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A 243mJ, Eye-Safe, Injection-Seeded, KTA Ring-Cavity Optical Parametric Oscillator

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ABSTRACT

We have demonstrated a 243mJ, eye-safe, injection seeded, non-critically phase-matched (NCPM), singly resonant oscillator (SRO), KTA ring-cavity optical parametric oscillator (OPO). The OPO was pumped with a single mode 7ns FWHM, 30Hz, Q-switched, Nd:YAG at a wavelength of 1064.162nm. The OPO was injection-seeded utilizing a single longitudinal (SLM) distributed feedback (DFB) diode laser. As a result, the KTA OPO generated an eye-safe signal wavelength of 1535.200nm with a maximum energy of 243mJ, a conversion efficiency of 27%, a cavity mode seed range of 853MHz FWHM, and a maximum M^2=30. This high energy, eye-safe OPO could potentially increase the sensitivity and range capabilities of elastic LIDAR and DIAL systems which are used for remote sensing applications.

Keywords: Injection-seeding, KTA, ring cavity, OPO, high-energy, eye-safe

1. INTRODUCTION

In the area of high-energy, eye-safe OPOs, Rines et al. [1] were the first to demonstrate the highest energy NCPM, standing wave, SRO with pump reflection, KTP OPO pumped by a multimode Nd:YAG. They produced a 1571 nm signal wave with a maximum output of 450mJ utilizing a 1.1J pump source which was a conversion efficiency of 41% [1]. However, there were limits to the maximum amount of signal energy they could generate from a KTP-based OPO. So, to overcome the material limits of the KTP, Webb et al. [2] demonstrated that they could generate high-energy eye-safe signal outputs from a NCPM OPO by using KTA crystals. With their KTA OPO, Webb generated a 1535nm signal wave with a maximum output of 330mJ, a conversion efficiency of 35%, and a signal FWHM spectral linewidth of 0.6nm (76GHz, 2.55cm^{-1}) [2]. However, Webb's OPO cavity design was very different from Rines' KTP OPO. Webb demonstrated a traveling, SRO, NCPM, four KTA, cavity that was pumped by a 100Hz multimode Nd:YAG [2]. The choice for the traveling cavity was based on eliminating the need for an optical isolator for the pump beam, lower energy fluences on the crystals which prevent crystal damage, and the ease of injection seeding. From Rines' and Webb's results, Qpeak developed a compact LIDAR transmitter based on a traveling wave, two crystal, NCPM KTP which was pumped by a multi-mode Nd:YLF running at 20Hz [3]. Qpeak successfully produced 210mJ of 1551nm light with a conversion efficiency of 36% [3]. In 2007, Gong et al. demonstrated an eye-safe compact scanning LIDAR based on an OPO source that generated 125mJ [4]. Recently, Foltynowicz et al. utilized Qpeak's two crystal, NCPM traveling wave KTA design and demonstrated the generation of 215mJ of 1533nm signal (22% conversion efficiency) utilizing a single mode Nd:YAG with a 30Hz repetition rate [5]. Our objectives for this investigation were to improve the performance of our traveling wave OPO cavity which is pumped by a single mode Nd:YAG and incorporates two KTA crystals. We are interested in improving both the signal energy output, and to demonstrate the reduction of the spectral linewidth of the signal output utilizing injection seeding techniques. The successful achievement of these objectives could potentially lead to a new high-energy and narrow linewidth OPO source that could be used for spectroscopic or remote sensing applications.

2. EXPERIMENTAL SETUP

The KTA OPO we built was pumped with a single mode, flashlamp, Q-switched Continuum Powerlite 9030 Nd:YAG at 1064.162nm ±0.005nm. The pump laser's output pulse width was 7ns FWHM, with a pulse repetition frequency of

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30Hz, and a maximum average power of 30W (1J/pulse). The pump laser was converted from multi-mode to single mode operation utilizing NP Photonics' seeder system. This injection seeding system utilized a SLM, Yb-doped fiber laser end pumped by a 976nm diode laser. The seed laser produced 30mW of CW power, reduced the FWHM spectral linewidth to $0.003cm^{-1}$ for the pump, and reduced the laser build up time by 10ns.

Figure 1 shows the beam path for the KTA ring-cavity OPO. The vertically-polarized pump beam entered the OPO through the output coupler (OC), which had a high transmission for the 1064nm pump beam and 30% reflectivity for the 1535nm signal wave. Once in the cavity, the pump beam passed through an x-cut, $\Theta = 90^o$, $\varphi = 0^o$ KTA1 which was NCPM. The polarizations of the pump and the generated signal and idler waves were o, o, and e, respectively. Both KTA crystals have dimensions of 10mm x10mm x20mm. At the exit of KTA1, the pump generated an idler wave (3468.300nm) and amplifies a signal wave (1535.200nm). All three beams enter the one-inch, right-angle, BK7 folding prism. However, only the pump and signal waves were retroreflected towards the KTA2. The idler wave was absorbed by the folding prism. Upon exiting KTA2, the pump beam and the horizontally-polarized idler beam passed through the high reflector (HR), but the signal wave reflected towards the output coupler. The HR was 99.5% transmissive for 1064nm and 99.5% reflective for the signal wave, 1535.200nm. The signal wave then exits from the OC and 30% of the signal wave power was fed back into the cavity. To injection-seed the OPO, we used an Anritsu CW DFB diode laser as our seed source. The seed laser delivered 20mW at 1535.200nm and had a spectral linewidth of 10MHz. The seed laser had both a polarization maintaining fiber (oriented vertically which matched the pump polarization), and a collimator to generate a low divergence (1.5 mrad) spherical beam. The diode produced 20mW of power at 1535.200nm which was the center of the OPO's signal wave gain bandwidth. To monitor whether the OPO was seeding or not, we devised an experimental setup that up-converted the wavelength of the 1535.200nm signal output to its second harmonic of 767.600nm such that we could view an etalon's changing fringe width with an IR camera. Figure 2 shows the measured signal gain bandwidth and the seeding linewidth of the OPO. The signal bandwidth for the OPO was 47GHz and the seeded OPO tuning range was 853MHz. However, the time-bandwidth limit of the signal wave's spectral linewidth was 140MHz.

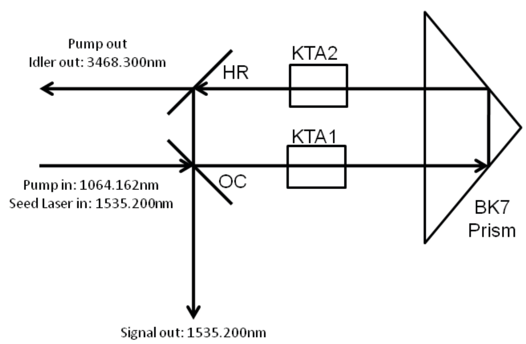

Figure 1. Component and beam path diagram of the KTA, ring-cavity, OPO. (HR) – high reflector (99.5% 1535nm, Highly transmissive 1064nm and 3468nm). (OC) – output coupler (highly transmissive to 1064nm and 30% reflectivity for 1535nm).

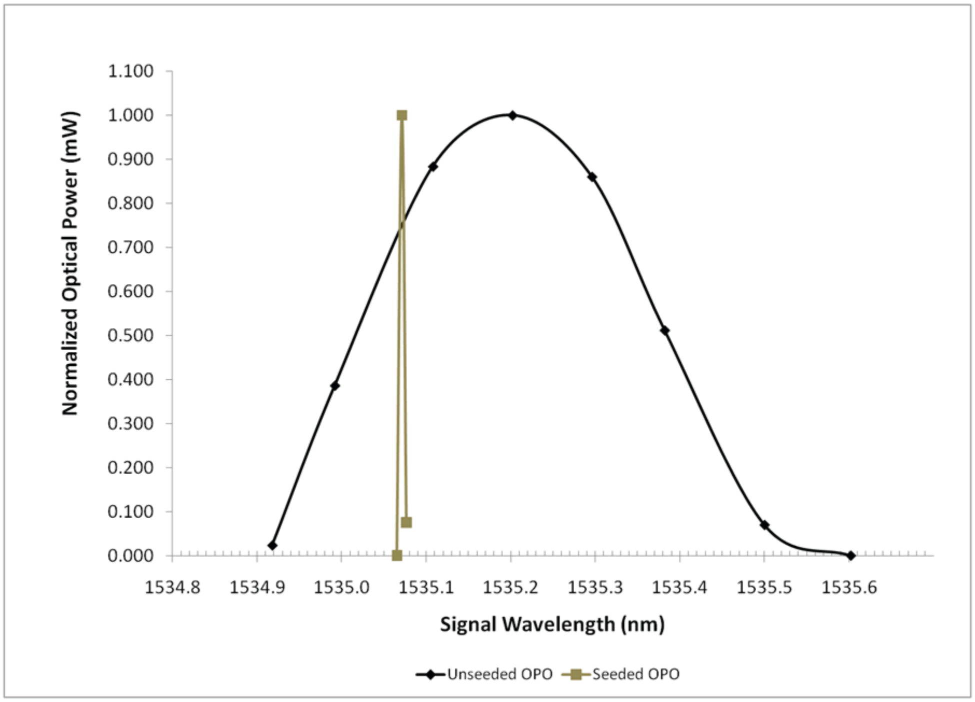

Figure 2. This is a plot that shows the OPO's signal wave gain bandwidth which is the darker curve with a FWHM of 47GHz. The lighter curve is the seed tuning range of 853MHz. The spectral linewidth of the OPO is no less than the transform-limit of 140MHz.

3. OPO PERFORMANCE

The performance parameters we measured for the KTA OPO were the pump oscillation threshold, pump-to-signal power conversion, and pump-to-signal conversion efficiency. The seeded OPO has a lower oscillation threshold (7.6W, 51.4MW/cm^2, 253mJ) compared to the unseeded OPO (8.3W, 56MW/cm^2, 277mJ). The lowering of the oscillation threshold for the seeded OPO was expected due to the higher gain of a selected signal mode provided by the DFB seed laser. The seed laser enables the OPO to exceed cavity losses and provide gain quicker at lower pump intensities than an unseeded cavity. In addition, the general trend of the signal power generated with the seeded OPO is systematically larger than the unseeded OPO for each pump power level measured. The maximum signal power generated by the seeded OPO was 7.3W compared to the unseeded case of 4.1W. The seeded OPO generated approximately 1.8 times more signal power than the unseeded OPO. Figure 3 shows the lowered oscillation threshold as well as the increased signal power in the seeded OPO.

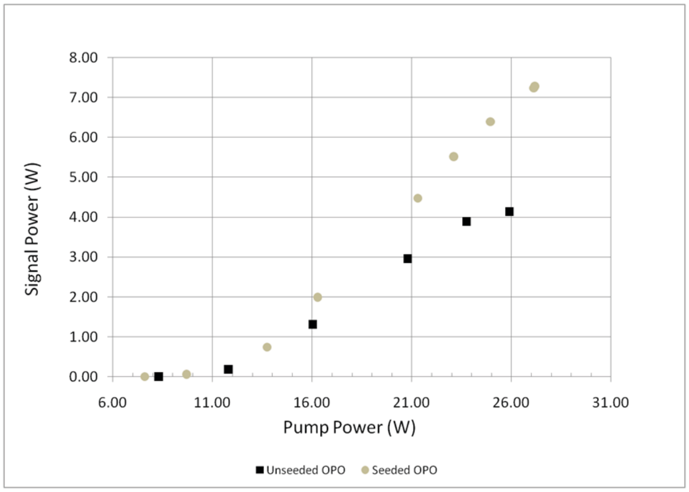

Figure 3. This plot shows the amount of signal power obtained given a variable pump power for the unseeded and seeded OPO. The seeded OPO is represented by grey circles and the unseeded OPO is represented by black squares. For the seeded OPO, the oscillation threshold is lowered compared to the unseeded OPO. Also, the maximum signal power generated for the seeded OPO was 7.3W which was 3.2W higher than the unseeded OPO.

Figure 4 shows a comparison between the unseeded and the seeded OPO conversion efficiencies (signal-to-pump). The maximum conversion efficiency for the unseeded OPO was 16% and 27% for the seeded OPO. The approximately 70% boost in conversion efficiency in the seeded OPO may have been associated with the early turn-on of the OPO in the presence of the seed laser, but it is difficult to exactly explain the underlying causes of the increased conversion efficiency of the seeded OPO.

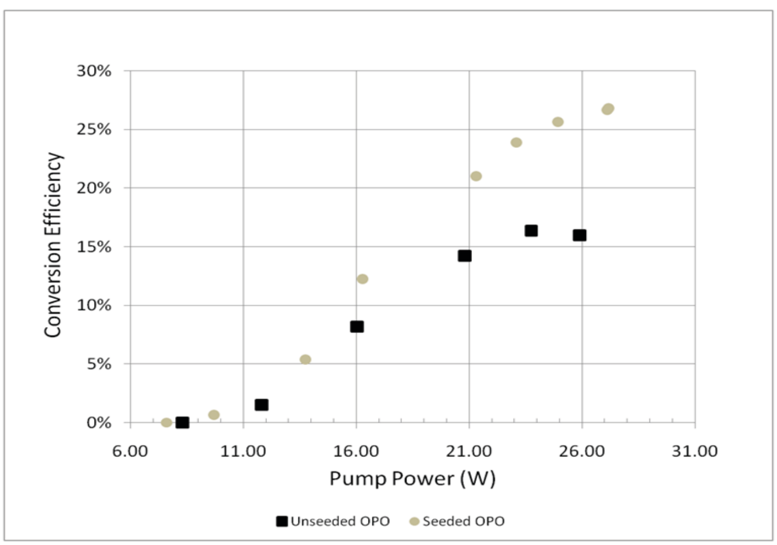

Figure 4. A comparison between the unseeded and seeded OPO pump-to-signal conversion efficiencies. The gray circles represent the seeded OPO and the black squares represent the unseeded OPO.

To further benchmark our performance results for the KTA OPO, we compared our results to a theoretical OPO model developed by Arlee Smith in his SNLO program [6]. Using the 2D-cav-LP function in SNLO, we modeled our ring cavity to get its theoretical performance. The results of the model showed a maximum signal energy output of 285mJ and conversion efficiency (signal-to-pump) of 32% using 900mJ of pump energy. Our experimental values were systematically lower than the SNLO values. The percent errors for the maximum signal energy and the conversion efficiency were 15% and 16% percent error, respectively. However, the differences in the conversion efficiency between the model and the lab results could have been due to many reasons. For example, the SNLO model assumes that the entire idler wave was transmitted at the HR and absorbed at the folding prism. However, it is very likely that our OPO may not have damped the entire idler wave as it propagated through the cavity which would result in an increase in backconversion and lowered conversion efficiencies. Nevertheless, SNLO' results compared reasonably well with our measured OPO performance.

4. CONCLUSIONS

In this investigation, we demonstrated a 243mJ, injection-seeded, eye-safe, traveling wave cavity, KTA OPO with two mirrors and a folding prism. The injection-seeding was accomplished using a current tunable DFB laser diode centered at 1535.200nm. When comparing the unseeded to the seeded OPO performance, the seeded OPO lowered the oscillation threshold by 0.7W, increased the signal energy output by 38mJ, increased the conversion efficiency by 11%, and reduced the signal linewidth from 47GHz to a seedable range of 0.853GHz.

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