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Near to Mid-Infrared (1.3–5 μm) Widely Tunable, High Power Picosecond Pulsed Laser

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Abstract: We present a high-power, widely tunable, synchronously pumped picosecond pulsed optical parametric oscillator (OPO) generating emissions in the near to mid-infrared wavelength ranges. The OPO is pumped using a Nd:YVO₄ picosecond pulsed laser and utilizes a fan-shaped, multi-grating MgO doped PPLN crystal (MgO:PPLN). The system generates near to mid-infrared output across the wavelength range 1.3–5 μm , with a high overall conversion efficiency of 75.15%.

Keywords: optical parametric oscillator; nonlinear optics; near to mid-infrared laser; ultrafast

1. Introduction

Near-infrared (1.3–2 μm) and mid-infrared (2.2–5 μm) wavelength tunable, short-pulse lasers have been applied to numerous applications across a diversity of fields. By generating laser emission at near-infrared wavelengths (and in particular, wavelengths in the eye-safe region), and with short-pulses, the Raman scattering microscopy has seen increasing use in cutting-edge applications in biology [1–3]. Lasers radiating in the mid-infrared wavelength range with picosecond pulse durations have found applications in ultrafast processes, time-domain spectroscopy and laser micromachining, this being due to wavelengths in this spectral band corresponding with the characteristic vibrational absorption of many organic materials [4,5]. This is also an important characteristic for material processing methods, including resonant infrared pulsed laser deposition [6,7]. There is hence great interest in expanding the range of novel lasers, which can further advance these applications.

Nonlinear frequency conversion is perhaps the most commonly used method of wavelength converting laser sources. Some of the most utilized processes include second harmonic generation [8], sum frequency generation [9], OPO [10–13], optical parametric amplification (OPA) [14] and Raman scattering [15]. For the generation of long-wavelength laser fields, OPOs and OPAs are the most commonly used techniques. Here, a short-wavelength pump field is used to generate two longer-wavelength fields. OPOs can be employed to generate widely tunable emissions in the near to mid-infrared wavelength region, with high conversion efficiency, and across both continuous-wave and pulsed regimes. Furthermore, utilization of an OPA with injection seeding can yield narrow linewidth, broadly tunable near to mid-IR laser emission [16–18].

Synchronously pumped optical parametric oscillators (SPOPOs) can be used to generate ultrashort laser pulses in new spectral regions. SPOPOs are typically used with lasers operating in the picosecond (ps) pulse regime and provide a wide wavelength tuning range while maintaining an all-solid-state design. They are useful for a variety of applications which require high power, short pulse durations and a narrow spectral bandwidth [19,20]. A key issue in the design of SPOPOs is the choice of the nonlinear conversion medium. For instance, there are several reports detailing the generation of near- and mid-infrared outputs based on the birefringent-phase-matching (BPM) crystals, including KTiOPO₄ (KTP) [12], KTiOAsO₄ (KTA) [21], and ZnGeP₂ (ZGP) [22]. However, large walk-off effects



Citation: Aihemaiti, M.; Jashaner, D.; Yang, X.; Li, Z.; Yusufu, T. Near to Mid-Infrared (1.3–5 μm) Widely Tunable, High Power Picosecond Pulsed Laser. *Appl. Sci.* **2024**, *14*, 2383. <https://doi.org/10.3390/app14062383>

Academic Editor: Andrey Miroshnichenko

Received: 13 February 2024

Revised: 6 March 2024

Accepted: 8 March 2024

Published: 12 March 2024



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and the low nonlinear coefficient of these crystals impact the optical conversion efficiency and limit the generation of excellent beam quality and high power output. Recent improvements in nonlinear materials have allowed highly efficient and high beam quality laser radiation in the near- and mid-infrared wavelength ranges.

Compared with birefringent crystals, crystals which utilize quasi phase matching (QPM) have been widely employed in the generation of near- and mid-infrared lasers based on optical parametric oscillators due to appealing characteristics of large effective nonlinearity, large acceptance angles, lower walk-off effects, and low susceptibility to photorefractive damage. Several reports are available concerning near- or mid-infrared OPOs utilizing quasi phase matched crystals. These include works based on periodically poled KTiOPO₄ (PPKTP) crystals with a fan-out grating design. From these systems, wavelength tunability in (741–922 nm) and (1258–1884 nm) were achieved with the output powers of 150 mW and 400 mW [23]. Shining Zhu et al. achieved 1.2 W emission from an idler field at 3.8 μm and 3 W emission from a signal field at 1.48 μm from a periodically poled LiTaO₃ (PPLT) crystal-based OPO [24]. MgO:PPLN (magnesium-doped periodically poled lithium niobate) has also attracted significant attention as a non-linear material for use in OPOs due to its multiple properties of high nonlinear coefficient ($\sim 17 \text{ pm/V}$), large transparency range (0.5–5 μm), and its resistance to optical damage.

In recent years, there have been numerous reports investigating the generation of near- to mid-infrared picosecond laser emission using periodically poled crystals with synchronously pumped X-shaped cavities [25–32]. For instance, the team of S. Chaitanya Kumar reported a 1064 nm, 81.1 MHz, picosecond Yb-fiber laser pumped MgO:sPPLT crystal mid-infrared wavelength tunable OPO. The wavelength tunability of the OPO is obtained in the range of 1530–1640 nm (signal beam) and 3022–3488 nm (idler beam), obtaining the maximum tuning length of 577 nm. The high signal output power of 4.3 W at wavelength of 1595 nm and mid-infrared idler output power of 2 W at wavelength of 3200 nm were achieved by adjusting the cavity mirrors, corresponding a total (signal and idler) conversion efficiency of 47%. In 2013, the team reported a 160 Mhz, 532 nm frequency-doubled Yb-fiber laser synchronously pumped picosecond OPO, which consisted of a fan-shape grating designed PPKTP crystal. Resulting signal and idler outputs were widely tuned in the tuning range of 726–955 nm and 1201–1998 nm, respectively. The maximum tuning length of this OPO was 1026 nm.

While the aforementioned results from the literature show the potential for generating wavelength tunable emissions from OPOs, they serve to highlight the complexity and difficulty associated with tuning and optimizing X-shaped cavity designs. Typically, the wavelength tunability of X-shaped cavity OPOs is in the range of 1.43–1.63 μm (signal field) and 3.06–4.16 μm (idler field), with a maximum conversion efficiency of $\sim 73\%$. Compared to X-shaped ring cavity OPOs, Z-shaped cavity OPOs have a simpler design, are easier to adjust and optimize, and are more broadly tunable.

In this research, we investigate the operation of a high-power, widely tunable near- to mid-infrared picosecond pulsed, singly resonant Z-shaped OPO using a MgO:PPLN crystal. The OPO is pumped using a Nd:YVO₄ picosecond pulsed laser and widely tunable signal, and the idler field emission is generated by tuning the grating period and temperature of the MgO:PPLN crystal.

2. Experimental Setup

A schematic of the experimental system was depicted in Figure 1. The pump laser was an all-solid-state Nd:YVO₄ laser with a central wavelength of 1064 nm, a pulse duration of $\sim 15 \text{ ps}$ at a repetition rate of 120 MHz, a maximum power of 19 W, and a TEM₀₀ spatial mode. The pump beam was injected into the OPO, and its power was regulated by utilizing a half-wave plate (HWP) and a thin film polarizer (TFP). Another HWP in the setup was used to control the polarization of the pump beam so as to optimize the type-0 phase matching ($e \rightarrow e + e$) among the pump, signal, and the idler outputs within the nonlinear

crystal. The pump field was focused with a radius of 60 μm in the center of the MgO:PPLN crystal by using a focusing lens ($f = 125 \text{ mm}$).

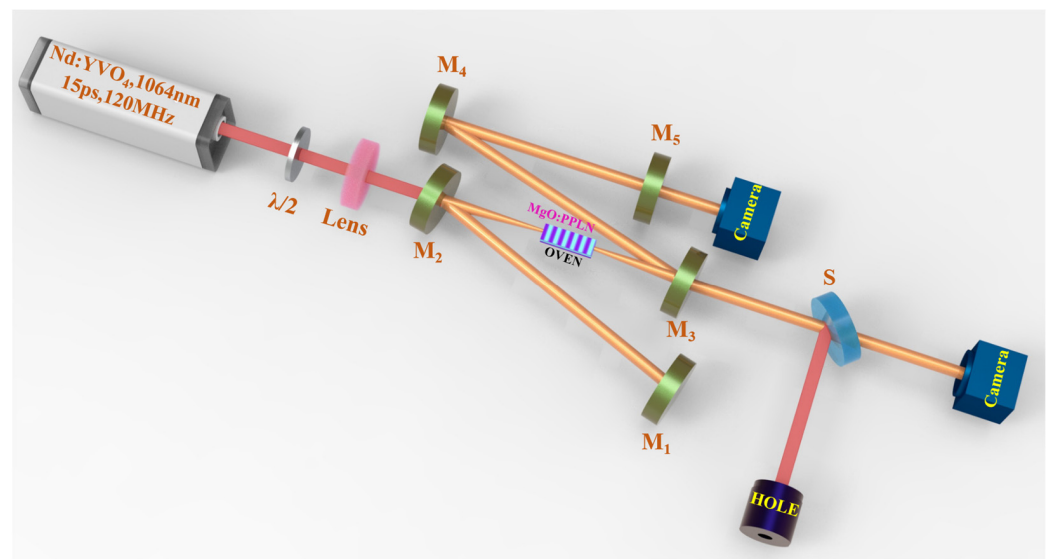


Figure 1. Schematic of the picosecond pulsed synchronously pumped, widely wavelength tunable optical parametric oscillator. $\lambda/2$: Half-wave plate, M1–M5: Cavity mirrors.

The nonlinear crystal used in the SPOPO was a MgO doped periodically polled lithium niobate (MgO:PPLN) crystal. It had a fan-grating with a period which varied from 26–32 μm and dimensions of $50 \times 16 \times 2 \text{ mm}^3$. Compared to MgO:PPLN crystals with ordinary gratings, a fan-shaped MgO:PPLN crystal ensures an output spectrum without wavelength gaps, which provides continuous wavelength tunability of the parametric outputs. The MgO:PPLN was placed in an oven and heated in a tuning range from 25 $^{\circ}\text{C}$ to 200 $^{\circ}\text{C}$ for phase matching. By varying both the phase matching temperature and the spatial position of the pump field within the MgO:PPLN crystal (so as to access different periods of the polled crystal), wide wavelength tunability of the OPO outputs could be obtained. The two end faces of the MgO:PPLN crystal were anti-reflection coated for the pump (1.064 μm), signal (wavelengths of 1.4–1.75 μm), and idler (wavelengths of 2.5–5 μm).

The OPO was constructed to be singly resonant for the signal field and comprised a Z-shaped standing wave cavity consisting of five reflective mirrors. Plane-concave mirrors M2 ($R = 150 \text{ mm}$), and M3 ($R = 150 \text{ mm}$) were positioned at a distance of 90 mm from the two end faces of the MgO:PPLN crystal. A plane-concave mirror M4 ($R = 500 \text{ mm}$) and flat mirrors M1 and M5 also formed the OPO cavity. The cavity mirrors M1–M4 were high-reflecting coated for the signal field (1.4–1.75 μm , $R > 99.9\%$) and anti-reflecting coated for the pump and idler fields (1064 nm, $R < 0.5\%$; 2.5–5 μm , $R < 2\%$). The cavity mirror M5 was coated partially transmitting for the signal field (1.4–1.75 μm , $R \sim 80\%$) to ensure the signal field was singly resonant with a low Q factor. Precise control of the cavity length was required in order to realize effective synchronous pumping of the OPO. It was also a significant factor for improvement of the broadband wavelength tunability of the system. In comparison to the X-shaped cavity, the Z-shaped cavity serves as a standing wave cavity, which has the advantages of simple operation and easy adjustment, and the fundamental mode spot size on the nonlinear crystal was also easy to control. The cavity mirror M1 was placed on a high-precision translation stage to control the cavity length. The round-trip optical path length of the cavity was set to $\sim 1250 \text{ mm}$ and then fine-tuned to achieve synchronization with the 120 MHz of the pump beam. In order to achieve good overlap between the pump and the signal in the cavity, we set the spot size of the signal to $\sim 65 \mu\text{m}$. The idler output beam was separated from the pump and signal beams using a wavelength separator (S), then measured using a pyroelectric camera. The signal beam was extracted from the reflecting mirror (M5) and imaged using a camera.

3. Results and Discussion

3.1. Output Beam Profiles

The spatial distributions of the OPO output beams were recorded by a Spiricon pyroelectric camera III. Depicted in Figure 2a–c are the spatial distributions of the signal field at 1.352 μm , 1.579 μm , and 2.015 μm , respectively, and Figure 2d–f are the spatial distributions of the idler output at 2.254 μm , 3.262 μm , and 4.992 μm , respectively. These images indicated that the OPO outputs oscillated with a Gaussian spatial distribution across the whole wavelength tuning range. The beam quality factor (M^2) of the mid-infrared idler beam at 3.262 μm was measured as 1.3 horizontally and 1.3 vertically, respectively.

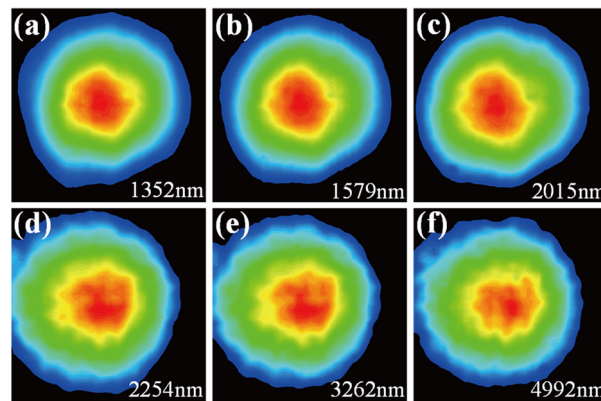


Figure 2. Images showing the spatial distribution of (a–c) signal fields and (d–f) idler fields at different output wavelengths.

3.2. Wavelength Tunability

We measured the wavelength tunability of the picosecond OPO, which was constructed from the 80% output coupler, by controlling the grating period and heating of the MgO:PPLN crystal. In this OPO, the quasi phase matching condition was fulfilled when the phase mismatching wavenumber was equal to zero. This can be described as follows:

$$\Delta k = 2\pi \left(\frac{n_e(\lambda_p, T)}{\lambda_p} - \frac{n_e(\lambda_i, T)}{\lambda_i} - \frac{n_e(\lambda_s, T)}{\lambda_s} - \frac{1}{\Lambda} \right) = 0 \quad (1)$$

where λ_p , λ_s , and λ_i are wavelengths of the pump, signal, and idler outputs, and Λ is the grating period. Additionally, n_e is the refractive index of extraordinary polarized waves in the MgO:PPLN crystal. This depends on the temperature and wavelength of the crystal and can be expressed using the Sellmeier equation [33]

$$n_e^2 = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - (a_3 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5^2} - (a_6 + b_5 f) \lambda^2 \quad (2)$$

where $f = (T - 24.5^\circ\text{C})(T + 570.82)$ is called the temperature parameter. The corresponding parameters a_i and b_i can be found in [33]. Therefore, when the wavelength of the incident pump beam is known, the wavelength tuning characteristics of the signal and the idler fields can be determined by the crystal period and the crystal temperature. Figure 3a shows the wavelength tuning range obtained by varying the crystal period when the crystal temperature is fixed at 25 $^\circ\text{C}$ where the points indicate the experimental values and the curves indicate the simulated theoretical curves. Figure 3b shows the experimental and simulated tuning curves of the output wavelengths of the signal and idler obtained by varying the crystal temperature when the grating period is $\sim 32 \mu\text{m}$. It can be observed from the figure that the tuning curves calculated using the Sellmeier equation are in good agreement with the experimental values.

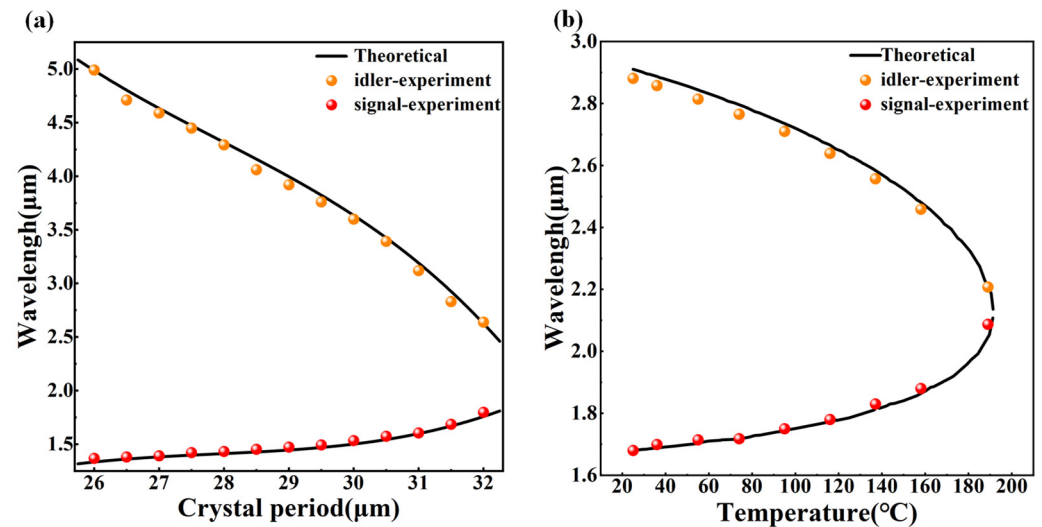


Figure 3. (a) Experimentally measured wavelengths and theoretically calculated tuning curves for different grating periods of the crystal at a MgO:PPLN temperature of 25 $^{\circ}\text{C}$. (b) The mid-infrared wavelength plots at various temperature of the MgO:PPLN. The points indicate experimental, and curves show the simulated theoretical curves.

Wavelength tuning of the OPO output fields generated from the picosecond OPO was investigated by tuning the period that the OPO fields interacted with and the temperature of the crystal, as shown in Figure 4. The wavelengths of the generated OPO output fields were collected with a SpectraPro HRS-500 spectrometer, and the representative spectra are shown in Figure 4. The wide tuning range of the signal (1352–1738 nm) and the idler (2743–4992 nm) output could be achieved with the MgO:PPLN crystal at room temperature (25 $^{\circ}\text{C}$) and by varying the interaction period of the grating. The wide tuning range of the OPO outputs could be further extended by temperature heating the MgO:PPLN. By increasing the temperature of the MgO:PPLN to 190 $^{\circ}\text{C}$, the signal field wavelength could reach 2015 nm, the idler field wavelength could reach 2254 nm, and the total signal and idler wavelength tuning was in the range of 3401 nm. As a result, by tuning both the temperature and period of the phase matching process, the total near to mid-infrared tuning range that could be achieved from the system was 1.3–5 μm . Figure 4 shows the full width at half maxima (FWHM) spectra of the near and mid-infrared laser outputs at different center wavelengths. The shown near infrared laser center wavelengths are 1352 nm, 1579 nm, and 2015 nm, and their half-height widths are $\Delta\lambda \approx 1.45$ nm, $\Delta\lambda \approx 2.09$ nm, $\Delta\lambda \approx 2.50$ nm, respectively. The shown mid-infrared laser center wavelengths are 2254 nm, 3262 nm, and 2992 nm, while their half-height widths are $\Delta\lambda \approx 2.38$ nm, $\Delta\lambda \approx 1.42$ nm, $\Delta\lambda \approx 1.30$ nm, respectively.

High output powers (signal and idler) were obtained in present synchronously pumped OPO by using an output coupling mirror (M5) with 20% transmittance for the signal field. This Z-shaped standing wave cavity design enabled easy control of the cavity spot size on the MgO:PPLN, which in-turn improved the overlap efficiency of the pump and signal, and therefore the optical conversion efficiency of the OPO. The power of OPO output fields were measured simultaneously over the entire wavelength tuning range of the system. As depicted in Figure 5, representative power-transfer curves at a number of output wavelengths are shown. When the incident pump power was 19 W, the signal field output power achieved was 8.67 W at 1.74 μm , and the corresponding power of the idler field was 5.61 W at 2.73 μm . The total optical conversion efficiencies of the system were 75.15% (with the signal field constituting 45.63% and the idler field 29.52%). The idler field output at 3.262 μm had a passive rms power stability of 3% over 2 h. As can be seen from the curves, the output power of the signal and the idler fields increases and then decreases as the wavelength increases. There are a number of reasons for this characteristic.

These include quantum loss and a reduction in the wavelength conversion efficiency as the difference in wavelength between the pump field and that of the signal and idler fields increases, prompting an increase in photon absorption within the MgO:PPLN crystal for increasingly longer wavelengths. The output power of the signal field hence increases and then decreases as its wavelength gets longer, this being consistent with conservation of energy.

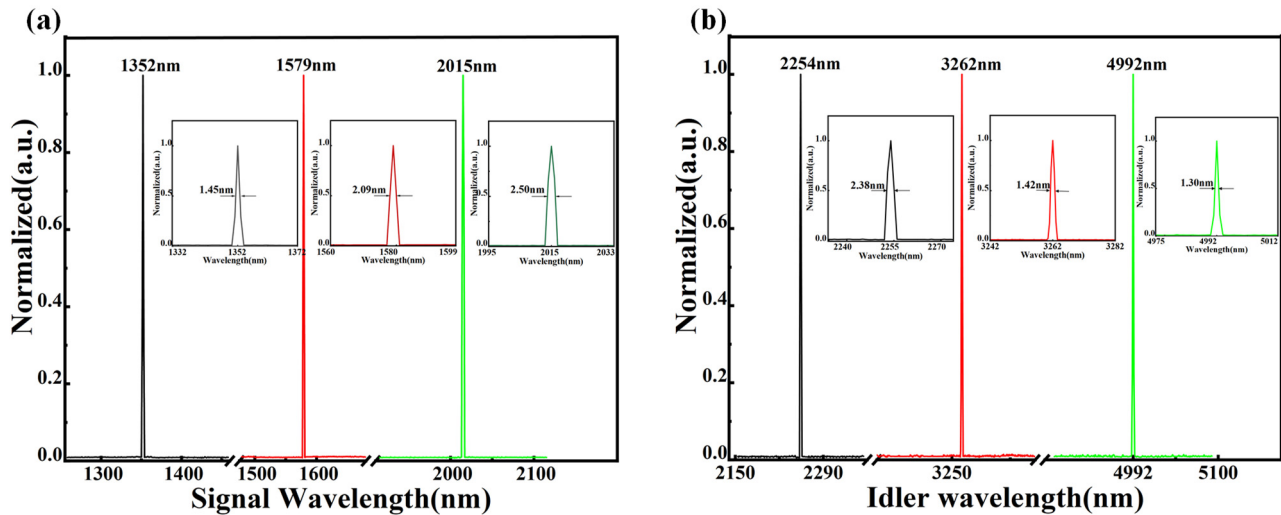


Figure 4. Plots showing the range of experimentally measured spectra of (a) signal and (b) idler fields. Insets show the signal and idler output spectral bandwidths from the synchronously pumped OPO.

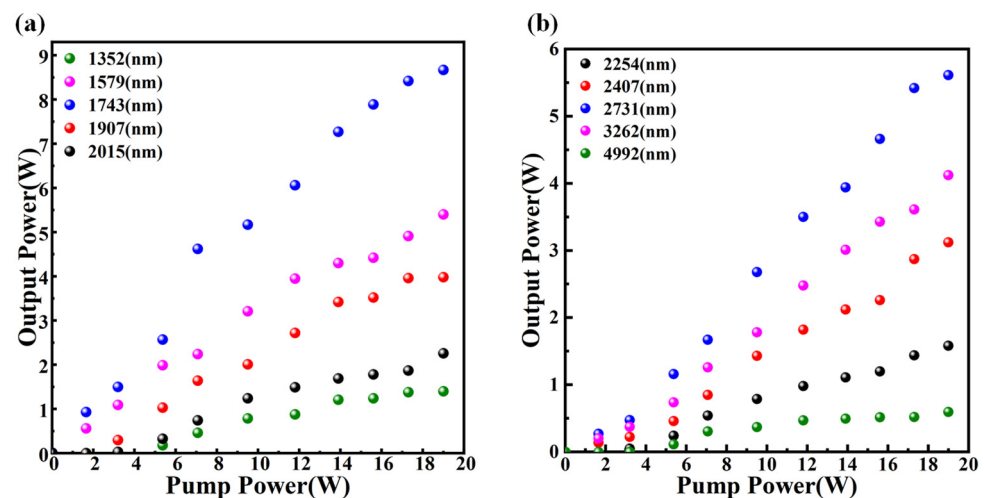


Figure 5. Plots showing the power transfer characteristics of (a) the signal field; and (b) the idler field for a range of output wavelengths.

We also investigated the change in the OPO field output powers as functions of output wavelength at a set input power of 19 W; these plots can be seen in Figure 6. The curves in the figure indicate that the incident power was fixed at 19 W, before the output power of the OPO fields increased and then decreased with increasing wavelengths, with these results being consistent with the data presented in Figure 5. We believe that the low output powers when the OPO outputs were close to degeneracy was largely due to the characteristics of the coatings applied to the cavity mirrors (M1–M4). These mirrors were only high-reflecting in the range of 1.4–1.75 μm , so, as the wavelength of the signal field became longer than 1.75 μm , the output power gradually decreased.

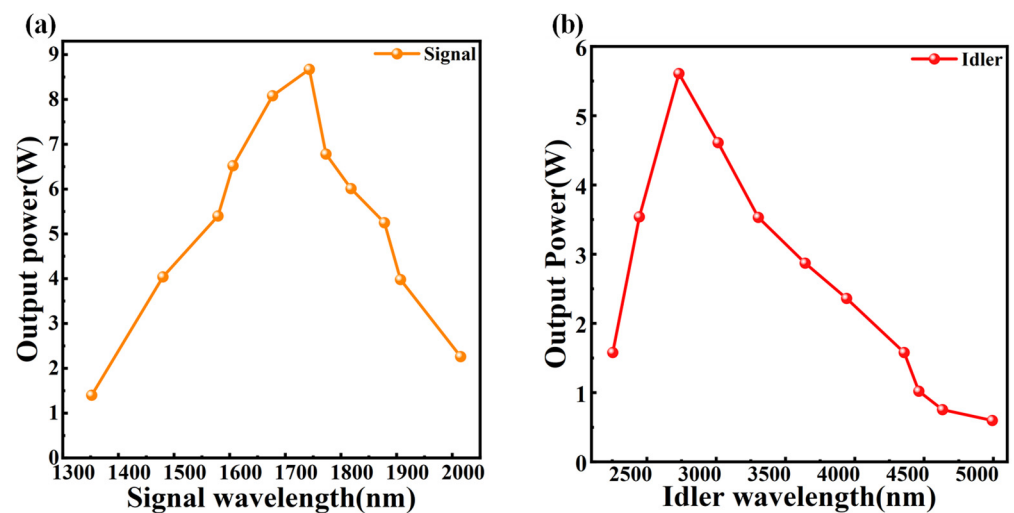


Figure 6. Plots showing (a) the signal field power; and (b) the idler field power, both as functions of wavelength, input power set as 19 W.

The high overall output powers achieved from this system can be attributed to a number of factors. These include the nonlinear gain of the resonant beam (in this case, the signal field) which is heavily influenced by the spatial overlapping efficiency of the interacting fields. The calculated beam radius of the signal field was $\sim 65 \mu\text{m}$ (using MatrixLaser), and this overlapped well with the pump field inside the crystal. Also, the output mirror M5 had a transmission of 20% for most of the signal field tuning range, and this struck a fine balance between the cavity Q factor and out-coupling to produce high-power picosecond laser output.

In the SPOPO, the spatial overlap efficiency (η) of the pump and signal beams determined the nonlinear gain of the resonant signal beam during the three-wave interaction. The beam size of the non-resonant idler was nearly equal to the pump beam, hence the spatial overlap efficiency was estimated using the radius of the pump (ω_p) and signal (ω_s) output beams. This can be described by Equation [34]:

$$\eta = \frac{4\omega_p^2\omega_s^2}{(\omega_p^2 + \omega_s^2)^2} \quad (3)$$

The equation shows that matching of the beam sizes is key to achieving high spatial overlapping efficiency. In the experiment, the radius of the pump beam was $60 \mu\text{m}$ and the beam waist radius of the resonant signal was $65 \mu\text{m}$. Subsequently, the estimated value of spatial overlapping efficiency is as high as 99.36%. This suggests that the pump and the signal fields can overlap well inside the cavity, thus contributing to the high total conversion efficiency of 75.15%.

4. Conclusions

We have investigated the operation of a high-power, widely tunable, synchronously pumped picosecond pulsed OPO generating emission in the near to mid-infrared wavelength ranges. The OPO is pumped using a Nd:YVO₄ picosecond pulsed laser (Wuhan Huazu Laser Technology Co., Ltd, in Wuhan, Hubei Province, China). By using a Z-shaped, signal singly resonant cavity, widely tunable OPO field outputs were generated with a total wavelength tuning range of 1.3–5 μm being demonstrated. This OPO design is simple and offers wide wavelength tunability. Critical to achieving this broad tunability was period and temperature heating of the MgO:PPLN crystal. When the pump power reached 19 W, the signal field output power was 8.67 W at 1.74 μm , and the corresponding idler field power was 5.61 W at 2.73 μm . We anticipate that, with such high power, widely tunable picosecond pulsed outputs will be utilized in ultrafast processes, time-domain

spectroscopy, and laser micromachining, this being due to wavelengths in this spectral band corresponding with the characteristic vibrational absorption of many organic materials.

Author Contributions: Conceptualization, M.A. and T.Y.; methodology, M.A. and X.Y.; software, M.A.; validation, T.Y. and X.Y.; formal analysis, M.A.; investigation, M.A.; resources, D.J.; data curation, M.A., D.J. and Z.L.; writing—original draft preparation, M.A., Z.L. and T.Y.; writing—review and editing, T.Y. and X.Y.; visualization, M.A.; supervision T.Y. and X.Y.; project administration and funding acquisition, T.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 12264049, 11664041), and the Foundation of Xinjiang Normal University Young Outstanding Talent Programmer (Grant No. XJNUQB2022-17).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Ganikhanov, F.; Carrasco, S.; Xie, X.S.; Katz, M.; Seitz, W.; Kopf, D. Broadly Tunable Dual-Wavelength Light Source for Coherent Anti-Stokes Raman Scattering Microscopy. *Opt. Lett.* **2006**, *31*, 1292–1294. [\[CrossRef\]](#)
- Jurna, M.; Korterik, J.; Offerhaus, H.; Otto, C. Noncritical Phase-Matched Lithium Triborate Optical Parametric Oscillator for High Resolution Coherent Anti-Stokes Raman Scattering Spectroscopy and Microscopy. *Appl. Phys. Lett.* **2006**, *89*, 251116. [\[CrossRef\]](#)
- Freudiger, C.W.; Min, W.; Saar, B.G.; Lu, S.; Holtom, G.R.; He, C.; Tsai, J.C.; Kang, J.X.; Xie, X.S. Label-Free Biomedical Imaging with High Sensitivity by Stimulated Raman Scattering Microscopy. *Science* **2008**, *322*, 1857–1861. [\[CrossRef\]](#)
- Woutersen, S.; Emmerichs, U.; Bakker, H.J. Femtosecond Mid-IR Pump-Probe Spectroscopy of Liquid Water: Evidence for a Two-Component Structure. *Science* **1997**, *278*, 658–660. [\[CrossRef\]](#)
- Papantonakis, M.R.; Haglund, R.F. Picosecond Pulsed Laser Deposition at High Vibrational Excitation Density: The Case of Poly(Tetrafluoroethylene). *Appl. Phys. A* **2004**, *79*, 1687–1694. [\[CrossRef\]](#)
- Kolev, V.Z.; Duering, M.W.; Luther-Davies, B.; Rode, A.V. Compact High-Power Optical Source for Resonant Infrared Pulsed Laser Ablation and Deposition of Polymer Materials. *Opt. Express* **2006**, *14*, 12302–12309. [\[CrossRef\]](#)
- McAlevy Bubb, D.-D.; Haglund, R.F., Jr. Resonant Infrared Pulsed Laser Ablation and Deposition of Thin Polymer Films. In *Pulsed Laser Deposition of Thin Films*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2006; pp. 33–61, ISBN 978-0-470-05212-9.
- Dholakia, K.; Simpson, N.B.; Padgett, M.J.; Allen, L. Second-Harmonic Generation and the Orbital Angular Momentum of Light. *Phys. Rev. A* **1996**, *54*, R3742–R3745. [\[CrossRef\]](#)
- Li, Y.; Zhou, Z.-Y.; Ding, D.-S.; Shi, B.-S. Sum Frequency Generation with Two Orbital Angular Momentum Carrying Laser Beams. *J. Opt. Soc. Am. B* **2015**, *32*, 407–411. [\[CrossRef\]](#)
- Sujian, N.; Aierken, P.; Tuerkun, P.; Ying, W.; Yusufu, T. Highly Efficient Millijoule-Level 3.5 Mm MgO-Doped Periodically Poled Lithium Niobate Optical Parametric Oscillator. *Jpn. J. Appl. Phys.* **2017**, *57*, 010304. [\[CrossRef\]](#)
- Niu, S.; Aierken, P.; Ababaike, M.; Wang, S.; Yusufu, T. Widely Tunable, High-Energy, Mid-Infrared (2.2–4.8 μm) Laser Based on a Multi-Grating MgO:PPLN Optical Parametric Oscillator. *Infrared Phys. Technol.* **2020**, *104*, 103121. [\[CrossRef\]](#)
- Zhu, H.; Guo, J.; Duan, Y.; Zhang, J.; Zhang, Y.; Xu, C.; Wang, H.; Fan, D. Efficient 1.7 Mm Light Source Based on KTA-OPO Derived by Nd:YVO₄ Self-Raman Laser. *Opt. Lett.* **2018**, *43*, 345–348. [\[CrossRef\]](#)
- Abulikemu, A.; Yakufu, S.; Zhou, Y.X.; Yusufu, T. Mid-Infrared Idler-Resonant Optical Vortex Parametric Oscillator Based on MgO:PPLN. *Opt. Laser Technol.* **2024**, *171*, 110341. [\[CrossRef\]](#)
- Baumgartner, R.; Byer, R. Optical Parametric Amplification. *IEEE J. Quantum Electron.* **1979**, *15*, 432–444. [\[CrossRef\]](#)
- Lee, A.J.; Omatsu, T.; Pask, H.M. Direct Generation of a First-Stokes Vortex Laser Beam from a Self-Raman Laser. *Opt. Express* **2013**, *21*, 12401–12409. [\[CrossRef\]](#)
- Piccoli, R.; Pirzio, F.; Agnesi, A.; Badikov, V.; Badikov, D.; Marchev, G.; Panyutin, V.; Petrov, V. Narrow Bandwidth, Picosecond, 1064 Nm Pumped Optical Parametric Generator for the Mid-IR Based on HgGa₂S₄. *Opt. Lett.* **2014**, *39*, 4895–4898. [\[CrossRef\]](#)
- Marchev, G.; Pirzio, F.; Piccoli, R.; Agnesi, A.; Reali, G.; Schunemann, P.G.; Zawilski, K.T.; Tyazhev, A.; Petrov, V. Narrow-Bandwidth, ~100 Ps Seeded Optical Parametric Generation in CdSiP₂ Pumped by Raman-Shifted Pulses at 1198 Nm. *Opt. Lett.* **2013**, *38*, 3344–3346. [\[CrossRef\]](#) [\[PubMed\]](#)
- Xu, L.; Chan, H.-Y.; Alam, S.; Richardson, D.J.; Shepherd, D.P. High-Energy, near- and Mid-IR Picosecond Pulses Generated by a Fiber-MOPA-Pumped Optical Parametric Generator and Amplifier. *Opt. Express* **2015**, *23*, 12613–12618. [\[CrossRef\]](#) [\[PubMed\]](#)
- Patterson, W.; Bigotta, S.; Sheik-Bahae, M.; Parisi, D.; Tonelli, M.; Epstein, R. Anti-Stokes Luminescence Cooling of Tm³⁺-Doped BaY₂F₈. *Opt. Express* **2008**, *16*, 1704–1710. [\[CrossRef\]](#) [\[PubMed\]](#)

20. Baron, A.; Rysanyanskiy, A.; Dubreuil, N.; Delaye, P.; Tran, Q.V.; Combrié, S.; de Rossi, A.; Frey, R.; Roosen, G. Light Localization Induced Enhancement of Third Order Nonlinearities in a GaAs Photonic Crystal Waveguide. *Opt. Express* **2009**, *17*, 552–557. [[CrossRef](#)] [[PubMed](#)]
21. Zhong, K.; Mei, J.; Liu, Y.; Qiao, H.; Liu, K.; Xu, D.; Yao, J. Widely Tunable Eye-Safe Optical Parametric Oscillator with Noncollinear Phase-Matching in a Ring Cavity. *Opt. Express* **2019**, *27*, 10449–10455. [[CrossRef](#)] [[PubMed](#)]
22. Schellhorn, M.; Spindler, G.; Eichhorn, M. Mid-Infrared ZGP OPO with Divergence Compensation and High Beam Quality. *Opt. Express* **2018**, *26*, 1402–1410. [[CrossRef](#)] [[PubMed](#)]
23. Devi, K.; Padhye, A.; Sukeert; Ebrahim-Zadeh, M. Widely Tunable Room-Temperature Continuous-Wave Optical Parametric Oscillator Based on Periodically-Poled KTiOPO₄. *Opt. Express* **2019**, *27*, 24093–24104. [[CrossRef](#)]
24. Lü, X.; Zhao, G.; Li, G.; Gao, Z.; Pan, S.; Zhu, S. Mid-Infrared Laser with 1.2 W Output Power Based on PPLT. *Sci. China Phys. Mech. Astron.* **2010**, *53*, 638–642. [[CrossRef](#)]
25. Kienle, F.; Chen, K.K.; Alam, S.; Gawith, C.B.E.; Mackenzie, J.I.; Hanna, D.C.; Richardson, D.J.; Shepherd, D.P. High-Power, Variable Repetition Rate, Picosecond Optical Parametric Oscillator Pumped by an Amplified Gain-Switched Diode. *Opt. Express* **2010**, *18*, 7602–7610. [[CrossRef](#)]
26. Kokabee, O.; Esteban-Martin, A.; Ebrahim-Zadeh, M. Efficient, High-Power, Ytterbium-Fiber-Laser-Pumped Picosecond Optical Parametric Oscillator. *Opt. Lett.* **2010**, *35*, 3210–3212. [[CrossRef](#)] [[PubMed](#)]
27. Xu, L.; Chan, H.-Y.; Alam, S.U.; Richardson, D.J.; Shepherd, D.P. Fiber-Laser-Pumped, High-Energy, Mid-IR, Picosecond Optical Parametric Oscillator with a High-Harmonic Cavity. *Opt. Lett.* **2015**, *40*, 3288–3291. [[CrossRef](#)] [[PubMed](#)]
28. Nandy, B.; Kumar, S.C.; Ebrahim-Zadeh, M. Yb-Fiber-Pumped High-Average-Power Picosecond Optical Parametric Oscillator Tunable across 1.3–1.5 μm . *Opt. Express* **2022**, *30*, 16340–16350. [[CrossRef](#)]
29. Kumar, S.C.; Ebrahim-Zadeh, M. High-Power, Fiber-Laser-Pumped, Picosecond Optical Parametric Oscillator Based on MgO:sPPLT. *Opt. Express* **2011**, *19*, 26660–26665. [[CrossRef](#)]
30. Kumar, S.C.; Ebrahim-Zadeh, M. Fiber-Laser-Based Green-Pumped Picosecond MgO:sPPLT Optical Parametric Oscillator. *Opt. Lett.* **2013**, *38*, 5349–5352. [[CrossRef](#)]
31. Kumar, S.C.; Parsa, S.; Ebrahim-Zadeh, M. Fiber-Laser-Based, Green-Pumped, Picosecond Optical Parametric Oscillator Using Fan-out Grating PPKTP. *Opt. Lett.* **2016**, *41*, 52–55. [[CrossRef](#)]
32. Kienle, F.; Teh, P.S.; Lin, D.; Alam, S.; Price, J.H.V.; Hanna, D.C.; Richardson, D.J.; Shepherd, D.P. High-Power, High Repetition-Rate, Green-Pumped, Picosecond LBO Optical Parametric Oscillator. *Opt. Express* **2012**, *20*, 7008–7014. [[CrossRef](#)] [[PubMed](#)]
33. Deng, L.H.; Gao, X.M.; Cao, Z.S.; Chen, W.D.; Yuan, Y.Q.; Zhang, W.J.; Gong, Z.B. Improvement to Sellmeier Equation for Periodically Poled LiNbO₃ Crystal Using Mid-Infrared Difference-Frequency Generation. *Opt. Commun.* **2006**, *268*, 110–114. [[CrossRef](#)]
34. Niu, S.J.; Wang, S.T.; Ababaike, M.; Yusufu, T.; Miyamoto, K.; Omatsu, T. Tunable near- and mid-infrared (1.36–1.63 μm and 3.07–4.81 μm) optical vortex laser source. *Laser Phys. Lett.* **2020**, *17*, 045402. [[CrossRef](#)]

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