Efficient periodically poled stoichiometric lithium tantalate optical parametric oscillator for the visible to near-infrared region

Shih-Yu Tu
Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan

A. H. Kung
Institute of Atomic and Molecular Sciences, Academia Sinica, Taipei, Taiwan and Department of Photonics and Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan

Z. D. Gao and S. N. Zhu
National Laboratory of Solid State Microstructures, Naijing University, Nanjing 210093, China

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A compact, efficient optical parametric oscillator (OPO) for the visible to near-infrared region based on periodically poled stoichiometric lithium tantalate pumped by a frequency-doubled multikilohertz Q-switched Nd:YAG laser is demonstrated. Up to 61% photon conversion with a 71% slope efficiency for photon conversion from 532 nm to the signal radiation was measured. We observed that the efficient conversion diminished the potential for photorefractive damage induced by the 532 nm radiation in the crystal and made sustained operation of the OPO device possible. © 2005 Optical Society of America

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Advances in the past decade in the use of electric field poling to fabricate periodically poled quasi-phase-matched ferroelectric crystals and in high-power diode-laser-pumped solid-state lasers have produced efficient and compact all solid-state optical parametric oscillators (OPOs). Yet ferroelectric material is known to be highly susceptible to photorefractive damage and visible-induced infrared absorption so that essentially all of these OPOs have been confined to operating in the infrared region. Reports of near-infrared OPOs using LiNbO3 and LiTaO3 as a gain medium were for low power in the milliwatt level.2–4 The serious problem of refractive damage has limited their subsequent development. Compact high-repetition-rate high-power OPOs broadly tunable in the visible and the near infrared would be a new type of laser source that could augment or replace existing laser sources in this spectral region in linear and nonlinear spectroscopy and other applications. They are still not available.

Recently near-stoichiometric LiTaO3 (SLT) was shown to have high resistance to photorefractive damage and to green-light-induced infrared absorption. In near-stoichiometric LiTaO3 the nonstoichiometric defect is significantly reduced. This leads to a reduction of the coercive field by 1 order of magnitude and an increase of the optical damage threshold by 2–3 orders.5 Hence, periodically poled near-stoichiometric LiTaO3 (PPSLT) has been fabricated and has begun to find applications in efficient second-harmonic generation and sum-frequency mixing to the green and blue region.6–8 In these applications the intensity of the green-blue radiation was kept below the photorefractive damage threshold of 2–3 MW/cm2. There were also reports of using PPSLT in high-average-power infrared-pumped OPOs that showed little or no sign of photorefractive damage.9,10 PPSLT therefore is an excellent candidate for a high-power visible OPO.

In this letter we report what we believe is the first sustained and efficient operation of a 532 nm pumped singly resonant PPSLT OPO, generating multikilohertz nanosecond light that can be tuned from the visible to the near infrared. With 1.0 W of average input power we obtained up to 370 mW of signal power and 120 mW of idler power for a 61.3% photon conversion efficiency and a 71% slope efficiency at 708 nm. The OPO uses an antireflection-coated bulk PPSLT crystal operating at elevated temperatures as the gain medium and uses a short cavity length to maximize the output power and photon conversion. Although photorefractive effects appeared in a test crystal at the intensities used, they have little or no effect on the performance of the OPO as long as the OPO oscillates well above threshold. We found that efficient conversion of the 532 nm power to the longer-wavelength signal and idler radiation depleted the intensity of the green beam inside the PPSLT crystal, allowing the OPO to function for months without green-induced damage up to the date of this report.

The PPSLT crystal was fabricated from a wafer obtained from the Oxide Corporation and was 20 mm long, 8 mm wide, and 0.83 mm thick. Inverted domains were poled by the conventional electrical poling technique.11 A total of seven sections with grating periods from 8 to 11 μm in 0.5 μm increments were fabricated in a single crystal. Figure 1 is a scanning electron microscope micrograph of the etched domain inverted patterns on the +C surface. The figure shows that the inverted domain distribution is uniform, and the duty cycle is close to the optimal value of 50%. The width of each poled section was 1 mm. The end faces of the crystal were antireflection...
coated for 532 nm (<1.5%) and from 640 nm to >2000 nm (<2.5%).

A Lightwave Electronics Model M210S diode-laser-pumped Q-switched Nd: YAG laser was used as the pump laser. The 1064 nm output was converted to the second harmonic in a type II KTP crystal, yielding 1.0 W of 532 nm radiation at a 3.5 kHz repetition rate. The pulse duration was 19 ns. The TEM$_{00}$ laser beam was focused to a Gaussian waist size of 135 μm at the center of the PPSLT crystal to provide a maximum intensity of 58 MW/cm$^2$. The crystal was embedded in an oven whose temperature was controlled to ±0.1°C. The 532 nm power transmitted through the PPSLT crystal was uniform at 88±1% up to the maximum intensity. The 12% transmission loss can be accounted for by Fresnel reflections (3%), internal absorption$^4$ (4%), and scattering and diffraction losses$^{12}$ through the long and narrow crystal channel (5%).

We first used the optical cavity shown in Fig. 2 to test for OPO action. It consisted of a flat high-reflecting silver mirror ($R>99.5\%$) and a flat SLT wafer output coupler. The spacing between the mirrors was 7 cm. The 532 nm beam was directed into the cavity at a right angle by a dichroic mirror coated for >99% reflection at 532 nm and >96% transmission for wavelengths longer than 633 nm. The uncoated SLT wafer has a reflectivity of 13% per surface that is nearly flat across the visible and near-infrared region. This low-Q cavity was hence useful for measuring the tuning characteristics of the OPO. A slight wedge on the SLT wafer kept it from being an étalon in the cavity. Oscillation in the cavity was singly resonant, favoring the signal because of the lower diffraction loss associated with the signal’s shorter wavelength compared with that of the idler. The output wavelength was determined with an optical spectrum analyzer (Agilent Model 86142B).

When the PPSLT crystal was at room temperature and the incident peak intensity was above 2 MW/cm$^2$, we observed effects of photorefractive, causing spatial distortion of the transmitted input beam. The degree of distortion reduced with increasing crystal temperature. Therefore we began with the PPSLT at 200°C and used the crystal section that has a 10.5 μm grating period. Under these conditions output appeared as an intense beam with a deep red color (∼665 nm) beginning at an incident pump intensity of ∼30 MW/cm$^2$. We found that stable oscillation could be sustained for every grating period when the crystal temperature was above 130°C. Below 130°C, the threshold increased rapidly. Below 90°C, photorefractive distorted the pump beam to an oblong shape and the OPO stopped oscillating. For this reason, all measurements were made above 130°C.

Output wavelengths were determined at an input intensity of 55 MW/cm$^2$, about 2–3 times above threshold, depending on the grating period. Figure 3 shows the measured output wavelengths for the temperatures of 130°C and 200°C. Tuning from 648 to 940 nm and from 1230 to 2980 nm was possible. As can be seen, there are gaps in the tuning curve that the present crystal could not reach. A crystal with grating periods spaced closer to one another would make up for this deficiency. Also shown are the calculated tuning curves. We used the published temperature-dependent Sellmeier equation for SLT to calculate the quasi-phase-matching curves$^{13}$ The temperature discrepancy of ∼10°C–15°C between the calculated and the measured values is slightly

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**Fig. 1.** Scanning electron microscope micrograph of etched domain-inverted patterns on the +C surface of the PPSLT in the region with a 11.0 μm grating period.

**Fig. 2.** Flat–flat cavity with dichroic mirror inside the cavity, designed for broad tuning operation.

**Fig. 3.** OPO tuning versus PPSLT crystal grating period, measured data (circles and crosses) and calculated tuning curve (solid curve) for a 532.3 nm pumped PPSLT OPO at the temperatures shown. Idler wavelengths above 1700 nm were inferred from the corresponding signal wavelengths. Inset, photon conversion efficiency obtained versus wavelength with the grating periods at 200°C.
more than that reported for LiTaO$_3$. Even with this low-$Q$ cavity, the photon conversion achieved was a respectable $\sim 30 \pm 10\%$ (inset, Fig. 3). The variation in conversion efficiency shown is mostly due to variations in the uniformity of the grating periods in the crystal.

Having demonstrated OPO action with this PPSLT crystal, we next constructed a cavity with an aim to maximize the conversion efficiency. We used a short flat–flat cavity consisting of an input mirror that has $99\%$ transmission $T$ at 532 nm and $99.5\%$ reflection $R$ from 660 to 760 nm, which was $>90\%$ transmitting for the idler wavelengths, and an output coupler that is $50\% \pm 5\%$ reflecting from 650 nm to 800 nm. The cavity length was 35 mm. All powers were measured with a calibrated thermopile detector. The measurements showed that the average signal and idler powers vary linearly with the average above threshold input power. This is exemplified in Fig. 4 by a power dependence plot of the signal at 708.3 nm (forward direction) and idler at 2141 nm (forward and backward sum). At these wavelengths the oscillation threshold was at 257 mW. The maximum signal and idler output power obtained of 370 and 120 mW, respectively, were limited by the available input of 1.0 W. The power conversion slope efficiencies are $53.5\%$ and $15.6\%$ for the signal and the idler, respectively. The corresponding pump-to-signal photon conversion slope efficiency is $71\%$. This high performance is replicated at essentially every other wavelength; see the inset in Fig. 4. In the inset, a different set of mirrors (output $R=75\% \pm 2\%$ and input $R=\sim 99\%$ 800–900 nm, $T>90\%$ at all other wavelengths) was employed for 800–900 nm. Output power stability, monitored for over several hours, was $\pm 1.8\%$ (1 standard deviation) for all wavelengths measured. The FWHM linewidth of the signal output was $\sim 0.2$ nm from 650 to 800 nm and then increased gradually to 1 nm at 900 nm as the wavelength moved toward degeneracy at 1064 nm. The output beam had a divergence of $\sim 5.4$ mrad and an $M^2$ of 1.5, which is reasonable for a flat–flat cavity. Beam pointing stability was better than 99%.

In the experiment we found that a slight amount of photorefractive pump beam distortion still existed at high temperatures when the OPO was not oscillating. However, once the OPO oscillated at $\geq 2$ times above threshold, the photorefractive distortion disappeared. Both the output beam and the residual green beam were stable in power and in pointing direction. We believe that this is the result of a substantial reduction of the green light intensity to below the damage level once the OPO operated at a state that has high photon conversion. These results indicate that reliable and efficient operation of a high-power green-pumped OPO based on PPSLT is feasible. The need to operate at an elevated temperature may be alleviated by using MgO-doped PPSLT. With further development it could become a powerful light source for the visible and near-infrared region.

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