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Test results for 320 nm and 390 nm remote sensing sources using a 150 mJ, 100 Hz repetition rate, injection-seeded diode-pumped Nd:YAG slab-laser developed by Coherent Technologies, Inc.

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developed by Coherent Technologies, Inc.**

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Abstract

This report describes results of tests using a laser system designed by Coherent Technologies, Inc., in conjunction with Sandia developed nonlinear optics technology. Test results are described for three different optical parametric oscillators built at Sandia. The report concludes with recommendations for future work.

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1 Introduction

The airborne remote sensing program at Sandia National Laboratories is evaluating the feasibility of deploying an airborne remote sensing platform that contains multiple UV light sources pumped by the harmonics of Nd:YAG that deliver pulse energies ≤ 40 mJ. The light sources under consideration are based on intra-cavity sum-frequency generation (SFG) and intra-cavity frequency doubling in optical parametric oscillators (OPO's) that use Sandia's image-rotating RISTRA cavity, where RISTRA denotes rotated image singly-resonant twisted rectangle [1]. A pulse repetition rate of 100–400 Hz is desired for this platform, however an impediment to deployment is the lack of a suitable pump laser. Lasers produced by the vendors of conventional research-grade commercial Nd:YAG systems don't meet the beam-quality, spectral purity, and pulse-energy requirements for pumping the UV-generating OPO's at these high repetition rates. In addition, most laser systems with adequate average power can't meet the packaging requirements to operate in the restricted volume of an airborne platform, especially with limited electrical power. One fundamental reason for the difficulties encountered in deploying a high average power laser system in a small package is inadequate extraction of heat from the laser gain medium.

To address the issues of thermal management in high average power laser systems, Coherent Technologies, Inc., (CTI) in Louisville, CO, has developed 150 - 200 mJ, 100 - 400 Hz repletion-rate, injection-seeded diode-pumped Nd:YAG slab-lasers that employ a proprietary heat extraction technology. When modified for airborne deployment, these lasers might meet the needs of the Sandia's remote sensing program. To assess their suitability, one of these lasers was tested over a two-week period during September 2005 at CTI using an optical breadboard prepared by Darrell Armstrong of Org. 1128 at Sandia National Laboratories. Laser preparation and experimental assistance at CTI was provided by Senior Scientist Larry Rubin and Research Engineer Neil Vanasse, with additional assistance and advice on Pound-Drever-Hall (PDH) stabilization by Bruce Tiemann.

2 Description of the optical breadboard

The breadboard was configured to test three different cw injection seeded OPO's, all pumped by the 532 nm second harmonic of Nd:YAG: a conventional two-crystal RISTRA resonating an 803 nm signal; a signal-resonant intra-cavity SFG RISTRA that summed the 803 nm signal with the 532 nm pump to generate 320 nm; and a signal-resonant intra-cavity frequency-doubled RISTRA that generated 390 nm from the second harmonic (2ω) of the 780 nm signal. All three OPO's used the crystal KTP to generate their signal and idler wavelengths, while the crystal BBO was used for sum-frequency mixing and 2ω generation. New Focus Vortex grating-tuned-diode lasers injection-seeded the OPO's, with one at 803 nm and one at 780 nm. Wavelengths of the Vortex lasers were locked to cavity fringes of the OPO's using a simple PDH frequency stabilization system. Additional details about the conventional and intra-cavity SFG OPO's can be found in Refs. [2, 3, 4]. Details of the design of the 390 nm OPO have not been published.

Video cameras and high-speed detectors on the breadboard monitored spatial and temporal properties of the pump beam and the OPO's signal or UV beams. One video camera monitored the pump spatial fluence profile at the OPO's input coupler (Cohu 4800), while the OPO signal or UV far-field fluence profiles were recorded by an externally-triggered, electronically-shuttered, 10-bit digital progressive scan camera (Cohu 6612-3000) that was synched to acquire sequences of individual profiles at a rate of 20–25 Hz. A second Cohu 4800 camera aided initial OPO seed-beam alignment, while a third was used in a simple grating spectrometer for angle tuning the KTP crystals to locate $\Delta k = 0$ with respect to the seed wavelength. All high-speed detectors were Hamamatsu 1328U vacuum photodiodes with bandwidths of approximately 5 GHz. These detectors monitored the input pump, depleted pump, OPO signal, and UV pulses. Data acquisition for the high-speed detectors was accomplished using a 1.5 GHz Tektronix TDS 7154B digital phosphor oscilloscope (DPO).

3 Results and discussion

Brief summaries of the performance of the pump laser, 1046 nm $\rightarrow$ 532 nm frequency-doubling LBO crystal, and OPO's used in the tests at CTI are given below.

3.1 Pump laser

The pump laser at CTI was not fully operational at the beginning of the two week test period. This was largely due to complications with its injection seeding system. The intermittent single-frequency operation and associated shot-to-shot fluctuations in pump bandwidth and pulse arrival time made reliable tests of the OPO's difficult. Furthermore, pump-beam pointing instability, which may have been related to unstable injection seeding, also diminished performance of the OPO's. Additional complications were initially encountered when the high-aspect ratio rectangular-shaped near-field spatial profile of the the pump beam was imaged near the 2ω crystal on the optical breadboard. After several iterations, a suitable solution was found for imaging the pump beam, however as shown in Fig. 1 the resulting spatial profile consisted of an approximately square ring with some "hot spots" surrounding a central region of near zero fluence. This spatial profile was far from ideal for pumping the OPO's. However, overlooking these shortcomings, access to CTI's laser did provide useful information about operating Sandia's OPO's at 100 Hz repetition rates, when their nominal operation rate is 10 Hz. Throughout the two week period, injection seeding remained problematic, making tests of the 320 nm intra-cavity SFG OPO especially difficult. Limited, but useful results at 100 Hz were obtained for the other two OPO's.

3.2 Lithium triborate frequency doubling crystal

The optical breadboard was configured to use a $10 \times 10 \times 25$ mm³ non-critically phase-matched temperature-stabilized lithium triborate (LBO) crystal supplied by Super Optronics for frequency doubling the Nd:YAG pump laser. Although phase-matching in LBO is highly temperature sensitive, it was selected over other crystals such as KTP because of the possibility of photorefractive damage due to the high average power at 100–400 Hz. During preliminary tests at Sandia the 2ω conversion efficiency for the LBO crystal was lower than expected, slightly exceeding 50%. During the tests at CTI the efficiency was much lower at 10–12%, with 532 nm pulse energy barely sufficient to pump the OPO's. Consequently the LBO crystal was replaced by a $10 \times 10 \times 9$ mm³ *xy*-cut KTP crystal supplied by ITI Electro-Optics. A quick measurement revealed the 2ω conversion efficiency with KTP was $> 50\%$ and no damage or "grey-tracking" in the KTP was observed during the experiments. The reason for the poor performance of LBO after the breadboard was installed at CTI has not been determined, but may be due to nonuniform heating of the crystal within the oven supplied by Super Optronics. An improved oven design might improve the LBO 2ω conversion efficiency.

Figure 1. Example of spatial fluence profile of the 532 nm pump beam viewed at the OPO input coupler on the optical breadboard. This profile was recorded using a Cohu 6612-3000 10-bit digital camera that was electronically-shuttered and synched to capture a single pump pulse.

3.3 Two-crystal KTP RISTRA OPO

Although Sandia’s remote sensing program requires UV wavelengths, a conventional cw-injection seeded two-crystal KTP RISTRA OPO with signal output at 803 nm was tested to provide a “baseline” for OPO performance using the CTI laser. Figure 2(a) shows an efficiency curve of signal energy versus pump energy for injection seeded oscillation. The maximum signal energy is ~ 8.5 mJ for ~ 37 mJ of pump, which corresponds to about 34% pump depletion. When pumped by a beam having a flatter spatial fluence profile, this OPO should achieve approximately 50% pump depletion.

While efficiency was low, the far-field spatial fluence profile in Fig. 2(b) illustrates the beam clean-up effects of an image-rotating cavity, and suggests that less than optimum pump-beam quality is acceptable for pure OPO operation. This fluence profile is one of a sequence of 100 recorded with the Cohu 6612 digital camera when the pump energy was approximately three times the oscillation threshold. Centroid analysis of these profiles indicates the rms pointing stability of the OPO signal beam is $\leq 4 \mu\text{r}$ in the vertical and horizontal directions. Pointing stability $\leq 2.5 \mu\text{r}$ has been previously measured for this OPO when pulse injection seeded and pumped by a flat-top beam with a diameter of 6 mm.

Because heating effects associated with the higher average power of 100–400 Hz operation are

always a concern, several sequences of 100 far-field spatial fluence profiles were recorded after the OPO was allowed to cool for several minutes. For all the sequences the pump fluence was at least three times the oscillation threshold. Observation of these sequences of profiles revealed no obvious absorption-induced crystal heating effects in the KTP OPO.

Figure 2. 803 nm signal energy versus 532 nm pump energy for the two-crystal KTP OPO with injection seeding for single-frequency oscillation. (b) The 803 nm far field spatial fluence profile when the pump energy was approximately three times the oscillation threshold.

3.4 390 nm intra-cavity doubled RISTRA OPO

Given the non-ideal pump beam spatial profile, the 390 nm intra-cavity 2ω RISTRA OPO performed reasonably well, however Sandia has no data from previous tests available for comparison. Doubling efficiency appears to be low, as shown by the curve of 390 nm energy versus pump energy in Fig. 3, but this may be partially due to broadband oscillation, as the injection seeding apparatus for the 780 nm signal was performing poorly. However, the far-field spatial fluence profiles in Figs. 4(a)–(c) suggest frequency doubling within an image-rotating OPO cavity is relatively insensitive to pump beam quality, as expected, because 2ω mixing involves the only OPO signal. Note that the asymmetric far-field fluence profiles for the 390 nm beam likely originate from angle-critical phase-matching in the BBO 2ω crystal, and not from asymmetry of the 780 nm cavity mode. Centroid analysis of a sequence of 100 of these far-field profiles with the pump energy two times threshold indicates rms pointing stability of $\leq 37 \mu\text{r}$ in the horizontal direction and $\leq 19 \mu\text{r}$ in the vertical direction. At three times threshold, the far-field profile in Fig. 4(c) can be

seen to fluctuate shot-to-shot, leading to reduced pointing stability in the vertical direction, with vertical and horizontal rms values of $\leq 79 \mu\text{r}$ and $\leq 15 \mu\text{r}$, respectively.

In principle there should be little or no heating in the intra-cavity 2ω crystal for $780 \text{ nm} \rightarrow 390 \text{ nm}$ because the band edge in BBO corresponds to the energy of a single photon at $\sim 170 \text{ nm}$, and the energy of two 390 nm photon falls short of this value. Nonetheless, it is prudent to test for heating effects in the BBO crystal. Using the same procedure described for the 803 nm OPO, there was no evidence of heating induced by two-photon absorption. However, the OPO was running broadband, where phase front distortion and nonuniform Δk may be less obvious than for single-frequency oscillation.

Figure 3. Broadband 390 nm intra-cavity 2ω energy versus 532 nm pump energy for the $780 \text{ nm} \rightarrow 390 \text{ nm}$ intra-cavity doubled OPO. Injection seeding at 780 nm was unstable due to a (unknown at the time) problem with optical feedback into the New Focus Vortex laser.

3.5 320 nm intra-cavity SFG RISTRA OPO

Unreliable injection seeding of the pump laser, combined with its square-ring-like spatial fluence profile, made testing the 320 nm intra-cavity SFG RISTRA OPO difficult at best. The only data recorded for this OPO were temporal profiles for the signal, depleted pump, and uv pulses, and far-field spatial fluence profiles for the UV beam shown in Fig. 5. The UV pulse energy for the profiles in Fig. 5 was only $1\text{--}2 \text{ mJ}$ and the pump energy was perhaps two times the oscillation threshold. Because this OPO performed so poorly, no attempt was made to record the 532 nm

Figure 4. Broadband 390 nm far field spatial fluence profiles with the pump energy near the oscillation threshold, two times threshold, and three times threshold.

to UV conversion efficiency. Comparing the far-field fluence of Fig. 5 to the intra-cavity 2ω fluence in Fig. 4 for emphasizes the susceptibility of intra-cavity SFG to the spatial and temporal characteristics of the pump beam. Intra-cavity 2ω involves *only* the high-quality signal wave resonated within the OPO cavity. In contrast, intra-cavity SFG requires the cavity mode and the pump, and it results in poor UV beam quality. While the poor 320 nm beam quality can be largely attributed to the pump beam, heating in the BBO crystal due to two-photon absorption may play a role as well. Because the far-field UV fluence was so unstable, there was no attempt to measure heating effects.

When the OPO was injection seeded, and the pump energy was approximately two times the seeded threshold, shot-to-shot signal and UV energy-stability for the intra-cavity SFG OPO was very poor. Integration and subsequent statistical analysis of 500 OPO signal- and UV-pulse temporal profiles that were recorded using the Tektronix TDS 7154B DPO indicated rms energy fluctuations of 42% and 45%, respectively. Signal and UV energies fluctuations were well correlated, with a coefficient 0.96. Pump beam pointing stability may be suspect given the 532 nm mixing-acceptance-angle of 0.39 mrad·cm for $803(e) + 532(o) \rightarrow 320(e)$ in BBO. However, the strong correlation of signal and UV energy fluctuations, along with acceptance angles in the KTP OPO crystal that are at least twice that of BBO, suggest an additional effect such as pump bandwidth. Unfortunately, a sequence of far-field spatial fluence profiles for the pump beam was not recorded. The rms pointing fluctuations from centroid analysis of those data would have helped identify the source of the UV and signal energy fluctuations.

Figure 5. Three examples of the 320 nm far field fluence for the intra-cavity SFG OPO with the OPO injection seeded for single-frequency oscillation at 803 nm. Pump laser oscillation was single frequency $\geq 70\%$ of the time with intermittent broadband pulses. The pump energy was approximately two times the oscillation threshold and the UV energy was only 1–2 mJ.

4 Recommendations for future work

Although in present configuration the CTI Nd:YAG pump laser fell short of expectations, it could serve as good starting point for a design better suited to pumping OPO's. A laser using the same heat extraction technology, but with the cavity redesigned to generate a more "filled in" beam, and having a lower aspect ratio, could serve as the starting point for development of a laser for Sandia's airborne platform. The OPO's could also be modified to generate UV with less susceptibility to pump beam quality, and less susceptibility to thermal effects due to two-photon absorption.

4.1 Numerical evaluation of a redesigned pump laser

The first step in any future work would be numerical modeling to determine the feasibility of using CTI's slab laser designs to obtain a more spatially flat, and more spatially filled-in beam profile having a lower aspect ratio than the current design. Overall the performance of the pump laser fell short of expectations due to intermittent single-frequency operation, pointing instability, and the ring-like spatial fluence profile. Near-field imaging of the high aspect ratio oscillator may have been problematic as well because the mostly one-dimensional linear magnification appears to enhance spatial fluence non-uniformity.

Despite seeding and imaging problems, an important feature of this laser is its potential for good beam quality. Real-time monitoring of the pump-beam phase front using a filtered Mach-Zehnder interferometer demonstrated that CTI's proprietary thermal extraction technology works well, as the Mach-Zehnder fringes indicate the phase front is nearly free of aberration. Ignoring inadequate preparation of the laser prior to the tests of Sandia's OPO's, a new design incorporating the same thermal management could result in a suitable laser for Sandia's airborne platform. However, experimental verification of CTI's existing laser models would be required to justify any further numerical modeling effort.

4.2 Replace BBO with LBO for intra-cavity mixing in the OPO's

The temperature dependence of the indexes of refraction of BBO can lead to phase front distortion and non-uniform phase mismatch Δk across the beam profiles. And unfortunately wavelengths shorter than approximately 340 nm are known to heat BBO by two-photon absorption. The 10–40 mJ UV pulses at repetition rates of 100–400 Hz required by Sandia's airborne platform will almost certainly heat the 320 nm intra-cavity SFG BBO crystal beyond the operational range of approximately 10 K-cm. The 390 nm intra-cavity 2ω crystal may be susceptible to heating as well. Although it was not reported in the literature, measurements at Sandia that generated 140–160 mJ 320 nm pulses at 10 Hz using intra-cavity SFG clearly demonstrated the effects of heating in BBO.

LBO has lower two-photon absorption than BBO, so it probably offers a good alternative for intra-cavity mixing. Furthermore, data obtained from the SNLO software package show that the internal phase-matching angle of LBO exhibits regions of very low temperature dependence for

temperatures that could be practical in a well engineered device. Plots of the temperature dependence of the difference in internal angle, referenced to the internal angle at 273 K, are shown in Figs. 6(a) and (b) for intra-cavity SFG where $803(e) + 532(o) \rightarrow 320(e)$. Replacing BBO with LBO would require new cavity mirrors and intra-cavity $\lambda/2$ plates for the 320 nm OPO.

Figure 6. (a) Difference in internal phase-matching angle in degrees, referenced to the internal angle at 273 K, versus temperature in K for SFG with $532(o) + 803(o) \rightarrow 320(e)$ in LBO. (b) Same as (a), but over a smaller temperature range and plotted in mr vs °F.

4.3 Investigate alternative OPO pump-beam wavelengths

Given the poor beam quality for the 320 nm intra-cavity SFG OPO and the relatively good beam quality of the 390 nm intra-cavity 2ω OPO, it may be reasonable to generate 320 nm light by intra-cavity 2ω as well. This could be achieved by configuring both OPO's for intra-cavity 2ω and pumping both OPO's with Nd:YAG 3ω at 355 nm. Sandia's airborne platform already uses 355 nm light for initial interrogation, with 320 nm and 390 nm proposed as secondary wavelengths for enhanced spectroscopic discrimination. 355 nm pumped intra-cavity 2ω can be achieved in both OPO's several different ways, depending on the choice of crystals. Two-photon absorption in BBO at 355 nm may pose a problem for 100–400 Hz repetition rates, however commercial vendors have sold 10–30 Hz 355 nm pumped type-I BBO OPO's for many years without serious problems. Note that thorough numerical modeling of OPO performance would be required to determine the feasibility of this approach, so for now we'll just list some of its potential benefits and drawbacks.

Potential benefits:

UV derived from RISTRA cavity mode alone – no mixing with pump beam. Susceptibility to pump-beam quality is much lower for intra-cavity 2ω compared to intra-cavity SFG.

Simpler airborne platform design? The initial interrogation wavelength and OPO pump wavelength would be 355 nm.

Potential drawbacks:

3ω generation required for pumping the OPO's may require more pump power.

Potentially greater risk of optical damage from 355 nm pump beam could lead to lower system reliability.

Type-II mixing is required to fully take advantage of image rotation in the RISTRA cavity. For 355-pumped type-II mixing in BBO, d_{eff} is smaller than for 532-pumped type-II mixing in KTP. The increase in field gain coefficient achieved by decreasing the pump wavelength to 355 nm only partially compensates for the smaller d_{eff} of BBO

Temperature sensitivity/incompatibility of BBO and LBO? 355 nm pumping will require that BBO and LBO be placed inside the same temperature-controlled OPO cavity for generation of 320 nm, but simultaneous temperature dependent phase-matching in both may become problematic at elevated temperatures. For 532 nm pumping, phase matching in KTP is relatively temperature insensitive and is not expected to pose serious problems when operated at slightly elevated temperatures, although this assumption has not been tested in the lab. We have not yet build a temperature controlled RISTRA cavity containing a KTP OPO crystal plus an LBO intra-cavity SFG crystal.

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