1024

532 nm PUMPED OPTICAL PARAMETRIC OSCILLATOR IN BULK PERIODICALLY POLED LITHIUM NIOBATE

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Abstract

We report a quasi-phase-matched optical parametric oscillator pumped by the second harmonic of a single frequency Q-switched Nd:YAG laser. Both the frequency doubling to 532 nm and the parametric oscillation are performed in periodically poled lithium niobate crystals with a nonlinearity of ~15 pm/V. The OPO has been operated in 'singly resonant' and 'doubly resonant' configurations. The threshold in the singly resonant case was ~0.14 J/cm^2, more than one order of magnitude below the damage limit. OPO tuning from 945 nm to 1225 nm was achieved by changing both the period of domain reversal (from 6.8 to 6.85 μm) and the temperature of the crystal.

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The development of periodically poled lithium niobate (PPLN) for quasi-phase-matched second order nonlinear applications has attracted much interest over the last few years. Compared to birefringence phase-matching, quasi-phase-matching (QPM) allows access to new wavelengths and to higher nonlinear coefficients. In PPLN the periodic reversal in the nonlinear coefficient, associated with periodic domain reversal, provides the mean for QPM between the interacting electromagnetic waves, thus allowing efficient frequency conversion via parametric processes [1] such as second harmonic generation (SHG) and optical parametric amplification/oscillation. The periodic domain inversion in lithium niobate can be achieved using high voltage pulses and domain reversal extends deep enough to allow use of both waveguide [2] and bulk geometries [3,4,5]. One of the main challenges in using this technique is to find the correct conditions for producing highly regular, fine pitch domain gratings in crystals of a thickness suitable for bulk applications. Clearly, the more perfect the domain inversion grating, the higher the effective nonlinear coefficient. In thicker samples the growth of the inverted domains becomes more difficult to control [6]. Recently the first optical parametric oscillator (OPO) was demonstrated in bulk PPLN, pumped by a Q-switched Nd:YAG laser at 1.064 μm [5]. The PPLN crystal used in that experiment had a pitch of 31 μm and a thickness of 500 μm. The tuning range of the OPO was centred around 2 μm. Two other devices working in the same frequency range have also been reported [7,8]. When the aim is the parametric generation of tunable radiation at shorter wavelengths (around 1 μm) in PPLN, it is necessary to achieve shorter periods (6-7 μm) and, as said above, it becomes more difficult to maintain the regularity of the domain reversal pattern. A further problem associated with going toward shorter wavelengths is the potential increase of susceptibility to photorefractive damage, causing distortion in the beam profiles, although in fact in a bulk PPLN sample the photorefractive effect can be very different from single domain material, and even be eventually eliminated [9].

We report here a PPLN optical parametric oscillator pumped at 0.532 μm which generates tunable radiation at around 1 μm. Two samples of PPLN, 0.2 mm thick, were used in the experiment. They were both fabricated using high voltage pulses applied via liquid electrodes [3,6,10]. The first sample (PPLN1), ~6 mm long, had a pitch of 6.8 μm. In the second sample (PPLN2), 4.3 mm long, we fabricated two adjacent gratings with pitches of 6.8 and 6.85 μm. Both samples were initially tested by carrying out CW second harmonic measurements in 1st order QPM, using a Nd:YAG laser at 1.064 μm. The measured effective nonlinear coefficients were 14 (PPLN1) and 16 pm/V (PPLN2) [10], close to the theoretical limit of ~21 pm/V. The experimental temperature bandwidths of the phase matching curves (SH power vs. temperature) were estimated to be ~4.5 °C and ~6.5 °C respectively. Both these values are in good agreement with the respective theoretical predictions (Fig.1). Visual assessment of the periodic pattern indicated that good quality was maintained over the whole length of the samples (i.e., mark to space ratio close to 50/50 and only slight randomness in the position of the domain walls).

The experimental set-up for the OPO is shown in Fig.2. The pump source was a diode-pumped Q-switched Nd:YAG laser which produces a single frequency TEMoo output in pulses of ~15 ns duration, at a repetition rate of 2 kHz [11]. These pulses were frequency doubled to 532 nm in PPLN1, whose temperature could be changed by a temperature-controlled oven. At the QPM temperature of ~35 °C, for an average fundamental power of

$\sim$50 mW, the average second harmonic power was $\sim$25 mW (the powers are internal values in the uncoated crystal). The internal average conversion efficiency was thus $\sim$50%, leading to an estimate of the effective nonlinear coefficient which agrees well with CW measurements. The pulse duration of the generated SH pulses was typically 12 ns (Fig.3). The green pump beam was focused into the PPLN2 sample to a spot size of $\sim$28 μm. Two different sets of mirrors were used for the plane-plane OPO resonator. The first set (A) consisted of one high reflectivity (HR) mirror and one of 99% reflectivity plane mirror in the range 980-1160 nm. The mirrors of the second set (B) were also both planar and both HR in the range 1100-1300 nm. The mirrors were always kept in optical contact with the faces of PPLN2, which was mounted, in the same way as PPLN1, in a temperature-controlled oven. A combination of a half-wave plate at 532 nm and a polarizer allowed the pump power incident on the OPO to be changed by rotation of the half-wave plate, without altering any other parameters.

Initially we achieved doubly resonant operation (DRO) for the OPO using mirror set A and a grating of pitch 6.8 μm. The typical threshold was $\sim$0.8 mW of average power, i.e. a fluence of 0.033 J/cm^2 per pulse, and peak pulse power of $\sim$30 W. The maximum signal+idler output power was 1.1 mW for a maximum internal pump power of 10 mW. The corresponding depletion of total pump energy was $\sim$35%. Fig.3 shows typical traces of the undepleted and depleted pump pulses for a total depletion of $\sim$30 %. The power and frequency stability of the OPO output was affected both by etalon effects associated with the uncoated faces of the sample and by the intrinsic axial mode-hopping and cluster-jumping effects characteristic of a DRO. Despite these instabilities the OPO could be temperature-tuned over the whole range of the reflectivity of the mirrors, from ~970 to ~1175 nm.

In order to achieve singly resonant operation (SRO) we used the mirror set B. The temperature dependence of the wavelengths of the generated signal and idler is shown in Fig.4. The small discrepancy between the calculated and experimental curves is mainly due to uncertainty in the Sellmeier equation used for the dependence of the refractive index on the wavelength and on the temperature. At a temperature of ~45 °C (λ_s=1.137 μm, λ_i=1 μm), the threshold was 3.3 mW which corresponds to a peak pump power of ~130 W and a pump fluence of ~0.14 J/cm^2 - about 15 times below our measured damage threshold. Fig.5 shows the output power as a function of pump power. The maximum output power of the idler was ~0.5 mW for 9 mW internal pump power (in order to block residual infrared from PPLN1, it was necessary to insert a filter which further reduced the incident pump power). The corresponding pump depletion was ~20 %. The stability of the OPO, in particular in wavelength, was greatly improved with respect to that for the doubly resonant configuration, showing no sign of cluster-jumping effects..

By moving the PPLN2 sample transversely we could access the region of the crystal with the domain reversal pitch of 6.85 μm. For this region singly resonant was then achieved over a different tuning range (Fig.4), giving access to further wavelengths. At 48.5 °C (λs=1.2 μm, λi=0.956 μm), the threshold was ~3.6 mW (Fig.5) and the maximum output for the idler was ~0.3 mW. The corresponding pump depletion was ~13%. The slight reduction in performance compared with the 6.8 μm pitch is due, in part, to additional geometrical imperfections in the grating structure.

We calculated the threshold for the OPO by taking account of the 'build-up time' needed to amplify the signal power from the noise level (P_o) to a given final value (P_n) [12]. Assuming the usual value $\ln(P_n/P_o) \sim 30$, it turns out that, in the case of SRO operation, the total cavity loss per round trip, which best fits the data, corresponds to ~4%. We also estimated that the diffraction loss related to a planar-planar cavity [13], limited in one-dimension by the small thickness of the sample (200 μm) and containing etalon effects, was ~1.2% for the possible oscillating modes. Therefore ~3% loss is probably related to the uncoated faces of the crystal, to bulk loss in the crystal and to clipping of the beam due to deviations with respect to a perfect planar-planar configuration. This is already a significantly lower loss than measured by us in earlier samples [6].

In conclusion, we have demonstrated singly and doubly resonant optical parametric oscillation at around 1 μm in PPLN when a frequency doubled Q-switched Nd:YAG laser was used as pump source. Low threshold operation was achieved as a result of the high effective nonlinearity (16 pm/V). There was no evidence of any significant photorefractive damage. The system was tuned both by changing the temperature and the period of domain reversal. In future work we plan to improve the performance by using thicker samples, with antireflection coated faces, and by using confocal resonator configurations. These measures, by decreasing losses, will allow further reduction in threshold, and will allow the higher slope efficiency, where potential is implied by the strong pump depletion, to be realized.

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Figure Captions

1. SH power as function of the crystal temperature for sample PPLN1. The solid curve is a calculated curve for a perfect crystal of the same length.

2. Experimental set-up of OPO: L:half-wave plate at 0.532 μm, P:polarizer, f1 =76 mm, f2=32 mm, M1 & M2:plane mirrors.

3. Input pump pulse (undepleted) and output (depleted) pump pulse, corresponding to a total energy depletion of ~30 %.

4. Tuning curves for singly resonant operation: signal and idler wavelengths as functions of temperature of the PPLN2 for two different periods of domain reversal. The lines are calculated traces which are horizontally shifted by ~10 ^{o}C from the corresponding experimental ones because of uncertainty in the Sellmeier equations used to evaluate the refractive index of lithium niobate as a function of temperature and wavelength.

5. Output of the SRO as function of the internal pump power for two different periods of domain reversal, at two different temperatures.

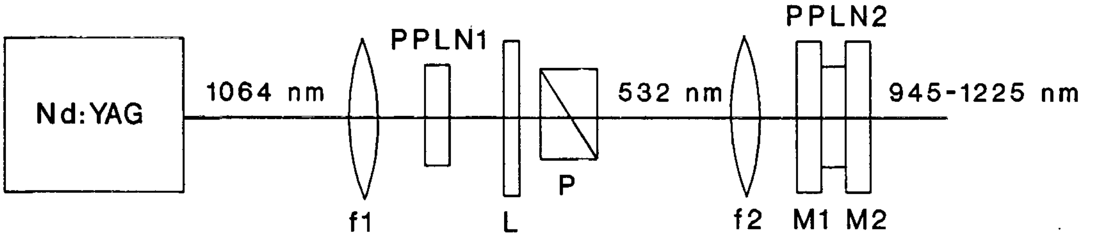


Fig.2

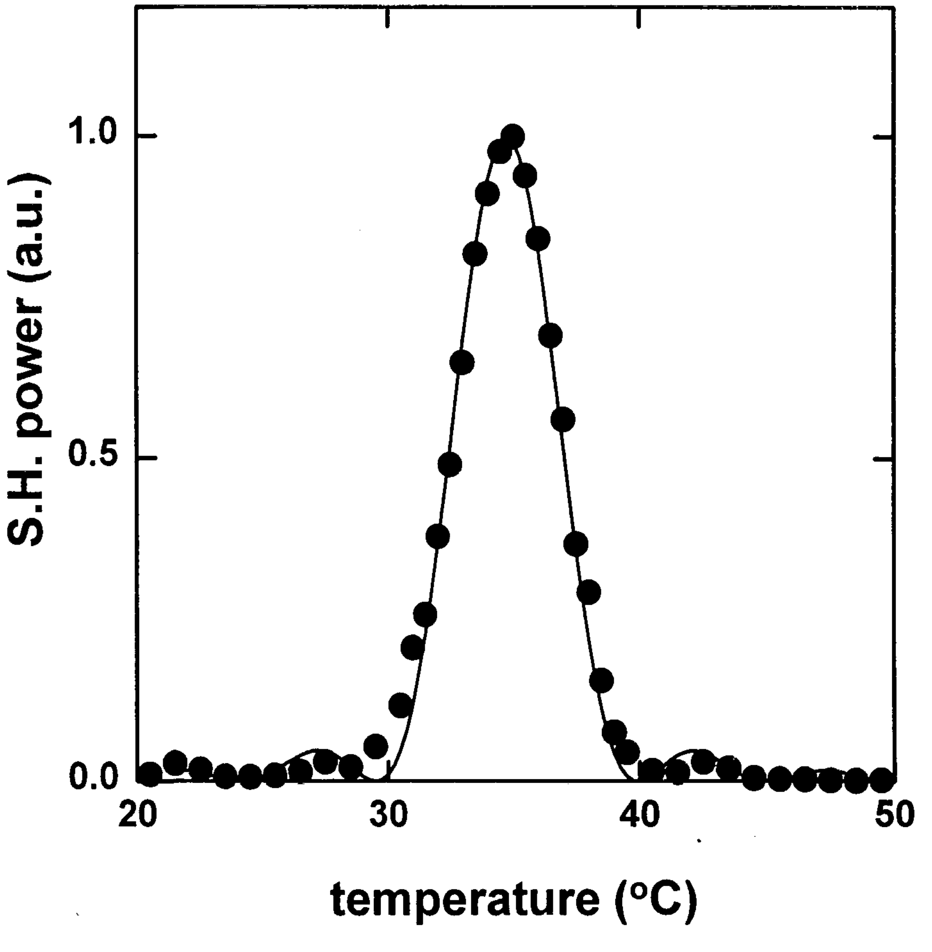


Fig.1

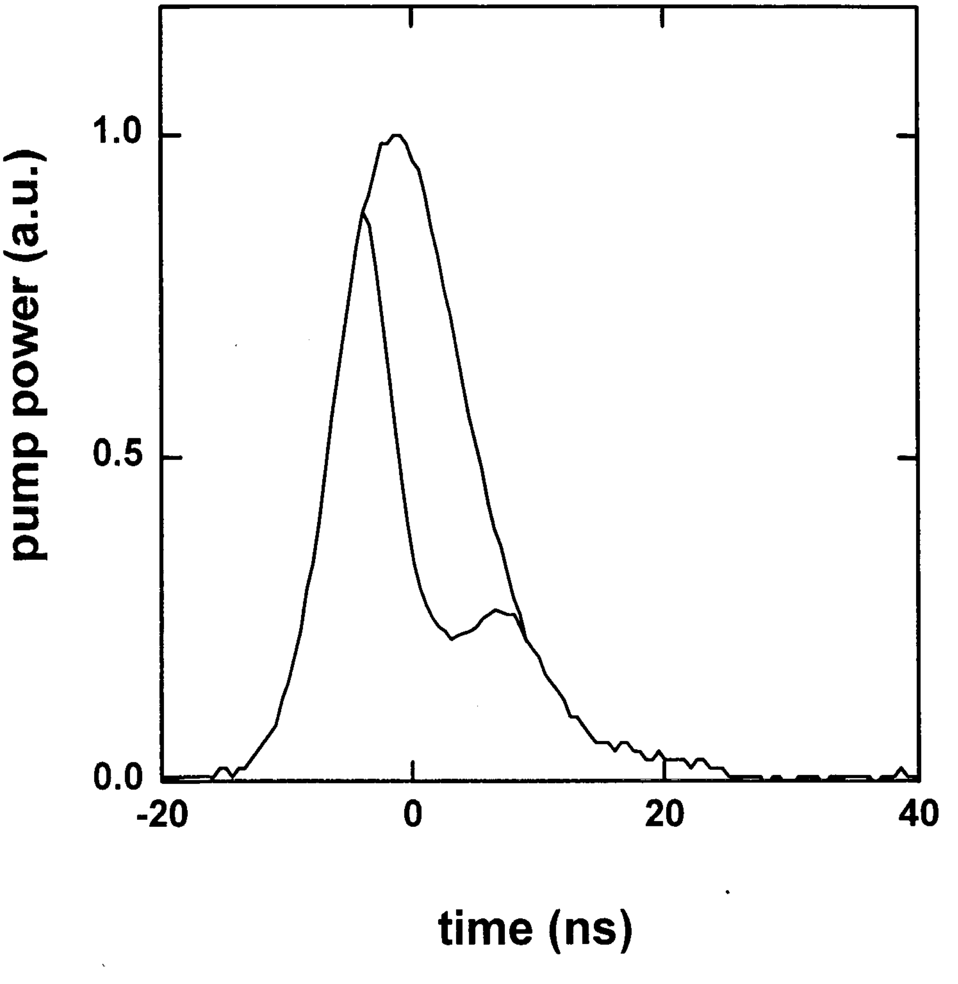
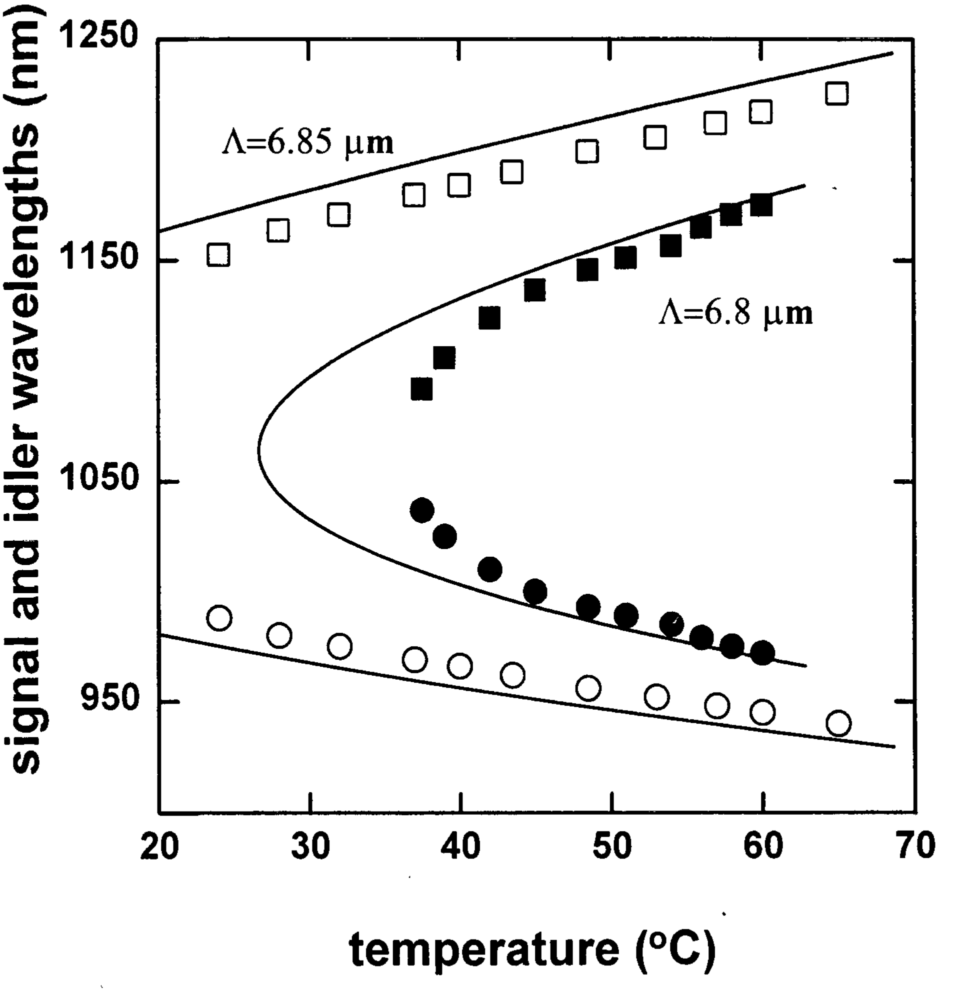
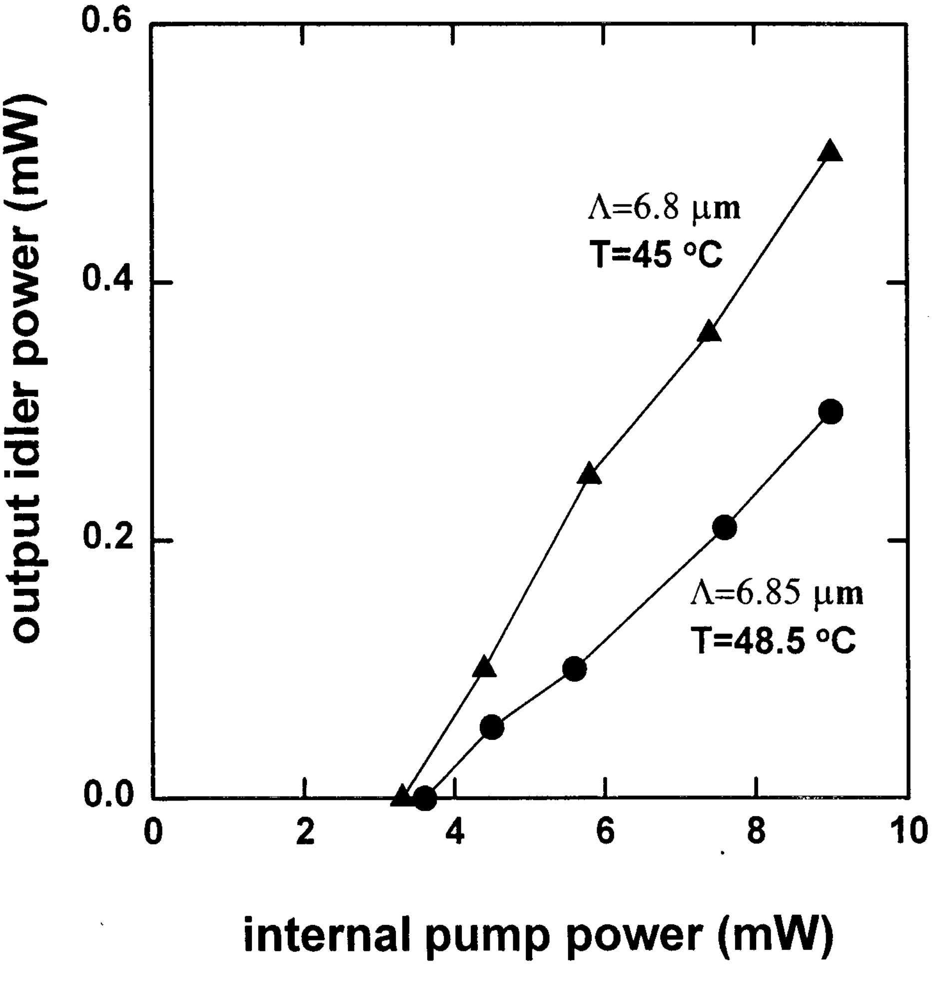


Fig.3



signal and idler wavelengths (nm)
1250
1150
1050
950
Λ=6.85 μm
Λ=6.8 μm
20
30
40
50
60
70
temperature (°C)

Fig.4



0.6
0.4
0.2
0.0
0
2
4
6
8
10
output idler power (mW)
internal pump power (mW)
Λ=6.8 μm
T=45 °C
Λ=6.85 μm
T=48.5 °C

Fig.5