High-efficiency high-energy wavelength-doubling optical parametric oscillator

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ABSTRACT

We have numerically modeled an efficient method of doubling the 1064 nm wavelength of a Q-switched Nd:YAG laser using a lambda-doubling nanosecond optical parametric oscillator (LDOPO). The LDOPO cavity is based on the four-mirror nonplanar RISTRA geometry, denoting rotated-image singly-resonant twisted rectangle, and contains a single type-II KTP crystal. By using the polarization-rotating properties of this cavity, and modifying its geometry to incorporate polarization-selective mirrors with angles of incidence near Brewster's angle, this design obtains stable, singly-resonant oscillation at degeneracy. If the pump laser is injection-seeded, and the LDOPO contains an intra-cavity étalon for single-longitudinal-mode oscillation, the phase of the wavelength-doubled 2128 nm light remains locked to the phase of the pump, independent of cavity length, so active frequency stabilization is not required. Numerical analysis indicates that a pulse-injection-seeded LDOPO can obtain 1064 nm to 2128 nm conversion efficiency exceeding 61%. However, analysis of a complete system incorporating a primary low-energy LDOPO that pulse-injection-seeds a secondary higher-energy LDOPO indicates total 1064 nm to 2128 nm efficiency of approximately 57%. A 2128 nm lambda-doubling system having conversion efficiency $> 50\%$ may offer a cost-effective alternative to conventional two micron laser sources such as Tm:Ho:YAG.

Keywords: Wavelength doubling, lambda doubling, degenerate optical parametric oscillator, phase locking, nonlinear optics, image rotation, nonplanar ring oscillator

1. INTRODUCTION

Narrow bandwidth sources of tunable coherent radiation in the 8–12 μm range are desirable for spectroscopic and remote sensing applications. For use in the field these sources should be compact, efficient, all solid state, and based on well-developed pump lasers such as Nd:YAG. Not surprisingly many laboratory prototype systems fitting this description appear in the literature, with Refs. 1–4 being typical examples. All of these systems access the 8–12 μm spectral region using a primary nanosecond optical parametric oscillator (OPO) to pump a secondary OPO that generates an idler wavelength > 5 μm. The various primary OPO's contain crystals of KTP, KTA, or $LiNbO_3$ and are pumped by the Nd:YAG fundamental at $\lambda = 1064$ nm. The secondary OPO's use either the crystal $AgGaSe_2$ with $\lambda_{\mathrm{pump}} \geq 1.5$ μm, or the crystal ZGP with $\lambda_{\mathrm{pump}} \geq 2.0$ μm. While these are good methods for realizing all solid state systems, low quantum conversion and the characteristic poor beam quality of nanosecond OPO's limits the optical-to-optical conversion efficiency (1064 nm energy to 8–12 μm energy) to approximately 1%.

The 1064 nm to 8–12 μm conversion efficiency of the cascaded OPO systems in Refs. 1–4 could be enhanced by using injection-seeded Nd:YAG lasers, and additionally, by using single-frequency injection seeded primary OPO's. A single frequency pump laser can improve the conversion efficiency and output beam quality of the primary OPO, which will improve conversion efficiency of the secondary OPO. Additionally, a single frequency primary OPO can further enhance efficiency of the secondary OPO, and if required, facilitate generation of single-frequency 8–12 μm light. Although injection seeded lasers increase system cost and complexity, well-engineered actively-stabilized Nd:YAG lasers are commercially available. On the other hand, actively-stabilized single-frequency OPO's are less common, so injection seeding the primary OPO requires additional engineering, and adds another layer of complexity to the system. One promising approach that eliminates the need for

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active frequency stabilization of the primary OPO is to replace it with a singly-resonant lambda-doubling OPO (LDOPO).

Lambda doubling in singly-resonant nanosecond OPO's is not an entirely new idea because LDOPO operating characteristics are related to optical frequency division in doubly resonant cw OPO's (DRO's).[5,6] When tuned near degeneracy, long term stability in frequency-dividing DRO's requires active cavity stabilization to phase-lock the signal and idler. However, for exact division by 2 the degenerate waves can "self phase lock" to the pump wave. This phase-locking of the degenerate waves was predicted in the early 1960's,[7] and was subsequently demonstrated while generating squeezed light in a DRO pumped below threshold,[8] and later demonstrated for oscillation in a type-I monolithic $MgO:LiNbO_3$ DRO.[5] Using the monolithic oscillator in Ref. 5, phase locking to the pump at degeneracy was shown to persist for as long as 20 min without active cavity stabilization. Although the self phase-locking range of degenerate cw DRO's is $\lesssim$ 100 MHz, especially for type-I mixing, the high-gain of nanosecond OPO's supports singly-resonant type-II oscillation at degeneracy, so that self phase-locking can occur over a comparatively limitless range. By interchanging the *e*- and *o*-polarizations each time the 2λ light enters the crystal, phase locking in singly-resonant LDOPO's becomes largely insensitive to changes in cavity length, eliminating the need for active cavity stabilization.

Despite their potential practicality, there may be only one published demonstration of a singly-resonant, degenerate, type-II LDOPO.[9] The measurements in Ref. 9 were carried out using a linear OPO cavity modified to rotate polarization 90° and reject one degenerate wave using intra-cavity polarization and retardation optics. The authors described their LDOPO to as a "polarization mixing OPO," however "polarization switching" better describes its operation. Although cavity-length-independent self phase-locking is fundamental to singly-resonant LDOPO's, the example in Ref. 9 was pumped by a broadband Q-switched Nd:YAG laser, and the temporal dynamics of the pump obscured signatures of phase locking. Also, the LDOPO in Ref. 9 produced pulse energies $\leq$ 300 μJ, however our numerical results suggest singly-resonant, type-II, degenerate oscillation can produce pulse energies exceeding 100 mJ.

The LDOPO we have numerically modeled, and plan to build and test, is designed for high energy oscillation without the use of intra-cavity polarization and retardation optics. It's based on a modification of the nonplanar RISTRA cavity, where RISTRA denotes rotated-image singly-resonant twisted rectangle.[10] We based our design on this cavity for the following reasons:

The RISTRA cavity's nonplanar geometry rotates the intra-cavity polarization 90°, which is ideal for switching between the *e*- and *o*-polarized waves of degenerate type-II mixing.

Nonplanar cavities are insensitive to small tilts of their cavity mirrors. Consequently, modifications to mirror geometry are simple if they don't disrupt the polarization- and image-rotating properties of the cavity. Rather than inserting intra-cavity polarization-rejecting optics, we achieve a high degree of polarization discrimination and efficient rejection of one degenerate wave by replacing two of the RISTRA's in-plane-reflecting cavity mirrors with near Brewster-Angled mirror pairs.

The RISTRA was designed to accommodate large diameter pump beams to achieve high output energy at low fluence, and to generate high quality beams. Because the LDOPO switches polarizations of the 2λ waves before type-II mixing in the crystal, there may be some reduction in the beam clean-up obtained from intra-cavity image rotation.[10,11] Nonetheless, the RISTRA cavity nominally produces very high quality output beams.

2. DESIGN FOR A HIGH-EFFICIENCY ND:YAG PUMPED LAMBDA-DOUBLING OPO SYSTEM

Singly-resonant polarization-switching type-II oscillation at degeneracy results in a high threshold and low conversion efficiency because output coupling is at least 50%. In addition, an LDOPO will oscillate on multiple longitudinal modes unless it is injection seeded or contains an intra-cavity étalon. To be practical, our lambda-doubling system must achieve high conversion efficiency and single-frequency oscillation, so we incorporate pulsed

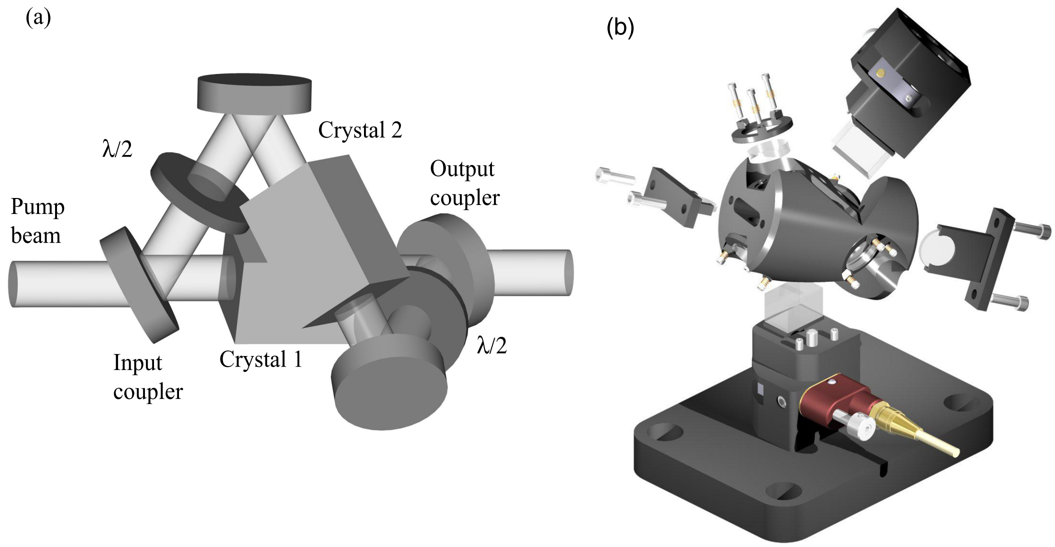

Figure 1. (a) Conventional two-crystal RISTRA OPO containing two $10 \times 10 \times 15$ mm^3 crystals and two $\lambda/2$ plates. The physical round-trip length of the cavity is 110 mm, and relative sizes of all optical components are to scale except thickness of the $\lambda/2$ plates. (b) Exploded view of an engineered RISTRA assembly. Owing to the RISTRA cavity's nonplanar geometry, adjustment for cavity mirror tilt is not required. Cavity mirrors are held in place against three-point contacts on the machined faces of the cylindrical body by spring-loaded retainers. See text for additional details.

injection seeding, with a single-frequency seed pulse provided by a small, low-energy primary LDOPO. Pulse injection seeding can result in pump depletion as high as 90% in singly-resonant nanosecond OPO's,[12] so it not only achieves single-frequency oscillation, but improves efficiency as well.

Although the RISTRA cavity with Brewster mirrors that we describe below rotates polarization 90° and rejects one degenerate wave without any intra-cavity optics, we don't use this design for our primary LDOPO. Incorporating Brewster mirrors increases the RISTRA cavity length from 110 mm to 230 mm, resulting in a high oscillation threshold and low efficiency. Consequently, our primary LDOPO is based on a conventional RISTRA cavity, so it must contain retardation plates and a thin-film polarizer. It also contains an angle-tuned intra-cavity solid étalon for single-frequency oscillation. While this design is probably unsuitable for high-energy operation, it's suitable as low-energy source for the 2128 nm seed light. Numerical modeling suggests the primary LDOPO requires approximately 30–40 mJ of 1064 nm light in a 2–3 mm diameter pump beam to generate a 2–3 mJ seed pulse at 2128 nm. Although the primary LDOPO increases the 1064 nm energy required for the system, the additional 30–40 mJ should be compensated for by the increase in output achieved by pulse injection-seeding secondary LDOPO.

The design of the primary LDOPO is illustrated in Figs. 1 and 2. We start with the two-crystal RISTRA cavity shown in Fig. 1(a) where a $10 \times 10 \times 15$ mm^3 crystal occupies each of its long legs, and an intra-cavity $\lambda/2$ plate is placed in each short leg. An exploded view of the engineered version of this same OPO is shown in Fig. 1(b). To convert the two-crystal RISTRA to a single-frequency, polarization switching LDOPO, we replace the second crystal with a thin-film polarizer to reject one degenerate wave from the cavity, and follow the polarizer with an angle-tuned étalon for single-frequency oscillation. The $\lambda/2$ plates are retained, with retardation set for polarization switching. The modified cavity is shown in Fig. 2.

The design of the high energy secondary LDOPO shown in Fig. 3 differs from the primary because it incorporates two pairs of cavity mirrors tilted to an angle of incidence near Brewster's Angle at 61.383°. Using Brewster mirrors results in a low-loss cavity containing only a nonlinear crystal. The nonplanar cavity provides 90° of polarization rotation to switch between e- and o-polarizations before the circulated 2λ wave returns to the crystal. While Brewster mirrors add complexity, their in-plane reflections are easily accommodated by the

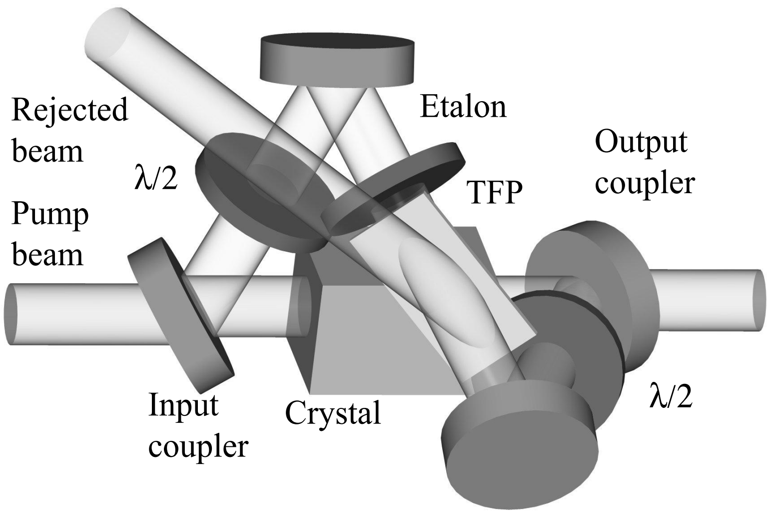

Figure 2. Modified RISTRA cavity incorporating a thin film polarizer and intra-cavity étalon. The thin film polarizer rejects one orthogonally polarized 2128 nm wave, resulting in a singly-resonant cavity at degeneracy. The $\lambda/2$ plates are oriented so e- and o-waves switch polarization for each trip around the cavity, and the angle-tuned étalon forces single-frequency oscillation. Relative sizes of all optical components are to scale, except thickness of the $\lambda/2$ plates, and the crystal shown here is $10 \times 10 \times 15$ mm^3. The crystal used in the primary LDOPO described in the text is $6 \times 6 \times 17$ mm^3 zx-cut KTP at $\theta = 51.4°$ for $2128(o) + 2128(e) \rightarrow 1064(o)$.

RISTRA cavity's insensitivity to mirror tilt. In a standard RISTRA cavity the angle of incidence on all mirrors is 32.765°. At this angle it is difficult to obtain high-damage-threshold dielectric coatings capable of discriminating between S- and P-polarizations $\gtrsim 60:40$, especially for degenerate wavelengths. However near Brewster's Angle, discrimination between orthogonal polarization states is nearly 100%. Consequently, two additional mirror reflections probably results in a cavity with higher Q than one containing a polarizer and retardation plates.

3. METHOD OF OPERATION

Final mechanical design of the Brewster-mirror LDOPO cavity is underway, as are plans for initial testing of the lambda-doubling system. After the system is assembled, the first step will be to obtain self phase-locked oscillation in the primary LDOPO. This is done by removing the intra-cavity étalon to observe the frequency spectrum of multi-longitudinal mode oscillation using a low resolution spectrometer comprised of a grazing-incidence diffraction grating, a far-field lens, and a pyroelectric camera. The spectrum of 2128 nm light should contain two near-degenerate clusters of modes that will coalesce into a single cluster when the OPO crystal's phase-matching angle is adjusted so $\Delta k \approx 0$. The solid étalon will then be inserted into the cavity and adjusted for maximum 2128 nm energy while monitoring the mode structure on the spectrometer. The LDOPO's 2128 nm light will then be frequency doubled to 1064 nm in an external 2ω crystal, and heterodyned with a small fraction of the cw light used to injection-seed the Nd:YAG pump laser. To generate a useful heterodyne signal will require frequency-shifting the 1064 nm seeder light electro- or acousto-optically by approximately 10 times the reciprocal of the Nd:YAG laser's pulse width, or about 1 GHz. The resulting heterodyne signal should consist of ≤ 10 cycles during a pulse from the OPO. The signature for degeneracy in the heterodyne signal may require more than simple observation because of phase evolution during the OPO pulse, and due to doubling the frequency of the 2128 nm light. When the signature of degeneracy is understood, final adjustments consist of rotating the OPO crystal so $\Delta k = 0$, and rotating the étalon for maximum transmission at degeneracy.

After degenerate oscillation is obtained in the primary LDOPO, its 2128 nm light will be used to pulse injection seed the secondary LDOPO. Both LDOPO's will be pumped by the same Nd:YAG laser, so an optical delay line in the pump-beam path for the secondary LDOPO will be used to optimize arrival time of the pulsed seed. Interferometrically aligning the pulsed seed beam to the secondary LDOPO cavity, along with adjusting

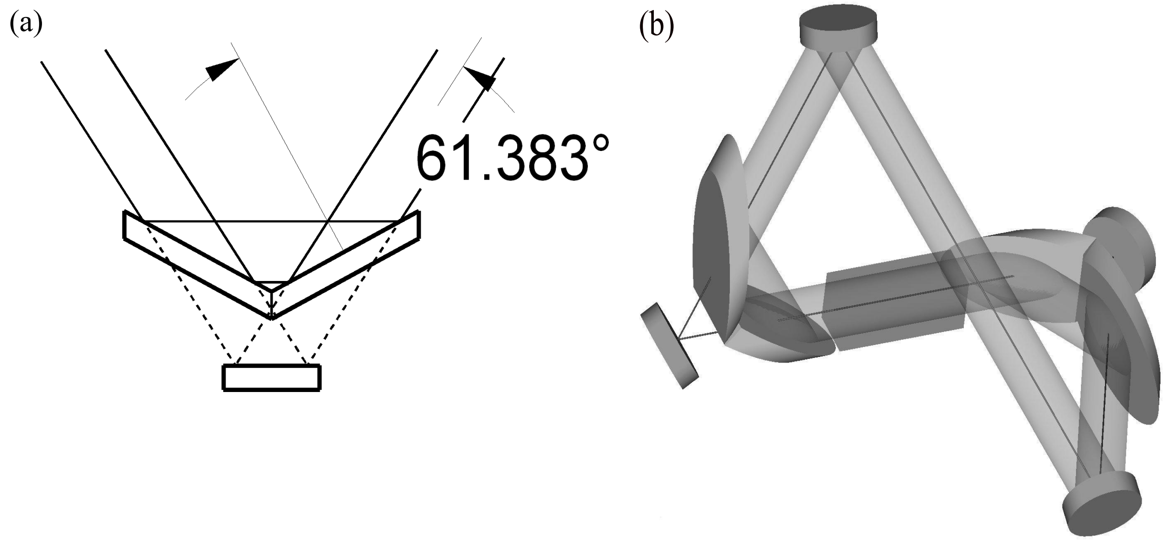

Figure 3. (a) Design of the near Brewster's Angle mirror pairs used in the secondary LDOPO. Because the reflected beams from each pair of elliptical mirrors are coincident with the mode of a conventional RISTRA cavity, there is no change to the cavity's polarization- and image-rotating properties. The dashed lines show the path of light from the mirrors in a standard cavity. (b) The geometric configuration of the secondary LDOPO showing how the near Brewster's Angle mirrors intersect the mode of a conventional RISTRA cavity. The crystal is $8 \times 8 \times 22$ mm^3 zx-cut KTP at $\theta = 51.4°$ for $2128(o) + 2128(e) \rightarrow 1064(o)$. An exploded view of the final mechanical design like that shown in Fig. 1(b) is not yet available. See text for additional details.

the phase matching angle of its KTP crystal, will optimize output energy. After stable operation is obtained, the important tests of cavity-length-independent self phase-locking will begin. These will consist of a additional heterodyne measurements for both LDOPO's. Their cavity lengths can be adjusted by mounting one cavity mirror on a PZT actuator, or by changing the temperature of the cavities. If the LDOPO's behave as expected, the observed heterodyne waveforms should indicate that degenerate oscillation is maintained, independent of changes in cavity length. Following these measurements, energy efficiency curves like those presented below in Sec. 4 will be recorded.

4. RESULTS OF NUMERICAL ANALYSIS

To predict the performance of our LDOPO system, we first modeled the efficiency of the low-energy primary LDOPO using a modified version of the SNLO two-dimensional long-pulse OPO code that includes the geometry and image rotation of the RISTRA cavity.[13] These results, shown in Fig. 4(a) suggest a 1064 nm pump energy of 30–40 mJ for the primary LDOPO. Given the difficulty of accurately modeling all losses in the primary LDOPO cavity, we conservatively estimate a pulsed-seed energy of 3 mJ. We then used this 2128 nm seed energy in a specially modified version of a RISTRA code to model the degenerate, type-II, polarization-switching secondary LDOPO. In our model the pulsed seed- and pump-beams have diameters of 7 mm with flat-top spatial fluence profiles. Although we've previously employed beam shaping to obtain a pulsed-seed beam with a flat-top spatial profile,[12] the initial lambda-doubling system will omit this enhancement. Consequently, the energy efficiency curves in Fig. 4(b) may slightly overestimate the performance. In Fig. 4(b), the 2128 nm energy efficiency curve indicated by diamonds neglects the 30 mJ used to pump the primary LDOPO, and the curve indicated by squares includes the primary LDOPO pump energy to accurately estimate total system efficiency. The maximum efficiencies are approximately 61% and 57%, respectively.

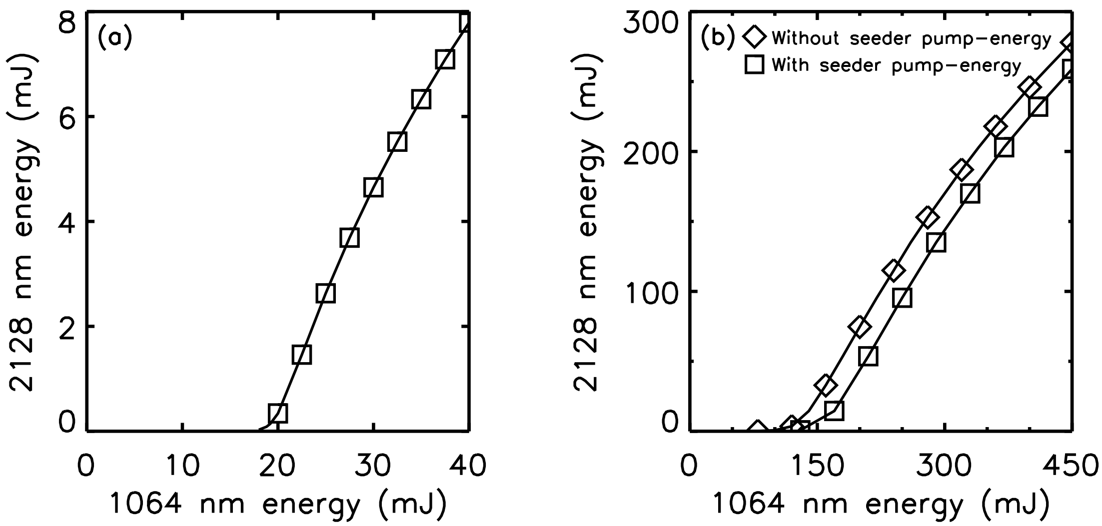

Figure 4. (a) Calculated 2128 nm energy efficiency curve for the primary LDOPO, and (b) two results for the pulse-injection seeded secondary LDOPO, with diamonds indicating 2128 nm efficiency when the energy used to pump the primary LDOPO is neglected, and squares indicating the total system efficiency. The maximum efficiencies are approximately 61% and 57%, respectively. See text for additional details.

5. CONCLUSIONS

We have designed and numerically modeled an efficient, high-energy, single-frequency, Nd:YAG laser wavelength-doubling system based on two lambda-doubling OPO's, or LDOPO's. The LDOPO designs are derived from the nonplanar image-rotating RISTRA cavity, where RISTRA denotes rotated-image singly-resonant twisted rectangle,[10] and both use type-II phase-matching in KTP. The system consists of an injection seeded Q-switched Nd:YAG laser that pumps a primary LDOPO that generates a low-energy single-frequency 2128 nm pulse for injection-seeding a high-energy secondary LDOPO. The secondary LDOPO cavity contains only a nonlinear crystal and uses polarization-discriminating Brewster-Angled mirrors to obtain singly-resonant oscillation. The primary LDOPO relies on intra-cavity polarization and retardation optics, and also requires an intra-cavity étalon for single-frequency oscillation. The primary LDOPO self phase-locks to the pump, and when its single-frequency pulse is injected into the secondary LDOPO, the secondary will phase lock as well. Self phase locking in singly-resonant, degenerate, type-II nanosecond LDOPO's is largely independent of cavity length, so long-term stable operation is possible without active frequency stabilization.

The secondary LDOPO was designed to be pumped by several hundred mJ of 1064 nm light to produce at least 100 mJ of single-frequency 2128 nm light. The calculated optical-to-optical efficiency (1064 nm energy to 2128 nm energy) of the system exceeds 57%, possibly making wavelength doubling a cost-effective alternative to conventional two micron laser systems.

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REFERENCES

1. S. Chandra, T. H. Allik, G. Catella, R. Utano, and J. A. Hutchinson, "Continuously tunable, 6–14 μm silver-gallium selenide optical parametric oscillator pumped at 1.57 μm," *Appl. Phys. Lett* **71**, pp. 584–586, 1997.

2. F. Ganikhanov, T. Caughey, and K. L. Vodopyanov, "Narrow-linewidth middle infrared $ZnGeP_2$ optical parametric oscillator," *J. Opt. Soc. Am. B* **18**, pp. 818–822, 2001.
3. Y. Ehrlich, S. Fastig, S. Pearl, and G. Cinader, "Compact high-perfromance tandem optical parametric oscillator for the 8–12 μm band," in *Lidar Remote Sensing for Environment Monitroing II*, U. Singh, ed. *Proc. SPIE* **4484**, 2002.
4. S. Haidar, K. Miyamoto, and H. Ito, "Generation of tunable mid-IR (5.5–9.3 μm) from a 2-μm pumped $ZnGeP_2$ optical paramtric oscillator," *Opt. Comm* **241**, pp. 173–178, 2004.
5. C. D. Nabors, S. T. Yang. and R. L. Byer, "Coherence properties of a doubly resonant monolithic optical parametric oscillator," *J. Opt. Soc. Am. B* **7**, pp. 815–820, 1990.
6. D. Lee and N. C. Wong, "Tunable optical frequency division using a phase-locked optical parametric oscillator," *Opt. Lett.* **17**, pp. 13–15, 1992.
7. W. H. Louisell, A. Yariv, and A. E. Siegman, "Quantum Fluctuations and Noise in Parametric Processes. I.," *Phys. Rev.* **124**, pp. 1646–1654, 1961.
8. L.–A. Wu, M. Xiao, and H. J. Kimble, "Squeezed states of light from an optical parametric oscillator," *J. Opt. Soc. Am. B* **4**, pp. 1465–1475, 1987.
9. G. Kalmani, A. Arie, P. Blau, S. Pearl, and A. V. Smith, "Polarization-mixing optical parametric oscillator," *Opt. Lett.* **30**, pp. 2146–2148, 2005.
10. A. V. Smith and D. J. Armstrong, "Nanosecond optical parametric oscillator with 90° image rotation: Design and performance," *J. Opt. Soc. Am. B* **19**, pp. 1801–1814, 2002.
11. D. J. Armstrong and A. V. Smith, "Demonstration of improved beam quality in an image-rotating optical parametric oscillator," *Opt. Lett.* **27**, pp. 40–42, 2002.
12. D. J. Armstrong and A. V. Smith, "90% pump depletion and good beam quality in a pulse-injection seeded nanosecond optical parametric oscillator," *Opt. Lett.* **in press**, 2005.
13. Numerical models for the RISTRA OPO are derived from the SNLO software package, which is written and distributed by Dr. Arlee V. Smith of Sandia National Labs. SNLO contains 17 different software tools that can be used for design and testing of OPA's, OPO's, and to calculate nonlinear crystal mixing parameters. SNLO can be downloaded free of charge from http://www.sandia.gov/imrl/X1118/xxtal.htm. Special codes for various versions of the one- and two-crystal image-rotating RISTRA OPO are available on request.