High-average-power KTiOAsO$_4$ optical parametric oscillator

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Using noncritically phase-matched 1-cm^2-aperture KTiOAsO$_4$ (KTA) crystals in an optical parametric oscillator (OPO), we have demonstrated a sustained average signal power of 33 W at 1534.7 nm. To our knowledge, this is the highest-average-power signal ever generated by an OPO. The pump source was a 100-Hz Q-switched 1064-nm Nd:YAG laser. Compared with that of the similar and more-common material KTiOPO$_4$, idler absorption in KTA is negligible, allowing high-power operation with minimal thermally induced refractive distortion in the OPO crystal. © 1998 Optical Society of America

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The KTiOPO$_4$ (KTP) optical parametric oscillator (OPO) has been extensively studied for use in frequency conversion of Nd-doped lasers to longer wavelengths and can be used as the basis for eye-safer lidar systems operating in the 1550-nm-wavelength region.[1] One of the major advantages of OPO's based on KTP and its isomorphs is the ability to operate with noncritical phase matching (NCPM). The large acceptance angle for NCPM permits efficient OPO operation even with multi-transverse-mode pump lasers. The development of flux-growth techniques[2] has allowed fabrication of 1-cm^2-aperture KTP crystals and the subsequent scaling-up of KTP OPO output. A high-power nanosecond-pulse OPO utilizing KTP was previously reported to generate a record signal energy of 450 mJ, have an average signal power of 7.4 W, and operate with a pump-to-signal conversion efficiency greater than 40%.[3,4] These results led us to investigate the possibility of a further increase in the average power from KTP OPO's. One possible limit to higher powers in KTP OPO's results from the absorption of the idler wave in the crystal under NCPM conditions. The isomorph KTiOAsO$_4$ (KTA) has phase-matching characteristics similar to those of KTP but greatly reduced idler absorption and thus is a candidate for operation at high output powers as well. Recent advances in the flux growth of KTA and its isomorphs[5] allowed fabrication of crystals similar in size to KTP.

In this Letter we provide a comparison of the performance of KTA and KTP in high-average-power NCPM OPO's. Next we present selected efficiency data on a ring KTA OPO using different output coupler reflectivities. We also show plots of the highest average signal power demonstrated by our OPO system when two separate pump lasers are used. Next we present an experimental validation of recently published Sellmeier coefficients[6] for KTA. Finally, we note the observation of bulk damage in some of our KTA crystals.

For our OPO experiments we utilized 100-Hz pulsed-diode-pumped Q-switched multimode Nd:YAG lasers. We employed two systems, each of which consisted of an oscillator and two amplifier stages. Both lasers had a measured output beam M^2 value of 5; lasers 1 and 2 were capable of power output at the exit aperture of 100 and 130 W, respectively. The optics used to relay the laser output to the OPO (1:1 imaging) and provide isolation and variable attenuation of the pump power reduced the maximum power that was deliverable to the OPO by approximately 20%. The output pulse widths (FWHM) were 22.5 and 17.5 ns for lasers 1 and 2, respectively, and the pulse shapes were approximately Gaussian with 20% modulation from mode beating superimposed upon them. The measured beam profiles were nominally flat topped (8-mm-diameter) with ~30% rms deviation from the mean irradiance; the two lasers differed somewhat in intensity profile.

We chose the singly resonant ring-cavity OPO design represented in Fig. 1 for a variety of practical reasons: higher damage threshold owing to reduced pump fluence, greatly reduced isolation requirements for the pump laser, the intrinsic ability to remove the idler from the cavity without specifically coating the optics for this purpose (45° incidence on the final cavity mirror with p polarization for the idler only), and ease of injection seeding if future applications require a narrow-linewidth signal. A double-pass standing-wave cavity, using only half the crystal length used in the ring, produced lower thresholds and equivalent

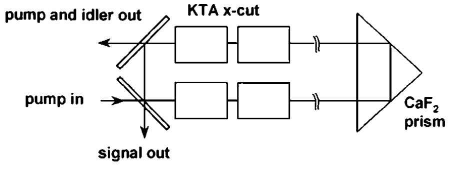

Fig. 1. Schematic of ring-cavity KTA OPO.

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peak efficiencies for the OPO signal, but the practical issues mentioned above made this option undesirable for our application.

Transmission data are shown in Fig. 2 for identically antireflection-coated x-cut KTP and KTA crystals. We used these data to calculate a linear absorption coefficient of 0.59 cm^{-1} in KTP at the idler wavelength 3297 nm that was expected with NCPM and a 1064-nm pump. Assuming negligible absorption in KTA for wavelengths shorter than 3500 nm,[7] the reduced transmission in our KTA sample in the range from 3000 to 3500 nm is due to absorption and (or) reflection at the coated optical surfaces and not in the bulk crystal. Increased absorption is known to cause phase mismatch and (or) thermal lensing at high average power (for detailed numerical studies, see, e.g., Ref. 8).

With a few simplifying assumptions we can use the idler absorption data to make a crude estimate of thermal lensing induced in a high-power 1064-nm-pumped NCPM KTP OPO crystal that generates 25 W of signal power. The assumptions are a cylindrical crystal with beam propagation down the length of the cylinder, a constant temperature of the entire cylindrical surface, negligible heat loss through the optical faces of the crystal, uniform heating down the length of the crystal and located on the exact center of the cylinder axis, isotropic thermal conductivity, and steady-state operation. Under these conditions, we derived an analytic solution to the heat conduction equation that dictates a parabolic temperature gradient as a function of radial distance from the axis of the crystal.

For a 4-cm length of crystal (many of our experiments utilized two 2-cm-long crystals), this temperature gradient, coupled with the temperature-dependent change of the optical index[9] and thermal conductivity of KTP,[10] leads us to predict a thermal lens of focal length +3.5 m. Introduced into a typical flat-mirror OPO cavity, this lens significantly reduces the mode volume of the lowest-order resonant mode in the cavity, increasing the risk of optical damage to cavity components. The use of alternative thermo-optic data for KTP (Ref. 11) leads to the calculation of an even more powerful thermal lens. Previous calculations in which an infinitely long slab of KTP was assumed led to similar results.[7]

Experimentally, for a KTP ring-cavity OPO using two 2-cm crystals, we observed the onset of a significant thermal lens at the modest signal-power level of 8 W. When we increased the signal-power level to 12 W the measured beam diameter of the resonated signal decreased to approximately one fifth of the 0.8-cm low-power diameter. To avoid possible optical damage, we did not increase the power of the KTP OPO beyond this level. In contrast, the beam diameter for an optimized ring cavity using KTA, as imaged at the plane of the ring-cavity output coupler, did not change measurably over our entire signal-power range up to 33 W.

After demonstrating that KTP developed a significant thermal lens for modest average signal power (8 W), we concentrated further efforts on optimization of the KTA ring OPO. In Fig. 3 we show sample plots of OPO net efficiency versus output coupler reflectivity. All plots in Fig. 3 were obtained with laser 1, an 8-cm total KTA length in the cavity, and a pump-beam diameter of 0.8 cm. The cavity was substantially longer than the minimum distance required for accommodation of the 8-cm total KTA crystal length. We maximized the length of the cavity to reduce the M^2 of the signal output, subject to the additional constraint that the maximum net efficiency not be lowered. The final length that we used to obtain the best results to data was a 52-cm physical round-trip length.

In Fig. 4 we present average signal power versus average pump power for each of the two pump lasers. These data were collected for a ring cavity with four 2-cm-long KTA crystals, a 30%-reflectivity signal-wave output coupler, and an OPO physical round-trip length of 52 cm. Figure 5 shows the overall conversion efficiency of pump-to-signal average power as a function of the integrated average pump irradiance that was incident upon the OPO input mirror. Laser 1 had slightly more intensity variation in the beam than laser 2, but both top-hat beams were 0.8 cm in diameter. The performance of the OPO for data taken with laser 2 may have suffered slightly from the presence of bulk damage sites in the OPO. The values of M^2 for the OPO signal output beam at maximum power were 30 and 41 with lasers 1 and 2, respectively. We measured the signal wavelength of the KTA ring

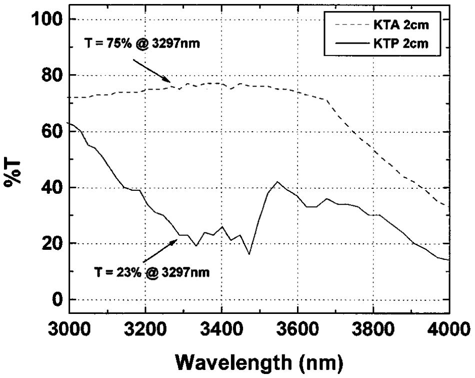

Fig. 2. Measured unpolarized transmission spectra for 2-cm-long antireflection-coated KTA and KTP.

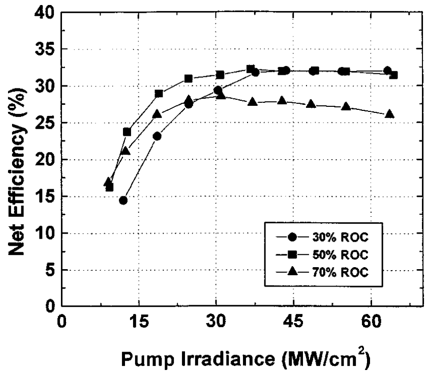

Fig. 3. OPO net efficiency (signal out–pump in) versus pump irradiance with three different output coupler reflectivities. ROC, radius of curvature.

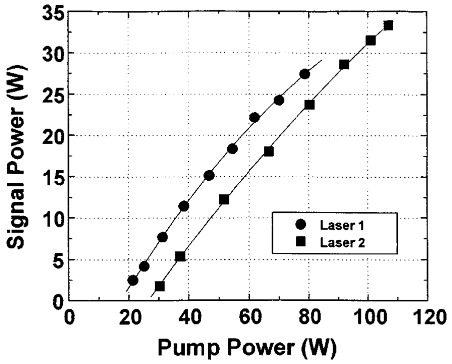

Fig. 4. Signal power as a function of pump power for KTA ring OPO for pump lasers 1 and 2.

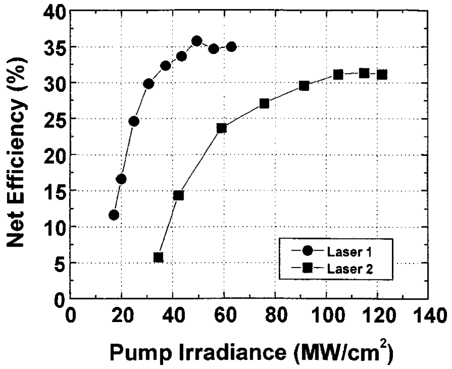

Fig. 5. Net efficiency (signal–pump) KTA ring-cavity OPO as a function of pump irradiance for pump lasers 1 and 2.

cavity to be 1534.7 ± 0.6 nm, compared with a calculated value of 1533.7 nm based on published Sellmeier coefficients.[6] The output linewidth was 0.6 nm FWHM. We note that our calculated and measured wavelengths do not agree so well as and are slightly higher than those in Ref. 7. We measured a signal wavelength of 1571.6 ± 0.6 nm for a multicrystal KTP ring OPO, which, within experimental error, agrees with the predicted value of 1571.1 nm.[7]

With regard to bulk damage, after several months of experimentation with a set of six KTA crystals we noticed the appearance of small, bubblelike inclusions in four 2-cm-long crystals. The inclusions occurred in different distributions and areas for each of the crystals. The other two 2.5-cm-long crystals, fabricated from crystal boules grown later than those used to make the shorter crystals, showed no visible sign of similar inclusions. Whether the differences in bulk damage were related to particular experimental conditions in the OPO testing or to differences in original defects in the source boules is a matter of continuing investigation. We are also studying the extent to which these bulk damage sites will have long-term detrimental effects on the performance of the high-average-power OPO's. Ongoing improvements in KTA crystal growth may eliminate the issue of bulk damage in the future.

By direct comparison with KTP, we have experimentally validated the claim that KTA is more suitable than KTP for high-average-power Nd-laser-pumped OPO operation in the eye-safe region near 1550 nm. What is to our knowledge the highest average-signal-power OPO to date was operated, and net efficiencies in excess of 30% at average power levels greater than 30 W were demonstrated.

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