Infrared OPO temperature tuning based on periodically-poled lithium niobate

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An optical parametric oscillator (OPO) based on periodically-poled lithium niobate (PPLN) and pumped by 1064.2-nm laser is demonstrated, which can be conveniently tuned by the means of changing its operating temperature. The parameters of the set-up and experimental results are introduced in this paper. We adjusted the operating temperature from 80 to 250 °C, the output wavelength shifted from 1485.4 to 1540.7 nm. The average of the shifts is 0.33 nm/°C.

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Quasi-phase-matching (QPM) technique is a rapidly growing field due to recent advances in the fabrication of periodically-poled ferroelectric materials. It is used in optical parametric oscillator (OPO)[1−4], difference frequency generator (DFG)[5,6], sum frequency generator (SFG)[7], and second harmonic generator (SHG)[8]. Periodically poled lithium niobate (PPLN) is a new nonlinear optical material which has excellent features suiting the frequency conversion of a laser beam at the spectrum range from 400 to 4500 nm[2]. Optical parametric generators (OPGs) based upon QPM have many potential applications, for example, in spectroscopy, medical diagnostics and therapies, physical, chemical, biophysical and biomolecular researches, environmental monitoring, defense and security, and optical communications. Temperature tuning is a unique feature of OPO, which makes its application scope enlarged. The temperature tuning feature of OPO based upon PPLN is the results that the operating temperature fluctuation of PPLN causes output wavelength shifts due to the changes of the length of PPLN and the refractive index of materials. The width of PPLN grating period will change because of the expansion coefficient of material when the operating temperature fluctuates. Temperature tuning of an OPO based on PPLN is studied in this paper. The results of experiment and theory calculation demonstrate that PPLN is very useful to configure an OPO which can tune the output wavelength easily. It is a good way to get versatile sources to meet various requirements due to the large span of the spectrum.

In a general three-wave interaction, the frequencies ω_1, ω_2, and ω_3 must meet the energy conversion criterion, i.e. $\omega_1 + \omega_2 = \omega_3$. The phase of the fields is also important because the phase relationship determines the direction of power flows between the interacting waves. The conversion efficiency is determined by the extent of phase-matching, i.e. $\Delta\kappa = \kappa_3 - \kappa_2 - \kappa_1$, where $\kappa_j = \omega_j n_j / c$ (j = 1, 2, 3) is the wave vector of the corresponding wave with the refractive index n_j. In OPO, the three wavelengths are constrained by the following energy conservation equation

$$\frac{1}{\lambda_s} + \frac{1}{\lambda_i} = \frac{1}{\lambda_p}, \tag{1}$$

where λ_p, λ_s, and λ_i are the pump, the signal and the idle vacuum wavelength, respectively. The highest conversion occurs at the center of the phase-matching peak, where the phase mismatch in a first-order QPM interaction, Δk, is given by the following equation[9]

$$\Delta k(T) = 2\pi \left[\frac{n_p(\lambda_p, T)}{\lambda_p} - \frac{n_s(\lambda_s, T)}{\lambda_s} - \frac{n_i(\lambda_i, T)}{\lambda_i} - \frac{1}{\Lambda(T)} \right], \tag{2}$$

where n_p is the extraordinary refractive index at the pump wavelength, and n_s and n_i are the corresponding qualities for the signal and the idle waves respectively. Λ presents the grating period of PPLN. The period required for QPM is calculated by setting the phase mismatch to be equal to zero in Eq. (2).

Lithium niobate (LN) has been a historically significant material for OPOs since the first Czochralski growth of large boules at Bell Laboratories in 1965. PPLN fabrication methods are electric-field poling techniques first demonstrated by Yamada *et al.* of Sony Corporation in 1992[10]. In some sense, PPLN serves nonlinear optics as silicon does the microelectronics industry. It is a generic well-developed substrate material from which a variety of devices can be fabricated.

Because the PPLN devices are manufactured and sold at room temperature, a thermal expansion of the QPM period at the operating temperature relating to that at room temperature needs to be considered. The PPLN crystal expands in the propagation direction, and the grating period increases correspondingly. The length l of crystal at temperature T is normalized to the length of 25 °C according with the following formula[11]

$$l = l_{25^\circ\mathrm{C}}[1 + \alpha(T - 25^\circ\mathrm{C}) + \beta(T - 25^\circ\mathrm{C})^2], \tag{3}$$

where $\alpha = 1.5 \times 10^{-5}$ K^{-1} and $\beta = 5.3 \times 10^{-9}$ K^{-2} are the expansion coefficients.

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The refractive index n is given as

$$n_e^2 = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - (a_3 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5^2} - a_6 \lambda^2, \tag{4}$$

where $a_1 = 5.35583$, $a_2 = 0.100473$, $a_3 = 0.20692$, $a_4 = 100$, $a_5 = 11.34927$, $a_6 = 1.53343 \times 10^{-2}$, $b_1 = 4.6293 \times 10^{-7}$, $b_2 = 3.8623 \times 10^{-8}$, $b_3 = 20.893 \times 10^{-8}$, and $b_4 = 2.6573 \times 10^{-5}$.

The temperature parameter f is the square of the absolute temperature in degrees Kelvin, with an added offset to make it vanish at the reference temperature $T_0 = 24.5$ °C. For temperatures T expressed in degrees Celsius, f is given as

$$f = (T - T_0)(T + T_0 + 2 \times 273.16). \tag{5}$$

Because the PPLN devices are manufactured at room temperature, thermal expansion needs to be considered in relating the PPLN period at the operating temperature to that at room temperature. The PPLN periods required for QPM according to the desired output wavelength around mid-IR are calculated by Eqs. (1) – (5). Pump wavelength λ_p is 1064.2 nm, and the operating temperature of PPLN is 100 °C. Calculation results are shown in Fig. 1.

Our set-up schematic diagram of PPLN-OPO is shown in Fig. 2. A 1064-nm acousto-optically Q-switched cw-diode-pumped Nd:YVO$_4$ laser is used as a pump source. A fiber-coupled 808-nm diode laser is coupled into the Nd:YVO$_4$ crystal by using two lenses. As a 1064-nm resonant mirror, one of the Nd:YVO$_4$ crystal faces is HR coated at 1064 nm and AR coated at 808 nm. The Nd:YVO$_4$ laser generated 1064-nm pump source for OPO with a duration of 30 ns at a 19-kHz repetition rate with maximum average power of 740 mW. We utilize a PPLN with width of 0.5 cm, thickness of 0.5 mm, length of 5 cm and 29-mm periods as a nonlinear material in the set-up. The PPLN is put in a resonator cavity. The resonator cavity is packaged in an oven, which is conveniently used to adjust and control the PPLN operating temperature. The temperature of the oven can be controlled with precision of 0.1 °C. The output coupler had 80 mm radius of curvature and transmissions of 89% at 1064 nm and 0.1% at signal wave. The input coupler of the PPLN-OPO cavity was coated for transmissions of 95% at 1064 nm and 0.1% at signal wave. The output coupler had 80 mm radius of curvature and transmissions of 89% at 1064 nm and 15% – 19% at signal wave (1480 – 1540 nm). The two mirrors were separated by 80 mm.

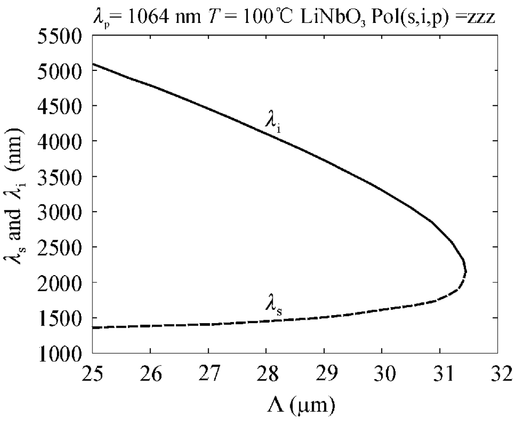

Fig. 1. Signal and idle wavelengths depending on the PPLN periods for an OPO pumped by a Nd:YAG laser, at the operating temperature of 100 °C.

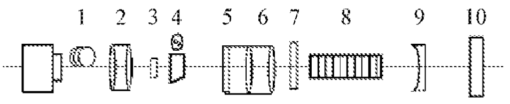

Fig. 2. Experimental schematic diagram of PPLN-OPO. 1: 808-nm fiber-coupled diode laser, 2: 808-nm coupling system, 3: Nd:YVO$_4$ crystal, 4: Q-switch, 5: 1064-nm output mirror, 6: 1064-nm coupling system, 7: PPLN-OPO input mirror, 8: PPLN and its heating oven, 9: PPLN-OPO output mirror, 10: filter.

The threshold of the PPLN-OPO was 210 mW under the conditions of the operating temperature 140 °C, 1064-nm pulse repetition rate of 19 kHz and pulse width of 30 ns. The maximum average power of 1500 nm was 137 mW. The output pulse spectra are shown in Fig. 3 corresponding to the PPLN operating temperature of 200 °C.

We adjusted the operating temperature from 80 to 250 °C, the experimental results are shown in Fig. 4. The rings are the results calculated with the Eqs. (1) – (5),

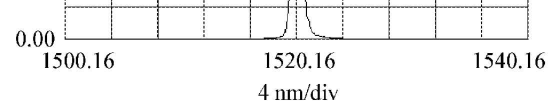

Fig. 3. Signal light pulse spectrum at the operation temperature of 200 °C.

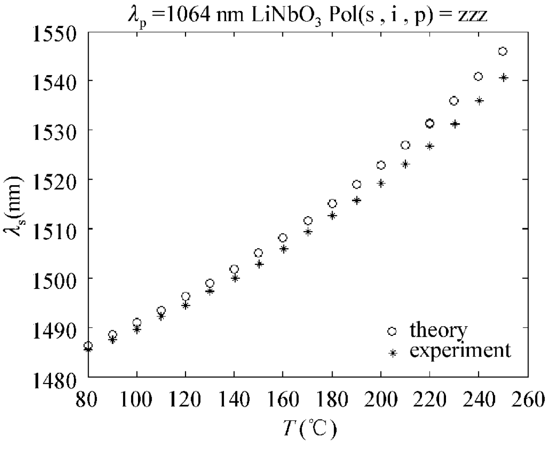

Fig. 4. Signal wavelengths curves of experiment and theory for temperature from 80 to 250 °C.

whereas the crosses are the experimental results. The theoretical analysis of the signal wavelength is in good agreement with our experimental results. When the operating temperature ascends from 80 to 250 °C, the output wavelength shifts from 1485.4 to 1540.7 nm. The average of the shifts is 0.33 nm/°C.

By the means of the QPM technique, IR OPO temperature tuning based on PPLN can provide more radiation sources for manifold applications. With the development of optical nonlinear materials, refined pump lasers and novel cavity geometries, commercial systems, which offering wide tuning ranges from the UV to the mid-IR and from nano- to femtosecond pluse durations, or even CW sources, are now widely available.

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