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High-repetition-rate intracavity optical parametric oscillator at 1.57 μm

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Abstract: The behaviour of passively Q-switched solid-state lasers containing intracavity optical parametric oscillators(OPOs) is described in detail. A diode-pumped passively Q-switched Nd:YAG, Cr^{4+}:YAG laser was employed to generate a high-repetition-rate, high-peak-power eye-safe laser beam with an intracavity optical parametric oscillator (OPO) by use of a $KTiOPO_4$ (KTP) crystal. Different ranges of repetition rates and pulse widths are obtained by using absorbers of different optical densities. With a Cr^{4+}:YAG wafer of T_0=80% low-intensity transmission, 3.8 W average power at 1.572 μm wavelength and repetition rate up to 80 kHz with pulse width as narrow as 30 ns are obtained. The peak power is up to 1.58 kW.

Key words: Optical parametric oscillator (OPO); $KTiOPO_4$ crystal; Passive Q- switch; Eye-safe

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高重频 1.57 μm 内腔光学参量振荡器

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摘要: 理论分析了被动调 Q 固体激光泵浦的光参量振荡器。利用激光二极管泵浦, Cr^{4+}:YAG 被动调 Q Nd:YAG 激光泵浦的内腔光学参量振荡器, 磷酸氧钛钾(KTP)晶体作为非线性晶体, 获得了高重复频率, 高峰值功率的人眼安全激光输出, 改变 Cr^{4+}:YAG 被动调 Q 晶体的参数, 可获得不同重频不同脉宽的调 Q 激光脉冲; 当 Cr^{4+}:YAG 晶体初始透过率为 T_0=80%时, 获得了平均功率大于 3.8 W, 重频约 80 kHz 的 1.572 μm 波长信号光输出, 脉宽 30 ns, 脉冲峰值功率达到 1.58 kW。

关键词: 光学参量振荡器; 磷酸氧钛钾; 被动调 Q; 人眼安全

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0 Introduction

Nanosecond pulsed lasers emitting in the eye-safe wavelength region (1 500~1 600 nm) are indispensable for applications such as telemetry and range finders. The need for high-peak-power eye-safe laser source has stimulated much interest in optical parametric oscillators (OPOs)[1,2].Typically,such a system consists of a separate pump laser and nonlinear crystal in an external-cavity OPO configuration,and the external OPOs have been considered and reviewed by some research groups in early stages [3]. However, in order to take advantage of the high intensity inside the pump laser cavity and increase overall efficiency, consideration has been given to intracavity OPOs(IOPOs), where the nonlinear crystal is placed in side of the Q-switched laser cavity[4-6] . The nonlinear process of IOPO occurs at the time while the pump is established. So the dynamic process is more complex than that of extra-cavity OPO (EOPO). One main idea of IOPO is to take advantage of the intense power existing in the laser cavity to pump the OPO more efficiently. The ratio of the intensity of pump in and out cavity is $I_1/I_0=1/(1-R)$.

A nanosecond pulse duration intracavity optical parametric oscillator (IOPO), compared with actively Q-switched fundamental lasers[7], passively Q-switched laser pumped IOPO, requires no high voltages or fast electrooptic drivers, and additionally, it also has the advantages such as simplicity, compactness, and light weight. Wan et al. recently have considered the performance of BDN dye film passively Q-switched IOPO[8]. But the organic dye BDN can only be employed in pulsed lasers for its poor photochemical and thermal stability in solutions, particularly in solid solutions when convective or forced mixing is impossible.Decomposition of organic dye molecules reduces both the Q-switching efficiency and the service life greatly . In recent years, Cr^{4+}:YAG crystals have attracted a great deal of attention as passive Q-switches. They have a large absorption cross section and low saturable intensity at the laser wavelength. In comparison with previously used saturable absorbers such as $LiF:F_2^-$ color centre crystal and BDN dye film, Cr^{4+}:YAG crystals are more photochemically and thermally stable and have a higher damage threshold. They can be used as Q-switches for both pulsed lasers and continuously pumped lasers, therefore become the most promising saturable absorbers for passively-switched lasers of stability, low cost, reliability, long life, compactness, and simplicity.

1 Theoretical basis

OPOs can provide efficient and relatively simple means of tunable frequency shifting. When the output of a high-power pulsed solid-state laser is focused on a nonlinear crystal, if the intensity of this pump laser is sufficiently high, the optical parametric process is initiated, and the output at frequencies that are different from that of the pump laser is generated. OPOs employ second-order nonlinearity to convert photons at the pump frequency ω_p into photons at two new frequencies, the so-called signal ω_s and idler ω_i frequencies. Energy conservation requires that the algebraic sum of the signal and idler frequencies be equal to the frequency of the pump[9].

$$\omega_p=\omega_s+\omega_i \tag{1}$$

And, like most nonlinear process, OPO must obey phase-matching constraints. Phase matching is satisfactory when the refractive indices of the pump n_p and the signal and idler waves n_s and n_i meet

$$n_p\,\omega_p=n_s\,\omega_s+n_i\,\omega_i \tag{2}$$

Since the refractive index in crystals is angularly dependent, the constraints of phase matching typically require that the OPO crystal be cut at a specific angle determined by dispersion. One can achieve efficient frequency conversion only within a narrow band of angles near this so called phase-matched angle. One generally obtains the most efficient frequency conversion for noncritically phase-matching where the optical fields propagate along principal axes of the crystal. Noncritical phase matching eliminates double refraction or walk-off effect, a phenomenon that reduces the overlap among the pump, signal, and idler beams as they propagate through the crystal. Also, noncritical phase matching increases the acceptance angle and maximizes the parametric gain.

$KTiOPO_4$ (KTP) belongs to the orthorhombic crystal system and therefore is optically biaxial. In our noncritically phase-matched configuration (θ=90°,ϕ=0°) pumped by λ_p=1 064 nm, the signal spectrum λ_s=1 572 nm just falls in the 1~2 μm atmospheric transmission window, and, most importantly, is in eye-safe spectral range[10].

The rate equations governing the behaviour of a passively Q-switched IOPO laser system, with the consideration of both the ground-state absorption and the exited–state absorption of the saturable absorber, are as follows[11]

$$\frac{dE_p(t)}{dt}=\left[\frac{\sigma n l_{laser}}{t_r}-\frac{\sigma_{gs} n_{gs} l_s+\sigma_{es} n_{es} l_s}{t_r}-\frac{\ln(1/R_p)+L}{2t_r}\right]\times E_p-\frac{\delta\omega_p I}{4\varepsilon_p}\frac{l_{crstal}}{l'}E_s(t)E_i(t)\sin\varphi(t) \tag{3a}$$

$$\frac{dE_s(t)}{dt}=-\frac{E_s(t)}{2\tau_s}-\frac{\delta\omega_s I}{4\varepsilon_s}\frac{l_{crystal}}{l_{opo}}E_p(t)E_i(t)\sin\varphi(t) \tag{3b}$$

$$\frac{dE_i(t)}{dt}=-\frac{E_i(t)}{2\tau_i}-\frac{\delta\omega_i I}{4\varepsilon_i}\frac{l_{crystal}}{l_{opo}}E_p(t)E_s(t)\sin\varphi(t) \tag{3c}$$

$$\frac{dn}{dt}=-\gamma\frac{\sigma c E_p^2(t)n}{4\hbar\omega_p} \tag{3d}$$

$$\frac{dn_{gs}}{dt}=-\gamma\frac{\sigma_{gs} c E_p^2(t)n_{gs}}{4\hbar\omega_p} \tag{3e}$$

$$\frac{dn_{es}}{dt}=-\gamma\frac{\sigma_{es} c E_p^2(t)n_{es}}{4\hbar\omega_p} \tag{3f}$$

$$n_{gs}+n_{es}=n_0 \tag{3g}$$

where $E_p(t)$, $E_s(t)$, and $E_i(t)$ are the electric fields of pump, signal and idler, respectively; and n, σ, l_{laser} are the population inversion density, the stimulated emission cross section, and the length of laser medium, respectively. R_p is the reflectivity of the output coupler mirror at pump frequency and in our experiments R_p=1, γ is the inversion reduction factor, and n_{gs}, n_{es}, are the absorber ground- and excited-state population densities, respectively. l' is the cavity optical length, and $t_r=2l'/c$ is the cavity round-trip time, where is the light speed. τ_s (τ_i) is the OPO cavity lifetime for the signal(idler), and ε_s (ε_i) is the dielectric constant of the signal (idler).For passive Q-switched lasers pumped IOPO, when the pump power exceeds a threshold condition, lasing action is initially prevented by the low transmission of the saturable absorber (i.e., low cavity Q state) while the gain medium is pumped to a high population inversion. As soon as the spontaneous emission bleaches saturable absorber, the laser resonator is in a high Q state, the fundamental laser initiats and starts to deplete the population inversion of active medium. The pump intensity builds up. When the fundamental pulse intensity exceeds the OPO threshold, the signal pulse begins to grow rapidly at the expense of the fundamental field. Then a signal pulse builds up and emits out through the OPO output coupler. Soon after the signal pulse launches, the saturable absorber is recovered to the initial state, and prepared for another pulse emission in the process. In a CW–pumped system, the process occurrs periodically at very high repetition rates in pulsed Q-switched regime. This process is illustrated in Fig.1.

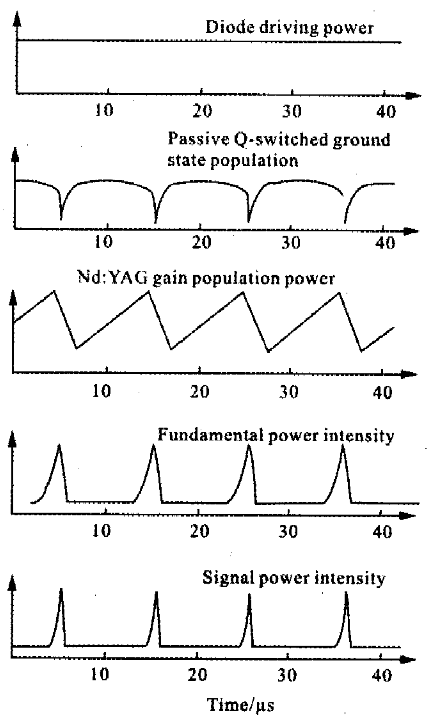

Fig.1 Passively Q-switched CW-pumped lasers with IOPO for high repetition rate signal pulses output

In optimizing the passively Q-switched IOPO, the key laser parameters can be defined in terms of three dimensionless parameters, defined as[8]

$$x=\frac{1}{L}\ln\left(\frac{1}{g_s R_s}\right) \tag{4a}$$

$$y=\frac{-\ln T_0}{\sigma n_i l_{laser}}=\frac{-\ln T_0}{\ln G_0} \tag{4b}$$

$$z=\frac{2\sigma n_i l_{laser}}{L}=\frac{\ln G_0^2}{L} \tag{4c}$$

where $g_s = w_p^2/(w_p^2 + w_s^2)$ is the signal spatial mode-coupling coefficient and in our plane-plane cavity, it is 0.85 near the threshold, and $L = L_R + L_c + 2\sigma_{es} n_0 l_s$ is the intracavity round-trip dissipative optical loss, with n_i the initial population inversion density.

The optimum value of x and y can be expressed in terms of z, as shown in Fig.2.

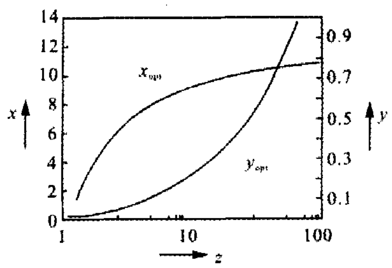

Fig.2 Optimum value of x and y versus z

For a give z(i.e., inversion density), there is a unique optimal choice of x and y.The optimum output signal coupler and unsaturated absorber transmission are given by

$$R_{sopt}=1/g_s.\exp(-x_{opt}L) \tag{5a}$$

$$T_{0opt}=\exp(-y_{opt}\ln G_0) \tag{5b}$$

to maximize the signal output energy and efficiency. In our experimental demonstration, the reflectivity R_s of the output coupler is unaltered due to the direct coating on the surface of the KTP crystal but the initial transmission T_0 of Cr^{4+}:YAG can be varied. Experimental results in T_0 optimization agree well with these analyses.

2 Experiment

2.1 Experimental setup

A schematic drawing of the experimental setup is shown in Fig.3. The active medium of the laser oscillator was a Nd:YAG rod, 75 mm long, 3 mm diameter, anti-reflective (AR)-coated on both end faces at 1 064 nm, CW-side-pumped by laser diode. Polished Cr^{4+}:YAG saturable absorber wafers, also AR-coated on both ends at 1 064 nm, were inserted inside the laser resonator as a passive Q-switched. Three different Cr^{4+}:YAG samples with various low-signal transmission T_0 =80%, 85% and 90% were tested, respectively. The KTP crystal, 7 mm×7 mm×20 mm, coated on one end face (face 2 as shown in Fig.2) highly reflective (HR) at 1 572 nm and anti-reflective(AR) at 1 064 nm, and on the other end face of the crystal (surface 1 as shown in Fig.3), HR coated at 1 064 nm but coated for partial reflection (PR) at 1 572 nm, was cut at θ=90° and ϕ=0° and placed with the X crystallographic axis along the axis of the laser cavity to yield type Ⅱ ($o \Rightarrow o + e$) noncritically phase-matching interaction for a signal wavelength of λ_s=1 572 nm. Here, according to the results of our earlier work on the signal output coupler reflectivity R_s optimization [7], we choose R_s=0.67 coated on the KTP crystal end face 1 as the signal output coupler and R_s unchanged during the experiments, while the initial transmission T_0 of Cr^{4+}:YAG can be varied. The laser diode package, Nd:YAG rod and nonlinear crystal were kept at a fixed temperature of about 24 ℃ employing a water chiller, for spectrally matching the diode emission to the Nd:YAG strongest absorption line at 808 nm and heat sinking of the laser crystal.

The fundamental 1 064 nm laser cavity consists of two HR coatings placed on M1 and on one end face of the KTP crystal (surface 1 as shown in Fig.3), respectively. The OPO cavity was constructed by coating the plane parallel end faces of the KTP crystal as shown in Fig. 3. Hence the OPO cavity length was actually the same as the length of KTP crystal. The threshold of pump intensity J_{th} was much lower due to the shortest OPO cavity length. The IOPO produced a signal wavelength λ_s=1 572 nm, whereas the idler wavelength λ_s was 3 293 nm. Because of high absorption of the idler radiation in the KTP crystal and low reflectivity of the IOPO mirrors at 3 293 nm, the IOPO resonated only at the signal frequency (SRO).

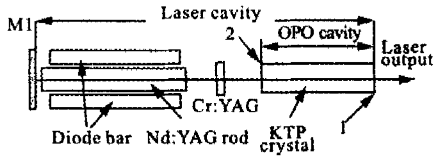

Fig.3 Schematic drawing of the experimental setup

2.2 Results and discussion

Firstly we took away the KTP crystal in Fig.3 and put a mirror with reflectivity at 1 064 nm R=85% near KTP surface 1 position ,the crystal should be as the output coupler instead, to test the output properties of the 1 064 nm laser. Three Cr^{4+}:YAG samples with different initial transmissions were employed in the experiment. The result is shown in Fig.4. The 1 064 nm laser powers and repetition rates are all increased in respect with the input diode power.

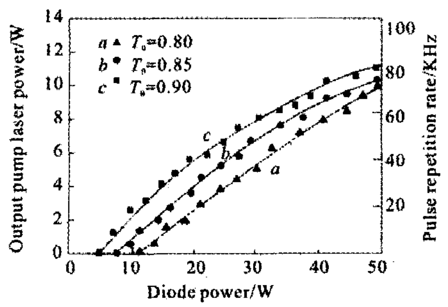

Fig.4 1 064 nm laser power and repetition rate versus the diode power with different T_0 of Cr^{4+}:YAG as the passive Q-switch in the laser cavity

Having obtained the parameters of the 1 064 nm laser output, the KTP crystal was employed into the system as shown in Fig.2 and adjusted carefully to collimating with the laser cavity. The average output signal power and repetition rate at 1 572 nm with respect to the diode driving power using three Cr^{4+}:YAG wafers the same been employed above in Fig.5. The average output power reached 3.8 W, 4.0 W and 4.1 W at about 45 W diode power with low-intensity transmission T_0= 80% , 85% and 90% of Cr^{4+}:YAG saturable absorber wafers, respectively. The pulse temporal behavior of 1 572 nm signal with saturable absorber T_0=80% in Fig.6, and the input diode pump power 46 W was measured by a Tektronix 784D digital oscilloscope (1 GHz bandwidth) with a fast InGaAs photodiode and shown in Fig. 6 and Fig.7 . The pulse width is 30 ns(FWHM) and stable within ±5% and the pulse repetition is 80 kHz, however, exhibited jitter up to ±15%. As comparing, the 1 064 nm laser was also measured through leakage of the output coupler by a silicon photodiode and presented in Fig.7 the up inner trace. The pulse width is 45 ns, a little wider than the signal pulse. Compared with the experimental result shown in Fig. 4, the OPO conversion efficiency is about 40% , and considering the pulse narrowing effect, the actual efficiency is over 60%. And from the input diode power to the 1 572 nm signal output, the efficiency is up to 8.3%.

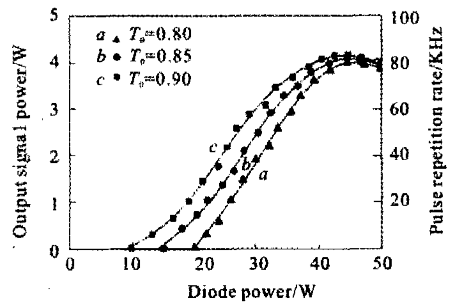

Fig.5 Output signal average power and repetition rate versus diode driving power with different T_0 of Cr^{4+}:YAG

From the result we can find that while the pump power reached a certain level, the conversion efficiency from the diode to signal output is reduced. The signal output power doesn't increase following the increasing diode pump power. And, as the diode power keeping on increasing, the signal power decreases instead of increasing. This is in part determined by the thermal effect during the nonlinear process. The refraction indexes of nonlinear crystal are variable with temperature. As the nonlinear interaction proceeds, a fraction of the radiation is absorbed (pump, signal and mostly, the idler photons). Because the heating of the nonlinear crystal by the absorbed radiation is volumetric while the conduct cooling tends to be a surface effect, thermal gradients are established. Through the variation of the refractive index with temperature, the thermal gradients also induce a spatial variation of the refractive indexes. However, for an efficient nonlinear interaction, the refractive indexes must meet the phase matching condition quite closely. A spatial variation of the refractive indices prohibits ideal phase matching throughout the volume of the nonlinear crystal. Failure to meet the phase matching condition reduces the efficiency of the nonlinear interaction. So the signal output power is limited.

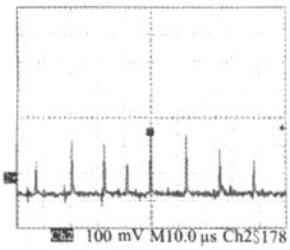

Fig.6 Oscilloscope traces

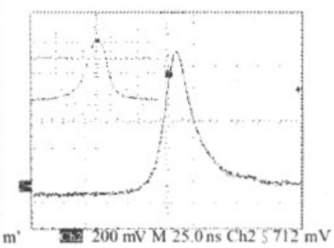

Fig.7 Expanded shape of a single signal pulse

The dependency of the pulse width (FWHM) on the low-intensity transmission of Cr^{4+}:YAG in our experiment is presented in Fig.8. Clearly, the saturable absorber with lower initial transmission exhibits a shorter pulse-width, and accordingly higher peak signal power of the output pulse. But the pump threshold will be a little higher as well as a little lower conversion efficiency. In the OPO design, other than the nonlinear crystal choice, the OPO signal output parameters can be varied by changing the pump power in the laser resonator (i.e., the diode power), as well as the optical density of the saturable absorber.

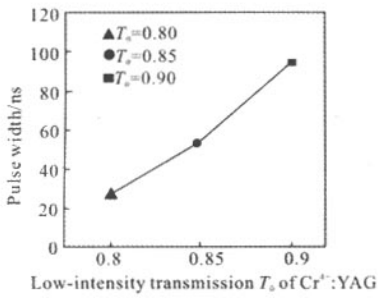

Fig.8 Pulse width versus the current of laser diode with different T_0 of Cr^{4+}:YAG

3 Summary

A nanosecond diode-pumped passively Q-switched eye-safe laser has been demonstrated by using Nd:YAG, Cr^{4+}:YAG, and KTP crystals to gain medium, saturable absorber, and nonlinear crystal for an intracavity OPO, respectively.Different eye-safe signal radiation parameters have been achieved with different Cr^{4+}:YAG samples. With low-intensity transmission of T_0=80% of the Cr^{4+}:YAG sample, 3.8 W average powers at 1.572 μm wavelength and repetition rate up to 80 kHz with pulse width as narrow as 30 ns is obtained. The peak power is higher than 1.58 kW. Such high-repetition-rate, high-peak power eye-safe lasers can find wide applications in several areas,such as range finding, monitoring of atmosphere, telecommunication ,etc.

References:

[1] MARSH ALL L R, KASINSKI J, HAYS A D,et al.Efficient optical parametric oscillator at 1.6μm[J].**Opt Lett**, 1991,**16**:681–683.

[2] GONG M, LI Z,WANG J,et al. Noncollinear-pumped KTP optical parametric oscillator[J].**App Opt**, 1999,**38**:7402–7405.

[3] Marshall L R, Kasinski J, Burnham R L.Diode-pumped eye-safe laser source exceeding 1% efficiency[J].**Opt Lett**, 1991,**16**:1680–1682.

[4] YASHKIR Yuri, DRIEL H M van. Passively Q-switched 1.57 μm intracavity optical parametric oscillator[J].**Appl Opt**, 1999,**38**:2554–2559.

[5] DABU R, FENIC C, STRATAN A.Intracavity pumped nanosecond optical parametric oscillator emitting in the eyesafe rang[J].**Appl Opt**, 2001,**40**:4334–4340.

[6] Debuisschert T, Raffy J, Pocholle J P, et al.Intracavity optical parametric oscillator: study of the dynamics in pulsed regime [J].**Opt Soc Am B**, 1996,**13**:1569–1587.

[7] WANY, ZENG Q Y, ZHU DY,et al.High repetition rate pulsed laser of twin wavelengths from KTiOPO4 optical parametric oscillation[J].**Chin Phys**, 2004,**13**:1402–1406.

[8] WAN Y, ZHU D Y, ZENG Q Y,et al.Brewster-oriented passive Q-switch intracavity optical parametric oscillator [J]. **Chin Phys**, 2005,**14**:714–719.

[9] MARSHALL L R , KAZ A.Eye-safe output from noncritically phase-matched parametric oscillators[J].**J Opt Soc Am B**, 1993,**10**:1730–1736.

[10] YAO J Q,Fahlen T S.Calculations of optimum phase match parameters for the biaxial crystal $KTiOPO_4$[J].**J Appl Phys**, 1984,**55**:65–68.

[11] XIAO G,BASS M,ACHAREKAR M.Passively Q-switched solid-statelasers with intracavity optical parametric oscillators [J].**J Quantum Electron**, 1998,**QE-34**:2241–2245.