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Mid-infrared generation based on a periodically poled $LiNbO_3$ optical parametric oscillator*

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We report a nanosecond Nd:YVO_4-pumped optical parametric oscillator (OPO) based on periodically poled $LiNbO_3$ (PPLN). Tuning is achieved in this experiment by varying the temperature and period of the PPLN. The design of double-pass singly resonant oscillator (DSRO) and confocal cavity enables the OPO threshold to be lowered considerably, resulting in a simple, compact, all-solid-state configuration with the mid-infrared idler powers of up to 466mW at 3.41μm.

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

Periodically poled $LiNbO_3$(PPLN) has become a reliable and efficient nonlinear material for quasi-phase-matched nonlinear processes.[1−4] A broad wavelength range can be accessed via the processes of second harmonic generation (SHG) and optical parametric oscillation by choosing an appropriate PPLN grating period.[5,6] Quasi-phase-matching (QPM) uses periodic modulation of the nonlinear properties of a crystal to compensate for the mismatch between the wave vectors of the interacting light beams,[7] enabling one to engineer the nonlinear properties of the crystal by fabricating a periodic structure with conventional photolithographic technique. This permits the utilization of any component of the nonlinear susceptibility tensor and the implementation of noncritical phase matching at any wavelength within the crystal's transparency range. Therefore, QPM permits efficient frequency conversion with substantially lower pumping power than that required in conventional birefringent phase matching, especially in PPLN which has a large nonlinear coefficient accessible only through QPM.

The generation of mid-infrared (mid-IR) light by PPLN in an optical parametric oscillator (OPO) is attractive for a variety of applications. Some work has been reported on mid-IR generation based on PPLN–OPO,[8,9] but few have achieved high output power.[10]

In a previous paper we reported multiwavelength generation from violet to near infrared based on PPLN–OPO;[11] the six output wavelengths obtained were measured and explained by multiwave coupling theory. Here we present results of long-wavelength output from PPLN–OPO, pumped by a Q-switched, diode-pumped Nd:YVO_4 laser. A maximum of 466mW at 3.41μm tunable light in the mid-IR has been obtained.

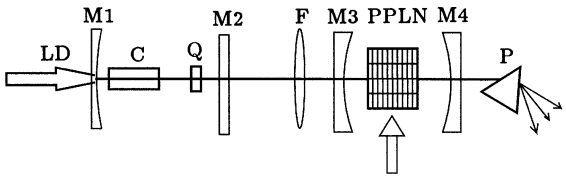


Fig.1. Schematic diagram of the PPLN–OPO. C is crystal of Nd:YVO_4. Q is the Q-switch, M1, M2, M3 and M4 are cavity mirrors. PPLN is the periodically poled $LiNbO_3$ and P, the dispersion prism.

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The experimental arrangement is shown in Fig.1. The pump laser is a diode-pumped Q-switched Nd:YVO_4 laser. The concave-parallel cavity for the 1064nm wavelength consists of a concave entrance mirror M1 (R=200) and an output coupler M2. In the 150-mm-long cavity the laser output of 1064nm, having the average power of 3.4W with 20ns pulse width and repetition rate of 16.2kHz and peak power 10.3kW, is applied to pump the PPLN–OPO.

The PPLN crystal is 20mm long (x-axis), 10mm wide (y-axis) and 1mm thick (z-axis). It has eight parallel gratings across the width of its aperture, grating periods varying from 28.2 to 31.0μm in 0.4μm steps. The PPLN crystal is mounted in an oven maintained at temperature 353±0.1K so as to minimize photorefractive distortion.

The OPO was configured as a two-mirror confocal cavity, with both concave mirrors M3 and M4 having a radius of curvature of 50mm. With the PPLN crystal in the resonator, the beam waist at its centre was approximately 100μm as calculated by $ABCD$ matrix.

The OPO mirrors M3 and M4 are designed for a double-pass singly resonant OPO (DSRO), resonating with the signal light. The mirrors are coated with calcium fluoride films to allow transmission of visible, signal and idler light. The input mirror M3 is coated for high reflectivity (99.5%) in the idler waveband 3.0–4.0μm, and its transmission of 1064nm was measured to be 72%. The output coupler M4 is coated for high reflectivity (99%) at 1064nm to enable double-pass of the pump light, and high transmission in the idler waveband 3.2–4.0μm (measured to be 95%). For both mirrors, high reflectivity (99.5%) in the signal waveband 1.4–1.7μm is achieved to ensure DSRO operation. In order to minimize losses, the end faces of the PPLN crystal are anti-reflective (AR) coated at 1064nm, 1.4–1.7μm and 3.0–4.0μm. The distance between the two cavities is about 180mm. A 50-mm-focus lens (F) is placed between them with a distance to M2 about 18mm, which focuses the pump light to the crystal of PPLN. The pump radius measured from the focus is about 100μm.

Owing to the reasons mentioned above, the lowest threshold of OPO obtained is only 6.5mW of average power, corresponding to a peak power of 20W. Oscillation identified by the emerging red beam owing to the sum frequency generation (SFG) of the signal and the pump beams was easily achieved. This experimental result indicates that the pump source can be replaced by a more compact single diode.

With the increase of pump power, we observed the visible lights such as the red, green (the second harmonic generation of the pump), blue (the third harmonic generation of the signal) and purple (the SFG of the pump and the doubled signal light) lights, among which the red light has the highest output power. As the transmission of visible light through this output coupler is not high (with the following measured transmissions: for the range of purple, ~20%; blue, ~40%; green, ~10%; and red, ~45%), and the red and green lights are visible in all the experiment setup.

We measured the wavelength of the output red light, and then deduced the wavelength of the signal and idler light by the following formulae:

$$\frac{1}{\lambda_{\mathrm{red}}} = \frac{1}{\lambda_{\mathrm{s}}} + \frac{1}{\lambda_{\mathrm{p}}}, \tag{1}$$

$$\frac{1}{\lambda_{\mathrm{p}}} = \frac{1}{\lambda_{\mathrm{s}}} + \frac{1}{\lambda_{\mathrm{i}}}. \tag{2}$$

The deduction based on the above formulae is logically strict, because these formulae truly describe the nature of the physical phenomenon.

Figure 2 shows the output powers of the signal and idler versus grating periods corresponding to the incident pump power of 2.43W with a pulse width of

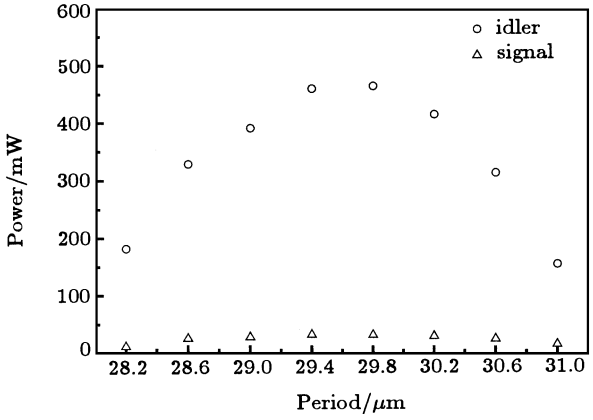


Fig.2. Output powers of the signal and idler light versus the variation of the period at incident pump power of 2.43W.

20ns and repetition rate of 16.2kHz at the temperature of 353K. The wavelength range of signal light is 1.44–1.74μm, and the idler light, 2.77–4.04μm. The maximum idler output power of 466mW at 3.41μm was obtained with the grating period of 29.8μm. The overall output power from visible to mid-IR was 673mW, leading to an overall optical-to-optical conversion efficiency of 28%. Theoretically, the idler output power should decline with the increase of the wavelength and the signal output power should rise at the same time

because of the conversion of the photon energy. However, in our experiment the idler and signal output power tend to increase at the beginning and then decrease with the increase of the idler wavelength. This could be attributed to the transmittance of the AR-film coated on the output mirror and the end faces of the PPLN.

We calculated the conversion intensity among the pump, deplete pump, signal and idler lights with the change of time using Runge–Kutta methods at the temperature of 353K with the period of 29.8μm, as shown in Fig.3. By means of dividing each pump pulse into hundreds of slices, we think each slice should be calculated in the OPO process according to the Sellmeier equation:[12]

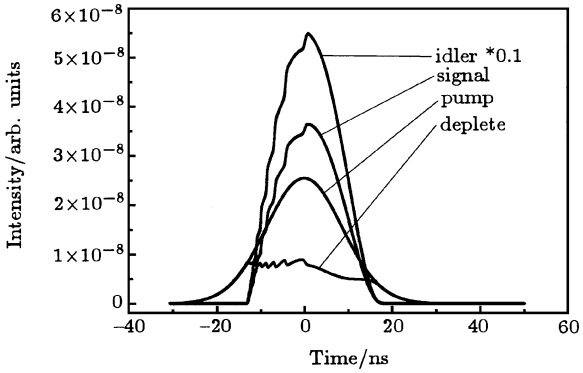


Fig.3. Calculation of pump, pump depletion and the generation of the signal and idler.

$$n_{\mathrm{e}}(\lambda,\mathrm{T}) = \sqrt{a_1 + b_1 f(\mathrm{T}) + \frac{a_2 + b_2 f(\mathrm{T})}{\lambda^2 - (a_3 + b_3 f(\mathrm{T}))^2} + \frac{a_4 + b_4 f(\mathrm{T})}{\lambda^2 - a_5^2} - a_6\lambda^2}, \tag{3}$$

where a_1=5.35583, a_2=0.100473, a_3=0.20692, a_4=100, a_5=11.34927, a_6=1.5334×10^{-2}, b_1=4.629×10^{-7}, b_2= 3.862 ×10^{-8}, b_3=–0.89×10^{-8}, and b_4=2.657×10^{-5}, and the temperature function $f(T)$ is given by

$$f(T) = (T - 24.5)(T + 570.82) \quad (T \text{ in Celsius scale}). \tag{4}$$

The result is the superimposition of the effects of each slice. When the pump light increases to a certain extent (the threshold), the signal and idler lights are generated simultaneously. Following the depletion of pump light, the intensity of the signal and idler lights increases. As a result of the high transmission, the idler has the maximum intensity of output. To compare its intensity with that of pump, deplete pump and signal light in the same figure conveniently, we reduced the intensity of idler 10 times in Fig.3. Because of the very low transmission of the output coupler, the output intensity of the signal is very low. Obviously, this calculation accords with the experiment of Fig.2.

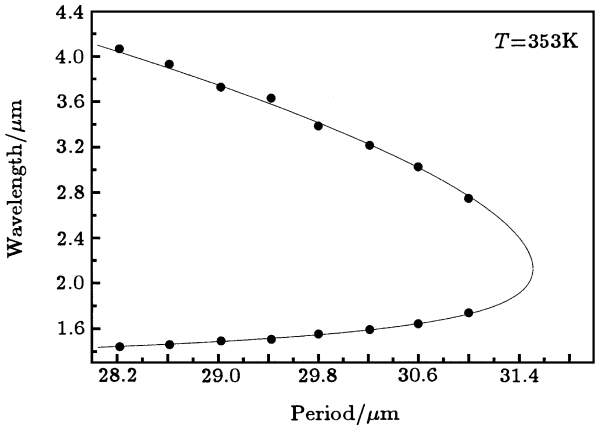


Fig.4. Period tuning curve for PPLN–OPO at the temperature of 353K. The points are experiment data, the curve is calculated.

The tuning of this DSRO, with 1.44–1.74, 2.77–4.04μm for the signal and idler branches, respectively, was achieved by changing the periods from 28.2 to 31.0μm. Also plotted in Fig.4 are the corresponding data points of signal and idler wavelengths deduced from the experiment corresponding to the temperature of 353K, showing a reasonable agreement with predictions.

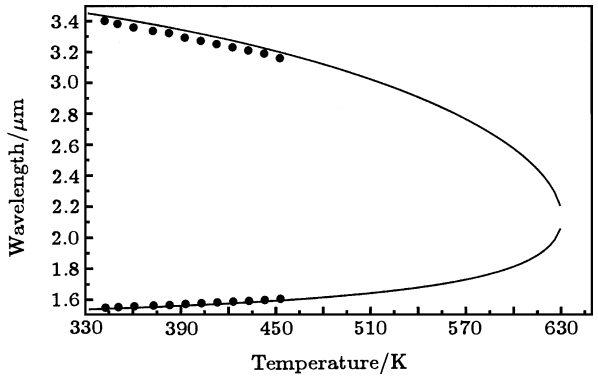


Fig.5. Temperature tuning curve for 1.064-μm-pumped PPLN–OPO at the period of 29.8μm. The points are experiment data, the curve is calculated.

The temperature tuning, for a 1.064μm pumping, was also achieved, with the temperature ranging from 343 to 453K at the step of 10K. The wavelength ranges of signal light, 1.55–1.60μm and the idler light, 3.16–3.41μm were obtained in the experiment at the period

of 29.8μm. Figure 5 shows the wavelengths measured and calculated. Obviously, the theoretical result is in good agreement with the experimental data.

In conclusion, we have demonstrated the performance of a PPLN–OPO pumped by a Q-switch Nd:YVO_4 laser. Tuning in a range from 1.44 to 4.04μm was achieved when the periods and temperature were tuned. Threshold as low as 6.5mW and an overall output power of 673mW were observed at the incident pump power of 2.43W, with the maximum idler output of 466mW at the wavelength of 3.41μm. The maximum optical-to-optical conversion efficiency from pump to total OPO output was 28%. This would provide a convenient and compact all-solid-state source of broadly tunable infrared pulses for spectroscopic applications.

References

[1] Philip S, Baxter W G and Iain T M 2000 *Opt. Commun.* **267** 176

[2] Xia J F, Wei Z Y and Zhang J 2003 *Acta Phys. Sin.* **49** 256 (in Chinese)

[3] Liu H J, Chen G F, Zhao W, Wang Q S and Zhao S H 2003 *Acta Phys. Sin.* **50** 1717 (in Chinese)

[4] Xie T, Yu J, Ni J W and Li S C 2002 *Acta Phys. Sin.* **51** 565 (in Chinese)

[5] Lefort L, Puech K, Butterworth S D, Ross G W, Smith P G, Hanna D C and Jundt D H 1998 *Opt. Commun.* **55** 152

[6] Mcewan K J and Terry J A 2000 *Opt. Commun.* **423** 182

[7] Du Y, Zhu S N, Zhu Y Y, Xu P, Zhang C, Chen Y B, Liu Z W, Ming N B, Zhang X R, Zhang F F and Zhang S Y 2002 *Appl. Phys. Lett.* **81** 1573

[8] Hsu C W and Yang C C 2001 *Opt. Lett.* **26** 1412

[9] Ebrahimzadeh M, Phillips P J and Das S 2001 *Appl. Phys.* B **72** 793

[10] Elder I F and Terry J A 2000 *J. Opt.* A **2** L19

[11] Lin X C, Li R N, Yao A Y, Bi Y, Cui D F and Xu Z Y 2003 *Chin. Phys.* **12** 514

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