Compact 21-W 2-μm intracavity optical parametric oscillator

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We report on an intracavity optical parametric oscillator (OPO) placed within a compact diode-pumped Nd:YALO laser cavity. This OPO utilizes a pair of KTP crystals, which are diffusion bonded together in a walk-off-compensated configuration. We have generated up to 21.4 W of 2-μm radiation, operating in a few-kilohertz range. © 2000 Optical Society of America

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Two-micrometer laser sources are useful for several applications in remote sensing and medical applications. They also serve as good sources for pumping nonlinear OPO crystals such as $ZnGeP_2$ so that the output reaches the mid-infrared spectral range.[1–3] Recently our group reported a 6.5-W 2-μm laser source[4] from a near-degenerate, type II KTP optical parametric oscillator (OPO) pumped within a Q-switched Nd:YAG laser cavity. The main difficulty in generating more than 10 W of 2-μm radiation from this configuration lies in the serious presence of a thermally induced birefringence effect that complicates the effort of generating polarized laser light with reasonable beam quality for pumping of an OPO at high average power. Compensation for this thermal birefringence effect with a single laser module, especially in the presence of an intracavity OPO, is nontrivial[5] and requires a complex cavity with more intracavity optical elements. In addition, because of the aperture effect owing to Poynting vector walk-off and the limited acceptance angle offered by this critically phase-matched KTP crystal, the OPO's efficiency is hampered by inefficient wavelength conversion of both the lower- and higher-order laser modes. Therefore, as reported in this Letter, we have exploited the advantages of a walk-off-compensated KTP crystal configuration[6–10] to enhance OPO conversion efficiency to providing, first, a longer effective gain length for the lower-order modes owing to the reduced aperture effect[9,10] and, second, an increased acceptance angle,[7] which is especially beneficial for the higher-order laser modes. To avoid optical losses and cumbersome alignment of two crystals in a walk-off-compensated configuration, we diffusion bonded the two crystals in a correct orientation that preserves the same signs of the effective nonlinear coefficients[10] for both crystals.

In Ref. 11 the potential of a diode-pumped Nd:YALO rod for generating a high-power polarized laser beams was demonstrated. Nd:YALO is one of the few laser crystals that exhibit high conductivity, hardness, and a large emission cross section that are comparable with those of Nd:YAG. The main advantage of Nd:YALO lies in its optical anisotropy, which provides a simple solution (with many fewer optical elements) for generation of polarized laser light for pumping an OPO. In this study we used a Nd:YALO laser to pump an intracavity OPO that utilizes a pair of diffusion-bonded walk-off-compensated (DBWOC) KTP crystals and managed to push the 2-μm intracavity OPO output power above 20 W at a repetition rate of a few kilohertz. This power is more than three times higher than the OPO intracavity power reported in Ref. 4, and, to our knowledge, using a Nd:YALO laser to pump an OPO is itself a novel approach. In addition, nonlinear processes that use DBWOC nonlinear crystals with less than a few watts of average power output were reported in Ref. 10. In this Letter, we clearly illustrate the power-handling capability of DBWOC KTP crystals in generating a few tens of watts of OPO output. It is also worthwhile to note that our combination of a Nd:YALO pump source with intracavity DBWOC KTP OPO crystals provides a feasible solution to the problem of generating a few tens of watts of OPO output in a compact laser head ($<$40 cm $\times$ 10 cm $\times$ 10 cm) with a simple layout that facilitates optical alignment and tuning.

A schematic diagram of the experimental setup is shown in Fig. 1. The laser cavity (~33 cm) was formed by high reflector M1 ($R > 99.5\%$ at 1 μm) and output coupler M2. To prevent optical damage when tuning the OPO cavity, we did not fully lock in the laser power inside its cavity (the 1-μm reflectivity of M2 is 95%). The OPO utilizes two type II, 51° cut, 5 mm $\times$ 5 mm $\times$ 10 mm, walk-off-compensated KTP crystals, which are diffusion bonded. To ensure identical crystallographic orientation of the two crystals, we fabricated them from a large crystal block (approximately 20 mm $\times$ 20 mm $\times$ 20 mm), which was correctly oriented and polished. This technique allowed us to achieve $<$10-arcsec parallelism as well as good flatness of $<\lambda/10$ at 632.8 nm. The block was then cut into two 5 mm $\times$ 5 mm $\times$ 10 mm crystals. Subsequently the crystals were placed in optical contact in a walk-off-compensation configuration[10] in a clean atmosphere (i.e., on a horizontal clean bench). We then subjected the crystal pair to thermal processing at high temperature for several hours to ensure permanent bonding between the two crystals.[12] The entrance and exit surfaces of this monolithic DBWOC KTP OPO were then antireflection (AR) coated for both 1079 and 2000–2300 nm. The DBWOC KTP

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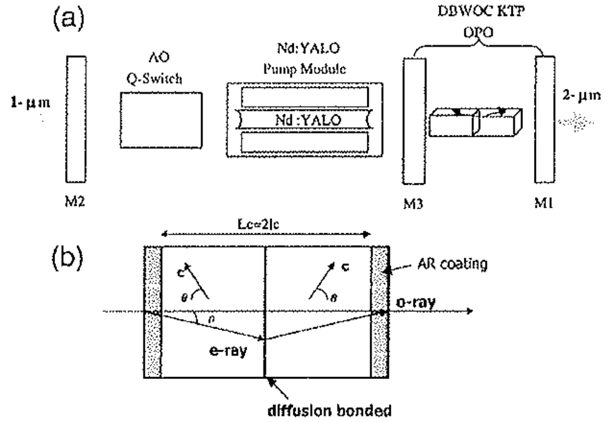

Fig. 1. (a) Experimental setup of the intracavity DBWOC KTP OPO within a diode-pumped Nd:YALO laser and (b) the DBWOC KTP, where c is the optical axis of the crystal, ρ is the walk-off angle of the e ray, θ is the phase-matching angle, l_c is the length of one KTP crystal, and L_c is the total length of the diffusion-bonded KTP crystals. See text for other definitions.

crystal was mounted on a water-cooled heat sink with indium thermal contacts and placed within the OPO cavity formed by mirrors M1 and M3. M3 is antireflection coated at 1 μm and highly reflective ($R > 99\%$) at 2 μm. Besides acting as the rear mirror for the laser cavity, M1 also serves as the output coupler for the OPO. We experimented with mirrors with $R = 60-75\%$ at 2 μm for M1. The distance between the surface of the laser rod and M2 was 11 cm, and the distance between the other surface of the laser rod and M1 was 11.5 cm. All mirrors used in the experiment were flat. The stable laser-cavity mode was derived from the thermal lensing induced in the strongly pumped Nd:YALO rod, with its two concave end faces. The KTP OPO cavity was 2.5 cm long and placed as near as possible to M1, which was the position of the laser beam waist. The laser beam at this position was elliptical, with estimated diameters of 2.3 mm (horizontal) and 3.4 mm (vertical). We also positioned an acousto-optic (AO) Q switch (NEOS Technology Model 33027-50-5-I) as near to M2 as possible to hold off at high laser gain.

The Nd:YALO pumping module consisted of a b-axis- (P_{bmn}-)cut, 4-mm-diameter by 97-mm-long water-cooled Nd:YALO rod side pumped by five close-coupled cw diode arrays.[11] Its end surfaces were curved (radius of curvature, -0.3 m). The rod was aligned with its c axis parallel to the vertical axis. The output of this 1079-nm laser was polarized along the c axis. The maximum diode-pumping power available was approximately 570 W. Without the KTP crystal and M3, the highest 1079-nm output power at 6.22 kHz was 67 W for Q-switched operation. The output power was obtained with $R = 80\%$ at 1079 nm for M2, and the cw output power was ~100 W. When we placed the KTP crystal and M3 inside the laser cavity without the OPO functioning (by changing M1 to a mirror that is highly reflective for 1 μm and antireflective for 2 μm), the 1079-nm output power decreased slightly to 62 W at 6.22 kHz. This result shows that our DBWOC KTP intracavity OPO does not introduce much optical loss.

The bonded KTP crystals were placed inside the Nd:YALO laser cavity with its walk-off plane perpendicular to the c axis of the Nd:YALO rod. We operated the 2-μm OPO with different M1 reflectivities (60%, 70%, and 75% at 2 μm) and achieved the highest 2-μm average output power (both signal and idler) of 21.4 W at 6.22 kHz with $R = 70\%$ at 2 μm. The exact wavelengths of the signal and idler waves were measured to be 2153 and 2166 nm, respectively, and were reasonably close to the degenerate wavelength of 2158 nm. It is worthwhile to highlight the subtle advantage of pumping with a Nd:YALO laser, as compared with Nd:YAG, which shifts the degenerate point farther from the 2-μm absorption edge of $ZnGeP_2$, if one intends to use this 2-μm OPO output subsequently to pump a $ZnGeP_2$ OPO. The measured FWHM linewidths for both the signal and the idler waves were ~6 nm. This result is comparable with what was observed with a single KTP crystal OPO (4 nm to ~10 nm),[3] which clearly indicates the precision of cutting and polishing when the crystals were bound together. All these wavelength results were measured with an Oriel Model MS 257 monochromator.

Figure 2 shows the 2-μm output power versus the diode-pumping power for various 2-μm reflectivities of M1. The maximum 2-μm average OPO power obtained is 21.4 W, with 21.5 W of 1-μm power coming from the laser output coupler, M2 ($R = 95\%$ at 1 μm), when the diode-pumping power is 570 W. This result was obtained when the laser was Q switched at 6.22 kHz and with $R = 70\%$ at 2 μm for M1. Even without locking in the full laser intensity inside the laser cavity, we demonstrated an OPO efficiency of 35% with respect to the maximum achievable 62 W of 1-μm power from this laser (at this particular repetition rate). When the repetition frequency was varied from 3.5 to 8 kHz, the 2-μm OPO power peaked at 6.22 kHz and stayed above 16 W for this entire frequency range. We observed that the OPO threshold almost coincides with the laser threshold. Moreover,

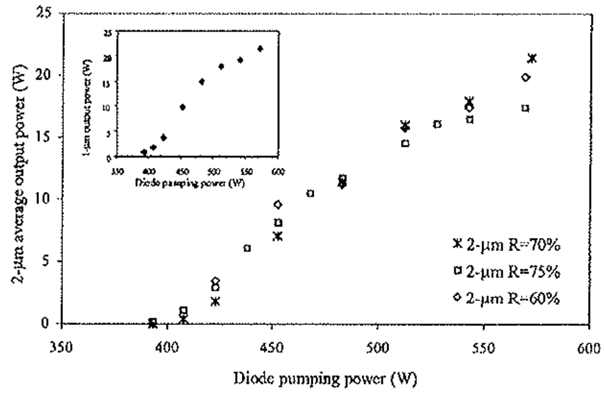

Fig. 2. 2-μm OPO output power versus diode-pumping power at 6.22 kHz for various M1 reflectivities. Inset, 1-μm power coming from M2 versus diode-pumping power when the OPO is operating with M1 reflectivity $R = 70\%$ at 2 μm.

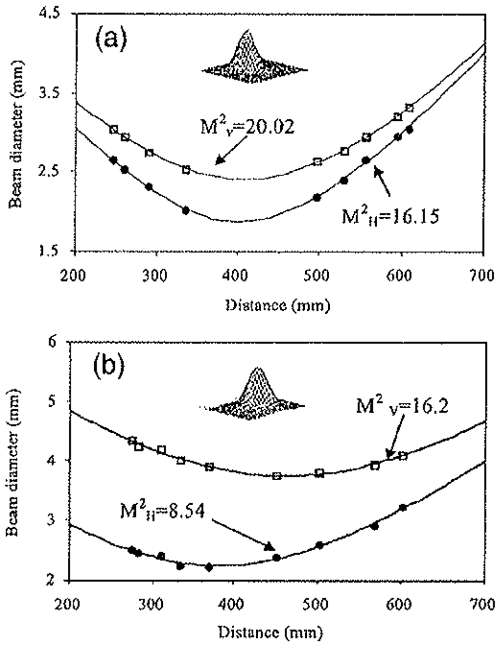

Fig. 3. M^2 measurements of the (a) 1-μm Nd:YALO laser and (b) 2-μm OPO output. Insets, three-dimensional beam profiles of the (a) 1-μm and (b) 2-μm output.

the 2-μm output is much more stable than in a previous experiment,[4] and we did not observe any long-term drift after more than 1 h of operation.

Measurements of the 1- and 2-μm pulse widths were carried out with a fast Oriel InGaAs detector and a HgCdZnTe detector, respectively. At the highest 2-μm OPO power, the pulse widths (FWHM) of the 2- and the 1-μm laser pulses were approximately 73.5 and 80.1 ns, respectively. We also measured the M^2 values for both 1- and 2-μm output (at a 2-μm OPO power of 21.4 W), as shown in Fig. 3. We did this by focusing the beams with an $f = 20$ cm lens, sampling the second-moment diameters along various positions with a Spiricon Beam Analyzer (Model LBA-300PC), and then fitting these data with the standard beam-propagation equation. The M^2 values for 2 μm were 16.2 (vertical) and 8.54 (horizontal), and the M^2 values for 1 μm were 20.02 (vertical) and 16.15 (horizontal). A better M^2 for 2 μm in the horizontal axis is expected because of the more-stringent phase-matching requirement in the walk-off plane. The better OPO beam quality than laser beam quality indicates that the lower-order laser transverse modes (which have better beam quality) generate the OPO output more efficiently than do the higher-order ones. To support this assertion we also measured the laser beam quality without the OPO operating, and the M^2 values were 17.3 (vertical) and 15.1 (horizontal). The degradation in the laser's beam quality when we operate the OPO is consistent with the idea that the lowest-order laser modes are more efficiently converted to 2-μm radiation.

In conclusion, we have obtained 21.4 W of 2-μm intracavity OPO output, which is, to the best of our knowledge, the highest intracavity OPO power reported. To achieve such high-average-power 2-μm OPO output in a simple and compact laser system we used a diffusion-bonded walk-off-compensated KTP OPO pumped by an anisotropic Nd:YALO laser. Using a Nd:YALO laser to pump OPO itself is new approach that offers good potential for generating a high-power compact tunable laser source. The advantages of this combination of a Nd:YALO laser and an OPO are as follows: (i) Nd:YALO provides a simple configuration for generating high-power linearly polarized laser for pumping an OPO; (ii) the walk-off-compensated twin KTP crystals reduce the aperture effect that is due to Poynting walk-off in critically phase-matched parametric generation and, at the same time, increase the acceptance angle of the nonlinear interaction, resulting in more-efficient OPO conversion; and (iii) the diffusion-bonded configuration of the twin crystals eliminates optical losses at the in–out facets and the need for alignment of the two crystals.

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References

1. E. Cheung, S. Palese, H. Injeyan, C. Hoefer, J. Ho, R. Hilyard, H. Komine, J. Berg, and W. Bosenberg, in *Advanced Solid State Lasers*, M. M. Fejer, H. Injeyan, and U. Keller, eds., Vol. 26 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 1999), p. 358.
2. P. B. Phua, K. S. Lai, R. F. Wu, and T. C. Chong, Opt. Lett. **23**, 1262 (1998).
3. P. B. Phua, K. S. Lai, R. Wu, and T. C. Chong, Appl. Opt. **38**, 563 (1998).
4. P. B. Phua, K. S. Lai, and R. Wu, Appl. Opt. **39**, 1435 (2000).
5. R. F. Wu, P. B. Phua, and K. S. Lai, in *Advanced Solid State Lasers*, H. Injeyan, U. Keller, and C. Marshall, eds., Vol. 34 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), p. 125.
6. W. R. Bosenberg, W. S. Pelouch, and C. L. Tang, Appl. Phys. Lett. **55**, 1952 (1989).
7. A. V. Smith, D. J. Armstrong, and W. J. Alford, J. Opt. Soc. Am. B **15**, 122 (1998).
8. D. J. Armstrong, W. J. Alford, T. D. Raymond, A. V. Smith, and M. S. Bowers, J. Opt. Soc. Am. B **14**, 460 (1997).
9. J. -J. Zondy, M. Abed, and S. Khodja, J. Opt. Soc. Am. B **11**, 2368 (1994).
10. J. P. Feve, J. J. Zondy, B. Boulanger, R. Bonnenberger, X. Cabirol, B. Menaert, and G. Marnie, Opt. Commun. **161**, 359 (1999).
11. R. Wu, P. B. Phua, and K. S. Lai, Proc. SPIE **3929**, 25 (2000).
12. H. E. Meissner, "Composites made from single crystal substances," U.S. patent 5,441,803 (August 15, 1995).