BROADLY TUNABLE PUMP-RESONANT DIODE-PUMPED CW PPLN OPO

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Abstract

We have observed low threshold operation of a broadly tunable (2.18-3.4 μm) pump-resonant cw periodically poled lithium niobate (PPLN) optical parametric oscillator (OPO). When pumped at 806 nm with 410 mW from a custom-built diode laser the OPO generated 20 mW of idler output at 3.3 μm.

Introduction

Many spectroscopic sensors require compact, robust sources of tunable light in the 2 to 5 μm wavelength range. The availability of periodically poled lithium niobate (PPLN) has revolutionized the use of continuous wave, singly resonant OPOs (SROs) because of its high effective optical nonlinearity and its broad temperature tuned phasematching range when pumped with 1 μm light from Nd-based lasers. Indeed these OPOs have achieved impressively high output power and efficiency. While the use of diode-pumped solid-state lasers to pump the PPLN OPO leads to a modestly compact and efficient source capable of many Watts of output power, direct pumping with diode lasers can lead to significant reductions in the system size and power requirements when less output power is needed. Unfortunately, the brightness of diode lasers is still insufficient to pump even PPLN SROs above threshold. The main challenge in pumping OPOs directly with diode lasers is reducing the threshold power to levels attainable in single mode diode lasers.

OPOs directly pumped by diode lasers have previously been reported, but those devices have typically been doubly resonant OPOs (DRO). It has long been known that resonating more than one wave in an OPO can lead to substantial reductions in the pump power required to achieve oscillation threshold. Unfortunately resonating both the signal and idler waves imposes tight constraints on the pump frequency and OPO cavity stability. Furthermore in the standard DRO configuration, tuning occurs in a cluster manner making them undesirable for sensing applications requiring broad tunability. The problem is compounded by the fact that active stabilization of the OPO cavity requires that either signal or idler be present.

Herein we describe a PPLN OPO designed to resonate the signal and pump waves. Two major simplifications occur when the pump wave rather than the idler is resonated: 1) the cavity can be stabilized to a wave that is always present, and 2) as the idler frequency is not constrained, cluster free tuning is achieved. The use of PPLN adds another benefit in that the pump cavity need not be of particularly high finesse; enhancement factors in the circulating pump power need only be about a factor of five to reach threshold with available diode lasers.

Experimental Setup

The experimental configuration is shown in Figure 1. The system consists of a MOPA diode pump laser, the standing wave PPLN OPO, and optional cavity locking electronics.

The MOPA diode laser uses a Spectra Diode Labs (SDL) model 5400 series single mode diode laser with an external tuning grating in Littrow configuration to form the master oscillator. This laser produces about 30 mW of single transverse and longitudinal mode radiation tunable around 806 nm. This light is coupled into the narrow end of a tapered waveguide semiconductor amplifier module (an SDL 8630 with the tuning grating removed). Approximately 60 dB of optical isolation is used between the master oscillator and the power amplifier to reduce the deleterious effects of feedback on the frequency of the master oscillator. The power amplifier increases the power at 806 nm to greater than 700 mW. When properly aligned, the output optics in the SDL 8630 yield a circular beam with little astigmatism and an M2 of less than 2. The output beam is passed through another 60 dB of optical isolation used between the master oscillator and the power amplifier to reduce the deleterious effects of feedback on the frequency of the master oscillator. The power amplifier increases the power at 806 nm to greater than 700 mW. When properly aligned, the output optics in the SDL 8630 yield a circular beam with little astigmatism and an M2 of less than 2. The output beam is passed through another 60 dB of optical isolation prior to coupling into the OPO. The beam is passed through a variable attenuator consisting of a half-wave plate (WP) and a polarizer (POL), and mode-matching optics. Approximately 410 mW of power was available to pump the OPO.
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The OPO system consists of a high power tunable diode pump laser, optical isolators, mode-matching optics, a variable attenuator, the linear cavity OPO and cavity locking electronics.

The OPO is a two-mirror standing wave symmetric resonator with 50 mm radius of curvature mirrors and a 50 mm long PPLN crystal. The physical cavity length of 122 mm produces a waist $e^{-2}$ radius of about 70 and 60 $\mu$m for the signal and pump waves. The input mirror (M1) is coated for 86% reflectivity at the 806 nm pump wavelength, high reflectance at the 1.03 to 1.3 $\mu$m signal wave, and for low reflection at the 3 to 3.5 $\mu$m idler wave. The output mirror (M2) is coated for high reflectance at the pump and signal waves and low reflectance at the idler wave. The input mirror is mounted on a piezoelectric transducer (PZT). The 0.5 mm thick PPLN crystal has poled regions with poling periods ranging from 20.5 to 22.0 $\mu$m. Its faces were antireflection coated for the signal, pump and idler. The PPLN is housed in an oven that permits its temperature to be varied from about 100°C to 200°C; photorefractive damage precludes OPO operation at temperatures below about 100°C.

The cavity can be locked to the pump frequency by driving the PZT with a signal derived from a photodiode that samples the reflected pump light. Initially the PZT was dithered at 3 kHz and lockin detection at twice that frequency produced an error signal suitable to minimize the pump reflection. As has been noted by others, high bandwidth is required because of the potential for small but rapid temperature changes in the crystal with cavity tuning. In our case the cavity was found to rapidly detune from resonance when it was tuned from the low frequency side to near resonance with the pump source; however, when tuned from the high frequency side, the cavity was stable until resonance was achieved. We found that the bandwidth afforded by this system was not sufficient to lock the operating OPO. While long term operation of the OPO at peak performance requires the use of the cavity lock loop, the OPO can be operated manually for brief periods (tens of seconds) near the resonance condition without the servo loop at a small penalty in output power. Indeed most of the data presented in this paper was taken without closing the locking circuit and by manually tuning the cavity resonance to be slightly greater than the pump frequency.

**Results**

The dots in Figure 2 show the observed output idler power versus the incident pump power for the diode-pumped pump-resonant OPO. At 3.3 $\mu$m, up to 20 mW of idler was emitted from the output mirror with an input power of 410 mW. The oscillation threshold was approximately 100 mW. A similar OPO, pumped by the high quality beam from a Ti:SAP laser achieved oscillation threshold at about 40 mW with the cavity lock loop activated; in that case we used a dither frequency of

![Graph of idler output power vs pump power](image)

**Figure 2** The idler output power at 3.3 $\mu$m measured in the free running mode and the model prediction.
Also shown for comparison are the results from a detailed model of the device. The model, based on a previously published model for pulsed OPOs, correctly includes diffraction in the cavity, mirror curvatures, mirror reflectivities, and solves the three-wave mixing equations in the crystal with full diffraction. The model propagates the pump, signal and idler wavefronts repeatedly through the cavity until a steady state is achieved. The round trip phase shift of the pump beam at the input mirror is adjusted to minimize the reflected pump power off the input mirror. As shown, the model is in reasonable agreement with the measurements. There are no adjustable parameters in the model; however, the results are sensitive to losses at both the pump and signal waves. The discrepancy between measurements and theory are most likely due to the sensitivity of the model predictions to cavity losses, the assumption of a perfect Gaussian pump beam in the model and perhaps thermal effects. Nonetheless, the comparison shows that the model predicts the performance quite well.

Figure 3 shows the tuning characteristics of the OPO. The signal wavelength was measured using a spectrometer. By using poling periods of 20.5 and 21 μm and temperature tuning, the signal was observed to tune from 1.06 to 1.28 μm. A fixed pump wavelength of 806 nm and conservation of energy imply that the idler wave simultaneously tuned from 3.24 to 2.18 μm. Calculated phase matching curves versus temperature are also shown in this figure. The idler tuning range covers a large fraction of the region of interest for detection of hydrocarbons. The linewidth of the signal wave was observed to be less than our instrument limits of 1 cm⁻¹. While the idler bandwidth was not directly measured, the pump bandwidth of <50 MHz and conservation of energy imply an idler bandwidth less than 1 cm⁻¹.

Conclusions

We have demonstrated a pump-resonant OPO that can be pumped directly with a diode laser. Unlike typical DROs that resonate the signal and idler waves, the pump resonant OPO can be broadly tuned. Given the low threshold demonstrated in this work, direct diode pumping of OPOs appears practical. With appropriate engineering, sources such as this could be made suitable for hydrocarbon detection.

References:


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