Subnanosecond mJ eye-safe laser with an intracavity optical parametric oscillator in a shared resonator

Y. P. Huang[1], H. L. Chang[1], Y. J. Huang[1], Y. T. Chang[1], K. W. Su[1], W. C. Yen[2], and Y. F. Chen[1]*

[1]*Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan*
[2]*Chung-Shan Institute of Science & Technology, Lung-Tan, Tao-Yuan, Taiwan*
**Corresponding author: yfchen@cc.nctu.edu.tw*

Abstract: We theoretically verify that the threshold of an intracavity optical parametric oscillator pumped by a passively Q-switched laser is entirely controlled by the bleach of the saturable absorber not by the signal output reflectivity. We use a series of different output couplers to optimize the output performance. With a signal output reflectivity of 15%, we experimentally achieve an efficient subnanosecond eye-safe laser with 3.3 mJ pulse energy and 1.5 MW peak power.

OCIS codes: (140.3540) Lasers, Q-switched; (190.4410) Nonlinear optics, parametric processes; (140.3480) Lasers, diode-pumped.

References and links

1. E. Gregor, D. E. Nieuwsma, and R. D. Stultz, "20 Hz eyesafe laser rangefinder for air defense," Proc. SPIE, **1207**, 124-134 (1990).
2. L. R. Marshall, A. D. Hays, and J. Kasinski, "Highly efficient optical parametric oscillators," Proc. SPIE **1419**, 141–152 (1991).
3. J. E. Nettleton, B. W. Schilling, D. N. Barr, and J. S. Lei, "Monoblock laser for a low-cost, eyesafe, microlaser range finder," Appl. Opt. **39**, 2428-2432 (2000).
4. T. Debuisschert, J. Raffy, J. P. Pocholle, and M. Papuchon, "Intracavity optical parametric oscillator: Study of the dynamics in pulsed regime," J. Opt. Soc. Am. **B 13**, 1569–1587 (1996).
5. Z. Liu, Q. Wang, X. Zhang, Z. Liu, J. Chang, H. Wang, S. Fan, W. Sun, G. Jin, X. Tao, S. Zhang, and H. Zhang, "Efficient acoustic-optically Q-switched intracavity Nd:YAG/ $KTiOAsO_4$ parametric oscillator," Appl. Phys. **B 92**, 37-41 (2008).
6. H. T. Huang, J. L. He, X. L. Dong, C. H. Zuo, B. T. Zhang, G. Qiu, and Z. K. Liu, "High-repetition-rate eye-safe intracavity KTA OPO driven by a diode-end-pumped Q-switched Nd:YVO_4 laser," Appl. Phys. **B 90**, 43-45 (2008).
7. Y. F. Chen, S. W. Chen, S. W. Tsai, and Y. P. Lan, "High repetition-rate eye-safe optical parametric oscillator intracavity pumped by a diode-pumped Q-switched Nd:YVO_4 laser," Appl. Phys. **B 76**, 263–266 (2003).
8. J. Miao, J. Peng, B. Wang, H. Tan, and H. Bian, "Compact low threshold Cr:YAG passively Q-switched intracavity optical parametric oscillator," Opt. Commun. **281**, 2265–2270 (2008).
9. Y. F. Chen, S. W. Chen, Y. C. Chen, Y. P. Lan, and S. W. Tsai, "Compact efficient intracavity optical parametric oscillator with a passively Q-switched Nd:YVO4/Cr^{4+}:YAG laser in a hemispherical cavity," Appl. Phys. **B 77**, 493-495 (2003).
10. Y. F. Chen, S. W. Chen, L. Y. Tsai, Y. C. Chen, and C. H. Chien,"Efficient subnanosecond intracavity optical parametric oscillator pumped with a passively Q-switched Nd:$GdVO_4$ laser," Appl. Phys. **B 79**, 823–825 (2004).
11. R. Dabu, C. Fenic, and A. Stratan, "Intracavity pumped nanosecond optical parametric oscillator emitting in the eye-safe range," Appl. Opt. **40**, 4334-4340 (2001).
12. Y. Yashkir and H. M. van Driel, "Passively Q-switched 1.57-μm intracavity optical parametric oscillator," Appl. Opt. **38**, 2554-2559 (1999).
13. A. Agnesi, S. Dell'Acqua, and G. Reali, "Diode-pumped quasi-cw intracavity optical parametric oscillator at 1.57 μm with efficient pulse shortening," Appl. Phys. B **70**, 751-753 (2000).
14. W. Zendzian, J. K. Jabczyński, and J. Kwiatkowski, "Intracavity optical parametric oscillator at 1572-nm wavelength pumped by passively Q-switched diode-pumped Nd:YAG laser," Appl. Phys. **B 76**, 355-358 (2003).

#104782 - $15.00 USD Received 1 Dec 2008; revised 18 Dec 2008; accepted 22 Dec 2008; published 26 Jan 2009

15. B. W. Schilling, S. R. Chinn, A. D. Hays, L. Goldberg, and C. W. Trussell, "End-pumped 1.5 μm monoblock laser for broad temperature operation," Appl. Opt. **45**, 6607-6615 (2006).
16. Y. F. Chen and L. Y. Tsai, "Comparison between shared and coupled resonators for passively Q-switched Nd:GdVO4 intracavity optical parametric oscillators," Appl. Phys. **B 82**, 403–406 (2006).
17. Y. F. Chen, K. W. Su, Y. T. Chang, and W. C. Yen, "Compact efficient eye-safe intracavity optical parametric oscillator with a shared cavity configuration," Appl. Opt. **46**, 3597-3601 (2007).
18. R. J. Beach, "Theory and optimization of lens ducts," Appl. Opt. **35**, 2005-2015 (1996).
19. R. Fu, G. Wang, Z. Wang, E. Ba, G. Mu, and X. Hu, "Design of efficient lens ducts," Appl. Opt. **37**, 4000-4003 (1998).
20. J. J. Degnan, "Optimization of passively Q-switched lasers," IEEE J. Quantum Electron., **vol. 31**, pp. 1890–1901, 1995.
21. S. J. Brosnan and R. L. Byer, "Optical parametric oscillator threshold and linewidth studies," IEEE J. Quantum Electron., **vol. 15**, pp. 415–431, 1979.

1. Introduction

Human exposure is usually inevitable in many applications such as laser radar, remote sensing, rangefinder, target designation, and laser countermeasures; consequently, protection again injury of the eye is one of the most important issues [1-3]. Since water absorption in eye tissue and the intraocular fluid prevents light in the spectral range of 1.4-1.8 μm from reaching the retina, there is a considerable interest in compact laser sources with wavelengths in this eye-safe regime. One of the most promising approaches for high-peak-power eye-safe laser sources is based on intracavity optical parametric oscillators (OPO) [4-15]. The advent of high damage threshold nonlinear crystals and diode-pumped Nd-doped lasers leads to a renaissance of interest in intracavity OPO's. In recent years, a number of efficient eye-safe intracavity OPOs pumped by actively [5-7] or passively [8-10] Q-switched Nd-doped lasers have been demonstrated to produce pulse energies of tens of μJ with pulse peak powers of 1-100 kW. Nevertheless, eye-safe laser systems with pulse energies in the mJ range and peak powers greater than MW are indispensable for the many long-distance applications [11-15].

The intracavity OPOs are mostly constructed with the coupled cavity configuration in which the resonators for the signal and fundamental wave fields are separate. Recently, it was found [16,17] that the shared cavity configuration in which the pump and signal beams share the same resonator provides a substantially superior amplitude stability, in comparison with the coupled cavity configuration. Even so, the maximum peak power in a shared cavity is usually several times lower than that in a coupled cavity under the circumstance of the same output coupler. Therefore, it is a practical interest to explore an intracavity OPO in a shared resonator in quest of optimal pulse energies and peak powers.

Here, for what is believed to be the first time, a subnanosecond mJ eye-safe laser is experimentally demonstrated with an intracavity OPO pumped in a shared resonator. We first confirm that the threshold of an intracavity OPO pumped by a passively Q-switched laser is essentially determined by the bleach of the saturable absorber not by the signal output reflectivity. As a result, a series of different output couplers are used to ascertain the design criteria for the output optimization. With a signal output reflectivity of 15%, we realize an efficient subnanosecond eye-safe laser with 3.3 mJ pulse energy and 1.5 MW peak power.

2. Experimental setup

Figure 1 shows the experimental setup for an intracavity OPO pumped by a high-power quasi-continuous-wave (QCW) diode-pumped passively Q-switched Nd:YAG laser in a shared resonator. The fundamental laser cavity was formed by a coated Nd:YAG crystal and an output coupler. The OPO cavity entirely overlapped with the fundamental laser cavity. The pump source is a high-power QCW diode stack (Quantel Laser Diodes) that consists of three 10-mm-long diode bars generating 130 W per bar, for a total of 390 W at the central wavelength of 808 nm. The diode stack is designed with 0.4 mm spacing between the diode bars so the overall area of emission is approximately 10 mm (slow axis) × 0.8 mm (fast axis). The full divergence angles in the fast and slow axes are approximately 35^o and 10^o, respectively. A lens duct was exploited to couple the pump light from the diode stack into the

#104782 - $15.00 USD Received 1 Dec 2008; revised 18 Dec 2008; accepted 22 Dec 2008; published 26 Jan 2009

laser crystal. The lens duct has the benefits of simple structure, high coupling efficiency, and unaffected by slight misalignment. The geometric parameters of a lens duct include r, L, H_1, H_2, and H_3, where r is the radius of the input surface, L is the length of the duct, H_1 is the width of the input surface, H_2 is the width of the output surface, and H_3 is the thickness of the duct [18, 19]. Here a lens duct with the parameters of r = 10 mm, L = 32 mm, H_1 = 12 mm, H_2 = 2.7 mm, and H_3 = 2.7 mm was manufactured and used in the experiment. The coupling efficiency of this lens duct is found to be approximately 85%.

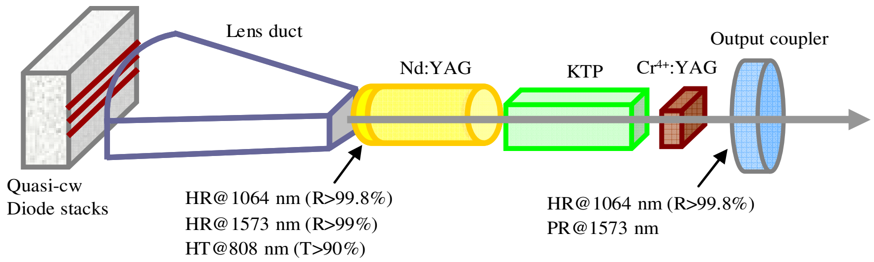

Fig. 1. Experimental setup for an intracavity OPO pumped by a high-power QCW diode-pumped passively Q-switched Nd:YAG laser in a shared resonator.

The gain medium was a 1.0 at. % Nd:YAG crystal with a diameter of 5 mm and a length of 10 mm. The incident surface of the laser crystal was coated to be highly reflective at 1064 nm and 1573 nm (R>99.8%) and highly transmitted at the pump wavelength of 808 nm (T>90%). The other surface of the laser crystal was coated to be antireflective at 1064 nm and 1573 nm (R<0.2%). The nonlinear material for the intracavity OPO was an x-cut KTP crystal with a size of 4×4×20 mm^3. The saturable absorber for the passive Q-switching was a Cr^{4+}:YAG crystal with a thickness of 3 mm and an initial transmission of 60% at 1064 nm. Both surfaces of the KTP and Cr^{4+}:YAG crystals were coated for antireflection at 1573 nm and 1064 nm. All crystals were wrapped with indium foil and mounted in conductively cooled copper blocks. The output coupler had a dichroic coating that was highly reflective at 1064 nm (R > 99.8%) and partially reflective at 1573 nm. Several output couplers with different reflectivities (10% ≤ Rs ≤ 70%) at 1573 nm were used in the experiment to investigate the output optimization. The total cavity length was approximately 5.5 cm. The pulse temporal behavior at 1063 nm and 1571 nm was recorded by a LeCroy digital oscilloscope (Wavepro 7100; 10 G samples/sec; 1 GHz bandwidth) with a fast InGaAs photodiode. The spectral information was monitored by an optical spectrum analyzer (Advantest Q8381A) that employs a diffraction grating monochromator to for measure high-speed light pulses with the resolution of 0.1 nm. In all investigations, the diode stack was driven to emit optical pulses 250 μs long, at a repetition rate less than 40 Hz, with a maximum duty cycle of 1%.

3. Theoretical analysis

The advantage of the intracavity OPO mainly consists in the exploit of high photon density of the fundamental wave. First of all, we analyze the maximum value of the intracavity photon density for the fundamental wave in a passively Q-switched laser. Next, we verify that the intracavity photon density of the present laser cavity can generally exceed the threshold of a singly resonant intracavity OPO by far, even though the reflectivity of the output mirror at the signal wavelength is nearly zero. In a passively Q-switched laser with a fast Q-switching condition, the maximum value of the intracavity photon density of the fundamental wave can be expressed as [20]

$$\phi_{f,\max} = \frac{l_{gm}}{l_{cav}} \left\{ n_i - n_t \left[1 + \ln\left(\frac{n_i}{n_t} \right) \right] \right\} \quad (1)$$

where $n_i = \frac{1}{2\sigma l_{gm}} \left[\ln\left(1/T_o^2\right) + \ln\left(1/R\right) + L \right]$; $n_t = \frac{1}{2\sigma l_{gm}} \left[\beta \ln\left(1/T_o^2\right) + \ln\left(1/R\right) + L \right]$; $\beta = \frac{\sigma_{es}}{\sigma_{gs}}$; n_i is the initial population density in the gain medium; σ is the stimulated emission cross section of the gain medium; l_{gm} is the length of the gain medium; l_{cav} is the cavity length; T_o is the initial transmission of the saturable absorber; σ_{gs} and σ_{es} are the ground-state and excited-state absorption cross sections in the saturable absorber, respectively; R is the reflectivity of the output mirror at the fundamental wavelength; and L is the nonsaturable intracavity round-trip loss. With the properties of the Nd:YAG and Cr^{4+}:YAG crystals and the typical cavity parameters: $\sigma = 2.8\times10^{-19}$ cm^2 , $\sigma_{gs} = 8.7\times10^{-19}$ cm^2, $\sigma_{es} = 2.2\times10^{-19}$ cm^2, $l_{cav} = 5.5$ cm, $R =$ 99.8%, $T_o = 0.6$, and $L = 0.01$, it can be found that $\phi_{f,\max}$ can be up to 1.56×10^{17} cm^{-3}.

With Brosnan and Byer's equation [21], the threshold photon density for the double-pass pumped, single resonant OPO is derived to be given by

$$\phi_{f,th}(R_s) = \frac{1.12}{G\, g_s\, (1+\gamma)^2} \left[33 \frac{l_{cav}}{c\,\tau_p} + \ln\left(\frac{1}{\sqrt{R_s}} \right) + L_s + \ln 4 \right]^2 \quad (2)$$

with the gain coefficient

$$G = \frac{2\hbar\omega_3\, \omega_1\, \omega_2\, d_{eff}^2\, l_{nl}^2}{n_3\, n_1\, n_2\, \varepsilon_0\, c^2} \quad (3)$$

where g_s is the mode coupling coefficient, γ is the ratio of backward to forward pump amplitude in the cavity; ω_1, ω_2 and ω_3 are the signal, idler and pump frequencies, respectively;, n_2 and n_3 are the refractive indices at the signal, idler and pump wavelengths, respectively; τ_p is the FWHM of the pump pulse; d_{eff} is the effective non-linear coefficient; ε_0 is the vacuum permittivity; c is the speed of light; l_{nl} is the length of the nonlinear crystal; L_s is the round-trip signal wave intensity loss in the cavity; and R_s is the output reflectivity at the signal wavelength.

Figure 2 depicts the calculated results for the dependence of the threshold photon density $\phi_{f,th}(R_s)$ on the output reflectivity R_s with the properties of the KTP crystal and the typical cavity parameters: $\omega_1 = 1.198\times10^{15}$ sec^{-1}, $\omega_2 = 5.712\times10^{14}$ sec^{-1}, $\hbar\omega_3 = 1.865\times10^{-19}$ J, $d_{eff} = 3.64$ pm/V, $l_{nl} = 20$ cm, $n_1 = 1.737$ $n_2 = 1.771$, $n_3 = 1.748$, $\varepsilon_0 = 8.854$ pF/m, $L_s = 0.01$, $\gamma =$ 0.9, $g_s = 0.9$, $\tau_p = 10$ ns and c = 3×10^8 m/s. It can be seen that the threshold photon density $\phi_{f,th}$ increases from 6×10^{15} cm^{-3} to 6×10^{16} cm^{-3} for the reflectivity R_s varying from 99.9% to 0.1%. As analyzed earlier, the obtainable intracavity photon density of the fundamental wave generally exceeds 10^{17} cm^{-3}. Therefore, the intracavity OPO for any value of R_s can be promisingly generated in the shared cavity, as long as the pump energy can excite the fundamental wave to bleach the saturable absorber and to overcome the lasing threshold.

#104782 - $15.00 USD Received 1 Dec 2008; revised 18 Dec 2008; accepted 22 Dec 2008; published 26 Jan 2009

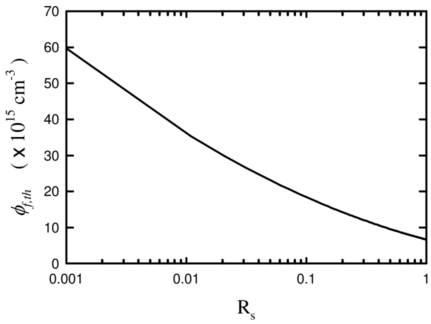

Fig. 2. Calculated results for the dependence of the threshold photon density on the output reflectivity R_s.

4. Experimental results and discussions

Figure 3 shows the experimental results for the threshold pump energy versus the OPO output reflectivity. Experimental results confirm that the threshold pump energy is determined by the bleach of the saturable absorber not by the signal output reflectivity. Consequently, a wide range of the signal output reflectivity can be used to optimize the output performance. Figure 4 depicts the experimental results for the pulse energy of the signal output versus the signal output reflectivity. The optimal output reflectivity for the output pulse energy can be found to be within R_s =40–50%. With the optimum output coupler, the conversion efficiency from the diode input energy to the signal output energy is approximately 7%, which is slightly superior to the efficiency of 4–6% obtained in a coupled cavity [15].

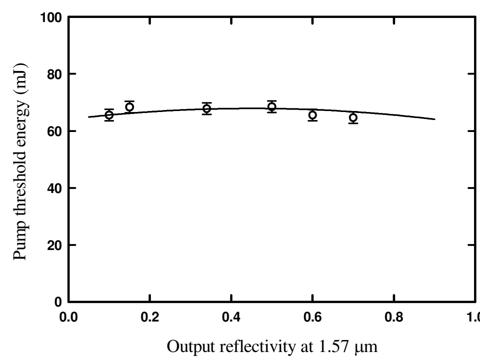

Fig. 3. Experimental results for the threshold pump energy versus the OPO output reflectivity.

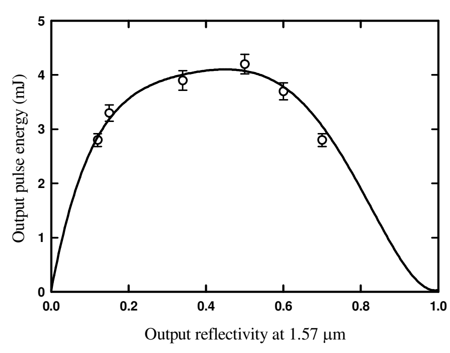

Fig. 4. Experimental results for the pulse energy of the signal output versus the OPO output reflectivity.

#104782 - $15.00 USD Received 1 Dec 2008; revised 18 Dec 2008; accepted 22 Dec 2008; published 26 Jan 2009

Figures 5(a)-(c) show the experimental results for the temporal shapes of the fundamental and the signal pulses obtained with three different output couplers. It can be seen that the pulse durations of the signal output are 4.4 ns, 2.1 ns, and 0.85 ns for R_s=60%, 50%, and 15%, respectively. The pulse width obtained with R_s = 15% is 2.4 times shorter than that obtained with R_s = 50%; however, the pulse energy is only 20% less than the maximum value. In other words, the peak power reached with R_s = 15% can be nearly two times higher than that obtained with R_s = 50%. To be more accurate, the output peak was calculated with the experimental pulse energy and the numerical integration of the measured temporal pulse profile. Figure 6 depicts the experimental results for the peak power of the signal output versus the OPO output reflectivity. The optimal output reflectivity for the output peak power can be found to be within R_s =10–20%. With the optimum output coupler, the maximum peak power can be up to 1.5 MW.

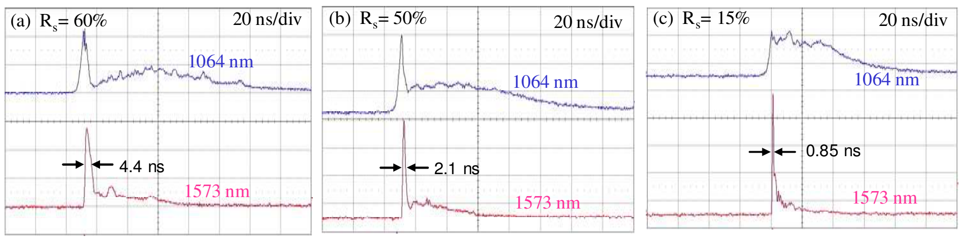

Fig. 5. Experimental results for the temporal shapes of the fundamental and the signal pulses.

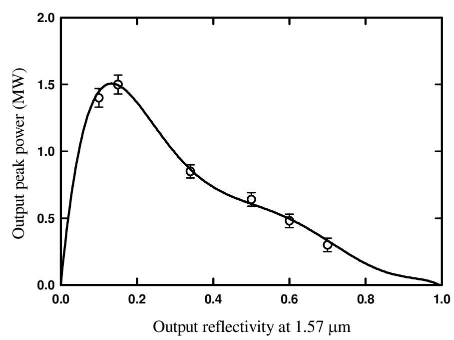

Fig. 6. experimental results for the peak power of the signal output versus the OPO output reflectivity.

5. Summary

In summary, we have theoretically and experimentally explored the output performance of an intracavity OPO in a shared cavity configuration. The threshold of an intracavity OPO pumped by a passively Q-switched Nd:YAG laser has been verified to be utterly controlled by the bleach of the saturable absorber not by the signal output reflectivity. Based on thorough experimental studies, we found that an efficient subnanosecond eye-safe laser with 3.3 mJ pulse energy and 1.5 MW peak power could be achieved with a signal output reflectivity of 15%.

Acknowledgments

The authors also thank the National Science Council for their financial support of this research under Contract No. NSC-97-2112-M-009-016-MY3.

#104782 - $15.00 USD Received 1 Dec 2008; revised 18 Dec 2008; accepted 22 Dec 2008; published 26 Jan 2009