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Nano-Second Periodically Poled Lithium Niobate Optical Parametric Oscillator with Planar Cavity Mirrors

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We investigated a high-output power, periodically poled lithium niobate(PPLN) optical parametric oscillator(OPO) pumped by a Q-switched Nd:YAG laser. Given the low optical damage threshold and the limited aperture (0.5 mm thick) of PPLN, we tried to maximize the signal output power in a linear cavity consisting of two flat mirrors with a loosely focused pump beam. It is found that this simple cavity structure allowed a robust OPO operation, which was not sensitive to alignment compared with the conventional ones using concave mirrors. A maximum energy of 100 μJ/pulse was achieved for the signal at 1.36 μm, while the oscillation threshold was 0.3 mJ/pulse for the pump at 1064 nm.

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I. INTRODUCTION

An optical parametric oscillator(OPO) provides a tunable coherent light source based on quadratic frequency conversion. Various nonlinear crystals have been used to meet specific demands for a variety of parameters such as wavelength range, power, pulse width, etc.[1,2] For example, beta barium borate(β-BBO) crystals are most widely used due to broad wavelength tunability, high output power and their excellent stability against intense UV pumping [3]. In this case, the birefringence phase matching method, for which one can change the refractive indices of the pump, signal, and idler wavelengths by varying the temperature of the medium or the angle of the pump incidence, is used to select wavelength.

Quasi-phase-matching(QPM), in which the nonlinear susceptibility($\chi^{(2)}$) is periodically modulated, is an alternative technique to birefringence phase matching for compensating phase velocity dispersion in frequency conversion applications [4]. The advantages of QPM are that any interaction within the transparency range of the material can be non-critically phase matched in principle, and that one is able to utilize the large diagonal nonlinear optical coefficient(d_{33}) of lithium niobate. Recently, efficient OPO's based on periodically poled lithium niobate(PPLN) have been demonstrated, since the electric field poling technique for lithium niobate was established [5]. PPLN OPO's are very efficient and of a low threshold for infrared generation due to the large nonlinear optical coefficient [6,7].

Research interest has been focused on obtaining high conversion efficiency from PPLN OPO's by adopting a properly designed resonator with a tightly focused gaussian beam[6], because the dimension of the crystal along the c-axis rarely exceeds 1 mm (typically 0.5 mm) due to the large coercive field. In addition to the high conversion efficiencies, such resonators also provide low oscillation thresholds for both the signal and idler, because the efficiency of this parametric process depends on the pump intensity and the pump beam waist overlaps well with the fundamental cavity mode. However, the total output energy from PPLN OPO with this tightly focused beam is not high enough for the pulsed pump of ns(nanosecond)-duration due to the limitation of optical damage threshold ($\sim$ 3 J/cm^2 for 10 ns pulse at 1064 nm in congruent $LiNbO_3$)[7]. On the other hand, one is more interested in the total output pulse energy rather than the conversion efficiency for ns-pulsed OPO's, because a Q-switched laser as a pump source emits abundant pulse energy. For this purpose, it is necessary to make the pump beam size as large as possible to avoid the optical damage and increase the pumping volume while keeping the total pumping pulse energy high[8] so that a cavity mirror with large radius of curvature is required.

In this paper we report output characteristics of ns-pulsed PPLN OPO operation by employing a linear cavity composed of two flat mirrors with a loosely focused beam for a pump. We obtained a maximum output energy of 100 μJ/pulse for the signal wavelength at 1.36 μm, while the threshold was 0.3 mJ/pulse for the pump at 1064 nm of a Q-switched Nd:YAG laser. These experimental results were compared to those from the similar OPO with the tightly focused beam. This simple cavity structure offers a robust OPO operation emitting relatively large output pulse energy, and easy alignment compared with the conventional ones using concave mirrors.

II. EXPERIMENTS

An experimental set-up for a ns-pulsed OPO experiment is shown in Fig. 1. The PPLN crystal was 0.5 mm thick, 11 mm wide, and 19 mm long, fabricated by Crystal Technology Inc. It consisted of seven different grating periods from 25.9 μm to 28.7 μm in 0.5 μm steps. The pump source was a Q-switched Nd:YAG laser(Spectron, SL802G) at 1064 nm with 7 ns pulse width operating at a repetition rate of 10 Hz. We tried to use as large a beam waist as possible to make full use of the limited aperture (0.5 mm) of the PPLN crystal. Thus, the pump beam was loosely focused to a 170 μm beam waist at the center of the PPLN placed between two flat mirrors separated by 22 mm. This short length of cavity is very important for the ns-pulsed OPO because the number of round-trips in the cavity is limited [7]. A CCD camera and a pyro-electric joule meter(Molectron, J-25) were used to monitor the beam waist and pulse energy, respectively. A monochromator(Spex, 1702) with 0.1 nm resolution was used to measure the spectral width of the signal beam.

If we were to match the above pump beam waist(170 μm) with the fundamental mode of a cavity consisting of a pair of concave mirrors with an identical radius of curvature (R), R $\sim$ 3.8 m would be needed for the same cavity length of 22mm. Instead, we used two flat mirrors(infinite radius of curvature) although they did not perfectly match the cavity mode. The cavity mirrors had energy reflectivities of 99% and 95% for the input mirror and output coupler, respectively, at the signal wavelength. Transmittance of both mirrors for the pump wave was 10%. All our experiments were performed at room temperature.

III. RESULTS AND DISCUSSION

First of all, we investigated characteristics of OPO output as a function of pump energy. Due to a large absorption of the idler wave, whose wavelengh is larger than 3μm, by the substrate of cavity mirrors (made of BK7), what we monitored as the output was only the pulse energy of the signal wave. The measured signal pulse energy is plotted against pump energy at the signal wavelength of 1.36 μm (corresponding to the QPM period of 25.9 μm) in Fig. 2. The pump energy was varied by rotating a half-wave plate with respect to a polarizer(Fig. 1). The threshold of the oscillation was $\sim$ 0.3 mJ, and the maximum signal was 100 μJ at a pump energy of 0.9 mJ, which is just below the optical damage threshold of PPLN. The spectral line width (FWHM) of the signal beam at 1.36 μm was also measured to be about 0.3 nm which is much narrower than the theoretical QPM bandwidth for the single pass difference frequency generation (0.8nm)[9].

We could tune the output signal wavelength from 1.36 μm to 1.46 μm using different grating periods at

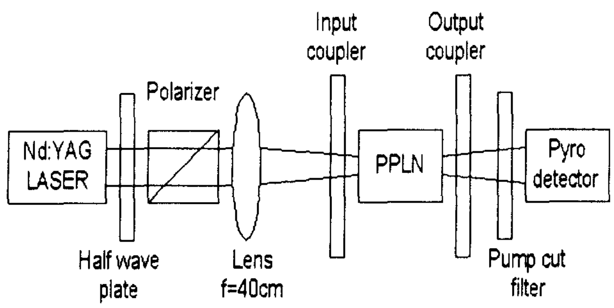

FIG. 1. Experimental set-up for PPLN OPO.

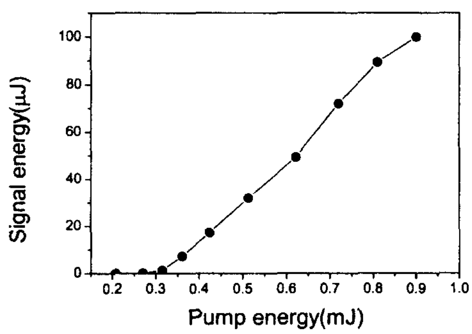

FIG. 2. OPO output energy versus input pump energy at signal wavelength of 1.36 μm (beam waist : 170 μm).

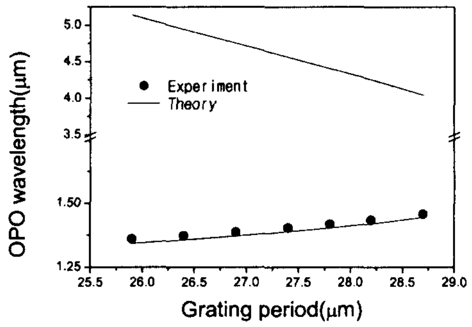

FIG. 3. Output signal wavelength versus grating period.

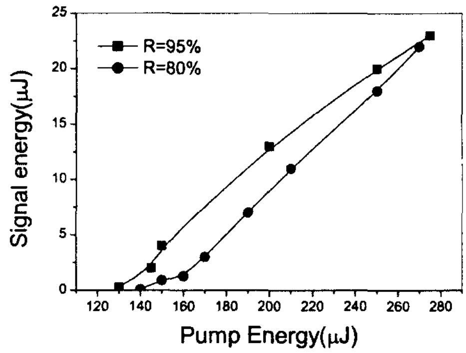

FIG. 4. OPO output energy versus input pump energy at signal wavelength of 1.36 μm with different reflectivity of output mirror.(□: 95%, •: 80%). Beam waist : 90 μm.

room temperature in steps of about 15 nm which can be selected by moving the PPLN along the transverse direction normal to the direction of beam propagation. Any cavity realignment was not required in these entire tuning process. Fig. 3 shows the signal and idler wavelengths of PPLN OPO versus grating period. The solid line was calculated from the QPM condition using the Sellmeier equation[9], which agreed well with the experimental data.

In order to compare these results to those from OPO with a tightly focused pump beam, we also measured the signal output energy with a pump beam waist of 90 μm by using the same cavity length of 22 mm. The obtained signal energy versus pump energy is shown in Fig. 4 for two different output couplers. The oscillation threshold was ~130 μJ for the output coupler with 95% reflectivity, and ~140 μJ for 80%, respectively, but the maximum signal energies are almost the same (22 μJ) for the two mirrors. A small distinction between the two cavities with different output coupler reflecivities can be explained by the fact that this resonator does not support ideal modes, and provides a much smaller number of cavity round-trips determined by the mirror reflectivity. With the 95% mirror and 90 μm pump beam waist, the oscillation threshold was smaller than that with 170 μm beam waist (Fig. 3) as expected. However, the pump energy could not be increased above 0.28 mJ (Fig. 4) compared to 0.9 mJ in Fig. 3 due to the optical damage threshold which roughly scales with the inverse of the pump spot area, because the optical damage depends on the intensity. The conversion efficiency was 8.2 % with a pump beam waist of 90 μm at the pump energy of 0.28 mJ, which was just below the optical damage threshold. It should be noted that it was 11 % with a beam waist of 170 μm which is closer to mode matching.

From these studies, it is found that the advantages of OPO using flat cavity mirrors with a loosely focused pump beam are as follows: (1) Pump pulses with large total energies can be used because the damage threshold depends on the input intensity. (2) A loosely focused gaussian beam provides a long Rayleigh range compared to the tightly focused case, keeping the direction of the pump beam wave vector nearly constant along the beam propagation throughout the crystal. Therefore, the QPM condition could be maintained at any point of the crystal improving overall conversion. (3) Cavity alignment was very simple compared to the case with concave mirrors, in which one should be more careful in optimizing the cavity length because a broad wavelength tuning with a concave mirror cavity would result in a mode mismatch between the pump and the signal in a certain wavelength range. Therefore, these experimental results show that a ns-pulsed PPLN OPO from the simple cavity composed of two flat mirrors provides not only high total output power with relatively narrow linewidth but also broad wavelength tunablity in the infrared.

IV. SUMMARY

We demonstrated a ns-pulsed PPLN OPO tunable in the wavelength range of 1.36μm-1.46μm, using a multiple grating structure (period : 25.9 μm-28.7 μm). To maximize total signal power while keeping the pump power below the optical damage threshold of the PPLN, we used a linear cavity composed of two planar mirrors with a loosely focused pump beam. By using this simple cavity, we obtained an oscillation threshold of 0.3 mJ, maximum output signal energy of 100 μJ/pulse and relatively high conversion efficiency at 1.36 μm signal wavelength. This simple linear cavity using two flat mirrors has the advantages of a robust OPO operation, and easy alignment compared to the conventional cavity using concave mirrors.

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