Influence of output coupling on the performance of a passively Q-switched Nd:YAG laser with intracavity optical parametric oscillator

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Abstract: A singly-resonant intracavity optical parametric oscillator (OPO), pumped by a passively Q-switched Nd:YAG laser, is systematically investigated by means of a series of the output mirrors with various reflectivities for the fundamental wavelength at 1064 nm. Experimental results reveal that the output mirror with partial reflectivity instead of high reflection at 1064 nm not only is practicable to avoid the optical coatings damaged, but also enhances the dual-wavelength output efficiency for the OPO signal and fundamental laser waves. The overall optical-to-optical conversion efficiency is enhanced from 6.4% to 8.2% for the reflectivity decreasing from 99.8% to 90%.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3540) Lasers, Q-switched; (190.4410) Nonlinear optics, parametric processes; (140.3530) Lasers, neodymium.

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1. Introduction

Nonlinear optical frequency conversions are quite attractive for wavelength extension of solid-state lasers. Optical parametric oscillators (OPOs), pumped with mature Nd-doped Q-switched lasers, are commonly utilized for extending into the eye-safe region. Intracavity OPO takes the advantage of higher circulating intensity within the laser cavity, which allows lower pump threshold and higher conversion efficiency compared with the external configuration. With the advent of high-damage-threshold nonlinear crystals, many eye-safe intracavity OPO systems with high-power or high-energy outputs have been reported [1–4], and they are currently of great interest in military applications, particularly for the long-range laser finders. Traditionally, intracavity OPO exploits the output mirror with high-reflectivity coating for the fundamental pump wavelength. The high-power or high-energy intracavity OPOs, however, suffer from optical damage problems due to the extremely intense intracavity fluence for reaching the OPO threshold [5,6]. Recently, the output mirror with partial reflectivity for the fundamental wavelength was exploited in the actively Q-switched intracavity OPO for the reduction of a risk of optical damage [6–8]. Nevertheless, the influence of output coupling on the performance of a Q-switched laser with the intracavity OPO has not been thoroughly investigated so far.

In this work, we systematically explore the singly-resonant KTP-based intracavity OPO with a shared resonator, pumped by a passively Q-switched Nd:YAG/Cr^{4+}:YAG laser, by means of a series of output mirrors with different reflectivitives for the fundamental wavelength. The intracavity fluence is diminished one order of magnitude by the usage of an output mirror with a partial-reflectivity of 90%–98% instead of the highly reflective one of 99.8%. In addition, the partial-reflectivity output mirrors are experimentally practicable to avoid the optical damage. With the reflectivity of 99.8%, 98%, 94%, and 90%, the output pulse energies at 1572 nm are 10.8, 9.1, 7.7, and 6.6 mJ, respectively; the corresponding pulse energies at 1064 nm are 0.1, 1.9, 5.3, and 8.9 mJ, respectively. The overall optical-to-optical conversion efficiency is enhanced from 6.4% to 8.2% for the reflectivity decreasing from 99.8% to 90%. It is also found that lowering the reflectivity from 99.8% to 90% brings an increase in 1572-nm peak power from 580 to 820 kW, and the peak power at 1064 nm had a maximum value of 300 kW for the reflectivity of 90%.

2. Experimental setup

Figure 1 depicts the experimental scheme for an intracavity OPO driven by a diode-pumped passively Q-switched Nd:YAG / Cr^{4+}:YAG laser with a shared resonator. The structure of the shared resonator is that the OPO cavity completely overlaps with the fundamental laser cavity. The present fundamental laser cavity comprised a coated Nd:YAG crystal and an output coupler. The pump source was a quasi-cw high-power diode stack (Coherent G-stack package, Santa Clara, Calif., USA) which consisted of six 10-mm-long diode bars with a maximum output power of 120 W per bar at the central wavelength of 808 nm. The diode stack was constructed with 400 μm spacing between the diode bars and consequently the whole emission area was approximately 10 mm (slow axis) × 2.4 mm (fast axis). The full divergence angles in the fast and slow axes were approximately 35° and 10°, respectively. In the experiment, the diode stack was driven to emit optical pulse durations of 300 μs at a repetition rate less than 30 Hz with a maximum duty cycle of 1%. The pump radiation was delivered into the gain medium with a lens duct that was possessed of the advantages of simple fabrication, high coupling efficiency, and insensitivity to slight misalignment. The design 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 [9,10]. In our experiment, the lens duct was manufactured with the parameters of r = 10 mm, L = 29 mm, H_1 = 12 mm, H_2 = 3.5 mm, and H_3 = 3.5 mm. The coupling efficiency of the lens duct was experimentally measured to be approximately 85%.

The gain medium was a 1.0 at. % Nd:YAG crystal with a diameter of 6 mm and a length of 20 mm. The entrance surface of the laser crystal was coated with high reflection at 1064 nm and 1572 nm (R>99.8%) and high transmission at 808 nm (T>90%); the other surface of the laser crystal was coated with antireflection at 1064 nm and 1572 nm (R<0.2%). The saturable absorber for the passively Q-switching was a Cr^{4+}:YAG crystal with a thickness of 2

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mm and an initial transmission of 50% at 1064 nm. The nonlinear crystal for the OPO was a KTP crystal with a cross section of 4 mm × 4 mm and a length of 20 mm. The KTP crystal was *x*-cut (θ = 90°, and φ = 0°) for type II noncritical phase-matching to eliminate walk-off effect between the fundamental, signal, and idler beams. Both surfaces of the KTP and Cr^{4+}:YAG crystals were coated for anti-reflection at 1064 and 1572 nm. All crystals were wrapped with indium foil and mounted in conductively cooled copper blocks. Several output couplers with the reflectivity of 99.8%, 98%, 94%, and 90% at 1064 nm were used to investigate the influence of output coupling on the performance of a passively Q-switched Nd:YAG laser with an intracavity OPO. The reflectivities at 1572 nm for all output couplers were experimentally measured to be around 25%. Note that the optimal output reflectivity at the signal wavelength for the intracavity OPO has been previously verified to be approximately 10–30% [2]. The total cavity length was approximately 55 mm. The spectral information was monitored by an optical spectrum analyzer (Advantest Q8381A) that employs a diffraction grating monochromator to measure high-speed light pulses with the resolution of 0.1 nm. A LeCroy digital oscilloscope (Wavepro 7100; 10 G samples/sec; 1 GHz bandwidth) with two fast InGaAs photodiodes was used to record the pulse temporal behavior.

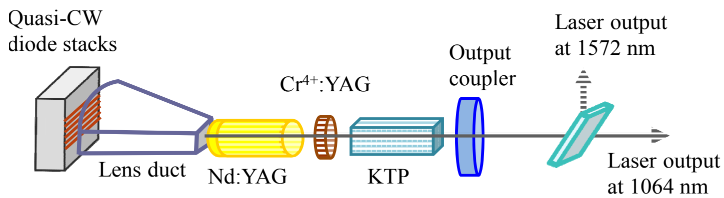

Fig. 1. Experimental setup for an intracavity OPO pumped by a diode-pumped passively Q-switched Nd:YAG / Cr^{4+}:YAG laser with a shared resonator.

3. Experimental results

Experimental results revealed that the pump threshold energies for the OPO were 170, 175, 182, and 188 mJ for the reflectivity of 99.8%, 98%, 94%, and 90% at 1064 nm, respectively. The pump threshold energy can be found to increase linearly with decreasing the output reflectivity. Note that the output coupler with a reflectivity below 90% was not employed in this experiment since the OPO threshold exceeded the available diode pump energy. The dependence of the pump threshold energy on the reflectivity can be calculated with [11]

$$E_{th} = \frac{1}{\eta_p} \frac{h\nu_p}{2\sigma} \left[\ln\left(1/T_o^{\,2}\right) + \ln\left(1/R\right) + L \right], \tag{1}$$

where η_p is the pump efficiency including the overlapping efficiency and the absorption efficiency, $h\nu_p$ is the pump photon energy, T_o is the initial transmission of the saturable absorber, L is the round-trip fundamental wave intensity loss in the cavity, and R is the output reflectivity at the fundamental laser wavelength. With the properties of the Nd:YAG and Cr^{4+}:YAG crystals and the typical cavity parameters: $\sigma = 2.8 \times 10^{-19}$ cm^2, $h\nu_p = 2.46 \times 10^{-19}$ J, $\eta_p = 0.54$, $A = 0.16$ cm^2, $T_o = 0.5$, and $L = 0.01$, the theoretical threshold energies were calculated to compare with the experimental results, as shown in Fig. 2. It can be seen that the experimental results agree very well with the theoretical values.

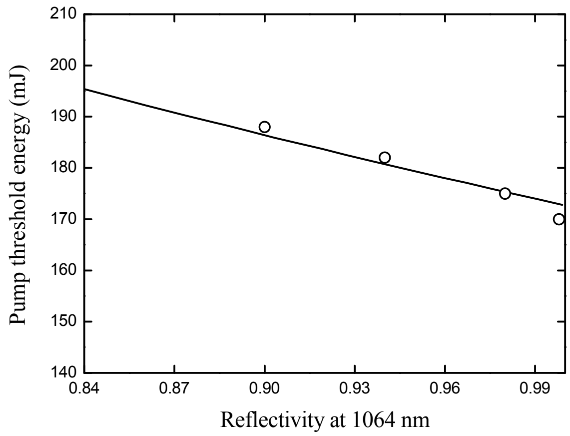

Fig. 2. The pump threshold energy with respect to the reflectivity at the fundamental laser wavelength of 1064 nm; solid lines: theoretical results; symbols: experimental values.

The experimental results for the output pulse energy with respect to the reflectivity at the fundamental wavelength of 1064 nm are shown in Fig. 3. Lowering the reflectivity at 1064 nm can be found to lead to a decrease in the signal output pulse energy at 1572 nm and a relative increase in the output pulse energy at 1064 nm. With the reflectivity of 99.8%, 98%, 94%, and 90%, the output pulse energies at 1572 nm were 10.8, 9.1, 7.7, and 6.6 mJ, respectively; the corresponding pulse energies at 1064 nm were 0.1, 1.9, 5.3, and 8.9 mJ, respectively. As a result, the total pulse energy of fundamental laser and OPO signal outputs increased from 10.9 mJ up to 15.5 mJ for the reflectivity decreasing from 99.8% to 90%. Divided by the pump threshold energy, the overall conversion efficiency was enhanced from 6.4% to 8.2% for the reflectivity decreasing from 99.8% to 90%. More importantly, the damage of the output coupler with the reflectivity of 99.8% was observed in this experiment, as illustrated in the insert of Fig. 3, but the output couplers with reflectivity of 90%–98% were not. In other words, the partial-reflectivity output coupler for the intracavity OPO not only is practicable to avoid the optical damage, but also enhances the overall output efficiency for the OPO signal and fundamental laser waves.

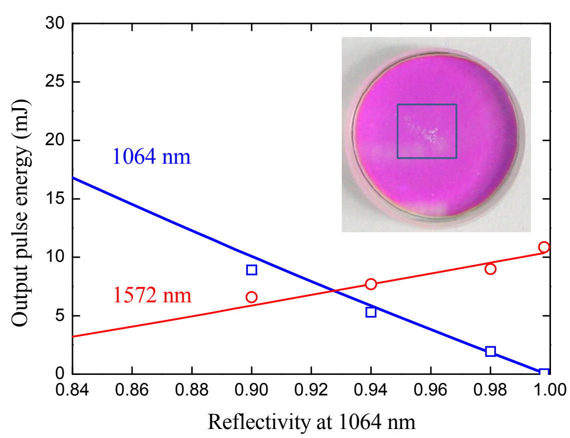

Fig. 3. Calculated and experimental results for the output pulse energy with respect to the reflectivity at the fundamental laser wavelength of 1064 nm; solid lines: theoretical results calculated from Eqs. (2)-(7); symbols: experimental results. Insert: a photograph for the damage of the output coupler with the reflectivity of 99.8%.

Based on the rate equation model for the passively Q-switched laser [12], the output pulse energies of the fundamental laser and OPO signal outputs for passively Q-switched

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intracavity OPOs with respect to the reflectivity at 1064 nm can be calculated. At first, the initial population of the passively Q-switched laser was employed in the rate equation model of Ref [12] to calculate the output pulse energies of the fundamental laser and OPO signal for passively Q-switched intracavity OPOs with a shared-resonator configuration. In a passively Q-switched laser, the initial population inversion density in the gain medium, $n(0) = n_i$, can be determined from the condition that the roundtrip gain is exactly equal to the roundtrip losses just before the Q-switch opens, i.e.

$$n_i = \frac{1}{2\sigma l}\left[\ln\left(1/T_o^2\right) + \ln\left(1/R\right) + L\right]. \tag{2}$$

Since only fundamental laser and signal waves were resonated in the shared resonator, the evolution equation of the idler wave was eliminated. The rate equations for the four-level Q switched laser with intracavity OPO are given by

$$\frac{dn}{dt} = -c\sigma\varphi_p n\ , \tag{3}$$

$$\frac{d\varphi_p}{dt} = \frac{l_{cr}}{l_{ca}}c\sigma n\left(\varphi_p + \Delta\varphi_p\right) - \frac{l_{nl}}{l_{ca}}\sigma_{opo}\varphi_s\varphi_p - \frac{\varphi_p}{t_r}\left[\ln\left(1/R\right) + L\right], \tag{4}$$

$$\frac{d\varphi_s}{dt} = \frac{l_{nl}}{l_{ca}}c\sigma_{opo}\varphi_p\left(\varphi_s + \Delta\varphi_s\right) - \frac{\varphi_s}{t_r}\left[\ln\left(1/R_s\right) + L_s\right], \tag{5}$$

where n is the inversion population density of the gain medium, σ is the stimulated emission cross section of the gain medium, c is the speed of light; φ_p is the fundamental laser photon density, φ_s is the OPO signal photon density, l_{ca} is the optical length of the laser cavity, l_{cr} is the length of the gain medium, l_{nl} is the length of the nonlinear crystal, σ_{opo} is the effective OPO conversion cross section, t_r is the round-trip time in the resonator cavity,⊗ $\Delta\varphi_p$ is the spontaneous emission intensity, $\Delta\varphi_s$ is the noise signal intensity, L_s is the round-trip signal wave intensity loss, and R_s is the output reflectivity at the OPO signal wavelength. The effective OPO cross section, σ_{opo}, is used to describe the conversion rate and derived from the parametric gain coefficient for small gains of the single resonator oscillator:

$$2\sigma_{opo}l_{nl} = \frac{8\omega_i\omega_s d_{eff}^2 l_{nl}^2}{n_i n_s n_p \varepsilon_o c^2}\frac{A_p}{A_s + A_p}, \tag{6}$$

where ω_i and ω_s are the idler and signal frequencies, respectively; n_1, n_2 and n_3 are the refractive indices at the idler, signal and fundamental laser wavelengths, respectively; d_{eff} is the effective nonlinear coefficient; ε_0 is the vacuum permittivity; A_s and A_p are the mode areas for the OPO signal and fundamental laser, respectively. The output pulse energy can be expressed as [13]

$$E_j = \frac{h\nu_j A_j}{2\sigma}\ln\left(1/R\right)\int\varphi_j(t)dt, \tag{7}$$

where hv is the photon energy, A is the beam area and φ is the above-mentioned photon density. The subscripts $j = s, p$ represents the OPO signal and fundamental laser, respectively.

The solid lines in Fig. 3 depicts the calculated results for the output pulse energies for the dependence of reflectivity at 1064 nm with the properties of the Nd:YAG, KTP crystals and the typical cavity parameters: $hv_s = 1.26 \times 10^{-19}$ J, $hv_p = 1.86 \times 10^{-19}$ J, $\omega_i = 5.712 \times 10^{14}$ sec^{-1}, $\omega_s = 1.198 \times 10^{15}$ sec^{-1}, $l_{cr} = 2.0$ cm, $l_{nl} = 2.0$ cm, $d_{eff} = 3.64$ pm/V, $n_i = 1.771$, $n_s = 1.737$, $n_p = 1.748$, $\varepsilon_0 = 8.854$ pF/m, $A_s = 0.108$ cm^2, $A_p = 0.16$ cm^2, $l_{ca} = 5.5$ cm, $R_s = 0.25$, L

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= L_s = 0.01, and $c = 3 \times 10^8$ m/s. The theoretical values agree very well with the experimental results. Moreover, it can be seen that the output energy of the OPO signal slightly decreases with decreasing the fundamental reflectivity, whereas the output energy of the fundamental laser considerably increases. Consequently, the dual-wavelength output efficiency for the OPO signal and fundamental laser waves was considerably greater than the output efficiency for only the OPO signal wave.

Typically temporal shapes for the OPO signal at 1572 nm were shown in Figs. 4(a)-4(d) for the reflectivity of 99.8%, 98%, 94%, and 90% at 1064 nm, respectively; the corresponding temporal shapes for the depleted fundamental laser at 1064 nm were simultaneously recorded. It can be seen that the OPO signal-pulse energy would be effectively concentrated in the first pulse for the reflectivity decreasing from 99.8% to 90%. As a result the peak power at 1572 nm increased from 580 to 820 kW as the reflectivity decreased from 99.8% to 90%, as shown in Fig. 5. The peak powers were precisely deduced by the numerical integration for the measured temporal pulse profiles to fit the experimental pulse energies. The peak power at 1064 nm had a maximum value of 300 kW for the reflectivity of 90%. We also employed the knife-edge method to evaluate the beam quality. The beam quality M^2 factor at 1572 nm was measured to be approximately 1.4.

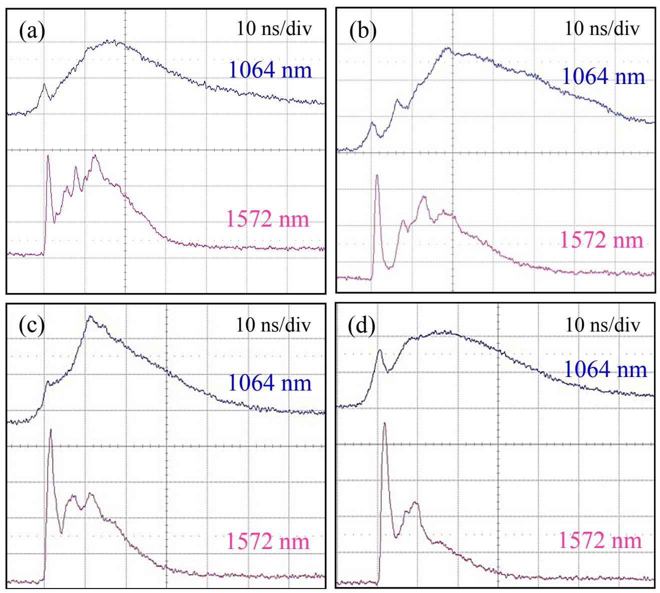

Fig. 4. Experimentally temporal shapes of the fundamental laser (1064 nm) and OPO signal (1572 nm) pulses for the reflectivity of (a) 0.998, (b) 0.98, (c) 0.94, and (d) 0.9.

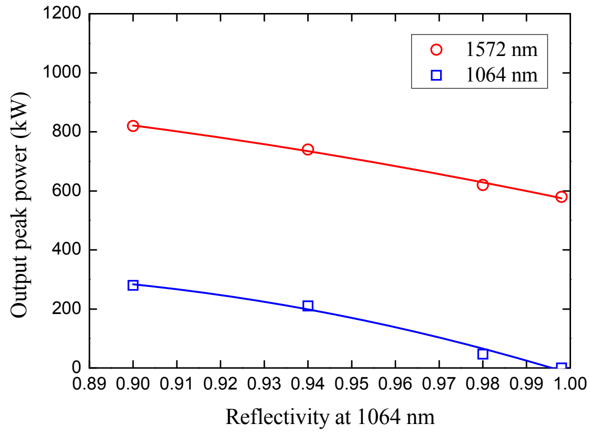

Fig. 5. The output peak power with respect to the reflectivity at the fundamental laser wavelength of 1064 nm.

4. Conclusion

We have systematically investigated the influence of output coupling on the performance of the singly-resonant intracavity OPO pumped by a passively Q-switched Nd:YAG/Cr^{4+}:YAG laser. Experimental results reveal that the output couplers with partial reflectivity for the fundamental laser wavelength at 1064 nm not only are practicable to avoid the optical coatings damaged, but also enhance the dual-wavelength output efficiency for the OPO signal wave at 1572 nm and fundamental laser wave at 1064 nm. The output pulse energies for OPO signal at 1572 nm were 10.8, 9.1, 7.7, and 6.6 mJ and the corresponding pulse energies for fundamental laser at 1064 nm were 0.1, 1.9, 5.3, and 8.9 mJ for the reflectivity of 99.8%, 98%, 94%, and 90% at 1064 nm, respectively. The overall optical-to-optical conversion efficiency was enhanced from 6.4% to 8.2% for the reflectivity decreasing from 99.8% to 90%.

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