High-power picosecond optical parametric oscillator based on periodically poled lithium niobate

C. W. Hoyt and M. Sheik-Bahae

Optical Sciences and Engineering, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131

M. Ebrahimzadeh

J. F. Allen Physics Research Laboratories, School of Physics and Astronomy, University of St. Andrews, Fife KY16 9SS, UK

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A high-power picosecond optical parametric oscillator (OPO) based on a 47-mm periodically poled lithium niobate crystal is described. More than 12 W of total average power—almost 8 W of signal power at 1.85 μm and more than 4 W of idler radiation at 2.5 μm—is simultaneously extracted from less than 18 W of average pump power. The OPO is synchronously pumped by 80-ps (FWHM) cw mode-locked pulses at 1.064 μm, and its output is tunable from 1.7 to 2.84 μm. Nearly transform-limited signal pulses are obtained following the introduction of two intracavity etalons.

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The tunability of and remarkable wavelength range available from optical parametric oscillators (OPOs) have made these oscillators attractive sources for a variety of applications. Picosecond OPOs offer a balance between short pulse duration and relatively narrow bandwidth. They also have the potential for large output powers. Contributing to this potential are factors such as the availability of high-power pump sources, low-threshold average powers, and long nonlinear interaction lengths in noncritically phase-matched schemes. Oscillators based on lithium triborate have generated combined output powers (signal + idler) of 5.5 W (Ref. 1) and 2.4 W.[2] A potassium titanyl phosphate (KTP) OPO (Ref. 3) has generated a combined 2.9 W of power, and a nontunable critically phase-matched potassium titanyl arsenide system[4] has produced a combined 21 W.

In recent years the development of periodically poled nonlinear materials has enhanced the flexibility and performance of OPOs.[5] In the case of much-studied periodically poled lithium niobate (PPLN), one can gain access to the material's highest effective nonlinearity as well as retain generous flexibility in phase-matching parameters and nonlinear interaction lengths. Both continuous-wave[6,7] (cw) and picosecond[8] OPO systems based on PPLN have generated multiwatt output powers. Combined outputs of as much as 4.85 W from a PPLN OPO synchronously pumped by a 7.9-W, 70-ps cw mode-locked source have been reported.[9]

Scaling PPLN-based OPOs to higher power levels is potentially problematic because of the onset of thermal lensing, thermal phase mismatching, and the increasing effects of photorefractive damage that arise from the large amounts of non-phase-matched visible light generated in the crystal. These can lead to spatial, temporal, and output power instabilities, limiting the practical utility of PPLN-based OPOs at high operating power levels. Here we report the successful operation of a picosecond PPLN OPO at outcoupled power levels greater than 12 W with good output stability, limited only by the stability of the pump source. This is what is to our knowledge the highest average power obtained from a PPLN-based OPO in any temporal regime. The OPO is synchronously pumped by a high-power picosecond Nd:YAG laser at 1.064 μm and is continuously tunable from 1.7 to 2.84 μm. As much as 7.7 W of signal radiation at 1.85 μm and 4.7 W of idler radiation at 2.5 μm is simultaneously extracted from 17.7 W of average pump power, corresponding to a total external efficiency of 70%. We avoid photorefractive damage by keeping the 1-mm-thick PPLN crystal at elevated temperatures (~150 °C), precise to 0.1°. Although slight cavity adjustments are required when one is scaling pump powers from lowest to highest, we have noticed no detrimental thermal effects. Operation near the degeneracy wavelength of 2.128 μm reduces thermal lensing because the signal and the idler wavelengths fall within the highest transparency range of lithium niobate. Over a period of 1 h the output power is stable to within 5% and is correlated to the stability of the pump laser. This behavior implies that the deleterious effects discussed above are absent even at high powers. Further, more than 20 cumulative hours of high-power operation have been achieved without noticeable degradation in performance or crystal condition. We also have achieved spectral narrowing of the OPO pulses, resulting in transform-limited performance at multiwatt power levels. Our results indicate that further power scaling of the PPLN OPO to greater than 12 W should also be attainable, making the device a stable source of high-power, high-quality picosecond pulses for many applications.

Figure 1 shows the simple asymmetric gamma-cavity configuration of the OPO. The 80-ps (FWHM) cw mode-locked pulses from a Nd:YAG (Coherent Antares) laser at a wavelength of 1.064 μm and a repetition rate of 76 MHz are focused into a standard, undoped 47-mm PPLN crystal (Crystal Technology) that contains eight quasi-phase-matching periods. The waists of the pump and the resonated idler inside the crystal are 37 and 66 μm, respectively, corresponding to an optimum overlap parameter[10] of $\xi \approx 2$, where $\xi \equiv L_{\mathrm{crystal}}/2z_0$. The waist of the signal is 58 μm. The two curved mirrors (M1 and M2,

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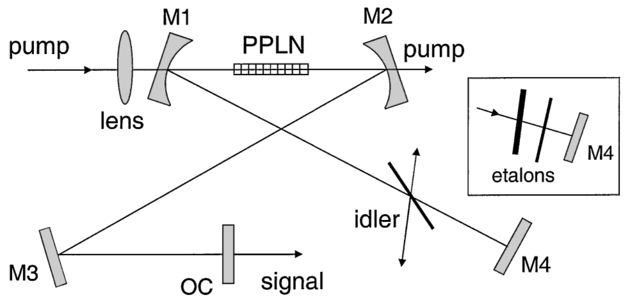

Fig. 1. Asymmetric gamma-cavity OPO. The output coupler is highly reflecting for the idler and highly transmitting for the signal. All other mirrors are highly reflecting for both signal and idler and highly transmitting for the pump. Fresnel reflections from a transparent window at a finite angle are used to couple idler radiation from the cavity. We obtain high-power, nearly transform-limited pulses by replacing the transparent window with two dielectric-coated glass etalons, as shown in the inset.

$R = 20$ cm) are highly reflecting for both the signal and the idler, and mirror M1 transmits 85.5% of the pump. The planar output coupler (OC) is highly transmitting for the signal and highly reflecting for the idler ($T \approx 98\%$, 0.1% at 1.85, 2.5 μm, respectively), and the other planar mirrors (M3 and M4) are highly reflecting for both signal and idler. Idler radiation is coupled from the cavity through the Fresnel reflections from an intracavity transparent material. This partially reflecting element is placed in the cavity arm opposite that which contains the OC to prevent loss of the nonresonated signal. We tuned the signal and corresponding idler wavelengths by changing the temperature of the crystal. Tuning data for three of the eight available quasi-phase-matching periods (31.2, 31.1, and 30.95 μm) are shown in Fig. 2, along with the corresponding theoretical curves based on the appropriate Sellmeier equations.

Inasmuch as the OPO is operating at high powers near degeneracy (2.128 μm), an expected large signal bandwidth is observed.[11] With 16.9-W pump power incident upon the crystal, three polished silicon substrates are placed in the cavity arm containing mirror M4 with their normals at an angle of 38° with respect to the propagation direction of the resonated idler. Together these substrates serve as both an idler loss mechanism and frequency-stabilizing etalons. Under these conditions we extract 4.3 W of idler power from reflections and 5.3 W of signal power from the output coupler, and the bandwidth of the signal radiation is reduced from a maximum of tens of nanometers at highest powers to within the limitations of our current spectrometer (~1 nm). Replacing the silicon substrates with two dielectric-coated glass etalons (0.5- and 0.25-mm thickness) with their normals at small angles with respect to the cavity beam and to each other also significantly reduces the signal bandwidth. We obtain 6.5 W of signal light at 1.87 μm from the OC at a pump power of 16.4 W—a loss of 9% compared to that of a cavity with no intracavity elements. First- and second-order autocorrelations of this signal radiation yield a time–bandwidth product of $\Delta\tau_{\mathrm{FWHM}}\Delta\nu_{\mathrm{FWHM}} = 72\ \mathrm{ps} \times 6.6\ \mathrm{GHz} = 0.48$. Signal pulse widths are ~77 ps (FWHM) at highest powers without any frequency-selecting elements in the cavity.

Figure 3 shows the average output idler, signal, and total powers as a function of pump power before the crystal for the case of optimum coupling for the idler. Threshold is at 980 mW, and output slope efficiencies for the idler, signal, and total powers are 28%, 46%, and 74%, respectively. The slope efficiency remains linear even at pump powers 18 times above threshold, which implies that further scaling is possible. Both threshold and slope efficiency are changed with the introduction of loss for the idler. The optimum loss for maximum extracted total power (~60%) can be figured from the data in Fig. 4, which show total signal and idler output powers as a function of intracavity loss associated with the Fresnel reflections of a thin glass window. Pump depletion (Fig. 3) is approximately 80% at this optimum value. The bandwidth is decreased by approximately a factor of 5 when large losses are introduced for the idler. The highest loss is obtained by use of a glass wedge in place of mirror

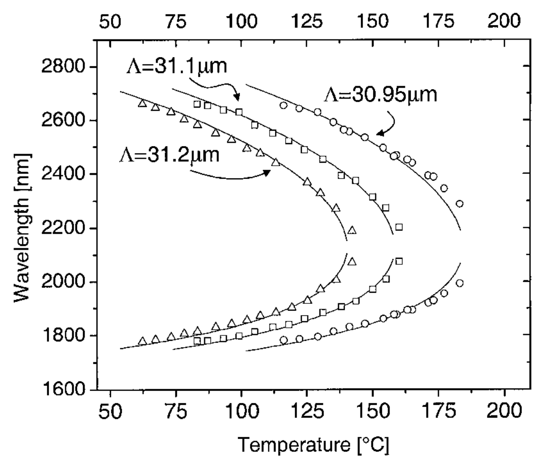

Fig. 2. Tuning curves for three quasi-phase-matching periods of the 47-mm PPLN crystal. Points show periods of 31.2, 31.3, and 30.95 μm. Solid curves show the corresponding theoretical tuning curves.

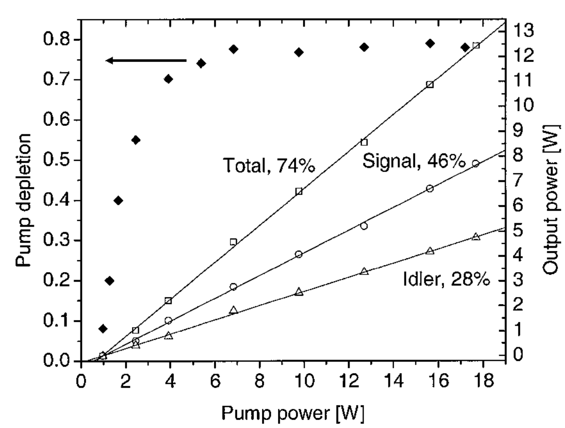

Fig. 3. Pump depletion and output powers as functions of average input pump power before the crystal for optimum intracavity loss for the idler. Open triangles, idler; open circles, signal; open squares, total extracted power. Slope efficiencies are 28%, 46%, and 74%, respectively. Solid diamonds, pump depletion.

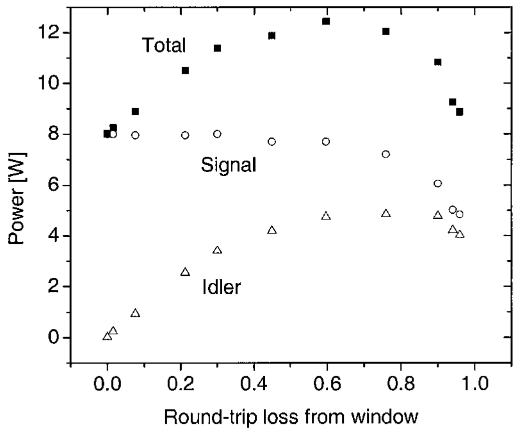

Fig. 4. Output powers as functions of round-trip intracavity loss for the idler owing to the insertion of a glass window in the arm containing mirror M4 (see Fig. 1). Circles, signal power extracted from the output coupler; triangles, total idler power extracted from the glass window; filled squares, total extracted power. The highest loss is obtained by use of a glass wedge in place of mirror M4.

M4. When there is no intracavity loss (i.e., a window at Brewster's angle and low cavity losses) we extract 8.0 W of average power from the output coupler at a signal wavelength of 1.85 μm and 17.7 W of pump power.

Our system is designed primarily for use in solid-state optical cooling experiments. We have used signal radiation from this optical parametric oscillator to demonstrate anti-Stokes fluorescence cooling in thulium-doped glass for the first time.[12] An acceptable bandwidth for cooling corresponds to a fraction of thermal energy ($k_B T$, where k_B is the Boltzmann constant and T is temperature), which is approximately 75 nm at room temperature and 25 nm at 100 K. Our estimations show that using multiple-pass schemes to absorb the full 8 W produced by the OPO can achieve temperatures as low as 100 K.

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