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Output optimization of a high-repetition-rate diode-pumped Q-switched intracavity optical parametric oscillator at 1.57 μm

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ABSTRACT The output optimization of a high-repetition-rate diode-pumped Q-switched intracavity optical parametric oscillator at 1573 nm with a type-II non-critically phase-matched *x*-cut KTP is experimentally and theoretically studied. The optimum output reflectivity is found to be 85%–90% for the maximum average power. The average conversion efficiency from diode-laser input power to OPO signal output power is up to 15% at a pulse repetition of 80 kHz. However, the optimum output reflectivity for the maximum peak power is found to be 60%–70%; the overall peak power amounts to 3–4 kW at a pulse repetition of 80 kHz.

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1 Introduction

High-peak-power laser sources at wavelengths greater than 1.5 μm are vital for applications involving coherent laser radar, remote sensing and active imaging [1]. In this spectral range, radiation is mostly absorbed in the ocular fluid of the eye rather than in the retina. Eye safety is an important requirement for laser applications involving free-space propagation. This need has stimulated much interest in intracavity optical parametric oscillators (OPOs). In comparison with extracavity configurations, intracavity OPOs take advantage of the high power level within the oscillator to allow a low threshold and high efficiency. Even though intracavity OPOs have been proposed for over 30 years [2–4], only recently have their merits been noted by the availability of high-damage-threshold non-linear crystals and diode-pumped Nd-doped lasers [1, 5–7]. Several crystals belonging to the potassium titanyl phosphate (KTP) family, when pumped by Nd-doped laser pumps around 1050–1070 nm, generate signal wavelengths around 1.55 μm [8–11]. The conventional intracavity OPOs in which flash lamps or quasi-cw diodes are used as the pump sources typically restrict operations to low repetition rates, less than 1 kHz [12, 13]. Although a compact diode-pumped Q-switched intracavity OPO has been demonstrated at a frequency repetition rate from 1 to 20 kHz, the overall average power is less than 60 mW [14].

Recently, we demonstrated 1.33 W of 1573-nm output from an intracavity OPO based on a non-critically phase-matched KTP pumped by a diode-pumped acousto-optically (AO) Q-switched Nd : YVO$_4$ laser operating at 80 kHz [15]. In this work, we experimentally study the output optimization of a high-repetition-rate diode-pumped Q-switched intracavity optical parametric oscillator at 1.57 μm. Experimental results reveal that the output reflectivity for the maximum conversion efficiency is in the range 85%–90%, whereas the highest peak power can be obtained with the output reflectivity around 60%–70%. Numerical analysis is performed to confirm the experimental results.

2 Experimental set-up

A schematic of the actively Q-switched intracavity OPO laser is shown in Fig. 1. The active medium was an *a*-cut 0.3 − at%. Nd^{3+}, 7-mm-long Nd : YVO$_4$ crystal. A Nd : YVO$_4$ crystal of low doping concentration was used to avoid thermally induced fracture [16]. Both sides of the laser crystal were coated for antireflection at 1064 nm ($R < 0.2\%$). The pump source was a 15-W 809-nm fiber-coupled laser diode with a core diameter of 0.8-mm and a numerical aperture of 0.16. A focusing lens with 12.5-mm focal length and 85% coupling efficiency was used to re-image the pump beam into the laser crystal. The waist radius of the pump beam was around 0.36 mm. The input mirror, M1, was a 1-m radius-of-curvature concave mirror with antireflection coating at the diode wavelength on the entrance face ($R < 0.2\%$), high-reflection coating at the lasing wavelength ($R > 99.8\%$) and high-transmission coating at the diode wavelength on the other surface ($T > 95\%$). 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 ($50\% \le R_s \le 95\%$) at 1573 nm were used in the experiment to study the output optimization. The 10-mm-long AO Q-switcher (NEOS) was antireflection coated at 1064 nm on both faces and was driven at a 80 MHz center frequency with 3.0 W of rf power. To avoid damage to the intracavity optical components, the Q-switcher was operated above 10 kHz. The OPO cavity was formed by a coated KTP crystal and an output coupler. The 20-mm-long KTP crystal was used in type-II non-critical phase-matching configuration along the *x*-axis ($\theta = 90°$ and $\varphi = 0°$) to have both

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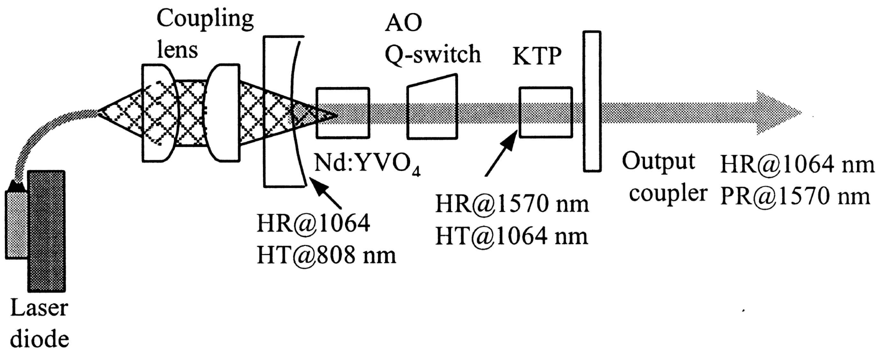

FIGURE 1 Schematic of the actively Q-switched intracavity OPO laser

a maximum effective non-linear coefficient and no walk-off between the pump, signal and idler beams. One surface of the KTP crystal was coated to have high reflectivity at the signal wavelength of 1573 nm ($R > 99.8\%$) and high transmission at the pump wavelength of 1064 nm ($T > 95\%$). The other face of the KTP crystal was antireflection coated at 1573 nm and 1064 nm. Both the Nd : YVO$_4$ and KTP crystals were wrapped with indium foil and mounted in a water-cooled copper block. The water temperature was maintained at 25 °C. The overall Nd : YVO$_4$ laser cavity length was 55 mm and the OPO cavity length was 23 mm. The pulse temporal behavior at 1573 nm was recorded by a LeCroy 9362 digital oscilloscope (500 MHz bandwidth) with a fast germanium photodiode.

3 Results and discussion

Figure 2 shows the average output power at 1573 nm as a function of the repetition for different output couplers at an absorbed pump power of 12.6 W. The radius of the OPO beam was estimated to be around 0.3 mm. Over the entire frequency range, the beam quality M^2 factor was found to be less than 1.3. Basically, increasing the pulse repetition rate can efficiently increase the average output power at 1573 nm, except that the OPO reflectivity is too low ($R_s = 50\%$). It can be also seen that a higher output coupler reflectivity ($85\% \leq R_s \leq 90\%$), on average, leads to higher conversion efficiency. However, if the OPO output reflectivity is too high, the stored energy is not fully extracted in a single output pulse. Since the remaining energy is sufficient to evolve the pump field, the OPO threshold can be reached again and a second signal pulse is produced. As shown in Fig. 3a and b, a train of OPO pulses is usually produced for higher values of R_s, whereas a single pulse can be generated with a lower output reflectivity. In addition, the pulse width was found to be generally less than 5 ns. The short pulse width

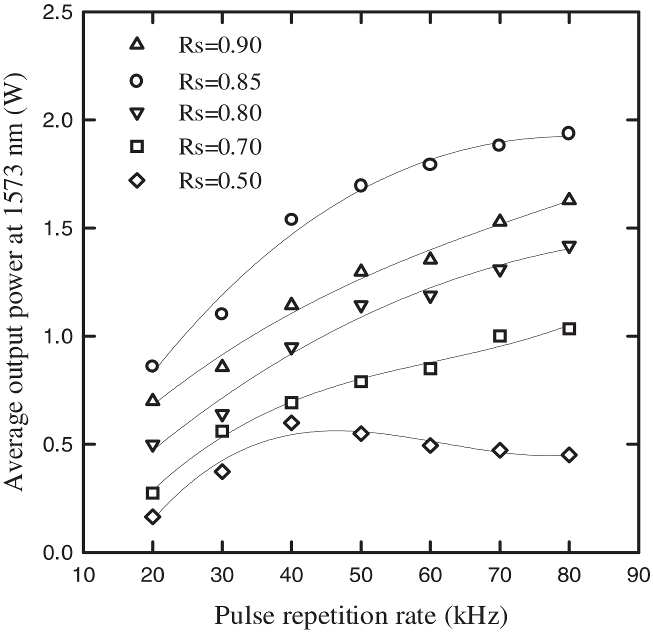

FIGURE 2 The average output power at 1573 nm as a function of the repetition for different output couplers at an absorbed pump power of 12.6 W

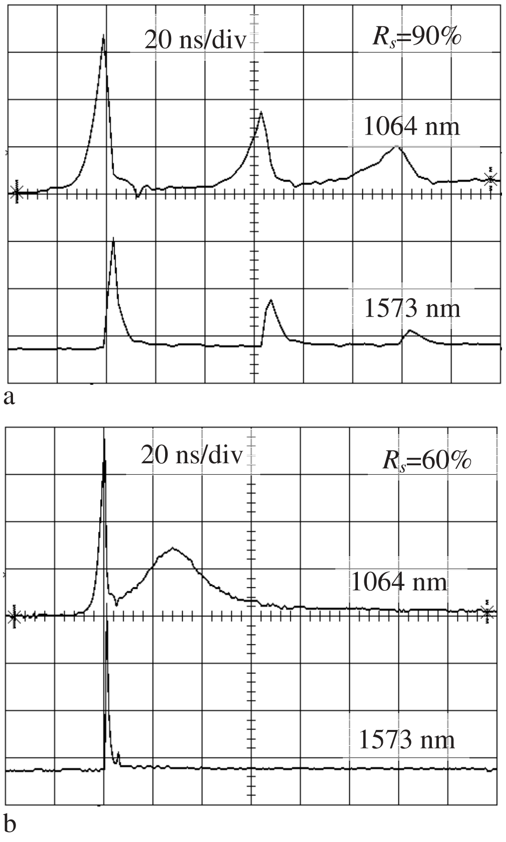

FIGURE 3 Oscilloscope traces showing a train of pump and signal pulses when $R_s = 90\%$ (**a**), and a single pulse for pump and signal fields when $R_s = 60\%$ (**b**). Both results were measured at a pulse repetition rate of 80 kHz and an absorbed pump power of 12.6 W

comes from the effective cavity dump of the intracavity OPO. Therefore, if high peak power is preferred, the OPO output reflectivity needs to be chosen to maximize the conversion in a single pulse.

We have employed the rate equation model developed by Debuisschert et al. [17] to confirm the experimental results. Since the present IOPO is resonant only on the signal, the evolution equation of the idler field can be suppressed. With this adiabatic elimination, the rate equations for the four-level Q-switched laser with IOPO are given by:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -c\sigma\varphi_{\mathrm{P}} n\,, \tag{1}$$

$$\frac{\mathrm{d}\varphi_{\mathrm{p}}}{\mathrm{d}t} = \frac{l_{\mathrm{cr}}}{l_{\mathrm{ca}}} c\sigma n\left(\varphi_{\mathrm{p}} + \Delta\varphi_{\mathrm{p}}\right) - \frac{l_{\mathrm{nl}}}{l_{\mathrm{ca}}} \sigma_{\mathrm{opo}}\,\varphi_{\mathrm{s}}\varphi_{\mathrm{p}} - \frac{\varphi_{\mathrm{p}}}{t_{\mathrm{rp}}}\left[\ln\left(\frac{1}{R}\right) + L\right], \tag{2}$$

$$\frac{\mathrm{d}\varphi_{\mathrm{s}}}{\mathrm{d}t} = c\sigma_{\mathrm{opo}}\varphi_{\mathrm{p}}\left(\varphi_{\mathrm{s}} + \Delta\varphi_{\mathrm{s}}\right) - \frac{\varphi_{\mathrm{s}}}{t_{\mathrm{rs}}}\left[\ln\left(\frac{1}{R_{\mathrm{s}}}\right) + L_{\mathrm{s}}\right], \tag{3}$$

where n is the inversion population density of the gain medium, c is the speed of light, φ_{p} is the pump photon density, φ_{s} is the signal photon density, l_{ca} is the optical length of the laser cavity, σ is the stimulated emission cross section of the gain medium, t_{rp} is the round-trip time in the laser cavity, l_{cr} is the length of the gain medium, l_{nl} is the length of the non-linear crystal, $\Delta\varphi_{\mathrm{p}}$ is the spontaneous emission intensity, L is the round-trip pump wave intensity loss in the laser cavity, R is the global reflectivity of the laser cavity mirrors, t_{rs} is the round-trip time in the OPO resonator, σ_{opo} is the effective OPO conversion cross section, $\Delta\varphi_{\mathrm{s}}$ is the noise signal intensity, L_{s} is the round-trip signal wave intensity loss in the OPO cavity and R_{s} is the output reflectivity of the OPO mirror. Equations 1–3 are essentially identical to those used by Debuisschert et al. [17], except that the effective OPO cross section is used to describe the conversion rate. The effective OPO cross section, σ_{opo}, can be derived from the parametric gain coefficient for small gains of the single resonator oscillator:

$$2\sigma_{\mathrm{opo}} l_{\mathrm{nl}} = \frac{8\omega_1\omega_2 \mathrm{d}_{\mathrm{eff}}^2 l_{\mathrm{nl}}^2}{n_1 n_2 n_3 \varepsilon_o c^2} \frac{w_3^2}{w_2^2 + w_3^2}\,, \tag{4}$$

where ω_1 and ω_2 are the idler and signal frequencies, respectively; n_1, n_2 and n_3 are the refractive indices at the idler, signal and pump wavelengths, respectively; d_{eff} is the effective non-linear coefficient; ε_0 is the vacuum permittivity; and w_2 and w_3 are the mode sizes for the signal and laser waves, respectively.

Figure 4a and b depicts the calculated temporal profiles corresponding to the experimental results shown in Fig. 3a and b, respectively. The good agreement between experimental and numerical results indicates that the theoretical model is successful in predicting the production of several signal pulses. Figure 5 shows the experimental and theoretical results for the average output power versus the OPO output reflectivity at a repetition rate of 80-kHz and an absorbed pump power of 12.6-W. It can be seen that the theoretical calculations agree quite well with the experimental data. The optimum output coupler for the maximum average power is

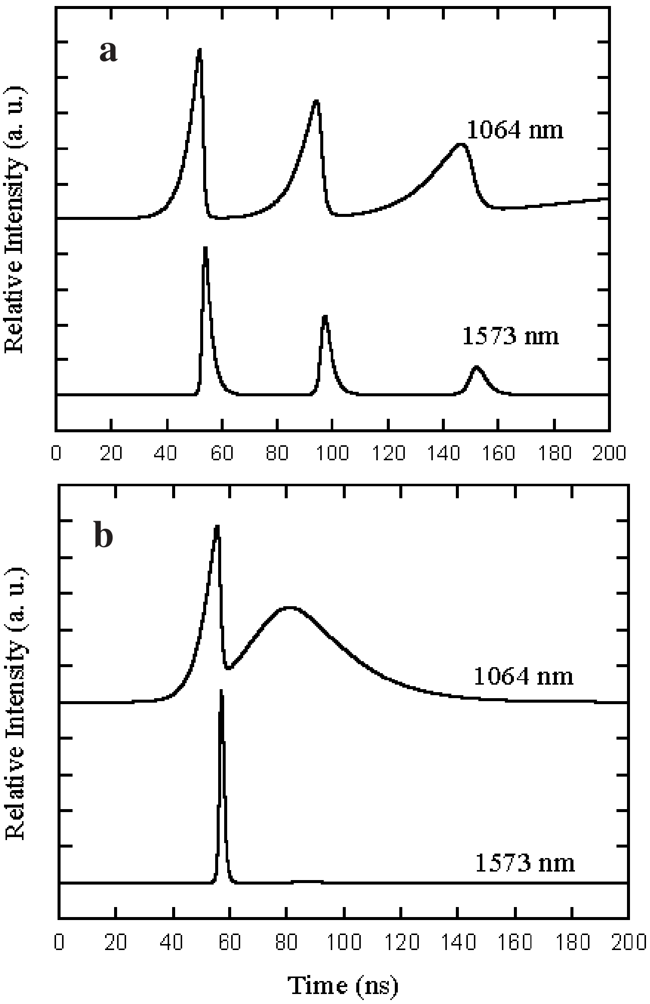

FIGURE 4 The calculated temporal profiles corresponding to the experimental results shown in Fig. 3a and b, respectively

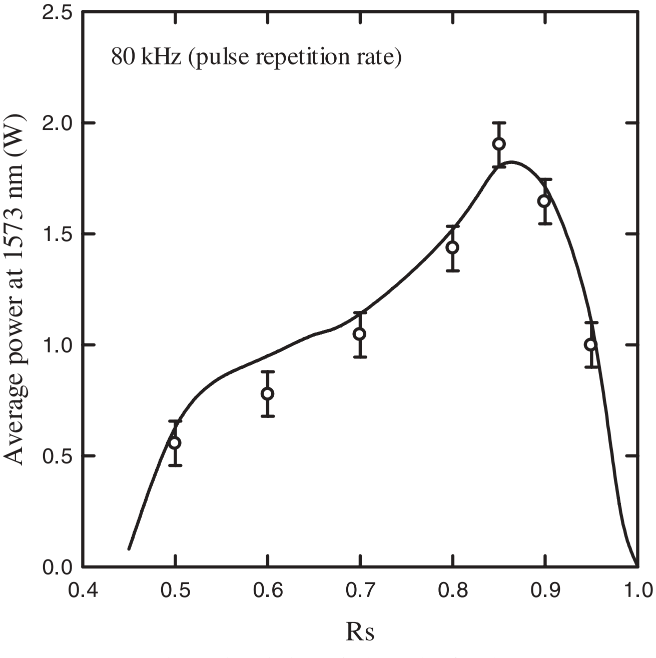

FIGURE 5 Experimental and theoretical results for the average output power versus the OPO output reflectivity at a repetition rate of 80 kHz and an absorbed pump power of 12.6 W

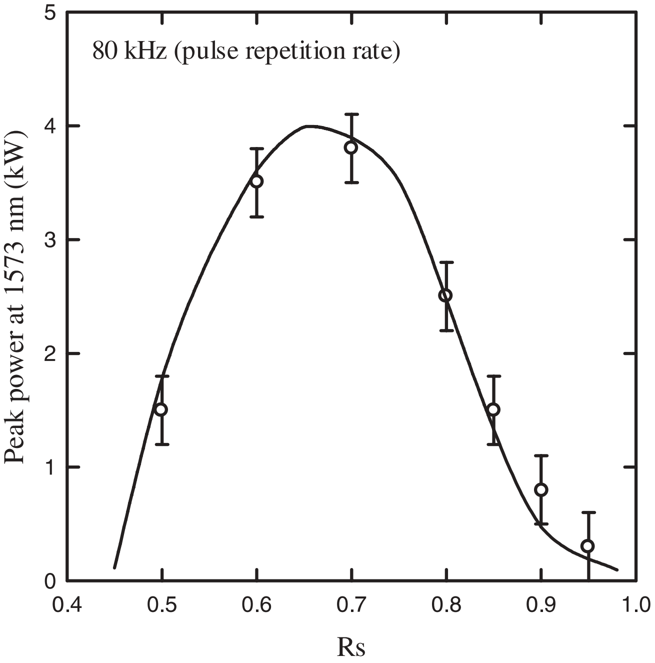

FIGURE 6 Experimental and theoretical results for the output peak power versus the OPO output reflectivity at a repetition rate of 80 kHz and an absorbed pump power of 12.6 W

found to be approximately $R_s = 85\%$. With the optimum output coupler, the conversion efficiency from the diode laser input power to OPO signal output power is up to 15%.

Although the highest conversion efficiency was obtained with an output coupler of $R_s = 85\%$, the peak power was a maximum with an output coupler of $R_s = 60\%–70\%$, as shown in Fig. 6. It can be seen that with an output coupler of $R_s = 60\%–70\%$, the peak power can amount to 3–4 kW at a pulse repetition rate of 80 kHz and an absorbed pump power of 12.6 W. From the experimental results shown in Figs. 5 and 6, an output coupler of $R_s = 80\%$ is found to be a better choice for the tradeoff between the average power and the peak power.

Finally, it is worthwhile to mention that the pulse repetition rates in the present experiment (> 20 kHz) are considerably higher than those in conventional Q-switched lasers (< 1 kHz). On the whole, the optimum output reflectivity increases with increasing pulse repetition rate; this is the reason why the optimum output reflectivity is significantly higher than that for conventional output couplers in Q-switched lasers.

4 Conclusions

We have studied the output optimization of a high-repetition-rate diode-pumped Q-switched intracavity optical parametric oscillator at 1573 nm with a type-II non-critically phase-matched x-cut KTP crystal. Numerical calculations have also been performed to confirm the experimental results. It was found that the maximum conversion efficiency can be obtained with an output coupler of 85%–90% at the cost of peak power. If high peak power is desired, the output reflectivity needs to be around 60%–70%.

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