Widely and continuously tunable optical parametric generator based on MgO-doped periodically poled $LiNbO_3$ crystal

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Received January 5, 2006

A widely and continuously tunable optical parametric generator (OPG) pumped by a 1064-nm acousto-optically Q-switched diode-end-pumped Nd:YAG laser based on MgO-doped periodically poled $LiNbO_3$ crystal with a multigrating structure (29.2—30.4 μm) is reported. A broad continuous signal spectrum of 1513—1700 nm is obtained by changing the crystal grating periods from 29.2 to 30.4 μm and by tuning the crystal temperature from 30 to 180 °C simultaneously. When the average pump power is 1.82 W with pulse duration of about 70 ns operating at a repetition rate of 10 kHz, the maximum signal output power of the periodically poled MgO-doped lithium niobate (PPMgLN) OPG is about 210 mW corresponding to the idler and total powers of 118.4 and 328.4 mW respectively.

OCIS codes: 190.4970, 140.3600, 140.3070.

Pulsed optical parametric generators (OPGs) and optical parametric oscillators (OPOs) have been extensively studied and developed for generating tunable coherent sources[1−6] that cover the wide spectral range from the near ultraviolet (UV) to the mid infrared (IR). In recent years there has been increasing interest in the use of quasi-phase-matched (QPM) periodically poled lithium niobate (PPLN) for a variety of frequency conversion applications. Lithium niobate ($LiNbO_3$) doped with magnesium oxide (MgO) is an important nonlinear optical material since it has greatly improved resistance to photorefractive damage in contrast to the normal $LiNbO_3$ crystal[7,8]. So the periodically poled 5 mol% MgO-doped $LiNbO_3$ crystals are selected as the OPG nonlinear gain medium in this experiment.

In OPGs, no optical resonator restriction is placed on the direction of the mixing waves. For a given pump wavelength and grating period, there are only one pair of on-axis modes and many near-axis signal and idler modes which can satisfy the quasi phase match condition

$$\overrightarrow{k_{\rm p}} = \overrightarrow{k_{\rm s}} + \overrightarrow{k_{\rm i}} + \overrightarrow{k_{\rm g}}, \quad (1)$$

where k_j $(j = {\rm p, s, i})$ are the vectors of pump wave, signal wave and idler wave; $k_{\rm g} = \frac{2\pi}{\Lambda}$ is the grating vector of the periodically poled crystal; Λ is the grating period. Figure 1 shows the k-vector diagram for various phase-matched beams.

We assume the pump wave vector is parallel to the grating vector. In the mixing of the optical parametric waves the output wavelengths are determined by the energy conservation criterion $\omega_{\rm p} = \omega_{\rm s} + \omega_{\rm i}$, where ω_j $(j = {\rm p, s, i})$ are the angular frequencies of pump wave, signal wave, and idler wave, respectively. Under the condition of collinear, Eq. (1) can be described as

$$n_{\rm p}(\omega_{\rm p}, T) \cdot \omega_{\rm p} = n_{\rm s}(\omega_{\rm s}, T) \cdot \omega_{\rm s} + n_{\rm i}(\omega_{\rm i}, T) \cdot \omega_{\rm i} + \frac{2\pi mc}{\Lambda}, \quad (2)$$

where $n_j(\omega_j, T)$ $(j = {\rm p, s, i})$ are the refractive indexes of the periodically poled MgO-doped lithium niobate (PPMgLN) crystal at the angular frequency ω_j and the temperature T; m is the QPM order; c is the speed of light in vacuum.

Under the condition of noncollinear, Eq. (1) can be described as

$$n_{\rm p}(\omega_{\rm p}, T) \cdot \omega_{\rm p} = n_{\rm s}(\omega_{\rm s}, T) \cdot \omega_{\rm s} \cdot \cos\alpha + n_{\rm i}(\omega_{\rm i}, T) \cdot \omega_{\rm i} \cdot \cos\beta + \frac{2\pi c}{\Lambda}, \quad (3)$$

$$n_{\rm s}(\omega_{\rm s}, T) \cdot \omega_{\rm s} \cdot \sin\alpha = n_{\rm i}(\omega_{\rm i}, T) \cdot \omega_{\rm i} \cdot \sin\beta, \quad (4)$$

where α is the angle between signal wave vector and grating vector, β is the angle between idler wave vector and grating vector. From Eqs. (3) and (4) we can obtain

$$\cos\alpha = \frac{n_{\rm s}^2\omega_{\rm s}^2 - n_{\rm i}^2\omega_{\rm i}^2 + (n_{\rm p}\omega_{\rm p} - \frac{2\pi c}{\Lambda})^2}{2n_{\rm s}\omega_{\rm s}(n_{\rm p}\omega_{\rm p} - \frac{2\pi c}{\Lambda})}. \quad (5)$$

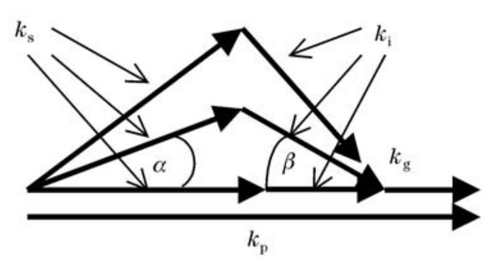

Fig. 1. Phase-matching diagram for on-axis and near-axis modes.

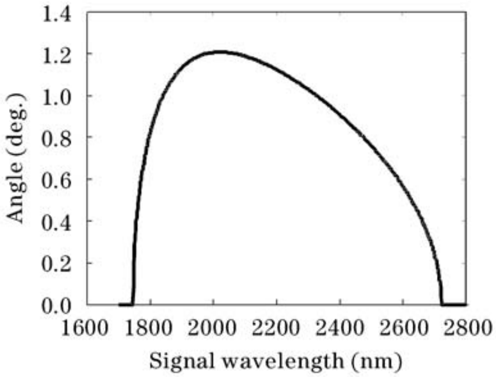

Fig. 2. Noncollinear phase-match angles versus signal wavelength.

Figure 2 shows the noncollinear phase-match angle as a function of the signal wavelength. The largest noncollinear signal wave direction that will phase-match is around 1.23°. The transverse dimension of the pump beam defines a gain channel in the material. Small diameter pump beam permits only collinear or near collinear signal and idler pairs to see significant gain throughout the length of the crystal. The figure indicates that the noncollinear angle is zero in the range of the signal spectrum. In our experiment, the crystal is commonly periodically poled along z-axis and the OPG of a small diameter pump beam permites the three wave vectors k_p, k_s and k_i are collinear along x-axis.

As mentioned above we can see that many wavelength-tuning methods in QPM OPG are available, such as the grating period tuning[9], the temperature tuning[10], the angle tuning[11], the electro-optic tuning[12], and the pump wavelength tuning[13]. The grating period tuning method is a convenient and high speed tuning method, but the output wavelength tuning is discrete. Obviously we can obtain broad and continuous wavelength tuning by changing the crystal periods and its temperature simultaneously. Figure 3 shows the multigrating crystal OPG wavelength tuning curvers as function of crystal temperature pumped by a 1064-nm laser. The theoretical tuning curves were generated by the dispersion equation for 5 mol% MgO-doped $LiNbO_3$ crystal[14].

Figure 4 shows a schematic of the experimental setup, which includes the pump source at a wavelength of 1064

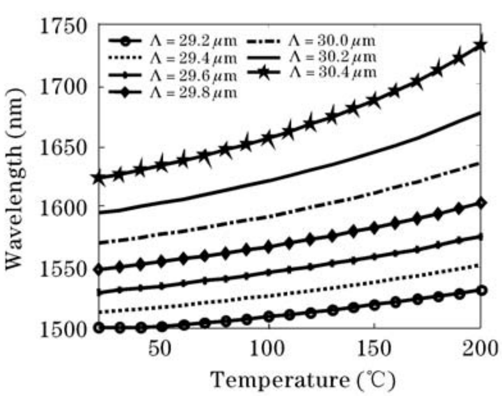

Fig. 3. Multigrating crystal OPG wavelength tuning curvers as function of the crystal temperature pumped by a 1064-nm laser.

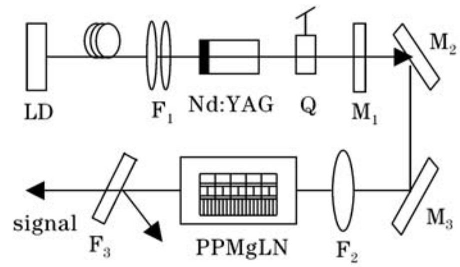

Fig. 4. Experimental setup of OPG. F_1: coupling systems; Q: acousto-optically Q-switch; M: flat mirror; F_2: coupling lens (f = 50 mm); F_3: filter mirror.

nm and the optical parametric generator. The pump source is a diode-pumped acousto-optically Q-switched Nd:YAG laser operating at 1064 nm, which produces a single frequency TEM_{00} output in pulses of 70-ns duration, at a repetition rate of 4.3 kHz with a maximum average power of 2.37 W. The dimension of the Nd:YAG crystal is $\Phi 4 \times 9$ (mm) and the Nd^{3+} concentration is 1 at.-%. The entrance face of the Nd:YAG crystal with a antireflection coating at 808 nm and high-reflection coating at 1064 nm is used for the incident coupling mirror of 1064-nm resonant cavity. The other end face is antireflection-coated at 808 and 1064 nm. M_1 is a flat mirror used for the output coupler of the 1064 nm, its transmission optimized is 10%. The pump beam was focused onto the PPMgLN crystal by a 50-mm-focal-length lens. The focus spot of approximate 200 μm in diameter inside the sample was estimated. The highest average fundamental power incident on the crystal was 1.82 W.

The sample of PPMgLN crystal acquired from HC Photonics had a 50/50 poling ratio and an interaction length of 50 mm with 5-mm width and 1-mm thickness. It is of multigrating form with seven different grating periods ranging from 29.2 to 30.4 μm in steps of 0.2 μm. The output end facets are cut with a wedge angle of 5° to prevent feedback of laser and OPG radiations into the crystal by Fresnel reflections. It has high transmission at 1064, 1350—1700, and 2800—5000 nm on both end facets for reduction of cavity loss. The crystal was placed in an oven whose temperature could be varied up to 250 °C with an accuracy of 0.1 °C. The crystal was aligned so that the gratings were perpendicular to the direction of the pump. The OPG was tuned by traslating the crystal perpendicular to the x-axis. No realignment was needed, and all grating sections oscillated with good efficiency. All of the mirrors were made of K9-glass which absorbed the OPG idler wave in the range of 3—4 μm. A filter mirror which reflected the residual pump wave, doubled fundamental wave, and visible light was used so that the OPG output wave was single singnal wave.

Coarse tuning of the signal output power was accomplished by changing the PPMgLN crystal grating periods, with precise tuning by its temperature. We measured the dependence of the signal output power on the PPMgLN temperature and deduced the idler power and total power according to the Manley-Rowe relationships at a fixed period of 30.4 μm, as shown in Fig. 5. The average pump power of 1064 nm was kept at 1.82 W and 1064-nm pulse repetition rate was 10 kHz with the pulse width of 70 ns. The average signal output power increased from 125 to 210 mW by varying the crystal temperature from 30 to

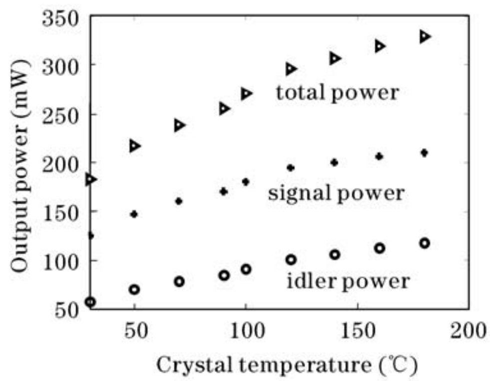

Fig. 5. Average signal output power, idler power, and total power versus temperature of the PPMgLN crystal.

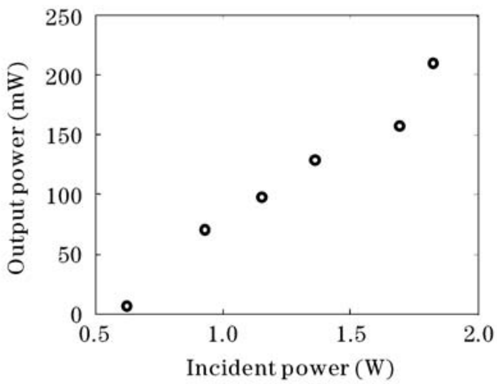

Fig. 6. Average signal power versus average pump power.

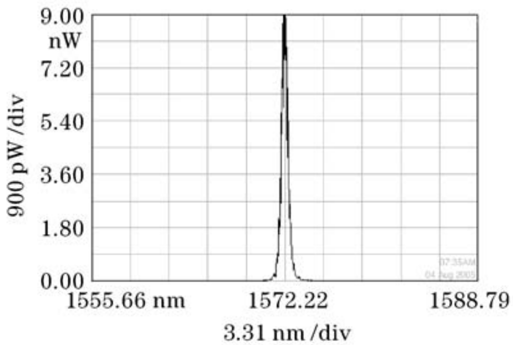

Fig. 7. Signal spectrum of 1572.22-nm laser emission.

180 °C, corresponding the idler output power from 58 to 118.4 mW, the total power from 183 to 328.4 mW.

As is indicated in Fig. 6, with increasing pump power, the signal output power increases. For the maximum pump power of 1.82 W the OPG emitted 210 mW of signal radiation at the constant temperature of 180 °C.

An Agilent 86142B optical spectrum analyser was used to measure the output pulse spectra. The output signal spectrum of the PPMgLN OPG is shown in Fig. 7. The maximum signal wavelength restricted by the measurement range of the spectrum analyser is 1700 nm. The theoretical maximum signal wavelength is 1732 nm.

Figure 8 shows the measured wavelengths of the signal and idler versus the crystal temperature pumped by a 1064-nm laser in pulse duration of 70 ns, 10-kHz repetition rate with an average power of 1.017 W, the crystal temperarute is 100 °C. From it we can see that the experimental results are well agreement with the theoretical

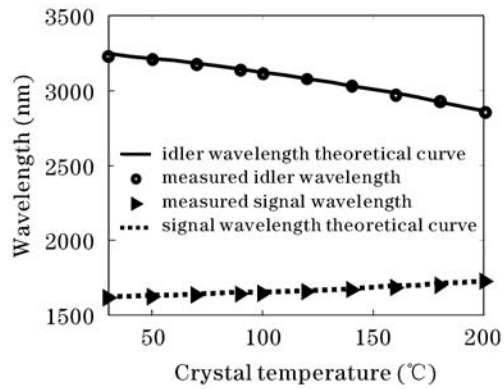

Fig. 8. Temperature tuning curves for PPMgLN-OPG.

analysis with the increase of the temperature.

In summary, the length of the PPMgLN nonlinear crystal used in the experiment is 50 mm with multigrating periods from 29.2 to 30.4 μm. When the average pump power incident on the crystal is 1.82 W, the maximum total output power is 323.58 mW, which includes 210 mW of 1664-nm signal and 118.4 mW of 2950-nm idler radiations. A broad continuous signal spectrum of 1513—1700 nm are obtained by changing the crystal periods and temperature simultaneously.

The authors would like to thank HC Photons corp. for the PPMgLN crystal. S. Diao's e-mail address is dsyzxy@163.com.

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