Vol 12 No 5, May 2003
1009-1963/2003/12(05)/0514-04

Chinese Physics

© 2003 Chin. Phys. Soc.
and IOP Publishing Ltd

Period and temperature tuning of cascaded optical parametric oscillator based on periodically poled $LiNbO_3$*

Lin Xue-Chun(林学春)†, Li Rui-Ning(李瑞宁), Yao Ai-Yun(姚爱云),
Bi Yong(毕 勇), Cui Da-Fu(崔大复), and Xu Zu-Yan(许祖彦)

Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, *China*

(Received 17 December 2002; revised manuscript received 10 January 2003)

We report the broadly tunable source by a cascaded optical parametric oscillator in the periodically poled $LiNbO_3$ (PPLN) with domain grating period and temperature tuning. The optical parametric oscillator was pumped by a passive Q-switched Nd:YVO_4 laser. Multi-wavelength outputs from visible to infrared were obtained. The temperature of the PPLN crystal changed within the range of 70–150°C with different periods of PPLN. The tunable range covered from 433 to 1657nm.

Keywords: optical parametric oscillator, tuning, periodically poled lithium niobate
PACC: 4265K, 4260F, 4270

A tunable radiation is important for high-resolution spectroscopy. Quasi-phase-matched (QPM)[1,2] optical parametric oscillators (OPOs)[3] are attractive sources of tunable coherent radiation. Periodically poled $LiNbO_3$ (PPLN) is now available as a bulk nonlinear optical crystal for QPM OPO.[4–7] There are three commonly used tuning methods based on PPLN, i.e. pump-wavelength, grating-period or temperature tunings. By means of period tuning, McEwan *et al*[8] obtained 2–5μm radiation by using a PPLN with eight different grating periods ranging from 25.5 to 28.7μm. Myers and Terry[9] obtained the wavelength in the range of 1.66–2.95μm by heating a bulk PPLN with a 31μm period from room temperature to 180°C. In this paper we demonstrated the broadly tunable from violet to infrared by the combination of varying the temperature and the grating period in a PPLN using a cascaded OPO. Five different wave-ranges are tuned simultaneously, which covered wavelengths from 433 to 1657 nm.

For a collinear optical parametric interaction, the theory that underlies QPM has been explained in detail.[10] In essence the equations governing the process are almost the same as those for describing the critical or noncritical phase-matching. One difference is that the value of the wavevector mismatch, Δk, is modified by a vector taking account of the grating, $k_{\rm m}$. Hence for an OPO utilizing QPM, Δk is given by

$$\Delta k = k_{\rm p} - k_{\rm s} - k_{\rm i} - k_m, \tag{1}$$

where the subscripts p, s, and i refers to the pump, the signal and the idler, respectively, and k_m is given by $k_m = 2\pi m/\Lambda$, with m being order of the QPM process and Λ is the domain grating period. In a three-wave-nonlinear interaction, the frequencies are related by

$$\omega_{\rm p} = \omega_{\rm s} + \omega_{\rm i}, \tag{2}$$

where $\omega_{\rm p}$, $\omega_{\rm s}$ and $\omega_{\rm i}$ are the frequencies of the pump, signal and idler, respectively.

Due to the versatile characteristics of QPM in periodically poled crystals, the phase-velocity mismatch between the interacting waves is compensated such that nonlinear effects will be enhanced when waves pass through the crystals. There a cascaded OPO process is observed simultaneously, such as the signal light, the second harmonic generation (SHG) of the signal light, the sum frequency generation (SFG) of the signal and the pump light, the SHG of pump light, the third harmonic generation (THG) of the signal light and the SFG of the pump and the doubled

*Project supported by the National Natural Science Foundation of China (Grant No 69938010), the State Key Program for Basic Research of China (Grant No 1998061405-5), and a Grant Program of the Chinese Academy of Sciences.

†Author to whom correspondence should be addressed. E-mail: bj54lxc@sina.com.cn

signal light, their corresponding frequencies are ω_s, $2\omega_s$, $\omega_s+\omega_p$, $2\omega_p$, $3\omega_s$, and $2\omega_s+\omega_p$, respectively. The cascaded OPO process can be explained by a multi-wave coupling theory.[11] No idler radiation has been measured because of the absorption of the substrate material (K9 glass) in our case.

The experimental set-up of an external cavity PPLN-OPO is illustrated in Fig.1.

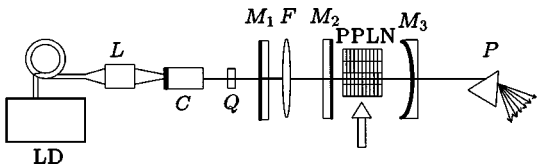


Fig.1. Schematic diagram of the PPLN-OPO. L is a focusing lens. C is the crystal of Nd:YVO_4. Q is Cr^{4+}:YAG. F is focusing lens. M_1, M_2 and M_3 are cavity mirrors. PPLN is the periodically poled crystal and P, the dispersion prism.

The pump laser was a diode-pumped passive Q-switched Nd:YVO_4 laser. The diode-laser was a commercially available fibre-coupled diode-laser-array (Product of SDL 830, NA=0.42), which delivered a maximum power of 10W at the wavelength of 808 nm. The output beam from the fibre bundle end, which is 0.4 mm in diameter, was focused into the Nd:YVO_4 crystal by a ϕ2mm×5mm self-focusing lens (NA=0.46). The laser crystal utilized was 0.5 at% Nd^{3+}-doped Nd:YVO_4 with dimensions of $4\times4\times8mm^3$. The light propagated along the Nd:YVO_4 x-axis with a length of 8mm. It was cooled by refrigerant water. The plane–plane cavity for 1064nm consisted of the entrance face of the laser crystal as the plane enter mirror and a plane mirror for the output coupler. The entrance face of Nd:YVO_4, was coated high-reflectivity (HR) at 1064nm and antireflectivity (AR) at 808nm; AR was coated at 1064nm on the other face; M_1 was coated part reflectivity (PR) (R=90%) at 1064nm. A passive Q-switch crystal of Cr^{4+}-doped YAG was set between Nd:YVO_4 and M_1, whose transmittance of static state was 60%. In this 70-mm-long plane-parallel cavity, the average power at 1064nm as the pump light of PPLN-OPO was 557mW with a 10.3ns pulse width and repetition frequency of 19.8kHz, its peak power was 2.7kW.

In our experiment, the cavity for PPLN-OPO was a flat-concave cavity with a length about 27mm. It consisted of M_2 used as the plane enter mirror and a concave mirror M_3 used as the output coupler. The entrance face of M_2 was coated AR at 1064nm; PR (R ≈8.2%) in 400–850nm and HR (R ≈99.7%) in 1450–1650nm on the other face. The concave mirror M_3, having a radius of curvature of 50mm, was coated HR (R=99.9%) at 1064nm, PR (R ≈8.5%) in 400–850nm and PR (R ≈96.3%) in 1450–1650nm.

The distance between the two cavities is about 60mm. A 50-mm-focus-lens is placed between them at a distance to M_2 about 52mm. We have found in the experiment that the power threshold is very sensitive to the distance between PPLN and M_2. In order to lower the threshold, we have to place PPLN as close to M_2 as possible. The OPO threshold power is 1.3kW.

Because the PPLN sample was designed for 1064nm pumping OPO process, the value of wavevector mismatch for this OPO process is equal to zero, i.e, Δk=0, corresponding to m=1. Meanwhile, the higher-order collinear process can be obtained even in the case of phase mismatched. The reason for this can be the following three points. Firstly, the effective nonlinear coefficient of QPM-PPLN is very large, so the nonlinear conversion efficiency is high. Secondly, the collinear matching mode has no walk-off effect which enhances the efficiency further. Thirdly, the Q value of the singly resonant oscillator for the signal light is very high in our experiment, in which a strong signal light in the cavity can generate the higher-order nonlinear processes.

The PPLN temperature was varied from 70 to 150°C for four PPLN grating periods of 28.7, 29.3, 29.7 and 30.4μm. We have measured the cascade OPO output wavelengths versus temperature corresponding to these periods. The results are summarized and shown in Fig.2.

Figure 2(a) shows the four wavelength-temperature tuning ranges for signal ω_s (corresponding to m=1): i.e. 1.463–1.482μm with 28.7μm grating, 1.498–1.527μm with 29.3μm grating, 1.527–1.563μm with 29.7μm grating, and 1.598–1.657μm with 30.2μm grating. In Fig.2(b), the wavelength tuning ranges and the corresponding grating period for the SHG ($2\omega_s$) of the signal are presented (m=1): 0.731–0.741μm at the period of 28.7μm, 0.749–0.763μm at 29.3μm, 0.763–0.782μm at 29.7μm and 0.798–0.828μm at 30.2μm. In Fig.2(c), the tuning ranges for the SFG ($\omega_s+\omega_p$) of the signal and pump are shown (m=3): 0.616–0.619μm at 28.7μm, 0.622–0.627μm at 29.3μm, 0.627–0.633μm at 29.7μm and 0.639–0.648μm at 30.2μm. In Fig.2(d), the tuning for the THG ($3\omega_s$)

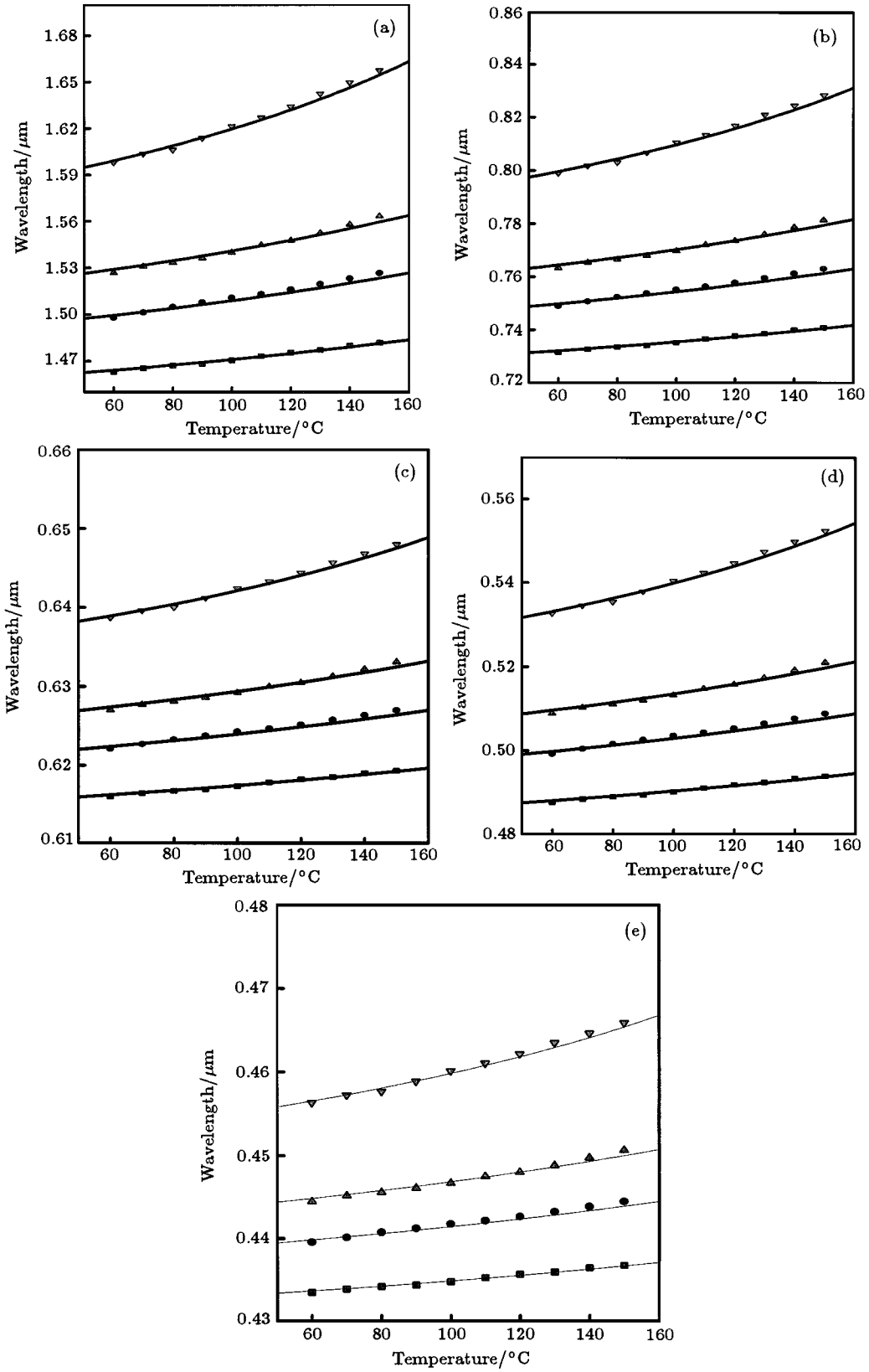


Fig.2. The temperature-tuning curves for the cascaded OPO in a PPLN crystal with four grating periods of 28.7, 29.3, 29.7 and 30.4μm and a pump wavelength of 1.064μm. The solid lines are the calculated results and the dots are experimental data. The curves from (a) to (e) represent the signal, SHG of the signal, SFG of the pump and signal, THG of the signal, SFG of the pump, and the doubled signal, respectively. ▼: Λ=30.4μm, ▲: Λ=29.7μm, ●: Λ=29.3μm, ■: Λ=28.7μm.

of the signal are presented (m=5): 0.488–0.494μm at 28.7μm, 0.499–0.509μm at 29.3μm, 0.509–0.521μm at 29.7μm and 0.533–0.553μm at 30.2μm. Finally, the tuning data for the SFG (ω_p+2ω_s) from the pump and the doubled signal are shown in Fig.2(e) (m=7): 0.433–0.437μm at 28.7μm, 0.440–0.444μm at 29.3μm, 0.444–0.451μm at 29.7μm and 0.456–0.465μm at 30.2μm. All the calculated curves plotted in Figs.2(a)–2(e) are based on the Sellmeier equations,[12] which are in good agreement with the experimental results. However, there is not any tuning in SHG ($2\omega_p$) of the pump, because the pump wavelength is fixed at 1.064μm.

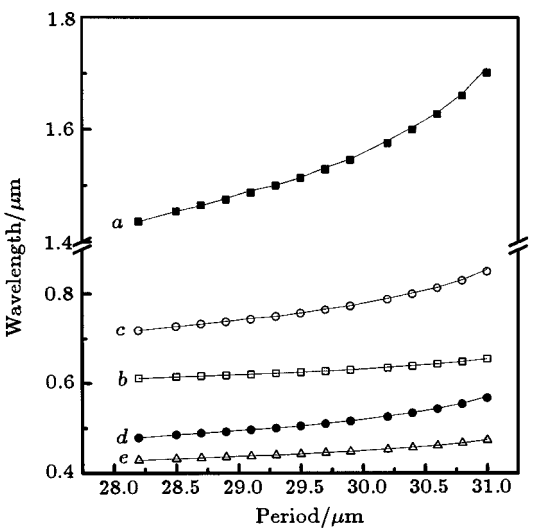


Fig.3. Period-tuning curves for 1064nm-pumped cascaded OPO in the bulk PPLN at 70°C. The symbols (experimental) together with the curves (calculated) represent (*a*): the signal, (*b*): SHG of the signal, (*c*): SFG of the pump and signal, (*d*): THG of the signal, (*e*): SFG of the pump and doubled signal, respectively.

We predict that a broadband ranging from 0.43 to 1.7μm will be feasible. In fact, we have also carried out the cascaded OPO experiment at a fixed temperature of 70°C in a 20mm long PPLN sample with 14 grating periods of 28.2, 28.5, 28.7, 28.9, 29.1, 29.3, 29.5, 29.7, 29.9, 30.2, 30.4, 30.6, 30.8 and 31.0μm. Their wavelength-period tuning ranges have been measured as follows: 1.440–1.702μm for ω_s; 0.718–0.851μm for $2\omega_s$; 0.611–0.654μm for $\omega_s + \omega_p$; 0.479–0.567μm for $3\omega_s$ and 0.429–0.474μm for ω_p+2ω_s as shown in Fig.3.

Obviously, neither pure period tuning nor pure temperature tuning can make wide wave-range continually tuning. However, this drawback can be overcome by a suitable choice of both grating period and temperature.

The cascaded OPO output power versus wavelength has been measured corresponding to Λ= 30.4μm at 70°C as is seen in Table 1.

Table 1. The cascaded OPO output power versus wavelength for PPLN with a grating period of Λ=30.4μm at 70°C.

	Wavelength/nm	Power/mW
ω_s	1592.0	47
$2\omega_s$	797.1	2.14
$\omega_s+\omega_p$	637.7	2.33
$3\omega_s$	525.6	0.011
$2\omega_s+\omega_p$	452.5	0.081

Obviously, the power is decreased with the increase QPM orders. The minimal output of them is 0.011mW at $3\omega_s$, which is strong enough for optical frequency synthesis and high-resolution spectroscopy.[13]

In conclusion, we have demonstrated that a convenient and compact all-solid-state source of broadly tunable laser can be obtained by the cascaded OPO with grating period and temperature tuning synchronously in a PPLN. The broad waveband from 433 to 1657nm has been generated in this way. It can be applied widely in the study of spectrum, biology or iatrology.

References

[1] Ming N B, Hong J F and Feng D 1982 *J. Mater. Sci.* **17** 1663

[2] Fejer M M, Magel G A, Jundt D H and Byer R L 1992 *IEEE J. Quantum Electron.* **28** 2631

[3] Ebrahimzadeh M, Turnbull G A, Edwards T J, Stothard D J M, Lindsay I D and Dunn M H 1999 *J. Opt. Soc. Am.* B **16** 1499

[4] Richman B A, Aniolek K W, Kulp T J and Bisson S E 2000 *J. Opt. Soc. Am.* B **17** 1233

[5] Finsterbusch K, Urschel R and Zacharias H 2000 *Appl. Phys.* B **70** 741

[6] Schlup P, Baxter G W and Mckinnie L T 2000 *Opt. Commun.* **176** 267

[7] Hanssion G and Smith D D 2000 *Opt. Lett.* **25** 1783

[8] McEwan K J and Terry J A C 2000 *Opt. Commun.* **182** 423

[9] Myers L E, Miller G D, Eckardt R C, Fejer M M, Byer R L and Bosenberg W 1995 *Opt. Lett.* **20** 52

[10] Myers L E, Eckardt R C, Fejer M M, Byer R L and Pierce J W 1995 *J. Opt. Soc. Am.* B **12** 2102

[11] Xu Z Y, Liang X Y, Li J, Yao A Y, Lin X C, Cui D F and Wu L A 2002 *Chin. Phys. Lett.* **19** 801

[12] Jundt D H 1997 *Opt. Lett.* **22** 1553

[13] Butterworth S D, Smith P G R and Hanna D C 1997 *Opt. Lett.* **22** 618