Compact and tunable mid-infrared source based on a 2 μm dual-wavelength $KTiOPO_4$ intracavity optical parametric oscillator*

Geng You-Fu(耿优福)[a)c)], Tan Xiao-Ling(谭晓玲)[b)], Li Xue-Jin(李学金)[a)†], and Yao Jian-Quan(姚建铨)[c)]

[a)] *College of Physics Science and Technology, Shenzhen Key Laboratory of Sensor Technology, Shenzhen University, Shenzhen* 518060, *China*

[b)] *Faculty of Science, Ningbo University, Ningbo* 315211, *China*

[c)] *College of Precision Instrument and Optoelectronics Engineering, Institute of Laser and Optoelectronics, Tianjin University, Tianjin* 300072, *China*

(Received 31 March 2010; revised manuscript received 20 May 2010)

Using a double resonant $KTiOPO_4$ (KTP) intracavity optical parametric oscillator operating at degenerated point of 2 μm, we demonstrate a unique mid-infrared source based on difference frequency generation in GaSe crystal. The output tuning range is 8.42–19.52 μm, and a peak power of 834 W for type-I phase matching scheme and 730 W for type-II phase matching scheme are achieved. Experimental results show that this oscillator is a good alternative to the generator of a compact and tabletop mid-infrared radiation with a widely tunable range.

Keywords: mid-infrared radiation, difference frequency generation, optical parametric oscillator, phase matching scheme

PACC: 4265K, 4265M, 9580G

1. Introduction

Laser spectrum technology is one of the most important methods to detect and reveal the structures of matters, and it has been used in many areas such as optical remote sensing, environmental monitoring and toxic gas detecting.[1] Since 8–12 μm is a fingerprint region in which most molecules, especially toxic gas molecules, have obvious absorption spectra, tunable mid-infrared sources are necessary. Thus how to achieve it has attracted much attention. To date, the main methods of mid-infrared (Mid-IR) generation are as follows: quantum cascade lasers (QCLs),[2−5] CO_2 lasers, optical parameter sources.[6−14] However, CO_2 lasers and QCLs restrict their applications for their narrow tuning range and complicated structures. Optical parameter sources including optical parametric oscillation, optical parametric generation, and difference-frequency generation (DFG) have many advantages such as large tuning range covering 3–19 μm, watt-level high repetition output, high energy pulse output and compact tabletop structure. In 1998, Mennerat and Kupecek[7] realised a 10 mJ Mid-IR pulse output using DFG in CdSe crystal; In 1999, Vodopyanov[6] obtained 3–19 μm Mid-IR radiation using optical parametric generation in GaSe crystal; Recently, Zakel *et al.*[10] achieved Mid-IR radiation with an average power of 1.1 W and tuning range of 8.2–8.8 μm by a CdSe optical parametric oscillation.

Among the above techniques, the DFG has many extra advantages such as no threshold and more compact structure due to no oscillation mirrors. In 2002, Shi *et al.*[15] obtained 2.7–28.7 μm Mid-IR radiation using DFG pumped by 1.064 μm laser. Different from the pump source in Ref. [15], the pump source in this paper is a dual-wavelength intracavity optical parametric oscillator operating around 2 μm. Due to the simultaneous dual-wavelength output, the experimental construction can be made simpler and more compact, which is advantage in practical application. Based on type-I and type-II collinear phase matching (PM) schemes in GaSe crystal, a tabletop Mid-IR source with a wide tuning range is obtained, which supplies a good method for Mid-IR generation.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 60777036 and 60671036), and the National Basic Research Program of China (Grant No. 2007CB310403).

†Corresponding author. E-mail: lixuejin@szu.edu.cn

© 2010 Chinese Physical Society and IOP Publishing Ltd

2. Experimental setup

A KTP intracavity optical parametric oscillator (IOPO) is used as a dual-wavelength source, which is doubly resonant in the vicinity of degenerated point 2.1 μm and pumped by an electro-optically Q-switched Nd:YAG laser operating at a wavelength of 1.0645 μm, and then the Mid-IR radiation is generated by three-wave mixing of DFG.

The schematic of the experiment setup is shown in Fig. 1. The plane-parallel resonator of the Nd:YAG laser has two plane mirrors M1 and M3 with high-reflection at 1.0645 μm, which are separated by 420 mm. The Nd:YAG is pumped by a flash lamp with a repetition rate of 10 Hz. The plane mirrors M2 and M3 constitute a cavity of the IOPO with a length of 28 mm. The mirror M2 is dielectric coated with a reflectivity of $\sim$3% at 1.0645 μm and a high reflection of $>$ 99% in a range of 1.9–2.42 μm, and the M3 serving as the coupled output mirror is also coated with a reflectivity of $\sim$20% in a range of 1.9–2.42 μm. So with these dielectric coated mirrors, a double-pass gain and a double resonance in the KTP crystal can be obtained. The KTP crystal with dimensions of $7\times8\times12$ mm^3 is used as a nonlinear crystal which is cut at an angle of $\theta = 49.5^\circ$ to the z-axis in the xz plane for type II critical phase-matching interaction, and the two end surfaces are uncoated.

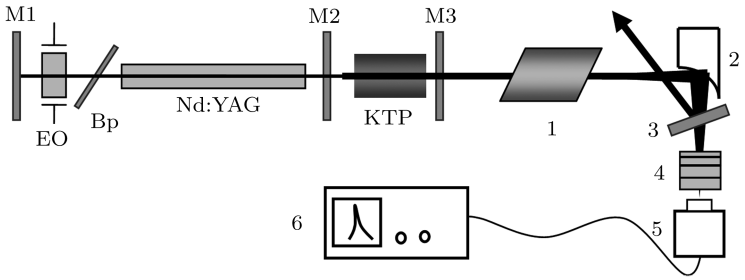


Fig. 1. Compact experimental setup for Mid-IR generation based on DFG in the GaSe crystal pumped by a KTP-IOPO. M1, M2 and M3 denote dielectric film-coated mirrors; EO represents the electro-optic crystal of KD*P; BP stands for Brewster plate; 1, GaSe crystal; 2, parabolic mirror; 3, germanium plate coated with high reflection dielectric film up to 2.5 μm; 4, composite filters; 5, DTGS detector; 6, analog oscilloscope or composite grating spectrometer.

GaSe crystal, found first in 1972,[16] is a high performance nonlinear crystal medium with a high figure of merit in a transparent range of 0.65–20 μm. Its birefringence is very large around 2 μm and the PM condition can be satisfied in a wide waveband. In our experiment, the GaSe crystal with dimensions of 16 mm (diameter)$\times$10 mm (length) is z-cut, and two end surfaces are uncoated. This crystal is placed on a rotating stage with high precision.

3. Experimental results and discussion

According to the principle of the nonlinear optical three-wave mixing, we know that for type-I eoo and type-II eoe DFG phase matchings in GaSe (o and e denote ordinary polarisation and extraordinary polarisation, respectively), the polarisation directions of the dual waves incident to GaSe are required to be orthogonal to each other, so type-II PM scheme is adopted in KTP-IOPO where the signal wave and idler wave are simultaneously produced with orthogonal polarisations. Figure 2 shows the tuning curve of type-II KTP-IOPO pumped by 1.0645 μm laser, where the solid line represents the theoretical results according to the KTP Sellmeier dispersion equation reported by Vanherzeele *et al.*[17] However, limited by the maximum scanning range of optical spectrum analyser (Agilent 86142B, just up to 1.7 μm) we used in the study, the output signal and idler wavelengths are obtained by measuring the second harmonic generation (SHG) light of the output with another KTP crystal. As shown by the solid dot in Fig. 2, the tuning range of signal wave is 1.856–2.127 μm with corresponding idler wave tuning range of 2.497–2.129 μm shown as solid square symbols, and the angle of KTP crystal changes from 47.1° to 50.77°. From Fig. 2, it can also be seen that the experimental results are consistent well with the theoretical values. The SHG spectra

of signal waves at different KTP angles are shown in Fig. 3. The linewidth of KTP-IOPO is ∼1 nm and the pulse width is ∼7 ns in the whole tuning range.

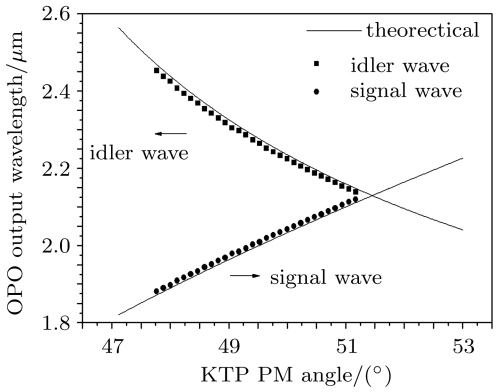


Fig. 2. Angle tuning curves of KTP-IOPO pumped by 1.0645 μm laser.

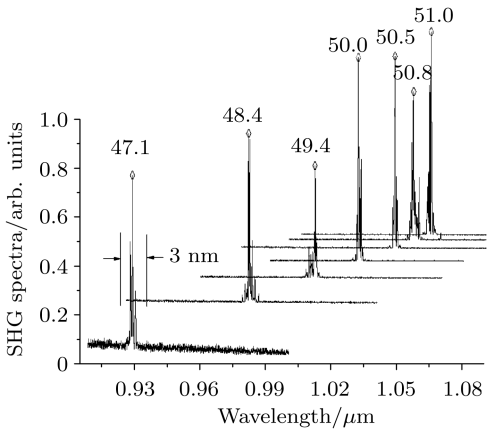


Fig. 3. SHG spectra of signal waves at different KTP angles.

Figure 4 shows the total output energy versus signal wavelength of KTP-IOPO. The maximum energy is ∼31 mJ at 2034.56 nm when pump light of 1.0645 μm is incident vertically on the end surface of the KTP crystal. Because the KTP crystal is no anti-reflecting coating, as the rotated angle of KTP crystal increases, the total energy decreases dramatically for the enlarged insertion loss, especially, in this intracavity pumped optical parametric oscillator.

In order to generate the Mid-IR radiation in GaSe crystal, type-I eoo and type-II eoe PM schemes need to be employed. The PM angle can be obtained by energy and momentum conservation equations combined with the dispersion equation of the GaSe crystal. The effective nonlinear coefficients of the two types PM schemes can be obtained from the following formula:

$$d_{\text{eff}} = d_{22}\cos\theta\sin(3\varphi) \quad \text{(Type I)}, \tag{1}$$

$$d_{\text{eff}} = d_{22}\cos^2\theta\cos(3\varphi) \quad \text{(Type II)}, \tag{2}$$

where θ is the PM angle, and ϕ is the azimuthal angles of GaSe. It is indicted that the maximum effective nonlinear optical coefficient (NLO) can be reached when $|\sin(3\phi)| = 1$ and $|\cos(3\phi)| = 1$ for the type-I scheme and the type-II PM scheme, respectively, that is, azimuthal angles of $\phi = \pm 30°, \pm 90°, \pm 150°$ for the type-I scheme and $\phi = 0°, \pm 60°, \pm 120°, \pm 180°$ for the type-II scheme must be chosen. Therefore, in experiment, the values of ϕ are set to be 30° and 0° for the type-I scheme and the type-II scheme, respectively.

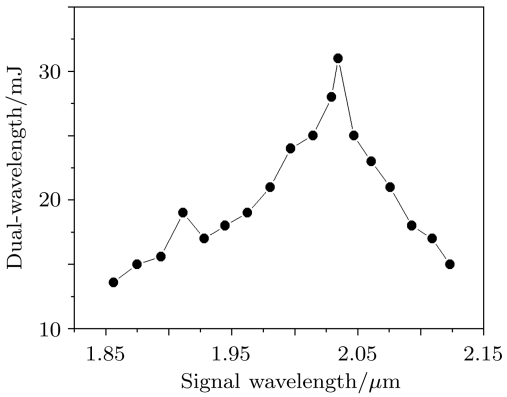


Fig. 4. Total energy versus wavelength of signal wave.

The Mid-IR energy is detected and measured using a KBr packaged deuterated tri-glycine sulfate pyroeletric detector (DTGS) with a response spectrum range of 2.5–25 μm and a high sensitivity pyroeletric detector (Coherent. J3-09). The Mid-IR wavelength is measured by a compound grating spectrograph with a TGS detector. In order to block the residual pumped light, a Ge plate coated with high reflection dielectric film in a wavelength of 1.8–2.5 μm is placed in front of the detector.

Figure 5 shows the tuning curves of type-I DFG scheme where the solid line represents the theoretical results calculated using Sellmeier equation[18] and the solid circles represent the experimental data. The measured tuning range is from 8.42 μm to 19.52 μm, corresponding to rotated angle range of the GaSe crystal from 31.99° to 35.96° (external PM angle). It can be seen from Fig. 5 that a turning point exists at ∼11.2 μm, corresponding to a minimum external PM angle of 31.99°, while the theoretical result is 32.0°, which indicates that the theoretical and the experimental results are in excellent agreement. Figure 6 shows the frequency dependence of generated Mid-IR energy for type-I DFG scheme. The maximum energy actually measured is 4.17 μJ at 12.35 μm when the total energy of signal wave and idler wave is 9.4 mJ, and

the peak power is ∼834 W. The conversion efficiency is about 0.044%.

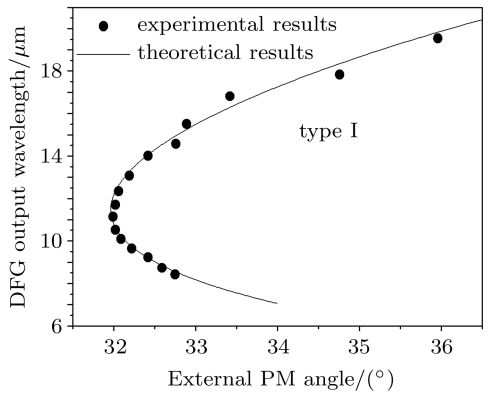


Fig. 5. Mid-IR wavelength versus external PM angle for type-I DFG scheme.

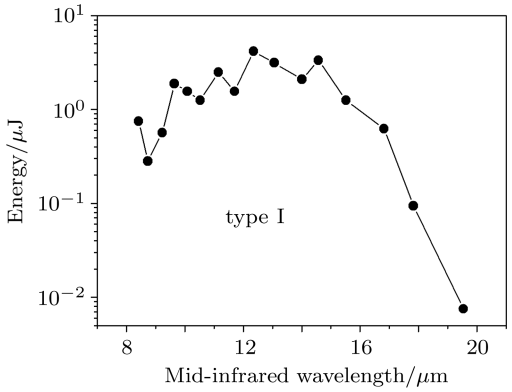


Fig. 6. Output Mid-IR energy versus wavelength for type-I DFG scheme.

The type-II DFG PM scheme is also investigated experimentally, and the variation of the Mid-IR wavelength with an external PM angle of GaSe crystal is shown in Fig. 7 where the solid line represents the theoretical results and the solid circles represent the experimental results. It can be seen that the Mid-IR radiation is in a range from 8.42 μm to 17.82 μm with an external PM angle ranging from 34.82° to 37.82°. The turning point exists at 14.01 μm, and its corresponding external PM angle is 34.82° which is also the minimum tuning angle of GaSe crystal. In the region of lower Mid-IR frequency, the small discrepancy between experiment and theoretical results maybe results from an accident vibration of the rotating stage. Figure 8 shows the energy variation with Mid-IR wavelength for the type-II DFG scheme. The maximum energy is 3.65 μJ at 14.56 μm when the total energy of signal wave and idler wave is 10.4 mJ, and the maximum peak power is around 730 W. The corresponding conversion efficiency is 0.035%.

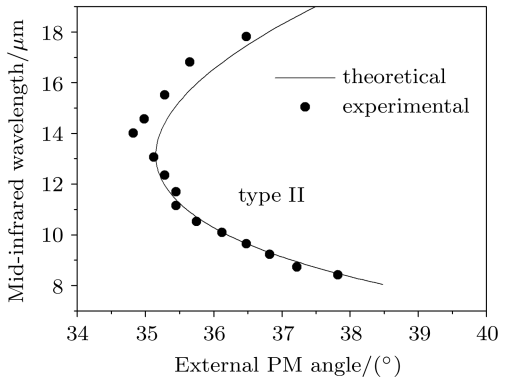


Fig. 7. Mid-IR wavelength versus external PM angle for type-II DFG scheme.

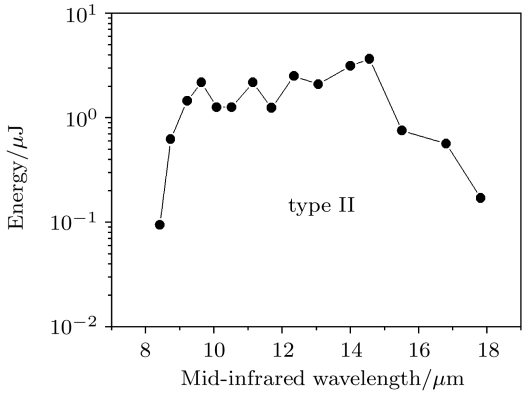


Fig. 8. Output Mid-IR energy versus wavelength for type-II DFG scheme.

A comparison between the above two DFG PM schemes shows that the type-I PM scheme produces higher energy than type-II PM scheme, and also has a wider tuning range, which could be explained by the different effective NLO coefficients and polarised-dependent transmissions. In addition, the output energies in both PM schemes decrease 18 μm or more, which is because the measured transmission of GaSe crystal beyond 18 μm spectral region is very low and exhibits cutoff property. However, compared with the case in Ref. [15], the output peak power is relatively low, which is due mainly to the low intensity (∼4 MW/cm^2) and wide spectral linewidth of signal and idler waves. If a linewidth narrowing device is adopted and the pumped dual-wavelength light beam is tightly and safely focused, much higher peak power is expected to be realised.

4. Conclusion

A double resonant KTP-IOPO operating at degenerated point of 2 μm is employed to generate Mid-IR radiation in GaSe crystal by DFG. Based

on two types of PM schemes, the tuning range of 8.42–19.52 μm is achieved and the peak powers are 834 W for the type-I PM scheme and 730 W for the type-II PM scheme. It is believed that a higher energy of Mid-IR radiation with a wide tuning range could be achieved using an optimised 2 μm dual-wavelength KTP-IOPO, and a compact and portable Mid-IR source can be realised.

References

[1] Liu Y Y, Liu H P, Guo Y Q, Lin J L, Liu X Y, Huang G M, Li F Y and Li J R 2000 *Chin. Phys.* **9** 184

[2] Forget S, Faugeras C, Bengloan J Y, Calliqaro M, Parillaud O, Giovannini M, Faist J and Sirtori C 2005 *Electron. Lett.* **41** 418

[3] Hofstetter D, Beck M, Aellen T, Faist J, Oesterle U, Llegenms M, Gini E and Melchior H 2001 *Appl. Phys. Lett.* **78** 1964

[4] Faugeras C, Forget S, Duchemin E B, Page H, Bengloan J Y, Parillaud O, Calligaro M, Sirtori C, Giovannini M and Faist J 2005 *IEEE J. Quantum. Electron.* **41** 1430

[5] Yu J S, Slivken S, Evans A, Darvish S R, Nguyen J and Razeghi M 2006 *Appl. Phys. Lett.* **88** 091113

[6] Vodopyanov K L 1999*J. Opt. Soc. Am.* B **16** 1579

[7] Mennerat G and Kupecek P 1998 *ASSL FC* paper **13**

[8] Schunemann P G, S D Setzler, Mohnkern L, Pollak T M, Bliss D F, Weyburne D and Hearn O 2005 *CLEO* **3** 1835

[9] Budni P A, Knights M G, Chicklis E P and Schepler K L 1993 *Opt. Lett.* **18** 1068

[10] Zakel A, Wagner G J, Alford W J and Carrig T J 2005 *ASSP* paper MD5

[11] Vodopyanov K L, Levi O, Kuo P S, Pingust T J, Harris J S, Fejer M M, Gerard B, Becouarn L and Lallier E 2004 *Opt. Lett.* **29** 1912

[12] Ding X, Zhang S M, Ma H M, Pang M, Yao J Q and Li Z 2008 *Chin. Phys.* B **17** 211

[13] Zhang T L, Zhang B G, Xu D G, Wang P, Ji F and Yao J Q 2008 *Chin. Phys.* B **17** 633

[14] Zhang C M, Wang J L, Wei P F, Song L W, Li C, Kim C J and Leng Y X 2009 *Chin. Phys.* B **18** 1469

[15] Shi W, Ding Y J, Mu X D and Fernelius N 2002 *Appl. Phys. Lett.* **80** 3889

[16] Abdullaev G B, Kulevskii L A, Prokhorov A M, Savelev A D, Salaev E Y and Smirnov V V 1972 *JETP Lett.* **16** 90

[17] Vanherzeele H, Beerlein J D and Zunsteg F C 1988 *Appl. Opt.* **27** 3314

[18] Vodopyanov K L and Kulevskii L A 1995 *Opt. Commun.* **118** 375