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High repetition rate pulsed laser of twin wavelengths from $KTiOPO_4$ optical parametric oscillation

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In this paper, some key techniques of $KTiOPO_4$ optical parametric oscillation (OPO) laser with repetitive frequencies and twin wavelengths output have been analysed theoretically and studied experimentally in detail. An intracavity optical parametric oscillator (IOPO) has been applied. Operating under 20Hz, laser output energy of more than 38mJ with twin wavelengths 1.57μm and 1.06μm has been achieved. Results of the experiments agree well with the theoretical discussion.

Keywords: noncritically phase-matching (NCPM), optical parametric oscillators (OPO), $KTiOPO_4$ (KTP), eye-safe

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1. Introduction

Q-switched Nd^{3+}-doped solid-state lasers operating near 1064nm are widely used in laser radar, ranging, and designation applications. However, lasers with wavelength in the visible and near-infrared spectral regions (400–1400nm) can pose serious eye safety risks to users. As a result, there has been considerable research devoted to the development of pulsed lasers operating at more eye-safe wavelengths (>1500nm). Optical parametric oscillators (OPOs) provide efficient means of wavelength conversion to obtain extra wavelengths of lasers.[1,2] For this eye-safe region of the spectrum we can start with light from a Q-switched Nd^{3+}-doped solid-state laser. Typically such a system consists of a separate pump laser and a nonlinear crystal in an external-cavity OPO configuration. Such external OPOs were considered and reviewed by some research groups in early stages.[3] But later, in order to take advantage of the high intensity inside the pump laser cavity and increase the overall efficiency, consideration turned to intracavity OPOs (IOPOs), where the nonlinear crystal is placed in side of the Q-switched laser cavity.[4−6] In the IOPO, when the Q-switch is opened, the pump laser flux grows to the threshold point for parametric oscillation. Then the nonlinear process converts the fundamental field into the desired signal and/or idler radiation at an eye-safe wavelength. The IOPO within the laser resonator serves as a nonlinear cavity dump to extract energy stored in the intracavity optical field.

In time, Q-switched Nd^{3+}-doped solid state lasers operating near 1064nm and OPO converted eye-safe lasers will be surely used together in some fields, especially in military countermeasures. There are strong needs for some lasers to launch these two wavelengths simultaneously. In this paper, we introduce some results of our research to this kind of twin-wavelength laser.

2. Theoretical basis

OPOs can provide an efficient and relatively simple means of frequency shifting. When the output of a high-power pulsed solid-state laser is focused onto 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

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employ second-order nonlinearity to convert photons at the pump frequency $\omega_{\rm p}$ into photons at two new frequencies, the so-called signal $\omega_{\rm s}$ and idler $\omega_{\rm i}$ frequencies. Conservation of energy requires that the algebraic sum of the signal and idler frequencies be equal to the frequency of the pump.

The signal and idler outputs are generated by interaction between the intense pump and weak quantum noise at the signal and idler frequencies. Assuming no pump depletion, this interaction can be described by the coupled-wave equations[7]

$$\frac{{\rm d}E_j}{{\rm d}z} + \alpha_j E_j = {\rm i}\kappa E_{\rm p} E_k^*, \tag{1}$$

where E_j is the electric field at frequency ω_j, α is the absorption coefficient at frequency ω_j, and j=signal s when k=idler i, or j=i when k=s. The interaction occurs through the second-order nonlinearity of the crystal medium by means of the interaction coefficient $\kappa_{\rm m}$

$$\kappa_{\rm m} = \frac{2\omega_{\rm s}\omega_{\rm i} d_{\rm eff}^2}{n_{\rm s} n_{\rm i} n_{\rm p} \varepsilon_0 c^3}, \tag{2}$$

where $d_{\rm eff}$ is the effective nonlinear coefficient and $n_{\rm m}$ is the refractive index of the nonlinear crystal at angular frequency $\omega_{\rm m}$. As we know, the subsequent amplification of the signal and idler fields occurs at the expense of the pump field.

Like most nonlinear processes, optical parametric oscillation must obey phase-matching constraints. Phase matching is satisfied when the refractive indices of the pump $n_{\rm p}$ and of the signal and idler waves $n_{\rm s}$ and $n_{\rm i}$ satisfy

$$n_{\rm p}\omega_{\rm p} = n_{\rm s}\omega_{\rm s} + n_{\rm i}\omega_{\rm i}. \tag{3}$$

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 noncritical 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 ($\theta = 90°$, $\phi = 0°$) pumped by $\lambda_{\rm p} = 1.06\mu$m, the refractive indices are $n_{\rm s} = 1.7348$, $n_{\rm i} = 1.7793$, $n_{\rm p} = 1.7474$, where $\lambda_{\rm s} = 1.57\mu$m, $\lambda_{\rm i} = 3.3\mu$m and $\lambda_{\rm p} = 1.06\mu$m.

The generated signal wave is amplified to a steady intensity when it makes m cavity transits from an initial parametric noise power, giving rationally a threshold power to noise power ratio of $\ln(P_{\rm m}/P_0)$=33, as basically one parameter to calculate the pump threshold intensity to generate OPO. The threshold of pump intensity $J_{\rm th}$ for a singly resonant OPO with reflection of the pump from the OPO output coupler is given by[8]

$$J_{\rm th} = \frac{1.8}{\kappa g_{\rm s} L_{\rm eff}^2 (1+\gamma)^2}\tau \times \left[\frac{25L}{c\tau} + 2\alpha l + \ln\frac{1}{\sqrt{R_{\rm s}}} + \ln 2\right]^2, \tag{4}$$

where τ is the full width at half maximum (FWHM) of the pump pulse and $\gamma = R_{\rm p}$ (at threshold) equals to the reflection coefficient of the output mirror at pump wavelength or the ratio of backward to forward pump amplitudes in the OPO cavity. The round-trip loss of the OPO crystal is $2\alpha l \approx 0.01$, including losses resulting from the optical coatings on the crystal faces. L is the optical length of the cavity, and l is the crystal length. $g_{\rm s} = \dfrac{w_{\rm p}^2}{w_{\rm p}^2 + w_{\rm s}^2}$ is the mode-coupling coefficient; for the present configuration it is 0.85 near the threshold. $L_{\rm eff}$ is the effective gain length, determined by walk-off. In the present case of noncritical phase matching, the walk-off is negligible so that for a small crystal length we have $L_{\rm eff} \approx l$. $R_{\rm s}$ is the reflectivity of the output coupler at resonated signal wavelength.

From Eq.(4), some key coefficients in our OPO can be discussed and considered. First, optical length L, we can find that the shorter L, the smaller $J_{\rm th}$. So the threshold pump intensity of OPO can be minimized by shortening the optical length of OPO cavity. Second, recast of Eq.(4) by simply differentiation with τ will have a minimum value of $J_{\rm th}$ for an optimum pulse width $\tau_{\rm opt}$, given by[9]

$$\tau_{\rm opt} = \frac{25L}{c\left(2\alpha l + \ln\dfrac{1}{\sqrt{R}} + \ln 2\right)}. \tag{5}$$

According to these analyses, while operating an OPO, to obtain the lowest pump threshold, we should do the best we can in practice to shorten OPO cavity,

and optimize the pump pulse width according to the parameters determined by Eq.(5).

3. IOPO

For IOPO, its OPO cavity is in the pump laser cavity. The process OPO is occurring at the time while the pump is established. So the dynamic process is more complex than that of extracavity OPO (EOPO). Thus the development of its theories and experiments has followed that of EOPO. One main idea of the 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 of cavity is $I_{\rm i}/I_{\rm o} = 1/(1-R)$.

4. Experiments

A schematic illustration of the experimental setup is shown in Fig.1. The plane-parallel optical resonator of the Nd:YAG laser oscillator is formed by mirrors M_1 and M_2. The rear mirror M_1 is high reflective at 1.064μm, whereas the mirror M_2 is double coated and partial reflective both at 1.064μm and 1.57μm. The IOPO cavity comprises a pair of plane-parallel mirrors M_2 and M_3. M_3 is highly reflective at 1.57μm, and transparent at 1.064μm. The active medium of the laser oscillator is a Nd:YAG rod,75mm long, 5mm in diameter, AR-coated on both ends at 1.064μm. The KD*P and polarizer here are used as Q-switch. The KTP crystal, $7\times7\times20{\rm mm}^3$, is cut for type II noncritical phase-matching interaction along the x crystallographic axis ($\theta = 90°$, $\varphi = 0°$). The polarization of the pump wave is along the y axis (o wave) of the crystal, as is that of the signal wave, whereas the idler is polarized along the z axis (e wave). The IOPO produces a signal wavelength $\lambda_{\rm s}$ of 1.57μm, whereas the idler wavelength $\lambda_{\rm i}$ is 3.3μm. Because of the high absorption of the idler radiation in the KTP crystal and the low reflectivity of the IOPO mirrors at 3.3μm, the IOPO is resonant at the signal frequency only (SRO).

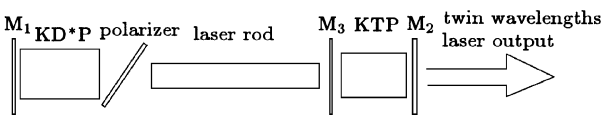


Fig.1. Schematic illustration of the experimental setup.

The Nd:YAG rod is pulse pumped by a linear flashlamp with a repetition rate of 1–20Hz. After sufficient energy is accumulated on the upper laser level, the Q-switch is opened and permitted to build a laser pulse inside the laser cavity. As the pulse penetrates through the KTP crystal, while its intensity reaches the OPO threshold, the KTP changes partially the 1.06μm wavelength of the intracavity photon flux to the 1.57μm signal wavelength and oscillator inside the OPO cavity comprised of M_2 and M_3. Both the pump and signal are permitted to pass through the output mirror M_2 to form the twin-wavelength laser output we need.

In Fig.1, firstly we take away the mirror M_3 and the KTP crystal, then the remainder forms a typical Q-switching Nd:YAG laser. We then have the basic parameter of this laser output as shown in Fig.2.

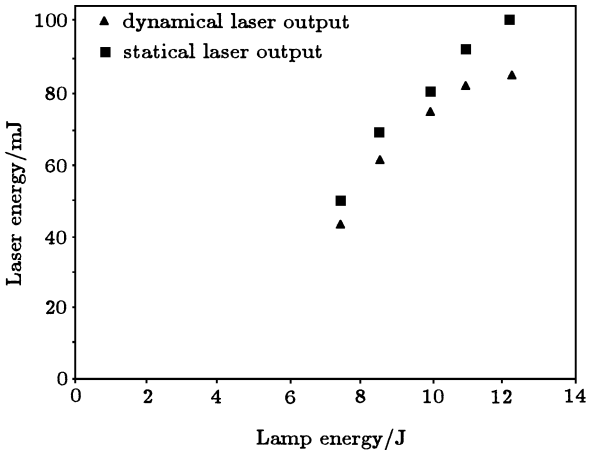


Fig.2. Pump laser output pulse energy versus the lamp energy input.

Because the output mirror was not optimized, the efficiency of output pulse energy was not at its optimization. Figure 2 shows the oscilloscope trace of the laser output. Its pulse width is about 8ns.

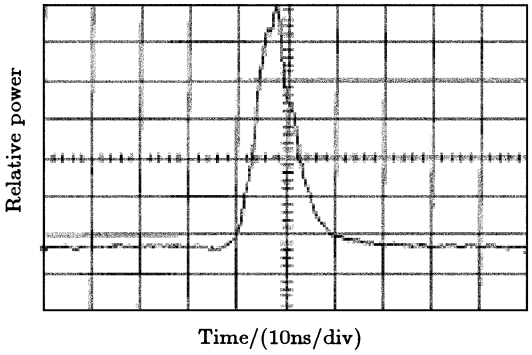


Fig.3. Oscilloscope trace of 1.06μm laser output.

Having obtained the parameters of the 1.06μm laser output, we have achieved the experiments of OPO to gain the twin-wavelength laser output. The OPO cavity is composed of M_2 and M_3. According to

Eq.(5), the shorter the OPO cavity length, the lower the oscillator threshold. So, assuring that the KTP can be put into the cavity and there is enough space to adjust the cavity, we should make the cavity as short as possible. The Nd:YAG rod is pumped in a pulsed way by a linear flashlamp. After sufficient energy is accumulated on the upper laser level, the Q-switch is opened and we permit a laser pulse to build up inside the laser cavity. This pump laser pulse penetrates through the KTP while it builds up. When its intensity achieves the OPO threshold, the KTP converts 1.06μm pump laser into 1.57μm signal and 3.3 μm idler laser through the parametric process and the 1.57μm signal wave oscillates inside the OPO cavity composed of M_2 and M_3 as shown in Fig.1. For the output mirror M_2 is partly reflected both in pump and signal. So, while oscillator is in the cavity, there will be a laser pulse including 1.06μm and 1.57μm, two wavelengths which are permitted to send out through M_2. This device gives us the twin-wavelength laser as the output we need. The output also includes some other wavelength light such as 3.3μm idler, and 0.53μm from second harmonic generation, but they all can be ignored from the output due to their small proportion.

To obtain the twin-wavelength laser output, it is vital to keep the mirrors M_2 and M_1 precisely parallel to form the OPO cavity during the experiment, while, benefiting from the noncritical phase-matching (NCPM) used here, the orientation of the KTP is not so critical. The so-called permitting angle here is some dozens of milliradians.

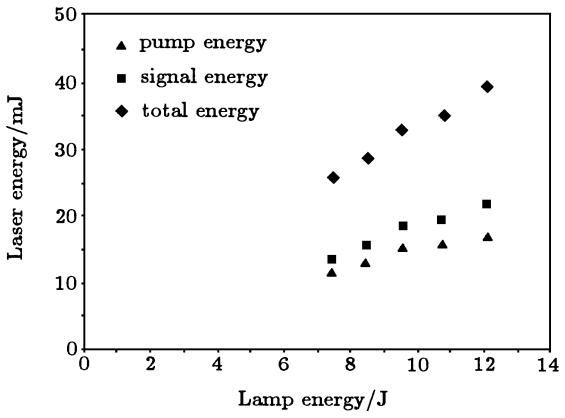


Fig.4. Twin-wavelength output pulse energy versus the Nd:YAG rod pumping.

Finally, we chose an output mirror with parameters $T_{1.57\mu m}$=39%; $T_{1.06\mu m}$=19%. The results are shown in Fig.4. The oscilloscope traces are shown in Figs.5 and 6, respectively. While operating in 20Hz, laser output energy of more than 38mJ with twin wavelengths of 1.57μm (22mJ) and 1.06μm (16mJ) has been achieved. Their pulse widths are about 5ns.

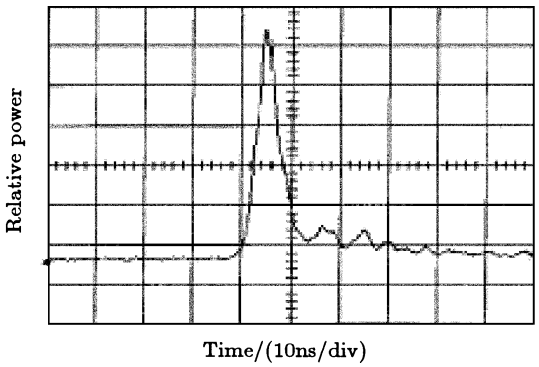


Fig.5. Oscilloscope trace of 1.57μm laser in twin-wavelength output.

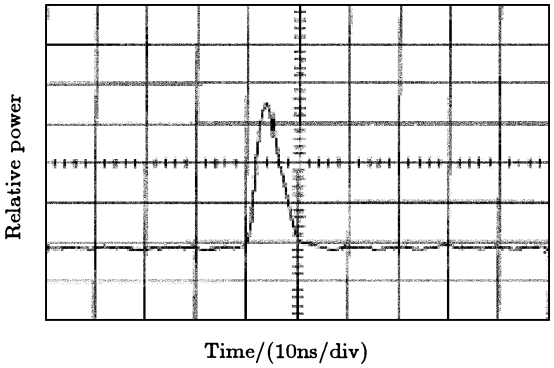


Fig.6. Oscilloscope trace of 1.06μm laser in twin-wavelength output.

5. Conclusion

In summary, we have demonstrated the operation of a singly resonant pulsed KTP IOPO, pumped by an electro-optically Q-switched Nd:YAG laser. Eye-safe signal radiation at 1.57μm wavelength is generated together with 1.06μm pump laser in a type II noncritically phase-matched x-cut KTP crystal located in a plane-parallel IOPO resonator. A twin-wavelength laser has been obtained successfully, and, at the same time, the more important point is that the waveform of a depleted pump laser is preserved well in our experiments, much better than the traces shown in Refs.[10] and [11] which were obtained from external-cavity OPOs.

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