Recent progress made in the development of high-energy UV Transmitter

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Abstract-: In this paper, the status of an all-solid-state UV converter development for ozone sensing applications is discussed. A high energy Nd:YAG laser for pumping the UV converter arrangement was recently reported. The pump is an all-solid-state, single longitudinal mode, and conductively cooled Nd:YAG laser operating at 1064 nm wavelength. Currently, this pump laser provides an output pulse energy of >1J/pulse at 50 Hz PRF and a pulsewidth of 22 ns with an electrical-to-optical system efficiency of greater than 7% and a M^2 value of ~2. The spatial profile of the output beam is a rectangular super Gaussian. This Nd:YAG pump laser has been developed to pump the nonlinear optics based UV converter arrangement to generate 320 nm and 308 nm wavelengths by means of 532 nm wavelength. Previously, this UV converter arrangement has demonstrated IR-to-UV conversion efficiency of 24% using a flash lamp pumped laser providing a round, flat top spatial profile. Recently, the UV converter was assembled and tested at NASA LaRC for pumping with the diode pumped Nd:YAG laser. With current spatial profile, the UV converter was made operational. Current efforts to maximize the nonlinear conversion efficiency by refining its spatial profile to match RISTRA OPO requirements are progressing.

I. INTRODUCTION

NASA is actively engaged in the development of space-based active remote sensing missions using lidar techniques. To develop reliable and robust laser based lidar systems, NASA began the Laser Risk Reduction Program (LRRP) in 2002 [1]. Jointly run by Langley Research center (LaRC) and Goddard Space Flight Center, the LRRP is designed to advance laser performances as well as to mitigate associated risks in critical components such as pump diodes for remote sensing applications from space based platforms. The technical objective of LRRP is to develop high-energy, solid-state, conductively cooled and single longitudinal mode 1 micron and 2 micron lasers and appropriate wavelength conversion technologies suitable for four lidar techniques namely altimetry, Doppler, Differential Absorption Lidar (DIAL), and basic backscatter signal strength profiling. These four techniques would enable six priority earth science measurements of surface and ice mapping, horizontal vector wind profiling, river currents monitoring, carbon dioxide (CO_2) profiling, ozone (O_3) profiling, and aerosols/clouds monitoring. The overall goal of LRRP is to advance laser technologies to the point that science mission proposals could be confident of acceptable risk upon selection.

For ozone profiling, efficient 1-micron to UV wavelength conversion technology to generate tunable, pulsed UV wavelengths of 308 nm and 320 nm is being pursued. Accordingly, the Nd:YAG laser has been developed to pump a nonlinear optics based UV converter arrangement to generate 320 nm and 308 nm wavelengths by means of 532 nm wavelength. The 532 nm wavelength is obtained from the 1064 nm wavelength using a LBO crystal via second harmonic generation process. The nonlinear optics arrangement consists of a novel optical parametric oscillator (OPO), known as Rotated Image Singly Resonant Twisted Rectangle (RISTRA) module and a sum frequency generation unit. This high energy low repetition rate UV transmitter is being developed for atmospheric ozone profiling using differential absorption lidar (DIAL) technique suitable for space-based platforms.

Modeling and simulation studies have indicated the requirement of high pulse energy of >200 mJ with low pulse repetition rates at UV wavelengths to achieve enhanced performance during strong daylight conditions from a space based platform. The viability of a relatively efficient scheme involving a Nd:YAG pump laser operating at 1064 nm and the nonlinear optics based arrangement comprising of an optical parametric oscillator (OPO) and a sum frequency generator (SFG) to obtain >200 mJ/pulse at UV wavelengths has been established under laboratory conditions. The RISTRA configuration has demonstrated to provide enhanced output beam quality. So far, the RISTRA OPO has demonstrated ~90% pump depletion and subsequently, up to 24% optical conversion efficiency with stable mode quality at Sandia National Laboratory [2-4]. For these experiments, a flash lamp pumped Nd:YAG laser that had a top hat spatial profile was used.

The goal of the ongoing LRRP is to pump the UV converter arrangement with an all solid-state 1 micron pump laser. Hence, the diode pumped Nd:YAG laser development was pursued in parallel to the development of UV converter technology [5]. For flight worthy and space-qualifiable systems, all solid-state, conductively cooled, and compact design configuration is vital [6,7].

The technical approach for the development of a reliable, robust and efficient diode-pumped Nd:YAG pump laser is based on an oscillator/amplifier design configuration. The diode pumping increases efficiency and reduces size and weight. The other important features of the all solid-state pump laser are as follows: (a) injection seeded ring laser that improves emission brightness (M^2)), (b) diode-pumped zigzag slab amplifiers that allow robust and efficient design for use in space environment, (c) advanced E-O phase modulator material that allows high frequency cavity modulation for improved stability injection seeding, (d) alignment insensitive/boresight stable 1.0 mm cavity and optical bench for achieving stable and reliable operation, (e) conduction cooled operation that eliminates circulating liquids within cavity, and (e) space-qualifiable component designs that establishes a path to a space-based mission. Following this approach, the pump laser was built by upgrading a 300 mJ/pulse and 50 Hz Nd:YAG laser that was developed under NASA’s Advanced Technology Initiative Program (ATIP). This ATIP laser consisted of a ring oscillator that was optimally coupled to two pre-amplifier modules that generated up to 300 mJ/pulse at 50 Hz pump repetition frequency (PRF). Upon upgrading the ATIP laser with two amplifiers, up to 1.2 J/pulse was recently obtained [8-10]. The amplifier design for the system is based on a higher efficiency version of the well developed zigzag slab technology. The configuration for amplifiers 3 and 4 was based on double-sided pumped and cooled head design. The 2-sided pumped Brewster angle slab designs were utilized for amplifiers. The entire laser setup was packaged inside a box. Near-normal incidence simplifies AR coatings and pump on bounce geometry allows high gain fill factor and hence, high slope efficiency. Custom designed turn-key drive electronics conveniently facilitates the laser operation. The output had features of a rectangular super Gaussian spatial profile. Figure 1 shows the laser and Figure 2 illustrates the near-field spatial profile and average power measurement. The next logical step is to effectively integrate the UV converter with the diode pumped Nd:YAG laser to generate 320 nm wavelength and subsequently 308 nm.

Figure 1. The final Nd:YAG pump laser assembly packages inside a box with ring laser oscillator and four amplifiers.

Figure 2. Near-field beam profile and a typical average output power reading due to amplifier 4 at 50 Hz PRF. Maximum average power measured so far is ~53 W.

The UV converter generating 320 nm was reassembled at NASA LaRC and tested using the above discussed diode-pumped Nd:YAG laser. The beam quality influenced the output performance. In our previous experiments at Sandia National Laboratory, it was demonstrated that the flat top pump profile is critical for achieving highly efficient RISTRA OPO and SFG operation [3]. In the following sections, the status of the UV converter performance using the current the solid-state Nd:YAG pump laser is presented.

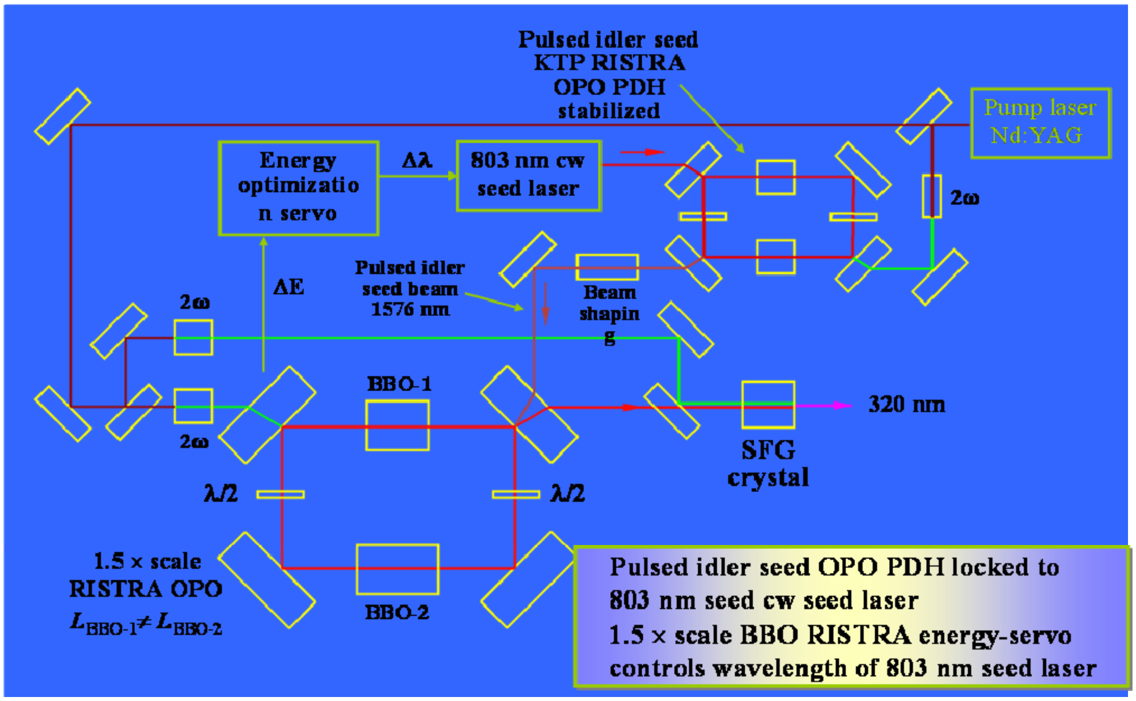
II. THE UV CONVERTER

The UV converter went through several design iterations. The design configuration of the current version is illustrated in Figure 3. Figure 4 shows the hardware implementation on a laboratory bench at NASA LaRC.

The UV converter is pumped by 532 nm wavelength obtained by SHG using a KTP crystal. The UV converter consists of four main sections. They are: a) tunable single frequency laser diode based CW seeding of a small seeder OPO at 803 nm wavelength, (b) the “seeder” small OPO that generates idler pulses at 1576 nm used as a pulse seed for the big OPO, c) The big RISTRA OPO generates 803 nm signal wavelength, and d) the SFG module that mixes 803 nm with the 532 nm to generate 320 nm. In the case of 308 nm wavelength generation, the 731.5 nm wavelength tunable laser diode is utilized for seeding purposes.

The current version 4 for the 320 nm generation addresses several shortcomings of previous versions. They include:

- The dimensions of OPO was increased by a factor of 1.5 to accommodate larger beam diameters for higher energy at low fluence
- The OPO cavity design parameters were optimized by having unequal length crystals for late onset of back-conversion. This eliminates the need for amplification stage
- The KTP crystals in OPO were replaced with BBO since BBO has higher radiation hardness than KTP
- The BBO SFG crystal was replaced with LBO. This allows lower two-photon absorption in LBO
- The “self seeding” scheme at 803 nm signal wavelength was replaced with pulsed idler seeding at 1576. Advantages include deployable seed lasers exist at 1576 nm, but not at 803 nm and idler seeding may also improve beam quality in OPO



Pulsed idler seed OPO PDH locked to 803 nm seed cw seed laser

1.5 × scale BBO RISTRA energy-servo controls wavelength of 803 nm seed laser

Figure 3. The block diagram of the 320 nm UV converter setup

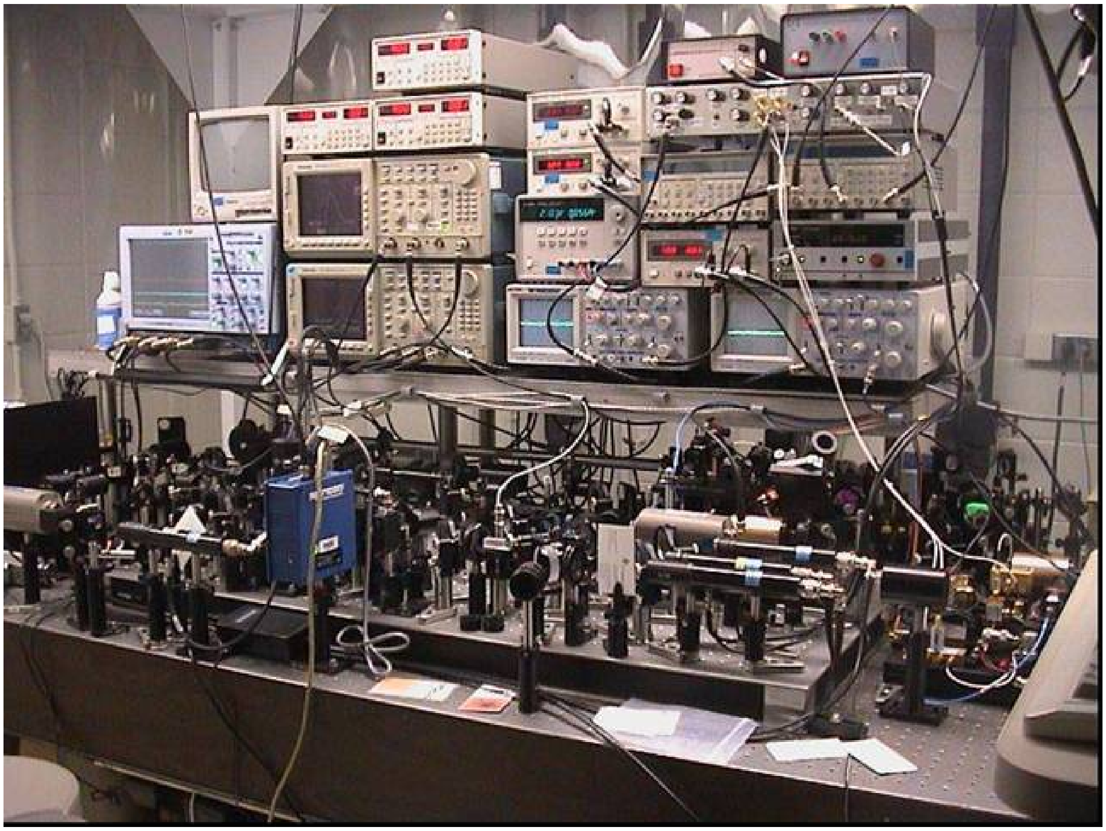


Figure 4. The breadboard UV converter setup for generating 320 nm.

- Modifications to allow the use of one pump laser were carried out
- Pound-Drever-Hall stabilization technique was incorporated for small “seeder” OPO.

Figure 5 shows the RISTRA OPO design configuration and the compact mechanical module. RISTA assembly is mechanically robust and it provides long term stability with no mirror adjustments.

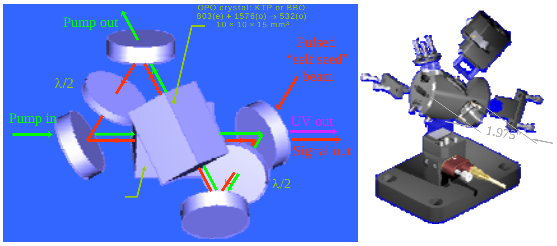


Figure 5. RISTRA cavity configuration and its mechanical assembly (JOSA B 19, 1801–1814, 2002).

III. EXPERMINTATION

The breadboard UV converter was coupled to the diode pumped Nd:YAG laser. No external beam shaping optics was used to modify the output beam from the laser. The beam diameter was around 3 mm. The typical near-field beam profile is shown in Figure 2. The laser beam is divided into three segments using beam splitters, each generating 532 nm wavelength individually by SHG using KTP crystals. For pulse seeding, ~1 mJ was obtained. One 532 nm wavelength beam is incident on the small seeder RISTRA OPO. The second 532 nm is used to pump the big RISTRA OPO. The third 532 nm beam is used for mixing with 803 nm in a LBO crystal for the generation of 320 nm.

Following proper beam alignment and pump energy adjustments, the 320 nm UV transmitter was made functional. Only a few mJ of 320 nm UV radiation was generated. The UV beam incident on a card is shown in Figure 6. However, there was no significant UV conversion as the pump energy was increased to be around 700 mJ/pulse. Since large pump depletion was not observed, the pump energy was not increased beyond 300 mJ/pulse for further experimentation.

Subsequently, the pump beam quality was carefully analyzed at the big OPO using an imaging camera. The beam profile at the big OPO was corrupted as seen in top left picture of Figure 7. The beam profile was astigmatic with complex internal structures. The wavefront errors will significantly reduce the nonlinear conversion. An astigmatic beam will reduce the beam overlap inside a RISTRA cavity due to image rotation. The astigmatic beam with non uniform spatial profile significantly reduced the nonlinear conversion. As shown in top right picture of Figure 7, less than 10% pump depletion was observed. In our previous UV experiments, a round smooth pump beam with a Fresnel number of ~450 as shown in bottom right picture of Figure 7 was utilized. With that beam profile, nearly 90% beam depletion was observed as shown in bottom right picture of Figure 7. Hence, the Nd:YAG laser pump beam quality limited the performance of the UV Converter.

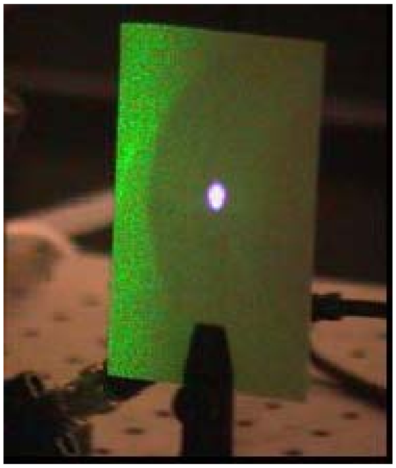


Figure 6. The 320 nm UV wavelength generation.

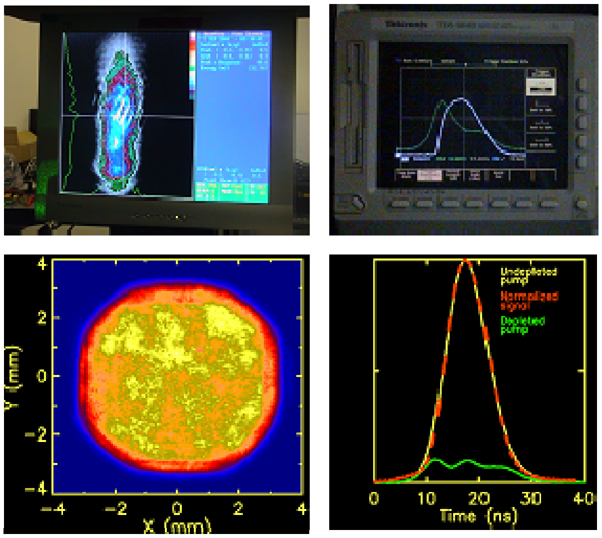


Figure 7. Peam profile analysis. Top Left: The 532 nm beam at the big 803 nm RISTRA OPO. Top right: Reduced beam depletion. Bottom left: The output beam profile from a modified flash lamp laser. Bottom right: Nearly 90% pump depletion in RISTRA OPO in which the pump beam profile shown in bottom left was used.

IV. RESULTS AND DISCUSSION

As illustrated in Figure 7, round and flat spatial profiles of pump beam have facilitated high pump depletion and hence high OPO conversion efficiency. Hence, round top hat pump profile is required for optimal nonlinear conversion. Previously, to obtain round top hat spatial profile, the flash lamp pumped Contimuum Powerlite 9010 was considerably modified. In this case, the oscillator beam was TEM_{00}.

Double pass amplification with low filling of amplifiers and vacuum imaging and a Keplerian telescope with aspheric lenses were used. Furthermore, a refractive shaper contributed in obtaining a smooth pump spatial profile.

Currently, efforts are underway to optimize the UV converter performance by addressing the solid-state Nd:YAG pump beam quality issues. Refurbishing of the Nd:YAG pump laser to obtain round, top-hat spatial fluence profile has began. Refinements to the ring oscillator cavity, pre-amplifiers and amplifiers of the diode-pumped Nd:YAG laser are being looked into. Besides beam quality, there were two more parameters that were not exactly similar as in flash-lamp pump laser based experiments. The pulse width and the pump beam diameter of the diode pump laser were 22 ns and ~3 mm, respectively. For the flash lamp pumped laser, these values were 10 ns and ~6 mm, respectively. Hence, the possibility of reducing the pulsewidth of the diode pump laser will be considered. Once round, top hat spatial profile with reduced pulsewidth is accomplished, beam diameter can be matched using a telescope.

The current UV setup will be further simplified as most of the operational requirements have been understood. The risk reduction experiments have provided significant insights into reducing the overall size of the UV converter. Most of the diagnostics used in the breadboard UV converter arrangement will be eliminated. Use of a DFB laser coupled to the big OPO is anticipated to provide more than 200 mJ/pulse at desired UV wavelengths in a robust package of less than 0.5 cu. ft. in volume.

VI. SUMMARY AND CONCLUSIONS

In this paper, the performance of a diode pumped, single longitudinal mode, and conductively cooled Nd:YAG laser used for pumping a UV converter arrangement is discussed. The all-solid-state and single longitudinal mode Nd:YAG laser provided greater than 1.1 J/pulse at 50 Hz and 22 ns pulsewidth. The UV converter was assembled and tested at NASA LaRC. Pump beam quality limited the performance of the UV converter to few mJ/pulse at 320 nm. The refurbishing of the pump laser to obtain round, top hat profile with reduced pulsewidth is progressing. The diode-pumped Nd:YAG laser will be utilized in laboratory risk reduction experiments for the generation of 320 nm and 308 nm wavelengths suitable for ozone sensing through DIAL technique.

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