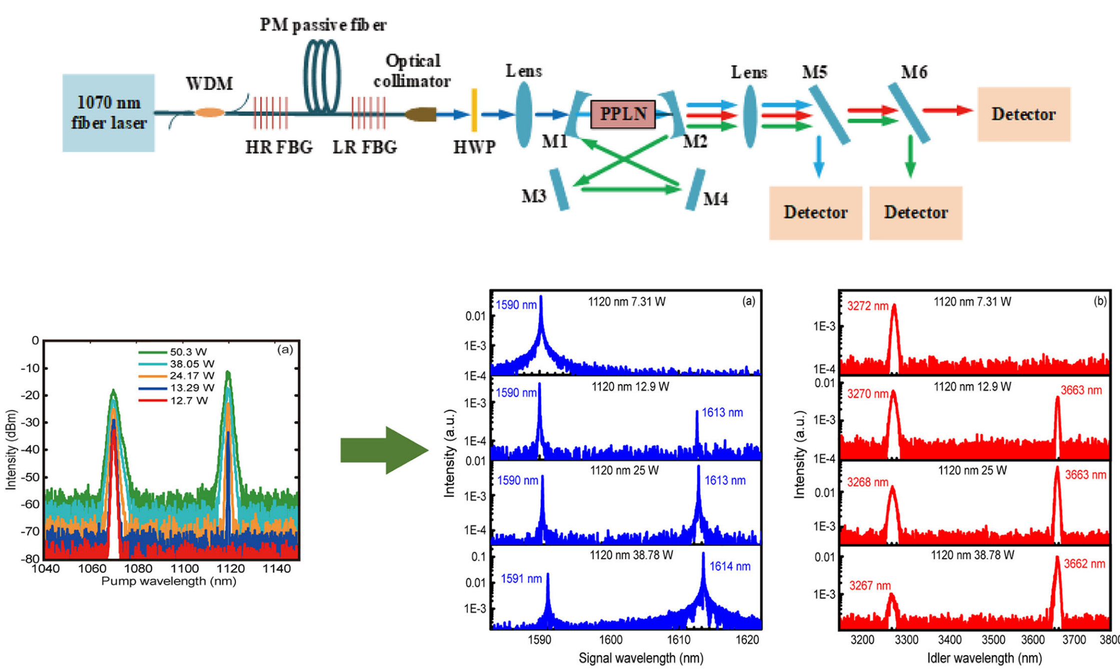
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

A High Efficient Dual-Wavelength Mid-Infrared Optical Parametric Oscillator Pumped by the Raman Fiber Oscillator

Volume 12, Number 3, June 2020

Jiacheng Feng
Peng Wang
Xi Cheng
Xiao Li
Weihong Hua
Kai Han



DOI: 10.1109/JPHOT.2020.3000752

IEEE photonics SOCIETY

IEEE

A High Efficient Dual-Wavelength Mid-Infrared Optical Parametric Oscillator Pumped by the Raman Fiber Oscillator

Jiacheng Feng [1,2,3] **Peng Wang** [1,2,3] **Xi Cheng** [1,2,3] **Xiao Li** [1,2,3] **Weihong Hua,** [1,2,3] **and Kai Han** [1,2,3]

[1]College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China
[2]State Key Laboratory of Pulsed Power Laser Technology, Changsha 410073, China
[3]Hunan Provincial Key Laboratory of High Energy Laser Technology, Changsha 410073, China

DOI:10.1109/JPHOT.2020.3000752

Manuscript received March 27, 2020; revised May 29, 2020; accepted June 4, 2020. Date of publication June 9, 2020; date of current version June 22, 2020. This work was supported by the National Natural Science Foundation of China under Grant 61975236. Corresponding authors: Xiao Li; Weihong Hua (e-mail: crazy.li@163.com; rosehua@hotmail.com).

Abstract: In this paper, a novel high efficient dual-wavelength mid-infrared optical parametric oscillator (OPO) was demonstrated, which was pumped by a dual-wavelength Raman fiber oscillator for the first time. The adoption of oscillator structure reduced the waste of power, increased Raman pump power and promoted its frequency conversion. The dual-wavelength pump source was fixed at 1070 nm and 1120 nm and the Raman conversion efficiency was greatly enhanced from 26.7% to 72.1%. The high Raman efficiency and low Raman threshold enabled the Raman laser to build optical parametric oscillation easily and the pump-to-idler conversion efficiency of Raman laser improved greatly from 4.2% to 13.3%. The generated dual-wavelength mid-infrared laser was fixed at 3272 nm and 3663 nm, with a maximum power of 6.87 W, indicating a 13.9% pump-to-idler conversion efficiency. The highest mid-infrared output power generated by optical parametric oscillation of Raman laser was also achieved, which is almost ten times than before.

Index Terms: Infrared lasers, nonlinear crystals, fiber lasers, nonlinear.

1. Introduction

Dual-wavelength mid-infrared OPOs can simultaneously generate mid-infrared emission with different wavelengths, which have great application value and prospects in THz generation, remote sensing and material detection [1]–[4]. Researchers have developed two major schemes to achieve dual-wavelength mid-infrared OPOs. One is using special cavity structure, which includes utilizing specially designed nonlinear crystals, adopting multiple crystals and using doubly resonant optical parametric oscillator (DRO). In 2009, Ji Feng *et al.* achieved a dual-wavelength mid-infrared OPO located at 3.82 μm and 3.73 μm using a periodically phase-reversed periodically polarized magnesia-doped lithium niobate crystal [5]. In 2015, Yuwei Jin *et al.* adopted two independent periodically poled magnesia-doped lithium niobate (MgO:PPLN) crystals in one cavity and achieved a widely tunable dual-wavelength OPO [6]. However, the whole optical system was relatively complex. DRO is also a way to generate dual-wavelength output and THz generation has been achieved by this method [7], [8]. However, it is relatively difficult to achieve stable output by DRO, since each oscillating light wave in the cavity must meet the energy conservation law, phase matching and mode matching between longitudinal modes. The other scheme is utilizing dual-wavelength pump sources, especially dual-wavelength fiber lasers. Compared with traditional solid state lasers, the advantages of fiber lasers include high efficiency, excellent beam quality and compact structure [9], [10]. Our research group has made some achievements in fiber-laser-pumped dual-wavelength mid-infrared OPOs. In 2016, our group achieved a dual-wavelength mid-infrared OPO which was pumped by a 1064&1080 nm dual-wavelength fiber laser [11]. In that experiment, parametric oscillation and difference frequency generation (DFG) simultaneously occurred and 3125&3323 nm dual-wavelength mid-infrared emission was observed. In 2018, our research group adopted a tunable dual-wavelength fiber laser as the pump source and realized tunable dual-wavelength mid-infrared output [12]. Compared with other schemes, it is obvious that dual-wavelength OPOs pumped by dual-wavelength fiber lasers have several advantages such as simple structure and can be implemented easily.

Utilizing the fiber nonlinear effect has been proved to be an effective way to achieve dual-wavelength fiber source. As a common application of frequency conversion, the stimulated Raman scattering (SRS) effect has been studied thoroughly [13]–[15]. In 2018, our research group built a 1060&1111 nm dual-wavelength Raman fiber laser which was adopted as the OPO pump source and obtained 3054&3530 nm dual-wavelength mid-infrared radiation [16]. However, the fiber pump source did not involve a Raman resonant cavity, resulting in low Raman conversion efficiency at around 26.7%. Partial 1060 nm pump power was transferred to the backward Raman laser and leaked out, which led to the waste of power. The conversion of Raman laser transferring to mid-infrared laser was insufficient and the conversion efficiency was as low as 4.2%. The dual-wavelength pump-to-idler conversion efficiency dropped by a third from 18% to 12% when the Raman laser built the parametric oscillation. That is, the parametric oscillation of the Raman laser lowered the total conversion efficiency. The 3530 nm output power corresponding to the Raman laser reached maximum only at 0.5 W. Besides, the 2nd Raman effect appeared with increase of 1060 nm pump power and limited the 1st Raman conversion efficiency. Moreover, the threshold of the Raman laser was as high as 51.5 W, which made it even more difficult for the Raman laser to participate in the following parametric process.

In this paper, we realized a dual-wavelength Raman fiber oscillator pumped dual-wavelength mid-infrared OPO, in which the nonlinear effects of fiber and crystal were combined. The scheme is easy to implement and highly efficient. The dual-wavelength pump source consisted of a homemade 1070 nm fiber laser, a wavelength division multiplexer (WDM), a 35-meter long passive fiber and a pair of fiber Bragg gratings (FBGs). Its central wavelengths were fixed at 1070 nm and 1120 nm. The maximum 1120 nm laser power reached 38.78 W and the Raman conversion efficiency was 72.1%. When the 1120 nm pump power was relatively low, only the 1070 nm pump beam built parametric oscillation and generated 1590 nm signal beam as well as 3272 nm idler beam. The 3272 nm idler power kept around 2 W since the 1070 nm pump power kept around 13 W all the time. When the 1120 nm pump power reached 11.04 W, it was also high enough for 1120 nm pump beam to build another independent OPO process and generate 1614 nm signal beam as well as 3662 nm idler beam. The maximum 3662 nm idler power reached 4.98 W, which is currently the highest mid-infrared output power generated by optical parametric oscillation of Raman laser. During the whole process, the maximum dual-wavelength mid-infrared power reached 6.87 W, indicating a 13.9% pump-to-idler conversion efficiency. The adoption of oscillator structure reduced the waste of power, increased Raman pump power and promoted its frequency conversion. The Raman efficiency was greatly enhanced from 26.7% to 72.1% and the Raman threshold was reduced from 51.5 W to 12.7 W, which made it easier for the Raman laser to perform the oscillation and generate laser with longer wavelength. The passive fiber used was shortened from 137 meters to 35 meters, which means the scheme was much more efficient. The pump-to-idler conversion efficiency of Raman laser improved greatly from 4.2% to 13.3%, and the mid-infrared output power corresponding to Raman laser raised 10 times from 0.5 W to 4.98 W. The obtained 3 μm radiation have a great role in applications such as spectroscopy, chemical and medical diagnosis [17]–[19], while the 3272/3662 nm dual-wavelength mid-infrared radiation have great applications in trace gas sensing

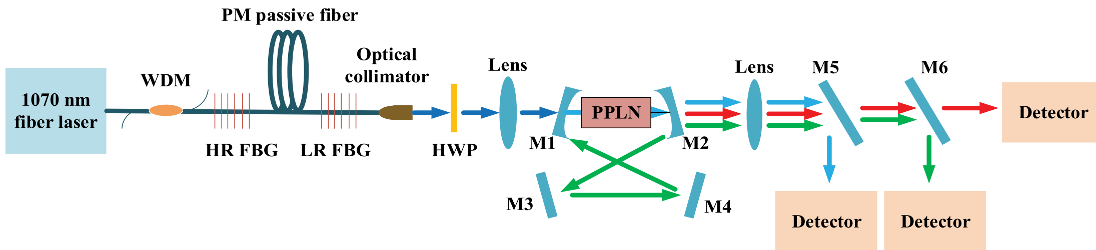


Fig. 1. The schematic diagram of dual-wavelength mid-infrared OPO.

[20]–[22]. The output spectroscopy and idler power of the dual-wavelength OPO can be regulated easily by adjusting the parameters of the Raman oscillator, which shows great potential in spectral regulation.

2. Experiment Setup

The schematic diagram is shown in Fig. 1. The whole system could be divided into two parts. The first part was a traditional Raman fiber oscillator, which was pumped by a homemade linearly-polarized 1070 nm fiber laser. A WDM was used to prohibit the backward Raman radiation from damaging the pump source. The polarization-maintaining (PM) passive 10/125 μm fiber was 35 meters long from Nufern Corporation. The PM passive fiber, high reflectivity (HR, 99%) fiber Bragg grating (FBG) and low reflectivity (LR, 52.4%) FBG at 1120 nm were combined and formed the oscillator. They were followed by a fiber optical collimator and a half wave plate (HWP), which was highly transimissive for the dual-wavelength pump beam (T $>$ 99%), to parallel the beam and adjust the polarization direction of the laser respectively. A focusing lens was used to focus the pump beam into the center of PPLN crystal. The second part was the OPO. A typical four-mirror ring cavity structure was adopted, which consisted of two concave mirrors M1 and M2 with a radius of curvature of 150 mm and two plane mirrors M3 and M4. M1, M3 and M4 were anti-reflection (AR) coated (T $>$ 95%) for the 1–1.1 μm pump beam and the 3–4 μm idler beam, and had a high reflectivity (R $>$ 99%) for the 1.4–1.7 μm signal beam, thus ensuring singly resonant oscillation (SRO). The output coupler M2 had high transmittance for the pump and idler beam, and partial transmittance for the signal beam (T $\sim$ 10%). The nonlinear crystal was a MgO: PPLN crystal with a grating period of 31 μm. Its size was 50 mm (length) $\times$ 10 mm (width) $\times$ 1 mm (height). Behind the cavity was an optical collimator, which allowed the output beam to be accurately parallel. Two beam splitters M5 and M6, which were made of CaF_2, were placed behind the collimator. M5 was mid-infrared HR coated (R $>$ 99%), with a reflective band of 3–5 μm, was used to separate the idler beam. M6, with a reflective band of 1.3–2 μm (R $>$ 99%), was used to separate the residual pump beam and signal beam. The dual-wavelength mid-infrared beam was then separated by a dichroic mirror (AR coated for 3.47–4 μm, T $>$ 99%), which was not shown in Fig. 1. The spectra were measured using a Bristol 721B Optical Spectrum Analyzer, and the power were measured using power meter probe S314C, S322C and header PM100D from Thorlabs Corporation.

3. Experiment Results and Discussion

The output spectra of the dual-wavelength pump source under different total power were measured by Yokogawa AQ6370D Optical Spectrum Analyzer and shown in Fig. 2(a). It can be seen that the central wavelengths of dual-wavelength output were 1070 nm and 1120 nm, which satisfied the wavelength shifting relationship. The second-order Raman laser did not appear in the whole process. The 1070 nm peak intensity was much higher than the 1120 nm laser at first. As the total power increased, the 1070 nm pump power was continuously transferred to the 1120 nm

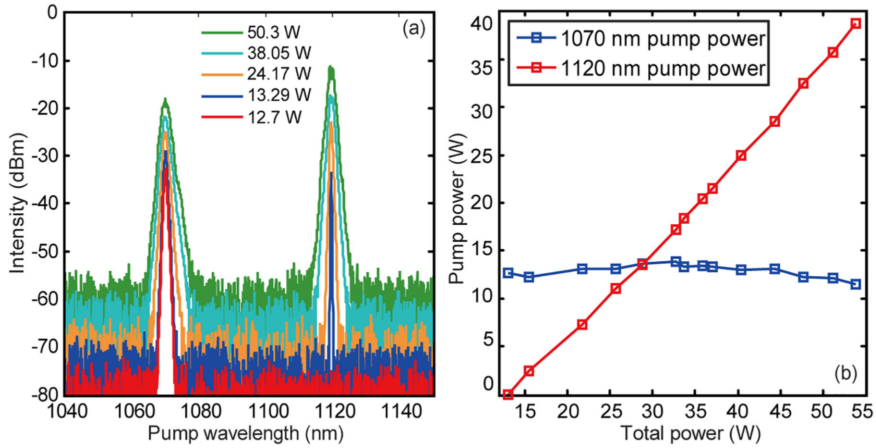


Fig. 2. (a) Measured spectra of dual-wavelength pump source under different total power. (b) Calculated 1070 nm and 1120 nm laser power versus total power.

radiation, making the 1120 nm peak intensity 5 dB (about 3.2 times) higher than the 1070 nm laser at last. The 1070 nm and 1120 nm output power under different total power were calculated using spectral integration and shown in Fig. 2(b). It indicates that the 1120 nm Raman beam didn't appear until the total power was over 12.7 W. After then, it kept growing rapidly and finally reached 38.78 W. The residual 1070 nm pump power firstly increased slowly and then decreased slightly to 11.52 W, remaining approximately 13 W at most of the time. It can be seen that just like traditional Raman fiber oscillators, the power was transferred to Raman laser rapidly, and consequently made the Raman conversion efficiency grew continuously and reached maximum at 72.1%, which was almost as 3 times high as that in the Ref. [16]. The slow depletion of residual 1070 nm laser limited the further improvement of Raman efficiency, however enabling the 1070 nm laser to participate in the following parametric process and generate dual-wavelength mid-infrared output. Besides, the Raman threshold was 12.7 W, which was also much lower than 51.5 W in the Ref. [16], enabling the Raman laser to build independent parametric oscillation in the following process more easily.

Then the dual-wavelength pump beam was used to pump the OPO for performing the frequency conversion. The signal and idler spectra in logarithmic coordinates under different 1120 nm pump power were measured and shown in Fig. 3(a) and (b) separately. In the whole experiment, the 1070 nm pump beam always independently built the parametric oscillation. The corresponding signal and idler wavelengths changed from 1590 nm to 1591 nm and from 3272 nm to 3267 nm with the increase of total pump power. It was analyzed that when the 1120 nm pump beam built another parametric oscillation, the thermal effect of PPLN crystal was induced due to the absorption of laser power and continuously enhanced with the increase of total pump power, finally resulting in the red shift of signal wavelength and blue shift of idler wavelength [23]. It was noticed that although the 1120 nm Raman laser appeared when the Raman threshold was reached, it did not perform the frequency conversion immediately since its power was not high enough to reach the threshold of OPO. Till the 1120 nm pump power was over 11.04 W, it built another parametric oscillation independently. The newly generated signal and idler wavelengths were 1613 nm and 3663 nm separately. Now the OPO can output mid-infrared radiation with two different wavelengths. As the 1120 nm power kept growing, the corresponded OPO process continued to become stronger and the embodiment in the picture was that the corresponded altitudes become higher. Though 1591 nm signal laser and 3267nm idler laser seemed to have a quite low altitude, it did not mean that the power of them were weak because the wavelengthmeter we used could only depict the wavelengths it measured and rough power relationship.

Based on Sellmeier equations [24], under room temperature of 25 °C, the generated signal and idler wavelengths are simulated and shown in Fig. 4(a). As can be seen from Fig. 4(a), the

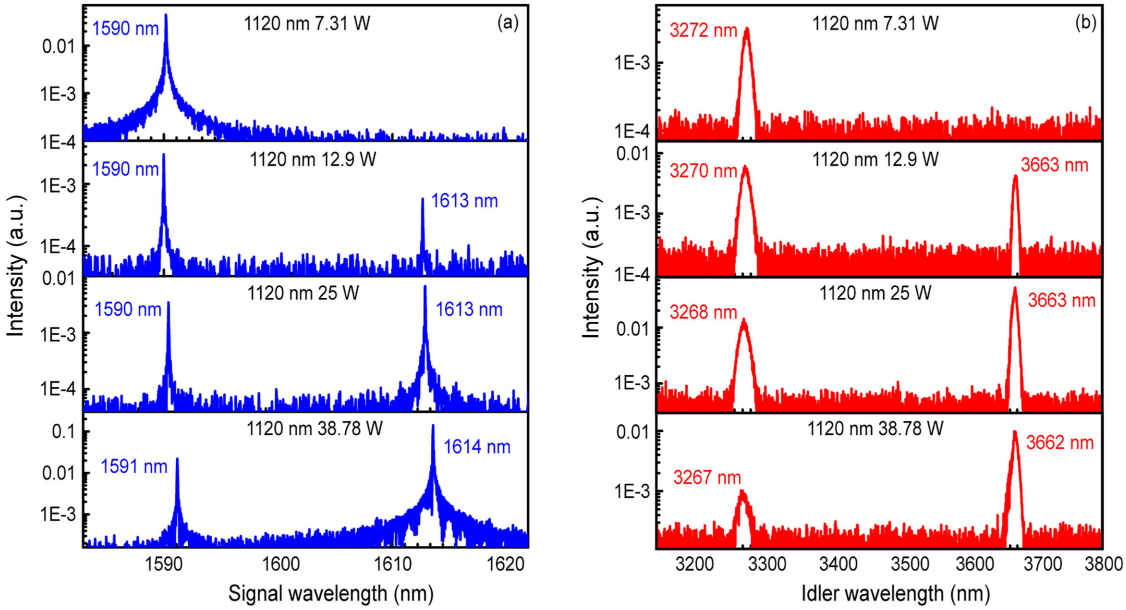


Fig. 3. Measured (a) signal and (b) idler spectra under different 1120 nm pump power.

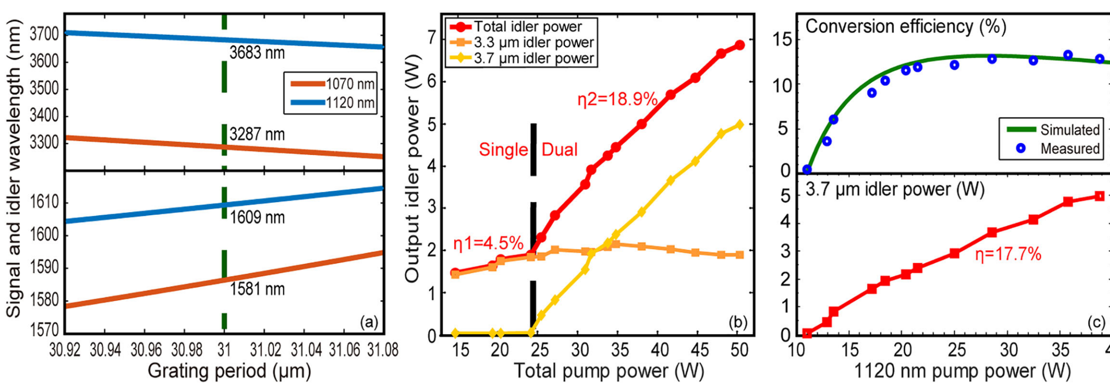


Fig. 4. (a) The simulated tuning curve of parametric oscillations of 1070 nm and 1120 nm beam under room temperature of 25 °C. (b) Total idler power, 3.3 μm and 3.7 μm idler power versus total pump power. (c) 3.7 μm idler power and conversion efficiency versus 1120 nm pump power.

calculated wavelengths of signal and idler beams are at 1581 nm & 3287 nm and 1609 nm & 3683 nm, which correspond to 1070 nm and 1120 nm pump beam, respectively. The simulation results are similar with experiment results, with at most 20 nm deviation, which is due to the temperature changes under high pump power. Temperature controller will be used to keep the crystal temperature unchanged in the future experiments.

For convenience, the 3270 nm and 3663 nm idler beams were abbreviated as 3.3 μm and 3.7 μm idler beams. The relationship of total idler power, 3.3 μm and 3.7 μm idler power versus total pump power was shown in Fig. 4(b), where single wavelength mid-infrared output and dual-wavelength output were separated by the dotted black line. It can be seen that the total idler power arose from 1.46 W to 1.89 W linearly with a slope efficiency of 4.5% when the total pump power was less than 24.17 W. At this time, only 1070 nm pump beam performed parametric process and generated 3.3 μm idler beam, while 3.7 μm idler beam was not obtained. When the total pump power was over

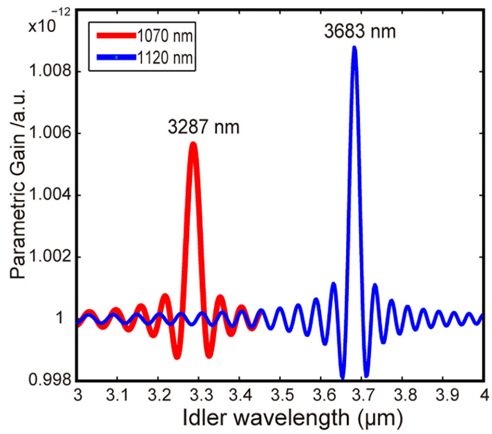


Fig. 5. The simulated dual-wavelength idler optical parametric gain curve.

24.17 W, that is, when 1120 nm pump power was over 11.04 W, 1120 nm pump laser was also able to perform the parametric oscillation and dual-wavelength mid-infrared laser was achieved. Under this condition, 3.7 μm idler power increased linearly while 3.3 μm idler power firstly increased and then declined, basically corresponding to the trend of 1070 nm pump power. The 3.3 μm idler power always kept around 2 W because the 1070 nm pump power did not change greatly and kept around 13 W. The maximum pump-to-idler conversion efficiency for 1070 nm pump beam was 16.1%. The dual-wavelength idler power increased linearly to 6.87 W with a slope efficiency of 18.9% and the maximum total pump-to-idler conversion efficiency was calculated to be 13.9%.

The relationship of 3.7 μm idler power as well as measured and simulated conversion efficiency versus 1120 nm pump power was separately shown in Fig. 4(c). It can be seen that after the 1120 nm Raman beam performed oscillation, 3.7 μm idler power rose linearly with a slope efficiency of 17.7%. When the 1120 nm pump power was 38.78 W, the 3.7 μm idler power reached maximum at 4.98 W, which was almost 10 times higher than the previous mid-infrared power generated by Raman laser. The conversion efficiency first increased rapidly as the 1120 nm pump power increased and finally remained around 13%, which demonstrated good agreement with simulation curve. The maximum pump-to-idler conversion efficiency of Raman laser was calculated to be 13.3%, which was greatly improved and was as 3 times as before [16]. The simulation results show that the conversion efficiency curve start to decline after reaching the maximum, which means that over-continued increase in power, however, will led to reduced efficiency due to the back conversion. It also proves that the efficiency we obtain is the highest based on the experiment conditions, and the efficiency varies with pump power.

The transfer matrix method is a common way to perform small signal gain simulation analysis [25], [26]. The coupled-wave equations, after being derived and simplified, can be solved and the solution can be written as:

$$\begin{bmatrix} A_1(z) \\ A_2^*(z) \end{bmatrix} = M \begin{bmatrix} A_1(0) \\ A_2^*(0) \end{bmatrix}$$

Where A is the amplitude at z, M is the transfer matrix:

$$M = \begin{bmatrix} e^{-j\Delta kz/2}(\cosh gz + \frac{j\Delta k}{2g}\sinh gz) & e^{-j\Delta kz/2}(\frac{K_1}{g})\sinh gz \\ e^{j\Delta kz/2}(\frac{K_2^*}{g})\sinh gz & e^{j\Delta kz/2}(\cosh gz - \frac{j\Delta k}{2g}\sinh gz) \end{bmatrix}$$

Then, the iterative method is used to calculate the final idler gain. The idler gain of the whole process is shown in Fig. 5 when the 1120 nm pump power is as three times as 1070 nm pump power. The simulation results explain the dual-wavelength frequency conversion process. It can be seen that there are two gain peaks located at 3287 nm and 3683 nm which correspond to the parametric oscillations of 1070 nm and 1120 nm, respectively. The simulated idler parametric gain of 1120 nm is much higher than that of 1070 nm gain, and the manifestation in the result is that the idler power of 1120 nm is much higher than that of 1070 nm.

4. Conclusion

In conclusion, a novel high efficient dual-wavelength mid-infrared OPO was demonstrated, a dual-wavelength Raman fiber oscillator was used to pump the OPO for the first time, and the highest mid-infrared output power generated from parametric oscillation of Raman laser was achieved. The dual-wavelength pump source, utilizing a traditional Raman fiber oscillator structure, was fixed at 1070 nm and 1120 nm with a Raman conversion efficiency greatly improved from 26.7% to 72.1% and a Raman threshold notably decreased from 51.5 W to 12.7 W. The high efficiency and low Raman threshold enabled 1120 nm pump laser to build oscillation easily. The 1070 nm pump beam was able to build parametric oscillation all the time and generated 1590 nm signal beam as well as 3272 nm idler beam. The 3.3 μm idler power kept around 2 W and the maximum pump-to-idler conversion efficiency was 16.1%. When the 1120 nm pump power was over 11.04 W, it also reached the corresponding OPO threshold and performed the optical parametric oscillation. The newly generated signal and idler wavelengths were 1613 nm and 3663 nm separately. The high power Raman beam improved the Raman pump-to-idler conversion efficiency greatly from 4.2% to 13.3%. The 3.7 μm idler power reached the maximum of 4.98 W, which was almost 10 times higher than before. The passive fiber used was shortened from 137 meters to 35 meters, which means the scheme was much more efficient. In the experiment, the maximum dual-wavelength idler power reached 6.87 W with a total pump-to-idler conversion efficiency of 13.9%. The total conversion efficiency was relatively high since the oscillator structure reduced the waste of power. The obtained 3 μm radiation have important application value in spectroscopy, medical diagnosis and trace gas sensing. This scheme was simple and easy to implement compared with other schemes. Using Raman fiber oscillator as the pump source, dual-wavelength mid-infrared radiation can be easily obtained. Besides, the spectrum and power of the dual-wavelength mid-infrared laser can be regulated easily by adjusting the parameters of the Raman fiber oscillator, which shows great potential in spectral regulation.

Acknowledgment

The authors would like to thank Nanjing University, Zhejiang University and Fujian Institute of Research on the Structure for their offer of nonlinear crystals.

References

[1] K. Zhong, J. Yao, D. Xu, Z. Wang, Z. Li, and H. Zhang, “Enhancement of terahertz wave difference frequency generation based on a compact walk-off compensated KTP OPO,” *Opt. Commun.*, vol. 283, no. 18, pp. 3520–3524, 2010.
[2] A. Yu, X. Ye, D. Lonascu, W. Cao, and P. Champion, “Two-color pump-probe laser spectroscopy instrument with picosecond time-resolved electronic delay and extended scan range,” *Rev. Sci. Instrum.*, vol. 76, no. 11, 2015, Art. no. 114301.
[3] D. Kolker, I. Sherstov, N. Kostyukova, A. Boyko, K. Zenov, and R. Pustovalova, “Combined optical parametric oscillator with continuous tuning of radiation wavelength in the spectral range 2.5 10.8 μm,” *Quantum Electron.*, vol. 47, no. 1, pp. 14–19, 2017.
[4] Z. Lou *et al.*, “The characterization of laser-induced thermal damage mechanism of mid-infrared optical coatings with surface contaminants,” *Phys. Scr.*, vol. 95, no. 3, 2020, Art. no. 035507.
[5] F. Ji, R. Lu, B. Li, B. Zhang, and J. Yao, “Mid-infrared tunable dual-wavelength generation based on a quasi-phase-matched optical parametric oscillator,” *Opt. Commun.*, vol. 282, no. 1, pp. 126–128, 2009.
[6] Y. Jin, S. Cristescu, F. Harremm, and J. Mandon, “Broadly, independent-tunable, dual-wavelength mid-infrared ultrafast optical parametric oscillator,” *Opt. Express*, vol. 23, no. 16, pp. 20418–20427, 2015.
[7] J. Schaar, K. Vodopyanov, and M. Fejer, “Intracavity terahertz generation in a synchronously pumped optical parametric oscillator using quasi-phase-matched GaAs,” *Opt. Lett.*, vol. 32, no. 10, pp. 1284–1286, 2007.
[8] J. Mei *et al.*, “Widely tunable high-repetition-rate terahertz generation based on an efficient doubly resonant type-II PPLN OPO,” *IEEE Photon. J.*, vol. 8, no. 6, Dec. 2016, Art. no. 5502107.

[9] D. J. Richardson, J. Nilsson, and W. A. Clarkson, "High power fiber lasers: Current status and future perspectives," *J. Opt. Soc. Am. B.*, vol. 27, no. 11, pp. 63–92, 2010.

[10] M. Zervas and C. Codemard, "High power fiber lasers: A review," *IEEE J. Sel. Top. Quan.*, vol. 20, no. 5, Sep./Oct. 2014, Art. no. 0904123.

[11] Y. Shang, P. Wang, X. Li, M. Shen, and X. Xu, "Frequency down-conversion of a dual-wavelength fiber laser," *Optik*, vol. 127, no. 24, pp. 11871–11876, 2016.

[12] P. Wang, X. Cheng, X. Li, and X. Xu, "Tunable dual-wavelength, continuous-wave, mid-infrared generation using intracavity difference frequency mixing in PPLN-based optical parametric oscillator," *IEEE J. Sel. Top. Quan.*, vol. 24, no. 5, Sep./Oct. 2018, Art. no. 0902807.

[13] R. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering," *Appl. Opt.*, vol. 11, no. 11, pp. 2489–2494, 1972.

[14] F. Benabid, J. Knight, G. Antonopoulos, and P. Russel, "Stimulated Raman scattering in hydrogen-filled hollow-core photonics crystal fiber," *Sci.*, vol. 298, pp. 399–402, 2002.

[15] Y. Feng, L. Taylor, and D. Calia, "150 W highly-efficient Raman fiber laser," *Opt. Express*, vol. 17, no. 26, pp. 23678–23683, 2009.

[16] P. Wang, X. Cheng, X. Li, X. Xu, K. Han, and J. Chen, "Frequency down-conversion of dual-wavelength Raman fiber laser in PPLN-based optical parametric oscillator," *IEEE Photon. J.*, vol. 10, no. 5, Oct. 2018, Art. no. 1503607.

[17] S. Yang and S. Velsko, "Frequency-agile kilohertz repetition-rate optical parametric oscillator based on periodically poled lithium niobate," *Opt. Lett.*, vol. 24, no. 3, pp. 133–135, 1999.

[18] K. Vodopyanov and P. G. Schunemann, "Broadly tunable noncritically phase-matched ZnGeP2 optical parametric oscillator with a 2-μJ pump threshold," *Opt. Lett.*, vol. 28, no. 6, pp. 441–443, 2003.

[19] M. Henriksson, M. Tiihonen, V. Pasiskevicius, and F. Laurell, "Mid-infrared ZGP OPO pumped by near-degenerate narrowband type-I PPKTP parametric oscillator," *Appl. Phys. B-Lasers O.*, vol. 88, no.1, pp. 37–41, 2007.

[20] M. Fischer, M. Elinger, L. Nahle, J. Koeth, A. Bauer, and M. Dallner, "DFB laser for sensing applications in the 3.0–3.5 μm wavelength range," in *Proc. Soc. Photo-Opt. Instrum. Eng.*, vol. 7945, pp. 79450E-1–79450E-13, 2011.

[21] H. Tobben, "Room temperature CW fiber laser at 3.5 μm in Er3+-doped ZBLAN glass," *Electron. Lett.*, vol. 28, no. 14, pp. 1361–1362, 1992.

[22] D. Lancaster, D. Richter, R. Curl, and F. Tittel, "Real-time measurements of trace gases using a compact difference-frequency-based sensor operating at 3.5 μm," *Appl. Phys. B*, vol. 67, pp. 339–345, 1998.

[23] M. Vainio, J. Peltola, S. Persijn, F. J. M. Harren, and L. Halonen, "Thermal effects in singly resonant continuous-waveoptical parametric oscillator," *Appl. Phys. B*, vol. 94, no. 3, pp. 411–427, 2009.

[24] O. Gayer, Z. Sacks, E. Galun, and A. Arie, "Temperature and wavelength dependent refractive index equations for MgO-doped congruent and stoichiometric LiNbO3," *Appl. Phys. B*, vol. 91, no. 2, pp. 343–348, 2008.

[25] C. Xu and H. Okayama, "Optical frequency conversions in nonlinear medium with periodically modulated linear and nonlinear optical parameters," *IEEE J. Quantum Elect.*, vol. 31, no. 6, pp. 981–987, Jun. 1995.

[26] Y. Zhang and B. Gu, "Optimal design of aperiodically poled lithium niobate crystals for multiple wavelengths parametric amplification," *Opt. Commun.*, vol. 192, pp. 417–425, 2001.