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1.047 μm synchronously pumped optical parametric oscillator in bulk periodically poled $LiNbO_3$

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Abstract

Picosecond pulses have been efficiently generated over the tuning range 1.67-2.806 μm via cw 1.047 μm synchronously pumped optical parametric oscillation in periodically poled lithium niobate. Average signal and idler powers as high as 120 mW and 90 mW respectively have been generated with an overall slope efficiency of 61%. The corresponding pump depletion was 75% at 3 times above threshold.

Key Words

Nonlinear Optical Materials, Infrared Lasers, Parametric oscillators and amplifiers, Mode-locked Lasers.

Introduction

Over the last few years progress in the development of optical parametric oscillators (OPOs) has shown them to be attractive sources of coherent light with wider wavelength tuning range capability than conventional lasers [1]. In particular OPOs, operating in the picosecond pulse regime, have great potential, for example in time and frequency resolved spectroscopy. Among the nonlinear optical materials suitable for OPOs, periodically poled lithium niobate (PPLN) has recently been attracting rapidly growing interest. Its high effective nonlinear coefficient, d_{eff}, ~20pm/V in ideal material, can be exploited for frequency conversion over the entire transparency range of the material (0.4-4.8 μm). In particular singly resonant OPOs, quasi-cw and Q-switched pumped at 1.064 μm [2] and Q-switched pumped at 0.532 μm [3], have been demonstrated. Recently we have also reported a picosecond OPO based on PPLN, synchronously pumped at 523.5 nm by the second harmonic (SH) of an amplified 10 μs pulse train from an additive pulse mode-locked (APM) Nd:YLF laser [4]. Pulses of ~2 ps duration were produced over the range 883-1285 nm via temeperature tuning. The effective interaction length (l_{eff}), due to group velocity mismatch (GVM), was limited to ~2 mm for 2.3 ps pump pulses at 523.5 nm. However this shortcoming is outweighed by the large nonlinearity, and the results indicated that PPLN should be considered as a competitor to $KTiOPO_4$ (KTP) and LiB_3O_5 (LBO) for picosecond OPOs tunable around 1 μm.

In the case of pumping at 1 μm the constraint on l_{eff} due to GVM is less significant and samples as long as ~15 mm can be used for interactions involving 2 ps pulses, making PPLN very promising for efficient picosecond OPOs oscillating at around 2 μm. Operation at these longer wavelengths also reduces the degree of photorefraction, so that greater average powers should be possible before photorefractive damage is experienced. In fact, the photorefractive damage has been attributed to short wavelength (visible) generation from non-phasematched processes rather than the infrared wavelengths [2]. Here we report an OPO based on PPLN which generates picosecond pulses over the wavelength range 1.67-2.806 μm (singly-resonant operation in the range 1.73-2.65 μm). This OPO is synchronously pumped at 1.047 μm by an amplified cw APM Nd:YLF laser.

Fabrication and assessment of the PPLN sample via high order quasi-phase-matched SHG.

The sample of PPLN, 0.5 mm thick, used in the experiment was fabricated by applying a pulsed electric field as previously described [3,4]. The final

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grating, of pitch 30.5 μm, was 6 mm long. The grating was initially examined by etching the z+ and z- faces of the sample (before end-polishing). The periodic inversion was regular over the whole 6 mm length with an estimated mark/space ratio between 40/60 and 45/55 which should provide a d_{eff} in 1st order quasi-phase-matching (QPM) greater than 95% of the maximum theoretical value. This was confirmed by carrying out SH measurements using a Ti:Sapphire laser where we measured d_{eff} in 5th and 6th order QPM. By comparing the values obtained with theoretical predictions we estimated an average mark/space ratio of 43/57, which is consistent with the visual assessment of the grating and should provide d_{eff}>16pm/V. Fig.1 shows the QPM curve (SH power vs. fundamental wavelength) for the 5th order interaction.

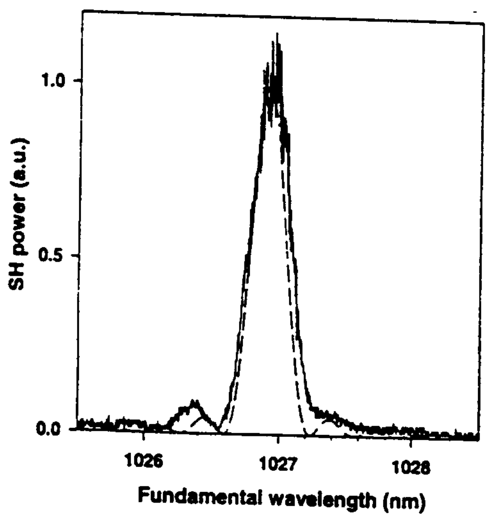

Figure 1. QPM curve for 5th order frequency doubling. The dashed line is a theoretical trace. For 6th order QPM the curve has a similar shape and is centered around 971 nm with a bandwidth of 0.22 nm.

Both faces of the PPLN sample were anti-reflection coated (AR) with a single layer of MgF_2 of appropriate thickness for 1.9 μm, implying a surface reflectivity <2% in the range 1.6-2.4 μm.

Optical parametric oscillation

The OPO layout is shown schematically in fig.2. The curved mirrors had high reflectivity (HR) over the range 1.65-2.1 μm and 84% transmission at 1.047 μm. The resonator was completed by a plane mirror M3, which was either HR or an output coupler with transmission that varied over this range. All the mirrors had reflectivities <30% @2.2-2.7 μm, thus implying a round trip idler feedback <0.8%. The pump source [5] (diode-pumped APM Nd:YLF laser with diode-pumped amplifier) delivered 2.8 ps pulses at 105 MHz repetition rate with average powers up to 700 mW, corresponding to ~500 mW in the PPLN sample. The pump and the signal spot sizes ($1/e^2$ intensity radius) in the PPLN sample were 33 and 39 μm respectively.

With the crystal at 170°C and all three mirrors HR, the incident power threshold (in the crystal) was 54mW. This increased to 140mW for an output coupler of 8% transmission at 1920nm. From these measurements we deduce an excess round-trip loss (ie. other than output coupler transmission) of 5.4% at this wavelength, increasing to 8.3% for a signal wavelength of 1804nm. These values also agree well with values implied by the observed output powers and corresponding pump depletion. The excess round trip loss has been attributed mainly to surface imperfections, i.e. polishing and the thickness and quality of the AR coatings on the crystal (a perfect coating MgF_2 would result in 0.3% loss/surface). Actual threshold powers agree well with numerical calculations, based on these known losses and the value of d_{eff}=16pm/V.

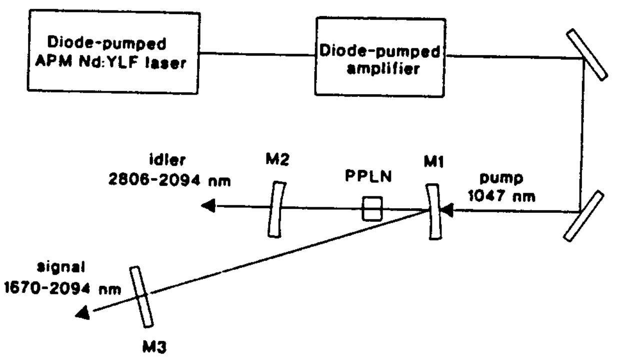

Figure 2. Experimental layout. M1 - HR with ROC=100mm, M2 - HR with ROC=150mm, M3 - HR or output coupler for signal wave.

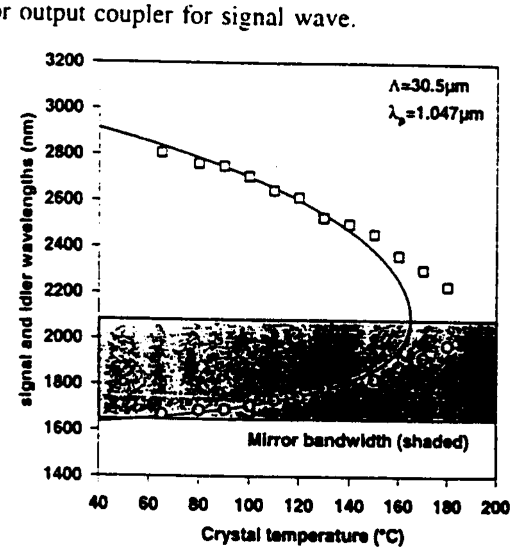

Figure 3. Tuning curve for the OPO. The continuous line is a calculated curve using Sellmeier equations from ref.6.

By changing the crystal temperature from 60°C to 190°C the OPO was tuned from 1.67 to 1.96μm (signal) and 2.24 to 2.8μm (idler). Operation at shorter signal wavelengths was limited by the HR bandwidth of the mirrors, as indicated in figure 3. At a crystal temperature of 170°C (λ_s=1920nm) the slope efficiencies for the signal and idler waves were 35% and 26% respectively. An output power of 123mW was measured at an incident power (in the crystal) of 500mW. The corresponding idler power was 92mW. The pump depletion (~70%) began to saturate when the OPO was operating at 3.3 times above threshold, as shown in figure 4.

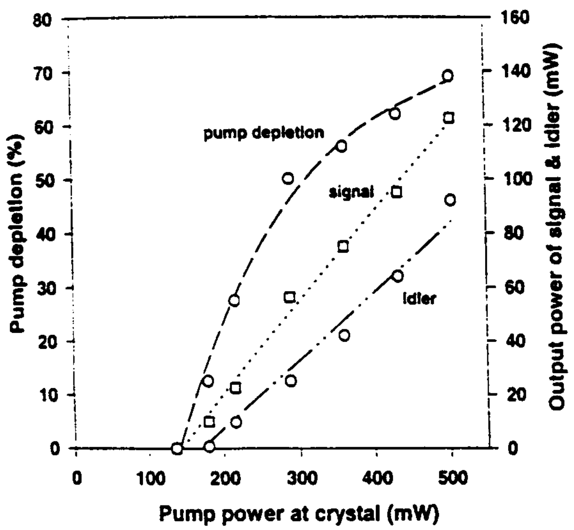

Figure 4. Dependence of the average signal and idler output powers and pump depletion on pump power with the crystal at 170 °C.

As well as the signal output power there was also ~2mW of 677nm light from sum-frequency mixing of the pump and signal waves, and ~5mW of 523.5nm from non-phase-matched harmonic generation of the pump.

The temporal characteristics of the signal pulses were measured by non-background-free autocorrelation using a 1.3mm thick critically phase-matched $LiNbO_3$ crystal cut at θ=47°. The signal pulse duration (τ_{ps}) fitted well to a $sech^2$ profile of duration 2.65psec. From a measurement of the signal bandwidth (Δv_s) we calculate a $\Delta v_s.\tau_{ps}$ product of 0.39, close to the transform limited value of 0.32 for $sech^2$ pulses.

The beam quality (M^2) of the signal output was calculated from a series of measured spot sizes at various distances from the focal plane of a lens (f=75mm) using slits and a PbS detector. The results gave a value for M^2 of 1.18 which indicates the lack of any significant photorefractive damage. It should be noted that operation of the PPLN at elevated temperatures ($T_{crystal}$ >60°C) helps to alleviate photorefractive damage as previously noted [2]. The output power stability of the OPO was excellent with a peak to peak noise of <5% (RMS <3%) as measured from DC to 2kHz using a PbS detector over a 5 second time interval. The low noise level can be attributed both to the low-noise of the diode-pumped laser source and also the large tolerance to cavity length detuning (Δl_{cav}) of the PPLN OPO, viz. Δl_{cav}~170μm at 3.3 times threshold (1920nm signal), and Δl_{cav}=90μm at 2 times threshold (1804nm signal).

In conclusion, we have demonstrated a highly efficient picosecond OPO based on PPLN, pumped at 1.047μm. Singly resonant operation has been achieved with low threshold due to the high parametric gain of the PPLN crystal. Significant future improvements in the performance of the OPO can be expected-lowering the threshold through the use of a longer sample (up to ~20mm), and also by reducing the excess cavity loss with better coatings or a Brewster angled crystal. This would result in higher slope efficiency. By fabricating gratings with different periods of domain reversal eg. 30.5μm down to 25μm it should be possible to extend the wavelength tuning range, potentially from 1.33μm through to 4.8μm. These prospects and the results already obtained show that PPLN is already a serious candidate for picosecond OPO's working in the near infra-red range.