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Diode-pumped Q-switched laser with intracavity sum frequency mixing in periodically poled KTP

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ABSTRACT We report on a diode pumped Q-switched yellow-orange laser, with intracavity sum-frequency generation, in a periodically poled KTiOPO$_4$ crystal in a diode-pumped Q-switched dual-wavelength laser at 1064 and 1342 nm. The conversion efficiency is measured as a function of crystal temperature, incident pump power, and pulse repetition rate. Under optimal phase-matching conditions, the highest yellow-orange average power was 610 mW at a pump power of 17 W.

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1 Introduction

Compact solid-state laser systems emitting yellow-orange spectra are currently of interest for applications in medical and biological technology [1]. Several systems have been developed including second-harmonic generation (SHG) of a Cr : fosterite laser [2], sum-frequency mixing (SFM) of a Q-switched Nd : YAG dual wavelength laser [3, 4], and frequency doubling of an intracavity-Raman-shifted Nd : YAG laser [5–7]. Recently, we use an intracavity BBO crystal in a diode-end-pumped Q-switched Nd : YVO$_4$ dual wavelength laser to obtain 340 mW SFM emission at 593 nm [8].

The development of periodically poled materials has made it possible for quasi-phase-matching (QPM) techniques to replace the conventional birefringent phase matching schemes [9]. Most research has focused on periodically poled lithium niobate (PPLN), because of its high nonlinear coefficient ($d_{33} = 27$ pm/V). In addition to PPLN, another material, periodically poled KTiOPO$_4$ (PPKTP), has also been successfully developed by using millimeter-thick samples [10–12]. The PPKTP crystal possesses a high damage threshold (> 900 MW/cm^2 for 5 ns pulse) and a high resistance to photorefractive damage [13], although its nonlinear coefficient ($d_{33} = 17$ pm/V) is lower than that of PPLN crystal.

In this work, we report on the investigation of intracavity Q-switched SFM of 1064 nm and 1342 nm wavelengths in a PPKTP crystal. In particular, the SFM efficiency as a function of input power, repetition rate, and crystal temperature is studied. With 17 W of incident pump power, the laser cavity under optimal phase-matching condition produces the maximum average power of 610 mW at a 35 kHz repetition rate and a peak power higher than 1.1 kW at a 20 kHz repetition rate.

2 Experimental setup

It is of essential importance for efficient pulsed SFM to have a good spatial and temporal overlap of the two different wavelengths. Previously, we have used a three-mirror configuration forming two separate cavities to achieve an intracavity Q-switched SFM of 1064 nm and 1342 nm in a β-barium borate (BBO) crystal [8]. A similar cavity configuration is used in the present investigation. Figure 1 shows the scheme of the diode-end-pumped Q-switched Nd : YVO$_4$ dual-wavelength laser cavity with a PPKTP for intracavity SFM. The length of the Nd : YVO$_4$ crystal was 8 mm with 0.3 at. % Nd^{3+} concentrations. A Nd : YVO$_4$ crystal with low doping concentration was used to avoid thermally induced fracture [14]. The Nd : YVO$_4$ crystal was mounted in a copper housing with water cooling to maintain a 20 °C operating temperature. Both sides of the laser crystal were coated for antireflection at 1064 nm and 1342 nm ($R < 0.2\%$). The pump source was a 20 W fiber-coupled laser diode with a core diameter of 0.8 mm and a numerical aperture of 0.18. The fiber output was focused into the crystal and the pump spot size was around 0.3 mm. The input mirror M1 was a 1 m radius-of curvature concave mirror with an antireflection coating at the pump wavelength on the entrance face ($R < 0.2\%$), and with a high-reflection coating at both lasing wavelengths ($R > 99.8\%$), and a high-transmission coating at the pump wavelength on the other surface ($T > 90\%$). One side of the flat mirror M2 was coated to be highly reflecting at 1342 nm ($R > 99.8\%$) and highly transmitting at 1064 nm ($T > 95\%$). The other side of the mirror M2 was antireflective at 1064 nm ($R < 0.2\%$). For the flat mirror M3, one side was coated to be highly reflective at 1064 nm and highly transmitting at 593 nm ($T > 90\%$). The other side of the mirror M3 was antireflective at 593 nm. The 20 mm long Q switcher (Gooch and Housego) had antireflection coatings at 1064 and 1342 nm on both faces and was driven at a 41 MHz center frequency with 3.0 W of rf power. An intracavity PPKTP crystal was employed to obtain a SFM 593 nm output. The PPKTP crystal was 5 mm

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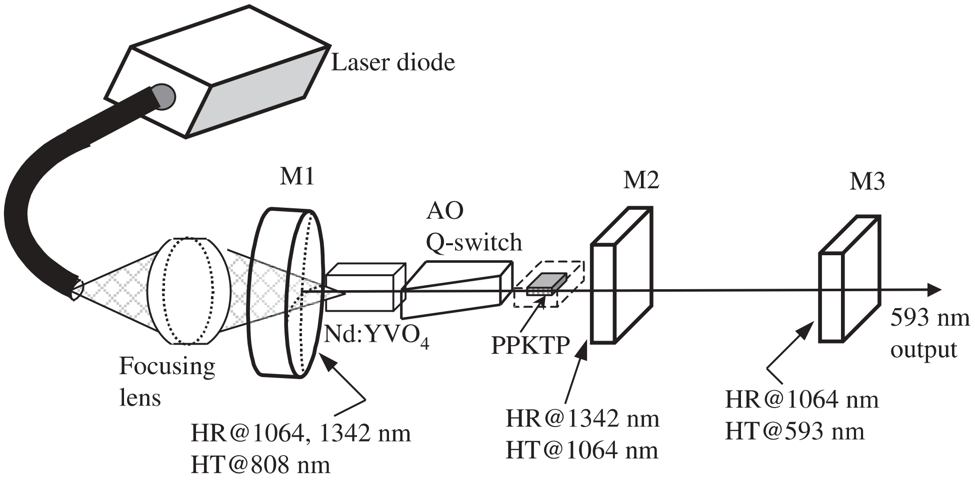

FIGURE 1 Schematic of intracavity sum frequency mixing in the diode-end-pumped Q-switched Nd : YVO$_4$ dual wavelength laser at 1064 and 1342 nm with a PPKTP crystal

long, 1 mm thick, and 2 mm high, and had a 12.6 μm grating period with antireflection coatings at 1064 and 1342 nm on both faces. The PPKTP was mounted in a copper housing with its temperature fixed by a thermoelectric device, a negative temperature coefficient thermistor and a controller. With this controller, the PPKTP temperature was stabilized with an uncertainty of 0.25 °C.

3 Results and discussion

The geometrical length between M1 and M2 for $\lambda_1 = 1342$ nm oscillation was fixed at $d_{1342} = 5$ cm. The geometrical length between M1 and M3 for 1064 nm emission was varied to obtain the maximum output at 593 nm. Experimental results reveal that the optimum geometrical length for $\lambda_2 = 1064$ nm was in the region of $d_{1064} \approx 15$ cm. The ratio of the optical resonator length for optimum performance can be found to be $d^*_{1064}/d^*_{1342} \approx 2.3$. This value is very close to the ratio of the stimulated-emission cross section between ${}^4F_{3/2} - {}^4I_{11/2}$ and ${}^4F_{3/2} - {}^4I_{13/2}$ transitions, $\sigma_{1064}/\sigma_{1342} \approx 2.1$. Lin and Shen [15] have theoretically proposed that the optimal temporal overlap of the wavelengths in a Q-switched laser can be achieved by adjusting the ratio of the optical resonator lengths for the two wavelengths relative to their emission cross sections. The present result for the optimum cavity configuration is consistent with their theoretical analysis.

Considering the SFM process in the PPKTP, the quasi-phase matched (QPM) condition in a collinear interaction is $(n_3/\lambda_3) - (n_2/\lambda_2) - (n_1/\lambda_1) = (1/\Lambda)$, where λ_3 is the wavelength of the sum-frequency beam, n_i is the refractive index of the wave at λ_i for $i = 1, 2, 3$, and Λ is the domain grating period of the PPKTP. Substituting the published Sellmeier equation [16, 17], into the QPM condition for SFM, we calculated the phase-matching temperature as a function of the grating period of the PPKTP and plotted the result in Fig. 2. In our experiment, the PPKTP sample was fabricated to have a 12.6 μm grating period. The optimum QPM temperature was found to be ~ 52.5 °C. Figure 3 shows the experimental result for the dependence of the average yellow-orange output power on the temperature of the PPKTP crystal at a pump power of 17 W and a pulse repetition rate of 35 kHz. It can be seen that the experimental optimum QPM temperature 51 ± 0.5 °C agreed very well with the theoretical result. Compared with the ideal sinc^2 shape related to the plane wave approximation, the asymmetry of the experimental results as seen in Fig. 3 is supposed to come from the condition of Gaussian beams in the laser cavity. A similar asymmetry in temperature dependence was also found in difference frequency mixing in PPKTP [13]. On the other hand, the phase-matching temperature full-width at half-maximum (FWHM) ΔT is about 17 °C. This result indicates the FWHM temperature acceptance bandwidth to be 8.5 °C cm, which is in agreement with the theoretical value 7.5 °C cm expected on the basis of the temperature dependent Sellmeier equation [16, 17].

With optimum phase-matching temperature, the SFM efficiency is investigated as a function of input power and pulse repetition rate. Figure 4 depicts the dependence of the average yellow-orange output power on the incident pump power at a pulse repetition rate of 35 kHz. The threshold for 593 nm

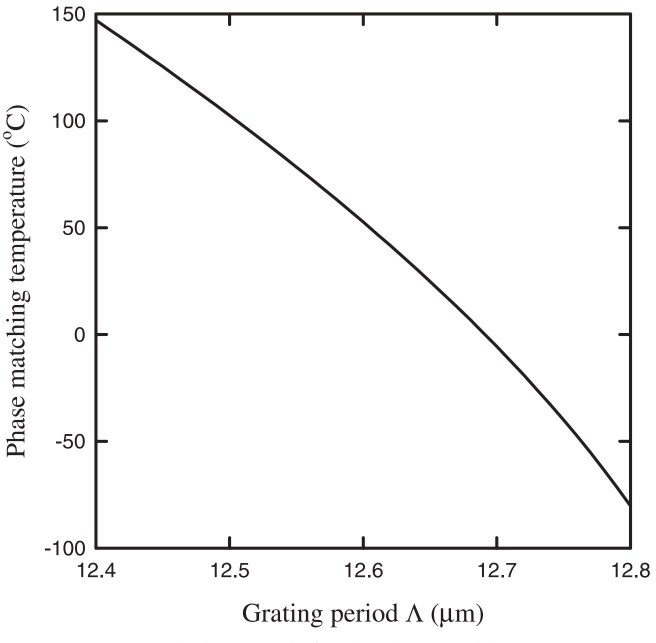

FIGURE 2 The calculated result for the phase-matching temperature as a function of the grating period of the PPKTP for SFM process at 1064 and 1342 nm

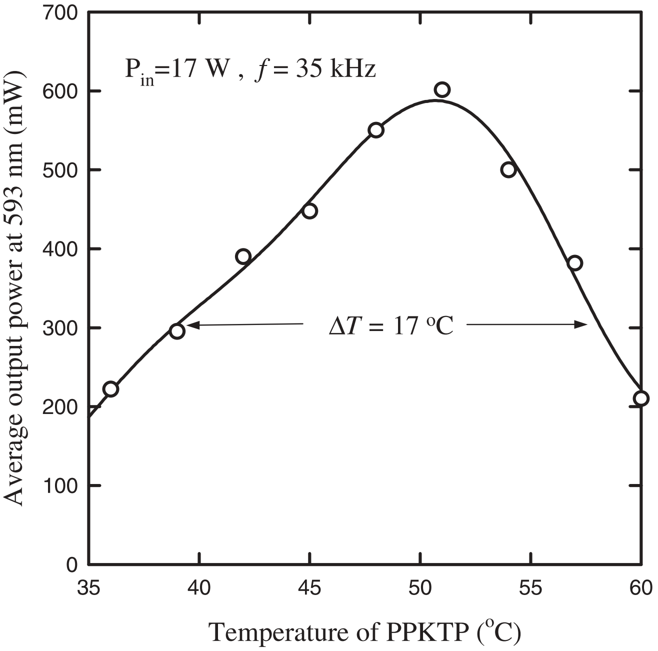

FIGURE 3 The experimental result for the dependence of the average yellow-orange output power on the temperature of the PPKTP crystal at a pump power of 17 W and a pulse repetition rate of 35 kHz

operation of the laser was approximately 3 W. At a repetition rate of 35 kHz, 610 mW of average yellow-orange output power was obtained at a pump power of 17 W. This corresponds to an optical conversion efficiency of 3.6%. The beam quality factor at the maximum output power was estimated to be less than 1.5. Exceeding 17 W of pump power, the output power was found to saturate because the thermal lensing effect was beginning to push the resonator into instability.

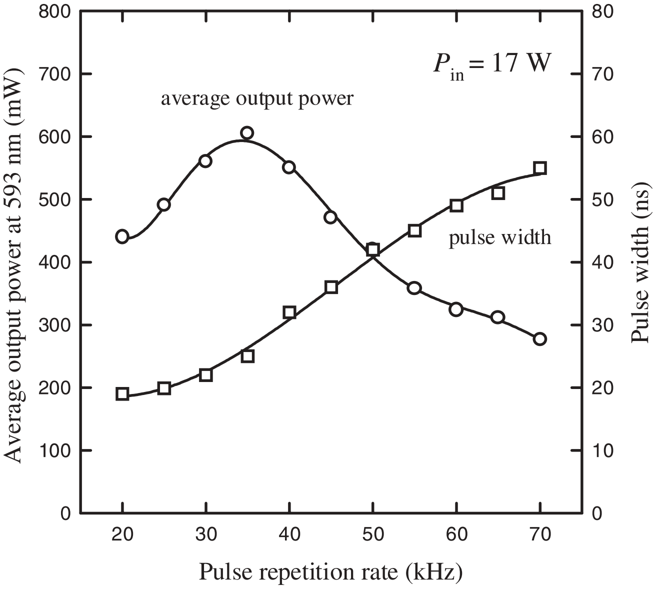

FIGURE 5 Average yellow-orange output power and the pulse width as a function of the pulse repetition rate at 17 W of pump power

The output pulses at 593 nm were recorded by a LeCroy 9354C digital oscilloscope (500 MHz bandwidth) and a fast Si PIN photodiode with a rise time of ∼ 0.35 ns. Figure 5 depicts the average output power at 593 nm and the pulse width as a function of the repetition rate at 17 W of pump power. The pulse width varied between 18.5 and 55 ns as a function of the repetition rate. Figure 6 shows the peak power at 593 nm versus the pulse repetition rate at 17 W of pump power. The peak power was found to increase from 70 W to 1.1 kW when the pulse repetition rate varied from 70 kHz to 20 kHz.

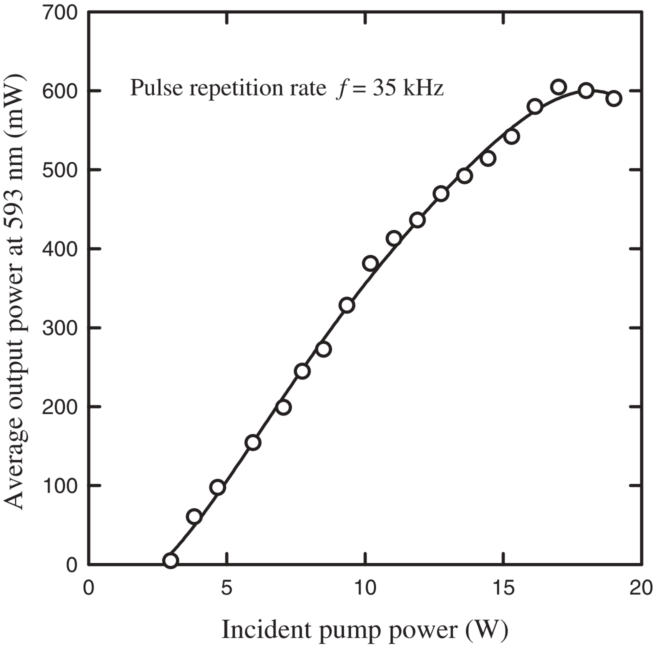

FIGURE 4 Dependence of the average output power at 593 nm on the incident pump power at a pulse repetition rate of 35 kHz

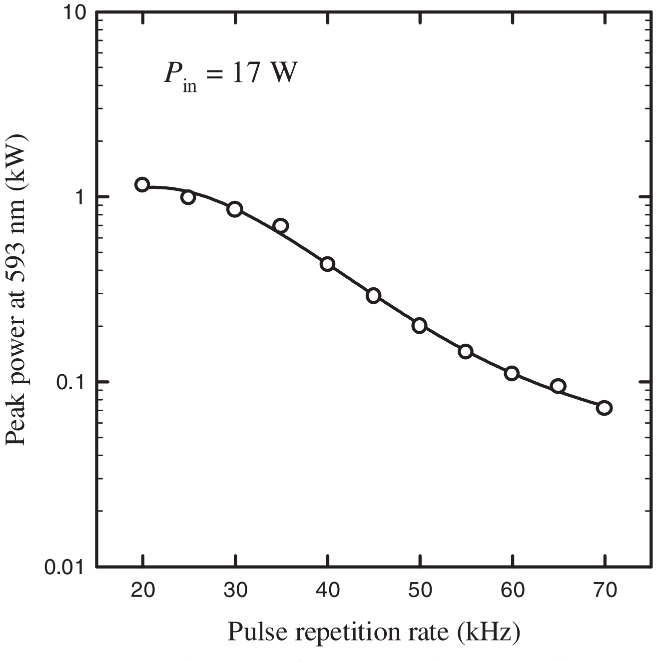

FIGURE 6 The peak power at 593 nm versus the pulse repetition rate at 17 W of pump power

4 Conclusion

We have used a PPKTP crystal in a diode-pumped Q-switched dual-wavelength laser to efficiently generate high-peak-power yellow-orange light at 593 nm through the SFM process. The optimum phase-matching temperature is in good agreement with the result calculated from the reported values of temperature-dependent refractive index for the KTP crystal. The temperature acceptance bandwidth was found to be 17 °C for a 5 mm length PPKTP crystal. Under optimal phase-matching conditions, the maximum average power exceeds 600 mW at a pulse repetition rate of 35 kHz, and the highest peak power amounts to 1.1 kW at 10 kHz.

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