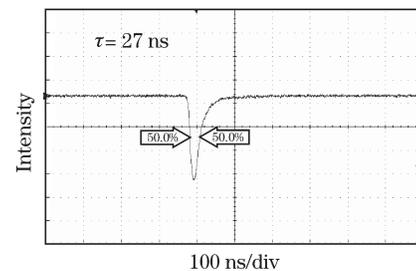


Fig. 5. Temporal profile of ZGP OPO output laser pulse. τ is the pulse width.

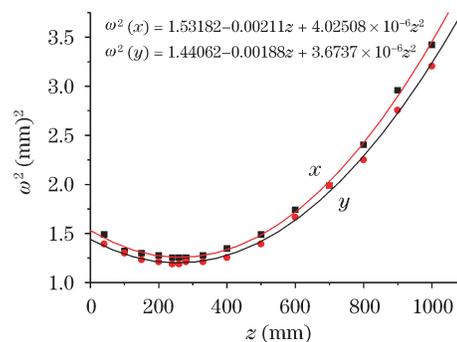


Fig. 6. Nonlinear curve fit of spot radius.

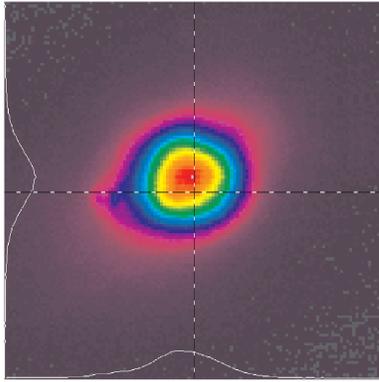


Fig. 7. Near field intensity distribution of the ZGP OPO output laser.

of 3–5 μm is achieved by changing the angle of the ZGP crystal. The output power in the 3.9–4.6 μm range is higher than other wavelength ranges as limited by the coating parameters of ZGP OPO in 3.7–4.6 μm . The pulse width of the ZGP OPO output laser is measured with a detector responsible within 1–12 μm . The pulse width is about 27 ns, as shown in Fig. 5. The beam quality factor M^2 is measured by the size of the laser spot at different locations, and by hyperbolic fitting of the measured data. The data are taken around the beam waist after a focusing lens with focal length of 200 mm. The beam quality factor M^2 is calculated in accordance with curve fitting parameters, as shown in Fig. 6. The beam quality factors M^2 of ZGP OPO are 1.72 and 1.61 in the parallel and perpendicular directions, respectively. Figure 7 shows the near field intensity distribution of ZGP OPO. In a similar configuration, the s-polarized 2.1- μm laser from KTP OPO can also be used to pump ZGP OPO to achieve the MIR laser output.

In conclusion, a 5.7-W MIR laser with $M^2 < 1.8$ and slope efficiency of 46.6% is achieved by ZGP OPO pumped by KTP OPO in the Nd:YAG laser cavity. Further work will focus on the optimization of the ex-

periment to increase the 3–5- μm output power and the conversion efficiency of ZGP OPO, such as by increasing the transmission rate of the coupled system and the ZGP coating, using high quality ZGP crystal with less loss, and higher power of the 2- μm pump source.

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