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Angle-tuned signal-resonated optical parametric oscillator based on periodically poled lithium niobate

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We demonstrate an angle-tuned signal-resonated optical parametric oscillator (OPO) with periodically poled lithium niobate (PPLN) pumped by a diode-pumped Nd:YVO$_4$ laser. 1499.8 − 1506.6 nm of signal wavelength is achieved at 140°C by rotating a 29-μm period PPLN from 0° − 10.22° in the x-y plane while keeping the pump wave vertical to the resonator mirrors. Two pairs of the signal and idler waves of the same wavelengths can be achieved symmetrically for each pair of angles of rotation with same absolute value and opposite sign. Theoretical analyses on angle-tuned PPLN-OPO with pump wave vertical to the resonator mirrors are presented and in good agreement with our experimental results. It is also found that all interacting waves in the cavity (not inside the crystal) are always collinear for PPLN-OPO with the pump wave vertical to the resonator mirrors while phase-matching is noncollinear within the crystal.

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Quasi-phase-matching (QPM) is a competitive technique, in which a periodical modulation of the nonlinear susceptibility is used to compensate for the difference of propagation vectors by grating vector in a nonlinear crystal. The advantages of QPM over conventional birefringent phase matching (BPM) are that it has no restriction imposed on the directions of wave vector and polarization and can use a larger or the largest tensor component which allows high conversion efficiency, because the phase matching condition for QPM can be satisfied by grating period irrelative to the inherent properties of the crystal. QPM has been applied in several kinds of periodically poled crystals, such as periodically poled KTiOPO$_4$[1−3], periodically poled KTiOAsO$_4$[4], periodically poled Lithium Tantalite[5] and so on. However, periodically poled LiNbO$_3$ (PPLN)[6−9] is one of the most popular ferroelectric crystals for QPM due to its large nonlinear coefficient ($d_{33} \sim 27$ pm/V) and well developed periodically poled technique.

For QPM optical parametric oscillator (QPM-OPO), the wavelength tuning methods with a fixed pump wavelength in common use are temperature tuning[6], position tuning for multi-grating periodically poled crystal[10] and angle tuning[3]. In comparison with temperature tuning, angle tuning allows to construct a more rapidly tunable source. In comparison with position tuning, though the tunable wavelength range of angle tuning is generally smaller, the output wavelength can be tuned continuously. In addition, the multi-grating periodically poled crystal used in position-tuned QPM-OPO imposes some difficulties on production.

In this paper, we report theoretical analyses and experiment results for angle-tuned signal-resonated PPLN-OPO with pump wave vertical to the resonator mirrors (called vertically pumped PPLN-OPO in this paper for convenience).

In QPM, the crystal is generally periodically poled along the crystal z-axis and all interacting waves are polarized parallel to the crystal z-axis. In this case, the phase mismatch $\Delta\mathbf{k}$ is given by[6]

$$\Delta\mathbf{k} = \mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i - \mathbf{k}_m,$$

where $\mathbf{k}_m$ called "grating vector", is a parameter introduced by the periodically poled crystal and meets $k_m = 2\pi m/\Lambda$. Λ is the grating period and m is the QPM order. Here, $\mathbf{k}_p$, $\mathbf{k}_s$ and $\mathbf{k}_i$ are the wave vectors of the pump, signal and idler, respectively.

Two fundamental conditions should be satisfied to realize nonlinear optical frequency conversion with a nonlinear material. One is the energy conservation law

$$\omega_p = \omega_s + \omega_i \quad \text{or} \quad \frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i},$$

where ω_p, ω_s and ω_i represent the angular frequencies of the pump, signal and idler, respectively. λ_p, λ_s and λ_i represent the wavelengths correspondingly. $\Delta\mathbf{k} = 0$, is called the phase matching condition with the maximum gain.

Figure 1 shows the configuration of an angle-tuned signal-resonated vertically pumped PPLN-OPO, where M_1 and M_2 are the resonator mirrors. Angle θ_p is defined between the wave vector of the pump beam and the QPM axis, i.e., the angle between $\mathbf{k}_p$ and $\mathbf{k}_m$. Angle θ_s is the angle between $\mathbf{k}_s$ and $\mathbf{k}_m$, and θ_i is the angle between $\mathbf{k}_i$ and $\mathbf{k}_m$. The angles of incidence of the pump, signal and idler in air are α_p, α_s and α_i (α_i is not shown in Fig. 1). In this case, because the direction of the signal beam is determined by the

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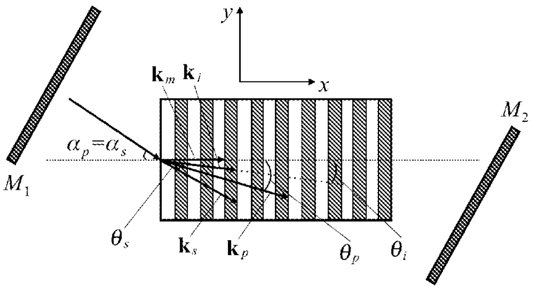

Fig. 1. The configuration of an angle-tuned signal-resonated vertically pumped PPLN-OPO.

resonator mirrors[11], both the pump wave and the signal wave are vertical to the resonator mirrors. In other words, α_p is equal to α_s. We set $\alpha_p = \alpha_s = \alpha$ (α is called the angle of rotation for PPLN in the following). The law of refraction is satisfied through the relationship shown in Eqs. (1)−(3)

$$\sin\theta_p = \frac{\sin\alpha}{n(\omega_p)}, \tag{1}$$

$$\sin\theta_s = \frac{\sin\alpha}{n(\omega_s)}, \tag{2}$$

$$\sin\theta_i = \frac{\sin\alpha_i}{n(\omega_i)}. \tag{3}$$

The phase matching condition can be described as

$$n(\omega_p)\cdot\omega_p\cdot\sin\theta_p - n(\omega_s)\cdot\omega_s\cdot\sin\theta_s$$
$$-n(\omega_i)\cdot\omega_i\cdot\sin\theta_i = 0, \tag{4}$$

$$n(\omega_p)\cdot\omega_p\cdot\cos\theta_p - n(\omega_s)\cdot\omega_s\cdot\cos\theta_s$$
$$-n(\omega_i)\cdot\omega_i\cdot\cos\theta_i - \frac{2\pi cm}{\Lambda} = 0, \tag{5}$$

where c is the speed of light in vacuum. $n(\omega_p)$, $n(\omega_s)$ and $n(\omega_i)$ are determined by the temperature-dependent Sellmeier equations for the refraction index of the periodically poled crystal. The substitutions of Eqs. (1)−(3) into Eq. (4) give

$$(\omega_p - \omega_s)\cdot\sin\alpha - \omega_i\cdot\sin\alpha_i = 0.$$

From $\omega_p = \omega_s + \omega_i$ and the equation above we can get $\alpha_i = \alpha = \alpha_p = \alpha_s$. This is a very interesting result, which means that all interacting waves in the cavity are always collinear (not inside the crystal) for a noncollinear signal-resonated vertically pumped PPLN-OPO while phase-matching is noncollinear within the crystal. In comparison with angle-tuned PPLN-OPO by rotating the OPO resonator mirrors or changing the direction of the pump wave while keeping the crystal position, vertically pumped PPLN-OPO by only rotating crystal can realize collinear outputs for signal and idler.

Equation (5) can be expressed as

$$\omega_p\cdot\sqrt{n(\omega_p)^2 - \sin^2\alpha} - \omega_s\cdot\sqrt{n(\omega_s)^2 - \sin^2\alpha}$$
$$-\omega_i\cdot\sqrt{n(\omega_i)^2 - \sin^2\alpha} - \frac{2\pi cm}{\Lambda} = 0, \tag{6}$$

or

$$\frac{1}{\lambda_p}\cdot\sqrt{n(\lambda_p)^2 - \sin^2\alpha} - \frac{1}{\lambda_s}\cdot\sqrt{n(\lambda_s)^2 - \sin^2\alpha}$$
$$-\frac{1}{\lambda_i}\cdot\sqrt{n(\lambda_i)^2 - \sin^2\alpha} - \frac{m}{\Lambda} = 0, \tag{7}$$

where $n(\lambda_p)$, $n(\lambda_s)$ and $n(\lambda_i)$ are the refraction indices of the periodically poled crystal[12]. Obviously, when the PPLN crystal rotates about the crystal z-axis, α, as well as the frequencies of signal and idler, will change. Consequently, continuous tuning of the PPLN-OPO output wavelength can be realized by rotating PPLN crystal with fixed resonator mirrors and pump wave direction. Equation (7) gives the relation between the phase-matched angle of rotation and output wavelengths for angle-tuned vertically pumped PPLN-OPO.

In paraxial approximation, Eq. (6) can be simplified as

$$\left(n(\omega_p)\cdot\omega_p - \frac{\omega_p}{2n(\omega_p)}\alpha^2\right) - \left(n(\omega_s)\cdot\omega_s - \frac{\omega_s}{2n(\omega_s)}\alpha^2\right)$$
$$-\left(n(\omega_i)\cdot\omega_i - \frac{\omega_i}{2n(\omega_i)}\alpha^2\right) - \frac{2\pi cm}{\Lambda} = 0.$$

So we can get another formula for calculating phase-matched angle

$$\alpha = \pm\sqrt{2\frac{n(\omega_p)\cdot\omega_p - n(\omega_s)\cdot\omega_s - n(\omega_i)\cdot\omega_i - \frac{2\pi cm}{\Lambda}}{\frac{\omega_p}{n(\omega_p)} - \frac{\omega_s}{n(\omega_s)} - \frac{\omega_i}{n(\omega_i)}}}.$$

The phase-matched angle in terms of wavelength is

$$\alpha = \pm\sqrt{2\frac{\frac{n(\lambda_p)}{\lambda_p} - \frac{n(\lambda_s)}{\lambda_s} - \frac{n(\lambda_i)}{\lambda_i} - \frac{m}{\Lambda}}{\frac{1}{n(\lambda_p)\cdot\lambda_p} - \frac{1}{n(\lambda_s)\cdot\lambda_s} - \frac{1}{n(\lambda_i)\cdot\lambda_i}}}. \tag{8}$$

It is easy to understand that there are two possibilities of α with same absolute value and opposite sign for one set of λ_p, λ_s, λ_i, m and Λ.

The same theoretical analysis is also suitable for idler-resonated PPLN-OPO which can resonate with the long-wavelength component and has broader tunable wavelength range than signal-resonated PPLN-OPO. All interacting waves inside idler-resonated vertically pumped PPLN-OPO cavity are also always collinear while phase-matching is noncollinear in the crystal. So either Eq. (7) or (8) is suitable for calculating the relation between the phase-matched angle and output wavelengths for all kinds of angle-tuned vertically pumped PPLN-OPO including signal-resonated, idler-resonated and doubly-resonant OPO.

Figure 2 shows the set-up of our angle-tuned signal-resonated PPLN-OPO. The PPLN crystal can be rotated about the crystal z-axis while keeping the pump wave vertical to the resonator mirrors. A 1064-nm acousto-optically Q-switched cw-diode-pumped Nd:YVO$_4$ laser was used to pump the PPLN crystal. The repetition rate

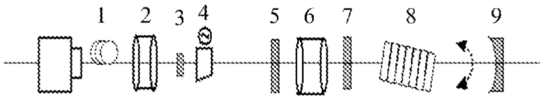

Fig. 2. Experimental set-up of the angle-tuned signal-resonated PPLN-OPO. 1: 808-nm fiber coupled diode laser; 2: 808-nm coupling system; 3: Nd:YVO4 crystal; 4: Q-switch; 5: 1064-nm output mirror; 6: 1064-nm coupling system; 7: PPLN-OPO input mirror; 8: PPLN and its heating oven and 9: PPLN-OPO output mirror.

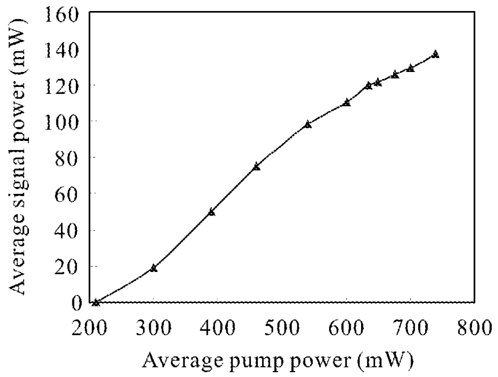

Fig. 3. The average 1499.8-nm signal power as a function of the average 1064-nm pump power. The PPLN temperature was kept at 140°C, and 1064-nm pulse repetition rate was 19 kHz with pulse width of 30 ns.

can be adjusted from 1 to 19 kHz. In the case of 19 kHz, the Nd:YVO4 laser generated 30-ns pulses with average power of 740 mW. Behind the 1064-nm output mirror, a coupling system focused the 1064-nm pump beam inside the PPLN crystal, with the radius of its waist inside the OPO cavity of 100 μm.

The PPLN crystal used in this experiment was 1 mm thick and 50 mm long, and it had a grating period of 29 μm with periodically poled along the crystal z-axis. Both two end faces of the PPLN were anti-reflection coated at 1064 and 1480 – 1520 nm. The PPLN crystal was placed in a heating oven to keep its temperature at ~ 140°C in order to avoid the effect of photorefractive damage. A plano-concave resonator was chosen as the PPLN-OPO cavity. The input flat mirror was coated for transmission of 95% at pump wave and reflectivity of 99.9% at signal wave (1480 – 1520 nm). The output mirror had 80-mm radius of curvature and transmissions of 89% at pump wave and ~ 17% at signal wave. The OPO cavity length was 80 mm.

The PPLN-OPO threshold in the collinear case ($\alpha = 0°$) was 210 mW with output signal wavelength of 1499.8 nm under the conditions of 140°C, 1064-nm pulse repetition rate of 19 kHz and pulse width of 30 ns. Figure 3 shows the average power of 1499.8-nm signal as a function of the average 1064-nm pump power.

We measured the output signal wavelength as a function of the angle of rotation (α) for PPLN at 140°C. The results shown in Fig. 4 demonstrate that the output signal wavelength can be tuned by rotating the PPLN crystal. We tuned the signal wavelength of the PPLN-OPO infrared radiation from 1499.8 to 1506.6 nm by changing α in the range 0° – 10.22° and the corresponding idler wavelength tuning was from 3.66 to 3.32 μm. There were two pairs of the signal and idler waves of the same wavelengths achieved symmetrically for each pair of angles of rotation with same absolute value and opposite sign. This result is consistent with the theoretical prediction above. The measured signal wavelength (square spots) and the calculated signal wavelength by using Eq. (7) (solid curve) and Eq. (8) (dashed curve) as functions of the angle of rotation for PPLN at 140°C are shown in Fig. 4 together. As can be seen from it, experimental result shows good agreement with the theoretical analyses. Either Eq. (7) or (8) is suitable for calculating the relation between the phase-matched angle of rotation and output wavelengths for angle-tuned vertically pumped PPLN-OPO.

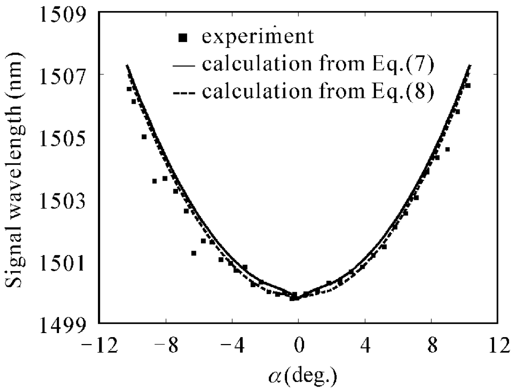

Fig. 4. The measured and calculated output signal wavelengths as functions of the angle of rotation for 1064nm-pumped PPLN at 140°C.

In summary, we have reported theoretical analyses and experiment results for angle-tuned signal-resonated vertically pumped PPLN-OPO. From theoretical analyses it can be found that all interacting waves in the cavity are always collinear (not inside the crystal) for vertically pumped PPLN-OPO while phase-matching is noncollinear within the crystal. Two equations for calculating the relation between the phase-matched angle of rotation and output wavelength are given and both of them are suitable for all kinds of angle-tuned vertically pumped PPLN-OPO including signal-resonated, idler-resonated and doubly-resonant OPO. Pumped with a 1064 nm acousto-optically Q-switched cw-diode-pumped Nd:YVO4 laser, infrared radiation from 1499.8 to 1506.6 nm is achieved at 140°C by rotating the 29-μm period PPLN crystal from 0° to 10.22° about the crystal z-axis. Two pairs of the signal and idler waves of the same wavelengths can be achieved symmetrically for rotation. Experimental results are in good agreement with theoretical analyses.

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