Influence of the KTP crystal boundary temperature on conversion efficiency in high power green laser

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The influence of the $KTiOPO_4$ (KTP) crystal boundary temperature on conversion efficiency in high power green laser has been studied theoretically and experimentally. Temperature distribution inside the KTP crystal has been analyzed by solving the thermal conductivity equation. From the temperature distribution inside the KTP crystal, we have calculated the optimal phase-matching angles of the type-II KTP crystal as a function of temperature. The second-harmonic conversion efficiency as a function of temperature has also been calculated. In the experiment, two KTP crystals with different phase-matching angles were used in the intrcavity-frequency-doubled resonator. When the boundary temperature of KTP-A ($\phi = 23.6°$, $\theta = 90°$ under the condition of 27 °C temperature) was setting at 4 °C, a maximum green light power of 104 W was generated at repetition rate of 20.7 kHz and pulse width of 132 nm with pumping current of laser diode of 18.3 A, leading to 10.2% optical-to-optical conversion efficiency. When KTP-B crystal ($\phi = 24.68°$, $\theta = 90°$ under the condition of 80 °C temperature) was employed, an average output power of 110 W at 532 nm has been achieved with values of 11.5% and 2% for the optical-to-optical efficiency and the instability, respectively. The optimal boundary temperature of this KTP crystal has been found to be 48.8 °C.

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High power all-solid-state green laser with high stability and high repetition rate operation has wide applications, such as material processing, coherent telecommunication, and medicine. One of the promising methods to obtain high power green laser source is using an intracavity frequency doubling scheme based on the nonlinear crystal. $KTiOPO_4$ (KTP) crystal is an excellent nonlinear crystal with a high nonlinear conversion coefficient, large allowed angle and temperature, and small walk-off angle. The KTP crystal has been widely applied to generate high power green light in intracavity-frequency-doubled Nd:YAG laser. Garrec *et al.*[1] employed a Z-cavity to demonstrate an output power of more than 100 W at 532 nm with a diode-side-pumped Nd:YAG laser rod and a KTP intracavity crystal. Honea *et al.*[2] reported a diode-end-pumped, double acousto-optical Q-switched Nd:YAG laser with an intracavity KTP in a V-cavity arrangement. An output power of 140 W at 532 nm was achieved. Kojima *et al.*[3] suppressed the power instability of green laser by compensating the thermal lensing effect of the KTP crystal. Stable continuous wave (CW) green power of 27 W was generated in a diode-side-pumped intracavity-frequency-doubled Nd:YAG. Yi *et al.*[4] achieved a 101-W green laser by use of a monolithic diffusive reflector having three slits and a rod with low doping concentration, leading to 25.4% optical-to-optical efficiency. Jiang *et al.*[5] reported a 68-W green laser with intracavity KTP in an L-cavity scheme. However, all the published research works did not show the influence of the thermal effect in the KTP crystal on conversion efficiency at a high power level.

The temperature gradient in the KTP crystal generates due to absorbing the fundamental- and second-harmonic wave powers. The phase-matching conditions are changed at different positions inside the KTP crystal. So the conversion efficiency decreases significantly in intracavity-frequency-doubled resonator. As a consequence, the output power becomes unstable. Zheng *et al.*[6] theoretically analyzed the influence of the thermal effect on the conversion efficiency and the intensity profile of the type-II phase-matching second-harmonic wave in the KTP crystal. However, they did not show the temperature distribution inside the KTP crystal, and the influence of the KTP temperature on the nonlinear parameter. Reference [7] reported a method of tilting the KTP crystal in resonator to compensate the phase mismatching. However, this method increases the reflection loss on the end of the KTP crystal and makes green beam worse.

In this paper, the KTP crystal temperature distribution was analyzed by solving thermal conduction equation. The phase-matching angles as a function of temperarue were calculated by using the temperature derivative of refractive indices in the KTP crystal. The second-harmonic conversion efficiency of KTP was also analyzed at different temperatures. From the calculated results, we identify the optimal boundary temperature, at which the center temperature of the KTP crystal is stabilized at the optical phase-matching temperature, hence the conversion efficiency and the output beam stability increase. In the experiment, an average output power of 104 W at 532 nm was generated at repetition rate of 10.6 kHz and pulse width of 132 ns in a diode-side-pumped Nd:YAG laser when the boundary temperature of the KTP-A crystal ($\phi = 23.6°$, $\theta = 90°$ under the condition of 27 °C temperature) was set at 4 °C, leading to 10.2% optical-to-optical conversion efficiency. A 110-W high stability green laser was obtained by setting the boundary temperature of KTP-B crystal ($\phi = 24.68°$, $\theta = 90°$ under the condition of 80 °C temperature) at 48.8 °C, leading to 11% optical-to-optical conversion efficiency.

In an intracavity-frequency-doubled Nd:YAG laser, the thermal power in the KTP crystal is uniform along the direction of fundamental wave, which is suitable for the case of the intracavity-frequency-doubled lasers. Therefore, the variations of temperature along the axial direction can be neglected when the temperature distributions is analyzed inside the KTP crystal. Because the cooling-surface convection coefficient is orders of magnitude larger than the natural convection coefficient on the ends, the thermal power has a radial distribution and the power dissipation at end face can be neglected. Hence, the KTP temperature should satisfy the two-dimensional thermal conduction equation[8]

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{Q}{K}, \tag{1}$$

where x, y indicate the positions inside the KTP crystal, T is the temperature at the different positions inside the KTP crystal, K is the thermal conductivity, Q is the calorific power, described with

$$Q = \frac{2P\alpha l}{\pi r_0^2} \mathrm{e}^{\frac{-2(x^2+y^2)}{r_0^2}}, \tag{2}$$

where the size of the KTP crystal is $6\times6\times9.2$ mm^3, the power of the fundamental wave P is 180 W, the average absorption coefficient α is 0.6% cm^{-1}, and the size of the fundamental wave beam r_0 is 3 mm. The calculated temperature distributions inside the KTP crystal are depicted in Fig. 1.

It is well known that the principal values of refractive indices n_X, n_Y, and n_Z in the KTP crystal are the functions of temperature. According to the formulas of Ref. [9,10], phase matching angle ϕ_{pm} is calculated at different temperatures for type-II phase-matching KTP crystal. Figure 2 shows the phase-matching angles as a function of temperature.

We assume that the thermal conductivity of the KTP crystal is constant. So the center temperature of the KTP crystal changes with the boundary temperature.

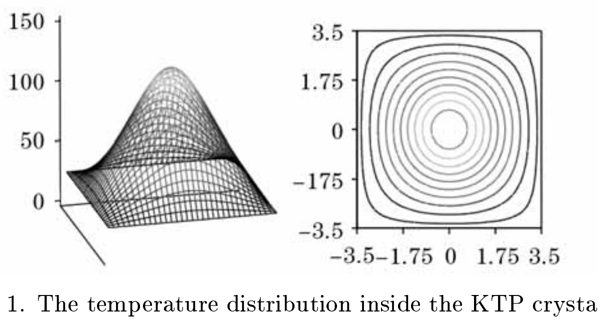

Fig. 1. The temperature distribution inside the KTP crystal.

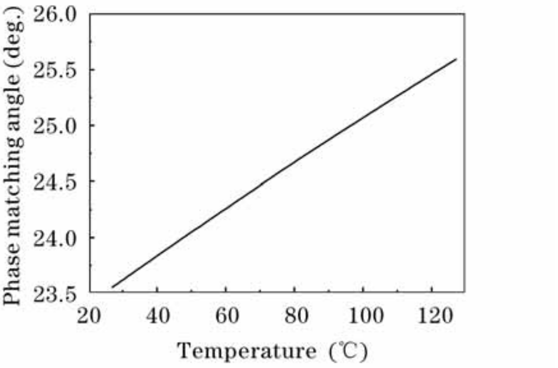

Fig. 2. The phase-matching angles versus KTP temperatures ($\theta = 90°$).

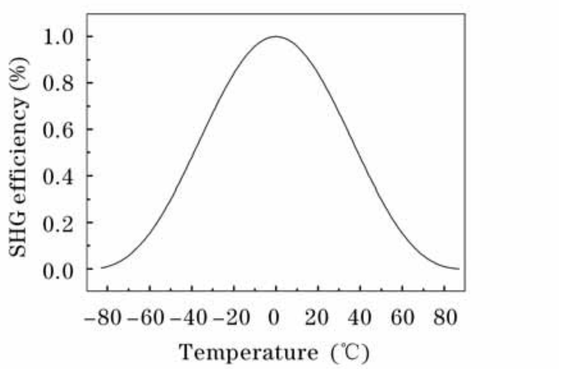

Fig. 3. The SHG conversion efficiency as a function of temperature in the KTP crystal.

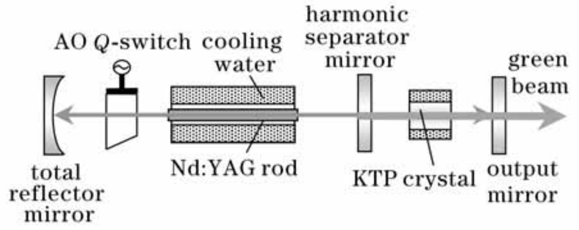

Fig. 4. Schematic diagram of the high power green laser.

From Fig. 1, it can be seen that the temperature difference between the center and the boundary is larger than the allowed phase-matching temperature of the KTP crystal, hence the second-harmonic-generation (SHG) efficiency decreases. In the intracavity resonator, the power intensity distribution of the fundamental wave is a Gaussian-like distribution, so most of the fundamental wave energy is in the center part of the KTP crystal. Therefore, as long as stabilizing the temperature of center part of the KTP crystal, most of fundamental wave energy could satisfy the optimal phase-matching temperature inside the KTP crystal. By controlling KTP crystal boundary temperature, the temperature of the center parts of the KTP crystal could be stabilized, the SHG efficiency will be improved. Figure 3 shows the normalized SHG efficiency as a function of temperature in the KTP crystal.

Resonator scheme of high power intracavity-frequency-doubled laser is shown in Fig. 4.

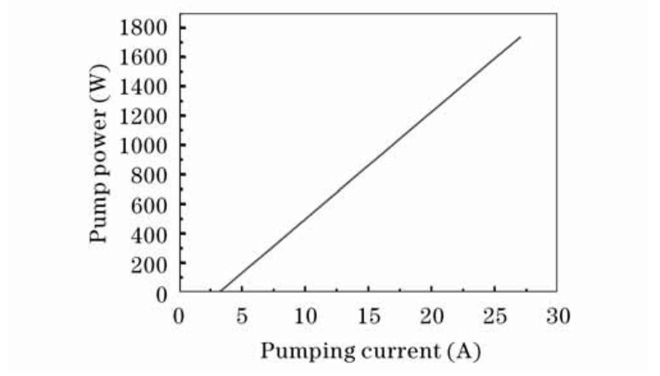

Fig. 5. The curve of output power versus pumping current of pump module.

In our experiment, we used a diode laser pump module (CEO Inc.). The pump module consists of 80 diode bars (808-nm wavelength, 20-W output power), with a pentagon pump model. The curve of output power versus pumping current of pump module is shown in Fig. 5. The water faucet of the pump module can be connected to a water-cooled temperature control system. Considering the thermal lens effect of the Nd:YAG rod and the KTP crystal in high power operation, we employed plano-concave cavity structure in order to achieve high satiability output and increase output power. The total cavity length was 550 mm. The dimension of Nd:YAG rod was $\phi 6.36 \times 142$ mm. An acousto-optic modulator (provided by NEOS Inc., USA.) with high diffraction loss was used as Q-switch. Two KTP crystals with different phase-matching angles were employed. The KTP crystal was coated with dual-wavelength antireflection and was placed between output mirror ($T > 98\%$ at 532 nm, $R > 99.5\%$ at 1064 nm, where T is transmission and R is reflection) and harmonic separator mirror ($R > 99.5\%$ at 532 nm, $T > 98\%$ at 1064 nm). The dimension of KTP-A crystal was $7 \times 7 \times 10$ mm^3 (CSK Photonics Co. Ltd., Jinan, China). Its boundary temperature was controlled in the heating sink by cooling system. The dimension of KTP-B crystal was $6 \times 6 \times 9.2$ mm^3. Its boundary temperature was controlled in the oven by a digital temperature controller (Fuji Inc., Japan). By changing boundary temperature of KTP crystals, the condition of optimum phase matching angles could be satisfied in the center part of KTP crystals.

The KTP-A crystal was used under the condition of lower temperature in order to satisfy the phase matching condition of the center parts of crystal. The green laser output power changed with the boundary temperature of KTP crystal. The green laser output powers at the different boundary temperatures of the KTP crystal are shown in Fig. 6.

When the temperature of the KTP crystal decreased, the green laser output power increased obviously. A maximum green laser power of 104 W was generated at repetition rate of 20.7 kHz and pulse width of 132 ns when pumping current of laser diodes was 18.3 A, the temperature of KTP was 4.3 °C, leading to 10.2% optical-to-optical conversion efficiency. Figure 7 shows the 532-nm output power at the different pumping currents of diode laser.

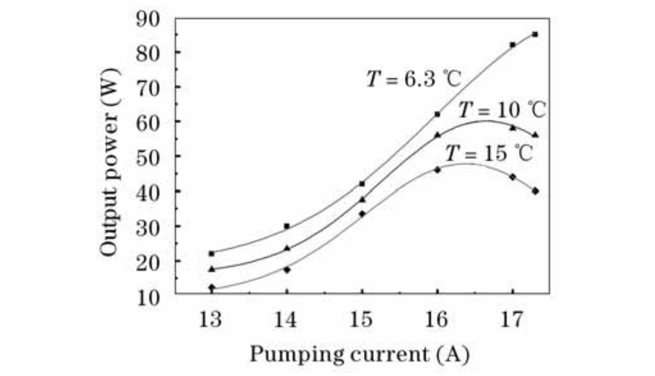

Fig. 6. The curve of output power versus pumping current at different boundary temperatures of the KTP crystal.

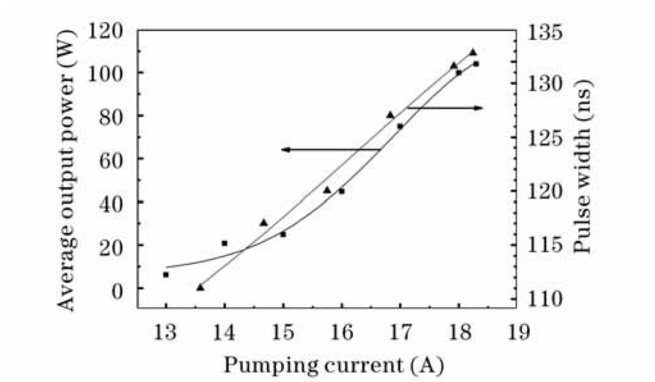

Fig. 7. 532-nm output power at different pumping currents of diode laser.

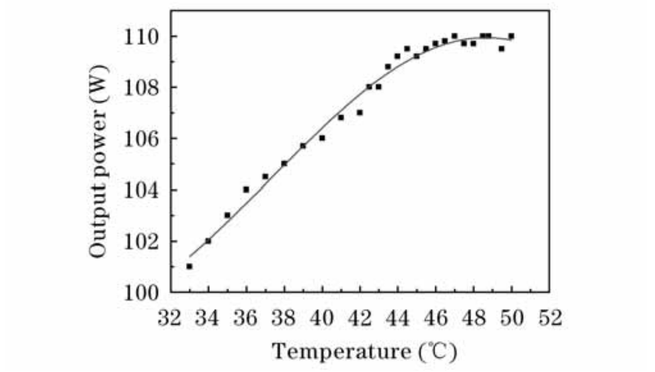

Fig. 8. The green laser output power versus KTP crystal temperature.

The KTP-B crystal was used under the high temperature condition. In the experiment, when we adjusted the heating oven temperature, the green laser output power fluctuated. With the temperature decreasing, the output power reduced obviously. Figure 8 shows that the green laser output power changes with KTP crystal temperature. The output power falls down about 10 W when the boundary temperature changes from 50 to 33 °C. From 50 to 47 °C, the fluctuation of green laser output power is very small. This is because the temperature difference between the center and the boundary of the KTP crystal is less than allowed temperature of 25 °C. So phase mismatching will be negligible. In order to keep the output

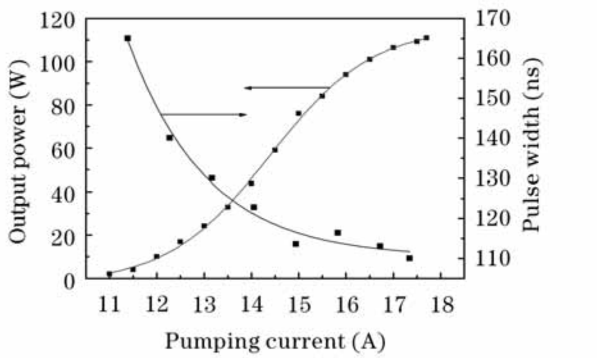

Fig. 9. The green laser output power and pulse width versus diode pumping current.

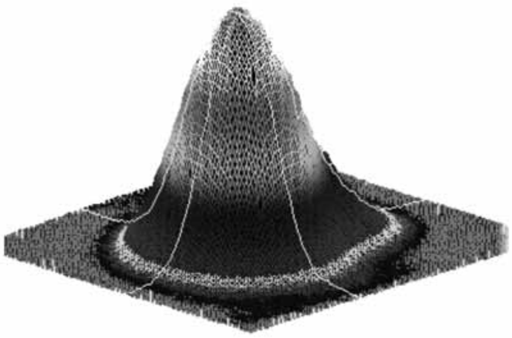

Fig. 10. The distribution of green laser beam at 110-W output power.

power stability, we control the heating oven of the KTP crystal with a long-term stability of ±0.1 °C. When the pump power is 1000 W, the repetition rate is 10.6 kHz, under the temperature of KTP crystal heating oven of 48.8 °C, the maximum green laser output power is 110 W, and the pulse width is 110 ns.

At 100-W green laser output power, the green laser remained stable operation at least for 5 hours, with an output power fluctuation of less than 2% and pulse-to-pulse instability of 5%. We believe that our technologies of employing high operating temperature KTP crystal and precisely controlling its boundary temperature can effectively suppress the instability. Figure 9 shows the green laser output power and pulse width as functions of diode pumping current. Figure 10 shows the distribution of green laser beam at 110-W output power, which was measured by LBA-300PC laser beam analyzer (provided by American Spiricon Inc.).

In this work we employed two KTP crystals with difference phase-matching angles. When the boundary temperature of KTP-A was 4 °C, a maximum green laser power of 104 W at 532 nm was generated at repetition rate of 20.7 kHz and pulse width of 132 ns with pumping current of laser diode of 18.3 A, leading to 10.2% optical-to-optical conversion efficiency. However, it is easy to generate 'graying track' and appears condensation at the surface of KTP crystal under the condition of low temperature, leading to low conversion efficiency and damage threshold. When the boundary temperature of KTP-B was 48.8 °C, the maximum average output power of 110 W was generated with values of 11.5% and 2% for the optical-to-optical efficiency and the instability, respectively. The condition of high temperature could prevent the KTP crystal from generating 'graying track' and increase damage threshold. So the KTP crystal with high temperature is more suitable for high power laser.

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