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Efficient Single-Pass Optical Parametric Generation and Amplification using a Periodically Poled Stoichiometric Lithium Tantalate

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A high-conversion efficiency, nanosecond pulsed optical parametric generation and amplification with repetition rate of 20 kHz based on a periodically poled MgO-doped stoichiometric lithium tantalate was presented. Pumped by a Q-switched Nd:YVO_4 laser at 1064 nm with a pumping power of 4.8 W, the generated output power was 1.6W for the signal and idler waves, achieving a slope efficiency of 50%. Using a seed source at signal wave the amplified signal output-pulse energy reached 65 μJ. The obtained maximum gain was 72.4 dB.

OCIS codes : 190.019, 190.2620, 190.4410

I. INTRODUCTION

In general, remote-sensing application of various absorptions or differential scattering requires simultaneously tunable mid-IR laser sources and narrow line-width for high spectral resolution. Optical parametric oscillators (OPO's) with injection seeded at single-frequency are mainly used in the applications. However, it is a difficult task to maintain narrow line-width over a wide tuning range. The system requires complicated alignment for frequency matching between the injection seeding and resonated oscillation. An optical parametric generation (OPG) is an alternative method to obtain coherent tunable laser sources without a complicated resonator. In OPG the generated waves are amplified from quantum noise or an injected signal during a single or multi-pass through the nonlinear crystal. Therefore, the crystal length will be the limiting factor for the efficiency of OPG unless group-velocity mismatch between the pump and the generated waves is present. The efficiency of a birefringent phase-matched OPG with nanosecond pulse was low and the effective crystal length of critical birefringent phase matching was shorter than the physical crystal length as a result of spatial beam walk-off [1]. During the past decade, development of a quasi-phase-matching (QPM) technique based on ferro-electric nonlinear material using an electrical poling method [2] has increased the possibilities of efficient OPG [3,4]. Periodically poled lithium niobate (PPLN) crystals have been extensively used for OPG and OPO's because of their large nonlinear coefficient, the big size of single crystal wafer (diameter more than 4 inch) and reproducible periodical poling method [5,6]. However, PPLN crystals suffer photo-refractive damage at room temperature, which results in efficiency reduction and poor output-beam quality [7]. Thus the PPLN crystals had required a high temperature operation about 160 ℃ to suppress the photo-refractive damage [8].

In this work we used an MgO-doped stoichiometric lithium tantalate (SLT) crystal to achieve parametric interactions without photo-refractive damage at room temperature [9] and demonstrated an efficient single-pass OPG. A small signal from an extended-cavity laser (semiconductor laser at telecommunication range) was also amplified by the optical parametric amplification (OPA) at signal waves.

II. OPTICAL PARAMETRIC GAIN AND EXPERIMENTAL SET-UP

In the quasi-phase matched optical parametric process all of the waves (pump, signal and idler) propagating in a QPM device are extraordinary waves to utilize the largest nonlinear coefficient. The coupling of the waves can be described by the coupled-wave questions and the analytical solutions have been developed. To discuss the theoretical conversion efficiency of OPG, we need to know the gain curve as a function of pump intensity, device length and QPM condition. The expression of

OPG gain was already well derived by Myers *et al.* and could be written as at the phase matching case [10,11].

$$G(L) \equiv \frac{\left|E_1(L)\right|^2 - \left|E_{10}\right|^2}{\left|E_{10}\right|^2} \approx \frac{1}{4}\exp(2\Gamma L), \qquad \Gamma^2 = \frac{2\omega_s\omega_i\, d_{eff}^2\, I_o}{n_s n_i n_p \varepsilon_o c^3} \tag{1}$$

where, E_{10} is the electric field of the signal wave. It can be a quantum noise at OPG and input seeding at OPA of the signal frequency. $E_1(L)$ is the generated electric field at the signal wave along the interaction length L. ω_s, ω_i are the angular frequencies of the signal and idler waves; d_{eff} is the effective nonlinear coefficient; I_o is the input pump intensity; n_s, n_i, n_p are the refractive indexes of the signal, idler, and pump waves, respectively; ε_o is the vacuum electric susceptibility; c is the light velocity in vacuum; $\Delta k = k_p - k_s - k_i$ is the wave-vector mismatch between the pump, signal and idler waves. From Eq. (1) one can see that the gain is proportional to the input pump intensity, the square of the effective nonlinear coefficient and crystal length.

Figure 1 shows a schematic diagram of the single-pass OPG and OPA. A diode pumped Q-switched Nd:YVO_4 laser was operated at 1064 nm with a repetition rate of 20 kHz as a pump laser, and an extended-cavity laser (ECL, OSICS-1560, Nettest) adopted as a seeding source at signal wavelength(1550~1650 nm). The pump laser was focused about 200 μm in diameter at the beam waist. A 0.7 mol% MgO-doped SLT crystal was grown by the double-crucible Czochralski method [9] and periodically poled structure was fabricated by the electrical poling method at room temperature [12]. The periodically poled MgO-doped SLT (PPMgSLT) crystal has a single QPM period of 31.4 μm for MIR generation about 3 μm by OPG process based on 1064 nm pumping. The PPMgSLT length is 35 mm.

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 2 shows the emission wavelength as a function of device temperature. The tunable signal and idler waves are 1614 to 1650 nm and 3043 to 3122 nm respectively. The inset of Fig. 2 shows signal spectrum at three different temperatures. The signal bandwidth was about 2.2 nm at full-width-half maximum (FWHM) whereas the bandwidth of pump laser was about 0.1 nm at 1064 nm. Generally OPG spectrum is much broader than the pump because the parametric generation starts from a whit-light quantum noise.

To reduce the spectral bandwidth we applied an injection seeding technique at signal waves using a fiber coupled CW extended-cavity laser (ECL). The seeding and pump beam were focused into the PPSLT sample with a diameter of 200 μm. A representative OPA spectrum was shown in Fig. 3 using the seeded power of 1 mW at the seeded wavelength of 1614.4 nm. The narrowness of the spectral bandwidth of the signal wave is limited by the finite bandwidth of both the seed and the pump. In this experiment the band-width of the ECL is negligible compared to the bandwidth of the pump laser. The bandwidth of signal beam could be estimated as follow

$$\Delta\lambda_s \approx \frac{\lambda_s^2}{\lambda_p^2}\Delta\lambda_p \tag{2}$$

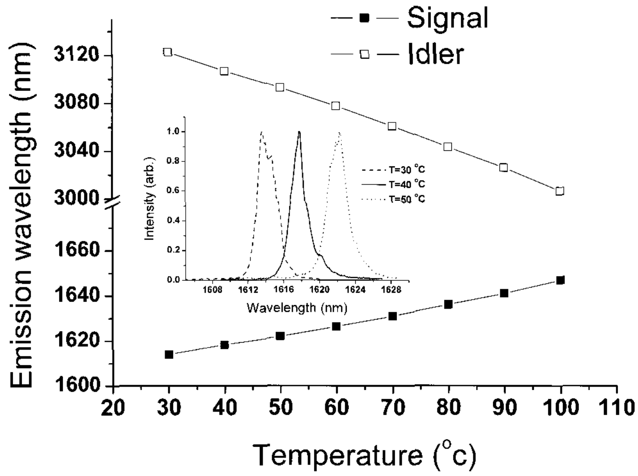

FIG. 2. Emission wavelength as a function of device temperature.

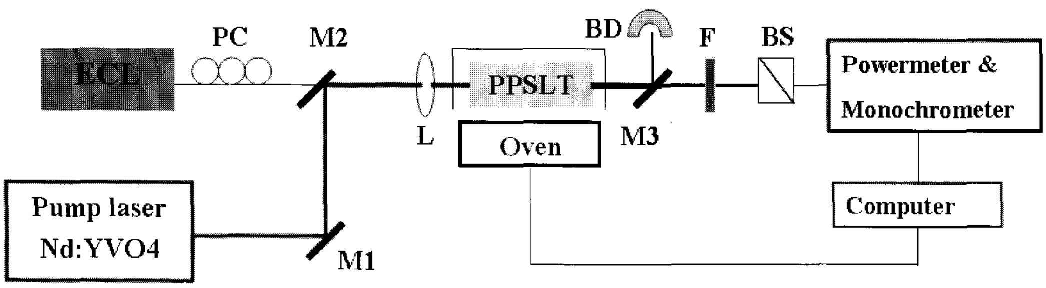

FIG. 1. Experimental setup for optical parametric generation and amplification.
PC: polarization controller, M1-M3: mirrors, BD: beam dumper, F: Filter, BS: beam splitter

where λ_s , λ_i , and λ_p are the signal, idler and pump wavelength, respectively, and $\triangle\lambda_p$ is the bandwidth of the pump. The measured bandwidth of pump laser $\triangle\lambda_p$ = 0.13 nm at FWHM, so we can expect to obtain $\triangle\lambda_s$ = 0.31 nm. We measured the bandwidth of the signal wave under the different conditions using a spectrum analyzer with a resolution of 0.01 nm. For a pump power of 1.5 W, which is approximately the minimum power for detection of the OPA signal, the FWHM bandwidth was about 0.33 nm, which agrees with the calculated value of signal bandwidth($\triangle\lambda_s$ = 0.31 nm) from Eq. (2). However, the bandwidth of the signal beam increases with the input pump power. We consider the broadening of the bandwidth at high pump power is because of incomplete saturation of the parametric amplification gain by the seeding.

Next, we measured the output power as a function of pump power at room temperature.

As shown in Fig. 4 we obtained the signal and idler power of 1.1 W and 0.5W, respectively, at pump power of 4.8 W. The total slope efficiency was 50% at OPG. Exactly speaking, the concept of threshold which can be exactly defined in OPO does not exist in OPG and OPA. However, practically the moment in which the outputs begin to be measurable is used as the threshold. In this work the OPG and OPA threshold power were measured to be about 1.6 and 1.2 W, respectively. The slope efficiency of OPA was about 37% and it was slightly higher than that of the OPG, 34%. Although it is difficult to predict thresholds and slope efficiencies in two cases, we can expect that the OPA will have lower threshold and higher slope efficiency than the OPG, because the electric field of the generated signal, has the form of a cosign hyperbolic function as where are the initial electric field of the incident signal, gain coefficient, and the crystal length, respectively. From Eq. (1) the estimated maximum gain of our OPG was about 7×10^{22} at the input power of 4.8 W with the ΓL=27.

For the signal amplification the seed beam was set at the center wavelength of OPG such as 1614.4 nm. The CW seeding power of 1 mW was contributed for 3.7 ns because the measured pulse-width of OPG was 3.7 ns at signal wave even though the pump laser pulse-width was 10 ns. Thus the seeding power of 1 mW corresponded to 3.7 pJ for the pulse energy. In the amplification we obtained the maximum energy of 65 μJ. The maximum gain was 72.4 dB in this particular single-pass OPA system. In the idler wave there was no effect on the output power by the injection seeding. In our previous report [13] we had estimated the effective nonlinear coefficient of the SLT crystal, the value was lower than those of the lithium niobate crystal. However, SLT crystal is more suitable for watt-level high power generation owing to the high thermal conductivity and high optical damage threshold without photo-refraction. Even though we also demonstrated an OPG with a 70-mm long periodically poled stoichiometric lithium niobate crystal, the crystal suffered photorefractive damage at room temperature [6]. The watt-level total output power based on a PPSLT crystal was stable enough at room temperature. It is a very important application of spectroscopic study for remote and real time sensing.

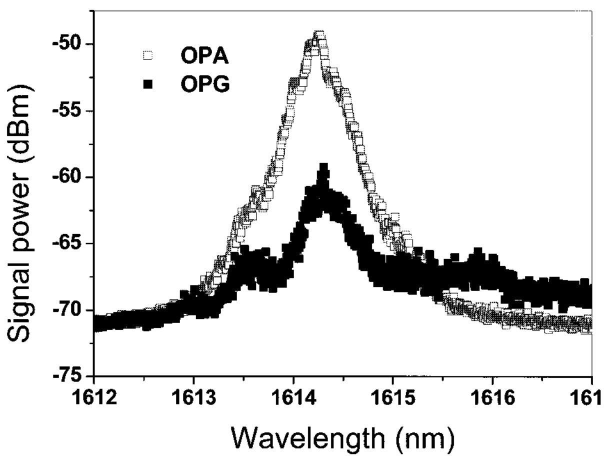

FIG. 3. Measured spectra of the OPA and OPG at signal wave.

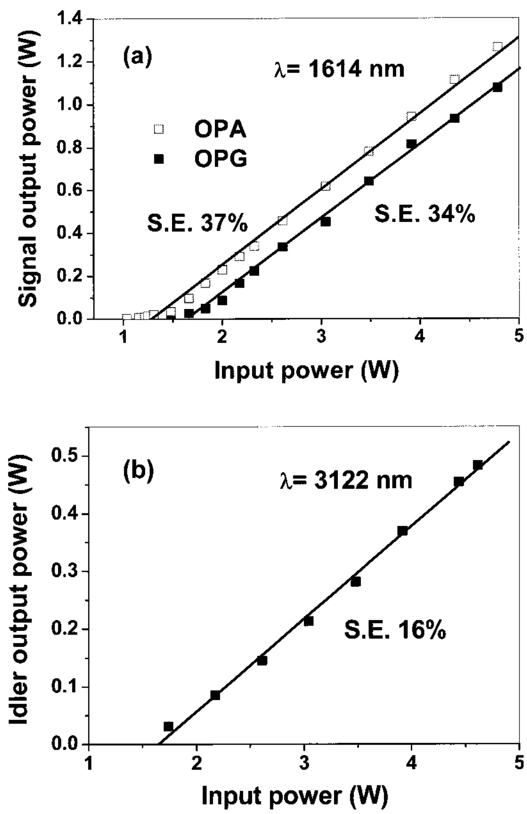

FIG. 4. Output power versus input power at room temperature at signal wavelength (a) and idler wavelength (b).

IV. CONCLUSION

We demonstrated a single-pass quasi-CW OPG for near and mid-IR generation from 1.6 to 3.4 μm range. An output power of 1.6 W and a slope conversion efficiency of 50% were successfully achieved. Furthermore a small signal was amplified at optical telecommunication band and the obtained maximum gain was 72.4 dB. For the next step, the compact OPG system will be used for environmental gas detection around 3 μm, and will confirm the feasibility of the system for realizing the real time environmental gas sensing.

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