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Brewster-oriented passive Q-switch intracavity optical parametric oscillator

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The behaviour of passively Q-switched solid-state lasers containing intracavity optical parametric oscillators (OPOs) is described, and a model to optimize this system's performance is developed. Meanwhile, an Nd:YAG laser-pumped $KTiOPO_4$ (KTP) intracavity OPO for eye safe laser output is studied experimentally. A Brewster-oriented bis-(4-dimethylaminodithiobenzil)-nickel (BDN) dye film is employed in laser cavity, which plays the double role of a passive Q-switch and a Brewster plate, to Q-switch the light to increase its intensity and polarize the light so that the polarization plane of fundamental irradiation is perpendicular to the Z-axis of KTP serving as the OPO nonlinear crystal, thereby providing type II phase matching conditions to generate 1.572μm eye-safe signal laser. Eye-safe signal radiations of 6.6mJ per pulse at 1.572μm wavelength and pulse width as narrow as 6.0ns (FWHM) were obtained. Peak power was up to 1.1MW.

Keywords: optical parametric oscillator, $KTiOPO_4$ crystal, passive Q-switch, eye-safe
PACC: 0760, 4280, 4265K

1. Introduction

Eye-safe radiation sources based on optical parametric oscillators (OPOs) pumped by nanosecond solid-state lasers were developed as an alternative to lasers with erbium (Er) doped medium and Raman shifted Nd:YAG lasers emitting at 1.54μm wavelength.[1] The fundamental frequency of Q-switched Nd:YAG laser is shifted to the signal frequency in the eye-safe band of 1.57μm in a $KTiOPO_4$(KTP) OPO.

A nanosecond pulse duration intracavity optical parametric oscillator (IOPO), compared with actively Q-switched fundamental lasers,[2] 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. Although Cr^{4+}:YAG crystal, LiF:F_2^- color centre crystal and BDN dye film are the most important examples of Q-switching, in this work, BDN dye film is still employed. A simple tilt of the Q-switch plate to Brewster's angle with respect to optical axis of the laser resonator shown in Fig.1 would make it perform as a Brewster polarizing plate as well, diminishing the Fresnel reflection loss of the beam "P" polarized component.[3] This saves the need of antireflection coating, and results in a linearly polarized pump flux in the cavity, which is crucially important for the process of optical parametric oscillations in nonlinear crystal.

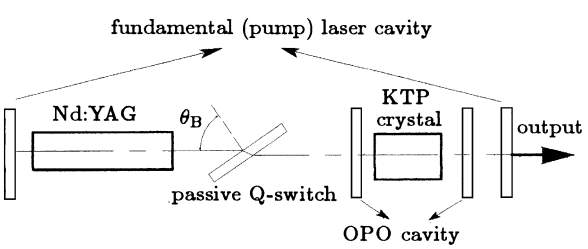


Fig.1. Schematic of a passively Q-switched IOPO with Brewster's angle settled Q-switch plate.

2. Theoretical basis of passively Q-switched IOPO

The four-level model of the saturable dye is shown in Fig.2. Absorption at the laser wavelength occurs

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for both the 1–3 and the 2–4 transitions and the corresponding absorption cross sections are σ_{gs} and σ_{es}, respectively. τ_{21}, τ_{32}, and τ_{42} are the lifetimes of energy levels 2, 3, and 4, with $\tau_{32} \ll \tau_{21}$, $\tau_{42} \ll \tau_{21}$. The small signal transmission (initial transmission) of dye is

$$T_0 = \exp(-\sigma_{gs} n_0 l_s), \tag{1}$$

where n_0 is the absorber total population density, and l_s is the length of the saturable absorber along the cavity axis. From this model, when the laser intensity is I, the transmission of the dye can be written as[4]

$$\ln T - \ln T_0 = \left(\frac{1}{\delta} - 1\right) \ln\left(\frac{1/\delta + I/I_s}{1/\delta + IT/I_s}\right), \tag{2}$$

where $\delta = \sigma_{es}/\sigma_{gs}$; the value of δ for BDN is 0.24, $I_s = h\nu/\sigma_{gs}\tau_{21}$ is called the saturation intensity, $h\nu$ is the photon energy. When $I \gg I_s$, from Eq.(2) we obtain

$$T = T_0^{\delta}. \tag{3}$$

The rate equations governing the behaviour of a passively Q-switched IOPO laser system are as follows:[5]

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

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

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

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

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

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

$$n_{gs} + n_{es} = n_0, \tag{4g}$$

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 c is the speed of light. $\tau_s(\tau_i)$ is the OPO cavity lifetime for the signal(idler), and $\varepsilon_s(\varepsilon_i)$ is the dielectric constant of the signal (idler).

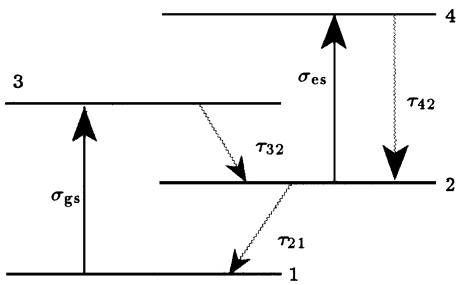


Fig.2. The four-level model of the saturable dye.

From Eqs.(4a)–(4g), the dynamic processes of passively Q-switched IOPO can be established as follows. When the pump initiates, lasing action is initially prevented by the low transmission T_0 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 the dye film, its transmission approximates $T = T_0^{\delta}$, and the laser resonator is in a high Q state. The fundamental pulse starts to deplete the population inversion and the pump intensity builds up. When the fundamental pulse intensity exceeds the OPO threshold, the signal pulse begins to grow very rapidly at the expense of the fundamental field. This process is shown in Fig.3.

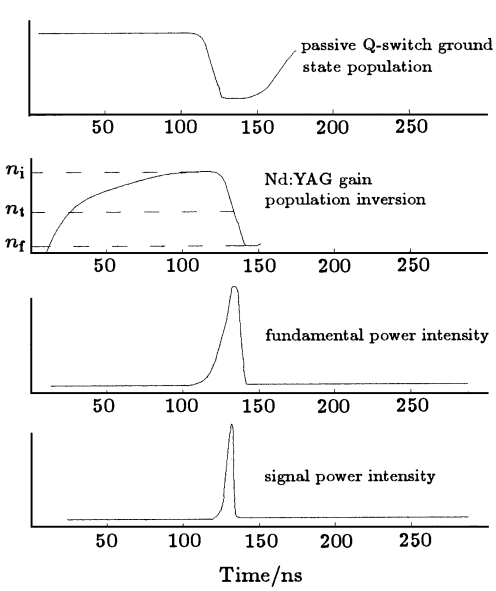


Fig.3. Passively Q-switched IOPO with single pulse output.

When operated well above the threshold, immediate recovery of BDN to the ground state enables the build up of a new population inversion in the gain medium by the continuing pumping flash, which then establishes conditions for the pump field to evolve again until a signal pulse is again formed. In this manner, a Q-switched OPO pulse may consist of several spikes, as shown in Fig.4. This is observed successfully in our experiments as is described in Section 3.

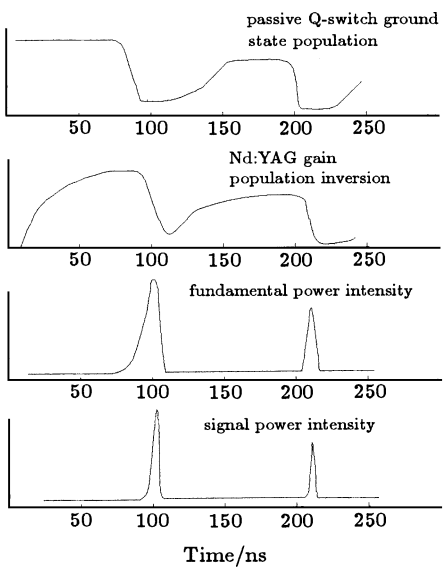


Fig.4. Passively Q-switched IOPO with two-spike output in one pump pulse.

In a passively Q-switched IOPO with closed resonator of the pump, there is a unique optimal choice of signal output coupler and unsaturated absorber transmission other than the nonlinear crystal choice which maximizes the OPO signal output energy and efficiency for a given pump intensity (i.e. inversion density). The optimization theories of actively and passively Q-switched lasers can be found in Refs.[4–7]. However, there has been no reference on the optimization of passively Q-switched IOPO. Here, we will give some derivations to extend their models of passively Q-switched laser optimization to passively Q-switched IOPO parameters optimization.

In the model of Degnan on passively Q-switched laser optimization,[6] the key laser parameters were defined in terms of three dimensionless parameters. Following Degnan's approach, we extend these three parameters, x, y and z, in additional consideration of the process with OPO in the laser cavity, redefined as

$$\begin{aligned} x &= \frac{1}{L}\ln\left(\frac{1}{g_{\mathrm{s}}R_{\mathrm{s}}}\right), \\ y &= \frac{-\ln T_0}{\sigma n_{\mathrm{i}} l_{\mathrm{laser}}} = \frac{-\ln T_0}{\ln G_0}, \\ z &= \frac{2\sigma n_{\mathrm{i}} l_{\mathrm{laser}}}{L} = \frac{\ln G_0^2}{L}, \end{aligned} \tag{5}$$

where $g_{\mathrm{s}} = w_{\mathrm{p}}^2/\left(w_{\mathrm{p}}^2 + w_{\mathrm{s}}^2\right)$ is the signal spatial mode-coupling coefficient and in our plane-plane cavity it is 0.85 near the threshold,[8] and $L = L_{\mathrm{R}} + L_{\mathrm{c}} + 2\sigma_{\mathrm{es}} n_0 l_{\mathrm{s}}$ is the intracavity round-trip dissipative optical loss, with n_{i} the initial population inversion density.

The above equations differ from the original Degnan formulations in two points. First, since the IOPO within the laser resonator serves as a nonlinear cavity dump to extract energy stored in the intracavity optical field, the parameter $g_{\mathrm{s}}R_{\mathrm{s}}$ in Eq.(5) acts as the equivalent reflection coefficient of the output mirror at pump wavelength during the lasing process. Secondly, the dissipative optical loss L includes an extra term L_{c}, which represents the idler wave dissipative optical loss. When the parametric process converts the pump laser flux to the signal and idler radiation, the signal photons are regarded as a useful laser output, but the idler wave is regarded as a dissipative optical loss added in L.

Following Degnan's model in Ref.[6] but with redefined parameters, the optimum value of x and y can be expressed in terms of z, as shown in Fig.5.

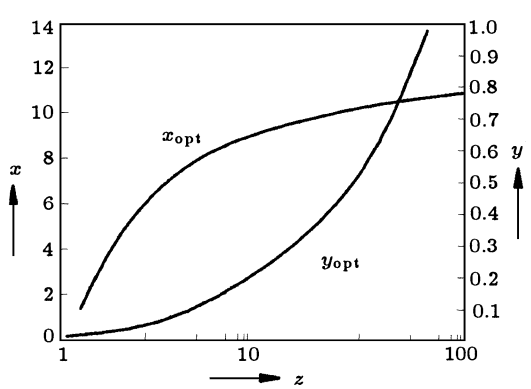


Fig.5. The optimum value of x and y versus z.

For a given 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

$$R_{\mathrm{s\ opt}} = 1/g_{\mathrm{s}} \cdot \exp\left(-x_{\mathrm{opt}} L\right), \tag{6}$$

$$T_{0\ \mathrm{opt}} = \exp\left(-y_{\mathrm{opt}} \ln G_0\right), \tag{7}$$

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 the bleachable dye can be varied. The results of our experiments in T_0 optimization agree well with these analyses.

In passively Q-switched IOPO, if the Q-switching plate is placed inside the laser resonance cavity normal to the laser axis,[5,9,10] the initiated fundamental (pump) laser oscillation in the resonator is arbitrarily polarized. Among the photon fluxes of the pump wave, only the component polarized parallel to y-axis of the nonlinear crystal KTP matches the phase-matching constraints of OPO and thus is effective in the parametric process to be transformed into signal and idler, while the photons polarized perpendicular to the given direction are useless in the OPO process and are wasted. This will result in a higher pump threshold, a lower transform efficiency and the need of antireflection coating for the Q-switching plate. However, a simple tilt of the Q-switch plate to the Brewster angle would make it perform as a Brewster-plate as well, thus diminishing the Fresnel reflection loss of the polarized component of beam "P". This saves the need of its antireflection coating, and the oscillation threshold of "P" is lower than the "S" polarized component, which results in a linearly polarized fundamental laser in the cavity. The extinction ratio can be better than 300:1.[8] Since the process of OPO prefers linearly polarized pump laser, the OPO threshold can be significantly lowered while its conversion efficiency is enhanced in this configuration.

3. Experiment

3.1. Experimental setup

A schematic drawing of the experimental setup is shown in Fig.6. The active medium of the laser oscillator was a Nd:YAG rod, 60mm long, 4mm diameter, housed in a diffused reflector cavity equipped with a linear xenon flashtube. A polished BDN dye film was tilted to the Brewster's angle inside the laser resonator as a passive Q-switch. The KTP crystal, 7mm×7mm×20mm, was cut at $\theta = 90°$ and $\phi = 0°$ 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 $\lambda_s = 1572$nm.[11]

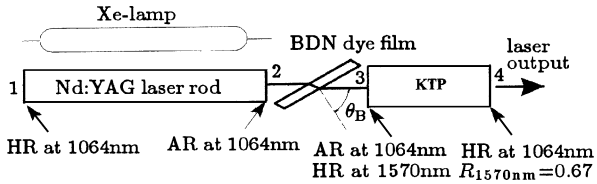


Fig.6. Schematic drawing of the experimental setup.

To simplify the system, all of the resonator mirrors were formed by coatings deposited directly to the surfaces of the Nd:YAG rod and the KTP crystal. The 1.064μm laser cavity consisting of two high reflection (HR) coatings on surface 1of the Nd:YAG laser rod and surface 4 of the KTP crystal. The OPO cavity was constructed by coatings on the plane parallel surfaces 3 and 4 of the KTP crystal. Surface 2 of the Nd:YAG rod and surface 3 of the KTP crystal were antireflection (AR)-coated at 1.064μm, as shown in Fig.6. 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.[8] The KTP crystal was fixed inside the laser cavity, and the optical axis Y was parallel to the direction the dye tilted to, as was the initiated pump laser polarization; thus the polarization of the pump wave was the ordinary wave in the crystal. The transformed signal wave was along the same direction as the above, whereas the idler was the extraordinary wave polarized along the Z axis. The IOPO produced a signal of wavelength λ_s=1.572μm, whereas the idler wavelength λ_i was 3.293μm. Because of high absorption of the idler radiation in the KTP crystal and low reflectivity of the IOPO mirrors at 3.293μm, the IOPO resonated only at the signal frequency.

3.2. Results and discussion

For a given pump level (i.e. for a given n_i), in order to obtain the maximum output energy and efficiency from a dye film passively Q-switched Nd:YAG laser with IOPO, one should select R_s for the output coupler, and initial transmission T_0 for the saturated absorber. Since some parameters in the models aforementioned were largely diverse from each other and uncertain, they can give only some approximate estimates. Here, according to the results of our earlier works on R_s optimization,[2] we choose $R_s = 0.67$ coated on one end of the KTP crystal as the signal output couple and unchanged during the experiments, while the initial transmission T_0 of the dye film can be varied. The input energy of the xenon flashtube can be

adjusted by varying the voltage of the xenon flashtube to ensure a single laser pulse to be obtained. A beam splitter is used after the output coupler of OPO to divert the residual 1.064μm pump energy away prior entering an energy meter.

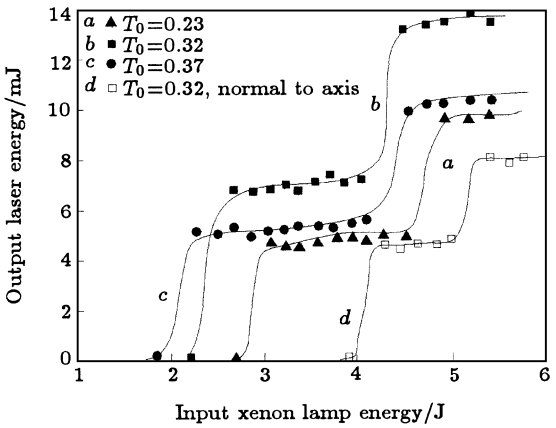


Fig.7. Signal output pulse energy versus the Nd:YAG rod pumping energy with different T_0 of the dye film.

Figure 7 shows the signal laser output versus input pump energy. Curves a, b and c are obtained with different initial transmissions of the dye film T_0=0.23, 0.32, and 0.37, respectively, which is tilted to Brewster's angle. Curve d is obtained with initial transmission of the dye film T_0=0.32, the same as curve b but placed inside the laser resonance cavity normal to the laser axis, for comparison. All these curves exhibit two steep steps, while the upper step reflects the appearance of the second spike in one pump pulse.

As shown in curve b in Fig.7, under the condition of the initial transmission T_0=0.32 of the dye film tilted to Brewster's angle, and with xenon lamp pumping energy from 2.5J to 4.0J, single pulse signal laser of average 6.6mJ was obtained. The oscilloscope trace is shown in Fig.8(a). The pulse width is as narrow as 6.0ns (FWHM), hence the peak power can be up to 1.1MW. For comparison, curve d shows our experimental results of the dye film with T_0=0.32, the same sample employed in the curve b, but placed in the laser cavity normal to its axis. The threshold is much higher, the efficiency is lower, and voltage range is narrower (4.0J to 5.0J) in performing single pulse.

When the pump energy is increased, a second spike and even a third spike can appear in the oscilloscope traces, as shown in Fig.8(b).

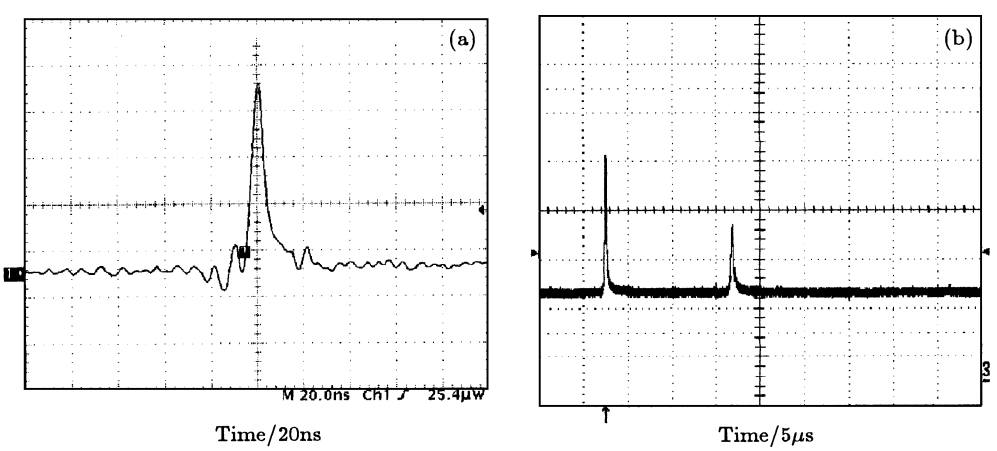


Fig.8. Oscilloscope traces of signal pulse from IOPO. (a) Single pulse oscilloscope trace at an expanded time scale: 20ns/division, (b) Two spikes generated in one pump pulse.

4. Conclusion

We have considered the dynamic processes of passively Q-switched IOPO theoretically. Unlike the actively Q-switched IOPO, there may be two or even more signal spikes formed in one pump pulse as the pump intensity increases. The efficiency optimization of IOPO passively Q-switched by a saturable absorber has been discussed. Following Degnan's approach in optimization of passively Q-switched lasers, we have extended his model with additional consideration of the process with OPO in the laser cavity. Optimal output coupler of IOPO and the unsaturated absorber transmission to maximize the OPO signal output energy and efficiency versus the pump intensity (i.e., inversion density n_i) have been considered. At the same time, the performance of Nd:YAG laser pumped IOPO, in the cavity a Brewster angle oriented BDN dye film acting as both passive Q-switch and Brewster plate, to generate 1.572μm eye-safe signal laser

has been demonstrated. All of the resonator mirrors were formed by coatings deposited directly to the surfaces of the Nd:YAG rod and the KTP crystal to simplify the system. Eye-safe signal radiations of more than 6.6mJ in single pulse of about 6.0ns pulse width (FWHM) at 1.572μm wavelength were obtained. The peak power was as high as 1.1MW. Such efficient high peak power eye-safe lasers can find wide applications in several areas: such as range finding, monitoring of atmosphere, telecommunication etc.

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